Benchmarking of SuperMC Code against the Experimental Results of the TRIGA Mark II Research Reactor

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Abstract— The TRIGA Mark II research reactor has been operating at Atominstitute (ATI) of University of Technology Vienna attained its initial criticality on 7th March 1962 with loading of 57 Fuel Elements (FEs). This paper describes the development of the SuperMC model of TRIGA reactor and its benchmarking against three different experiments i.e. initial criticality, reactivity distribution and thermal flux mapping experiment in the reactor core. For the initial criticality experiment, the model predicts keff as 1.00205 with an estimated standard deviation 0.00018 as compare to the experimental value 1.00114. The second experiment measures four FE(s) and one GE for their reactivity values. In comparison with SuperMC simulated results, the percentage difference ranges from 4 to 16 except for the graphite element. The third experiment verifies the model at local level i.e. Though the trends are similar but SuperMC computer code overestimates the radial thermal flux density in the core and underestimates these results at the core periphery.

Key words: ATI, CAD, Initial criticality, Monte Carlo, Reactivity distribution, SuperMC, TRIGA Mark II research reactor

1 INTRODUCTION

Atominstitut (ATI) of Vienna University of Technology, Austria, operates the TRIGA Mark II research reactor at 250 kW since March 1962. The main objective of this research work is to develop a detailed 3D model of the TRIGA Mark II research reactor core using SuperMC Computer code and validate against the experimental results of initial criticality, reactivity distribution and thermal flux mapping experiments performed on the initial core of the reactor.

1.1 Initial Reactor Core

The TRIGA Mark II research reactor is a swimming-pool type research reactor. The reactor has a cylindrical core lattice and is employed with Uranium- Zirconium Hydride (U-ZrH) fuel which is homogeneous mixture of U and ZrH [1]. It operates at 250 kW normally and can also generate a pulse of 250 MW for 40 mille seconds in its pulse mode operation [8]. Its first criticality was achieved on 7th March 1962 with the core loading of 57 FE(s) [2]. The initial core was a completely uniform core with 20% enriched Aluminum (Al) clad FE(s). The fuel meat is sandwiched by two Samarium poison disks and two axial graphite reflectors. The top and bottom Al-fixings align each FE into the core. The geometrical and material characteristics of the Al-clad TRIGA fuel are described in Table 1 [4].

TABLE 1

SPECIFICATIONS OF TRIGA MARK II RESEARCH REACTOR FUEL ELEMENT.

Fuel meat	
Material	U-ZrH
Density (g/cc)	6.21
Length (cm)	35.6
Diameter (cm)	3.58
Mass of U per F.E	184.028
U in Fuel (Wt. %)	8.0
Mass of U235 per F.E	36.77
Enrichment (Wt. %)	20
Poison disks	
Material	2 Sm2O3-disks
Density (g/cc)	2.8
thickness (cm)	0.075
Diameter (cm)	3.58
Axial Reflector	
Material	Graphite
Density (g/cc)	1.6
Length	10.21
Diameter (cm)	3.58
Fuel Cladding	
Material	Al-1100 F
Density (g/cc)	2.7
Thickness (cm)	0.076
Overall dimensions	
Total length (cm)	72.06
Outer diameter (cm)	3.750

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The schematic diagram of the FE and the initial core map are shown in Fig. 1 where the ZBR shows the CIR, "TST, RST and IST" show the shim, regulating and transient-safety CR(s) respectively. The positions F11and F21 show two pneumatic transfer systems while F6 is occupied by the neutron SE.

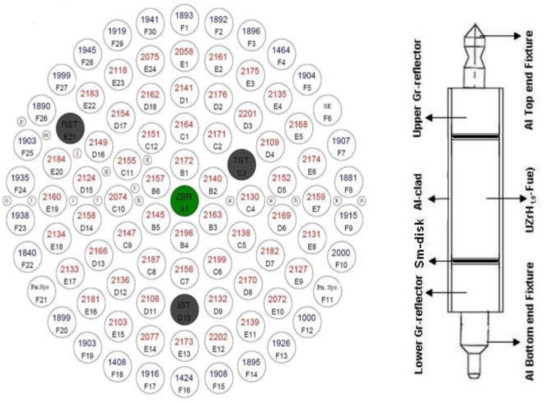

Fig. 1: The initial core map (left) and Al-clad FE (right).

The heat produced is released into a channel of the river Danube via a primary coolant circuit (deionized water at temperatures between 20 and 40 °C) and a secondary coolant circuit (ground water at temperatures between 12 and 18 °C), the two circuits being separated by a heat exchanger [2].

1.2 SuperMC Computer Code

Practical computer simulations of nuclear system like reactors use either deterministic or Monte Carlo codes. Due to continuous energy cross sections and flexible geometrical capabilities, Monte Carlo (MC) method are distinctive to simulate complicated nuclear systems and is envisioned as a routine method for nuclear design and analysis in the future. The SuperMC computer code, developed by FDS team in China, is general purpose CAD-based MC based radiation transport code. It can simulate neutron, photon and their coupled behaviour. It performs transport calculation, geometry and physics modelling and visualization of results and geometry. It has been developed and verified by using a series of benchmarking cases such as the fusion reactor ITER model and the fast reactor BN-600 model. SuperMC is still in its evolution process toward a general and routine tool for the simulation of nuclear systems [5].

SuperMC computer program exploits the hybrid MC-deterministic method concept and advanced computer technologies. Being general-purpose radiation transport program, SuperMC is designed for high-fidelity simulation of nuclear-system problems such as reactor analysis, radiation shielding and dosimetry, medical physics and radiation detection [3]. SuperMC code can be applied to transport calculation of various types of particles, depletion and activation calculation including isotope burnup, material activation and shutdown dose, and multi-physics coupling calculation including thermo-hydraulics, fuel performance and structural mechanics. The powerful bi-directional automatic conversion between general CAD models and calculation models can be easily performed. Results and process of simulation can be visualized with dynamical 3D dataset and geometry model.

Advanced cloud computing framework makes the simulation, which is extremely intensive in computation and data storage, more attractive just as a network service. The modular design and generic interface promotes its flexible manipulation and coupling of external solvers. The architecture of SuperMC is shown in Fig. 2.

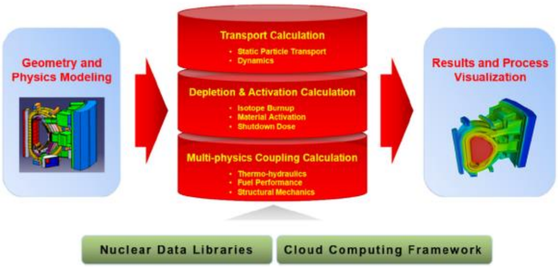

Fig. 2: Schematic architecture of the SuperMC radiation transport code.

2 MODEL DEVELOPMENT

SuperMC is a general-purpose, intelligent, accurate and precise Monte Carlo simulation software system that can be used for neutron and photon or coupled neutron/photon transport, including the capability to calculate eigenvalues for critical systems and burnup depletion calculations. The arbitrary three-dimensional configuration of materials in geometric cells can be constructed by using GUI based CAD system of SuperMC computer code.

CAD models can be imported or created and pre-processed by ''geometry creator''. The ''physics modelling'' can interactively construct materials, sources, tallies and other process parameters for comprehensive neutronic simulation including transport, burnup and activation.

Based on the hybrid MC-deterministic transport method, transport simulation of neutron and photon can be performed with continuous-energy cross-section libraries and accurate physical models in wide energy range.

Applying all the geometrical and material information from various reliable sources [4], a detailed three-dimensional model of the very first core of the TRIGA Mark II is developed in SuperMC using its CAD system as shown in Fig. 3.

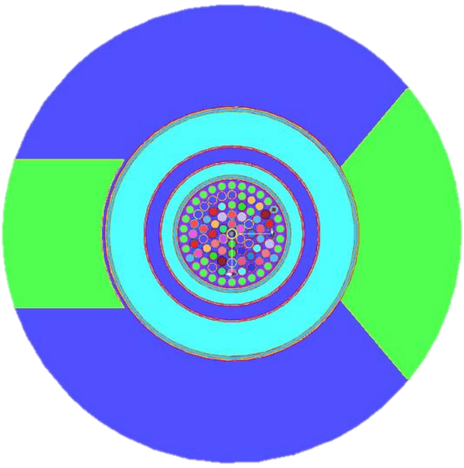

Fig. 3: Top view of the SuperMC model of the TRIGA Mark II research reactor.

The SuperMC model employs the average values of fuel inventory taken from the shipment documents [1]. All the FE components (fuel meat, 2 Sm-disks, 2 axial graphite reflectors and Al-cladding) have been modeled as shown in the Fig. 4. The exact geometry of the top and bottom Al fixtures was not modeled because of the minimal impact on the core neutronics. The different colors in Fig. 3 and Fig. 4 present the different materials employed in the model. The model (Fig. 3) includes FEs in B, C, D and E rings, SE (F06) and 27 GEs in F-ring of the core. Accordingly, each FE in the core will be treated separately because of their individual different burn up values as shown in Fig. 5. Therefore, keeping this plan in view, the FE in this initial core model are assigned different material numbers (different colors) in spite of the fact that all FE are fresh and employing average material composition. The core is surrounded by an annular grooved graphite reflector. Outside the reflector, the water acts as radiation shield as shown in Fig. 4 & Fig. 5. The Initial criticality experiment is modeled with 56 and 57 fuel elements without the control rods. A second configuration of core is modeled with 62 fuel elements and with three control rods (shim, regulating and safety rod) positioned at their real locations as shown in Fig. 5.

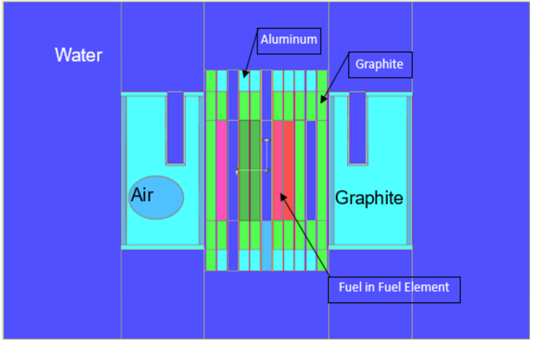

Fig. 4: Side (YZ) view of the SuperMC model of the reactor.

TABLE 2
THEORETICAL AND EXPERIMENTAL RESULTS OF THE FIRST CRITICALITY EXPERIMENT.

Fuel elements	SuperMC Results	Experiment Results
keff with 56 FE(s)	0.99741	Sub critical
keff with 57 FE(s)	1.00205	1.00114
Core excess reactivity (cents)	28.0	15.7

All three CR(s) are modeled separately in their exact grid location (i.e. C03, D10 and E21). The material and geometrical specifications of all three CR(s) are taken from reference [4]. The GE, SE and the CIR can be seen in the model exclusively.

For simplification, the model makes some geometrical and material assumptions. Most of the outer core geometries are imported using the MCNP input file the core geometries are designed and configured using the CAD system of the SuperMC. The model employs an average value of the fuel meat while the actual mass of each FE is slightly different. Moreover, the top and bottom Al fittings of the FE are simplified in the model instead of the actual complicated geometry as shown in Fig. 4. The reactivity of the core is very sensitive to the Hydrogen to Zirconium (H/Zr) ratio of the fuel meat while model uses the average value instead of actual values. These assumptions may become the common reason of the discrepancies between the calculations and measurements. This model uses the JEFF3.1 data library.

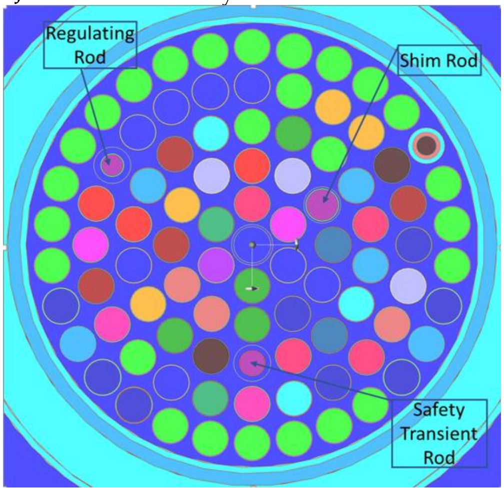

Fig. 5: SuperMC model of the initial TRIGA reactor core.

3 RESULTS AND DISCUSSIONS

A detailed 3D SuperMC model of the TRIGA Mark II research reactor is validated against the experimental observations of the initial criticality, reactivity distribution and radial & axial thermal flux measurements performed on the initial core configuration of the reactor.

3.1 Initial Criticality Experiment and its Model

According to initial criticality experiment performed on 7th March 1962 [4], the FE(s) were added to the core one by one, observing the count rate from the fission chamber. The addition of 56th FE (fuel ID 2075) to E23 position measured the core in just subcritical state. The loading of 57th FE to E24 position, observed the initial criticality with excess reactivity of 15.7 cents [2]. The SuperMC computer model is modified for given experimental conditions to predict the values of initial criticality. The comparison between simulated and experimental results is demonstrated in the Table 2.

The theoretical and experimental results are agreed to the fact that the core remains in just subcritical state with loading of 56 FE(s) and achieves its initial criticality when 57th FE is loaded to the core. On loading of 57th FE, the model calculates an excess reactivity of 25.0 cents as compared to the experimental value 15.7 cents. The difference of 9.3 cents for whole core may be acceptable variation keeping in view all possible sources of errors (model assumptions and errors due to cross sections and reaction rates). Despite the efforts of collecting accurate possible geometrical and material data of the fuel, a very small uncertainty either in the dimensions or material composition of the fuel may create significant deviation.

3.2 Reactivity Distribution Experiment and its Model

This experiment was performed in December 1963 at 100 watts [6]. The effect of one GE (at position F1) and four FE(s) from different rings positions (i.e. B1, C1, D1, and E1) were measured applying the core excess reactivity method. The experimental core configuration is shown in Fig. 6.

The SuperMC computer model does not incorporate any change in material composition and employs the fresh fuel only. The calculated results of reactivity worth of five elements are compared with the experimental values in Table 3.

The deviations between the calculations and experimental observations may be due to the assumptions applied to the model. For example, the Model employs the fresh fuel while actual fuel is slightly burned fuel. Both the theoretical and experimental results are agreed that inner FE(s) are more reactive than outer elements. The reactivity of the inner FE(s) is larger than the outer FE(s) which may be due to more leakage at the core periphery than the core center. However, the discrepancy is gradually increased as the insertion position is closer to the center of core, it may be due to the cylindrical core lattice. In such a lattice, generally, a FE worth for a well-thermalized, small, compact and uniform core is approximately proportional to the square of the thermal neutron flux density, integrated over the entire fissile volume of the FE [7]. The thermal flux density is higher in the inner rings than the core outer rings; therefore the FE in the inner ring is more reactive than in the outer ring.

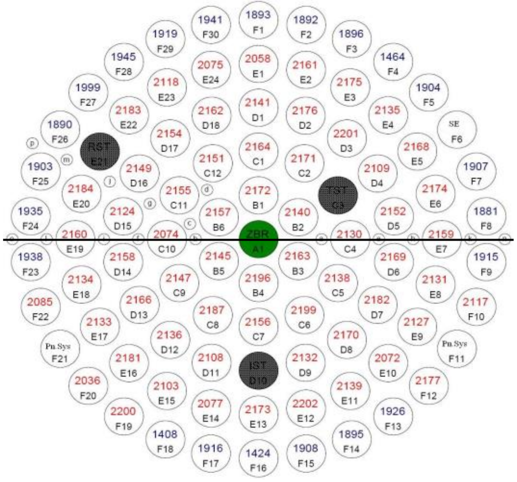

Fig. 6: The core configuration of the reactivity worth distribution experiment.

TABLE 3
RESULTS OF THE REACTIVITY DISTRIBUTION EXPERIMENT.

Elements	**keff**	**SuperMC results (cents)**	**Exp. Results (cents)**	**%age difference**
GE: 1893 (F1)	1.00469	2	10.5	77
FE: 2058 (E1)	1.00092	54	56	4
GE: 2141 (D1)	0.99971	70	65	-8
FE: 2164 (C1)	0.99815	92	80	-15
FE: 2172 (B1)	0.99284	165	143	-16

3.3 Thermal Flux Mapping Experiment and its Model

The radial and axial thermal flux densities are calculated for further assessment of the model of initial core configuration [8] and are compared with the experimental observations. The experimental core map and the 16 irradiation radial positions (a, e, h, k, n, b, c, d, g, j, m, p, f, i, l, and o) are shown in Fig. 4. The axial thermal flux was measured at each 5 cm along the center irradiation channel ZBR using the gold foil activation technique.

3.4 Radial Flux Distribution

The thermal flux distribution at the core mid plane, shown in Fig. 7, is computed using SuperMC core model. The flux density profile looks symmetrical i.e. it has a maximum value in the center and decreases in the radial direction. It can be clearly seen the flux density depression due to the regulating control rod insertion in E ring. The thermal flux values are higher in shim rod position (C3) due to presence of water when Shim rod is kept higher than mid plane.

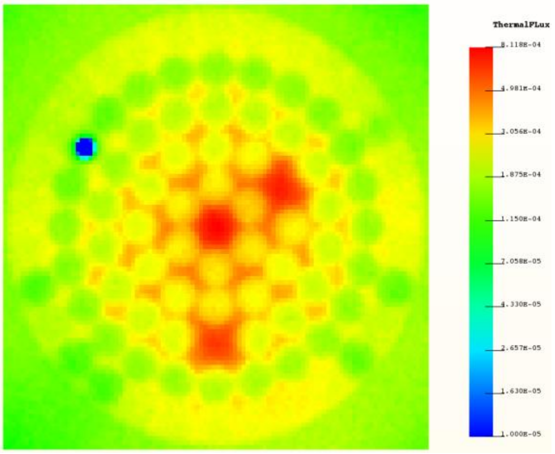

Fig. 7: Mid plane (or XY) thermal flux density profile computed using SuperMC mesh tally.

The experimental and SuperMC computed radial thermal flux density profile is compared in Fig. 8. The experimental radial flux density profile is peaked at the center and decreases along the radius of the reactor core. The SuperMC predicted values captures the experimental trends except at the edges of the core it may be because of minute inaccuracy in gold foil positioning and difference between shape of the gold foil and SuperMC voxels. A major source of deviations in values is may be the employment of fresh fuel while actual fuel was not fresh at the time of the experiment. Due to less parasitic absorption, the fresh fuel is more reactive than the burned fuel. The difference between calculations and measurements at the core edges may be attributed to the density difference of the graphite reflector. The model uses the density of 1.6 g/cm3 for annular graphite reflector while its actual density is still not confirmed and may vary from the applied value. The trends in thermal flux profiles are quite similar.

3.3.2 Axial Flux Distribution

The axial thermal flux density profile along the ZBR has been computed using the SuperMC TRIGA core model. Fig. 7 shows the comparison between the measured and SuperMC computed results. The experimental axial thermal flux profile was mapped using gold foil activation method and foils were irradiated at a thermal power of 100 Watts for 1.05 hours [8]. The axial profile generally looks symmetrical about its peak i.e. both experimental and theoretical results are agreed that axial thermal flux is peaked in the center and decreases along the axial length of the CIR following the cosine distribution.

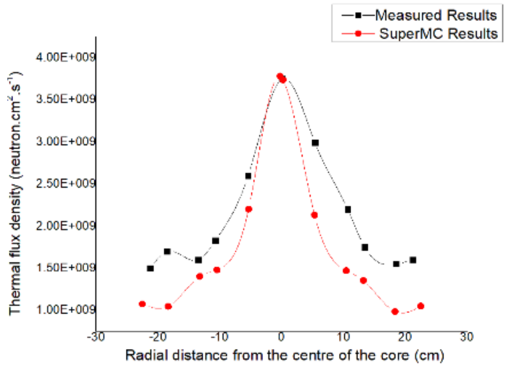

Fig. 8: Thermal flux distribution along the radius of the reactor core.

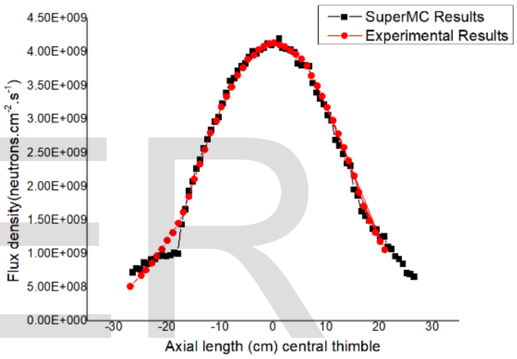

Fig. 8: Axial thermal flux distribution along the CIR of the TRIGA Vienna reactor.

4 CONCLUSIONS

A comprehensive 3D model of initial core of the TRIGA Mark II research reactor is developed employing the SuperMC Monte Carlo transport code. This model applies the fresh fuel and has been validated against three different experiments i.e. initial criticality, reactivity distribution and thermal flux distribution experiments. The SuperMC model confirms that initial core achieves its first criticality on the core loading of 57 FE(s). The reactivity distribution experiment verifies the model for reactivity worth of 4 FE(s) in B1, C1, D1 and E1 ring positions and one GE in F1 position. Thermal flux mapping experiments assess the further accuracy of the model and agrees with the simulated results along the radius of the core and along the axial length of the ZBR in the center of the reactor core.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Key Lab of neutronics and radiation safety, INEST, CAS, China. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors upon reasonable request and with the permission of Key Lab of neutronics and radiation safety, INEST, CAS, China.

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