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MHTGR-350MW Cross-section Uncertainty Analysis for Exercise I on UAM benchmark

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1. Introduction

The High Temperature Gas Cooled Reactor (HTGR) has drawn attention from the worldwide nuclear community. As HTGR technology continues to advance, it is essential to verify the HTGR design and safety features due to its peculiarity relative to generic Light Water Reactors (LWR). Uncertainty and sensitivity analysis (UA/SA) should be involved in a thorough assessment for HTGR design and safety features. The IAEA Coordinated Research Project (CRP) on HTGR uncertainty analysis in modelling (UAM) was officially launched in 2012 to estimate uncertainty propagation in the whole simulation process and to validate the relevant methodology [1]. For the HTGR UAM benchmark, the different characteristics compared to LWRs [2] are expected to result in significantly different effects and importance in the uncertainty calculations. This paper represents the evaluation of the uncertainties using SCALE code system and the comparative analyses with different model tests, based on the latest MHTGR-350 UAM benchmark specification [3].

2. MHTGR-350MW UAM Benchmark

The MHTGR-350MW UAM benchmark contains four different phases of stand-alone and coupled calculations, which investigates the quantification of uncertainties in different areas and aspects of the propagation of uncertainties from one set of analyses to the next. This study focuses on the MHTGR-350MWth prismatic stand-alone neutronic cell calculations of Phase I, defined to quantify the contribution of the cross section uncertainties, as defined in covariance matrices, to the multiplication factor. Two hexagonal cell designs and two triangular cell designs are used in the evaluation of the multi-group cross section uncertainties and the uncertainties on methods and modelling approximations in the calculation with the reference results.

2.1 Exercise I: Fuel Compact Unit Cell Calculations

Exercise I-1 consists of four cases. Ex.I-1a and I-1c have a homogenous fuel region (the TRISO fuel particles are smeared with the graphite matrix), while in Ex.I-1b and I-1d explicitly modelled TRISO fuel particles are defined in the fuel region. One of the issues identified was the “harder spectrum” of the hexagonal unit cell denoted as Exercise I-1a (homogeneous) and I-1b (heterogeneous), where the moderator to fuel ratio was nearly 0.5. To mitigate the spectrum hardening a triangular unit cell was newly introduced. Subsequently Exercise I-1c (homogeneous) and I-1d (heterogeneous), as shown in Figure 1 and 2, were added. This should be a better representation of the fuel assembly since it includes the additional matrix graphite and the coolant hole, thus reducing the fuel to moderator ratio.

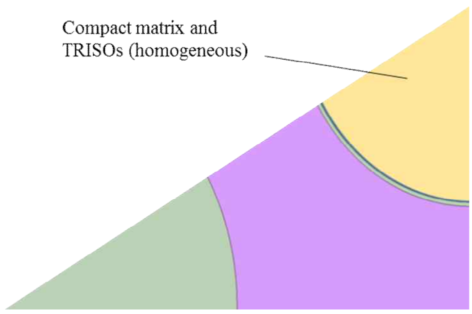

Figure 1. Triangular MHTGR unit cell for Exercise I-1c

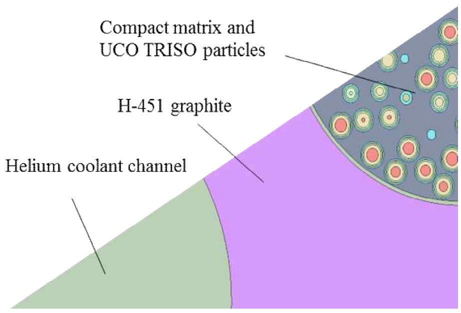

Figure 2. Triangular MHTGR unit cell for Exercise I-1d

Two sub cases with varying operating conditions, defined as Cold Zero Power (CZP) and Hot Full Power (HFP) conditions, were found to be consistent with the data (293K and 1200K). The TRISO particle fuel consists of $UC_{0.5}O_{1.5}$ fuel kernels with ^{235}U enrichment of 15.5 wt%, surrounded by a buffer, a PyC, SiC, and again a PyC coating or layer. The packing fraction of TRISO particles within the fuel compact is 35%, with the remaining part filled with graphite matrix. The fuel compact is surrounded by H-451 block graphite. The hexagonal and triangular unit cells have same nuclide composition and geometry on the fuel compact, but Ex.I-1c and I-1d include the additional matrix graphite and the coolant hole.

2.2 Calculation Models and Codes

Uncertainty and sensitivity analyses (UA/SA) are performed with TSUNAMI [4] but the latest released version of SCALE 6.1.3 is not capable of generating UA/SA data for DOUBLEHET cell models. This feature is required in the double-heterogeneous models. In order to facilitate more freedom to perform UA/SA with SCALE, the Reactivity-Equivalent Physical Transformation (RPT) method [5], which eliminates the need to model the double-heterogeneity explicitly, was used for these cases. The more realistic lattice model represents uniformly distributed particles which can be constructed by a regular square lattice. All the calculations are performed using 4.0 x 10^7 neutron histories with the ENDF/B-VII.0 238 multi-group energy cross section library. The reflective boundary condition is used in all the exercises, which are surrounded by identical unit cells. All the RPT cases were calculated by applying one RPT radius that was derived at Cold Zero Power (CZP) conditions by using SERPENT2 reference results (Randomly distributed particles). Further sensitivity tests will be required to evaluate the effect of, or need for, RPT radii to be derived for each of the operating conditions (CZP and HFP).

3. SCALE/TSUNAMI Uncertainty Results

The TSUNAMI-3D module is used in this uncertainty and sensitivity analysis by calculating the sensitivity coefficients, as well as the forward and adjoint neutron transport solutions [4]. Making use of the 44-group covariance data file, the total uncertainty in k_{inf} (% Δk/k) due to the cross section covariance data is shown in Table I for each exercise. The contribution to the uncertainty in k_{inf} (% Δk/k) by individual energy covariance matrices is shown in Table II.

Table I: Relative standard deviation of k_{inf} (% Δk/k) due to cross section covariance data for Ex.I-1c and Ex.I-1d

	Relative standard deviation of k_{inf} (% Δk/k) due to cross section covariance data	
	CZP	HFP
Ex. I-1c (Homo.)	0.5012 ± 0.0002	0.5502 ± 0.0003
Ex. I-1d (Lattice)	0.4929 ± 0.0003	0.5279 ± 0.0004
Ex. I-1d (RPT)	0.4830 ± 0.0002	0.5195 ± 0.0003

The differences of relative standard deviation of k_{inf} (% Δk/k) between Exercise I-1c and Exercise I-1d (Lattice) are 0.0073 and 0.0223 in each state (CZP and HFP). The differences with the RPT model compared to the lattice model are 0.0099 and 0.0084 in each state.

Table II: Top 5 contributions to uncertainty in k_{inf} (% Δk/k) by covariance matrices for Ex.I-1c and Ex.I-1d

	Nuclide reaction	Contribution to uncertainty in k_{inf} (% Δk/k) due to this matrix	
		CZP	HFP
Ex.I-1c (Homo.)	^{238}U(n,γ)	0.290	0.362
	^{235}U(nubar)	0.273	0.270
	^{235}U(n,γ)	0.244	0.243
	C-graphite elastic	0.105	0.127
	^{235}U(n,f)	0.099	0.101
Ex.I-1d (Lattice)	^{235}U(nubar)	0.274	0.322
	^{238}U(n,γ)	0.263	0.271
	^{235}U(n,γ)	0.248	0.246
	C-graphite elastic	0.129	0.146
	^{235}U(n,f)	0.098	0.101
Ex.I-1d (RPT)	^{235}U(nubar)	0.274	0.312
	^{238}U(n,γ)	0.256	0.272
	^{235}U(n,γ)	0.245	0.244
	C-graphite elastic	0.105	0.122
	^{235}U(n,f)	0.098	0.102

As shown in Table II, Exercise I-1d has top priority on contribution for ^{235}U nubar, resulting in the contributions to uncertainty in k_{inf} (% Δk/k). Compared to the hexagonal results [1], the contribution of the ^{238}U elastic scattering reaction is not presented for the most part. The lattice model has more contribution of a graphite elastic scattering than the homogeneous one. RPT model has more similar value for the contribution of a graphite elastic scattering with homogeneous model rather than lattice model. Other contributions except for graphite elastic scattering have similar values to the lattice model, having less than 5% in both states. The homogeneous model has a difference of ~10% for the ^{238}U capture reaction compared to the lattice model at CZP state. Furthermore at HFP the difference increases to ~33%. Likewise, for the contribution of ^{235}U nubar, the difference between the lattice model and the homogeneous one at HFP is greater than in the CZP state.

Figures 3 and 4 show the sensitivity profiles for ^{235}U(nubar), ^{238}U(n,γ), ^{235}U(n,γ) and ^{235}U(n,f) covariance matrices. The contributions by the fission reaction in the thermal region are clearly represented by the contributions of ^{235}U(nubar) and ^{235}U(n,f). In the resonance region, the contribution of ^{238}U capture reaction is also visible.

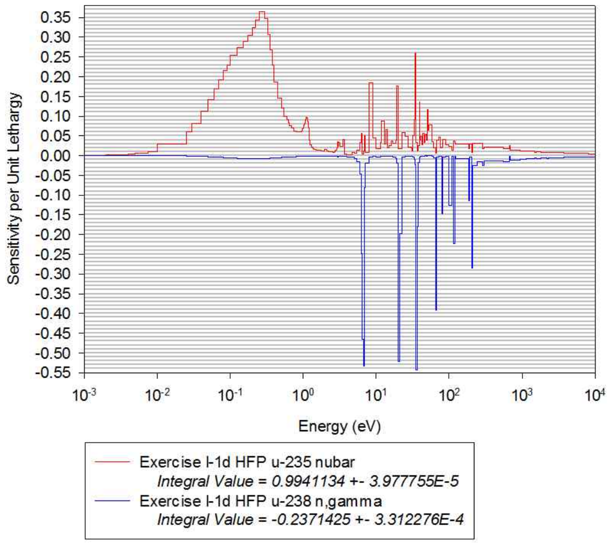

Figure 3. k_{inf} sensitivity profiles for ^{235}U(nubar) and ^{238}U(n,γ) covariance matrices in Exercise I-1d(Lattice) at HFP.

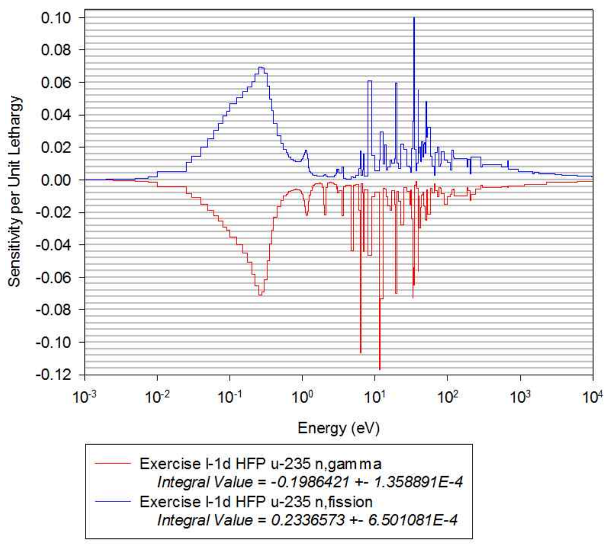

Figure 4. k_{inf} sensitivity profiles for ^{235}U(n,γ) and ^{235}U(n,f) covariance matrices in Exercise I-1d(Lattice) at HFP.

4. Conclusions

The SCALE/TSUNAMI uncertainty calculations were performed for Exercise I-1c and I-1d within the scope of IAEA CRP on HTGR uncertainty analysis in modelling. Both operating conditions (CZP and HFP state) were used in these calculations. The uncertainty calculations in the multiplication factor due to covariance cross section data were performed for both exercises. The overall uncertainty in the multiplication factor are between σ = 0.4830 and 0.5502 %Δk/k. The uncertainty calculation results using the RPT model show good agreement with those from the lattice model. It thus seems to be consistent with the heterogeneous model, but detailed and systematic uncertainty investigations (and a comparison to DOUBLEHET) will be needed in order to confirm this.

^{235}U(nubar) covariance contributions to the uncertainty in k_{inf} (Δ%k/k) are of greater importance in heterogeneous models than in homogeneous model. It is also noticeable that contributions resulted from ^{235}U(nubar) and ^{238}U(n,γ) covariance matrices have a larger difference at HFP when comparing homogeneous and heterogeneous models. The uncertainty calculation results shows that the major contributors resulted from ^{235}U(nubar) and ^{238}U(n,γ) covariance matrices similar to the LWR UAM result, while contributors, such as graphite, are only important in HTGR uncertainty analysis.

ACKNOWLEDGMENTS

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