INL/CON-23-74124-Revision-0

ATF-2 Sensitivity M&C 2023 (Slides)

August 2023

Changing the World's Energy Future

Travis J Labossiere-Hickman, Tristen Rogers, Michael Jason Worrall, Mehmet Turkmen

Idaho National Laboratory

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Sensitivity of Accident Tolerant Fuels Experiments in the Center Flux Trap of the Advanced Test Reactor to Adjacent Experiments

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

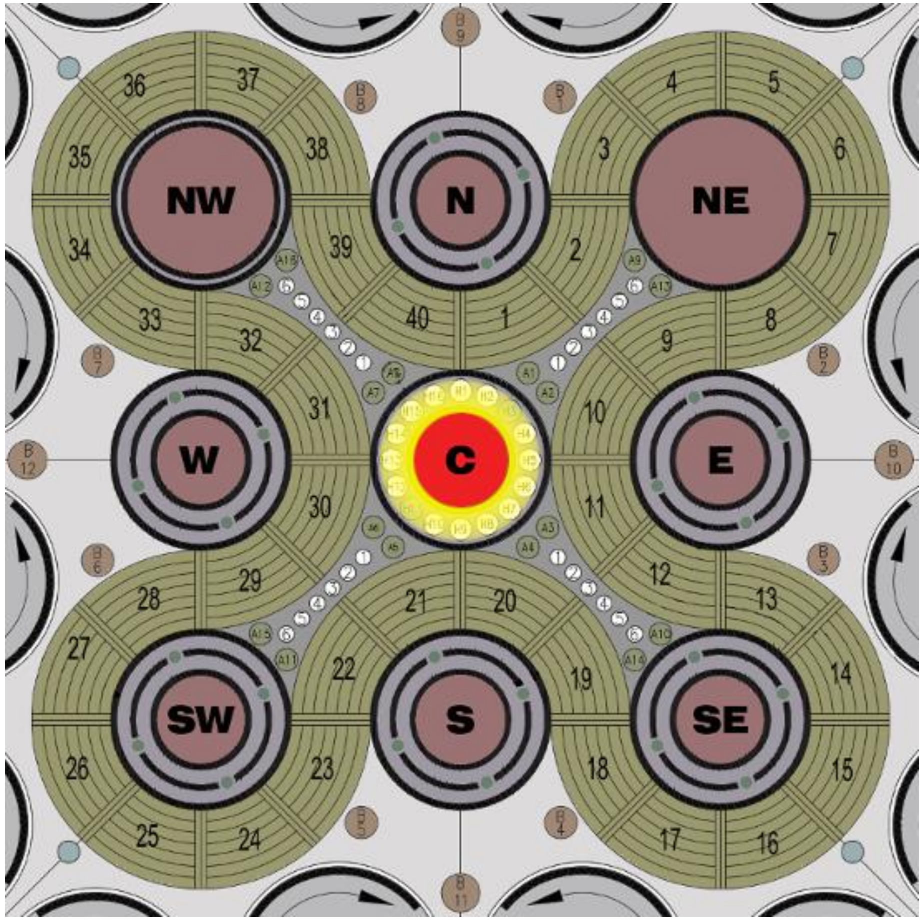
Idaho National Laboratory

Background

- The Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) offers some of the world's highest neutron fluxes for nuclear research.
- The unique design of the ATR allows regions of the reactor to be at different powers, with experiments irradiated independently of one another.
  - Experiment design and analysis is done with either best guess at the cycle configuration, or a bounding case.
  - Sometimes other experiments get moved/replaced based on sponsors' needs.
  - Details of other experiment designs may be not even be known (restrictions).
- We wanted to study how sensitive ATF-2 is to the adjacent H and inner-A positions.

Can we predict what our experiment will do if an adjacent experiment is changed?

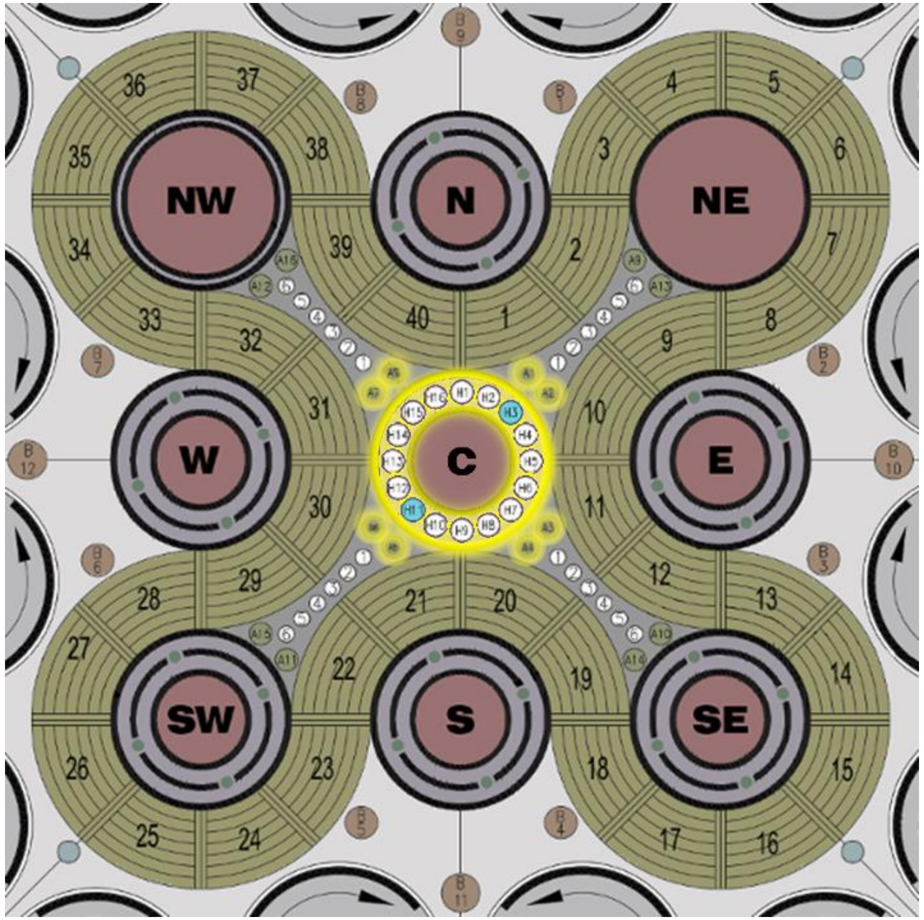
Advanced Test Reactor Layout



Typical Fluxes

Location	Diameter (inches)	Thermal Flux (n/cm^2-s)	Fast Flux (n/cm^2-s)
North Flux Trap	3.250	4.4E+14	9.7E+13
West Flux Trap	3.250	4.4E+14	9.7E+13
East Flux Trap	3.250	4.4E+14	9.7E+13
South Flux Trap	3.250	4.4E+14	9.7E+13
Center Flux Trap	**3.160**	**4.4E+14**	**9.7E+13**
Northwest Flux Trap	5.375	4.4E+14	2.2E+14
Northeast Flux Trap	5.375	4.4E+14	2.2E+14
Southwest Flux Trap	3.250	4.4E+14	9.7E+13
Southeast Flux Trap	3.250	4.4E+14	9.7E+13
Small B-Position	0.875	2.5E+14	8.1E+13
Large B-Position	1.500	1.1E+14	1.6E+13
Inner-A Position	0.625	1.9E+14	1.7E+14
Outer-A Position	0.500/0.625	2.0E+14	2.3E+14
H-Hole	0.625	1.9E+14	1.7E+14
Small I-Position	1.500	8.4E+13	3.2E+12
Medium I-Position	3.250	3.4E+13	1.3E+12
Large I-Position	5.000	1.7E+13	1.3E+12

Advanced Test Reactor Layout



Typical Fluxes			
Location	**Diameter (inches)**	**Thermal Flux (n/cm^2-s)**	**Fast Flux (n/cm^2-s)**
North Flux Trap	3.250	4.4E+14	9.7E+13
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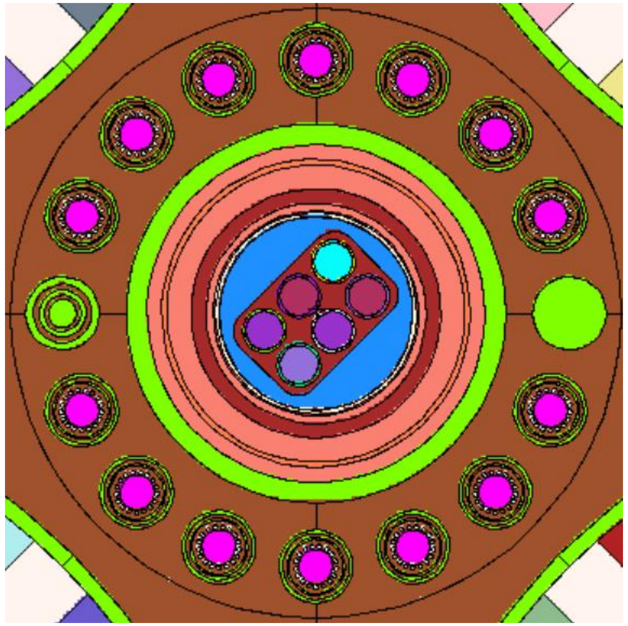
East Flux Trap	3.250	4.4E+14	9.7E+13
South Flux Trap	3.250	4.4E+14	9.7E+13
Center Flux Trap	3.160	4.4E+14	9.7E+13
Northwest Flux Trap	5.375	4.4E+14	2.2E+14
Northeast Flux Trap	5.375	4.4E+14	2.2E+14
Southwest Flux Trap	3.250	4.4E+14	9.7E+13
Southeast Flux Trap	3.250	4.4E+14	9.7E+13
Small B-Position	0.875	2.5E+14	8.1E+13
Large B-Position	1.500	1.1E+14	1.6E+13
Inner-A Position	**0.625**	**1.9E+14**	**1.7E+14**
Outer-A Position	0.500/0.625	2.0E+14	2.3E+14
H-Hole	**0.625**	**1.9E+14**	**1.7E+14**
Small I-Position	1.500	8.4E+13	3.2E+12
Medium I-Position	3.250	3.4E+13	1.3E+12
Large I-Position	5.000	1.7E+13	1.3E+12

ATF-2: Introduction

- The U.S. Accident-Tolerant Fuels (ATF) program is a congressionally mandated research and development (R&D) program to create and test light water reactor fuels and claddings with enhanced accident tolerance.
- ATF-2 is a series of irradiation experiments testing vendors' fuel and cladding samples in the center flux trap (CFT) of the ATR at INL.
- A typical test train (TT) comprises 4–6 tiers of specimens.
- A 6-pin tier from the ATF-2C experiment is shown here.



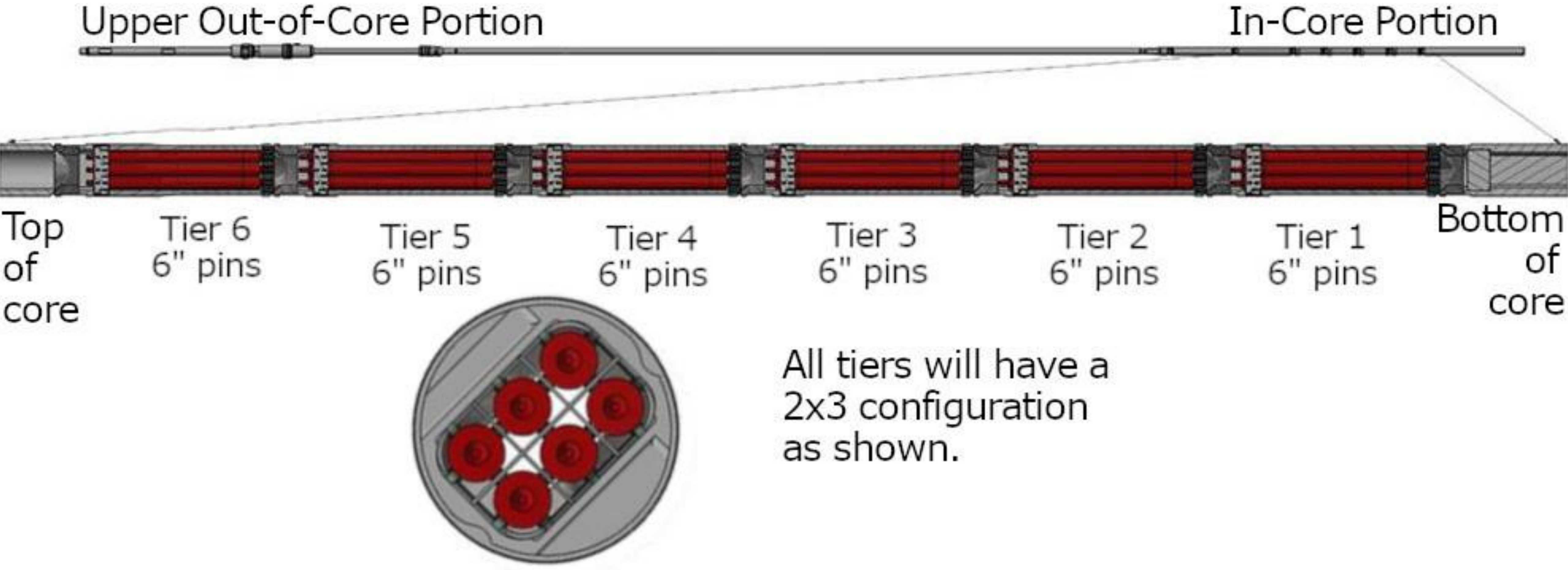
ATF-2: Experiment Parameters

- Each experiment aspires to attain certain programmatic parameters for R&D.
  - **Linear heat generation rates (LHGR)**
  - **Peaking factor**
  - Neutron fluence and **flux spectrum**
  - Material damage/displacements per atom (DPA)
- Experiments in ATR must also satisfy safety criteria.
  - **Maximum fission power**
  - Various **reactivity worth (ρ)** considerations
  - Temperature coefficient of reactivity
  - ATR driver fuel axial perturbation

ATF-2Pert: A Generic ATF-2 Experiment

- We created a generic ATF-2 TT to study various sensitivities and perturbations.
- This “ATF-2Pert” design:
  - Six identical tiers of six identical rodlets each.
  - All rodlets are fueled pressurized water reactor pins.
  - Each rodlet is made of 6 inches of Zircaloy-4 (Zr4).
  - All rodlets are fueled by a 4-inch stack of 10 UO_2 pellets enriched to 4.95%.
  - No experiment- or vendor-specific materials or properties are used.
- This makes ATF-2Pert “hotter” (in LHGR and ρ) than historical ATF-2 experiments.
  - Real experiments may have non-fueled tiers, varied enrichment, instrumentation, additional structural materials, and shielding or shrouding.
  - Such features can reduce overall sensitivity.

ATF-2Pert: Conceptual Sketch



Adjacent Targets

- The sensitivity of ATF-2Pert's parameters to adjacent targets was studied.
- A grid of irradiation targets from the adjacent H and inner-A positions was defined.
- We wanted to test a representative set of real experiments that been irradiated in those positions.
  - High specific activity (HSA) cobalt, low specific activity (LSA) cobalt, neptunium (Np) oxide, hafnium (Hf) control rods, aluminum and solid flow restrictor outboard position (SFROP) fillers, etc.
- A number of "academic" targets were defined as well.
  - Water, boron carbide (B_4C) control rods, cadmium (Cd), artificially dense Hf, etc.

Adjacent Targets (Continued)

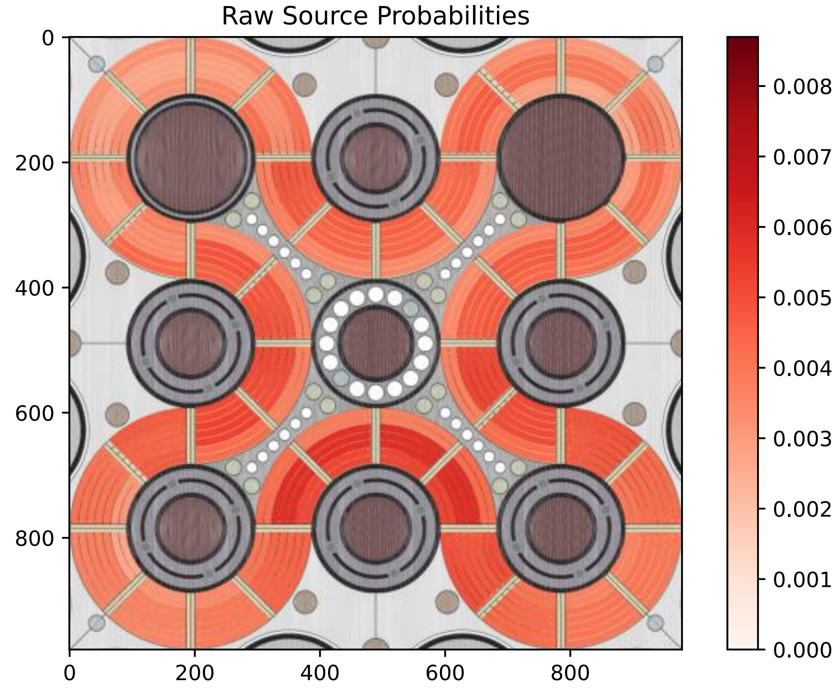
Cycle		H-1	H-2	H-3	H-4	H-5	H-6	H-7	H-8	H-9	H-10	H-11	H-12	H-13	H-14	H-15	H-16
160A-1	…	NEW HSA COBALT	NEW HSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT
159A-1	…		HAFNIUM ROD		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	LSA COBALT	HAFNIUM ROD
158B-1	…	LSA COBALT	LSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	LSA COBALT	LSA COBALT
158A-1	…	LSA COBALT	LSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	LSA COBALT	LSA COBALT
157D-1	…	LSA COBALT	LSA COBALT		NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT		NEW HSA COBALT	NEW HSA COBALT	LSA COBALT	LSA COBALT	LSA COBALT
157C-1	…	LSA COBALT	LSA COBALT		LSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	NEW HSA COBALT	LSA COBALT		LSA COBALT	LSA COBALT	LSA COBALT	LSA COBALT	LSA COBALT
157A-1	…	LSA COBALT	LSA COBALT		LSA COBALT	LSA COBALT	LSA COBALT		LSA COBALT		LSA COBALT		LSA COBALT		LSA COBALT	LSA COBALT	LSA COBALT
156A-1	…	AFIP HAFNIUM ROD	LSA COBALT		LSA COBALT	AFIP HAFNIUM ROD	LSA COBALT	HAFNIUM ROD	LSA COBALT	HAFNIUM ROD	LSA COBALT		LSA COBALT	AFIP HAFNIUM ROD	LSA COBALT	LSA COBALT	LSA COBALT

Methods: Overview

- Set up configurations of experiments in H and inner-A positions.
- Perform Monte Carlo neutron transport calculations using MCNP6.2.
- Tally reactivities and reaction rates.
- Calculate key safety and programmatic parameters.
- Plot mesh tally relative difference using Paraview.

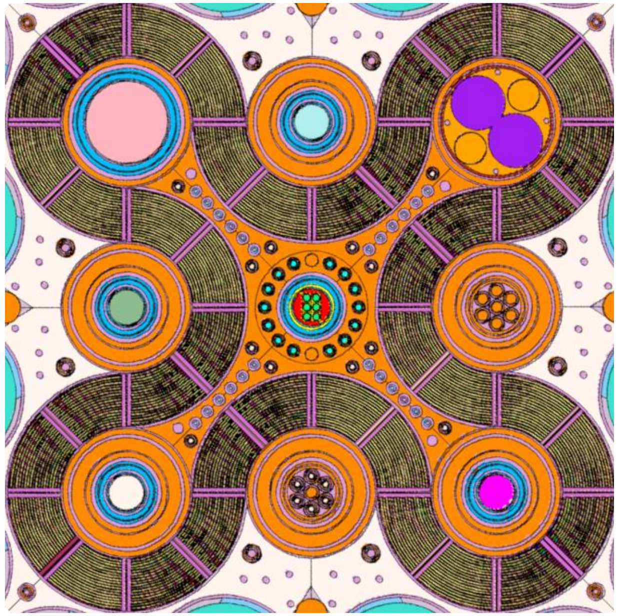
Methods: MCNP

- Fixed-Source Simulations performed using MCNP6.2
- Fluxes and reaction rates:
  - Calculation based on ATR Cycle 169A: the last cycle before the recent core internals changeout.
  - Simplified three-region model
  - Source spatial distribution, lobe power split, and shim configuration from near BOC.
    - Assumed 22.2 MW center lobe power.
    - Scaled to lobe-adjusted total core power (LATCP) of 101.9 MW
  - Energy distribution as Watt fission spectrum.



Methods: MCNP

- Eigenvalue simulations performed using MCNP6.2
- Model:
  - Used 94 CIC benchmark
  - Full 19-plate model
  - Standard stainless-steel backup (BU) assembly
- Reactivities:
  - Select a baseline H/A target configuration.
  - ρ_{ATF}: Worth of config vs. baseline, ATF-2 experiment
  - ρ_{BU}: Worth of config vs. baseline, BU assembly
  - ρ_{0}: Worth of ATF-2 experiment vs. BU assembly, same H/A target configuration



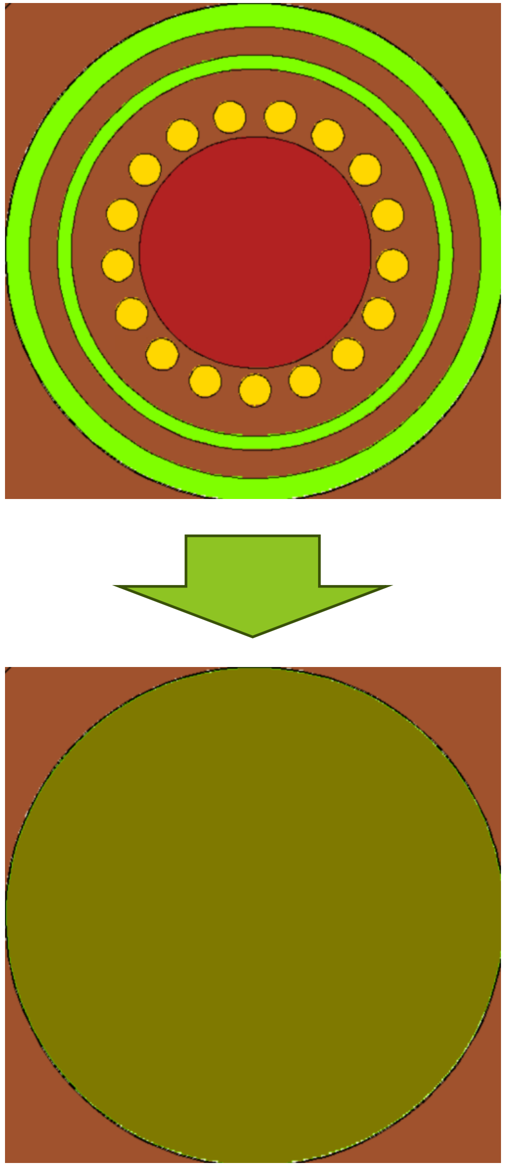
Cross Sections

- Clearly the flux incident on the ATF-2 experiment depends on the substances it has passed through.
- Is the sensitivity to an experiment merely a function of its cross section?
- Collapse each experiment and calculate a homogenized one-group cross section (1GXS).

$$\Sigma_x = \left(\frac{\mathtt{fm4}(x) \times \mathtt{fm4:n}}{\mathtt{fm4:n}} \right) N$$

- Evaluate changes in key parameters to 1GXS.

Does an increase in total or absorption 1GXS cause a corresponding change in safety or programmatic parameters?

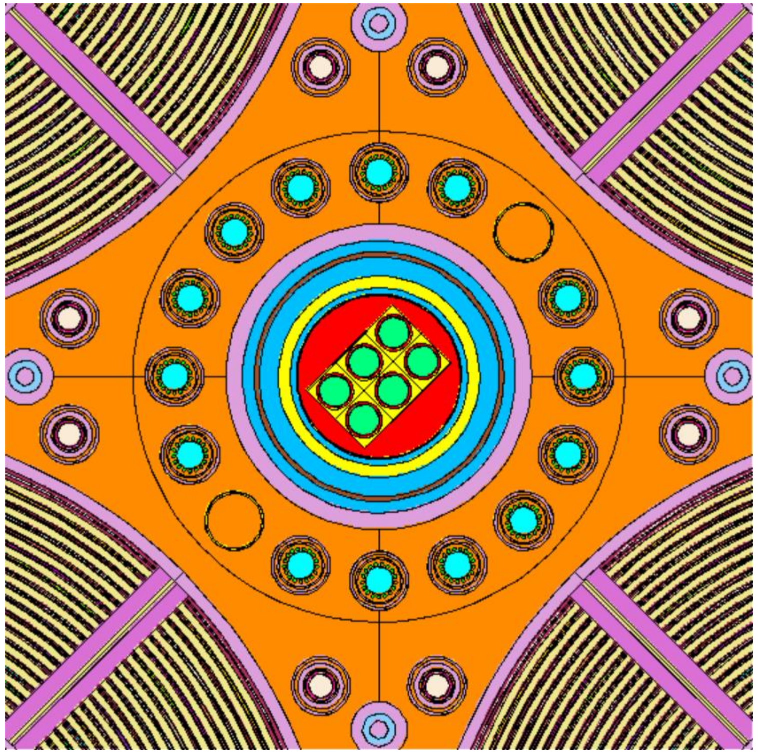


Summary of Results

- Tables of programmatic and safety parameters across configurations
- Flux perturbation plots between pairs of configurations
- One-group cross section tables and plots

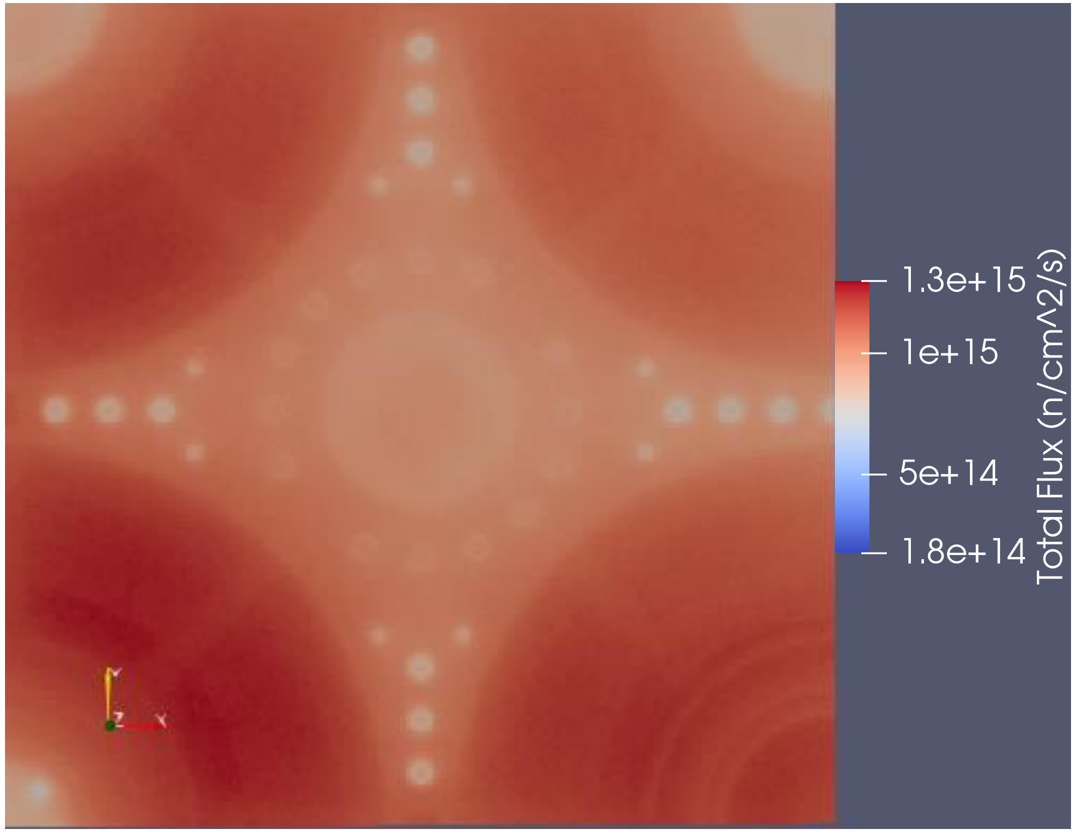
Base Configuration

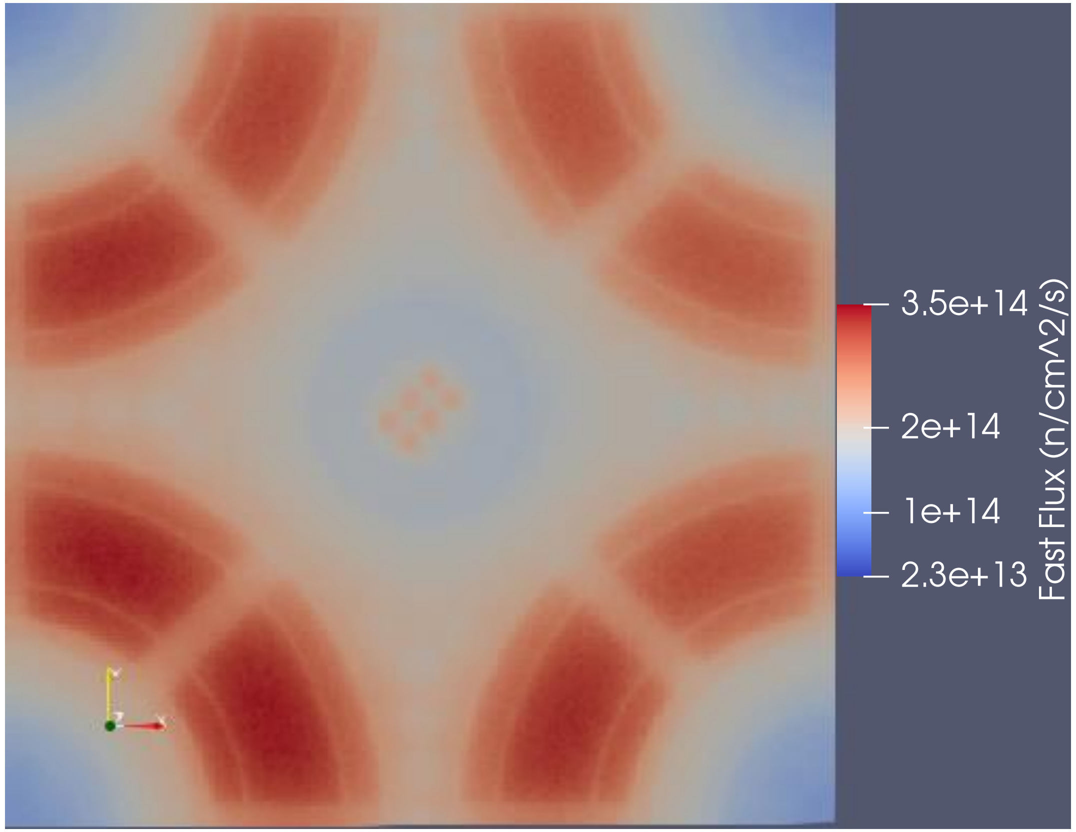
- A common adjacent-target layout was selected as the base configuration.
- The 16 H positions contain 14 HSA cobalt targets and 2 instrumentation positions.
- The 8 inner-A positions contain 8 LSA cobalt targets.



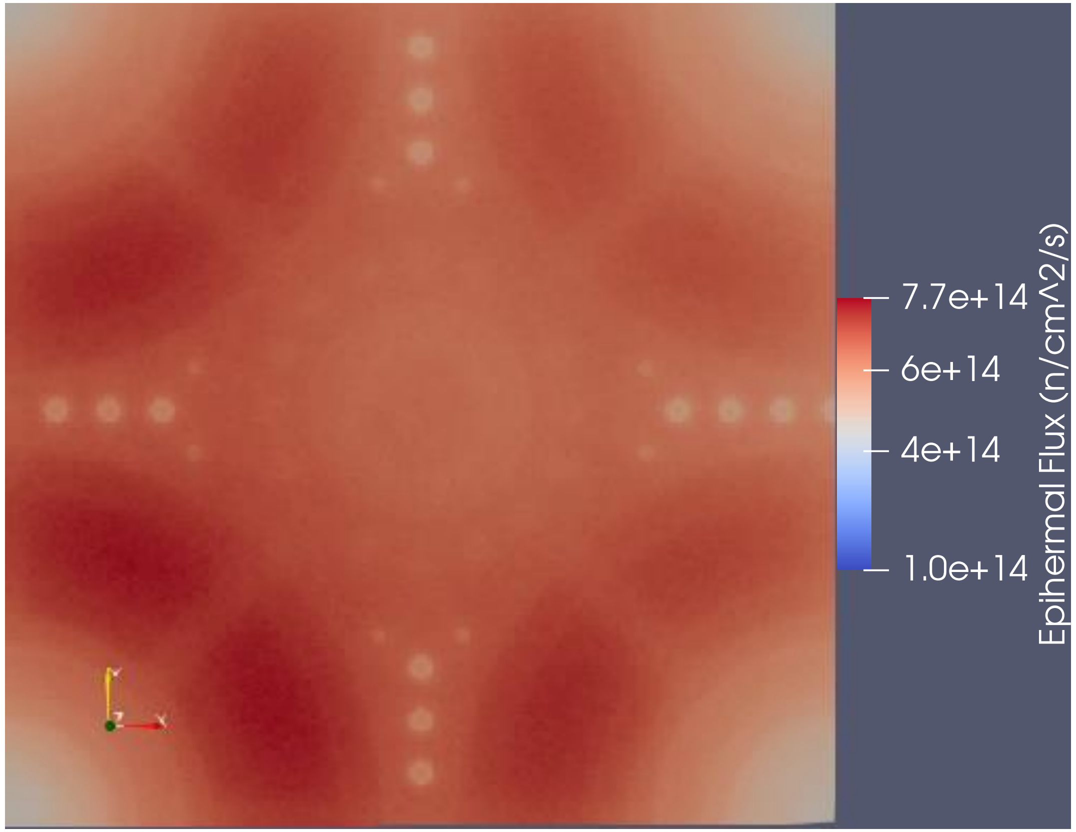
Parameters		
TT Power	181.9	kW
Tier 1 LHGR	406.1	W/cm
Tier 2 LHGR	591.8	W/cm
Tier 3 LHGR	643.9	W/cm
Tier 4 LHGR	608.7	W/cm
Tier 5 LHGR	429.1	W/cm
Tier 6 LHGR	210.2	W/cm
Tier 3 Peaking	1.135	—
Tier 6 Peaking	1.374	—
Thermal Flux	11.1	%
Epithermal Flux	66.8	%
Fast Flux	22.0	%
ρ_{ATF}	–	$
ρ_{BU}	–	$
ρ_0	0.36627	$

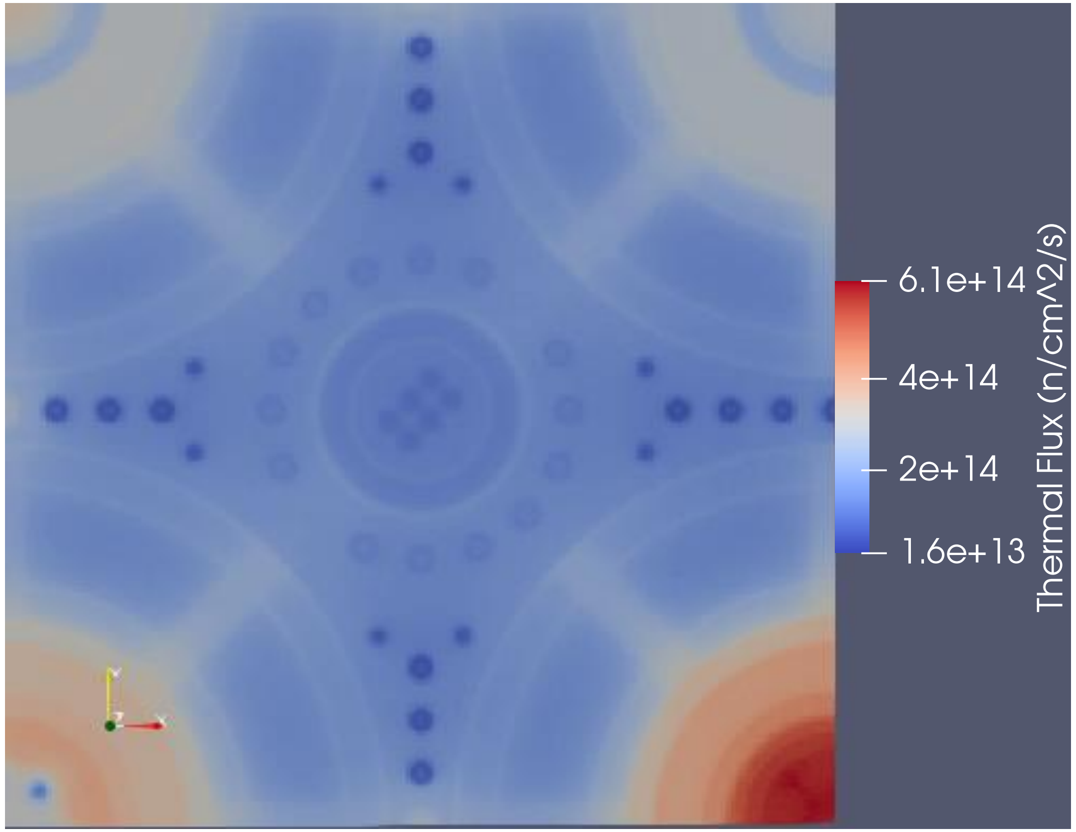
Baseline Flux Profiles





Baseline Flux Profiles



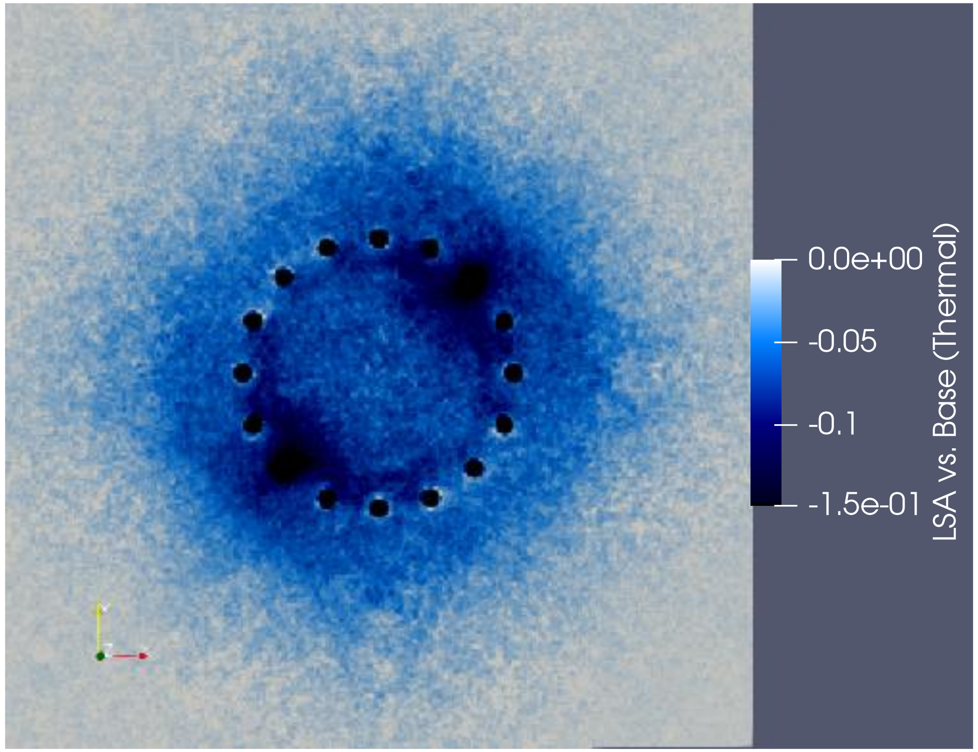


Some Numeric Results
(Extended Results - Appendix)

Inner-A Contents	H contents	TT Power (kw)	Tier 3 LHGR (W/cm)	Thermal Flux (frac)	Fast Flux (frac)	ρ_{ATF} ($)	ρ_{BU} ($)	ρ_0 ($)
LSA	**HSA +instruments**	**181.9**	**643.9**	**0.1114**	**0.2204**	**0**	**0**	**0.36627**
LSA	LSA	171.8	612.1	0.1081	0.2190	−0.78764	−0.74822	0.32685
HSA	HSA	181.5	640.5	0.1108	0.2207	+0.21691	+0.21389	0.36929
HSA	LSA	173.5	617.3	0.1086	0.2193	−0.47625	−0.44657	0.33659
HSA, LSA	HSA, LSA	176.8	626.7	0.1095	0.2199	−0.25508	−0.23967	0.35087
Np	HSA	181.9	642.8	0.1119	0.2214	+0.10370	+0.09731	0.37267
Np	Np	187.3	664.3	0.1170	0.2237	−0.12465	−0.13367	0.37529
HSA	Np	186.5	660.9	0.1158	0.2230	−0.04429	−0.05149	0.37347
HSA	B_4C	181.9	648.6	0.1175	0.2245	−0.82824	−0.80590	0.34392
Np	B_4C	182.0	650.1	0.1185	0.2252	−0.91512	−0.89602	0.34717
B_4C	Np	186.4	661.5	0.1176	0.2243	−0.49715	−0.49839	0.36751
HSA	^3He	178.9	640.7	0.1054	0.2237	+0.56639	+0.57352	0.35914
H_2O	H_2O	237.3	853.3	0.1539	0.2318	+1.39719	+1.20388	0.55958
B_4C	HSA	181.2	641.0	0.1125	0.2220	−0.26619	−0.25643	0.35651
B_4C	SFROP	198.5	711.9	0.1212	0.2220	+0.79658	+0.73199	0.43086
SFROP	Hf	150.8	539.4	0.0940	0.2144	−1.08497	−0.98343	0.26473
SFROP	B_4C	197.3	707.4	0.1244	0.2214	+0.66651	+0.61352	0.41926
HSA	B_4C	146.3	519.7	0.0936	0.2191	−2.02876	−1.91365	0.25117
HSA	HSA	183.6	648.9	0.1129	0.2217	+0.09956	+0.09731	0.36852
HSA	LSA	179.3	636.5	0.1117	0.2210	−0.28981	−0.27598	0.35244
B_4C	B_4C	180.9	645.9	0.1189	0.2257	−1.26933	−1.24350	0.34044
SFROP	SFROP	202.2	725.5	0.1213	0.2207	+1.88765	+1.79599	0.45793
SFROP	^{113}Cd	126.4	449.6	0.0770	0.2140	−1.92058	−1.75372	0.19941

Sensitivity to LSA Cobalt in H

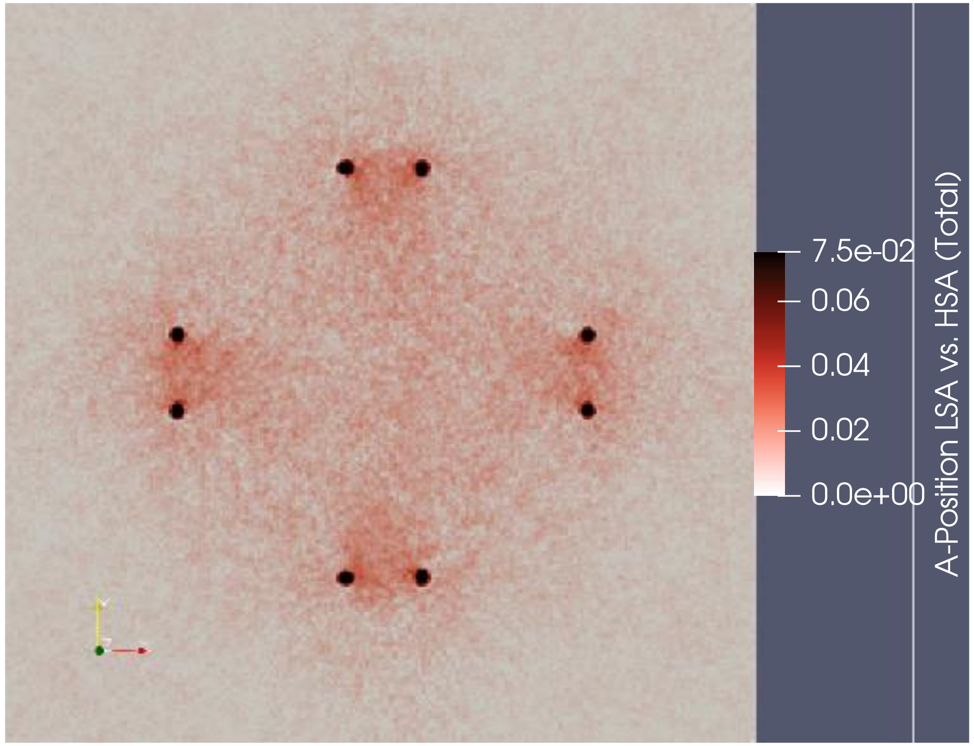
- Replace H-position HSA Cobalt and instrumentation positions with LSA Cobalt targets.
- Thermal flux depression of –7% (midplane, pictured) to –15% (ends)



Parameters		
TT Power	171.8	kW
Tier 1 LHGR	386.9	W/cm
Tier 2 LHGR	556.3	W/cm
Tier 3 LHGR	612.1	W/cm
Tier 4 LHGR	572.6	W/cm
Tier 5 LHGR	409.1	W/cm
Tier 6 LHGR	192.2	W/cm
Tier 3 Peaking	1.13	—
Tier 6 Peaking	1.43	—
Thermal Flux	10.8	%
Epithermal Flux	67.3	%
Fast Flux	21.9	%
ρ_{ATF}	–0.78764	$
ρ_{BU}	–0.74822	$
ρ_0	0.36627	$

Sensitivity to HSA Cobalt in Inner-A

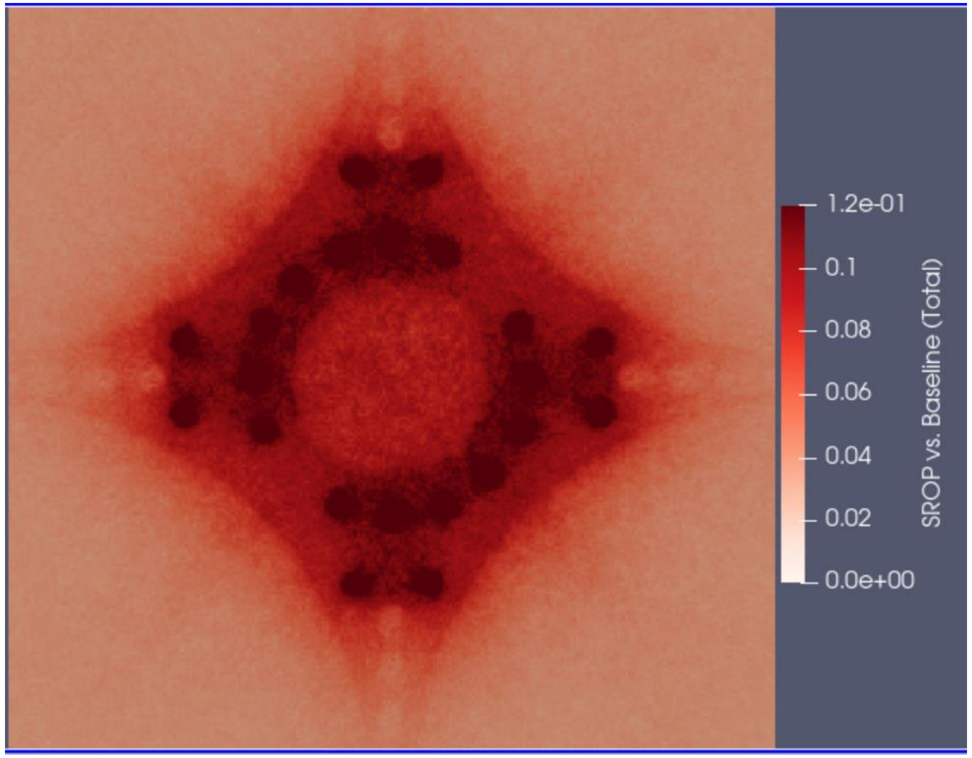
- Replace inner-A position LSA Cobalt targets with HSA Cobalt targets.
- Fewer positions, farther out. Flux increases by 1-2%.



Parameters		
TT Power	181.5	kW
Tier 1 LHGR	403.5	W/cm
Tier 2 LHGR	592.5	W/cm
Tier 3 LHGR	640.5	W/cm
Tier 4 LHGR	609.4	W/cm
Tier 5 LHGR	426.6	W/cm
Tier 6 LHGR	211.9	W/cm
Tier 3 Peaking	1.14	—
Tier 6 Peaking	1.36	—
Thermal Flux	11.1	%
Epithermal Flux	66.9	%
Fast Flux	22.1	%
ρ_{ATF}	+0.21691	$
ρ_{BU}	+0.21389	$
ρ_0	0.36929	$

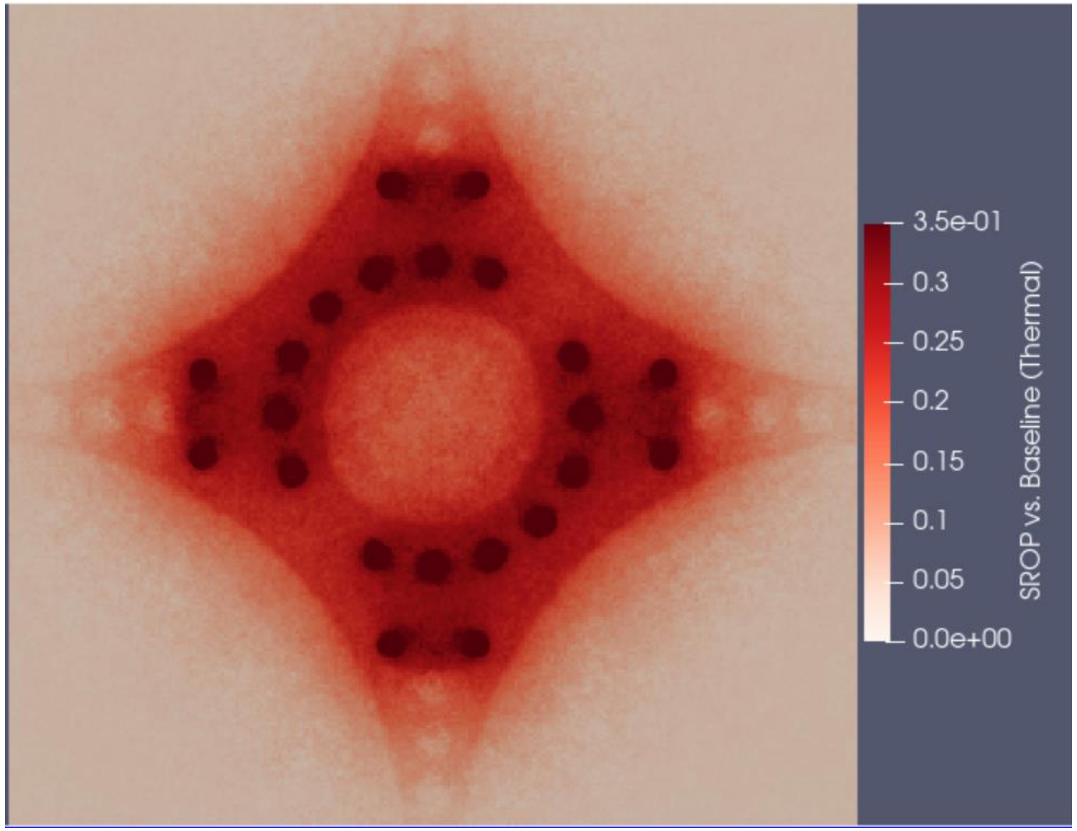
Sensitivity to SFROP "Filler"

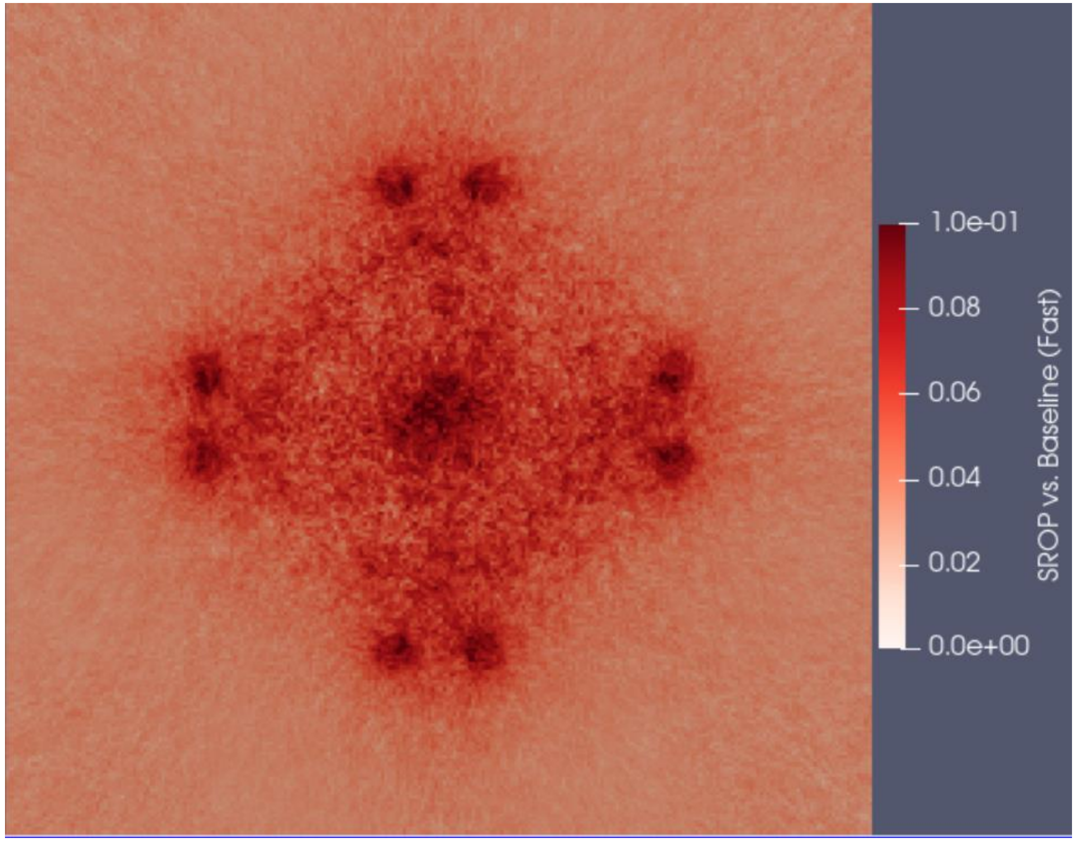
- Replacing absorptive isotope production targets with standard "fillers" causes a >10% increase in flux and experiment heating.



Parameters		
TT Power	202.0	kW
Tier 1 LHGR	454.1	W/cm
Tier 2 LHGR	647.5	W/cm
Tier 3 LHGR	725.5	W/cm
Tier 4 LHGR	668.6	W/cm
Tier 5 LHGR	479.9	W/cm
Tier 6 LHGR	273.0	W/cm
Tier 3 Peaking	1.14	—
Tier 6 Peaking	1.38	—
Thermal Flux	12.1	%
Epithermal Flux	65.8	%
Fast Flux	22.1	%
ρ_{ATF}	+1.88765	$
ρ_{BU}	+1.79599	$
ρ_0	0.45793	$

Sensitivity to SFROP "Filler"



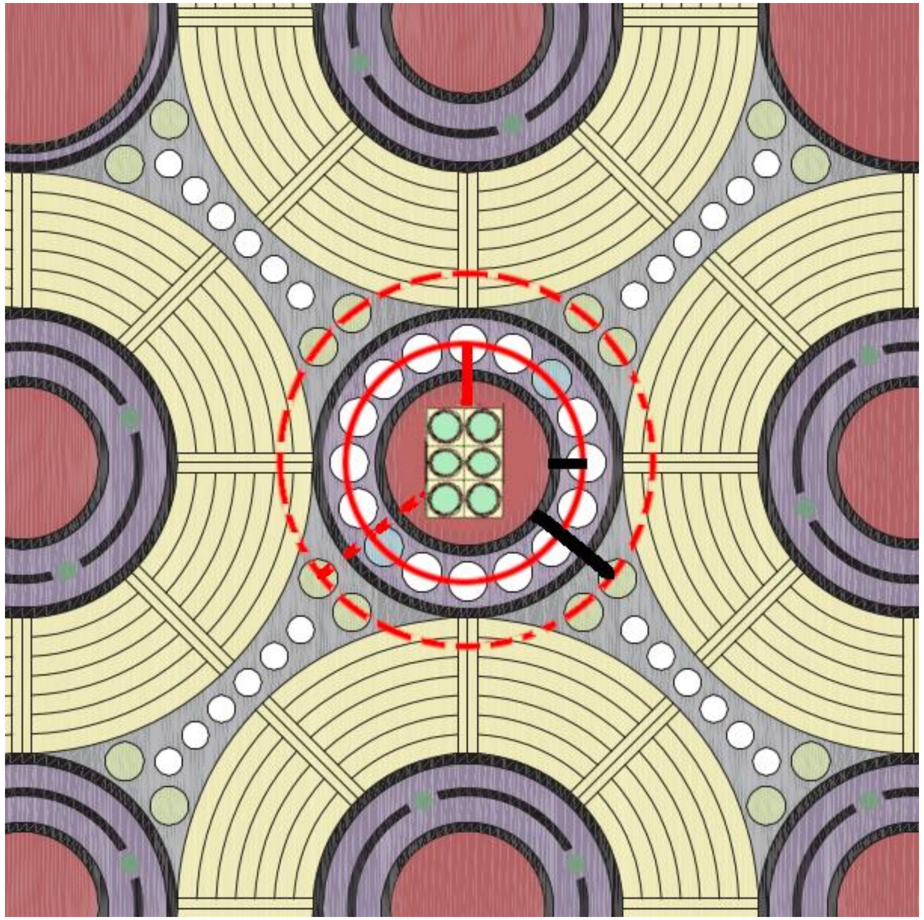


Relative Effect of H vs. Inner-A

- The SFROP configuration was perturbed by replacing either the H or inner-A contents with another target.
- The change in each parameter due to the target swap was calculated.
- The ratios of the relative influences of H:A was then tabulated.
  - Divide by two to account for the number of target positions.
- Total ATF-2Pert test train fission power results are shown.

Target	ΔPower, H (kW)	ΔPower, A (kW)	H/A Ratio	H/(2×A) Ratio
HSA	–17.3	–4.6	3.76	1.88
LSA	–26.1	–6.5	4.02	2.01
Np	–12.3	–2.8	4.39	2.20
Hf	–94.6	–30.1	3.14	1.57
^{113}Cd	–75.8	–23.9	3.17	1.58
Nat. Cd	–69.1	–21.7	3.19	1.60
B_4C rod	–17.7	–3.7	4.76	2.38
Be	+11.8	+3.7	3.18	1.59
H_2O	+28.5	+7.3	3.90	1.95

Relative Effect of H vs. Inner-A

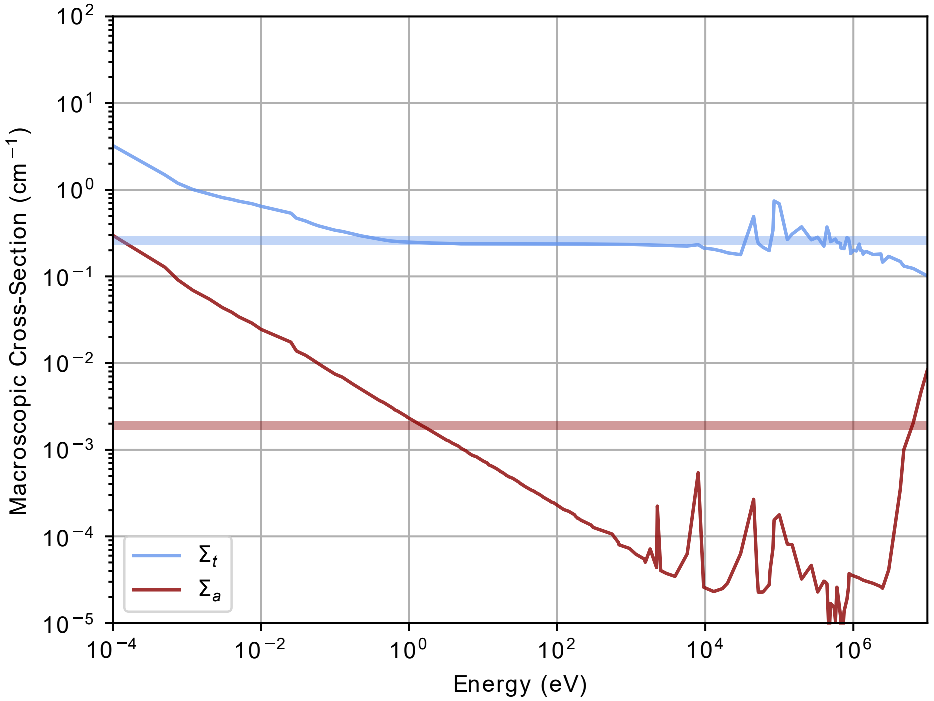


Number *n* of mean free paths *λ* from regions of interest

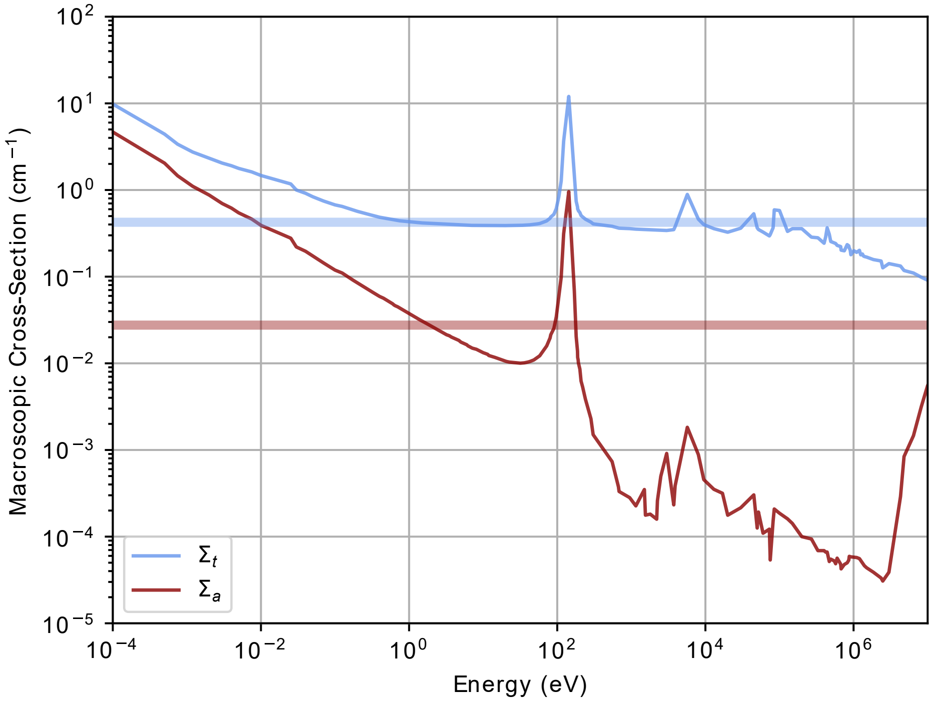
Position	*nλ* from ATF	*nλ* from CFT
H	4.4	2.1
Inner-A	7.2	5.0

One-Group Cross Sections

SFROP Filler

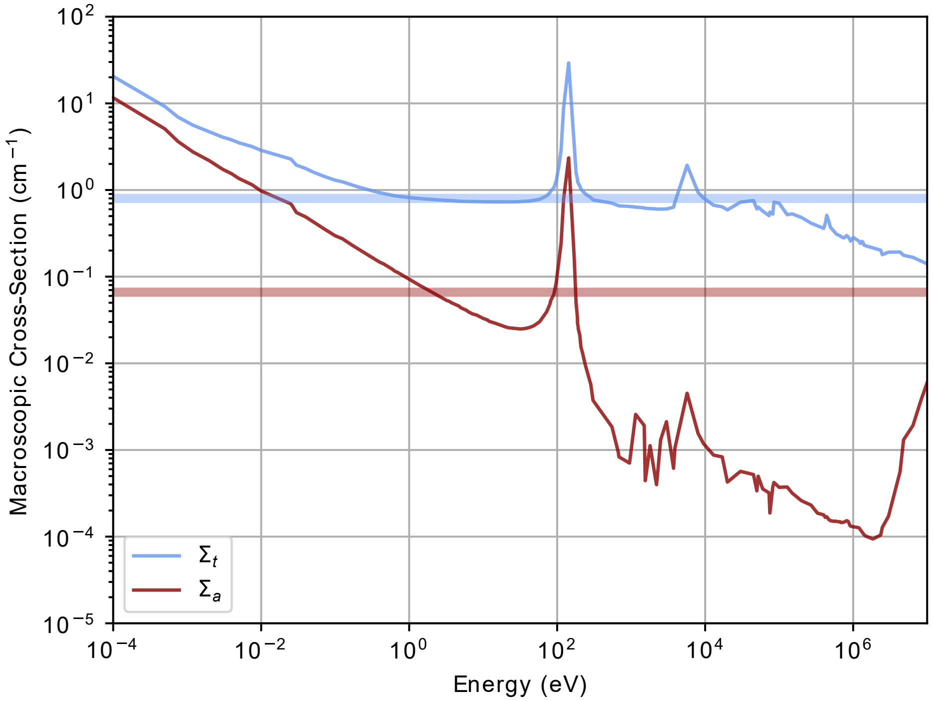


HSA Cobalt

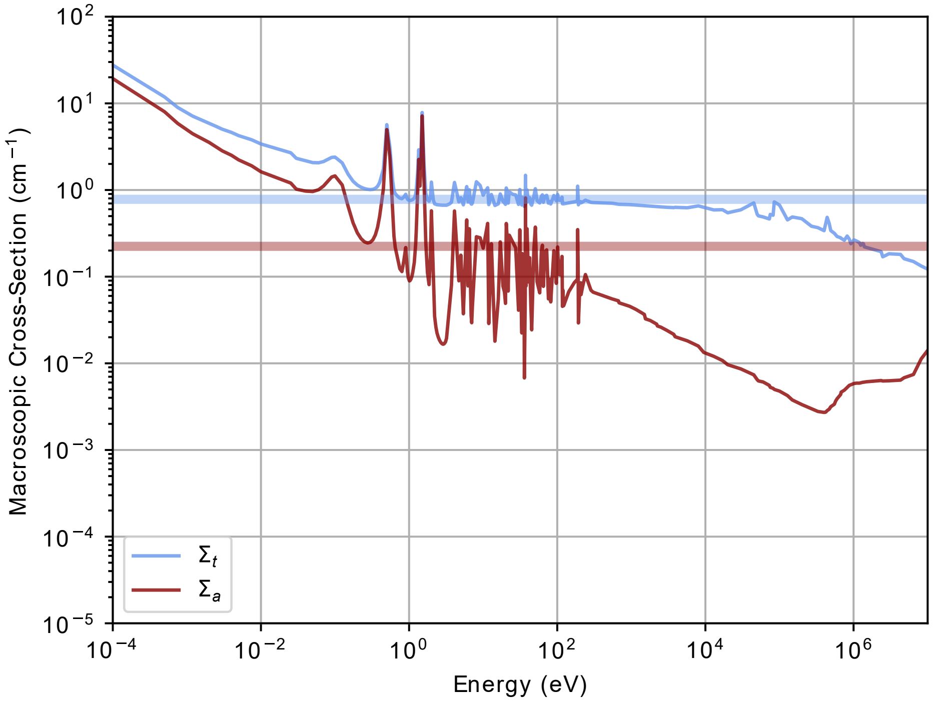


One-Group Cross Sections

LSA Cobalt

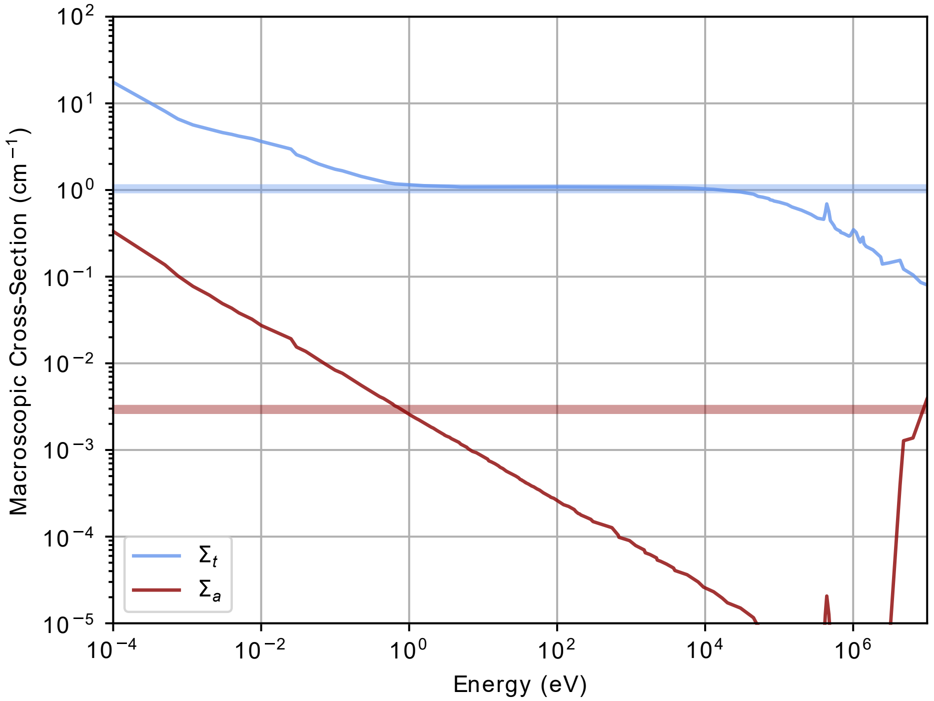


Neptunium Oxide



One-Group Cross Sections

Moderator



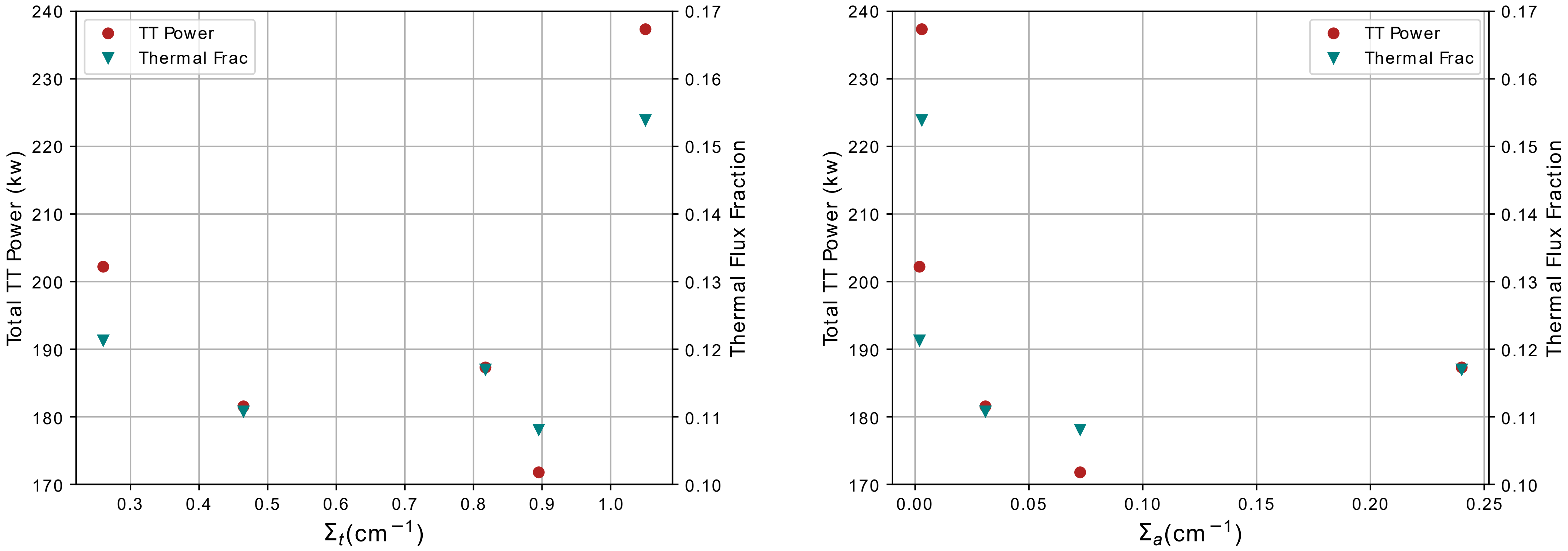
H-Position Results

Specimen	Σ_t (cm^{-1})	Σ_a (cm^{-1})
SFROP	2.603E-01	1.922E-03
HSA	4.647E-01	3.088E-02
LSA	8.953E-01	7.250E-02
Np	8.175E-01	2.401E-01
H_2O	1.051E±00	2.939E-03

1GXS As Predictor of Parameter Sensitivity

- The total and absorption macroscopic 1GXS were calculated for five targets.
- XS results were nearly identical for H and inner-A positions.
  - Spectrum is marginally faster for inner-A than H—negligible.
- The relationship between any ATF-2Pert experiment parameter to either total or absorption 1GXS exhibits no clear trend.
- Plots of the total test train fission power and the thermal flux fraction are presented on the next slide.

Two Parameters vs. Cross Sections



Future Work

- Examine asymmetric configurations.
- Generate integral experiment swap profiles: “clock” and “star” patterns
- Investigate effects of ATF-2 experiments with significant axial heterogeneities.
  - Early studies with ATF-2C (currently undergoing irradiation in ATR) suggests that the percentages are representative.
- Quantify sensitivities to reactor controls: neck shims and control drums.
- Evaluate sensitivities after multiple cycles of irradiation.
- Look at positions other than the CFT.
- Calculate sensitivities to different fueled experiments.
  - Example: AFC-FAST relies on high enrichment and fast fission.

Conclusions

- Assumptions of the contents of experiment positions near the CFT of ATR are relevant for ATF-2 neutronic analyses.
- Assuming the most conservative layout is excessively conservative, limiting the ability to achieve programmatic parameters.
- We now have a clearer idea of the sensitivity of ATF-2 to the nearby H and inner-A irradiation positions.
  - The tabulated parameter sensitivities now serve as a “cheat sheet” for adjacent experiment substitution.
  - ATF-2 is roughly twice as sensitive to perturbations in the H-positions as to the inner-A positions due to their proximity.
- Simply looking at the neutron cross sections of the adjacent positions is not sufficient. It is necessary to model them explicitly to capture the physics.

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Questions?

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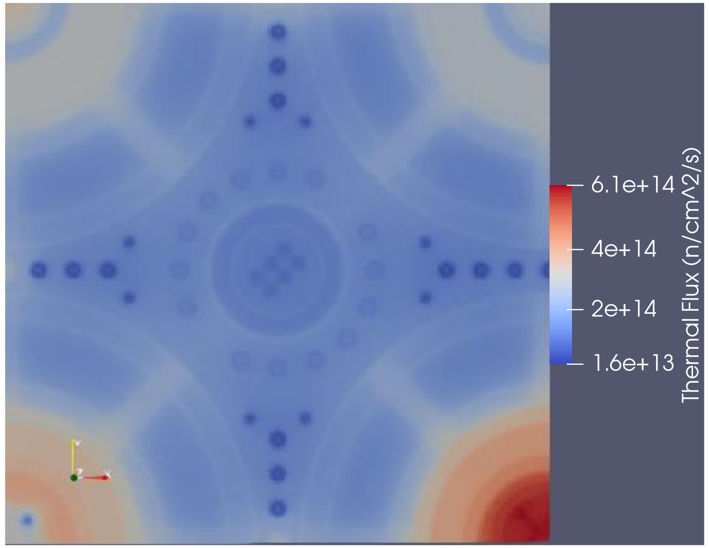
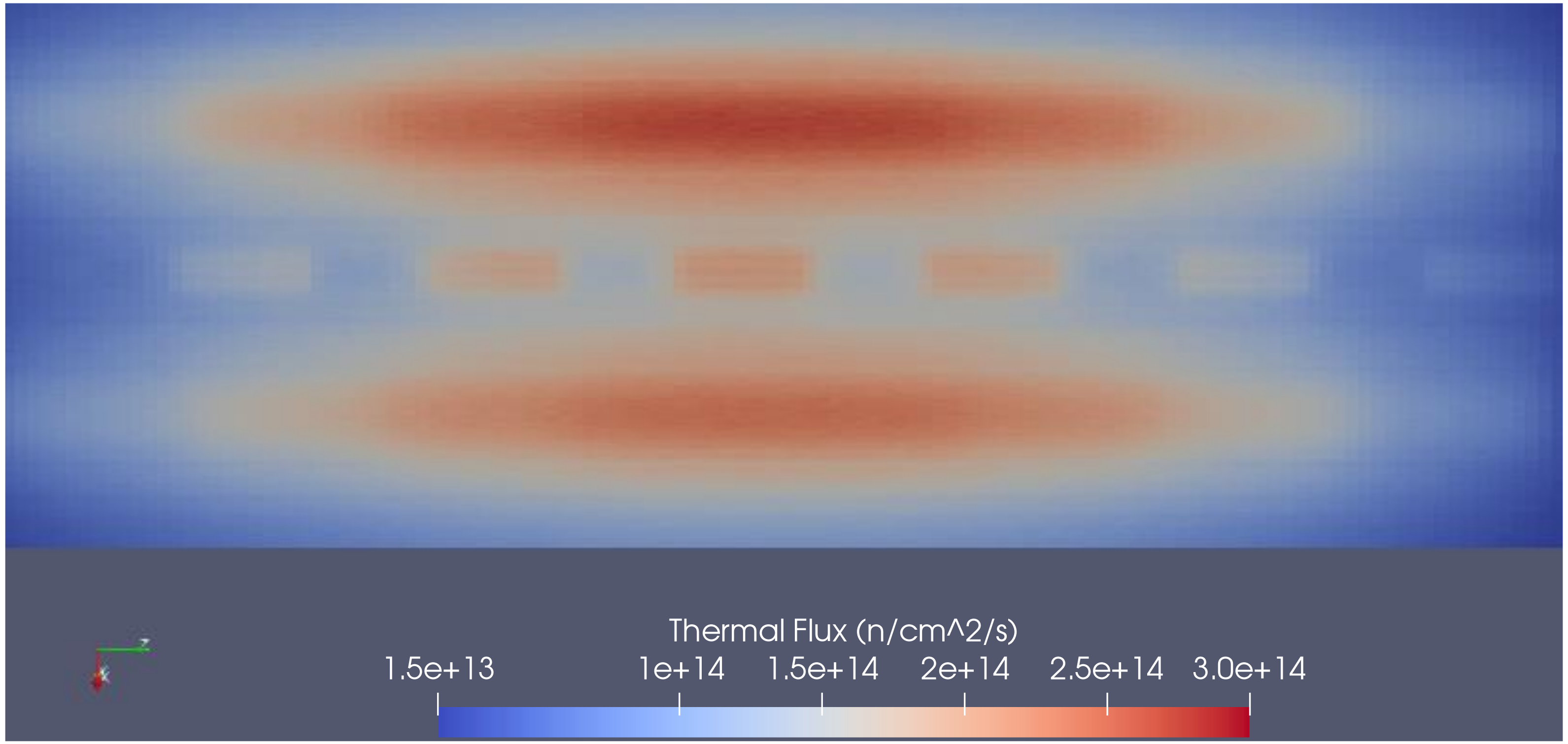
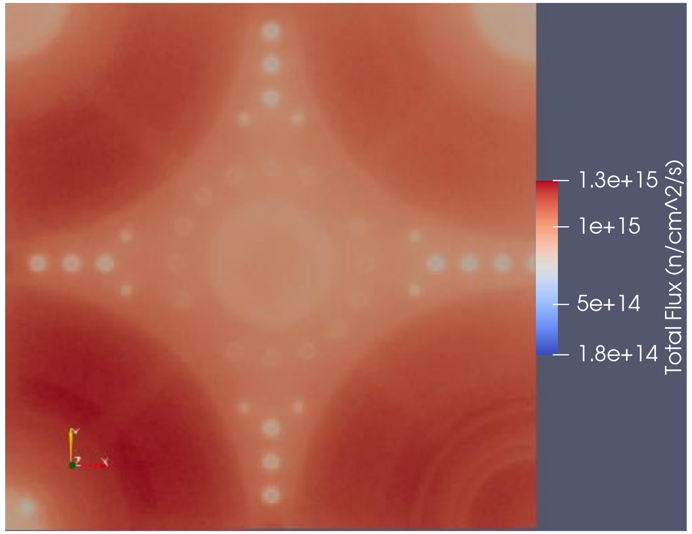
Backup slides

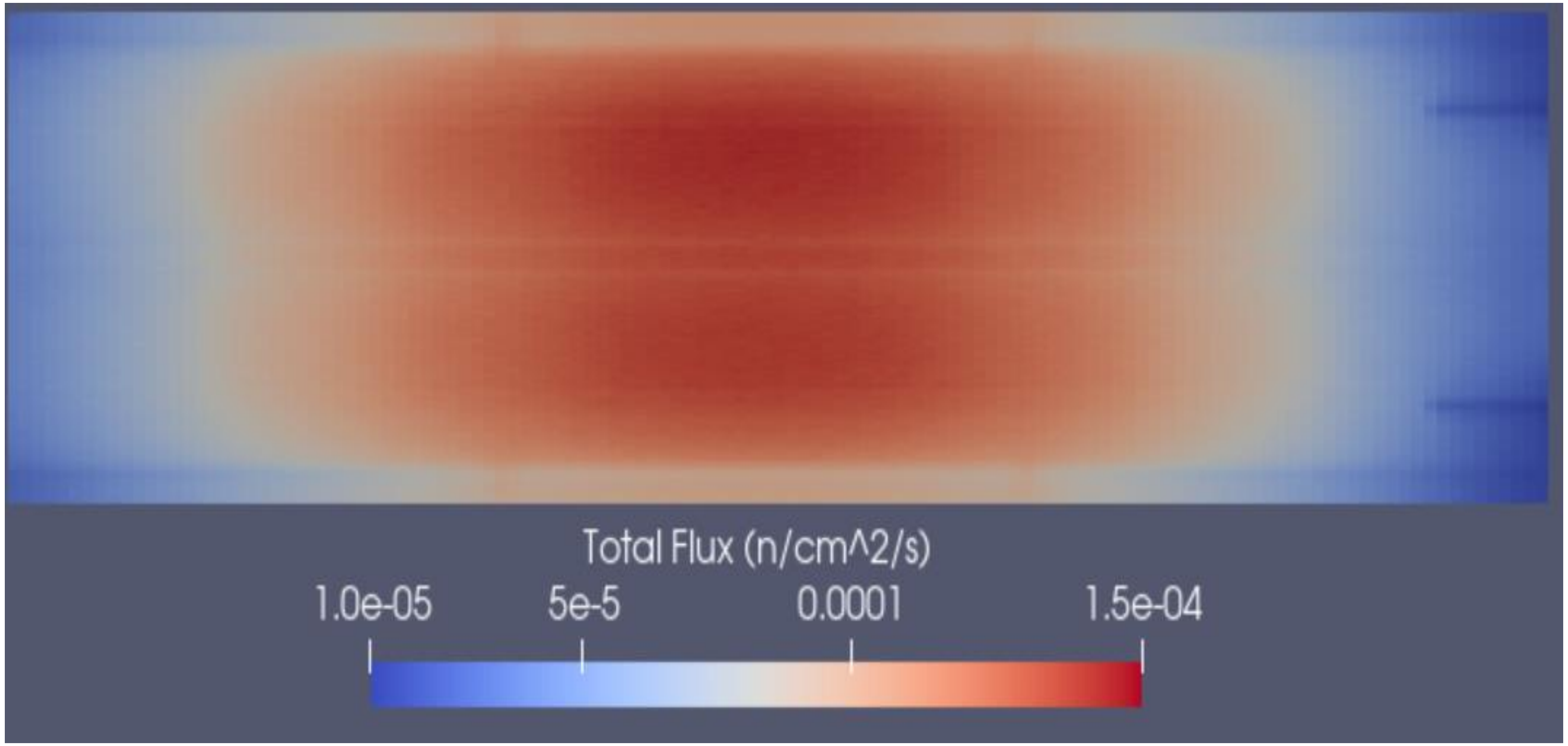
Baseline Flux Profiles





Baseline Flux Profiles





Methods: Equations

- HGR

$$Q = \frac{\nu}{\varepsilon}(LATCP)(\mathtt{f7:n}) \times m$$

- Flux

$$\phi = \frac{\nu}{\varepsilon}(LATCP)(\mathtt{f4:n})$$

- Reactivity

$$\Delta\rho\$ = \frac{1}{\beta_{eff}}\left(\frac{k_2 - k_1}{k_2 k_1}\right)$$

- Mesh tally

$$\Delta\,\phi = \frac{\phi_2 - \phi_1}{\phi_1}$$

Additional Results

Model #	--------------- Experiment Configurations -------					Average LHGR per Tier						Peak-to-Average LHGR Ratio per Tier						Neutron Flux Relative Fraction			Reactivity Worth: fueled experiment relative to case #1				Reactivity Worth: Unfueled experiment relative to case #1				Fueled to unfueled	
	A1 - A4	A5 - A8	H1 - H9	H10 - H16	Total HGR of TTT	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	Tier 6	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	Tier 6	Thermal flux	Epithermal Flux	Fast Flux	K Effective	STD dev	: in dollars	Error	K Effective	STD dev	: in dollars	Error	: in dollars	Error
1	LSA	LSA	H3 & H11: SFROP , Else: HSA		181883	406.1	591.8	643.9	608.7	429.1	210.2	1.291	1.183	1.135	1.159	1.275	1.374	0.1114	0.6682	0.2204	1.00186	2.00E-05	0	3.91E-03	0.99922	2.00E-05	0	3.93E-03	0.3662716	3.92E-03
5	LSA	LSA	LSA	LSA	171780	386.9	556.3	612.1	572.6	409.1	192.2	1.284	1.183	1.132	1.168	1.272	1.431	0.1081	0.6729	0.219	0.9962	2.00E-05	-0.7876447	3.94E-03	0.99387	2.00E-05	-0.74822219	3.96E-03	0.3268491	3.97E-03
6	HSA	HSA	LSA	LSA	173479	390.2	562.2	617.3	578.5	412.2	195.8	1.284	1.184	1.129	1.164	1.272	1.418	0.1086	0.6722	0.2193	0.99843	2.00E-05	-0.4762522	3.93E-03	0.99602	2.00E-05	-0.44656873	3.95E-03	0.3365882	3.95E-03
7	HSA	LSA	HSA	LSA	176835	395.6	574.6	626.7	591.6	418.6	202.5	1.281	1.178	1.129	1.159	1.276	1.391	0.1095	0.6706	0.2199	1.00002	2.00E-05	-0.255076	3.92E-03	0.9975	2.00E-05	-0.23967455	3.94E-03	0.3508702	3.94E-03
8	HSA	HSA	Odd #: HSA , Even #: LSA		177446	396.9	577.0	628.8	593.5	419.7	203.3	1.287	1.184	1.132	1.159	1.267	1.389	0.1097	0.6707	0.2196	1.00085	2.00E-05	-0.1398984	3.92E-03	0.99833	2.00E-05	-0.12391454	3.94E-03	0.3502877	3.93E-03
9	Np	Np	HSA	HSA	181942	405.6	592.4	642.8	609.2	428.2	212.4	1.29	1.185	1.133	1.158	1.275	1.367	0.1119	0.6667	0.2214	1.00261	2.00E-05	0.1037026	3.91E-03	0.99992	2.00E-05	0.0973059	3.93E-03	0.3726683	3.92E-03
10	Np	Np	Np	Np	187301	423.3	600.6	664.3	618.9	447.2	221.5	1.284	1.198	1.131	1.183	1.276	1.399	0.117	0.6593	0.2237	1.00096	2.00E-05	-0.1246483	3.92E-03	0.99826	2.00E-05	-0.13367	3.94E-03	0.3752934	3.93E-03
11	HSA	HSA	Np	Np	186543	420.5	599.9	660.9	618.0	444.4	220.2	1.289	1.197	1.129	1.18	1.272	1.389	0.1158	0.6613	0.223	1.00154	2.00E-05	-0.0442937	3.92E-03	0.99885	2.00E-05	-0.05148821	3.94E-03	0.3734661	3.93E-03
12	HSA	HSA	B4C	B4C	181919	410.7	583.8	648.6	602.1	435.8	209.2	1.296	1.193	1.13	1.185	1.271	1.41	0.1175	0.658	0.2245	0.99591	2.00E-05	-0.8282422	3.94E-03	0.99346	2.00E-05	-0.80589504	3.96E-03	0.3439245	3.97E-03
13	Np	Np	B4C	B4C	181991	412.0	582.6	650.1	601.0	436.3	209.3	1.295	1.198	1.132	1.189	1.278	1.414	0.1185	0.6563	0.2252	0.99529	2.00E-05	-0.9151161	3.94E-03	0.99282	2.00E-05	-0.89601616	3.96E-03	0.3471717	3.98E-03
14	B4C	B4C	Np	Np	186437	422.0	597.5	661.5	615.7	445.8	219.6	1.287	1.196	1.133	1.182	1.273	1.395	0.1176	0.6581	0.2243	0.99828	2.00E-05	-0.4971542	3.93E-03	0.99565	2.00E-05	-0.49838837	3.95E-03	0.3675058	3.95E-03
15	Np	B4C	Np	B4C	184197	416.6	590.2	655.2	608.5	441.0	215.0	1.292	1.193	1.128	1.181	1.271	1.401	0.1178	0.6576	0.2246	0.99707	2.00E-05	-0.665994	3.93E-03	0.99449	2.00E-05	-0.66109992	3.95E-03	0.3613775	3.96E-03
16	Np	Np	Beryllium	Beryllium	211600	477.2	679.5	760.1	700.0	504.7	240.3	1.294	1.196	1.136	1.187	1.279	1.417	0.1302	0.6511	0.2187	1.01153	2.00E-05	1.3252816	3.88E-03	1.00796	2.00E-05	1.20524273	3.90E-03	0.4863105	3.85E-03
17	Np	Np	Hafnium	Hafnium	105808	239.2	337.0	374.5	347.6	252.7	130.0	1.278	1.184	1.125	1.165	1.259	1.3	0.065	0.722	0.213	0.97887	2.00E-05	-3.2559252	4.01E-03	0.97781	2.00E-05	-3.04346687	4.02E-03	0.1538133	4.10E-03
17.1	Hf*10				77346	174.1	245.9	273.0	253.2	184.4	98.3	1.285	1.189	1.124	1.171	1.262	1.262	0.0626	0.7762	0.1612	0.96559	2.00E-05	-5.2073319	4.07E-03	0.96503	2.00E-05	-4.92452869	4.08E-03	0.0834684	4.22E-03
17.2	Hf*100				58504	131.0	184.9	205.7	190.7	138.2	79.1	1.28	1.192	1.121	1.172	1.266	1.384	0.0776	0.7357	0.1867	0.95549	2.00E-05	-6.7277743	4.11E-03	0.95526	2.00E-05	-6.39650106	4.12E-03	0.0349984	4.30E-03
18	Np	Np	Dense Boron	Dense Boron	72573	163.3	230.2	255.6	237.0	172.3	94.6	1.279	1.181	1.117	1.165	1.26	1.295	0.05	0.7162	0.2337	0.96268	2.00E-05	-5.6421282	4.08E-03	0.9621	2.00E-05	-5.36283134	4.09E-03	0.0869748	4.24E-03
19	Np	Np	Cadmiun 113	Cadmiun 113	124408	281.8	397.0	442.0	409.0	297.9	148.7	1.2759	1.181	1.124	1.167	1.259	1.347	0.0765	0.7086	0.2149	0.98556	2.00E-05	-2.2927938	3.98E-03	0.98417	2.00E-05	-2.12555704	4.00E-03	0.1990348	4.05E-03
20	Np	Np	Moderator	Moderator	228342	515.5	733.4	819.5	756.8	545.4	257.3	1.293	1.199	1.14	1.19	1.288	1.439	0.1462	0.6239	0.2299	1.00757	2.00E-05	0.7856359	3.89E-03	1.00383	2.00E-05	0.63833277	3.92E-03	0.5135748	3.88E-03
21	Np	Np	Dense Boron	SFROP	126123	284.6	403.2	448.8	415.2	299.6	152.4	1.446	1.35	1.277	1.327	1.432	1.485	0.0838	0.6895	0.2268	0.97873	2.00E-05	-3.2762211	4.01E-03	0.97758	2.00E-05	-3.07688549	4.02E-03	0.1669361	4.11E-03
22	Np	Np	SFROP	SFROP	199405	449.0	638.8	713.8	659.1	474.0	233.4	1.291	1.194	1.134	1.183	1.279	1.381	0.1205	0.658	0.2215	1.01071	2.00E-05	1.213884	3.88E-03	1.00753	2.00E-05	1.14643496	3.90E-03	0.4337206	3.86E-03
23	HSA	HSA	Dense Boron	B4C	118674	267.6	379.3	422.0	390.6	283.0	143.0	1.449	1.337	1.265	1.318	1.422	1.476	0.0813	0.69	0.2287	0.97528	2.00E-05	-3.7782103	4.02E-03	0.97414	2.00E-05	-3.57859492	4.04E-03	0.1666563	4.13E-03
24	HSA	HSA	Helium	Helium	193771	434.9	622.8	693.5	642.5	459.1	225.8	1.291	1.193	1.133	1.177	1.274	1.384	0.1137	0.6614	0.2249	1.01159	2.00E-05	1.3334256	3.88E-03	1.0085	2.00E-05	1.27902331	3.90E-03	0.4206739	3.85E-03
25	HSA	HSA	Helium 3	Helium 3	178881	403.0	575.3	640.7	593.6	425.7	203.8	1.288	1.19	1.128	1.172	1.271	1.408	0.1054	0.6709	0.2237	1.00597	2.00E-05	0.5663922	3.90E-03	1.00336	2.00E-05	0.57352182	3.92E-03	0.359142	3.89E-03
26	HSA	HSA	Helium 3 (*3 density)	Helium 3 (*3 density)	162366	367.3	521.9	581.3	538.9	388.1	182.1	1.285	1.187	1.123	1.166	1.267	1.428	0.0958	0.6816	0.2226	1.00024	2.00E-05	-0.2245284	3.92E-03	0.99803	2.00E-05	-0.16573329	3.94E-03	0.3074765	3.94E-03
27	Moderator	Moderator	Moderator	Moderator	237344	534.9	763.1	853.3	787.3	567.5	264.8	1.299	1.205	1.14	1.196	1.289	1.446	0.1539	0.6143	0.2318	1.01206	2.00E-05	1.3971865	3.87E-03	1.00795	2.00E-05	1.20387568	3.90E-03	0.5595824	3.85E-03
28	SFROP	SFROP	Dense Boron	Moderator	137516	310.3	439.5	491.6	453.3	327.3	162.8	1.503	1.396	1.329	1.37	1.49	1.563	0.0949	0.675	0.2301	0.98062	2.00E-05	-3.0027158	4.00E-03	0.9792	2.00E-05	-2.84183628	4.02E-03	0.2053921	4.09E-03
29	B4C	B4C	HSA	HSA	181210	403.8	589.6	641.0	606.6	426.9	211.1	1.287	1.184	1.133	1.157	1.272	1.365	0.1125	0.6655	0.222	0.99994	2.00E-05	-0.2661876	3.92E-03	0.99738	2.00E-05	-0.25642688	3.94E-03	0.3565109	3.94E-03
30	B4C	B4C	SFROP	SFROP	198492	446.8	635.1	711.9	656.4	471.8	231.6	1.292	1.194	1.135	1.183	1.279	1.38	0.1212	0.6568	0.222	1.00765	2.00E-05	0.7965799	3.89E-03	1.00451	2.00E-05	0.73199446	3.91E-03	0.430857	3.88E-03
31	SFROP	SFROP	Hafnium	Beryllium	150838	340.6	482.3	539.4	497.5	359.4	177.3	1.423	1.325	1.261	1.309	1.415	1.499	0.094	0.6916	0.2144	0.99408	2.00E-05	-1.0849725	3.94E-03	0.9922	2.00E-05	-0.98343186	3.96E-03	0.264731	3.98E-03
32	SFROP	SFROP	B4C	Beryllium	197287	445.3	632.4	707.4	652.7	471.3	225.4	1.316	1.225	1.161	1.213	1.309	1.437	0.1244	0.6542	0.2214	1.0067	2.00E-05	0.6665086	3.90E-03	1.00365	2.00E-05	0.61351873	3.92E-03	0.4192615	3.89E-03
33	HSA	HSA	B4C	Hafnium	146259	330.3	468.1	519.7	483.3	349.8	172.6	1.372	1.27	1.212	1.258	1.349	1.45	0.0936	0.6872	0.2191	0.98741	2.00E-05	-2.0287606	3.97E-03	0.98565	2.00E-05	-1.91365439	3.99E-03	0.2511655	4.04E-03
34	HSA	HSA	HSA	Np	183568	410.9	594.5	648.9	612.6	434.3	215.2	1.302	1.2	1.141	1.177	1.282	1.387	0.1129	0.6653	0.2217	1.00258	2.00E-05	0.0995575	3.91E-03	0.99992	2.00E-05	0.0973059	3.93E-03	0.3685232	3.92E-03
35	HSA	HSA	LSA	Np	179289	403.8	579.0	636.5	596.2	426.4	206.5	1.307	1.205	1.143	1.189	1.291	1.427	0.1117	0.6673	0.221	0.99977	2.00E-05	-0.2898055	3.92E-03	0.99724	2.00E-05	-0.27597636	3.94E-03	0.3524425	3.94E-03
36	B4C	B4C	B4C	B4C	180894	409.6	578.9	645.9	597.9	434.1	207.5	1.296	1.194	1.133	1.188	1.269	1.414	0.1189	0.6554	0.2257	0.99277	2.00E-05	-1.2693334	3.95E-03	0.99036	2.00E-05	-1.24350351	3.97E-03	0.3404417	4.00E-03
37	Moderator	Np	Moderator	Np	213680	482.0	686.0	763.6	707.8	510.5	245.0	1.328	1.232	1.173	1.217	1.323	1.463	0.1367	0.6352	0.2281	1.00641	2.00E-05	0.6267537	3.90E-03	1.00297	2.00E-05	0.5196964	3.92E-03	0.4733289	3.89E-03
38	SFROP	Beryllium	SFROP	Beryllium	208757	469.1	669.7	750.2	690.8	496.7	240.2	1.306	1.208	1.153	1.202	1.295	1.413	0.1269	0.654	0.2191	1.01662	2.00E-05	2.0127423	3.86E-03	1.01304	2.00E-05	1.89621612	3.88E-03	0.4827978	3.81E-03

Additional Results

	--------------------------- Experiment Configurations -------------------------------						Average LHGR per Tier (W/cm)							Peak-to-Average LHGR Ratio per Tier							Neutron Flux Relative Fraction		
Model #	A1 - A4	A5 - A8	H1 - H9	H10 - H16	FHGR of TT (kW)		Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	Tier 6		Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	Tier 6		Thermal flux	Epithermal Flux	Fast Flux
45	SFROP	SFROP	HSA	HSA	184867.4		411.5846	601.5678	653.8949	618.9132	434.9365	216.2475		1.29	1.19	1.13	1.16	1.28	1.36		0.1127	0.6667	0.2206
46	HSA	HSA	SFROP	SFROP	197595.8		443.1994	635.1692	706.3726	655.237	468.0432	231.3488		1.29	1.19	1.14	1.18	1.28	1.38		0.1187	0.6606	0.2207
47	SFROP	SFROP	LSA	LSA	176059.1		396.3546	569.3290	627.7836	585.9604	418.7886	198.9839		1.29	1.18	1.13	1.18	1.28	1.42		0.1101	0.6707	0.2192
48	LSA	LSA	SFROP	SFROP	195695.7		439.8492	628.5049	700.7786	648.0886	465.0478	226.9146		1.29	1.19	1.13	1.18	1.28	1.39		0.1182	0.6616	0.2203
49	SFROP	SFROP	Np	Np	189900.6		429.0640	608.5762	674.2629	627.5290	452.9434	224.7355		1.29	1.20	1.13	1.18	1.28	1.39		0.1177	0.6593	0.2229
50	Np	Np	SFROP	SFROP	199405.2		449.0155	638.7521	713.8399	659.1156	473.9535	233.4415		1.29	1.19	1.13	1.18	1.28	1.38		0.1205	0.658	0.2215
51	SFROP	SFROP	B4C	B4C	184537.6		417.1509	590.3829	660.2732	609.7876	442.1739	212.1359		1.30	1.20	1.14	1.19	1.28	1.40		0.1192	0.6566	0.2243
52	B4C	B4C	SFROP	SFROP	198491.9		446.7785	635.1214	711.8867	656.4437	471.7557	231.6227		1.29	1.19	1.14	1.18	1.28	1.38		0.1212	0.6568	0.2220
53	SFROP	SFROP	Moderator	Moderator	230736.7		519.9810	740.6770	829.6240	764.8375	550.7111	260.0789		1.30	1.20	1.14	1.19	1.29	1.45		0.1469	0.6240	0.2291
54	Moderator	Moderator	SFROP	SFROP	209525.6		471.3645	671.3934	752.4723	693.2739	497.6675	242.7386		1.29	1.20	1.14	1.19	1.28	1.39		0.1287	0.6478	0.2236
55	SFROP	SFROP	Beryllium	Beryllium	214055.0		481.6254	687.4600	770.2002	709.0344	509.7748	242.7775		1.30	1.20	1.14	1.19	1.28	1.42		0.1309	0.6513	0.2179
56	Beryllium	Beryllium	SFROP	SFROP	205928.2		462.9727	660.1351	739.4186	681.2676	488.8618	239.0997		1.29	1.20	1.14	1.19	1.29	1.39		0.1244	0.6556	0.2199
57	SFROP	SFROP	Cadmium	Cadmium	133079.7		301.5502	424.1664	473.3040	438.3825	318.6688	158.2770		1.28	1.19	1.12	1.17	1.26	1.36		0.0820	0.7068	0.2112
58	Cadmium	Cadmium	SFROP	SFROP	180544.0		406.6479	577.2405	645.7187	596.0623	429.7259	213.0597		1.29	1.19	1.13	1.18	1.28	1.37		0.1081	0.6743	0.2176
59	SFROP	SFROP	Cadmium 113	Cadmium 113	126428.0		286.3324	403.0099	449.5672	415.7548	302.5456	151.4589		1.28	1.19	1.13	1.16	1.26	1.34		0.0770	0.7090	0.2140
60	Cadmium 113	Cadmium 113	SFROP	SFROP	178293.7		401.6774	570.0490	637.5777	588.2098	424.3327	210.8556		1.29	1.19	1.13	1.18	1.27	1.36		0.1065	0.6753	0.2182
61	SFROP	SFROP	Dense Boron	Dense Boron	74130.6		166.4303	234.6570	261.7603	242.1453	175.8183	96.9637		1.28	1.19	1.12	1.16	1.26	1.32		0.0506	0.7168	0.2326
62	Dense Boron	Dense Boron	SFROP	SFROP	157285.8		354.2149	501.6655	561.8105	518.6620	373.8724	188.7076		1.29	1.19	1.13	1.18	1.27	1.34		0.0958	0.6816	0.2226
63	SFROP	SFROP	Hafnium	Hafnium	107652.6		242.9560	342.4924	381.9142	353.6680	256.7794	132.5579		1.28	1.18	1.12	1.17	1.26	1.30		0.0654	0.7225	0.2121
64	Hafnium	Hafnium	SFROP	SFROP	172097.9		387.6186	549.6671	615.2255	567.5937	409.5932	204.5670		1.29	1.19	1.13	1.18	1.27	1.36		0.1026	0.6798	0.2176

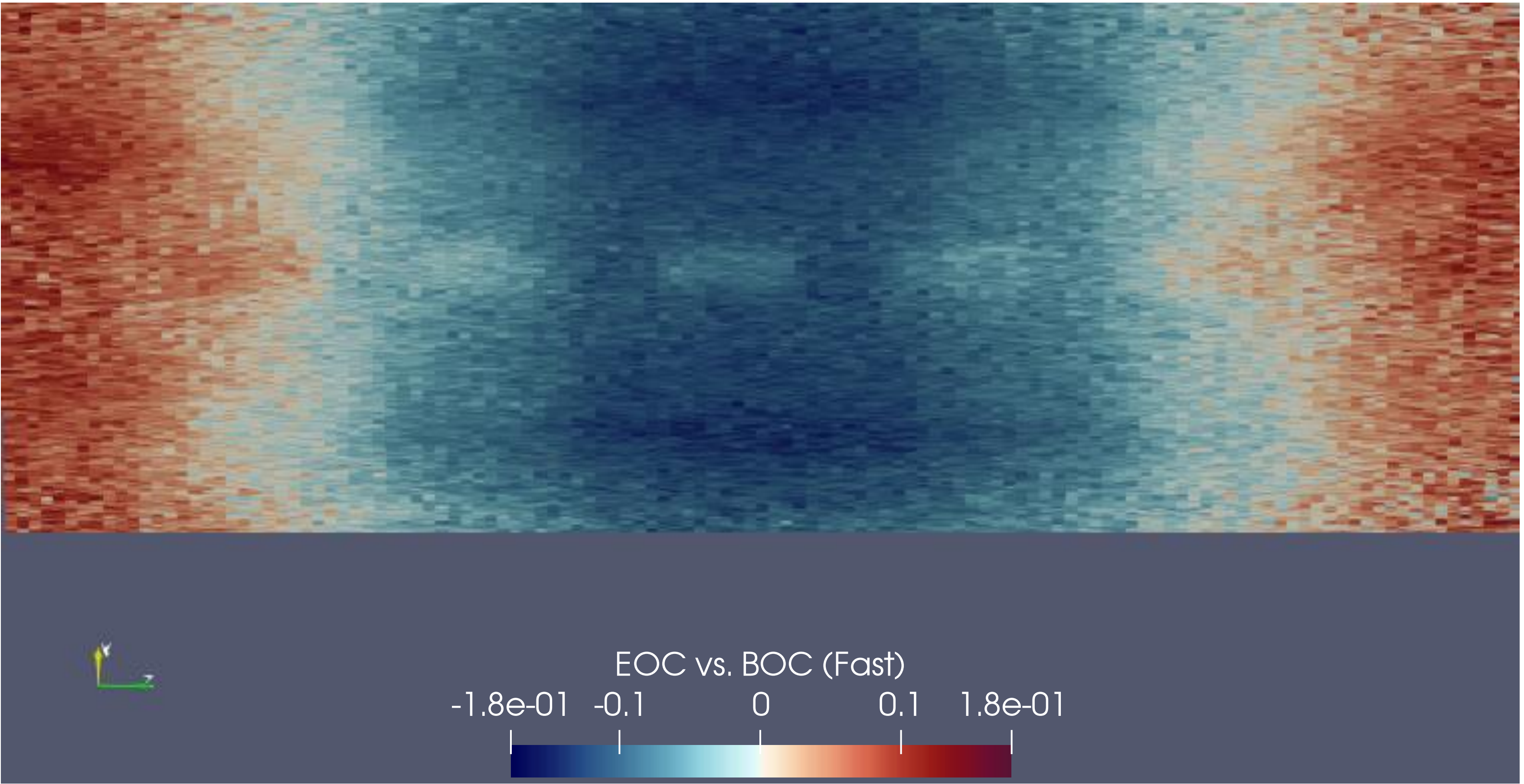
Additional Results

	--------------------------- Experiment Configurations ------------				FHGR of TT (kW)	H/Inner A "Influence Ratio"		Tier 1	H/A Ratio	Tier 2	H/A Ratio	Tier 3	H/A Ratio	Tier 4	H/A Ratio	Tier 5	H/A Ratio	Tier 6	H/A Ratio	Average H/A Ratio
45	SFROP	SFROP	HSA	HSA	-17338.1	3.761220904		-42.5322	3.89581769	-45.9717	3.71629629	-71.6237	3.7409224	-49.6482	3.7261115	-44.96	3.7930365	-20.7287	3.6835306	3.75928583
46	HSA	HSA	SFROP	SFROP	-4609.7			-10.9174		-12.3703		-19.146		-13.3244		-11.8533		-5.6274		
47	SFROP	SFROP	LSA	LSA	-26146.4	4.016493012		-57.762238	4.04848927	-78.21049	4.1088669	-97.73502	3.9504817	-82.60096	4.0346648	-61.1079	4.1153701	-37.992269	3.7759504	4.00563719
48	LSA	LSA	SFROP	SFROP	-6509.8			-14.2676031		-19.034564		-24.74002		-20.47282		-14.8487		-10.061644		
49	SFROP	SFROP	Np	Np	-12304.9	4.394073516		-25.0527824	4.91106518	-38.9633244	4.43401634	-51.25573	4.3888306	-41.03244	4.3439657	-26.9531	4.535296	-12.2406594	3.4629668	4.346023428
50	Np	Np	SFROP	SFROP	-2800.3			-5.101293		-8.787366		-11.67868		-9.445849		-5.94297		-3.534732		
51	SFROP	SFROP	B4C	B4C	-17667.9	4.757655639		-36.96595	5.03741058	-57.15663	4.60266871	-65.24542	4.7862467	-58.77384	4.8502611	-37.7226	4.6337887	-24.8402979	4.6400221	4.758399649
52	B4C	B4C	SFROP	SFROP	-3713.6			-7.3382841		-12.4181499		-13.63185		-12.11767		-8.14077		-5.353487		
53	SFROP	SFROP	Moderator	Moderator	28531.2	3.897656164		65.864169	3.81871832	93.1375178	3.9044989	104.10544	3.8623814	96.276119	3.8958407	70.81464	3.9848487	23.102693	4.0092134	3.912583578
54	Moderator	Moderator	SFROP	SFROP	7320.1			17.247716		23.8538978		26.953691		24.71254		17.77097		5.76240037		
55	SFROP	SFROP	Beryllium	Beryllium	11849.5	3.183020126		27.508614	3.10623275	39.920506	3.16939109	44.681646	3.2145055	40.472978	3.1853039	29.87831	3.3326653	5.801289	2.7319841	3.123347114
56	Beryllium	Beryllium	SFROP	SFROP	3722.7			8.855941		12.595639		13.900006		12.706159		8.96529		2.123471		
57	SFROP	SFROP	Cadmium	Cadmium	-69125.8	3.191184704		-152.56659	3.21403323	-223.37307	3.17747346	-252.2146	3.160588	-230.1789	3.1749194	-161.228	3.213591	-78.69919	3.2905819	3.205197837
58	Cadmium	Cadmium	SFROP	SFROP	-21661.5			-47.46889		-70.298957		-79.7999		-72.49912		-50.1706		-23.916496		
59	SFROP	SFROP	Cadmium 113	Cadmium 113	-75777.5	3.16903871		-167.784389	3.19958752	-244.52961	3.15560857	-275.9514	3.137921	-252.8066	3.1462545	-177.351	3.1918411	-85.517346	3.273945	3.184192939
60	Cadmium 113	Cadmium 113	SFROP	SFROP	-23911.8			-52.439381		-77.490476		-87.94085		-80.35162		-55.5638		-26.120581		
61	SFROP	SFROP	Dense Boron	Dense Boron	-128074.9	2.851199867		-287.686514	2.87968886	-412.882491	2.83040488	-463.7583	2.832837	-426.4161	2.8446819	-304.078	2.8680108	-140.012517	2.9006975	2.859386831
62	Dense Boron	Dense Boron	SFROP	SFROP	-44919.7			-99.9019436		-145.874003		-163.7081		-149.8994		-106.024		-48.2685682		
63	SFROP	SFROP	Hafnium	Hafnium	-94552.9	3.140501428		-211.160776	3.17543377	-305.047113	3.11678414	-343.6044	3.1153749	-314.8934	3.1187544	-223.117	3.1736344	-104.418327	3.2218728	3.153642395
64	Hafnium	Hafnium	SFROP	SFROP	-30107.6			-66.4982461		-97.87239		-110.2931		-100.9677		-70.3033		-32.409202		

Methods: Depletion

- Nominal depletion based on Cycle 169A operational data
  - Used Monte Carlo Constructor for ATR Fuel Elements (MCCAFE) for core model updates and driver fuel depletion
- Coupled MCNP to SCALE/ORIGEN
  - Used MCNP-ORIGEN Activation Automation tool (MOAA)
  - Predictor-corrector using MCNP for fluxes and ORIGEN for experiment depletion
- Examined flux sensitivity one cycle’s depletion

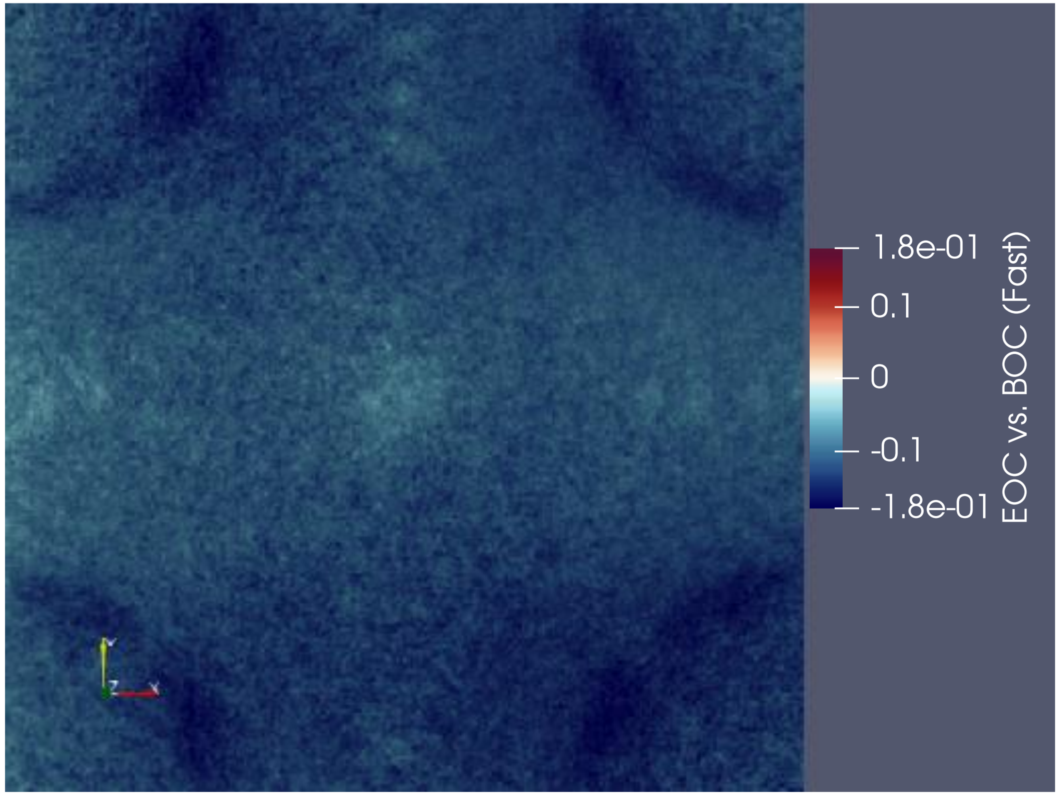
Effect of Depletion



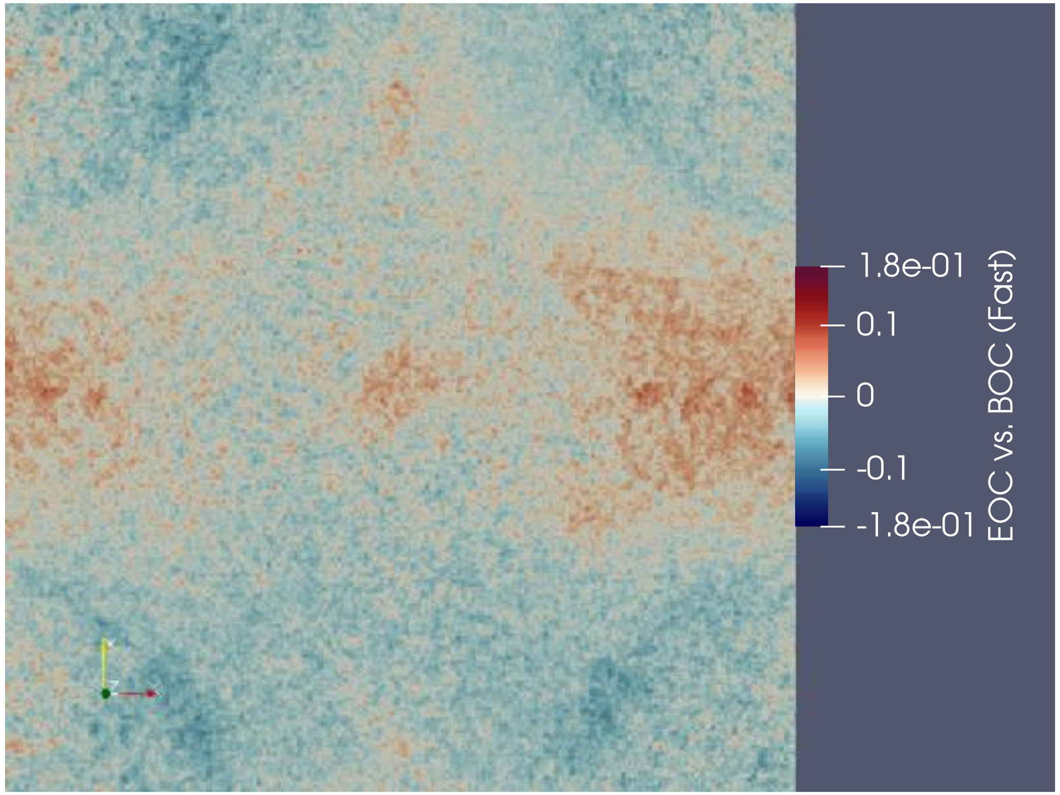
- Flux and power profiles shift axially
- Total test train heating remains similar
- Sensitivities to adjacent experiments remains similar

Changing Fast Flux Profile After Cycle Depletion

Core Midplane



Mid-Upper core



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