FHR/AHTR NEA Benchmark

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AHTR (FHR with plank fuel) benchmark

OUTLINE

- Background and motivation/rationale for the benchmark
- FHR/AHTR basic info and reactor physics challenges
- Benchmark high-level scope (Phase I, II & III)
- Specific cases by Phase
- Benchmark geometry specifications
- Timeline
- Required results
- Sample templates for results
- Sample results

Rationale for the NEA benchmark

Rationale:

- Attractive features of molten salt cooled reactors (high temperature and efficiency, low operating pressure
- Over the last 10+ years, renewed interest in USA, for the liquid-salt cooled designs, including with solid fuel (i.e., liquid salt used as coolant only, not as fuel)
- Denoted as FHR (**F**luoride-salt-cooled **H**igh-temperature **R**eactor)
- "Plank" fuel (AHTR, developed by ORNL) and pebble-bed (PB-FHR, UCB/Kairos) designs
- Very challenging modeling (reactor physics, and multi-physics in general)
- Need to verify and validate simulation capabilities
- Several participants/groups confirmed interest to participate in this benchmark

NOTE: More recently, in US, renewed interest also in traditional MSR→ separate issues

Modelling challenges (in reactor physics):

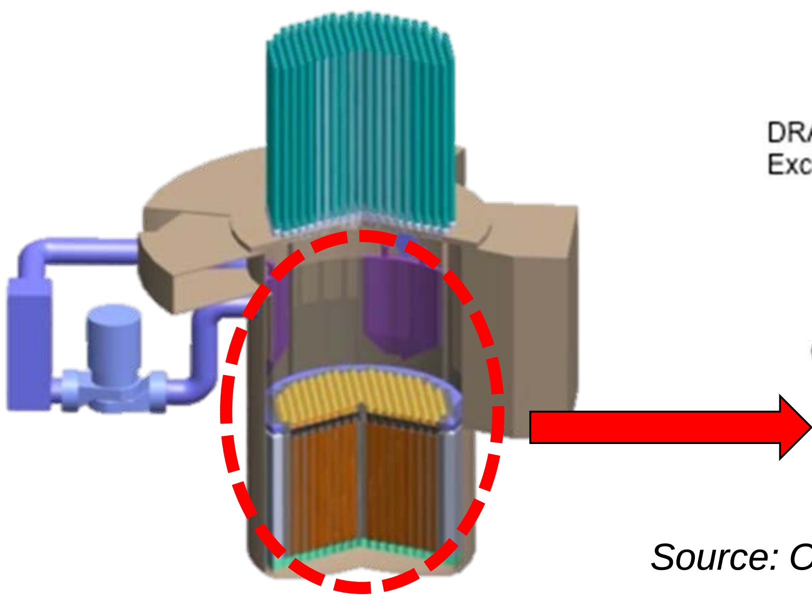
- AHTR plank fuel design has double (triple?) heterogeneity
- Error in reactivity may amount to thousands of pcm's if inadequately modeled

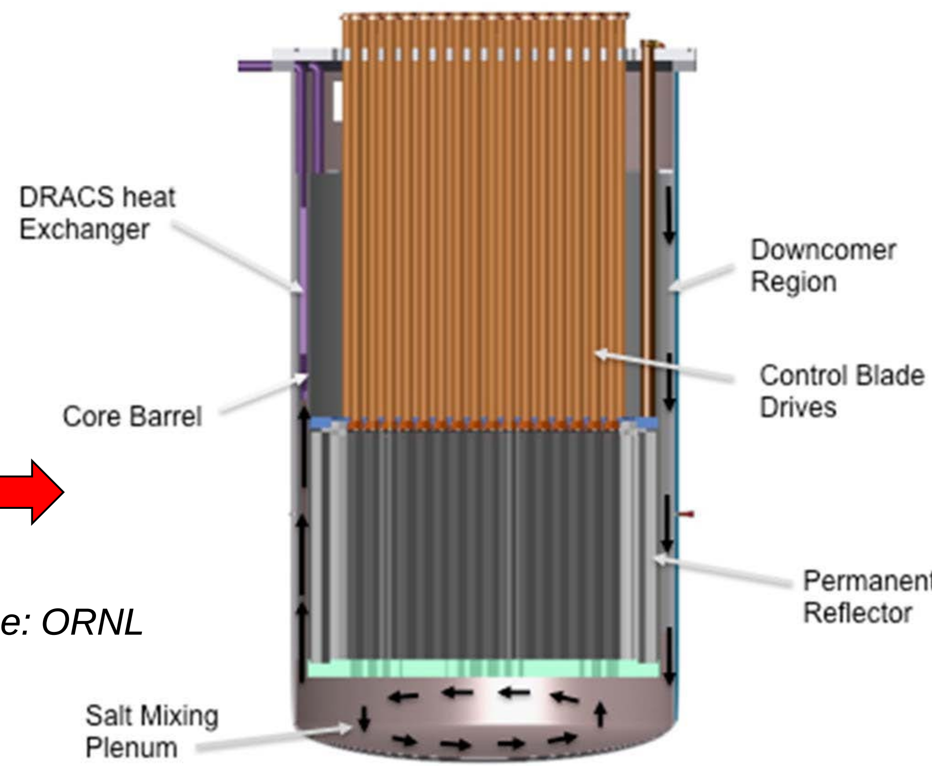
NEA benchmark:

- Multi-phase, start with a fuel element 2D depletion benchmark, develop a sequence to full core 3D with feedback and depletion

FHR design developed at ORNL: Advanced High Temperature Reactor (AHTR)

- 3,400 MWth
- Power density ~13 W/cm^3, i.e., higher than in gas-cooled reactors, but lower than in water-cooled reactors (PWR and BWR)
- Large (low pressure) reactor vessel, ~10m O.D.

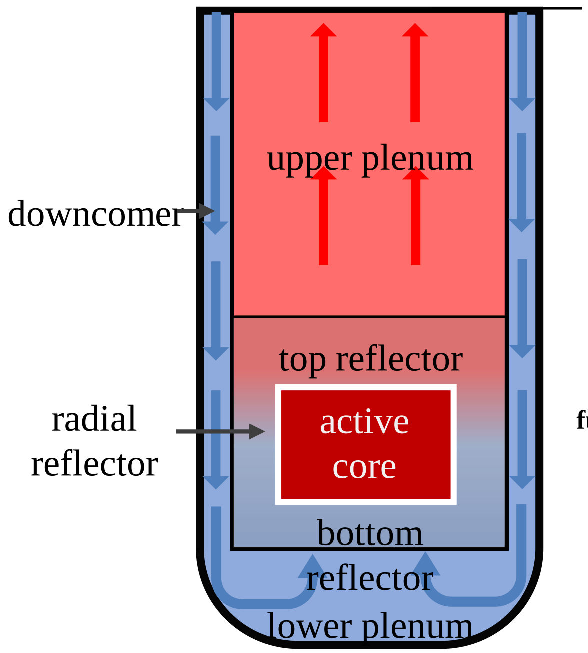




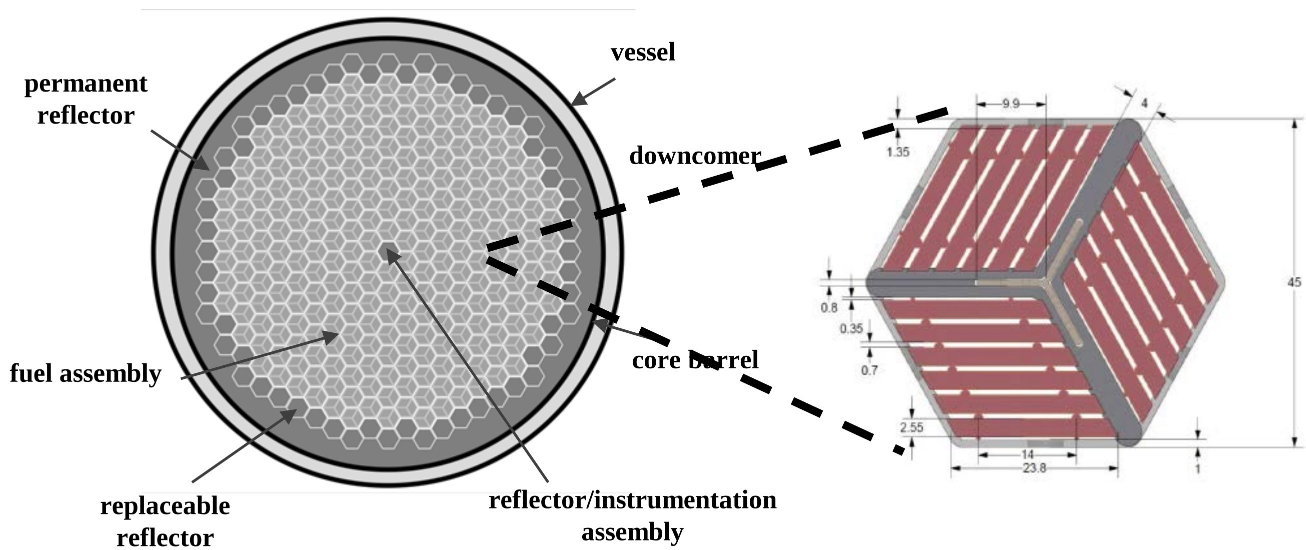
Source: ORNL

Advanced High Temperature Reactor (AHTR) Core Design

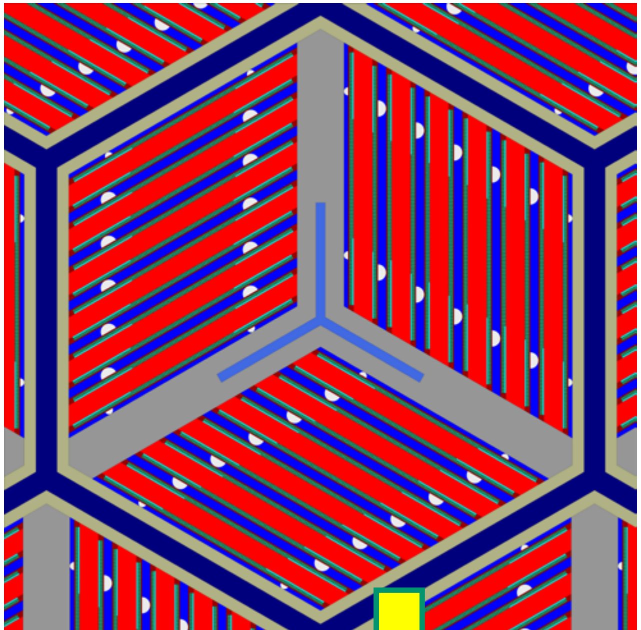
- 252 hexagonal fuel elements
- 5.5m active core height
- ~8m core radius



Reactor Vessel

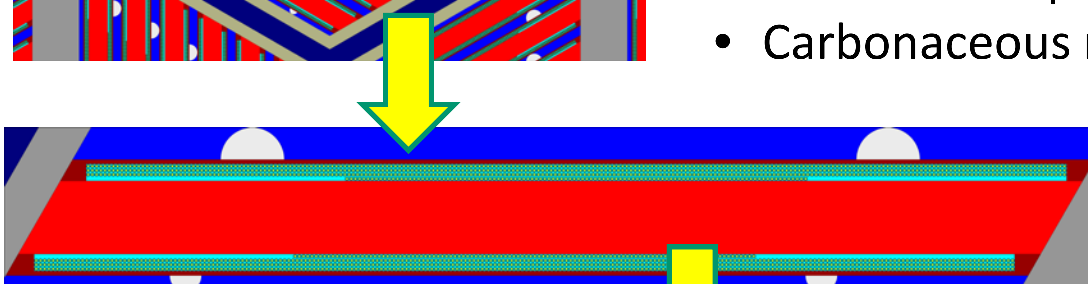


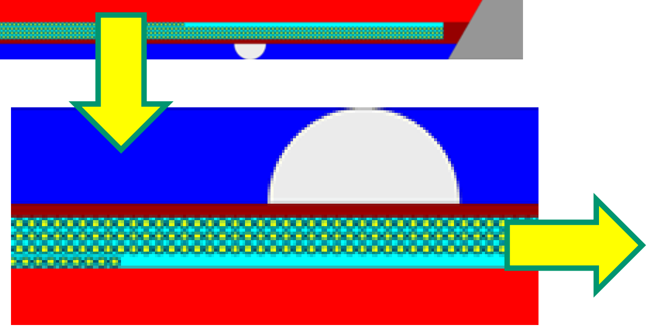
Double (triple?) heterogeneity
Fuel Assembly SERPENT Model

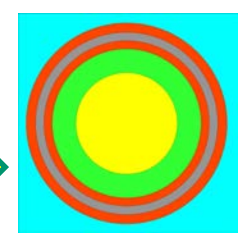


Fuel element

- 3 groups of 6 planks each; 120-deg rotational symmetry
- Fuel plank: two fuel stripes (TRISO particles embedded in matrix), one on each side
- TRISO particles – fuel kernel plus protective layers
- TRISO particles usually assumed in a “lattice”; in reality, randomized
- Central Y-shaped structure and control rod
- Carbonaceous materials (carbon, graphite, mix..?)







Series of incremental benchmarks
AHTR 2D/3D Fuel Assembly, 3D core & Depletion

Phase I – Fuel assembly
- Phase I-A – "2D" (pseudo)-2D, steady state (no depletion)
- Phase I-B – Depletion
- Phase I-C – 3D depletion

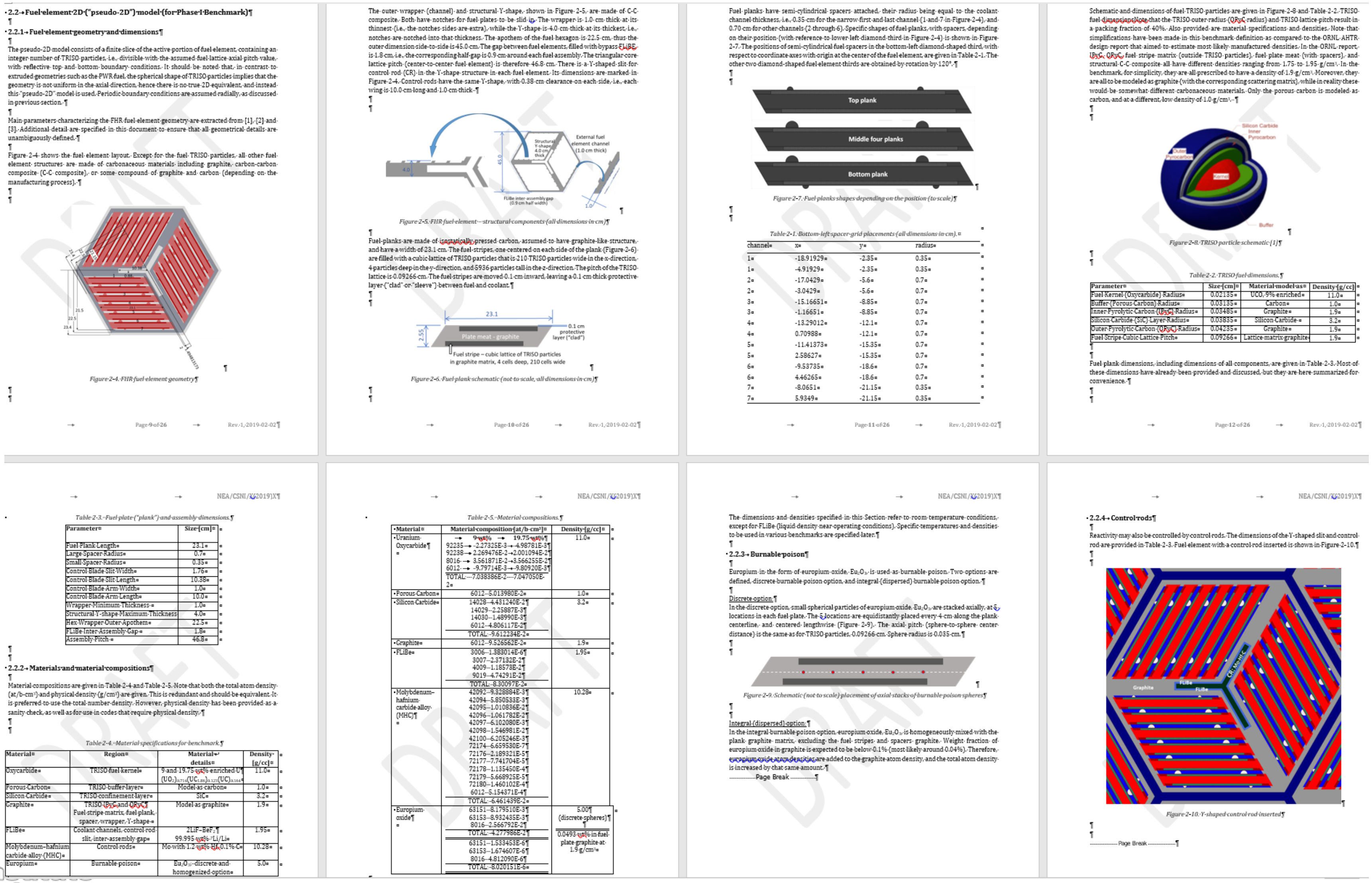
Phase II – 3D full core
- Phase II-A – Steady-state (no depletion)
- Phase II-B – Depletion with feedback
- Phase II-C – Multicycle

Overarching objective: Cross-verify codes and methodologies for challenging AHTR geometry, **for accurate and efficient reactor design and analyses**

NOTE: Since FHR uses spherical fuel, it is not "extruded" geometry, there is no true 2D equivalent. In Monte Carlo simulations, modeling a slice with reflective top/bottom is possible. In deterministic codes, a different approach needs to be used.

NEA Benchmark Document – Phase I Geometry Specification

Complex geometry. 120-deg rotational symmetry. Geometry defined (hopefully unambiguously) in tables and figures



NEA FHR/AHTR Benchmark, Phase I-A "2D" fuel element, no depletion

CASE 1A: Hot zero power (HZP) with uniform temperature of 923K in all regions, nominal (cold) dimensions, 9 wt% enrichment, no burnable poison (BP), control rods (CR) out.

CASE 2A: Reference case: Hot full power (HFP), with prescribed temperatures for fuel, graphite, and coolant, otherwise same as CASE 1.

Perturbation cases

CASE 3A: CR inserted, otherwise same as CASE 1.

CASE 4A: Discrete europia BP, otherwise same as CASE 1.

CASE 5A: Integral (dispersed) europia BP, otherwise same as CASE 1.

CASE 6A: Increased HM loading (4 to 8 layers of TRISO), hence decreased C/HM (from ~400 to ~200), otherwise same as CASE 1.

CASE 7A: Fuel enrichment 19.75 wt%, otherwise same as CASE 1.

OBJECTIVE: Identify/resolve major/fundamental discrepancies (due to ambiguous specifications, nuclear data, physics, ….) before proceeding to depletion and 3D

NEA FHR/AHTR Benchmark, Phase I-B "2D" fuel element, depletion

Downselect 4+3 cases for depletion. Deplete only fuel and burnable poison, i.e., FLiBe isotopics kept fixed except in CASE 2B4. Define what results at what steps.

CASE 2B: Hot full power (HFP), with prescribed temperatures for fuel, graphite, and coolant.

- CASE 2B1 → deplete with critical spectrum
- CASE 2B2 → deplete with "as-is" spectrum
- CASE 2B3 → deplete with reactivity control and near criticality
- CASE 2B4 → with critical spectrum, deplete fuel and FLiBe

CASE 4: Discrete europia BP, otherwise same as CASE 2B1.

CASE 6: Increased HM loading (4 to 8 layers of TRISO), hence decreased C/HM (from ~400 to ~200), otherwise same as CASE 2B1.

CASE 7: Fuel enrichment 19.75 wt%, otherwise same as CASE 2B1.

OBJECTIVE: Identify specific depletion-related effects, that may not be as pronounced in most other reactor types.
[This is a high-LEU enrichment, epithermal spectrum reactor, with high specific power, using non-traditional BP.]

NEA FHR/AHTR Benchmark, Phase I-B

Results requested at BU steps.

BURNUP [GWd/tU]	k-eff (a)	Fission source distribution (b)	3-group flux (c)	3-group flux distrib. (d)	Neutron spectrum (e)	Isotopics (f)
0	All	All	All	All	All	All
0.1	All		All			All
0.5	All		All			All
1	All	All	All	All	All	All
2	All		All			All
4	All		All			All
6	All		All			All
8	All		All			All
10	All		All			All
14	All		All			All
18	All		All			All
22	All		All			All
26	All		All			All
30	All	All	All	All	All	All
40	All		All			All
50	All		All			All
60	All		All			All
70	All	All	All	All	All	All
80	CASE 7		CASE 7			CASE 7
90	CASE 7		CASE 7			CASE 7
100	CASE 7		CASE 7			CASE 7
120	CASE 7		CASE 7			CASE 7
140	CASE 7		CASE 7			CASE 7
160	CASE 7	CASE 7	CASE 7	CASE 7	CASE 7	CASE 7

NEA FHR/AHTR Benchmark, Phase I-C
3D fuel element, depletion

Same 4 cases as I-B. Add top/bottom reflector regions.

CASE 2C: Hot full power (HFP), with prescribed temperatures for fuel, graphite, and coolant.

- CASE 2C1 → deplete with critical spectrum, uniform axial temp.
- CASE 2C2 → deplete with “as-is” spectrum, uniform axial temp.
- CASE 2C5 → 2C1 with prescribed axial temperature gradient

CASE 4C: Discrete europia BP, otherwise same as CASE 2C4.

CASE 6C: Increased HM loading (4 to 8 layers of TRISO), hence decreased C/HM (from ~400 to ~200), otherwise same as CASE 2C4.

CASE 7C: Fuel enrichment 19.75 wt%, otherwise same as CASE 2C4.

OBJECTIVE: Impact of reflector (expected larger than “usual”, large migration length!) and axial temperature gradient (expected small)

Required Results

2D FUEL ELEMENT (Phase I-A and I-B)

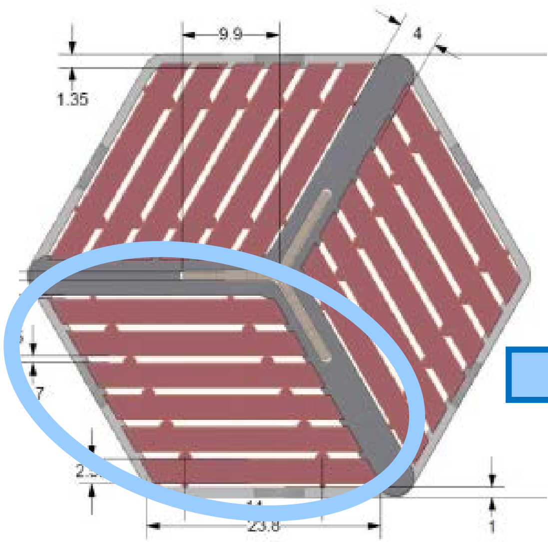
a) Effective multiplication factor, and its change with depletion.
b) Tabulated fission source distribution, at several levels of granularity (~~by fuel plate~~, by fuel stripe, by 1/5-th fuel stripe), and its change with depletion, at selected burnups. Optional: visualized fission density distribution.
c) Neutron flux, averaged over the whole model, tabulated in 3 coarse energy groups (upper energy boundaries 3 eV for thermal group and 0.1 MeV for intermediate group), and its change with depletion, at selected burnups.
d) Visualized distribution of the neutron flux distribution, in 3 coarse energy groups, and its change with depletion, at selected burnups.
e) Neutron spectrum, fuel assembly average. Optional: by region
f) Fuel (and burnable poison, when applicable) isotopic change with depletion. [Details, i.e., which isotopes at what burnup – specify.]
g) FLiBe isotopic change and tritium production (one case only)

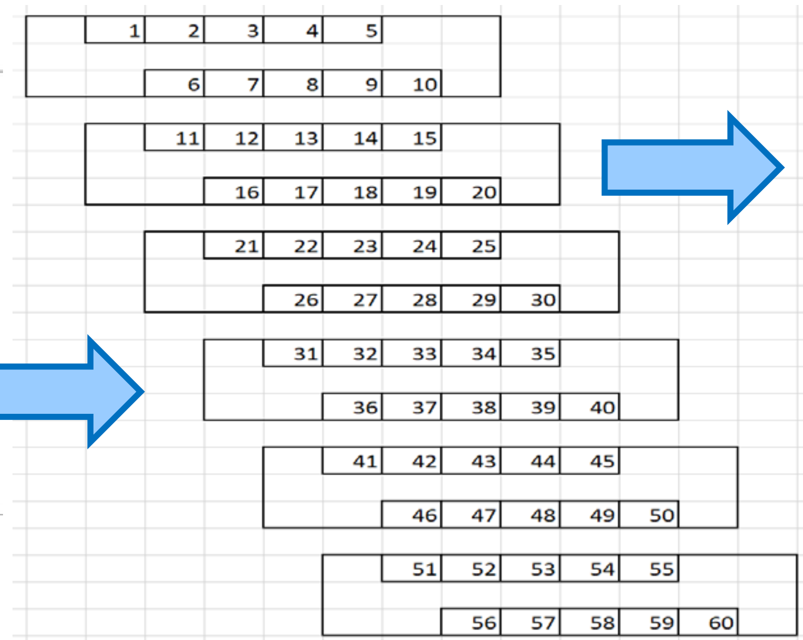
3D FUEL ELEMENT (Phase I-C), at prescribed burnups:

a) Effective multiplication factor
b) Axial fission density distribution
c) Axial 3-group flux distribution
d) Axial burnup distribution

Templates for Results – fission source

a) Tabulated fission source distribution, by fuel stripe and by 1/5-th fuel stripe, and its change with depletion, at selected burnups. [180 per assembly. Similar granularity to fuel pins per LWR assembly.]
Optional: visualized fission density distribution.





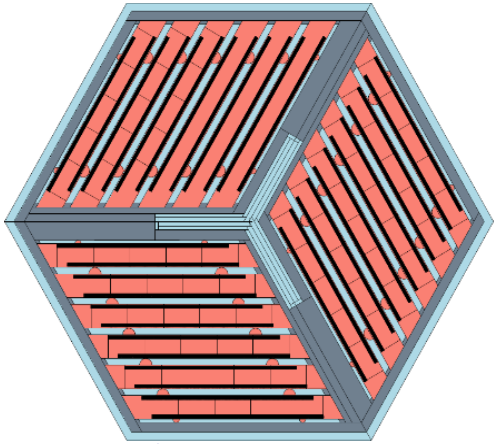
Zone	BU1	…	BUN
1			
2			
…			
60			

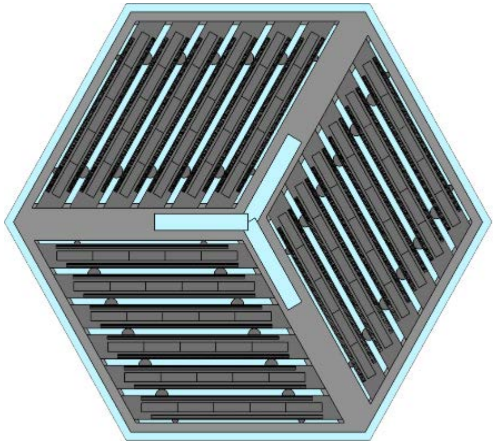
Preliminary Models and Results

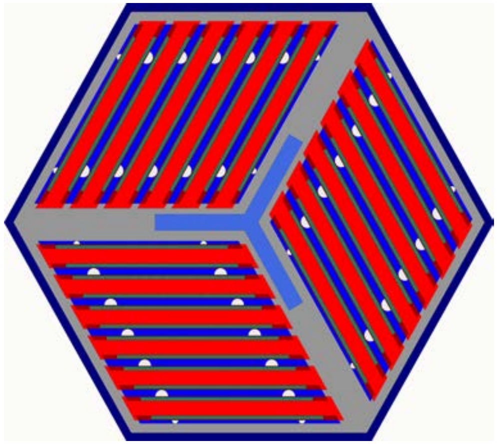
Developed SERPENT, SCALE and MCNP models, very similar to benchmark

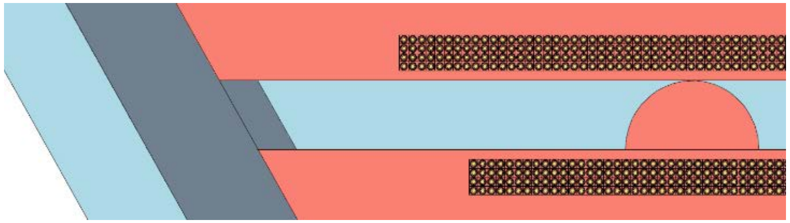
- To identify issues with benchmark specifications
- To get some feel for results, times, sensitivities, …..
- These preliminary results, while not providing results exactly corresponding to the benchmark cases, should help the participants to identify early misinterpretation of specifications or other errors (the unique and complex AHTR core design being more likely to such modeling issues)

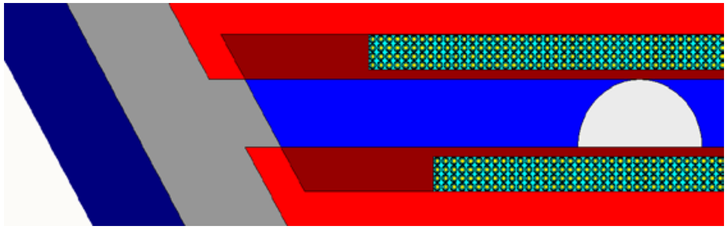
Sample Fuel Element Models/Results
MCNP, SCALE and SERPENT models

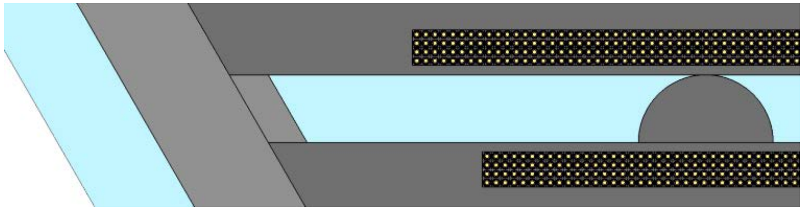

MCNP


SCALE


SERPENT



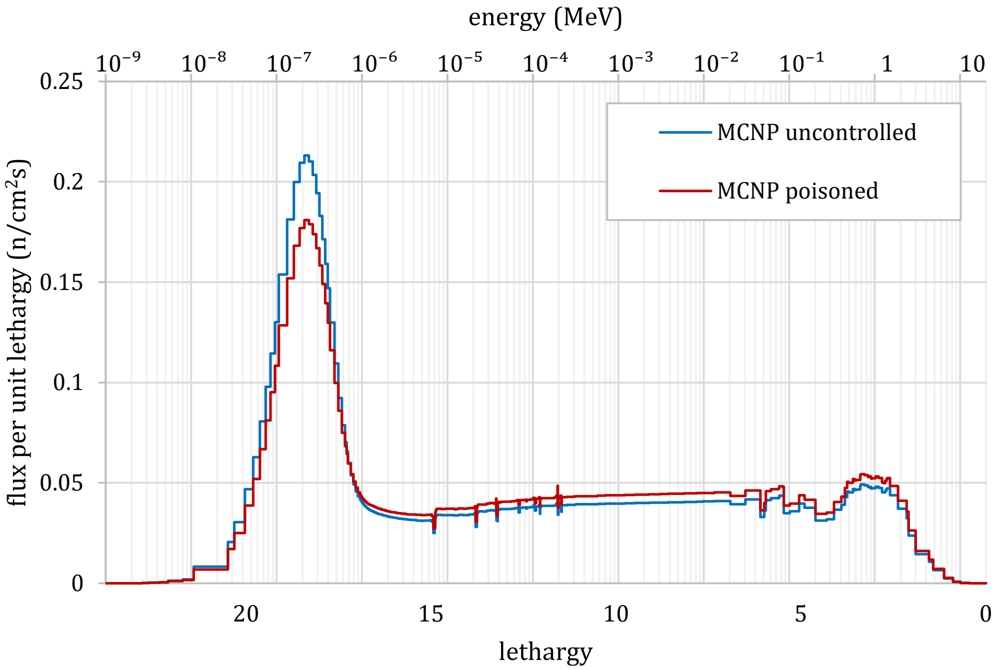


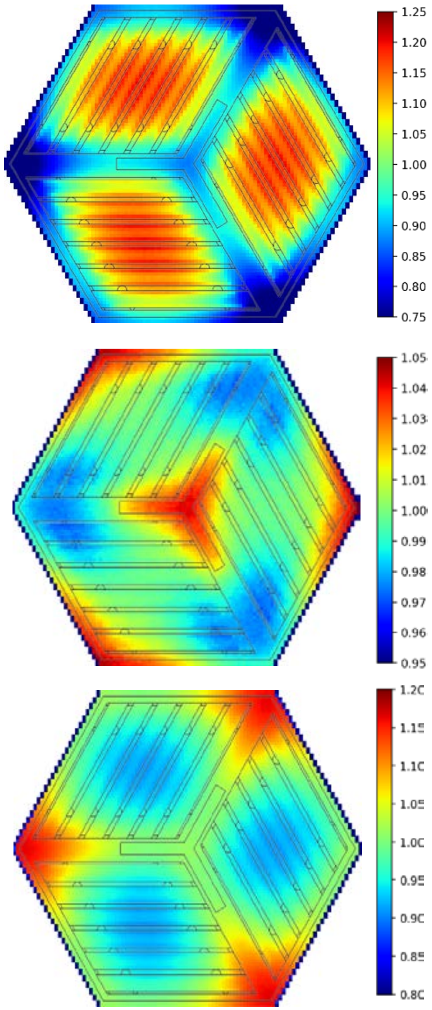


Sample BOC results:
Neutron spectrum and 3-group flux distribution

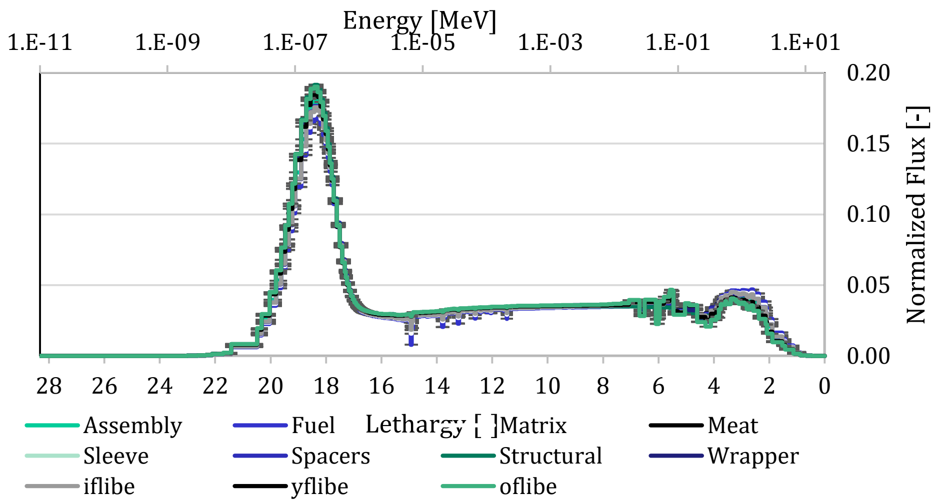
Energy groups boundaries:
10^{-5} eV, 3 eV, 0.1 MeV, 20 MeV

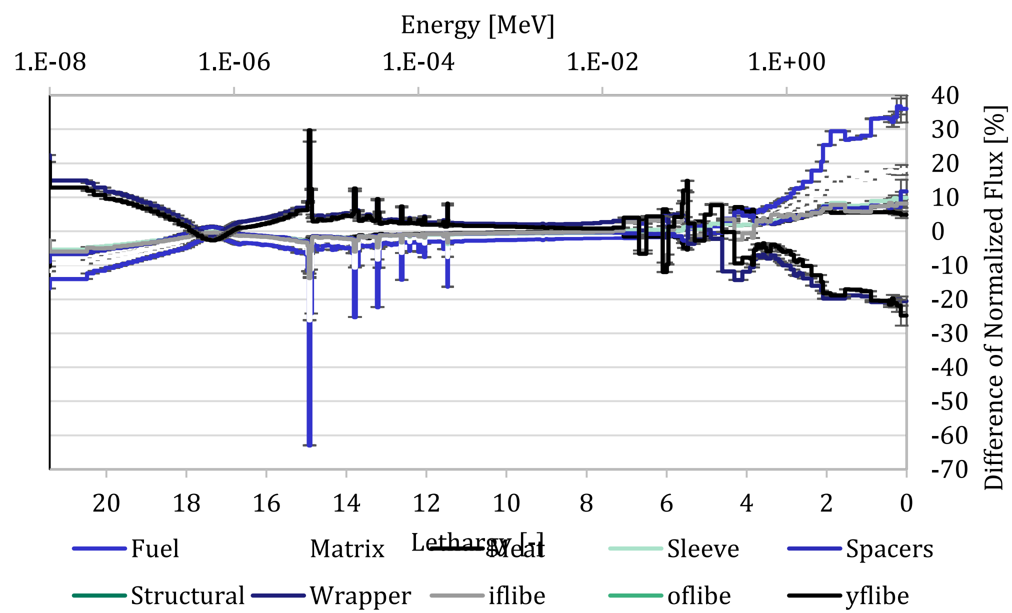
Neutron spectrum:
Unpoisoned and poisoned assembly





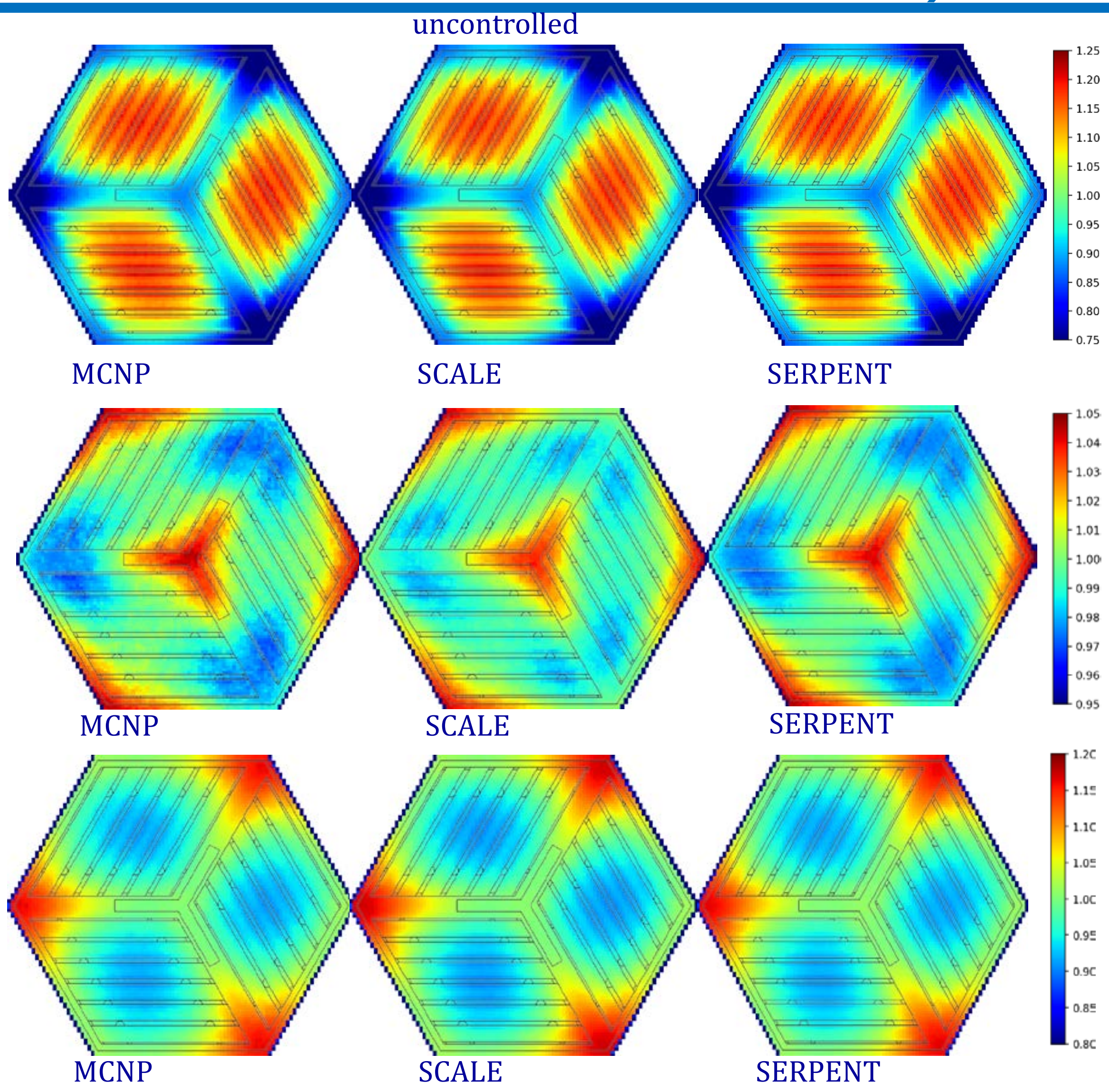
Sample results: Fuel element neutron spectrum and region-wise spectra differences





Sample results: 3-group flux distribution comparison (fast, intermediate, thermal)

Consistent results
Obtained for
Consistent models



Sample results: fission rate distribution (180 regions per assembly)

5 regions lengthwise per fuel stripe
2 fuel stripes per fuel plank
18 fuel planks per fuel assembly
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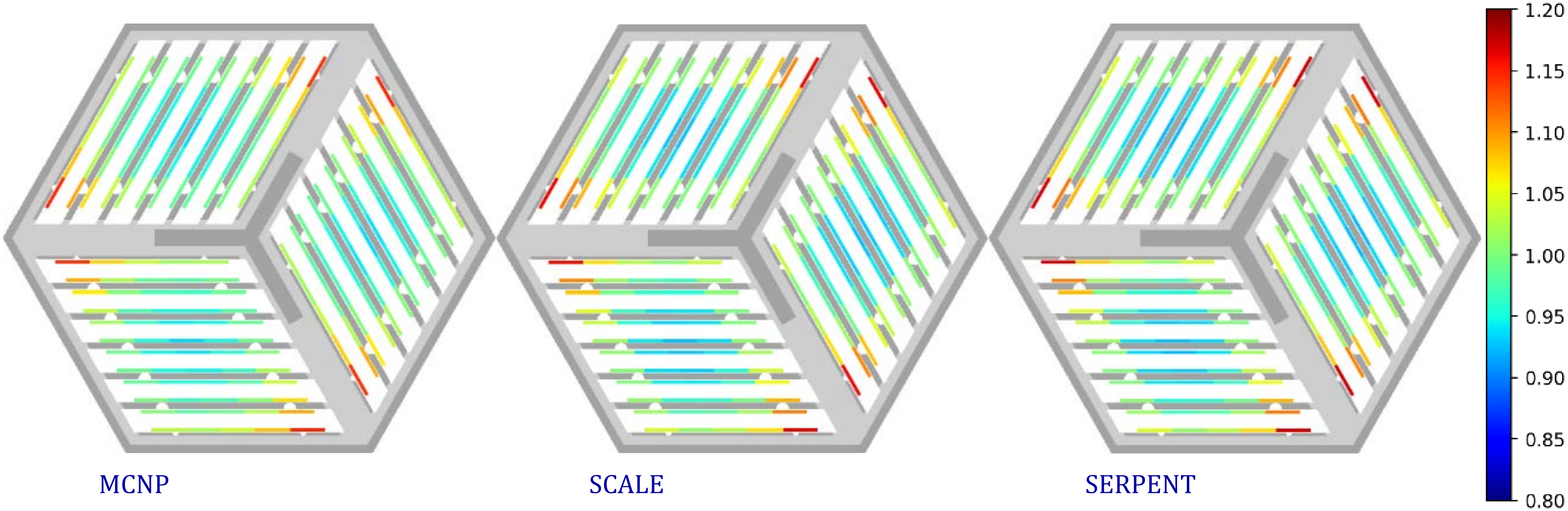
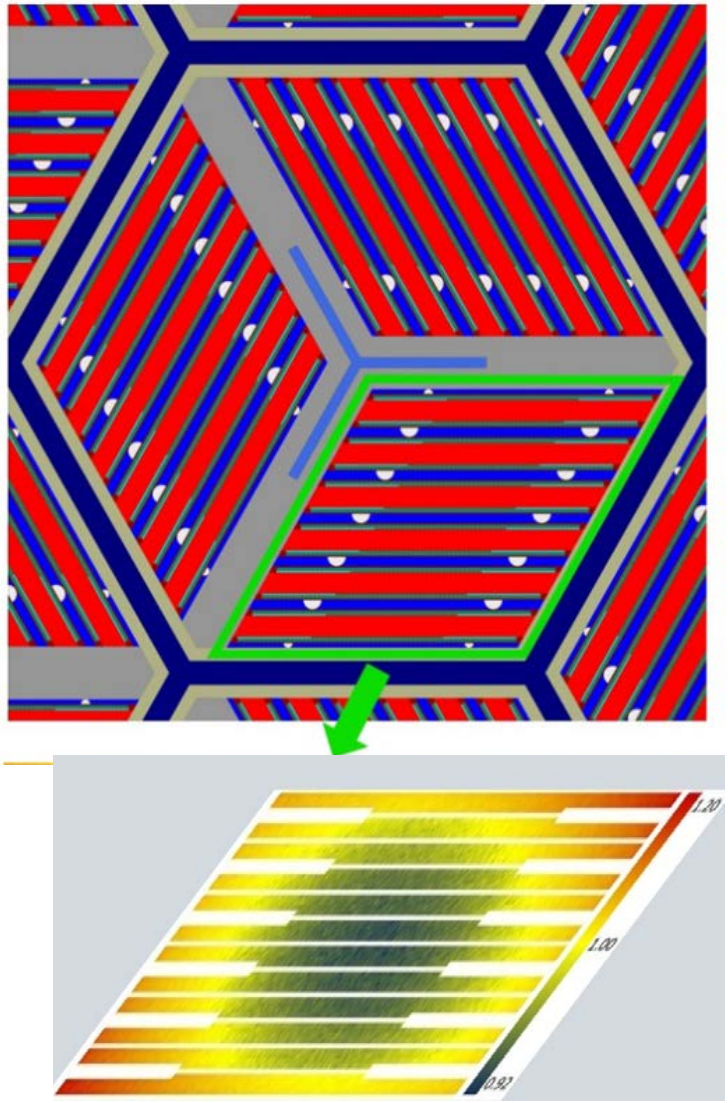
180 power (fission) regions for depletion
(similar granularity as pin-powers in PWR FA)



Sample results: optional fission rate distribution per individual TRISO particle

At fuel element level feasible to obtain TRISO-particle-wise fission density with acceptable statistics



Sample results:
Comparison of peaking factors

Case		Plank Peaking Factor (18)	Stripe Peaking Factor (36)	Fifth-Stripe Peaking Factor (180)
unpoisoned				
MCNP		1.042	1.064	1.148
SCALE		1.041	1.063	1.146
SERPENT		1.042	1.067	1.155
poisoned				
MCNP		1.050	1.075	1.172
SCALE		1.048	1.074	1.174
SERPENT		1.050	1.079	1.183

NOTE: Cross-sections used in simulations are not fully consistent between codes

Benchmark Specs and Participation

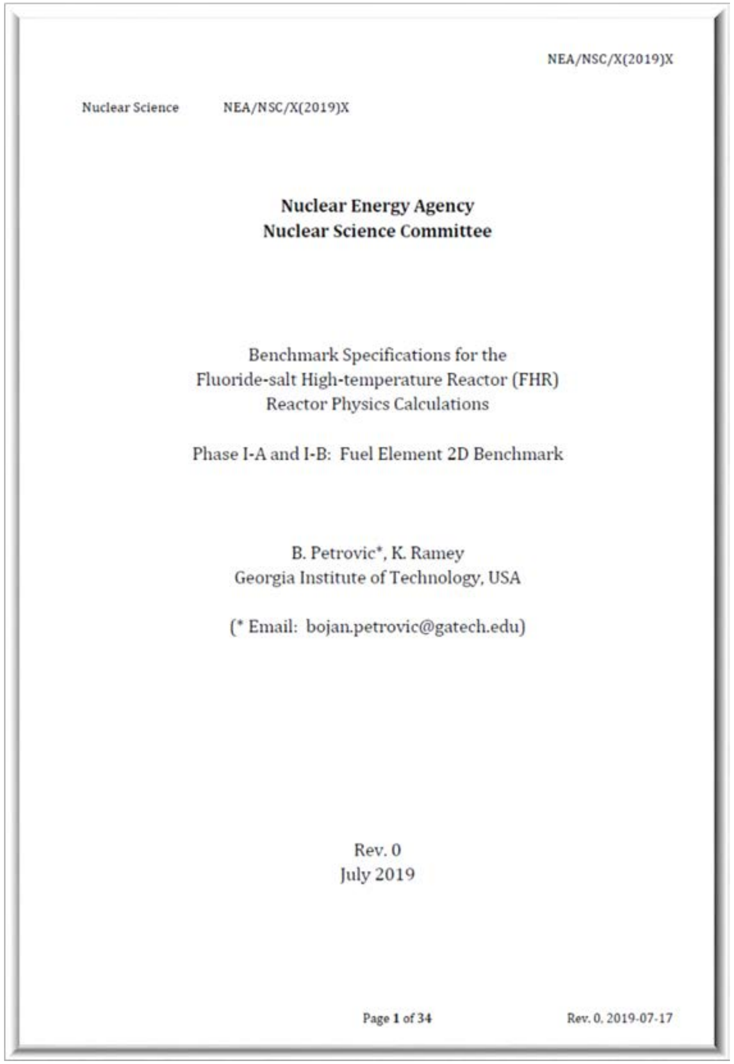
Benchmark accepted/approved by OECD/NEA [Expert Group on Reactor Physics and Advanced Nuclear Systems (EGRPANS) under the Working Party on Scientific Issues of Reactor Systems (WPRS)]

Benchmark homepage at OECD/NEA:
https://www.oecd-nea.org/science/wprs/fhr/index.html

Access to working area and full specifications granted to participants

If interested:

- **Download and complete/sign the participation conditions form (available at benchmark homepage)**
- **Email the form with participation request to wprs@oecd-nea.org (and cc-me)**



NEA/NSC/X(2019)X

Nuclear Science NEA/NSC/X(2019)X

Nuclear Energy Agency
Nuclear Science Committee

Benchmark Specifications for the
Fluoride-salt High-temperature Reactor (FHR)
Reactor Physics Calculations

Phase I-A and I-B: Fuel Element 2D Benchmark

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Rev. 0
July 2019

Page 1 of 34 Rev. 0, 2019-07-17

Benchmark Status and Timeline

- Benchmark released 7/30
- First group of participants approved (7 in August/September)

Tentative schedule

- Conference-call end-October or early November (informal kick-off, initial feedback/issues)
- Will introduce the benchmark at the ANS RPD meeting in D.C. in November
- Finalize (first batch) of participants by end-November
- Conference-call end-November (formally initiate)
- Preliminary results (Phase I-A) at the 2020 WPRS/EGRPANS meeting (NEA, Feb. 2020). Discuss, resolve inconsistencies.
- Phase I-A final results due by 4/30/2020.

- Phase I-B and I-C specifications – in 2020

- Phase I-B and I-C results, present/discuss, 2021 WPRS
- Phase-II specifications

- …….

Benchmark Participants/Codes

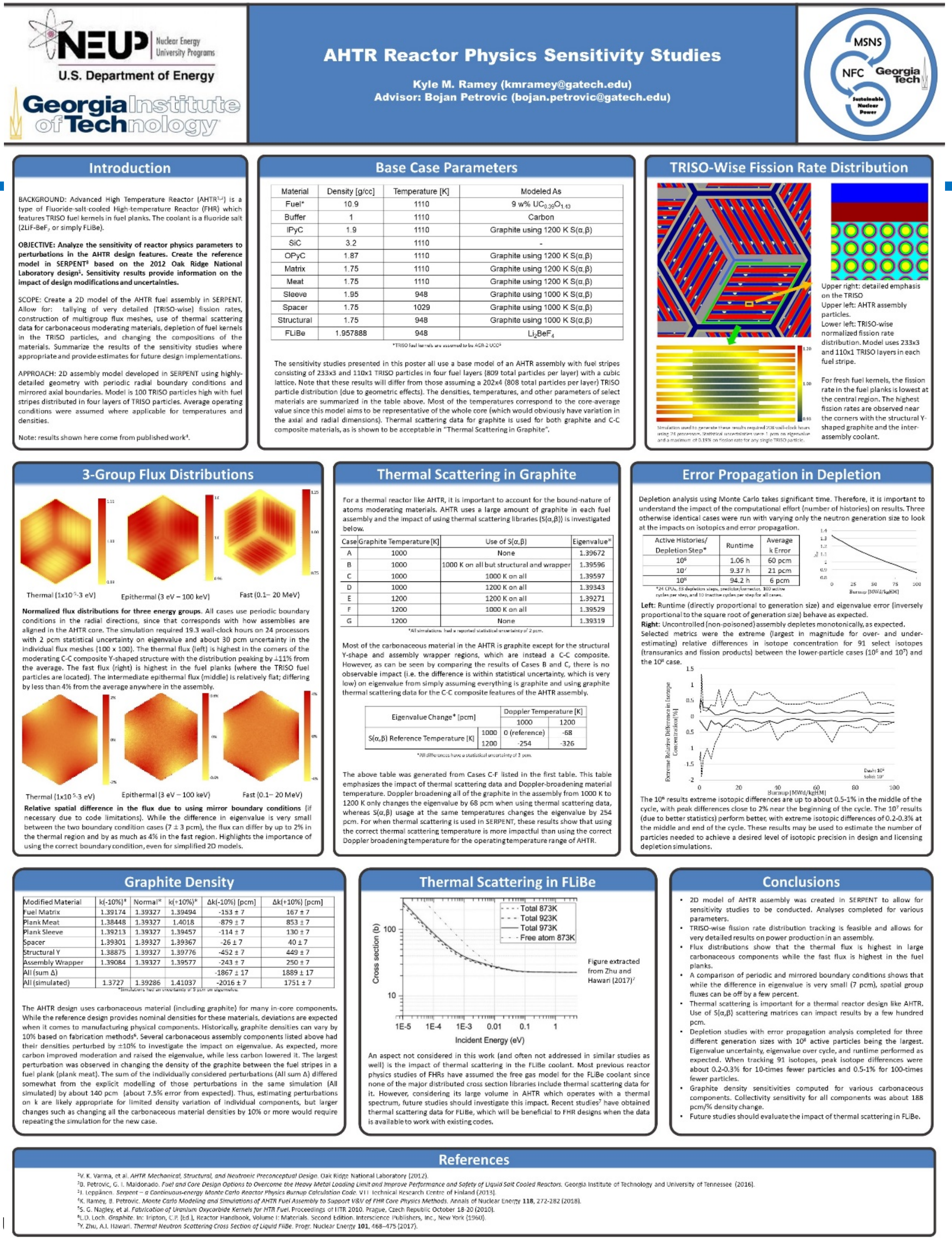
We are participating with SERPENT (Kyle Ramey)
[with some additional spot-comparisons to MCNP and SCALE]
Other participants using SERPENT are expected

Benefits of multiple participation with the same code:

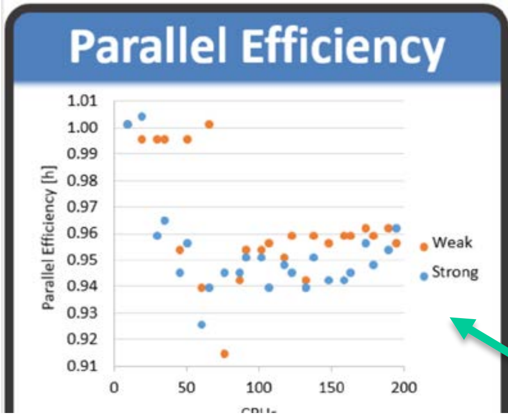
- Complex geometry, neutronics may be modeled in different ways, but core physics without feedback is expected to provide near-identical results for MC codes
- Comparison to deterministic results (if there are participants) will be very interesting; limited experience for this type of reactor
- May need to develop new options/interfaces (e.g., triangular mesh)
- There are many possible interesting sensitivity studies, that are outside of the benchmark scope, but important for FHR and even MSR (level of graphitization of carbonaceous materials, dimensional changes, material properties change with irradiation, etc.). The benchmark will provide a framework.
- For analyses with feedback, differences in approach and results are expected; it will be useful to quantify
- Efficiency and practicality issues (memory, parallel performance) for 3D full core cycle depletion analysis with feedback

Sample further studies at GT

Sensitivity studies



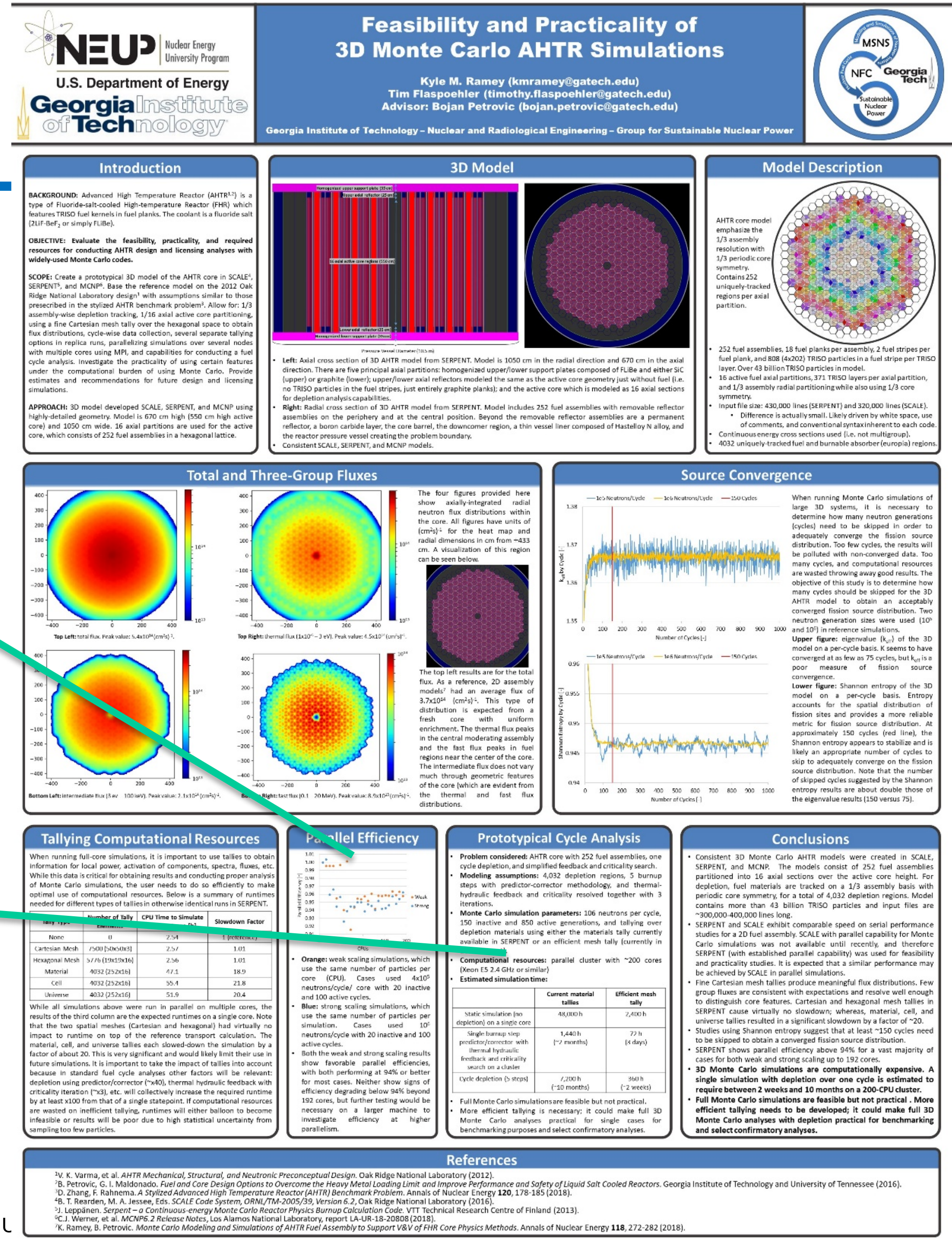
Sample further studies at GT



Prototypical Cycle Analysis

- **Problem considered:** AHTR core with 252 fuel assemblies, one cycle depletion, and simplified feedback and criticality search.
- **Modeling assumptions:** 4,032 depletion regions, 5 burnup steps with predictor-corrector methodology, and thermal-hydraulic feedback and criticality resolved together with 3 iterations.
- **Monte Carlo simulation parameters:** 106 neutrons per cycle, 150 inactive and 850 active generations, and tallying over depletion materials using either the materials tally currently available in SERPENT or an efficient mesh tally (currently in development).
- **Computational resources:** parallel cluster with ~200 cores (Xeon E5 2.4 GHz or similar)
- **Estimated simulation time:**

	Current material tallies	Efficient mesh tally
Static simulation (no depletion) on a single core	48,000 h	2,400 h
Single burnup step predictor/corrector with thermal hydraulic feedback and criticality search on a cluster	1,440 h (~2 months)	72 h (3 days)
Cycle depletion (5 steps)	7,200 h (~10 months)	360 h (~2 weeks)



Conclusions

- V&V for FHR simulation methodologies is needed
- Reactor physics is challenging for AHTR “plank” fuel, due to double (triple?) heterogeneity
- Complex problem, challenges code capabilities
- Short of measured data, benchmark provides cross-verification
- Benchmark provides framework for various sensitivity and efficiency/feasibility studies

Benchmark Status:

- Developed a multi-phase benchmark (2D assembly to 3D full core with depletion & feedback)
- Approved by OECD/NEA WPRS/EGRPANS
- Released; several groups/participants registered
- Preliminary Phase I-A results aimed at by Feb 2020
- Phase I-A full results and evaluation complete by 2021 WPRS
- Phase I-B, I-C, II, … to follow

Let me know if interested to participate (and contact NEA)

Thank you for your attention!

Questions?

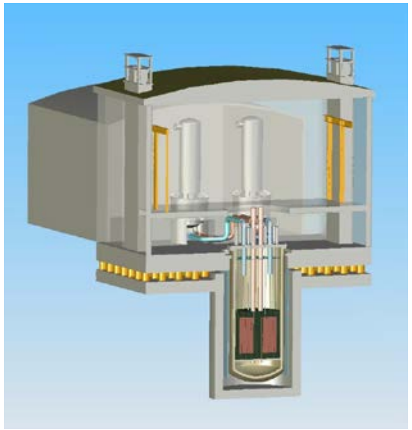
Molten Salt Reactors (MSR) and Fluoride-salt-cooled High-temperature Reactors (FHR)

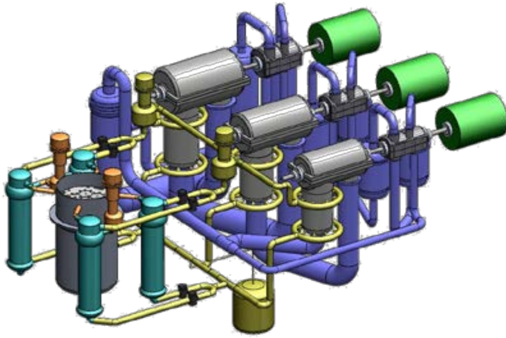
FHR - Use liquid salt as coolant

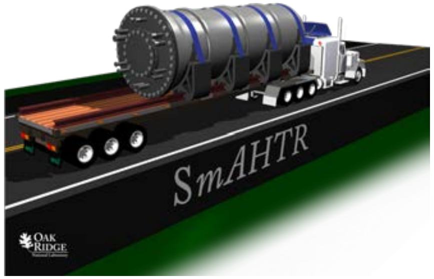
Several attractive features:
- Near-atmospheric pressure
- Large thermal margin
- High temperature → high efficiency, reduced reject heat
- Possible use for process heat

Fuel
- Molten Salt Reactors (MSR) with fuel dissolved in salt
- FHR reactors, with liquid salt used as coolant only – **focus of the NEA bFHR/AHTR benchmark**

Several FHR concepts currently under development
- ORNL: Advanced High Temperature Reactor (AHTR), large power plant 3,400MWth, **focus of the benchmark**
- Pebble Bed - AHTR; medium (410 MW_e) power plant at University of California Berkeley & Kairos
- SmAHTR; deliberately small (125 MW_{th}) process heat & electric system at ORNL
- Chinese test/demo reactors FHR (FHR-SF1, FHR-LF1)
- Other….







Source: ORNL

AHTR Main Parameters

Assembly Model Dimensions and Compositions at 40% PF	
Reactor Power	3400 MWt
Thermal Efficiency	~45%
Number of Fuel Assemblies	253
Assembly Half Pitch	23.375 cm
Plate Thickness	2.753 cm
Thickness of Fuel Regions	0.649 cm
Plate Sleeve Thickness	1 mm
TRISO Pitch	926 μm
Fuel Kernal Radius	213.5 μm
Fuel Material	Uranium Oxycarbide
Moderator Material	Graphite/Amorphous Carbon
Coolant	Li_2BeF_4 (Flibe)
Fuel Density	10.9 g/cc
Fuel Enrichment	< 20%
Average Coolant Temperature	948.15 K
Coolant Pressure	atmospheric
Core Volume	263.38 m^3
Core Power Density	12.91 MW/m^3
Mass Flow Rate	28408.1 kg/s
Average Coolant Velocty	1.93 m/s

Varma, V.K., Holcomb, D.E., Peretz, F.J., Bradley, E.C., Ilas, D., Qualls, A.L., Zaharia, N.M., 2012. AHTR mechanical, structural, and neutronic preconceptual design. Oak Ridge National Laboratory, ORNL/TM-2012/320.