NEUP Integrated Research Project Workshop 2:
FHR Benchmarking and VVUQ

Session 1.1:
FHR Neutronics Benchmark

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Overview

- Objectives of the benchmark
- Structure of work to date
- Stage 1 – Unit Cell Model
- Stage 2 – Simplified Core Model
- Stage 3 – The Next Step

Benchmark Objectives

- Code-to-code verification of pebble-fuelled FHR systems.
- Identify individual code capabilities and limitations.
- Identify modelling issues.
- Provide a common scenario for participants to model.

Structure of the Specification

- Three stages:
  - Stage 1: Unit Cell Model
    - » 3 separate cases with varying levels of homogenisation.
  - Stage 2: Simplified Core Model
    - » Based on TMSR-SF1.
  - Stage 3: TBA
    - » Still considering scope.
    - » May include burnup, reactivity insertion/feedback, fuel cycle, control rods.

Specified Results of Interest

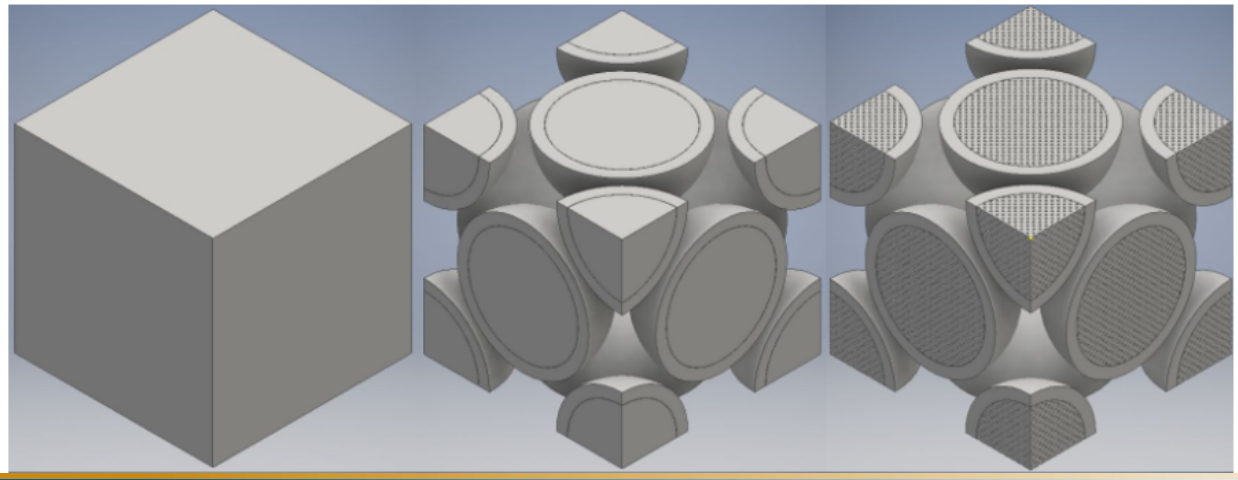
	Stage 1 Unit Cell	Stage 2 Simplified Core	Stage 3 TBA
keff	✓	✓	
Point Kinetics	✓	✓	
Cross Sections	✓		
Flux Spectra	✓	✓	
Flux Distributions		✓	
Power Distributions		✓	
Neutron Leakage		✓	
Reactivity Coefficients		✓	

Stage 1 - Unit Cell Model

- The nominal unit cell is a face-centred-cubic (FCC) arrangement of pebbles in FLiBe.
- Three level of heterogeneity were examined:
  - Case 1: Total homogenisation.
  - Case 2: Single level heterogeneity.
  - Case 3: Double heterogeneity.

Case 1 Case 2 Case 3

3D



Software Used

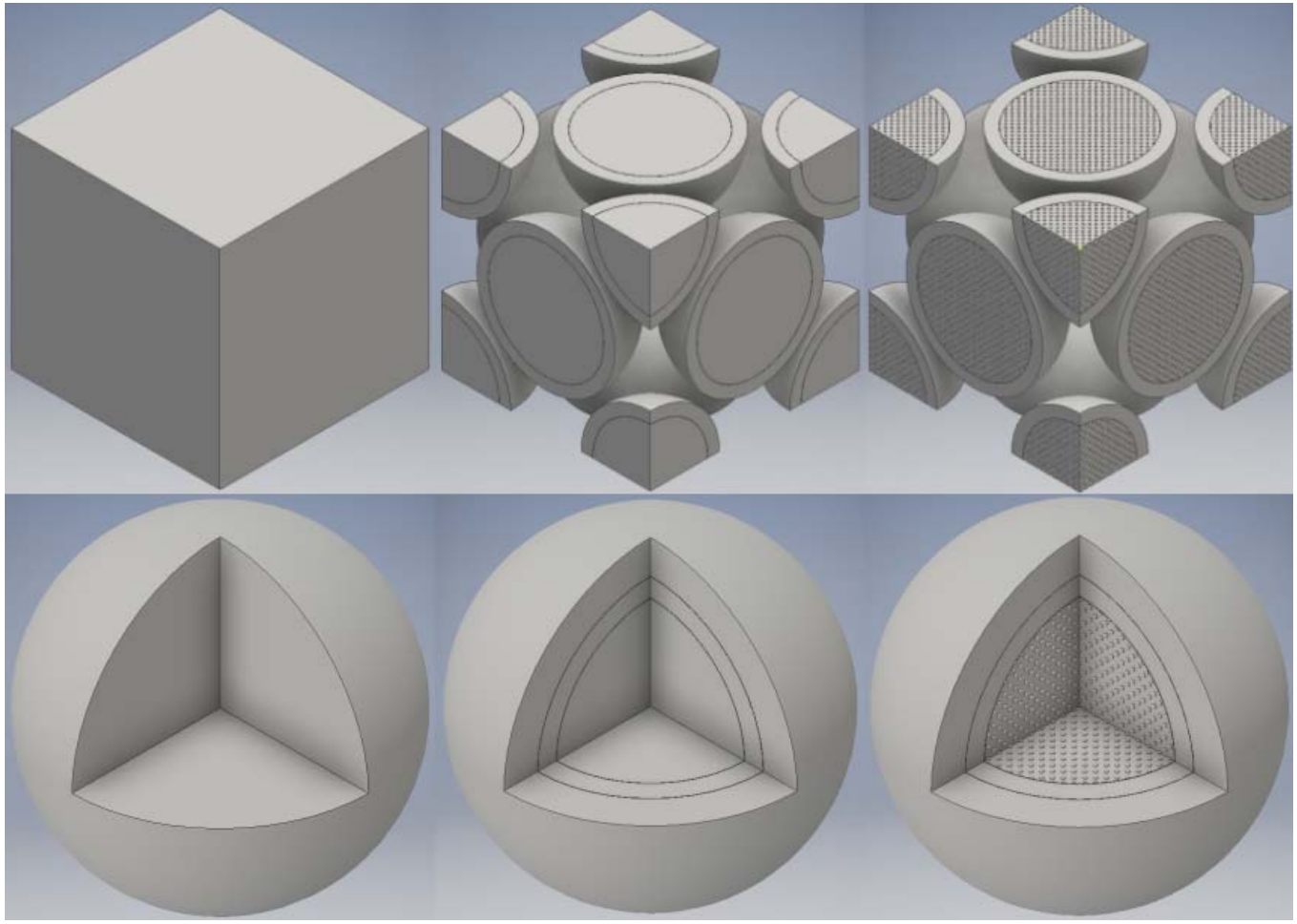
- Serpent – 3D Monte Carlo, continuous energy.
  - This code was used to provide our reference results.
- MCNP – 3D Monte Carlo, continuous energy.
- SCALE – Software suite with several transport codes:
  - KENO-VI – 3D Monte Carlo, continuous energy & multi-group.
  - T-XSDRN – 1D Discrete Ordinates, multi-group.
- ENDF/B-VII.0 library was used in every case.

3D and 1D simulation

Case 1 Case 2 Case 3

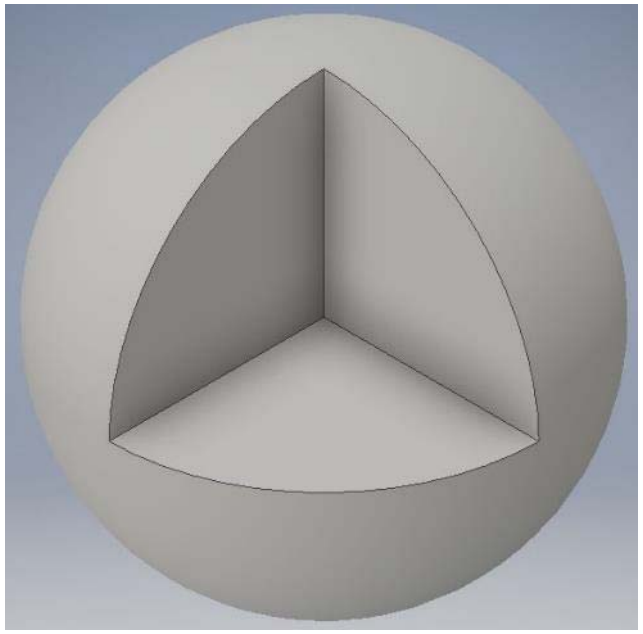
3D

1D

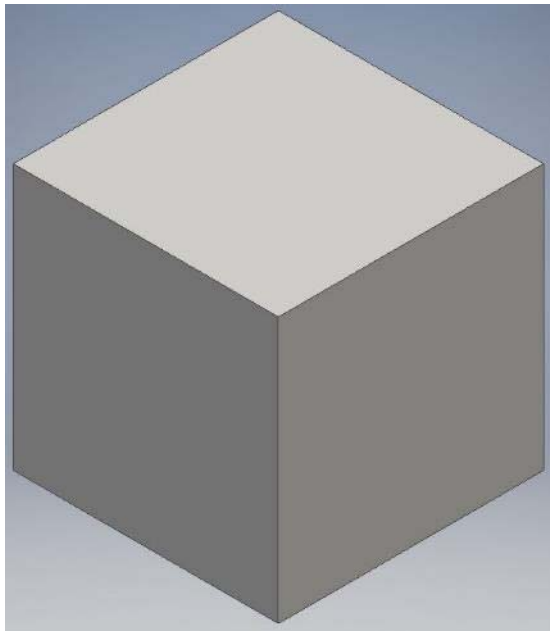


Case 1 - Homogenised Unit Cell

- Single region containing a mixture of pebbles and coolant.
- Unit cell with a side length of 9.2575cm with reflective boundary conditions.



1D



3D

Stage 1, Case 1 - Results

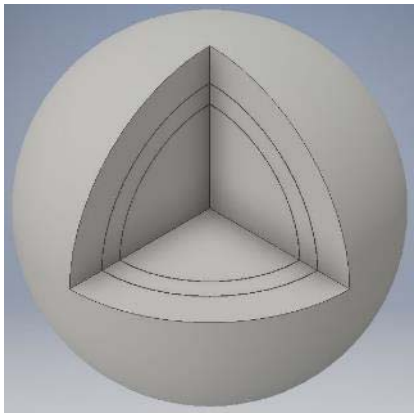
Transport	XS	Code	k_{eff}	±	vs. Ref [pcm]	β [pcm]	Λ [μs]
MC	CE	Serpent$_{REF}$	1.30535	0.00004	0	654	319
MC	CE	MCNP	1.30536	0.00007	1	656	290
MC	CE	KENO-VI	1.30537	0.00024	2	-	99.1
MC	MG	KENO-VI	1.30802	0.00018	267	-	99.3
DO	MG	T-XSDRN	1.30788	-	253	-	-

Case 1 Conclusions

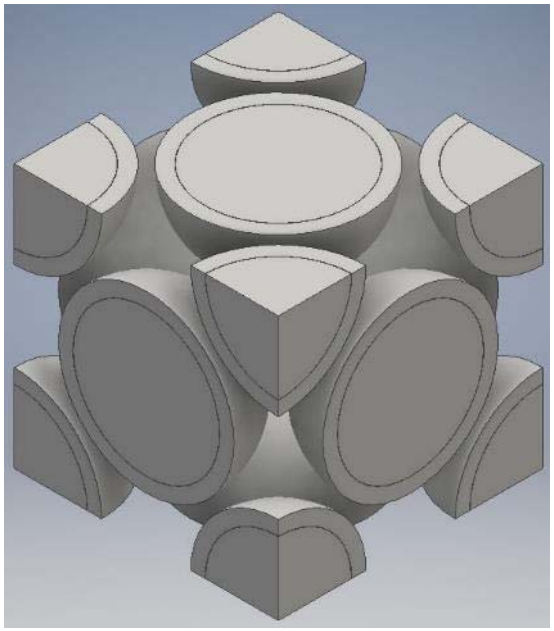
- Continuous energy codes produce similar k-eff values.
- Multigroup codes produce higher k-eff values than continuous energy codes.
- What within the cross-sections produces this difference?
- Are there any other results of interest that should be included for this case?

Case 2 - Single Heterogeneity Unit Cell

- Each pebble is composed of a 2.5cm radius homogenized fuel region and a 0.5 cm thick graphite shell.
- Unit cell containing 8 1/8 pebbles and 6 1/2 pebbles, totalling 4 full pebbles, immersed in coolant.
- Unit cell with a side length of 9.2575cm with reflective boundary conditions



1D



3D

Stage 1, Case 2 - Results

Transport	XS	Code	k_{eff}	±	vs. Ref [pcm]	β [pcm]	Λ [μs]
1D MC	CE	Serpent$_{REF}$	1.34636	0.00004	0	-	-
1D MC	CE	MCNP	1.34653	0.00007	17	-	-
1D MC	CE	KENO-VI	1.34668	0.00017	32	-	-
1D MC	MG	KENO-VI	1.34913	0.00018	177	-	-
1D DO	MG	T-XSDRN	1.34928	0.00001	292	-	-
3D MC	CE	Serpent$_{REF}$	1.34662	0.00004	0	656	303
3D MC	CE	MCNP	1.34678	0.00007	16	647	305
3D MC	CE	KENO-VI	1.34738	0.00019	76	-	251
3D MC	MG	KENO-VI	1.34933	0.00020	271	-	251

Case 2 Conclusions

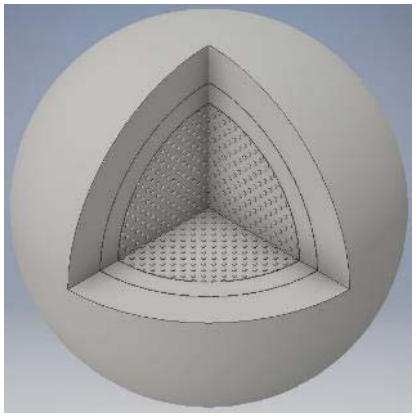
- Continuous energy codes produce similar k-eff values, but not identical.
- Multigroup codes produce higher k-eff values than continuous energy codes, same as Case 1.
- The 1D and 3D models seem equivalent in k-eff values.
- Are there any known methodological differences with these codes that might explain the discrepancy between k-eff values?

Case 3 – Double Heterogeneity Unit Cell

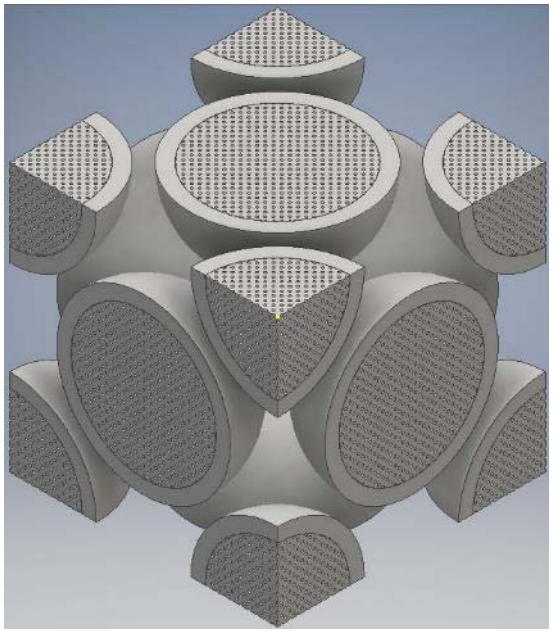
- Unit cell as Case 2, except for the fuel zone of each pebble: Each pebble is composed of a fuel zone populated with TRISO particles in a graphite matrix.

- Each TRISO particle is composed of 5 concentric spherical zones, with a UO2 fuel kernel at the centre and encased in 4 coatings.

- The TRISO particles are arranged in an FCC configuration. The packing factor for the TRISO particles is 6.97%.



1D



3D

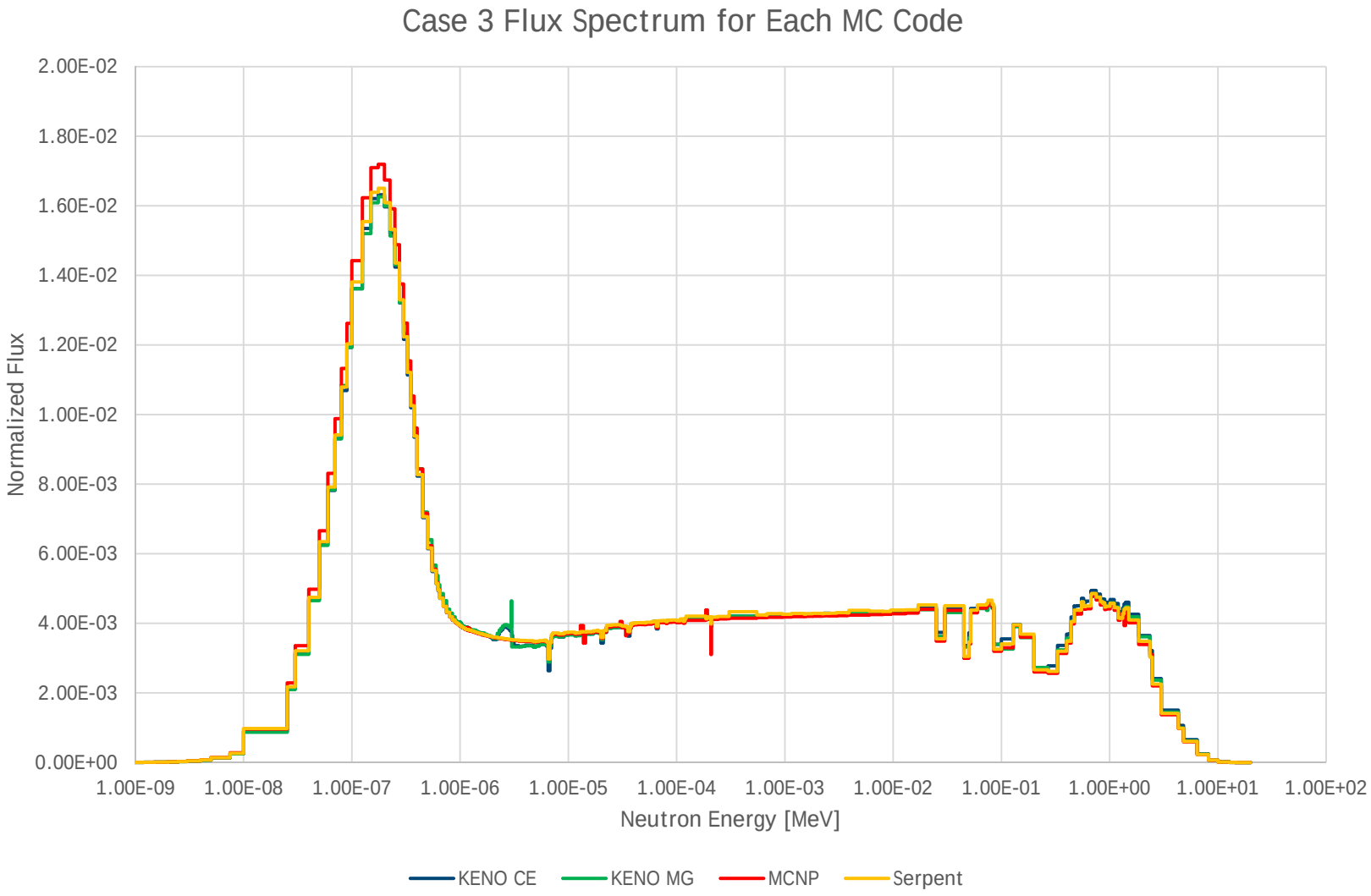
Stage 1, Case 3 - Results

Transport	XS	Code	k_{eff}	±	vs. Ref [pcm]	β [pcm]	Λ [μs]
1D MC	CE	Serpent$_{REF}$	1.42207	0.00004	0	651	-
1D MC	CE	MCNP	1.42198	0.00007	-9	647	-
1D MC	CE	KENO-VI	1.42279	0.00014	72	-	-
1D MC	MG	KENO-VI	1.42265	0.00017	58	-	-
1D DO	MG	T-XSDRN	1.42178	0.00001	-29	-	-
3D MC	CE	Serpent$_{REF}$	1.42214	0.00004	0	652	277
3D MC	CE	MCNP	1.42153	0.00007	-61	656	340
3D MC	CE	KENO-VI	1.42163	0.00020	-51	-	244
3D MC	MG	KENO-VI	1.42284	0.00017	70	-	257

Case 3 Conclusions

- Tightest comparison of results between codes in this case.
- Is this suspicious given the complexity of the problem?
- Are there other results of interest that could be investigated in this case?
- What other codes are capable of realising the double heterogeneity of fuel pebbles?

Stage 1, Case 3 - Results

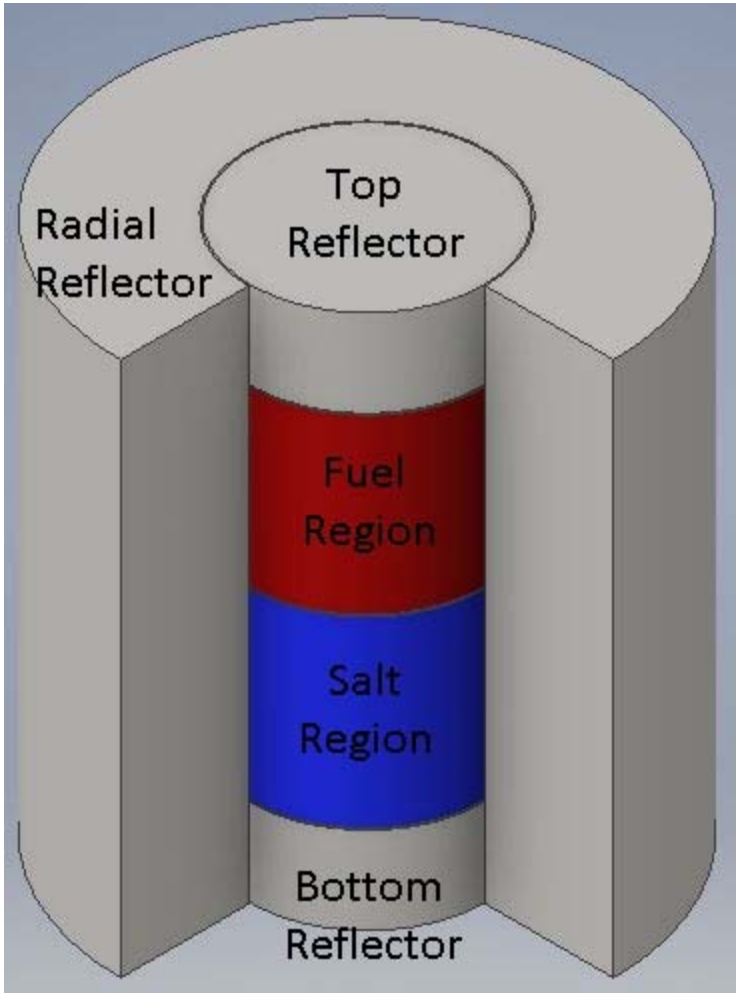


Reference Results for Each Case

Case	Thermal Scattering Library	TRISO Packing	k_{eff}	±	β [pcm]	Λ [μs]
1	Y	-	1.30504	0.00004	651	288
	N	-	1.30685	0.00004	651	287
2	Y	-	1.34638	0.00004	651	283
	N	-	1.34900	0.00004	656	281
3	Y	FCC	1.42187	0.00004	649	274
	N	FCC	1.42435	0.00004	652	273

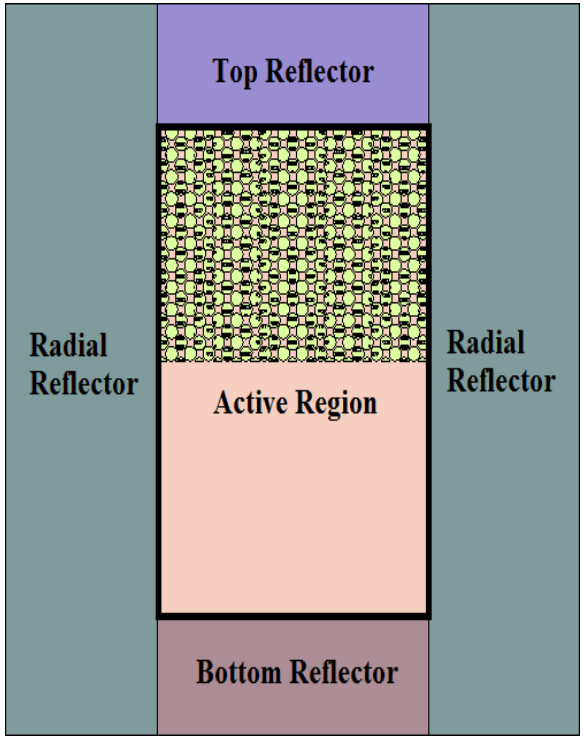
Stage 2 – Simplified Core

- This geometry includes a top reflector, bottom reflector, radial reflector, salt region and a fuel region.
- Populated with enough pebbles for criticality.
- Simplified geometry based on SINAP's 10MWth TMSR-SF1.



Stage 2 - Simplified Core

Section	Material	Radius [cm]	Height [cm]
Top Reflector	Graphite/FLiBe	67.5	50.35
Fuel Region	Pebbles + FLiBe	67.5	99.32
Salt Region	FLiBe	67.5	106.38
Bottom Reflector	Graphite/FLiBe	67.5	50.35
Radial Reflector	Graphite	142.5	306.4



- **The fuelled region includes 7168 pebbles.**

Software Used

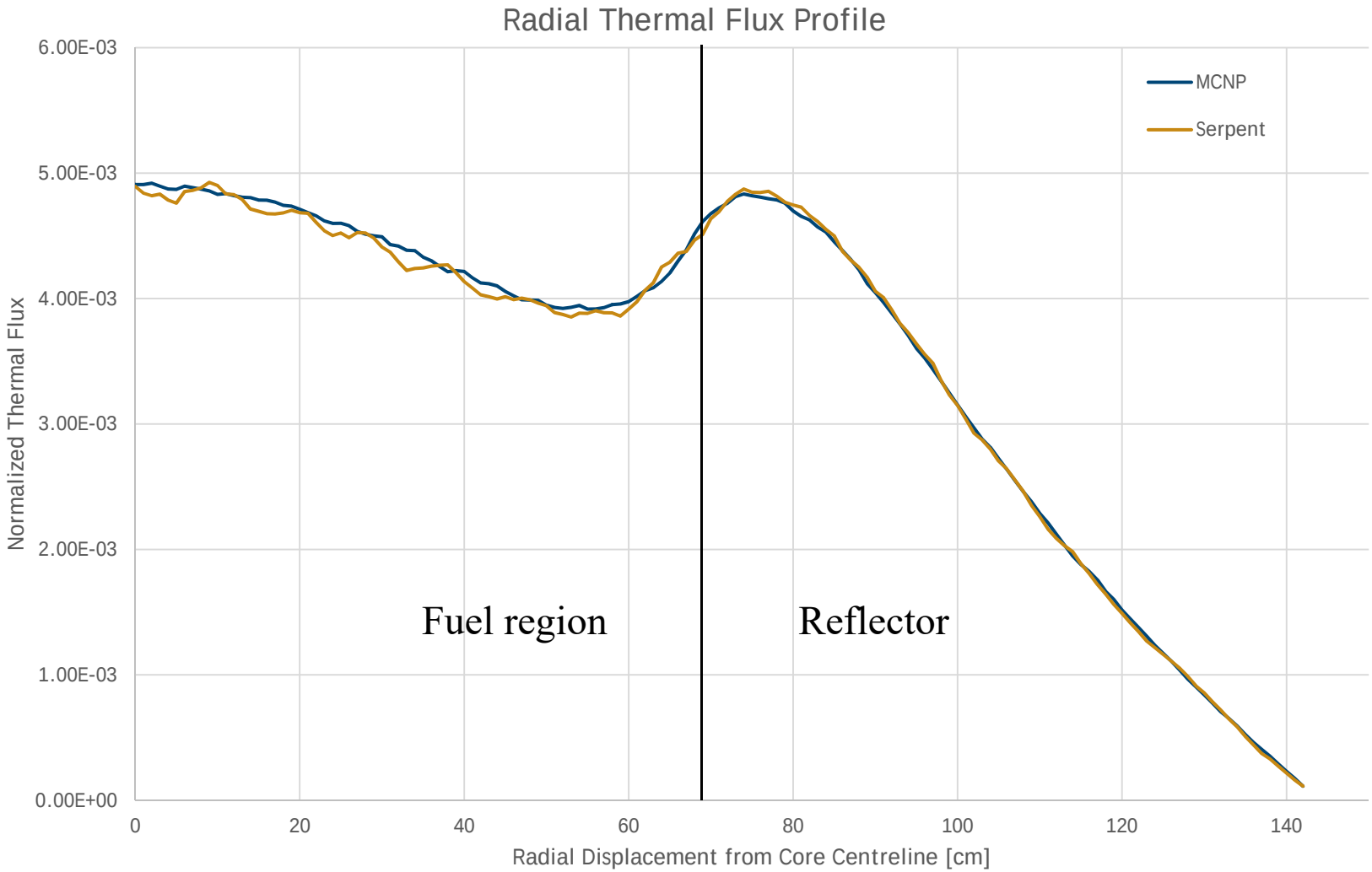
- Serpent – 3D Monte Carlo, continuous energy.
  - This code was used to provide our reference results.
- MCNP – 3D Monte Carlo, continuous energy.
- SCALE – Software suite with several transport codes:
  - KENO-VI – 3D Monte Carlo, continuous energy & multi-group.
- ENDF/B-VII.0 library was used in every case.
- Still need a reference result from a deterministic transport code. Exnihilio?

Stage 2 - Results

Transport	XS	Code	k_{eff}	±	vs. Ref [pcm]	β [pcm]	Λ [μs]
MC	CE	Serpent$_{REF}$	0.99338	0.00008	0	679	667
MC	CE	MCNP	0.98945	0.00008	-393	670	672
MC	CE	KENO-VI	0.99047	0.00020	-291	-	622
MC	MG	KENO-VI	0.99889	0.00023	551	-	702

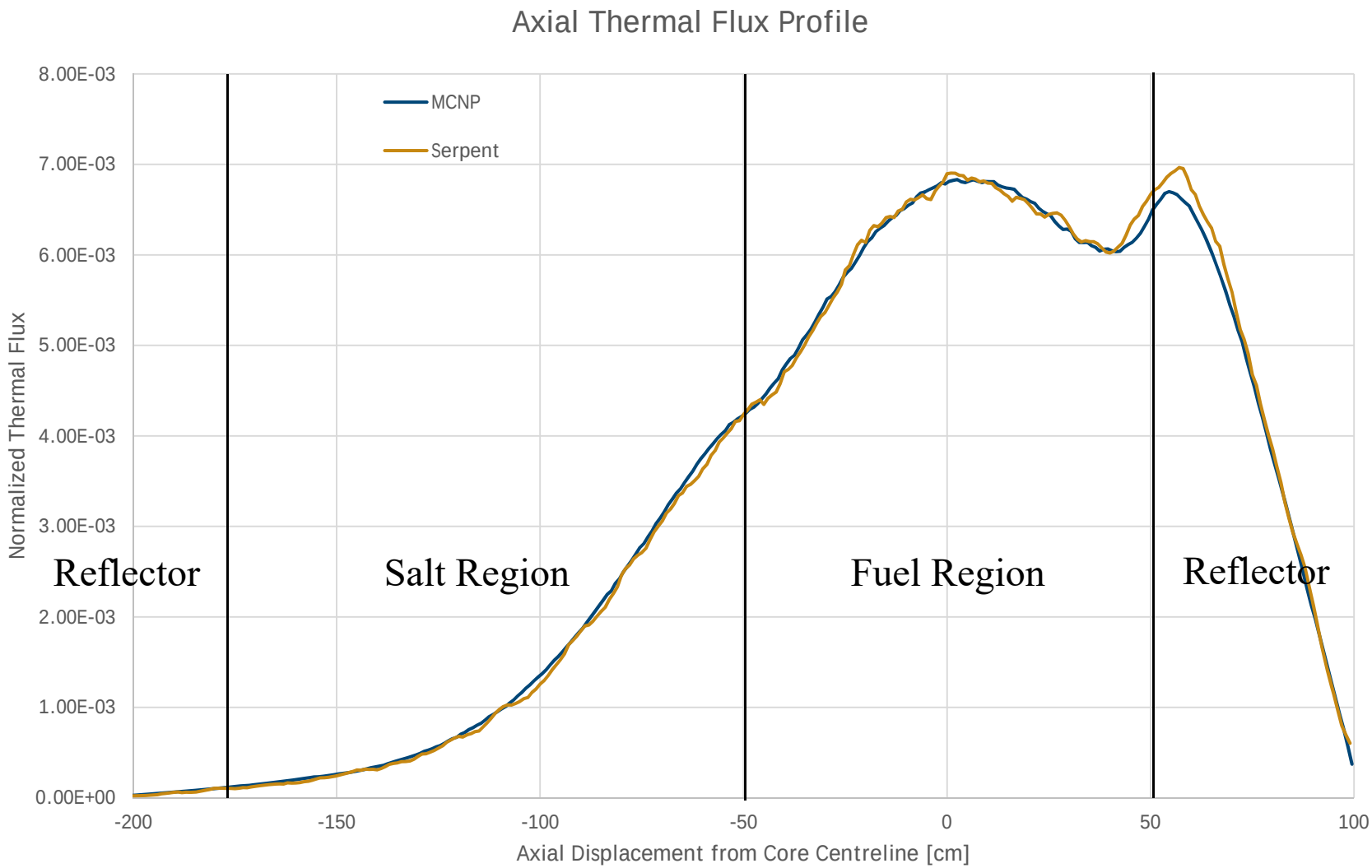
- **Largest discrepancy in k-eff is ~950pcm.**
- **Is this acceptable? What might have contributed to this difference?**

Stage 2 - Radial Thermal Flux



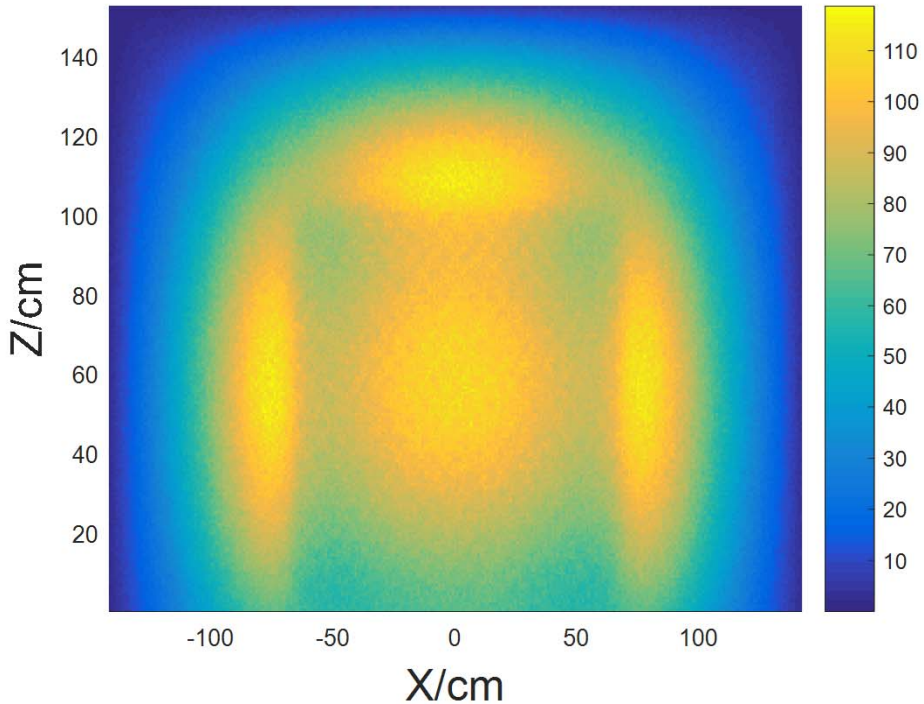
Radial thermal flux integrated from Z=3.5277 to Z=102.85cm

Stage 2 - Axial Thermal Flux

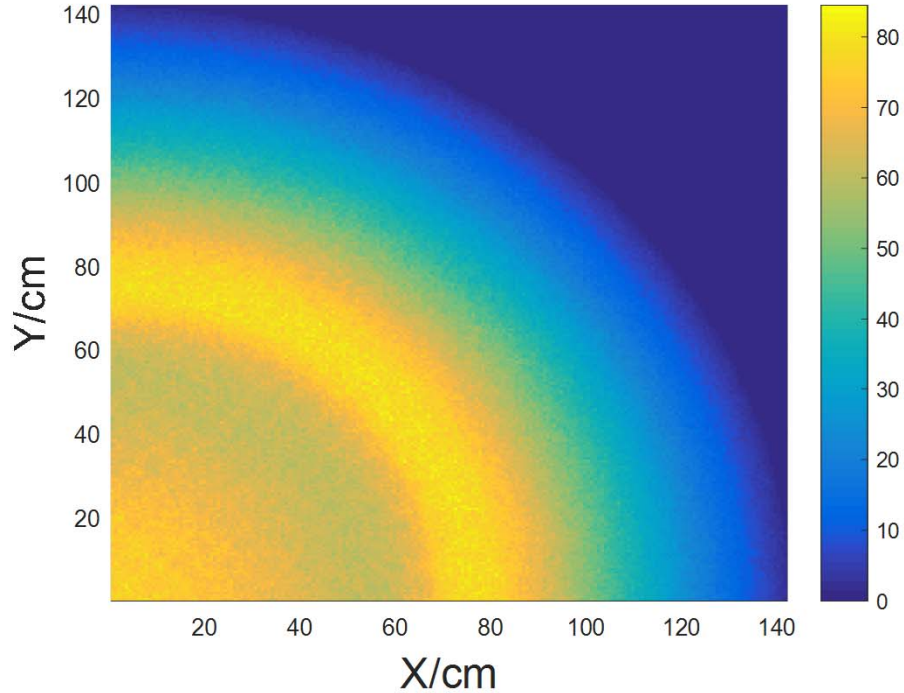


Axial thermal flux integrated from X=-67.5 to X=67.5cm

Stage 2 - Power Distribution



Axial View



Radial View

Stage 2 - Neutron Leakage, PPF & Reactivity Coefficients

Code	Neutron Leakage				Power Peaking Factor	
	Radial	Top	Bottom	Total	Axial	Radial
$Serpent_{REF}$	-11.46%	-5.68%	-0.16%	-17.30%	1.1479	1.1106
MCNP	-11.60%	-5.71%	-0.16%	-17.47%	1.1314	1.1236

Code	Coolant [Δρ/ΔT]	Void [Δρ/%void]	Doppler [Δρ/ΔT]
$Serpent_{REF}$	-1.630 ± 0.033	-13.73 ± 0.99	-2.160 ± 0.033
MCNP	-1.680 ± 0.039	-11.30 ± 1.13	-2.160 ± 0.038
KENO-VI CE	-1.557 ± 0.092	-8.70 ± 2.90	-2.083 ± 0.094
KENO-VI MG	-1.763 ± 0.108	-15.00 ± 3.25	-

Stage 3 – The Next Stage

- Scope is still not firm. Possible areas of interest:
  - Explicit, high-detail geometry.
  - Burnup
  - Control Rods
  - Reactivity Insertion/Feedback
- How should burnup be approached?
- Should partial refuelling be investigated?
- Burnable poisons?
- Control Rod worths?

Distributing the Benchmark

- Distributing the specification and receiving data from participants.
- Should we distribute to reference results to benchmark participants?
- How should we receive the data? Should we supply a template? What format?
- Are there any lessons from previous benchmarks that we can learn from?

Any Further Points of Discussion?

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