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Sensitivity and Uncertainty Analysis of IAEA CRP HTGR Benchmark Using McCARD

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IAEA CRP HTGR UAM Benchmark

- Technical Working Group on Gas Cooled Reactor (TWG-GCR) launched a series of UAM benchmark problems via IAEA Coordinated Research Program(CRP) on HTGR in 2013.

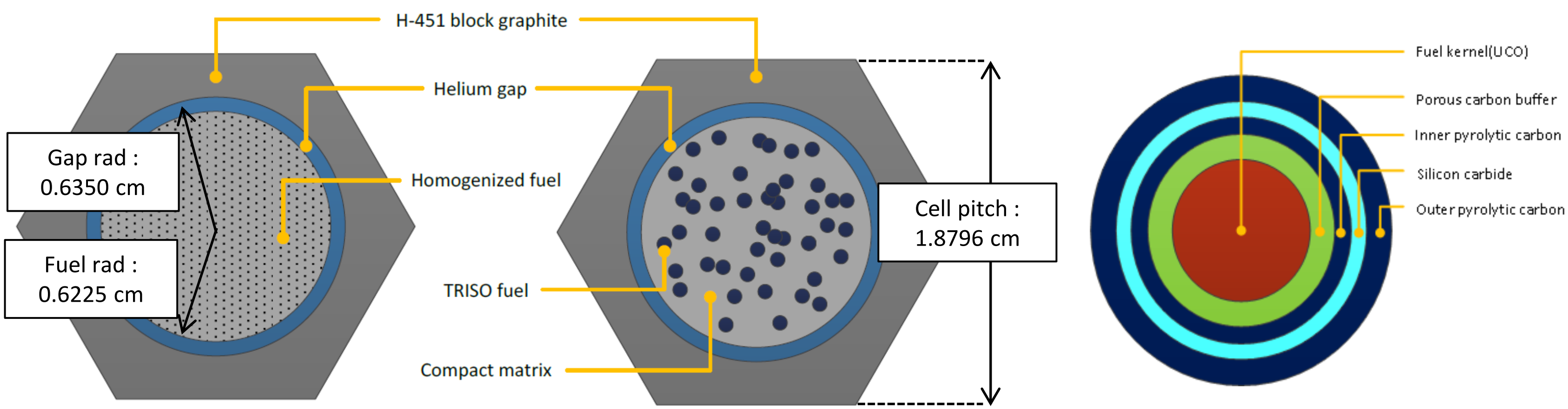
- Purpose
  - Verification of design and safety features of developing HTGR with reliable high fidelity physics models and robust, efficient and accurate codes
  - Predictive capability of coupled neutronics/thermal-hydraullics and depletion simulation for reactor design and safety analysis
  - Seeking for the best estimate condition and method by comparing the results of various group

IAEA CRP HTGR UAM Benchmark

- **Phase I — Local stand-alone**
  - Ex.I-1 & I-2 : Local neutronics; Cell and lattice
  - Ex.I-3 & I-4 : Local thermal-hydraulic; SS and transient
- **Phase II — Global stand-alone**
  - Ex.II-1 & II-2 : Global core neutronics; SS and kinetics
  - Ex.II-3 & II-4 : Global thermal-fluid; SS and transient
- **Phase III — Design calculation**
  - Ex.III-1 : Coupled steady-state calculation
  - Ex.III-2: Coupled Depletion
- **Phase IV — Safety calculation**
  - Ex.IV-1 : Coupled core transient calculation
  - Ex.IV-2 : Coupled system transient calculation

Description of MHTGR-350[1]

- Prismatic reference design of 350 MWth MHTGR of General Atomics
- Exercise.I-1 unit cell model
  - Ex.I-1a : homogenized fuel region
  - Ex.I-1b : explicit model with randomly distributed TRISO fuel particle (15.5 wt%)
    (packing fraction : 0.35)



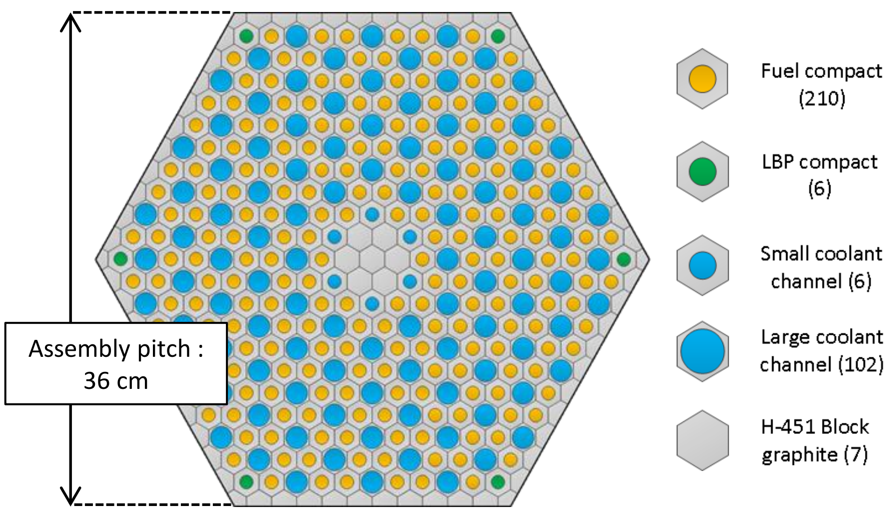
Rad(mm)
0.2125
0.3125
0.3525
0.3875
0.4275

Compact height : 4.928 cm

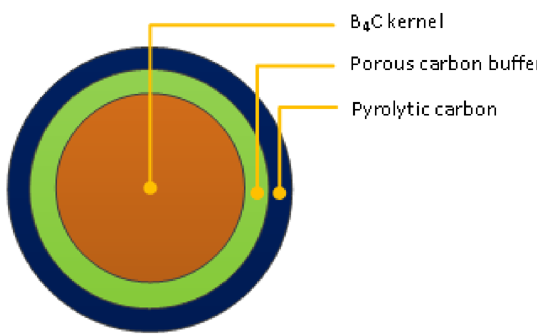
[1] "IAEA Coordinated Research Project on HTGR Reactor Physics, Thermal-hydraulics and Depletion Uncertainty Analysis," draft rev 4. , *IAEA*, (2014)

Description of MHTGR-350

- Exercise.I-2 lattice model
  - Ex.I-2a : fresh fuel assembly with 6 LBP compacts
  - Ex.I-2b : depleted fuel assembly with graphite substituting for LBP material
  - Explicit model with randomly distributed B_4C particles in LBP compact (packing fraction : 0.109)
  - Depleted fuel composition is calculated by Serpent without LBP material up to 100MWd/kgU. (279 isotopes)



Cell	Outer Rad (cm)
Fuel	0.6350
LBP	0.6350
Small Coolant	0.6350
Large coolant	0.7940

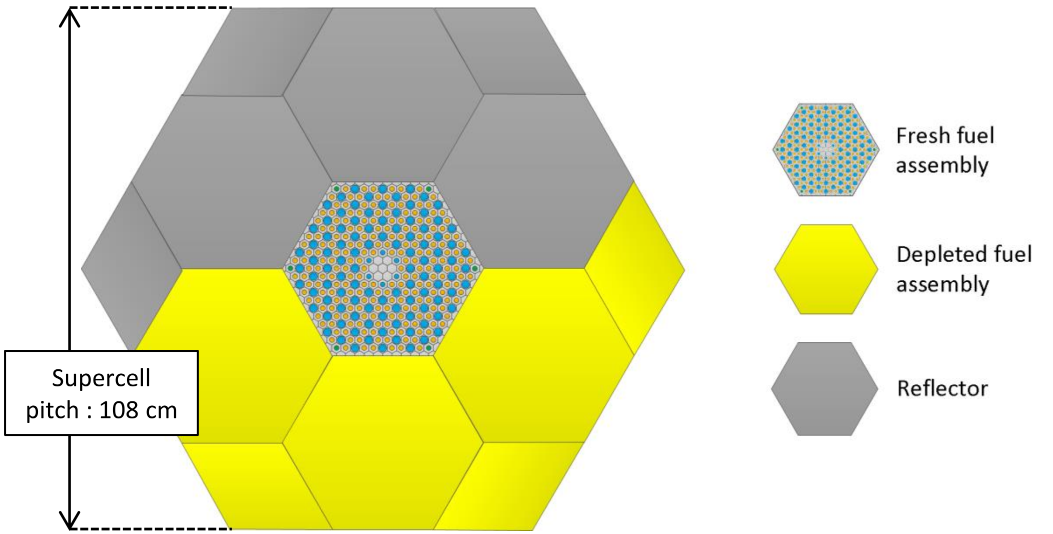


Rad (mm)
0.1000
0.1180
0.1410

Description of MHTGR-350

◆ Exercise.I-2 lattice model (cont.)

- Ex.I-2c : super cell model, homogenized depleted fuel assembly and reflector
- One fresh fuel assembly is surrounded by depleted fuel assemblies and reflectors on opposite sides.
- Depleted fuel composition is reduced for simplification compared with Ex.I-2b. (51 isotopes)



Calculation Options

- Temperature condition

	CZP [K]	HFP [K]
Fuel compact	600	1200
Helium gap	600	1200
H-451 block graphite	400	1000
Coolant channel	-	1000

- Nuclide data : ENDF/B-VII.0 , ENDF/B-VII.1
- 100,000 histories per cycle with 50/200 cycles (inactive/active)
- DBRC option is used for $^{238}\boldsymbol{U}$.
- For S/U analysis, first-order AWP method based on adjoint flux from MC forward calculation is used.
- Covariance data is processed using NJOY/ERRORR module with HELIOS 190 energy group structure from ENDF/B-VII.1

Eigenvalue Calculation Results

- Eigenvalue results with ENDF/B-VII.0 nuclide data

	ENDF/B-VII.0		
	Serpent (reference)	McCARD	Difference [pcm] (SD)
Case	k_{inf} (SD)	k_{inf} (SD)	McCARD – Serpent
Ex.I-1a CZP	1.25995 (0.00012)	1.26042(0.00016)	47 (20)
Ex.I-1a HFP	1.18462 (0.00014)	1.18449 (0.00017)	-13 (22)
Ex.I-1b CZP	1.31865 (0.00012)	1.32076 (0.00017)	221 (21)
Ex.I-1b HFP	1.24657 (0.00013)	1.24778 (0.00019)	121 (23)
Ex.I-2a HFP	1.06304 (0.00008)	1.06222 (0.00018)	-82 (20)
Ex.I-2b HFP	0.96528 (0.00013)	0.96615 (0.00017)	87 (21)
Ex.I-2c HFP	1.05010 (0.00005)	1.04945 (0.00018)	-65 (19)

Eigenvalue Calculation Results

◆ Eigenvalue results with ENDF/B-VII.1 nuclide data

	ENDF/B-VII.1		
	Serpent (reference)	McCARD	Difference [pcm] (SD)
Case	k_{inf} (SD)	k_{inf} (SD)	McCARD – Serpent
Ex.I-1a CZP	1.25841 (0.00013)	1.25880 (0.00016)	39 (21)
Ex.I-1a HFP	1.18357 (0.00015)	1.18328 (0.00017)	-29 (23)
Ex.I-1b CZP	1.31767 (0.00012)	1.31912 (0.00017)	145 (21)
Ex.I-1b HFP	1.24525(0.00014)	1.24683 (0.00018)	158 (23)
Ex.I-2a HFP	1.06177 (0.00008)	1.06128 (0.00018)	-49 (20)
Ex.I-2b HFP	0.96619 (0.00013)	0.96700 (0.00017)	81 (21)
Ex.I-2c HFP	1.04341 (0.00004)	1.04243 (0.00018)	-98 (18)

*Need to cross-check graphite thermal scattering library

Eigenvalue Calculation Results

- Eigenvalue results with ENDF/B-VII.1 nuclide data (before fixed)

	ENDF/B-VII.1		
	Serpent (reference)	McCARD	Difference [pcm] (SD)
Case	k_{inf} (SD)	k_{inf} (SD)	McCARD – Serpent
Ex.I-1a CZP	1.25841 (0.00013)	1.25910 (0.00011)	69 (17)
Ex.I-1a HFP	1.18357 (0.00015)	1.18313 (0.00017)	-44 (23)
Ex.I-1b CZP	1.31767 (0.00012)	1.31911 (0.00017)	144 (21)
Ex.I-1b HFP	1.24525(0.00014)	1.24628(0.00014)	103 (20)
Ex.I-2a HFP	1.06177 (0.00008)	1.05610 (0.00020)	-567 (22)
Ex.I-2b HFP	0.96619 (0.00013)	0.96691 (0.00016)	72 (21)
Ex.I-2c HFP	1.04341 (0.00004)	1.05263 (0.00018)	922 (18)

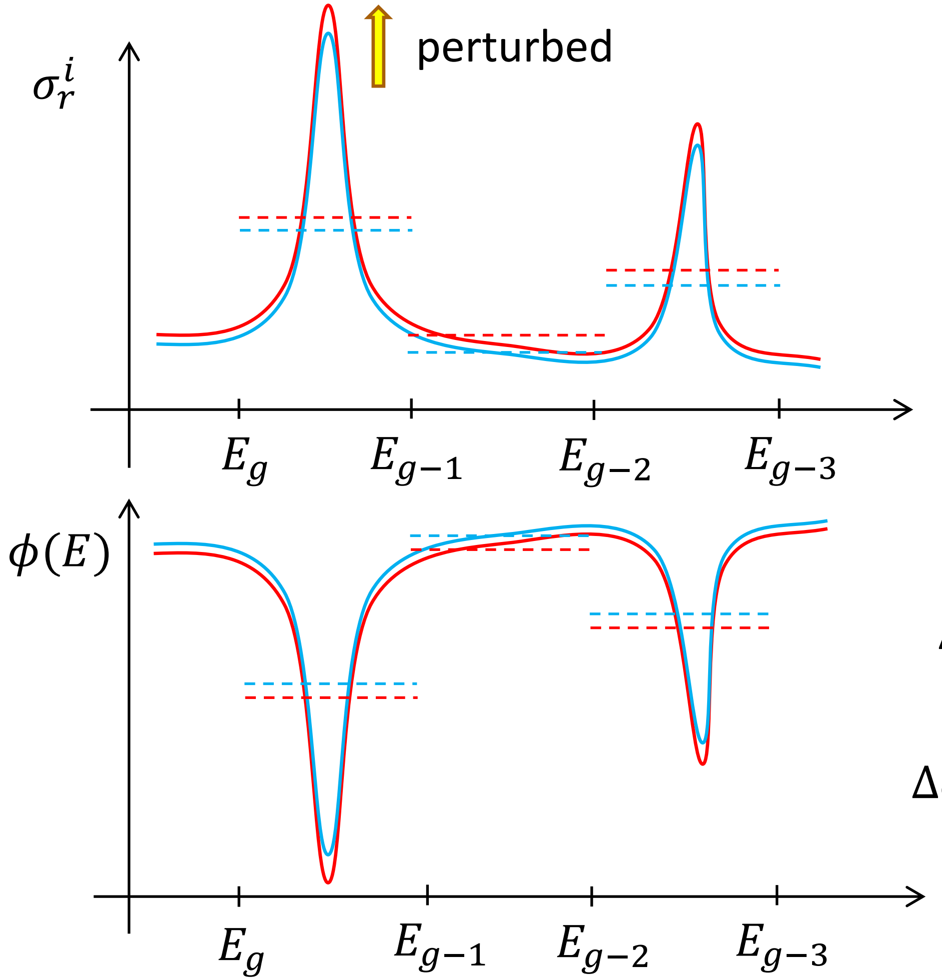
S/U Analysis Results

- S/U analysis comparison results with DeCART/MUSAD for Ex.I-1

Library		ENDF/B-VII.1			
Case		Ex.I-1a HFP		Ex.I-1b HFP	
Code		McCARD	DeCART/MUSAD	McCARD	DeCART/MUSAD
Unc. Due to ^{235}U ($\% \Delta k/k$)	ν, ν	0.610	0.610	0.612	0.613
	(n,γ), (n,γ)	0.236	0.236	0.238	0.237
	(n,γ), (n,fis)	0.074	0.074	0.074	0.073
	(n,fis), (n,fis)	0.073	0.073	0.071	0.071
Unc. Due to ^{238}U ($\% \Delta k/k$)	ν, ν	0.008	0.009	0.009	0.008
	(n,γ), (n,γ)	0.445	0.602	0.388	0.574
	(n,γ), (n,fis)	0.002	0.002	0.002	0.002
	(n,fis), (n,fis)	0.002	0.002	0.002	0.001
	total	0.801	0.896	0.773	0.878

S/U Analysis Results

- Implicit sensitivity in $^{238}U(n,\gamma)$[2]



$$\sigma_{r,g}^i = \frac{\int_{E_g}^{E_{g-1}} \sigma_r^i(E)\phi(E)dE}{\int_{E_g}^{E_{g-1}} \phi(E)dE}$$

$\Delta\sigma_{r,g}^i$ ⇨ $\Delta\phi_g$: explicit sensitivity

$\Delta\sigma_r^i(E)$ ⇨ $\Delta\sigma_{r,g}^i$: implicit sensitivity

[2] Pouya Sabouri. "Application of Perturbation Theory Methods to Nuclear Data Uncertainty Propagation using the Collision Probability Method", Computational Physics. Institut National Polytechnique de Grenoble - INPG, 2013.

S/U Analysis Results

- Similar effect of resonance self-shielding in uncertainty quantification is reported by Go Chiba[3].
- Inconsistency between multi-group cross section
  - Covariance data : infinitely-diluted cross section
  - Sensitivity calculation : self-shielded cross section
- It is reported about 30% of overestimation in uncertainty quantification with inconsistent method.

$$\sigma^2[k] \cong \sum_{i,r,g} \sum_{i',r',g'} cov[x^i_{r,g}, x^{i'}_{r',g'}](\frac{\partial k}{\partial x^i_{r,g}})(\frac{\partial k}{\partial x^{i'}_{r',g'}})$$

[3] Go Chiba et al, "RESONANCE SELF-SHIELDING EFFECT IN UNCERTAINTY QUANTIFICATION OF FISSION REACTOR NEUTRONICS PARAMETER", NET.01.2014.707

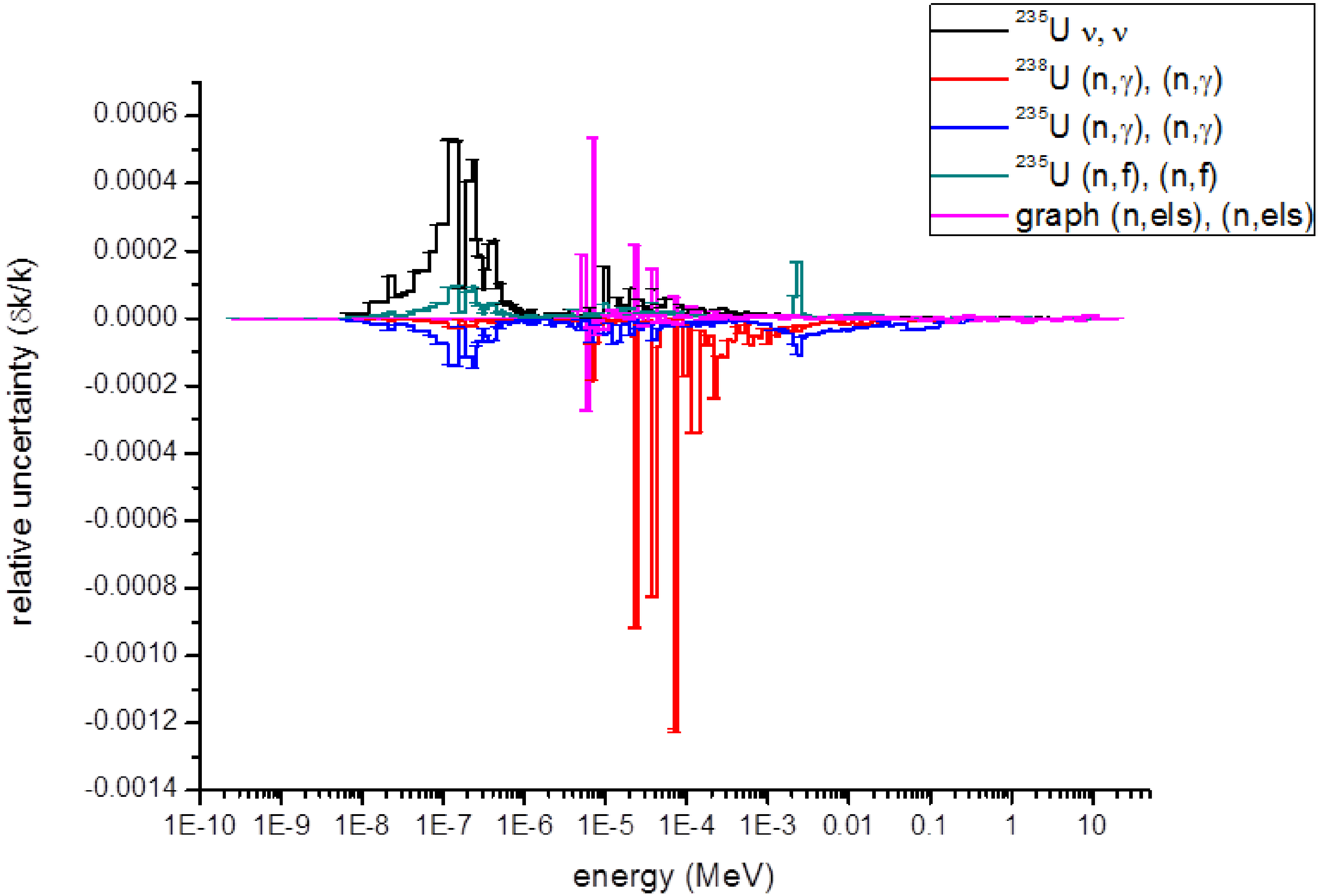
S/U Analysis Results

- S/U analysis results for main contributor on uncertainty for Ex.I-2

Library		ENDF/B-VII.1					
Case		Ex.I-2a HFP		Ex.I-2b HFP		Ex.I-2c HFP	
Code		McCARD		McCARD		McCARD	
		Cov. type	$\% \Delta k/k$	Cov. type	$\% \Delta k/k$	Cov. type	$\% \Delta k/k$
Rank	1	^{235}U ν, ν	0.619	^{238}U (n,γ), (n,γ)	0.287	^{235}U ν, ν	0.370
	2	^{238}U (n,γ), (n,γ)	0.289	^{235}U ν, ν	0.258	^{238}U (n,γ), (n,γ)	0.274
	3	^{235}U (n,γ), (n,γ)	0.185	^{239}Pu (n,γ), (n,γ)	0.188	^{239}Pu (n,γ), (n,γ)	0.144
	4	^{235}U (n,fis), (n,fis)	0.114	^{239}Pu (n,fis), (n,fis)	0.152	*Graphite* (n,γ), (n,γ)	0.134
	5	*Graphite* (n,els), (n,els)	0.100	^{147}Pm (n,γ), (n,γ)	0.144	^{239}Pu (n,fis), (n,fis)	0.114
		Total	0.736	Total	0.602	Total	0.570

S/U Analysis Results

- S/U analysis results for main contributor on uncertainty for Ex.I-2a



Conclusion & Future Work

- Eigenvalue calculation and S/U analysis for IAEA CRP HTGR UAM benchmark are conducted using McCARD.

- Eigenvalue calculation is done using both ENDF/B-VII.0 and ENDF/B-VII.1 cross section library and compared with Serpent results. The results show consistency between libraries but show some discrepancy treating double heterogeneity between codes. Also there is some problem in processing thermal scattering data of graphite and this needs to be checked.

- S/U analysis results are compared with DeCART/MUSAD code system. It shows good agreements except for uncertainty due to $^{238}\boldsymbol{U}$ (n,γ), (n,γ) covariance data. It shows about 35% overestimation in DeCART/MUSAD which results from implicit sensitivity effect.

Thank You for Your Attention