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Achieving High-Power Configuration in Missouri S&T Reactor (MSTR) for Potential Uprate

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INTRODUCTION

Research reactor is a powerful tool because of its wide contribution, almost to each field of science. It's considered to be an essential element for advancing research, development and improvement in nuclear industry [1]. The main goal of research reactor is to produce neutrons which are beneficially used for a wide range of applications such as industrial, agricultural, medical, etc [1]. Neutron spectrum impact it uses. Commonly, neutrons with low energy level, up to 0.5 eV, called thermal neutrons where neutrons with intermediate energy level, ranging from 0.5 eV to 0.10 MeV, called epithermal "resonance" neutrons and neutron with high energy level, above 0.10 MeV, called fast neutron [1, 2]. Thermal and epithermal neutrons can be used for a wide range of purposes such as basic irradiation experiments, neutron radiography, radiolysis, neutron activation analysis, low-scale isotope production and etc [1, 2]. Fast neutrons can be used for investigating radiation damages, advance test of materials behavior and large-scale isotope production [1, 2].

Research reactors are generally categorized by its utilization [1, 2]. However, according to research reactors database of the International Atomic Energy Agency (IAEA), research reactors are characterized by its power level and neutrons capabilities [2]. To this point, the neutron flux magnitude is linearly proportional to the reactor power level [2]. Therefore, the utilization of research reactor depends on its power level and flux magnitude alongside flux energy spectrum obtained in irradiation facilities inside the research reactors. The desired neutron spectrum should play a major role in designing a research reactor.

In the traditional design of thermal research reactors, thermal and epithermal neutrons are sufficiently produced [1]. In contrast, the fast neutrons are significantly limited due to the highly moderating environment [1]. The prevailing designs either focused on thermal or fast spectrum [1, 2]. The sustenance of fast neutrons in thermal research reactors is considered to be one of the challenges. This sort of challenge presents the need for high-power research reactor containing high flux facilities. Knowing that both thermal and hard spectra are needed, therefore, a combination of both spectrums in a flexible core configuration would allow for a diversity of irradiation experiments.

MSTR CURRENT DESIGN & CONFIGURATION

The Missouri University of Sciences and Technology Reactor (MSTR) is pool-type research reactor used for training and educating nuclear students along with research purposes [3]. MSTR operates up to 200 *kilowatt* (*kW*) [3]. Light-water is used for moderation and natural convective heat removal [3]. MSTR uses materials-test-reactor (MTR) type fuel. The grid plate is 9x6 aluminum array [3]. The core consists of nineteen fuel elements and three irradiation facilities along with the one source holder [3]. Four of the fuel elements are used for reactor power control (control rods) [3]. The current MSTR core configuration is presented in Fig. 1 [4].

	1	2	3	4	5	6	7	8	9
A									
B						S			
C					CR4	FE	FE	FE	
D				FE	FE	FE	CR1	FE	FE
E				FE	CR3	FE	CR2	FE	FE
F				CRT	FE	HC	FE	BRT	FE

S: Source Holder FE: Fuel Element CR#: Control Rod
HC: Hot Cell BRT: Bare Rabbit Tube CRT: Cadmium Rabbit Tube

Fig. 1. MSTR Current Core Configuration.

Each of the fuel element is 87 *cm* tall and has a cross-sectional area of 7.62 *cm* x 7.62 *cm*, see Fig. 2. (A). Each of the fuel elements consist of 18 curved fuel plates. Every fuel plate contains U_3Si_2-Al "meat" (19.75% ^{235}U enriched) sandwiched by aluminum clad [3]. The four elements used for reactor power control (control rods) are the same in design of the fuel element except the 10 middle fuel plates were removed to accommodate the control rods insertion, see Fig. 2. (B). Three of these are shim-safety rods which made of 1.5% natural-boron stainless steel [3]. The forth one is the regulating rod which made of stainless steel SS304 [3]. The three irradiation facilities are bare rabbit tube (BRT), cadmium rabbit tube (CRT) and hot cell (HC). More details about the MSTR designs is documented in reference 3 and 4 of the current study.

SCOPE OF WORK

The goal of this study is to overcome the attendant rigidity of the traditional design of MSTR and provide adaptability and flexibility in supporting a wide variety of advance experiments and research. This can be achieved by investigating a concep-

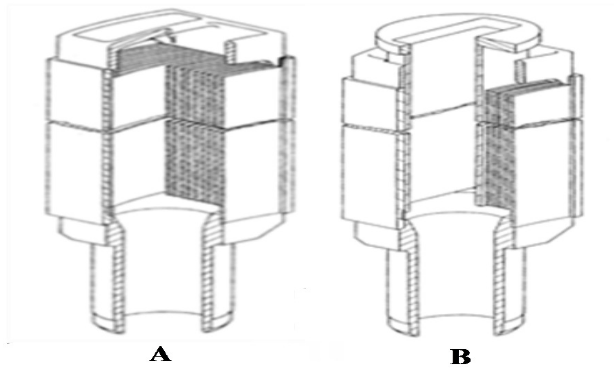

Fig. 2. Standard Fuel Element (A) and Control Rod (B).

tual upgrade of MSTR core design and configuration. In the presented study, the conceptual upgrade generally involves neutronic evaluation which will be discussed in the following sections. However, the conceptual upgrade comes with inevitable key considerations specially in term of thermohydraulic: for example, the heat removal/cooling requirements. For a comprehensive conceptual upgrade study, the thermohydraulic aspects must be studied and analyzed. This will be done in a future work, separate from the current study.

MSTR HIGH-POWER CONFIGURATION (MSTR-HPC)

The current MSTR designs will be the base of MSTR high-power configuration (MSTR-HPC). However, MSTR-HPC involves important modification factors. First factor, uprating the power level to 2 *MegaWatt* (*MW*) to facilitate higher neutron flux. Second factor, changing the fuel meat type to uranium-10 wt% molybdenum metallic alloy (U-10Mo) with 19.75% ^{235}U enrichment. The reasons behind the selection of U-10Mo are; it's very high uranium density (16.09 g/cm^3), stability and predictable irradiation behavior [5]. Thin zirconium layer of 25.4 μm-thick (1 mil) will surround the U-10Mo meat from all sides as well as the top and bottom, see Fig. 3. The goal of the thin zirconium layer is to avoid delamination and to prevent reaction between the aluminum and U-10Mo foil which could lead to swelling in case of high burnup and fission rate [5].

Third factor is the design of a flux trap (FT) facility to be positioned at the central region of the reactor core. The flux trap concept facilitates concentration and enhancement of flux in a specific region. A centrally located FT takes advantage of the higher neutrons population. The FT design is a cylinder with a radius of 3.2 *cm*, 59.055 *cm* tall and placed inside an empty standard fuel element shell.

Forth factor is the reconfiguration of the reactor core which adopted the compact core concept, see Fig. 4. The grid plate redesigned to be 9x9 aluminum array. The core contains four fuel elements, four control rods and three irradiation facilities namely, FT, BRT and CRT. The design of BRT and CRT remain unchanged. The core is surrounded by a graphite blocks for neutron reflection purpose and the achievement of critical core, see Fig. 4. The control rods

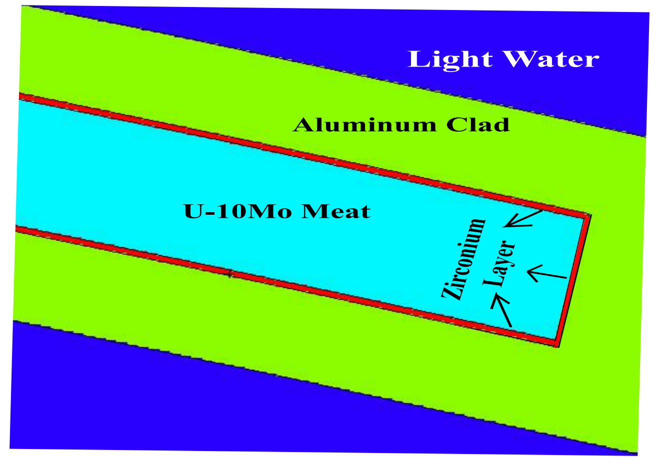

Fig. 3. Middle-Cut-View of a single fuel plate containing U-10Mo Meat surrounded by thin zirconium layer, aluminum clad and light water.

designs remain unchanged except the concentration of the boron in stainless steel which have been raised to 2.00% for an effective shutdown.

	1	2	3	4	5	6	7	8	9
A									
B						GB			
C			GB	GB	GB	BRT	GB		
D			GB	FE	CR1	FE	GB		
E			GB	CR4	FT	CR3	GB		
F			GB	FE	CR2	FE	GB		
G			GB	GB	GB	CRT	GB		
H						GB			
L									

GB: Graphite Block FE: Fuel Element CR#: Control Rod
BRT: Bare Rabbit Tube CRT: Cadmium Rabbit Tube

Fig. 4. MSTR-HPC Core Configuration.

MCNP SIMULATION

Based on Fig. 4 – MSTR-HPC core configuration, the model was designed and set up using Monte Carlo N-particle Code (MCNP), version 5 [6]. The simulation was performed to evaluate and determine; 1) the neutron multiplication factor (K_{eff}), 2) void effects, 3) the safety shutdown margin and more importantly 4) the neutron flux map and capabilities over the reactor core and inside the irradiation facilities. A KCODE criticality calculation was performed with 20000 particles per cycle, 300 active cycles, and 20 discarded cycles. Tally F4:n was used for the determination of flux. For the cross-section data library, ENDF/B-VI (.70c) was used for all isotopes in the model.

RESULTS AND DISCUSSION

Neutron Multiplication Factor (K_{eff}), Void Effects and Safety Shutdown Margin

The K_{eff} determination are evaluated in a room temperature ~ 293.6 K along with the control rods fully withdrawn "excess reactivity". K_{eff} determined to be 1.02239 with an estimated standard deviation of 0.00036. Herein study the interest is to see of such configured core would be critical or not. Thus, burnup calculations are crucial element for neutronic evaluation. This will be done in a future work. Void effect is determined by water ingress to places designed to be void namely, FT, BRT and CRT. After doing so, K_{eff} drops to 1.01670 with an estimated standard deviation of 0.00036. The K_{eff} drop is due to the positive void reactivity effect in the graphite-moderated water-cooled system. The water ingress to the void facilities introduce additional absorption and moderation in the core. The negative effect of absorption overcome the positive effect of moderation.

For the safety shutdown margin, two pair of control rods are assumed to be the shutdown control rods, the third one is the extra shutdown control rod and the fourth one is the regulating control rod. The pair shutdown control rods are tested in all of four control rods positions, see Fig. 4. The effective pairs shutdown control rods are determined to be in the position of CR1 and CR2, see Fig. 4. With a full insertion of CR1 and CR2, K_{eff} determined to be the lowest among other positions which is 0.93395 with an estimated standard deviation of 0.00037. Similarly, K_{eff} tests has been applied for the other control rods positions (CR3 and CR4) for determining the optimum position for the extra shutdown control rods and the regulating rods. Therefore, CR4 was assigned to be the extra shutdown control rods and CR3 was assigned to be the regulating rod. The control rod worth of CR1 and CR2 (the pair shutdown control rods) are plotted in Fig. 5.

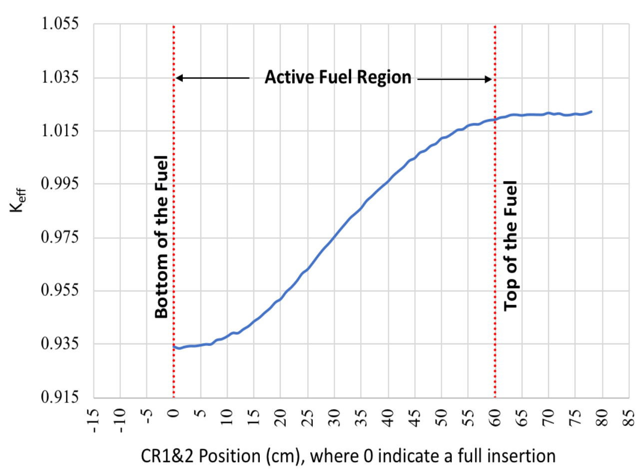

Fig. 5. The Worth of CR1 and CR2 (pair shutdown control rods).

Neutron Flux Map and Capabilities

The neutron flux profile for MSTR-HPC core is presented in Fig. 6. It can be seen, that the picture of actual core configuration is transparent over the flux profile for a better visualization. More importantly, Fig. 6 presents a symmetry core which allow flexibility in positioning the irradiation facilities either at the upper or lower side of the core (considering XY-View). The central region of the reactor core has the highest neutron flux (in darkest red color) which is the FT zone. At the FT region, the total neutron flux calculated by MCNP is $1.42 \times 10^{14} \pm 1.81 \times 10^{12}$ $n\ cm^2\ s^{-1}$. For the BRT and CRT, the total neutron flux calculated by MCNP are $8.25 \times 10^{13} \pm 6.62 \times 10^{12}$ $n\ cm^2\ s^{-1}$ and $4.22 \times 10^{13} \pm 4.77 \times 10^{12}$ $n\ cm^2\ s^{-1}$ respectively.

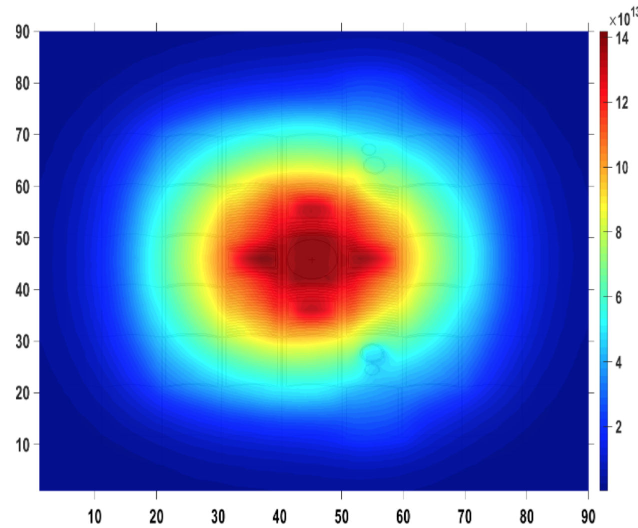

Fig. 6. Neutron Flux Profile for MSTR-HPC Core..

Table I. presents a comparison of total neutron flux obtained at irradiation facilities for both the current MSTR core configuration (as of Fig. 1) and the MSTR-HPC core configuration (as of Fig. 4). For the current MSTR core, the MCNP simulation performed under the same conditions of MSTR-HPC MCNP simulation except the power level-200 kW. As a comparison result, clearly the MSTR-HPC core allows achieving a very high neutron flux on all irradiation facilities, see Table I. Keeping in mind that MSTR-HPC core has only 8 fuel-bearing elements in comparing to the current MSTR core which has 19 fuel-bearing elements. However, for MSTR-HPC, the designs of irradiation facilities mainly the FT has room for improvement towards optimizing and achieving higher neutron flux.

SUMMARY AND CONCLUSION

The goal of the described work was to overcome the attendant rigidity of the traditional design of MSTR and provide adaptability and flexibility in supporting a wide variety of advance experiments and research. Several modification factors have been considered. The main purpose for considering such modification factors is to allow achievement of high neutron

TABLE I. Comparison of Total Neutron Flux at Irradiation Facilities for Both Configurations.

	Current MSTR Core			MSTR-HPC Core		
	Irradiation Facilities					
	HC	BRT	CRT	FT	BRT	CRT
Total Neutron Flux ($n\ cm^2\ s^{-1}$)	9.01E12 ± 6.77E11	5.26E12 ± 4.79E11	1.73 E12 ± 2.82E11	1.42 E14 ± 1.81E12	8.25E13 ± 6.62E12	4.22 E13 ± 4.77E12

flux. These factors are; 1) uprating the power level to 2 MW, 2) changing the fuel meat type to U-10Mo, 3) designing a FT facility at the central region of the reactor core and 4) reconfiguring the reactor core to adopt a compact core concept. The justifications of considering each factor have been explained in the body of this study. The model was designed and set up using Monte Carlo N-particle Code (MCNP), version 5. A general neutronic evaluation were performed.

The determined K_{eff} for MSTR-HPC was 1.02239 with an estimated standard deviation of 0.00036. The K_{eff} determination was evaluated in a room temperature ~ 294.6 K along with all control rods fully withdrawn. For the void effects "water ingress", K_{eff} drops to 1.01670 with an estimated standard deviation of 0.00036. Based on the K_{eff}, the pair shutdown control rods were assigned to CR1 and CR2. The extra shutdown control rods and regulating rod were assigned to CR4 and CR3 respectively. For FT, BRT and CRT, the total neutron flux calculated by MCNP were $1.42\times10^{14} \pm 1.81\times10^{12}$ $n\ cm^2\ s^{-1}$, $8.25\times10^{13} \pm 6.62\times10^{12}$ $n\ cm^2\ s^{-1}$ and $4.22\times10^{13} \pm 4.77\times10^{12}$ $n\ cm^2\ s^{-1}$ respectively. The MSTR-HPC core allows achievement of high neutron flux on all irradiation facilities with only 8 fuel-bearing elements. MSTR-HPC proves its capabilities and flexibility in supporting advance experiments and researches. In future work, thermohydraulic evaluations and burnup calculations will be perform for a comprehensive conceptual upgrade of MSTR.

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