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Extension of STREAM Double Heterogeneity Method to Coated TRISO Particles

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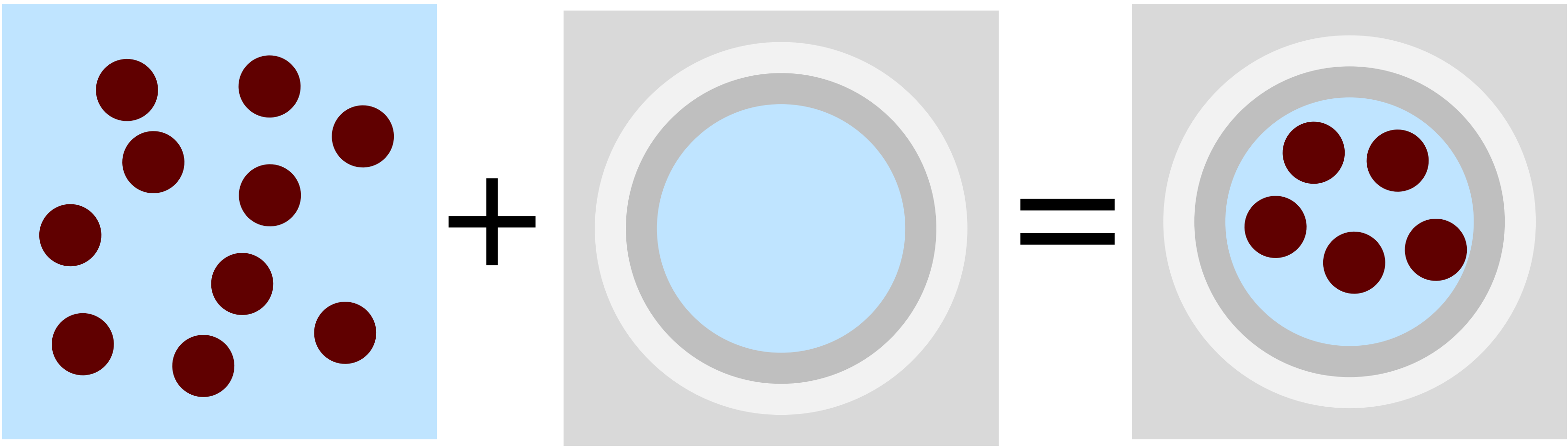
Contents

Introduction

- **Doubly Heterogeneous (DH) fuel**
  - Micro heterogeneity + Macro heterogeneity



- **VHTR employs TRISO particle fuel**
- **When Fuel Compact region is homogenized with volume weight, significant reduction in reactivity occur**
- **UNIST method based on Equivalence Theory**
  - Cannot account for the effect of coated layer of TRISO particle, which can cause 400 pcm – 600 pcm bias

Methodology

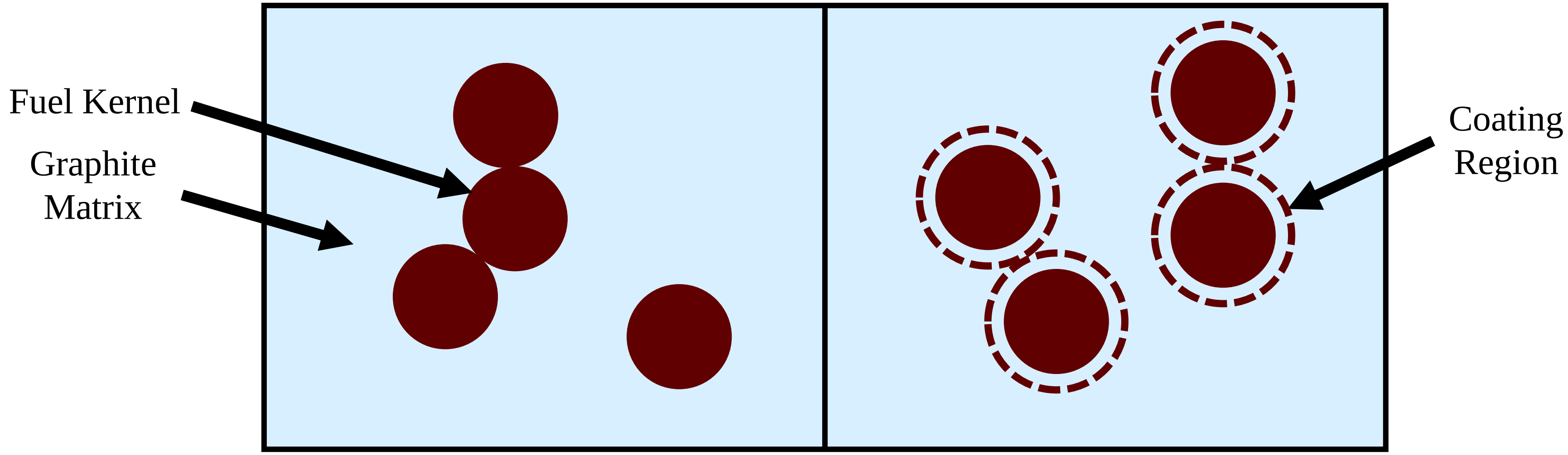
- **Microscopic Heterogeneity**
  - **Dancoff factor** $c = \frac{1}{1+\bar{l}_m \Sigma_m}$ **and Heterogeneity Parameter** $\beta = \frac{1-c}{\bar{l}_m \Sigma_m}$
  - **Escape XS** $\Sigma_e = \frac{1-c}{\bar{l}_f}$ **and Background XS** $\sigma_b^{(j)} = \frac{\lambda \Sigma_{f,p} + \Sigma_e}{N^{(j)}}$
  - **Parameter** $\omega = \frac{v_m (1-\beta)}{v_c \sigma_b^{(j)}}$

- **Macroscopic Heterogeneity**
  - **Background XS** $\tilde{\sigma}_0^{(j)} = \frac{\lambda \tilde{\Sigma}_{F,p} + \Sigma_E}{\tilde{N}^{(j)}}$
  - **DH Background XS** $\sigma_0^{*(j)} = \frac{\tilde{\sigma}_0^{(j)}}{1+\omega \tilde{\sigma}_0^{(j)}}$
  - **Effective XS** $\tilde{\sigma}_{X,g}^{(j)} = \frac{\sigma_{X,g}^{(j)}(\sigma_0^{*(j)})}{1+\omega \sigma_{a,g}^{(j)}(\sigma_0^{*(j)})}$ **where** $\sigma_{X,g}^{(j)}(\sigma_0^{*(j)}) = \frac{\left\langle \frac{\sigma_X^{(j)}(E)}{\sigma_a^{(j)}(E)+\sigma_0^{*(j)}} \frac{1}{E} \right\rangle}{\left\langle \frac{1}{\sigma_a^{(j)}(E)+\sigma_0^{*(j)}} \frac{1}{E} \right\rangle}$

indices: ***j*** **(nuclide),** ***X*** **(reaction),** ***g*** **(energy group)**

Methodology

- **Single-kernel model vs. Dual-kernel model**



- **Fuel kernel can be touched in single-kernel model**
- **Minimum distance between fuel kernels with coating layer**
- **Need new Dancoff factor calculation which account for coating layer**
- **Dancoff factor based on Chord method [3]**

[3] W. Ji et al, Analytical Dancoff factor evaluations for reactor designs loaded with TRISO particle fuel, Annals of Nuclear Energy, Vol.63, pp. 665-673, 2014.

Methodology

- **Dancoff Factor based on Chord Method**
  - **Dancoff factor of infinite medium is defined as**

$$c = \int_0^\infty f(l) \cdot \exp(-\frac{l}{\lambda}) dl$$

  - **Probability density function for chord length**

$$f(l) = 0 \quad \text{for} \quad 0 < l < \tau \quad \text{where } \tau \text{ is minimum chord length}$$

$$f(l) = \alpha \exp(-\frac{l}{\beta}) \quad \text{for} \quad \tau < l < \infty$$

  - **Two Normalize Conditions**

$$\int_0^\infty f(l) dl = 1$$

$$\int_0^\infty l \cdot f(l) dl = \frac{4r}{3} \frac{1 - frac}{frac}$$

Dancoff Factor based on Chord Method

- **Dancoff factor with dual-kernel model**

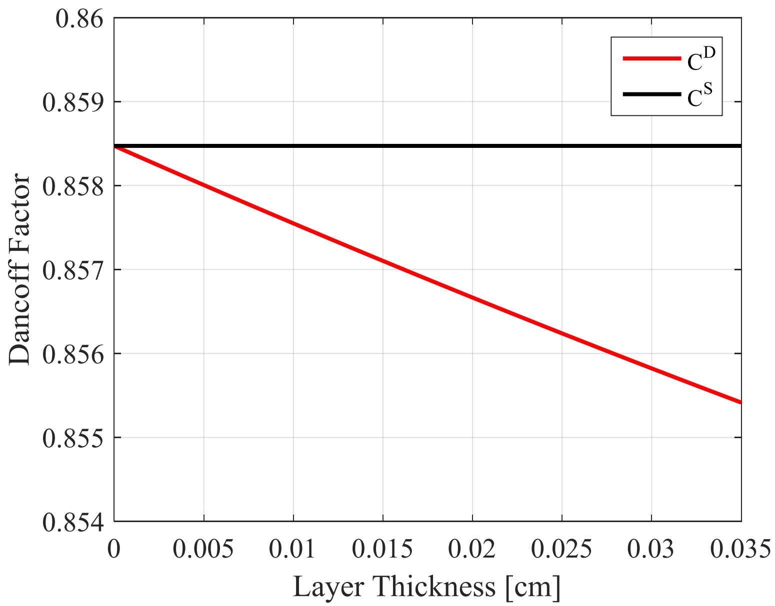
$$c^D = \frac{\exp\left(-\Sigma_m \tau\right)}{1+\left(\bar{l}_m - \tau\right)\Sigma_m}$$

where τ is minimum chord length

- **Limiting condition of Dancoff factor with 0-layer thickness**

$$\lim_{\tau \to 0} c^D = \lim_{\tau \to 0} \frac{\exp\left(-\Sigma_m \tau\right)}{1+\left(\bar{l}_m - \tau\right)\Sigma_m} = \frac{1}{1+\bar{l}_m \Sigma_m} = c^S$$

- **Dancoff Factor comparison with increasing layer thickness**



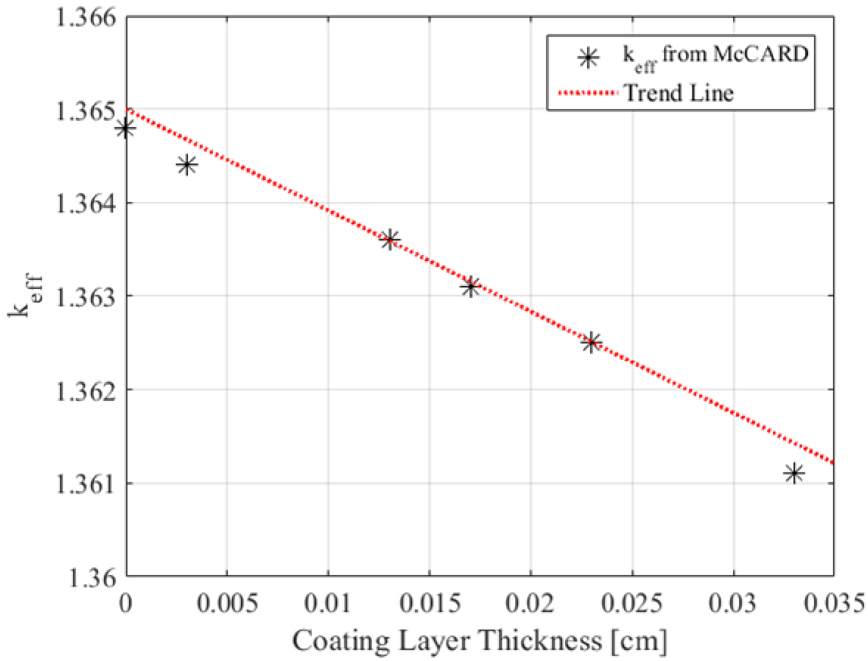
Methodology

- **Microscopic Heterogeneity**
  - **Dancoff factor** $c^D = \frac{\exp(-\Sigma_m \tau)}{1+(\bar{l}_m - \tau)\Sigma_m}$ **and Heterogeneity Parameter** $\beta = \frac{1-c}{\bar{l}_m \Sigma_m}$
  - **Escape XS** $\Sigma_e = \frac{1-c}{\bar{l}_f}$ **and Background XS** $\sigma_b^{(j)} = \frac{\lambda \Sigma_{f,p} + \Sigma_e}{N^{(j)}}$
  - **Parameter** $\omega = \frac{v_m (1-\beta)}{v_c \, \sigma_b^{(j)}}$

- **Macroscopic Heterogeneity**
  - **Background XS** $\tilde{\sigma}_0^{(j)} = \frac{\lambda \tilde{\Sigma}_{F,p} + \Sigma_E}{\tilde{N}^{(j)}}$
  - **DH Background XS** $\sigma_0^{*(j)} = \frac{\tilde{\sigma}_0^{(j)}}{1+\omega \, \tilde{\sigma}_0^{(j)}}$
  - **Effective XS** $\tilde{\sigma}_{X,g}^{(j)} = \frac{\sigma_{X,g}^{(j)}(\sigma_0^{*(j)})}{1+\omega \, \sigma_{a,g}^{(j)}(\sigma_0^{*(j)})}$ **where** $\sigma_{X,g}^{(j)}(\sigma_0^{*(j)}) = \frac{\left\langle \frac{\sigma_X^{(j)}(E)}{\sigma_a^{(j)}(E)+\sigma_0^{*(j)}} \frac{1}{E} \right\rangle}{\left\langle \frac{1}{\sigma_a^{(j)}(E)+\sigma_0^{*(j)}} \frac{1}{E} \right\rangle}$

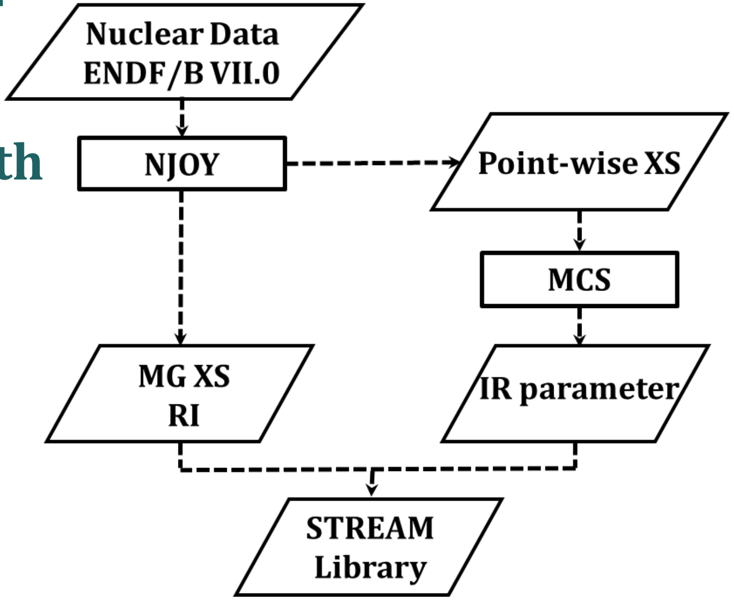
Methodology

- **With increasing Layer thickness, parameters including Dancoff factor of infinite array changes**
- **Continuous Energy Monte Carlo code McCARD**
- **Fuel condition in 4.3% fuel packing fraction**
- **Up to 400 pcm reactivity decrease with 0.035cm layer**



Implementation

- **Lattice Physics code STREAM**
  - Use Method of Characteristic (MOC)
  - Adopt Equivalence Theory for resonance treatment
  - Double-het Self-shielding method
  - MG XS library for VHTR based on ENDF/B VII.0
  - NJOY generate MG XS library and Resonance integral table
  - Monte Carlo code generate IR parameter
  - 8 isotopes, 997energy group used
  - Slowing down calculation carried out with carbon moderator



Verification

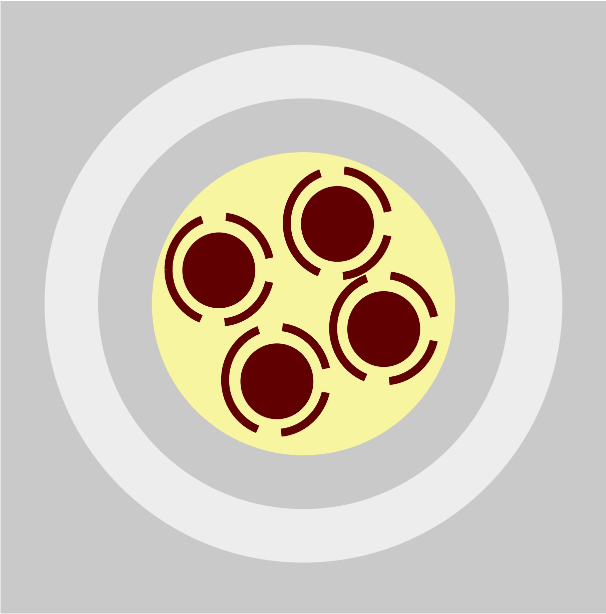
- **Single Pin-cell problems are used**
- **Verifications are basically based on HTTR fuel design model**
- **TRISO Fuel conditions are varying to cover other conventional VHTR fuel designs.**
- **Verification is focused on DH effect** $k_{eff}(DH)-k_{eff}(SH)$
- **TRISO fuel condition of conventional VHTRs**

	Kernel Radius [μm]	Layer Thickness [μm]	Fuel PF* [%]	Grain PF* [%]	Fuel Enrichment [w/o]
HTTR	300	165	8.0	30	3-10
PBMR-400	250	210	1.5	9	6
MHTGR-350	213	210	3.4	35	15
PMR-200	250	215	4.3	27	12

*PF = Packing Fraction

Verification : Model Description

- Top view of a pin-cell



r1	1.200 cm
r2	1.625 cm
r3	2.050 cm
Pitch	4.7926 cm
Graphite Moderator	1.75 g/cm^3
He Coolant	6.55x10^{-5} g/cm^3
Graphite	1.612 g/cm3
Si	0.192 g/cm3
UO2	10.41 g/cm3

- Fuel compact
  - Modified to increase variation of coating layer
  - 1st, HTTR A type of TRISO particle introduced
  - 2nd, Coating layers are smeared with moderator matrix
  - 3rd, Theoretical layer is introduced outside fuel kernels

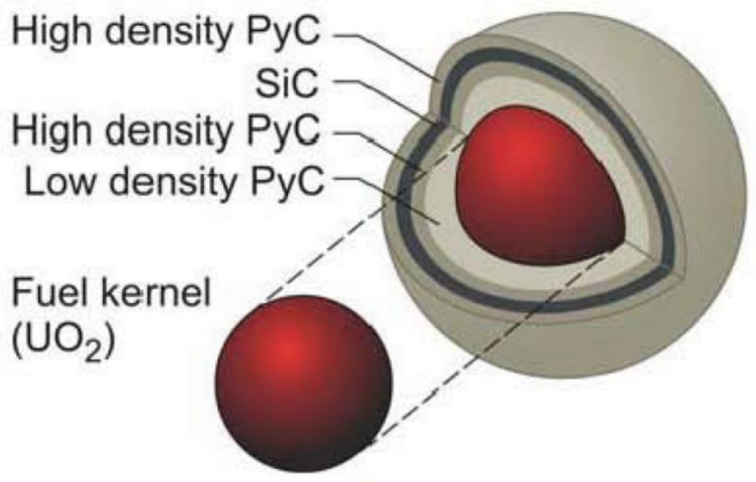
Verification : Reference Code

- **Reference code used for verification is continuous energy Monte Carlo code, McCARD developed from SNU**
  - **McCARD can simulate TRISO fuel model using implemented random distribution function**
  - **The function can handle up to 61% of fuel grain packing fraction**
  - **K_{eff} of each original models and imaginary layered models is compared with McCARD results**
  - **Comparing stochastic error both models are equivalent in reactivity**

Fuel Type	Fuel Enrichment [w/o]	Fuel PF [%]	Grain PF [%]	k_{eff} *results and Difference*		
				Original Model	Imaginary Layer	δ [pcm]
HTTR	3	9.33	33.65	1.23367(19)	1.23351(18)	-16
	6			1.33039(20)	1.32996(19)	-43
	10			1.37479(18)	1.37419(20)	-60

Verification : Description

- **Basically, HTTR TRISO fuel design is employed**
- **Fuel PF varies from 3% to 12% to cover conventional VHTR fuel designs.**
- **Layer thickness from 0 to 430μm (maximum grain PF to account for over-coating)**
- **Fuel Enrichment 3 w/o and 6 w/o**
- **Kernel radius from 250μm to 400μm**
- **HTTR TRISO particle**
  - **PyC = Pyrolytic Carbon**



Verification : Description and Results

- **Various Fuel PF, Layer Thickness**

Case Number	Fuel Enrichment [w/o]	Kernel Radius [µm]	Fuel PF [%]	Layer Thickness [µm]	DH Effect [pcm]		
					Mc	ST	Err
1	6	300	3	0	7018	7005	-13
2				130	6922	6884	-38
3				190	6920	6829	-91
4				430	6652	6613	-39
5			5	0	5532	5572	40
6				130	5419	5386	-33
7				190	5350	5302	-48
8				390	5108	5036	-72
9			7	0	4491	4485	-6
10				130	4330	4266	-64
11				190	4237	4168	-69
12				310	3954	3979	25
13			9	0	3678	3705	27
14				130	3481	3462	-19
15				190	3302	3355	53
16				260	3266	3235	-31
17			12	0	2851	2858	7
18				80	2741	2700	-41
19				130	2657	2605	-52
20				190	2434	2496	62

std for Mc results is about 20pcm

Verification : Description and Results

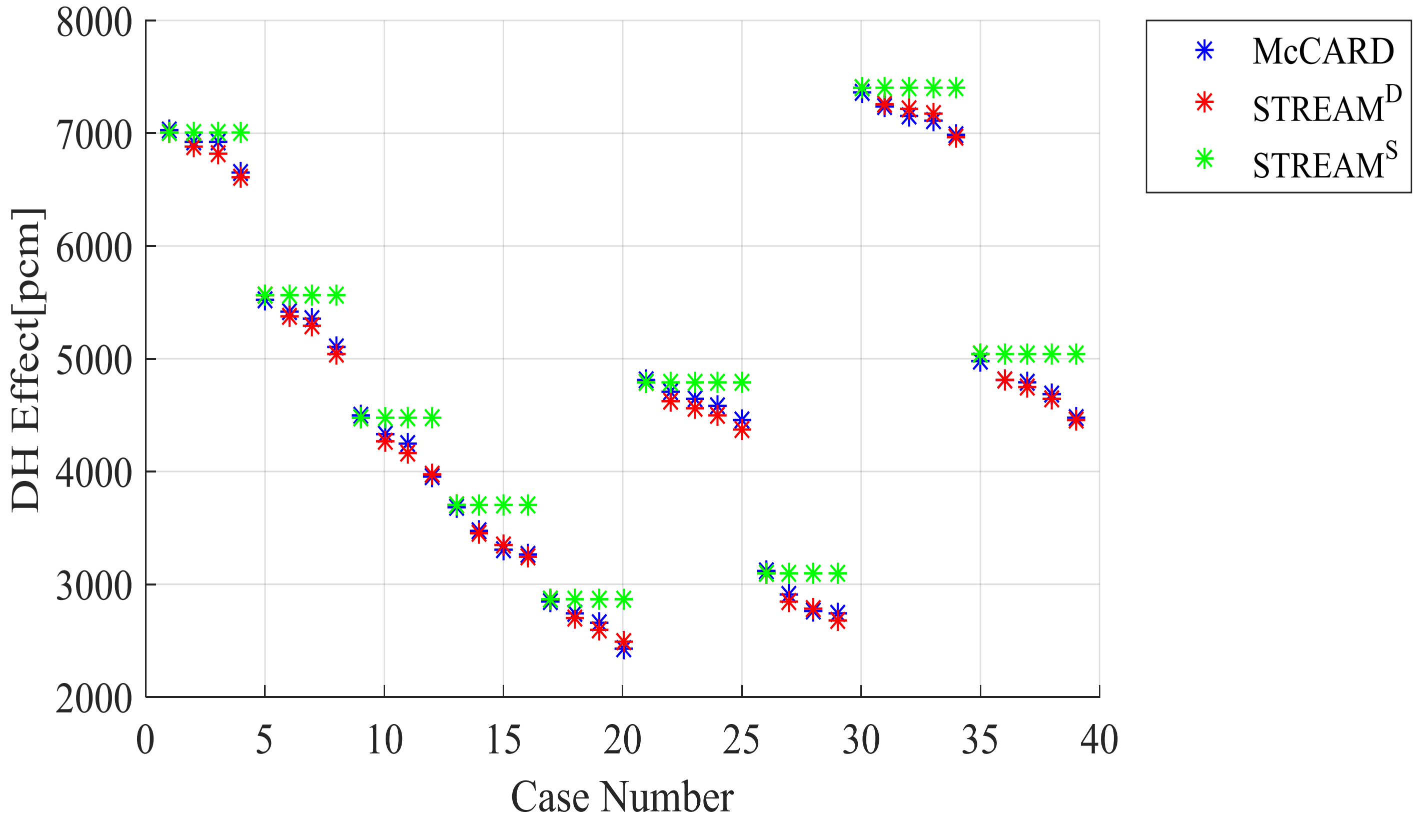
- **Lowered Fuel Enrichment, Various Fuel Kernel Size**

Case Number	Fuel Enrichment [w/o]	Kernel Radius [μm]	Fuel PF [%]	Layer Thickness [μm]	DH Effect [pcm]		
					Mc	ST	Err
21	3	250	4.3	0	4820	4787	-33
22				130	4697	4618	-79
23				170	4648	4567	-81
24				230	4582	4491	-91
25				330	4452	4368	-84
26			8.6	0	3116	3096	-20
27				130	2913	2855	-58
28				170	2754	2785	31
29				230	2748	2682	-66
30		400	4.3	0	7357	7400	43
31				130	7240	7265	25
32				170	7163	7225	62
33				230	7119	7164	45
34				430	6976	6965	-11
35			8.6	0	4984	5033	49
36				130	4808	4815	7
37				170	4785	4750	-35
38				230	4681	4653	-28
39				290	4473	4451	-22

std for Mc results is about 20pcm

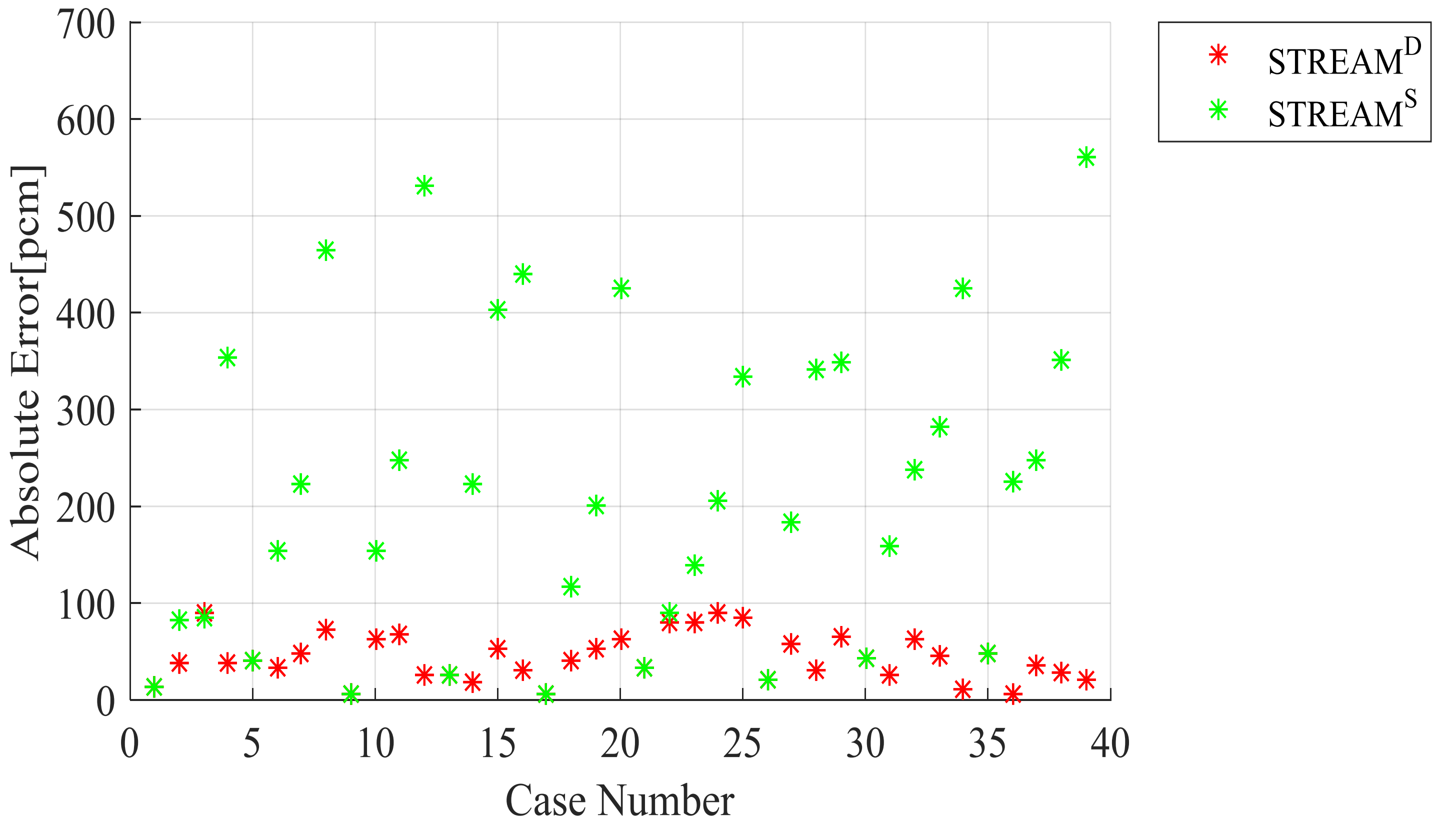
Verification : Results

- **DH Effect Comparison**



- **DH effect decrease with increasing layer thickness**
- **Layer affect reactivity up to 500 pcm, which was unable to predicted previously**
- **150μm increase of fuel kernel radius caused up to 2500 pcm increase in DH effect**
- **With increasing FP, DH effect decreases**

- **DH Effect Error Comparison**



- **With Single-Kernel Model, errors are up to 600 pcm**
- **Dual Kernel model errors are mostly within 100 pcm**
- **Modified method well evaluate effect of coating layer with various fuel condition**

Conclusion

- **Effect of coating layer on DH self-shielding cannot be negligible**
- **DH self-shielding has high sensitivity on size of fuel kernel and fuel volume packing fraction**
- **Newly modified methodology well evaluate the DH effect from reference Monte Carlo code McCARD**
- **The method successfully overcame the limit of the previous method of modelling the coating layer of TRISO particle**

UNIST CORE