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نمذجة مفاعل البحث TRIGA –1MW المنخفض الاستطاعة باستخدام الكود MCNP5-beta

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□ ملخّص □

يتناول هذا البحث التحليل النيوتروني لمفاعل الأبحاث TRIGA–1MW في مركز العلوم النووية بجامعة تكساس باستخدام وقود يورانيوم منخفض التخصيب جديد (إغناء الوقود باليورانيوم U^{235} ٢٠%). تم استخدام الكود MCNP5-beta ثلاثي الأبعاد مع طيف الطاقة المستمر لتطوير نموذج كامل ودقيق ومتعدد الاستخدامات لقلب المفاعل TRIGA–1MW. يمثل هذا النموذج بالتفصيل جميع مكونات قلب المفاعل دون أي تقريب مادي. تم وصف جميع عناصر الوقود، والتحكم بالإضافة إلى المنطقة المجاورة للقلب بدقة. وأخذت قيم المقاطع العرضية في حالة طيف الطاقة المستمر لجميع المواد الانشطارية وغير الانشطارية من المكتبة ENDF/B-VI وتوابع تشتت النوترونات الحرارية $s(\alpha,\beta)$ المستخدمة في الكود MCNP5-beta. تم تحديد التوافق والدقة في كل من نتائج الكود MCNP5-beta وفيزياء نقل النيوترونات من خلال المقارنة مع التجارب التي أجريت في المفاعلTRIGA–1MW. تم حساب واستخدام تفاعلية ست قضبان تحكم: أربعة قضبان آمان، وتفاعلية القضيب العابر وتفاعلية قضيب التحكم للمنظم في عملية التحقق من صحة النمذجة. لقد وجد أن نتائج الكود MCNP5-beta والقيم المحددة تجريبيا متوافقة بشكل جيد، مما يشير إلى أن محاكاة المفاعل TRIGA–1MW قد تم التعامل معها بشكل مناسب و جيد.

الكلمات المفتاحية: المفاعل TRIGA–1MW، الوسطاء الحرجية و الكود MCNP5-beta.

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Modelling of the Low Power Research Reactor TRIGA-1 MW by Using the MCNP5-beta code

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□ABSTRACT □

This research deals with the neutronic analysis of the TRIGA-1MW research reactor at the Texas A&M University Nuclear Science Center using a new low enriched uranium fuel (20% ^{235}U in fuel). The 3-D continuous-energy Monte Carlo MCNP5-beta code was used to develop a versatile and accurate full-core model of the TRIGA-1MW core. The model represents in detail all components of the core with literally no physical approximation. All fresh fuel and control elements as well as the vicinity of the core were precisely described. Continuous energy cross-section data of the all fissile and non-fissile materials from the ENDF/B-VI library and $s(\alpha, \beta)$ thermal neutron scattering functions distributed with the MCNP5-beta code were taken. The consistency and accuracy of both the MCNP5-beta code results and neutron transport physics was established by benchmarking the TRIGA-1MW experiments. The reactivity of six control rods: four safety rods, one regulating control rod and one transient rod were used in the validation process. The MCNP5-beta predictions and the experimentally determined values are found to be in very good agreement, which indicates that the simulation of TRIGA-1MW reactor is treated adequately.

Key words: TRIGA reactor, critically parameters, MCNP5-beta code.

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1. Introduction

1.1 TRIGA-1MW (Training, Research, Isotopes, General Atomics) reactor.

The Texas A&M University Nuclear Science Center (NSC) houses a 1-MW pool-type TRIGA reactor. The Nuclear Science Center Reactor (NSCR) used for various kinds of experiments including neutron activation analysis, isotope production, geochronology and other scientific applications [1], [2]. This type of research reactor is the most widely used in the world, so it is important to know its specifications and modeling to know the extent to which Monte Carlo computational methods are compatible with the physics of reactors and with the experimental values of the criticality parameters of this type of reactors.

The TRIGA- 1MW reactor belongs to the class of tank-in-pool research reactors, with thermal power rated at 1 MW. TRIGA- 1MW reactor uses light water as moderator, coolant and shield and graphite blokes as reflector of neutrons. Vertical cross–section of the TRIGA-1MW reactor is shown in Figure 1 [1].

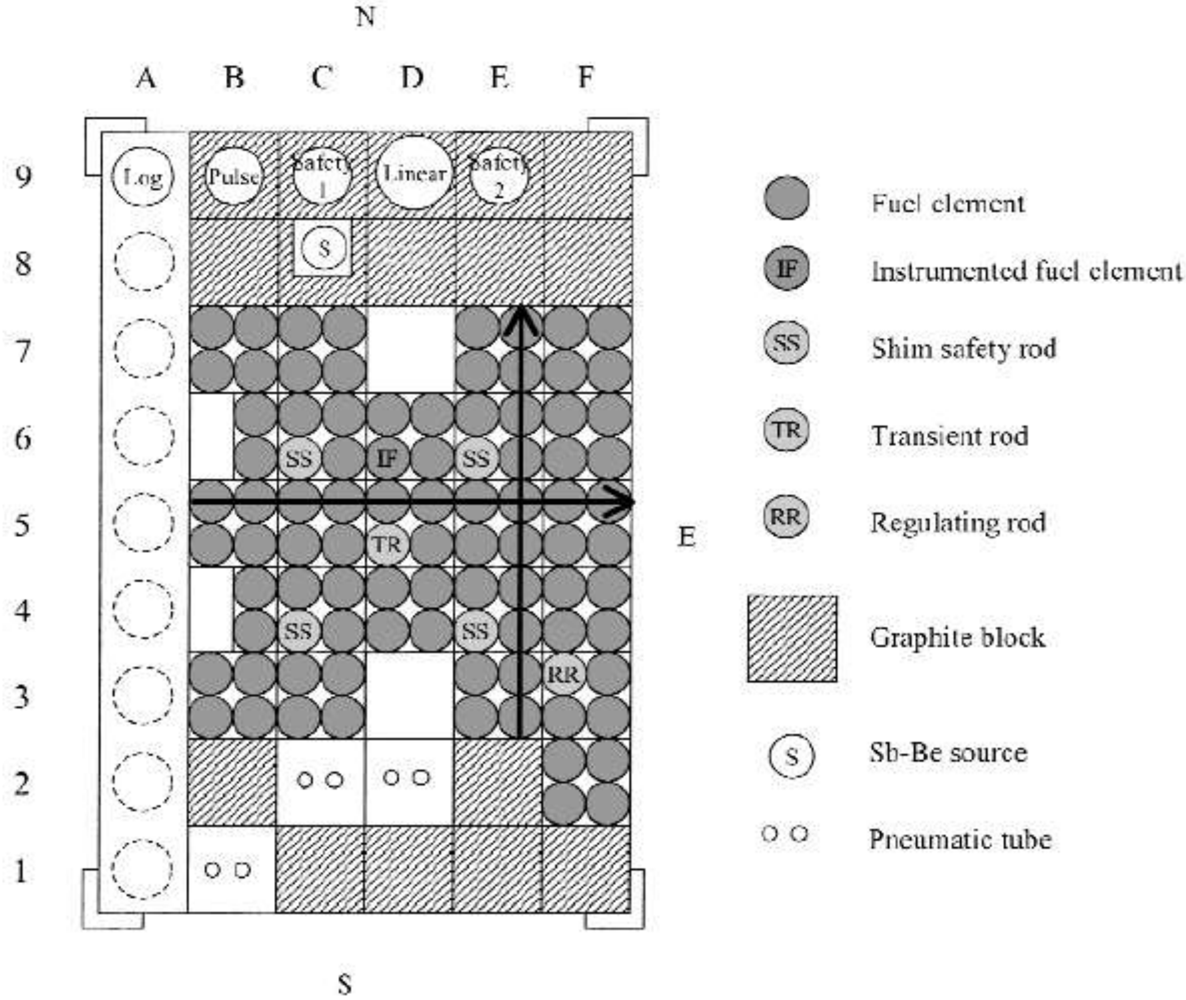

Figure 1: TRIGA-1MW reactor core, that is located in the NSCR.

2.1 TRIGA -1 MW reactor Core

The current TRIGA -1 MW reactor Core (See Figure 1) contains 85 regular fuel elements, an instrumented fuel element, four shim safety rods, a transient rod and a regulating rod. The fuel elements and control rods are grouped into four-rod bundles, which are positioned and supported by an aluminum grid plate containing a 639 array of holes. Graphite blocks, detectors, pneumatic devices, and various experiments are also positioned and supported by the holes in the grid plate [1], [2], [3].

The grid locations on the core are named by column (A, B, C, D, E and F) and row (1, 2, 3, 4, 5, 6, 7, 8 and 9) of the grid plate. The grid locations in column A (specifically, A2, A4, A6 and A8) are routinely used for various experiments or irradiation devices. The grid locations D3 and D7 are for experiments that require fast neutrons or higher neutron flux. Pneumatic irradiation devices are installed at B1, C2, and D2 for short irradiations. The main specifications of the TRIGA -1 MW reactor are summarized in Table 1 [1], [2], [3], [4].

Table 1: **Main Properties of the TRIGA-1MW research reactor.**

Parameter	Description
Reactor type	Tank-in-pool
Rated thermal power	1 MW
Fuel	U-ZrH
H/Zr ratio	1.6 to 1.7
U - 235 enrichment	20 %
Uranium content in one fuel element	151 g
Core shape	Rectangular
Burnable poison	Natural erbium
Fuel element shape	Cylindrical
Fuel element number in the core	85 fuel element
Refuel period	More than ten years
Control rod (B_4C)	4 control rods
Regulating rod (B_4C and U-ZrH)	1
Transient rod (B_4C)	1
Neutronic reflector	Graphite blocks
Maximum temperature fuel (C^o)	373
Total number of irradiation sites	10
Number of inner irradiation sites	2
Maximum thermal neutron flux in irradiation sites	$1x10^{13}$ $n/cm^2.s$
Reactor cooling mode	Natural convection

3.1 The TRIGA-1MW reactor fuel element

U-ZrH alloy has been used as fuel meat in the low-power research TRGIGA-1MW reactors. The diameter of the fuel rod meat is 3.4822 cm. The total length of the fuel element is 66.04 to 71.12 cm and the active length is 38.1cm. End of the fuel element, two graphite blocks are located and works as neutron reflector. In the middle of the fuel element there is a zirconium rod. The cross-sections of the fuel element are shown in the Figure 2 [1], [2].

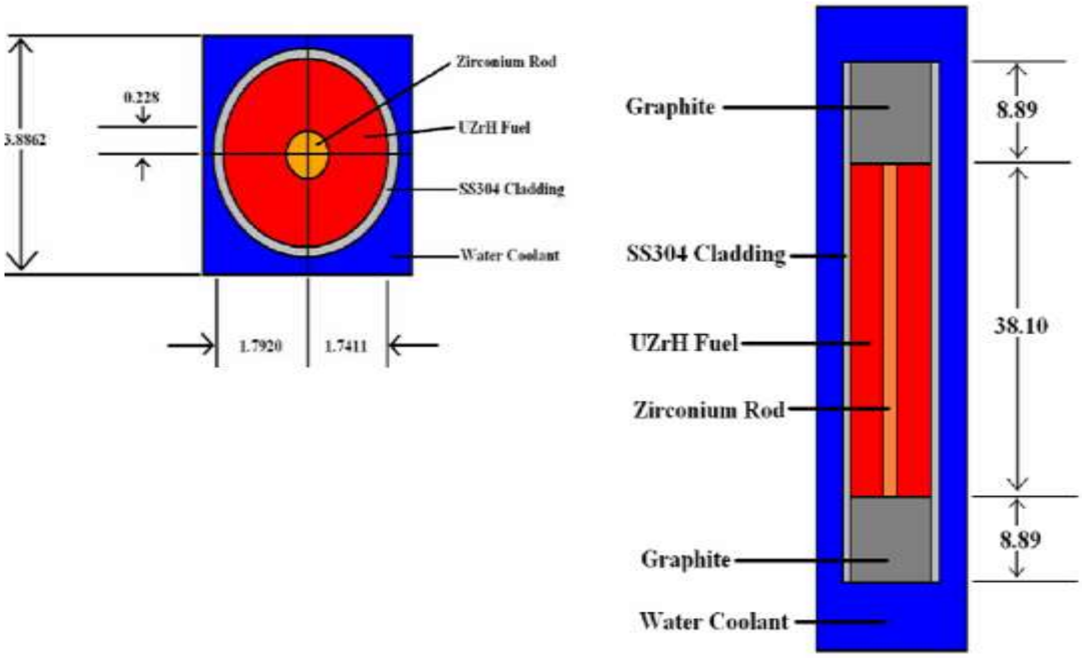

Figure 2: Cross-sections of the fuel element with dimensions (in cm) and materials

The main specifications of the fuel meat using in the TRGIGA-1MW reactor are tabulated in Table 2 [1], [4].

Table 2: Main specifications of the fuel meat using in the TRGIGA-1MW reactor.

Type	New fuel
Fuel moderator material	U-ZrH
Uranium content	30 wt %
U^{235} enrichment	20 %
U^{235} content in one fuel element	151 g
Density (g/cm^3)	5.64
Burnable poison	Natural Erbium
Length of fuel (cm)	38.1
Diameter of fuel (cm)	3.4822
Cladding type	304 SS
Cladding thickness (cm)	0.0509

4.1 Shims safety rods, regulating and transient rod used in the TRIGA-1MW reactor.

The reactor has six control rods: four shims safety rods, one regulating control rod, and one transient rod. The shim safety rods are fuel followed, this means that the bottom portion of the rod contains fuel while the top portion contains borated graphite powder (B_4C) to be used as a poison. The poison section is 35.56 cm long while the fuel section is 38.1 cm long. Both are contained in the same stainless steel cladding that is used for the fuel rods. Both the transient rod and regulating control rod are 38.1 cm in length. The shim safety and transient rods consists of borated graphite powder while the regulating rod is B4C powder. The cross-sections of the safety (control) rod, regulating and transient rod are shown in Figure 3, Figure 4 and Figure 5 [1], [2], [4].

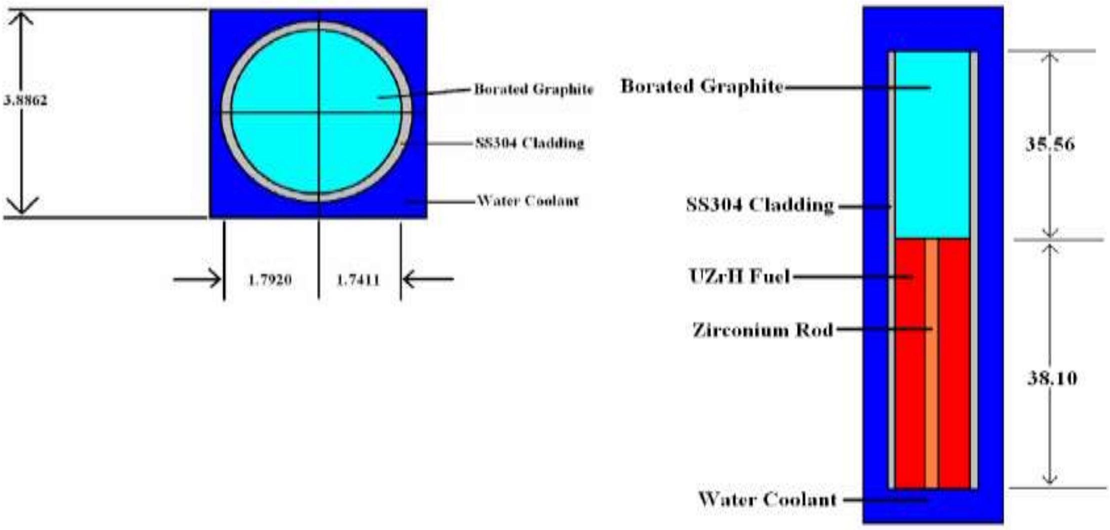

Figure 3: Cross-sections of the shim safety (control) rod with dimensions (in cm) and materials

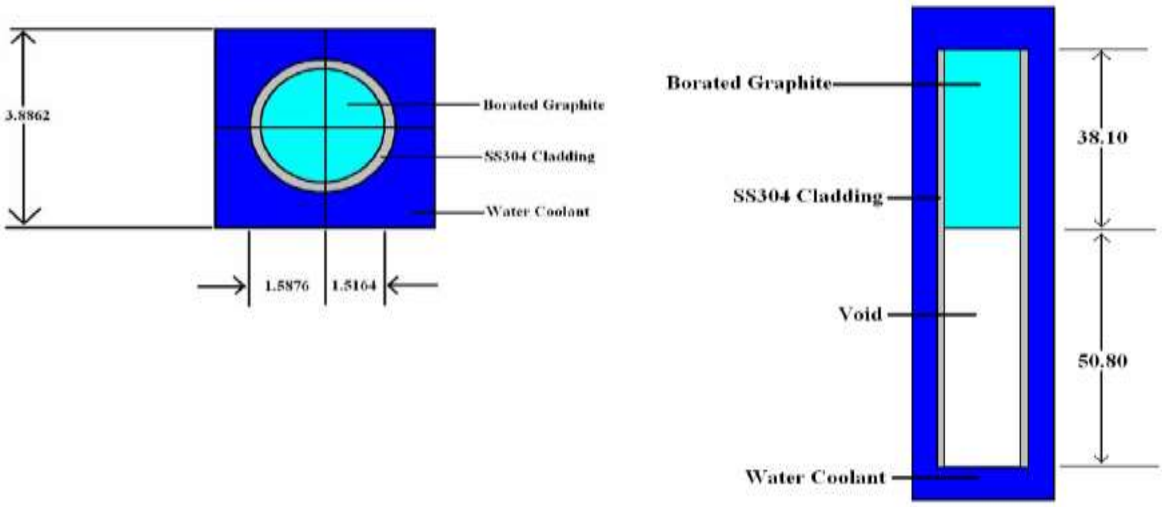

Figure 4: Cross-sections of the transient rod with dimensions (in cm) and materials

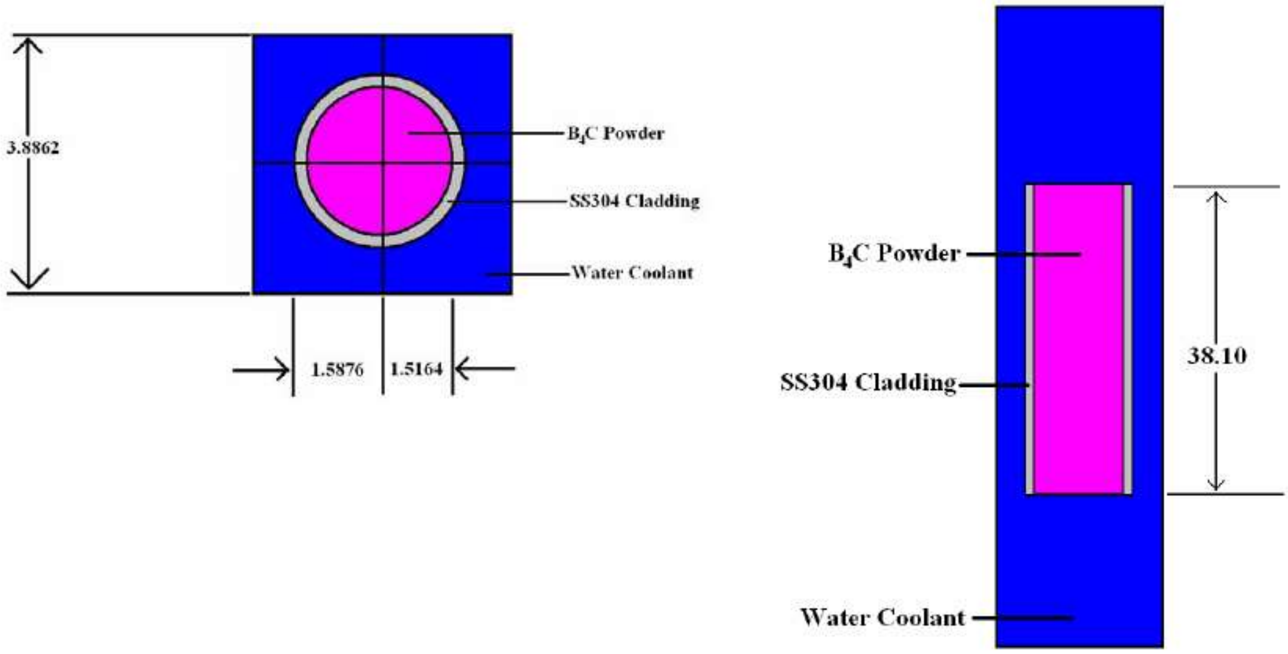

Figure 5: Cross-sections of the regulating control rod with dimensions (in cm) and materials

2. The main problem of this research

The main problem of this research is simulating the research TRIGA-1MW reactor using the MCNP5-beta code and determination the criticality parameters such as: Reactivity of shims rods, reactivity of regulating and transient rod.

3. The importance of this research

The importance of this research is using the Monte Carlo method (MCNP5-beta code) in criticality calculations in low–power research reactors, this helps in:

1. Increasing scientific experience and knowledge in criticality calculations of low-power research reactors.
2. Determining the criticality parameters of the reactor before making any modification in reactor core such as: replacing a depleted fuel rods with new fuel, replacing the control rods, replacing neutronic reflector and design neutronic channels for various scientific applications.

4. Importance of the MCNP5-beta code

The MCNP5-beta code is a popular, versatile multipurpose Monte Carlo particle transport code used worldwide. It has the capability to model and treat different geometries in 3-D, and also simulate the transport behavior of different particles and using a continuous energy cross section treatment as opposed to a multi-group approach thereby eliminating the errors in formulating few group cross sections. Additionally, MCNP5-beta the ability to treat complex nuclear interaction processes [5]. Therefore, in this work, the MCNP5-beta code was used to:

- simulate the low-power TRIGA-1MW research reactor.
- evaluate the critically parameters such as: effective multiplication factor (k_{eff}), reactivity of safety rods, reactivity of regulating and transient rod.

5. Modeling the TRIGA-1MW reactor by using the MCNP5-beta code

The low power TRIGA-1MW reactor was simulated by using MCNP5-beta code with three-dimensional detail to reduce possible systematic errors due to inexact geometry simulation. Therefore, this model of the low power TRIGA-1MW reactor represents in detail all components of the core with literally no physical approximation. In the simulation of the low power TRIGA-1MW reactor, the nuclear data for the fissile and the non-fissile materials such as:

- the fuel meat, fuel clad, coolant and moderator water, control rod, transient rod, regulating rod, and the reflector were taken from the ENDF/B-VI.1 nuclear data library.
- the thermal particle scattering $S(\alpha,\beta)$ was applied to treat the thermal scattering in both graphite and hydrogen of the coolant and moderated water.
- the composition, dimensions of reactor core, nuclear densities and dimensions of the fuel element, control rod, regulating rod, control material B_4C, fuel clad, graphite blocks, zirconium rod and other components located in the reactor core were taken from following references [1], [2], [6], [7].

The 3-D Monte Carlo MCNP5-beta plot of the TRIGA-1MW reactor core configuration is shown in Figure 6.

7. Results and discussion

7.1 Calculation the criticality parameters by using MCNP5-beta code.

The $3-D$ Monte Carlo MCNP5-beta model of the low power TRIGA-1MW reactor was used to estimate the nuclear criticality parameters such as: effective multiplication factor (k_{eff}), reactivity of four safety rods, reactivity of transient and regulating rod. In particular, neutron transport simulations were made for a 1 MW power of the TRIGA reactor.

7.2 Calculation the multiplication effective factor ($\mathbf{k_{eff}}$)

The effective multiplication factor k_{eff} is defined as the ratio of the number of fission or fission neutrons in the generation divided by the number of fissions or fission neutrons in the preceding generation [5]. In the equation form,

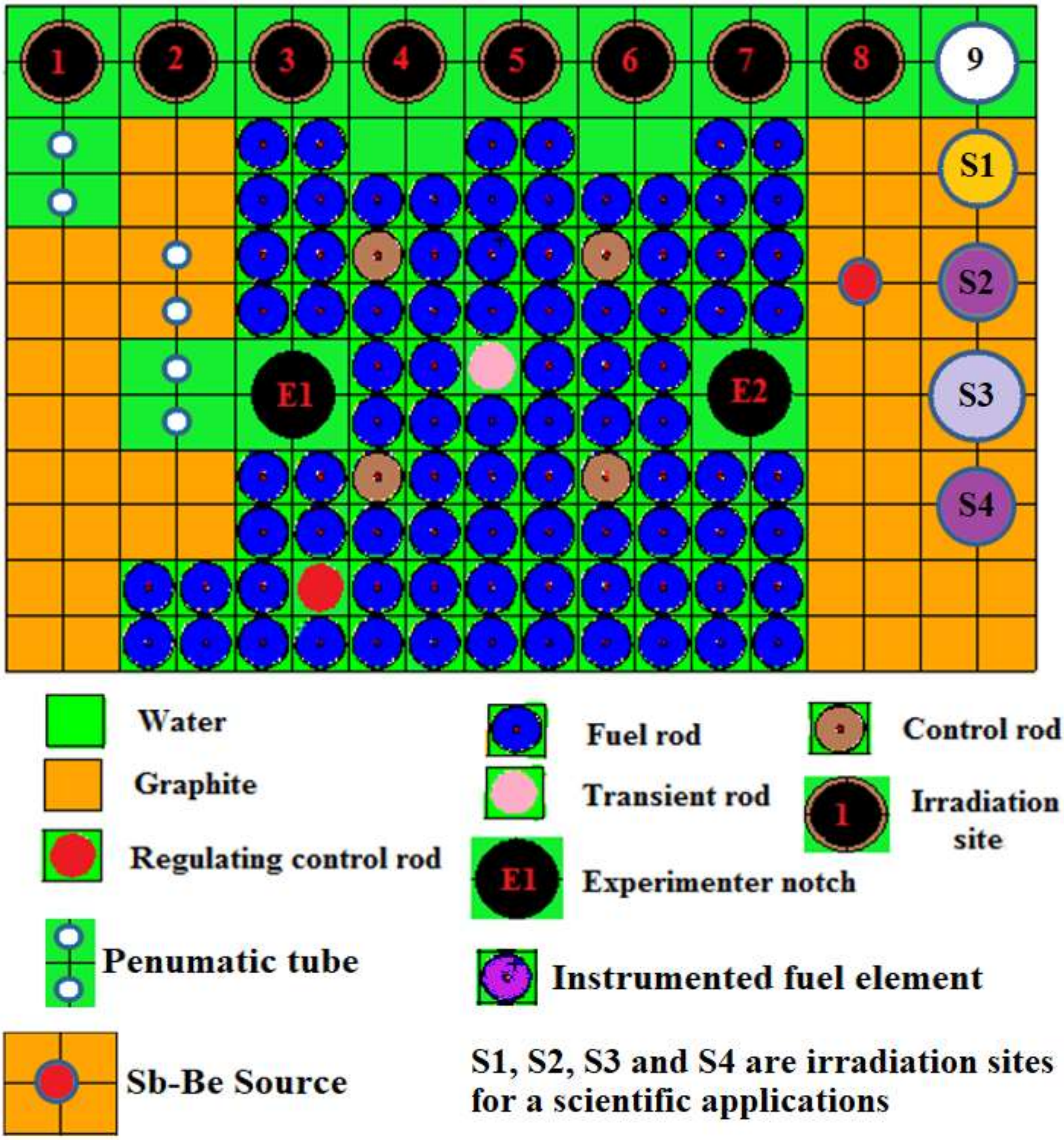

Figure 6: Cross-sections of the TRIGA-1MW reactor using MCNP5-beta code.

$$k_{eff} = \frac{Number\ of\ fissions\ in\ one\ generation\ (i+1)}{Number\ of\ fissions\ in\ preceding\ generation\ (i)}$$

The formula of k_{eff} comes directly from the time-integrated Boltzmann transport equation without external source. k_{eff} can be written as follow [5]:

$$k_{eff} = \frac{\rho_a \int_V \int_0^\infty \int_E \int_\Omega \nu\sigma_f \Phi dV dt dE d\Omega}{\int_V \int_0^\infty \int_E \int_\Omega \nabla J dV dt dE d\Omega + \rho_a \int_V \int_0^\infty \int_E \int_\Omega \upsilon(\sigma_f + \sigma_c + \sigma_m)\Phi dV dt dE d\Omega}$$

This equation is derived from integro-different neutron transport equation with energy (E), flux (Φ), direction of neutron (Ω), reactor volume (V), neutron velocity (v), time (t) and neutron current flux (J), material or atom density (ρ_a) by meant of σ_c, σ_f and σ_m are microscopic cross section for capture (n, pn) fission and multiplicity (n, xn) respectively.

The effective multiplication factor k_{eff} is computed in MCNP5-beta based on the calculation of three different estimators a collision-based k_{eff}^{C}, an absorption-based k_{eff}^{A} and a track length based k_{eff}^{TL} [5].

The effective multiplication factor k_{eff} was performed by the KCODE criticality source card to determine the k_{eff} and corresponding excess core reactivity ρ_{ex} using all fuel elements as fission source points [5]. For the initial source distribution, the KSRC card was used with five source points in each of the fuel elements [5]. In this analysis,

- 1×10^8 neutron histories were used to run the MCNP5-beta code.
- 400 cycles with 60 passive cycles before the active cycles begin.
- initial value of the k_{eff} effective multiplication factor is 1.
- the cross-sections of all the isotopes formed in the reactor core were taken from the ENDF-VI.1 nuclear data library.

To calculate the k_{eff}, the input file of the TRIGA-1MW reactor is ran using MCNP5-beta code with above mentioned conditions. The calculated values of the k_{eff} obtained from output file of the TRIGA-1MW for steady state of reactor are given in Table 3 and Table 4.

7.3 Calculation the effective delayed neutron fraction β_{eff} of the TRIGA-1MW reactor.

The effective delayed neutron fraction $\beta_{eff,}$ is given by the number of neutrons produced in reactions induced by delayed neutrons, divided by the total number of neutrons produced. To estimate the value of the effective delayed neutron frction β_{eff}, the input file of the TRIGA-1MW reactor was run by the MCNP5-beta code using the "TOTNU" card with "NO" as the only entry turns off delayed neutrons in k-code mode, producing a final k-eigenvalue corresponding to k_p. The value of the β_{eff} was calculated using the relation [8].

$$\beta_{eff} = 1 - (k_p/k_{eff})$$

Where:

$$k_{eff} = k_p + k_{deff}$$

Where k_p denotes the prompt neutron contribution to k_{eff} and k_{deff} is the contribution of delayed neutrons to $k_{eff.}$ The calculated value of the β_{eff} for TRIGA-1MW reactor obtained by using MCNP5-beta code is given in Table 3. Where, the calculated value of the k_p by using MCNP5-beta for TRIGA-1MW reactor is equal to $k_p = 1.03847 \mp 0.00071$.

7.4 Calculation the reactivity of the safety (control) rods, reactivity of the transient and regulating rod.

The reactivity ρ_{ex} of safety (control) rods together (combined) and the reactivity ρ_{ex} for each control rod (individually) were calculated using the following equation [8], [9].

$$\rho_{ex} = (k_{eff} - 1)/\beta_{eff}\, k_{eff}$$

Where:

β_{eff} - is effective delayed neutron fraction for TRIGA-1MW reactor.

The calculated and experimental values of the reactivity of control rods in both cases: One case, the control rods (six control rods see Figure 6) are fully inserted inside reactor core, and the second case, the control rods are fully withdrawn from reactor core are shown in Table 3. Whereas, the calculated and experimental values of the reactivity of each shim safety (control) rod, reactivity of the transient and regulating rod are given in Table 4.

Table 3: The calculated and experimental values of the reactivity for four control rods together (combined).

Parameter	Reactivity ($)		Relative error %
	Experimental values [3]	Calculated values by using MCNP5-beta code	
CRs in[1]	8.61	8.5435 ± 0.0598	0.77
CRs out[2]	6.22	6.2615 ± 0.0438	0.67
β_{eff}	-	0.00701±0.00045	-

[1] **CRs in** - is the all control rods are fully inserted inside reactor core.

[2] **CRs out** - is the all control rods are fully withdrawn from reactor core.

Table 4: The calculated and experimental values of the reactivity for each control rod, reactivity of the transient and the regulating rod.

Parameter	Reactivity ($)		Relative error %
	Experimental values [3]	Calculated values by using MCNP5-beta code	
CRs # 1[1]	3.17	3.086 ± 0.021	2.768
CRs # 2	2.03	2.003 ± 0.013	1.575
CRs # 3	2.90	2.812 ± 0.019	3.064
CRs # 4	4.60	4.532 ± 0.031	1.670
CRs # Tr[2]	1.02	1.063 ± 0.007	4.113
CRs # Re[3]	3.45	3.393 ± 0.023	1.851

[1] **CRs # 1**- is the all control rods fully inserted reactor core except safety shim (control rod) number 1.

[2] **CRs # Tr** - is all the control rods fully inserted reactor core except transient control rod.

[3] **CRs # Re** -is the control rods fully inserted reactor core except regulating control rod.

From Table 3, the calculated values of the reactivity in both cases, the control rods are fully inserted inside reactor core (***CRs in***), and the control rods are fully withdrawn from reactor core (***CRs out)*** for six shims safety (control) rods differ from the experimental results by about 0.77% and 0.67%, respectively. These differences in values between the experimental and MCNP٥-beta calculations are good and acceptable.

Table 4 show the calculated values of the criticality parameters such as: reactivity for each control rod, reactivity of the transient and regulating control rod. By comparing these values with the same experimental values of the TRIGA-1MW reactor, can find that the maximum error between them does not exceed 4.113%. This good agreement between the calculated and experimental values of the criticality parameters, confirm the accuracy of the 3-D Monte Carlo model of the TRIGA-1MW reactor using MCNP5-beta code.

As a final result, we can use this model to predict the values of the criticality parameters of the reactor before making any modification in reactor core such as: replacing a depleted fuel rods with new fuel, replacing the old control rods with new, replacing graphite blocks, calculation the neutron flux in the irradiation sites, power distribution in reactor core and design neutronic channels for various scientific applications.

Conclusion

The MCNP5-beta code was used to simulate and calculate the criticality parameters of the TRIGA-1MW reactor using a U-ZrH original fuel. The obtained results for the criticality parameters showed a good agreement with the reference values. This work provides the evidence that TRIGA-1MW reactor model using MCNP5-beta can be used for predict the negative effect on the criticality parameters of the reactor in the event of an emergency accident in the reactor or any change in the reactor core.

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