Fluoride-salt-cooled High-temperature Reactor Benchmark

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ILLINOIS

What is a benchmark?

OECD NEA Reactor Physics Benchmark

- The Nuclear Energy Agency (NEA) is a specialised agency within the Organisation for Economic Co-operation and Development (OECD)
- They have a list of reactor physics benchmarks, which are used to validate computer codes and nuclear data required for simulating reactor design and operation.

Fluoride-salt High-temperature Reactor (FHR)

- Low pressure liquid fluoride salt coolant
- Hexagonal fuel elements with TRISO particle fuel embedded in planks

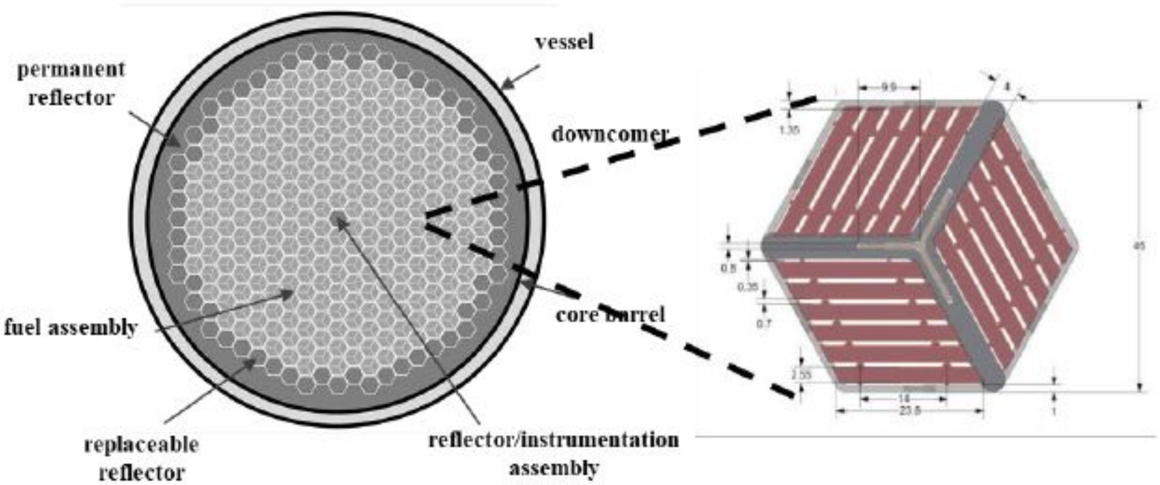
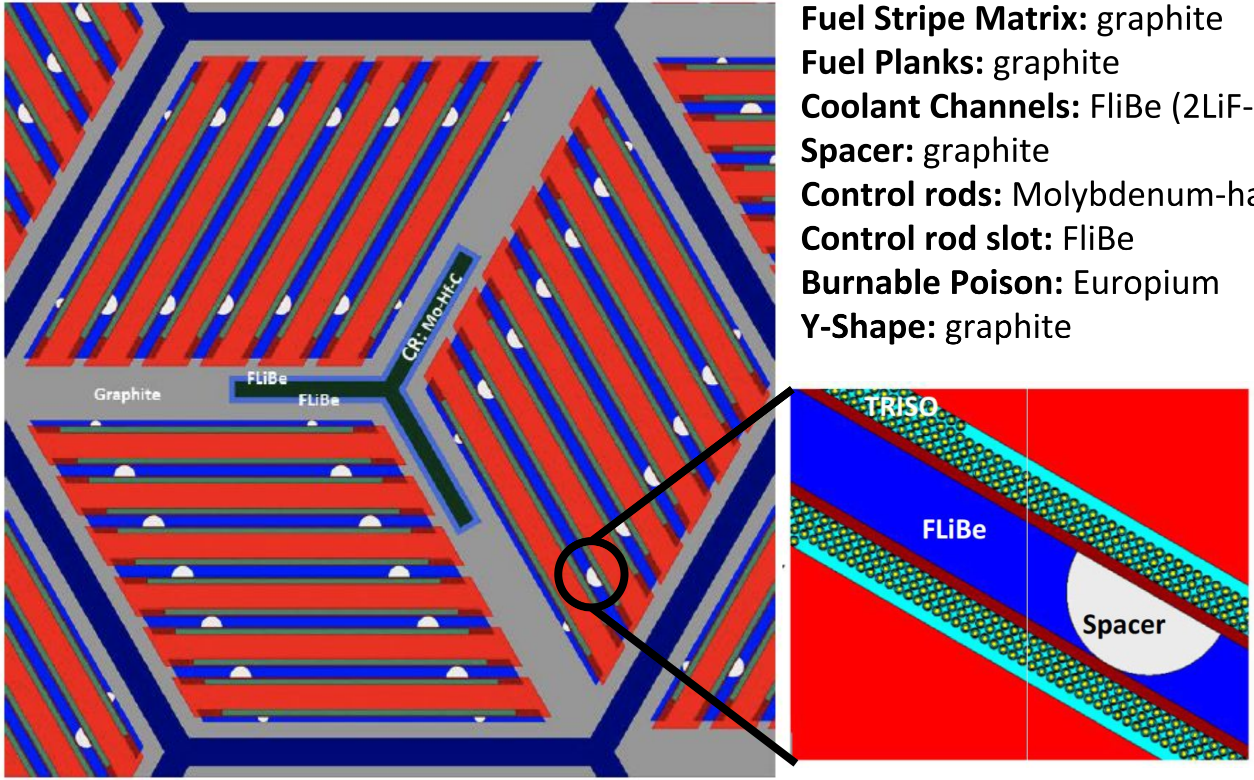
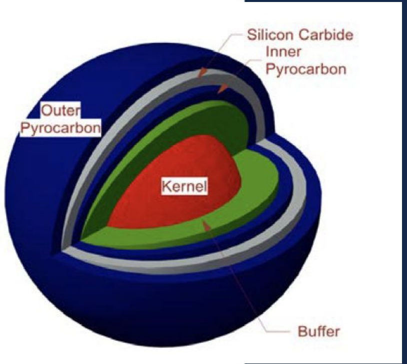


Figure 2-2. Core configuration and fuel element

Fluoride-salt-cooled High-temperature Reactor (FHR)

TRISO fuel kernel: 9% enriched U
Fuel Stripe Matrix: graphite
Fuel Planks: graphite
Coolant Channels: FliBe ($2LiF\text{-}BeF_2$)
Spacer: graphite
Control rods: Molybdenum-halfnium carbide alloy
Control rod slot: FliBe
Burnable Poison: Europium
Y-Shape: graphite





History of FHR

- Introduced in 2012.
- FHR technology combines the best aspects of Molten Salt Reactor and High Temperature Gas-Cooled Reactor technologies
- Molten salts coolant: inherent safety due to high boiling temperature and room pressure operation
- Solid TRISO fuel: Adds an extra barrier to fission product release

Fluoride-salt High-temperature Reactor (FHR) Benchmark

Why was this benchmark proposed?

- This reactor type has a complex fuel geometry which could be considered a form of “ triple heterogeneity” (hexagonal fuel elements with TRISO fuel particles embedded in planks).
- There are no experimentally obtained results of this reactor geometry, making cross-verification using different reactor physics codes and methods to verify performance and identify gaps in simulation capability.

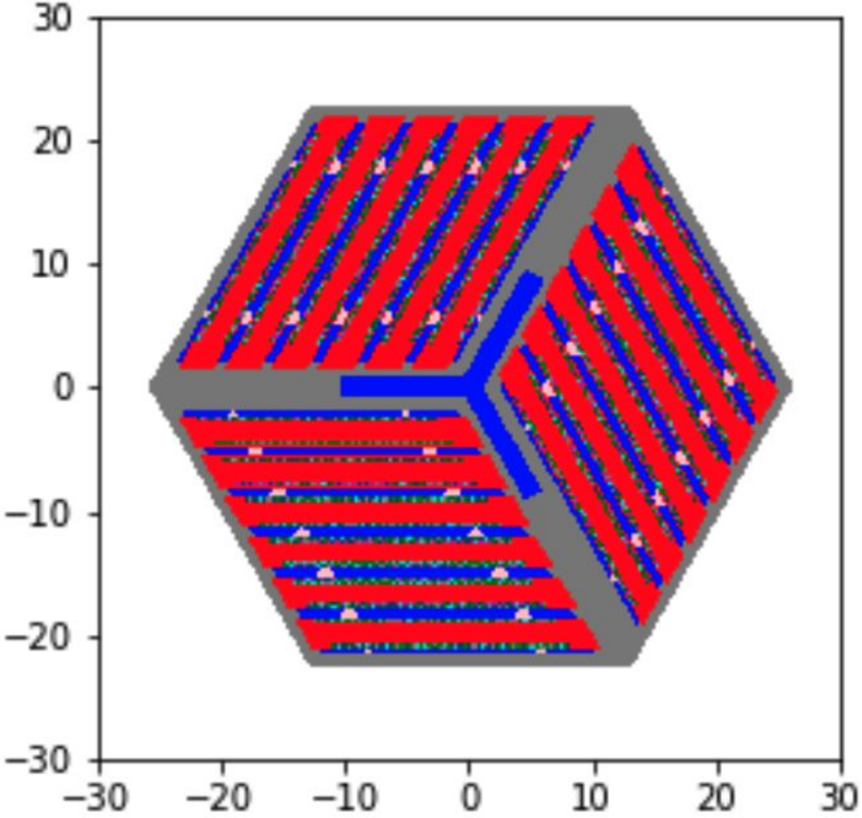
Phase I

Phase I-A: “2D” (pseudo-2D) model, steady state (no depletion)

- Pseudo because the model geometry is not uniform in the axial direction.
- The 2D model consists of a finite slice of the fuel element containing an integer number of TRISO particles (101 in our case).

Phase I-B: 2D model depletion

Phase I-A: Case 1A (reference case)



Reference case (Hot full power)

- Specific Power = 200 W/gU
- Fuel kernel temperature: 1110K
- Everything else temperature: 948K
- 9 wt% fuel enrichment
- No burnable poisons
- Control Rods out (FliBe in control rod place)
- TRISOs: 4 x 210 triso particles per fuel stripe

Phase I-A

Case 2AH: Hot zero power

- Same as Case 1A except uniform temperature of 948K in all regions

Case 2AC: Cold Zero Power

- Same as Case 1A except uniform temperature of 773K in all regions

Case 3A: Case 1A + Control Rods Inserted

Case 4A: Case 1A + Discrete Europia Burnable Poisons

Phase I-A

Case 4AR: Case 1A + Discrete Europia Burnable Poisons + Control Rods

Case 5A: Case 1A + Integral (dispersed) Europia Burnable Poisons

- Replace fuel plate graphite with graphite + europia mix

Case 6A: Case 1A + Increased HM Loading

- Add 4 more layers of TRISO particles (total = 8 layers), and decreased specific power to 100W/gU

Case 7A: Case 1A + 19.75% Fuel Enrichment

Quantities to be analyzed

a) Effective multiplication factor
b) Reactivity coefficients (B-eff, fuel Doppler coefficient, FliBe & graphite temperature coefficients.
c) Tabulated fission source distribution by 1/5th fuel stripe
d) Neutron flux, averaged over the whole model in 3 coarse energy groups
e) Neutron flux distribution in 100 x 100 mesh in 3 coarse energy groups
f) Neutron spectrum, fuel assembly averaged

(a): keff

Case 1A: Reference case
Case 2AH: Hot Zero Power (all 948K)
Case 2AC: Cold Zero Power (all 773K)
Case 3A: Case 1A + Control Rods Inserted
Case 4A: Case 1A + Discrete Europia Burnable Poisons
Case 4AR: Case 1A + Discrete Europia Burnable Poisons + Control Rods
Case 5A: Case 1A + Integral (dispersed) Europia Burnable Poisons
Case 6A: Case 1A + Increased HM Loading + decreased specific power
Case 7A: Case 1A + 19.75% Fuel Enrichment

	k-eff	1σ(k-eff)	Wallclocktime [hr]
CASE 1A	1.40752	0.00003	24.19
CASE 2AH	1.41823	0.00003	24.09
CASE 2AC	1.43456	0.00003	23.45
CASE 3A	1.02899	0.00003	21.19
CASE 4A	1.10551	0.00003	40.83
CASE 4AR	0.83771	0.00003	36.85
CASE 5A	0.85936	0.00003	20.54
CASE 6A	1.25501	0.00003	31.44
CASE 7A	1.50550	0.00003	19.38

Simulations are all run on BlueWaters
- 64 XE nodes

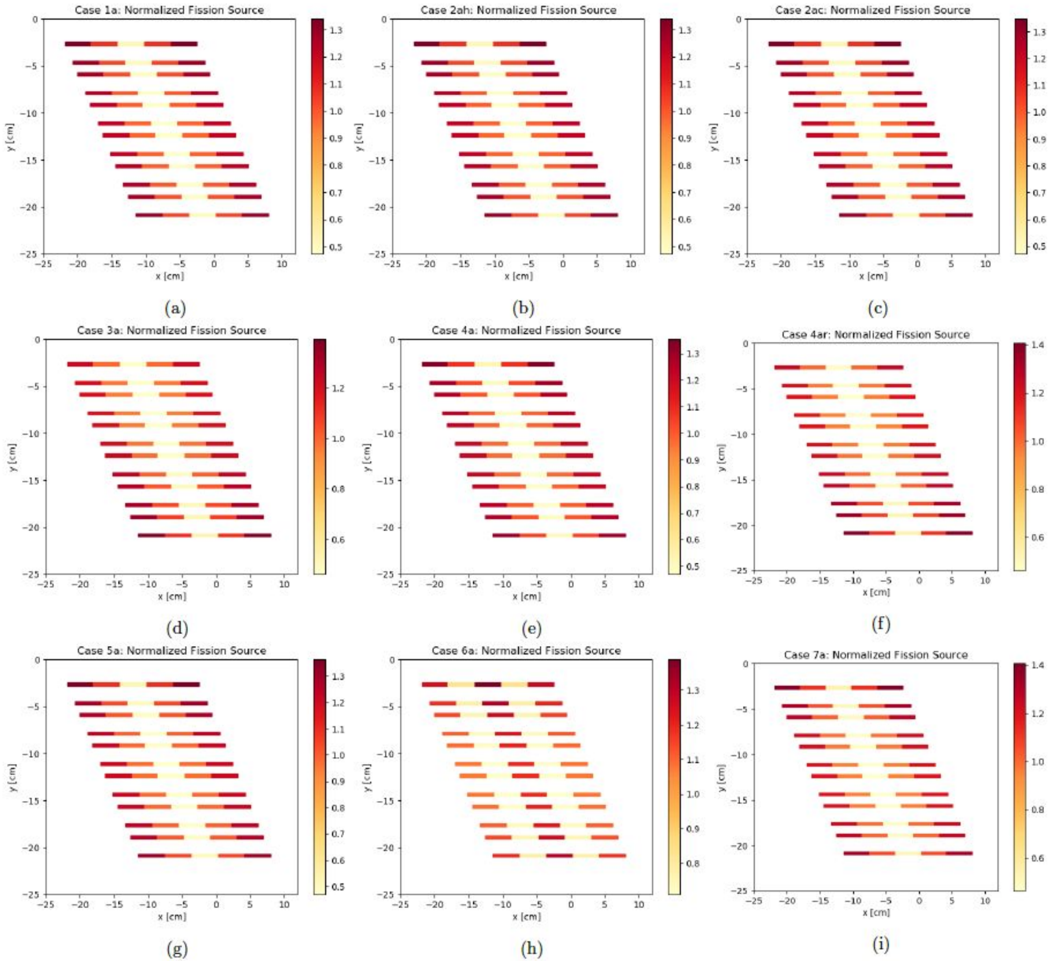
(b): Reactivity Coefficients

Case 1A: Reference case
Case 2AH: Hot Zero Power (all 948K)
Case 2AC: Cold Zero Power (all 773K)
Case 3A: Case 1A + Control Rods Inserted
Case 4A: Case 1A + Discrete Europia Burnable Poisons
Case 4AR: Case 1A + Discrete Europia Burnable Poisons + Control Rods
Case 5A: Case 1A + Integral (dispersed) Europia Burnable Poisons
Case 6A: Case 1A + Increased HM Loading + decreased specific power
Case 7A: Case 1A + 19.75% Fuel Enrichment

	β_{eff}	Fuel ($\Delta\rho/\Delta T$) [pcm/K]	FLiBe ($\Delta\rho/\Delta T$) [pcm/K]	Graphite ($\Delta\rho/\Delta T$) [pcm/K]
CASE 1A	0.006536	-6.14	-0.14	-1.56
CASE 2AH	0.006535	-6.98	-0.38	-1.86
CASE 2AC	0.006535	-7.90	-0.30	-0.58
CASE 3A	0.006547	-4.40	-0.28	-4.04
CASE 4A	0.006544	-4.98	-1.32	-8.98
CASE 4AR	0.006556	-3.42	-0.76	-7.46
CASE 5A	0.006555	-3.72	-1.90	-15.64
CASE 6A	0.006571	-8.34	-0.24	-1.28
CASE 7A	0.006531	-5.72	-0.04	-1.14

Uncertainty for all reactivity coefficients is 0.08 pcm/K.

(c): Tabulated fission source distribution by 1/5th fuel stripe



Interesting observation

- Intuitively I would assume that the fission source will be highest in the centre of the fuel stripes, but the opposite is true. Power peaking occurs in the exterior and is minimum in the interiors.
- This is because resonance escape probability is diminished in the interior due to a higher relative fuel-to-carbon volume ratio.
- This phenomenon is even more exaggerated in case 6a (increased TRISO particle layers) since it has an even higher fuel-to-carbon volume ratio.

(d): Neutron flux, averaged over the whole model in 3 coarse energy groups

Case 1A: Reference case

Case 2AH: Hot Zero Power (all 948

Case 2AC: Cold Zero Power (all 773

Case 3A: Case 1A + Control Rods In

Case 4A: Case 1A + Discrete Europi

Poisons

Case 4AR: Case 1A + Discrete Europ

Poisons

+ Control Rods

Case 5A: Case 1A + Integral (disper

Burnable Poisons

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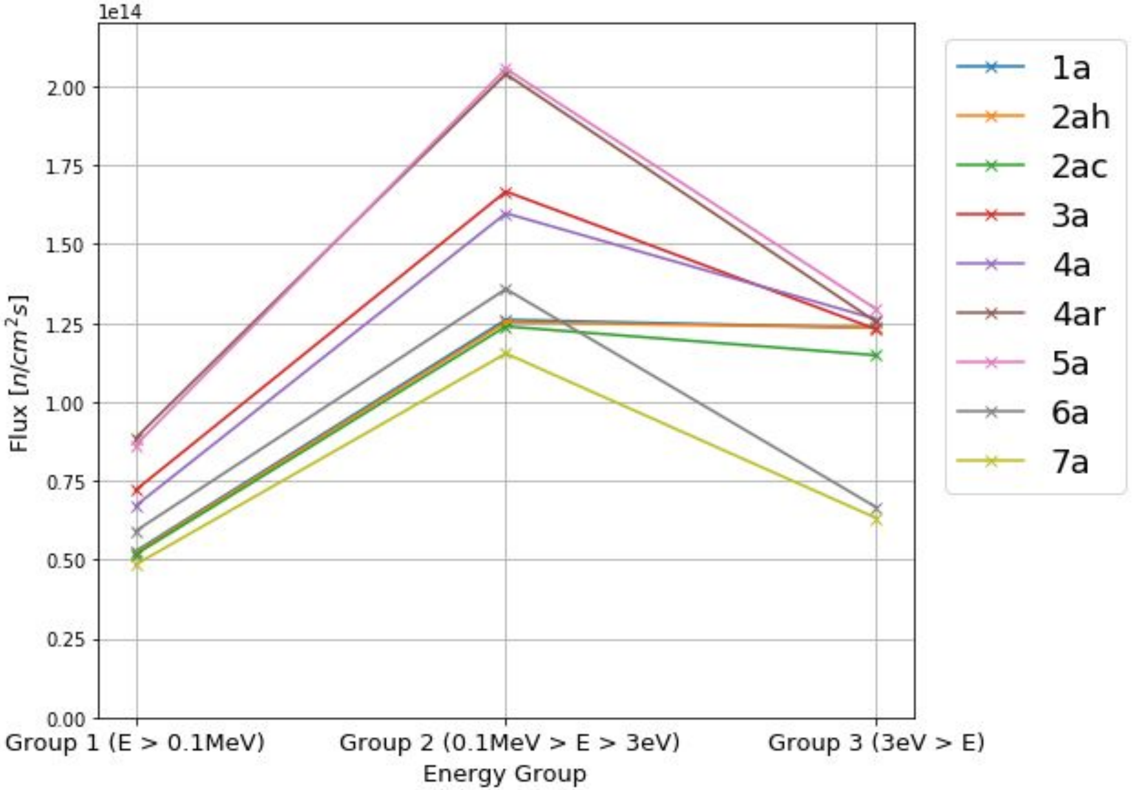
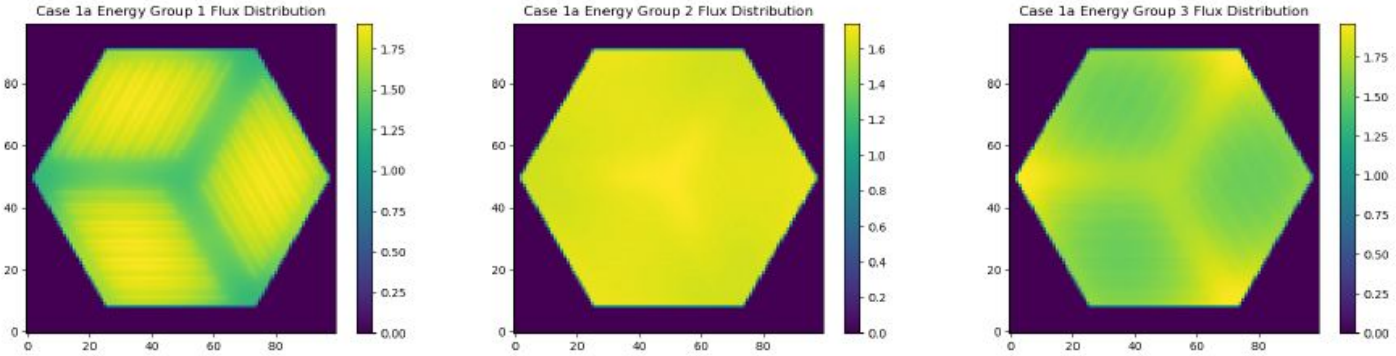
Case 7A: Case 1A + 19.75% Fuel En

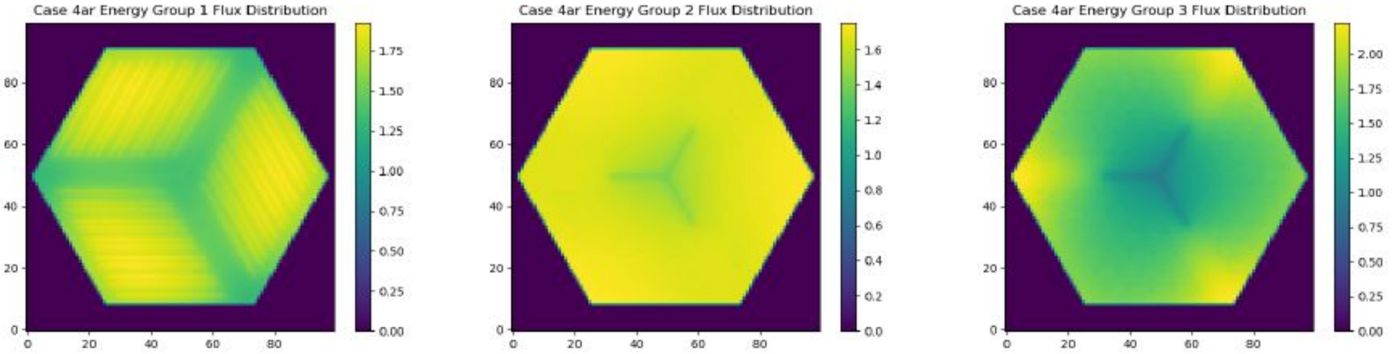


(e): Neutron flux distribution in 100 x 100 mesh in 3 coarse energy groups

Case 1A:
Reference case

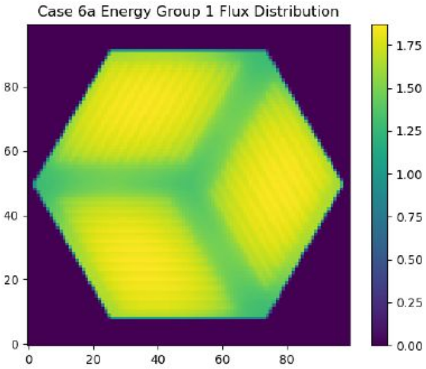


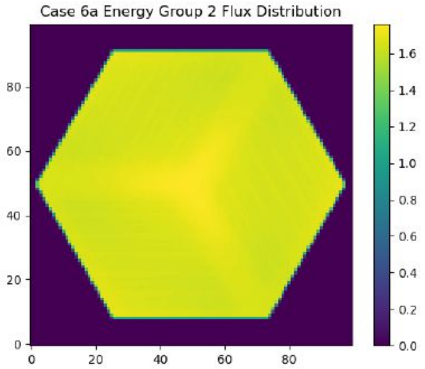
Case 4AR:
Case 1A + Discrete Europia Burnable Poisons

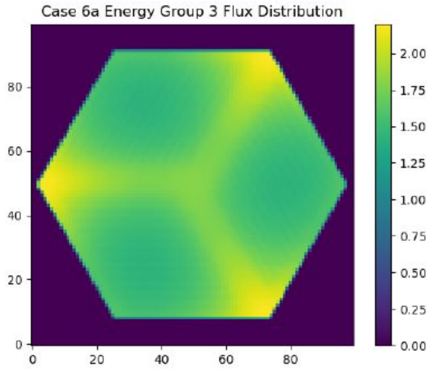


(e): Neutron flux distribution in 100 x 100 mesh in 3 coarse energy groups

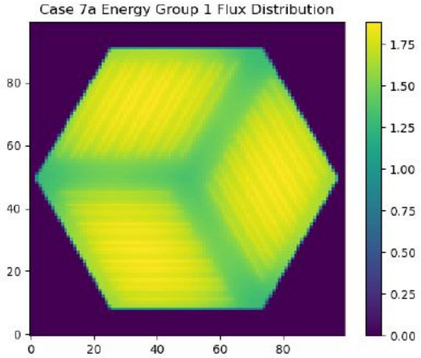
Case 6A:
Case 1A + Increased HM Loading + decreased specific power

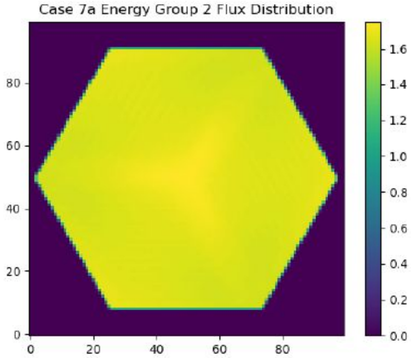


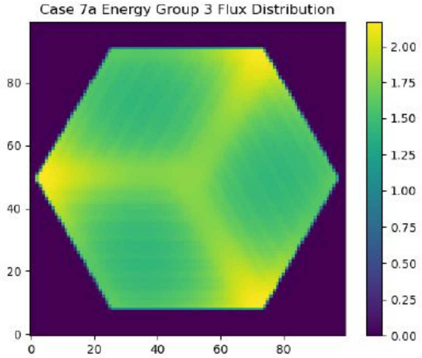




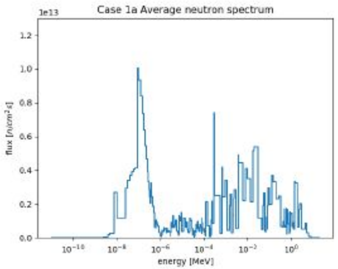
Case 7A:
Case 1A + 19.75% Fuel Enrichment



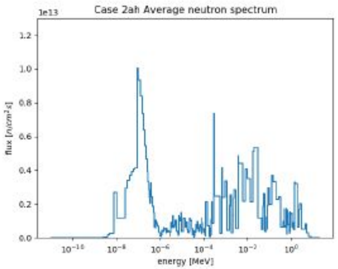




(f): Neutron spectrum, fuel assembly averaged



(a)



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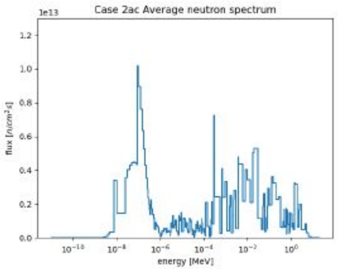
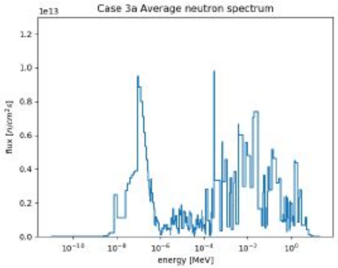


(c)



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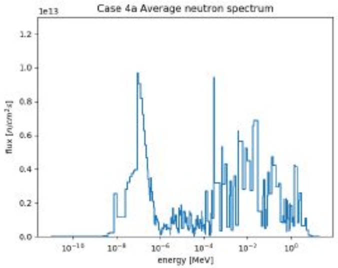
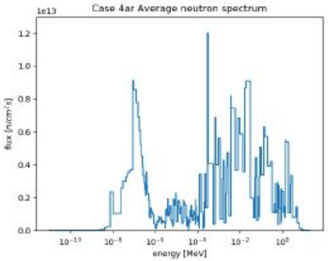
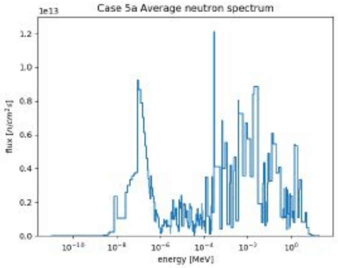


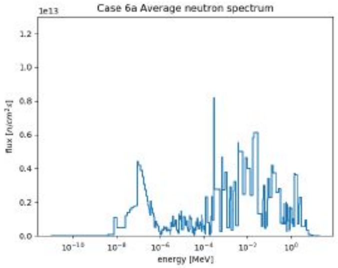
(e)



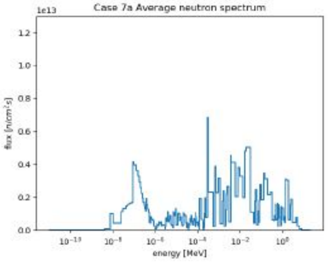
(f)



(g)



(h)



(i)

- Spectrum becomes faster for case 6a and case 7a due to more heavy metal loading and higher enrichment.

The End