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## INTRODUCTION

The Missouri University of Sciences and Technology Reactor (MSTR) is pool-type research reactor which operates up to 200 *kilowatt* (*kW*). MSTR used for training and educating nuclear engineering students at Missouri S&T [1]. A several of nuclear researches and irradiation experiments have been conducted in MSTR for example, neutron activation analysis (NAA), neutron radiography, radiolysis, image processing, etc. MSTR initial criticality took place on December 9, 1961. The first power level that MSTR operates at, was 10 *kW*. The power level alongside the core configuration was upgraded to the current ones, see Fig. 1 [1, 2]. MSTR used light-water for moderation and natural convective heat removal. MSTR core consists of 9×6 aluminum array grid plate, nineteen fuel elements, one source holder, a single beam port and three irradiation facilities namely, bare rabbit tube (BRT), cadmium rabbit tube (CRT) and hot cell (HC) [1, 2].

| | 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 fuel element has 87 *cm* height and an almost square cross-sectional area of 7.62 *cm* × 7.62 *cm* [1, 2]. There is a cylindrical nose piece attached at the bottom of each fuel element for allowing it to be plug into the grade plate, see Fig. 2. (A). There are eighteen curved fuel plates inside each fuel elements. Each fuel plate consists of 0.51mm thick fuel meat sandwiched by 0.38mm thick aluminum clad [1, 2]. The fuel meat is uranium silicide "$U_3Si_2$-A1" 19.75% $^{235}$U enriched. Four of the nineteen fuel elements are used for reactor power control (control rods), see Fig. 1 [1, 2]. The four control rods are like the design of the fuel element except the 10 central fuel plates were removed to accommodate the control rods insertion, see Fig. 2. (B). Three of the control rod are shim-safety rods and the forth one is a regulating rod. Shim-safety rods are made of 1.5% natural-boron stainless steel and use for controlling nuclear fission and shut-downing the reactor [1, 2]. The regulating rod are made of stainless steel SS304 and used to maintain stable reactor power.

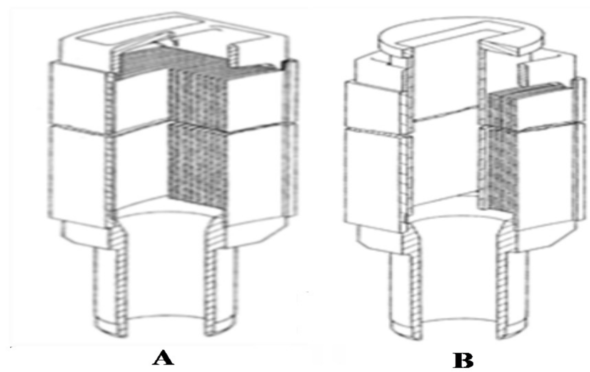


Fig. 2. Standard Fuel Element (A) and Control Rod (B).

## SCOPE OF WORK

The goal of this study is the enhancement of the current traditional design of MSTR for supporting advance irradiation experiments and researches. The objectives behind the enhancement are; 1) the achievement of high neutron flux and 2) the adaptability and flexibility in core configuration. The adaptability and flexibility allow configuring the core for both high-power core configuration and low-power core configuration. By shuffling the reactor core components around the core alongside changing the reactor power level, the user would be able to shift from low-power to high-power core configuration. The high-power core configuration is presented in a separate study. The tasks for achieving these objectives involve a modification factors which will be discussed in detail in the following section.

Once the model is designed and set up, a general neutronic evaluation was carried for the validate of the model. The neutronic evaluation was performed using Monte Carlo N-particle Code (MCNP), version 5 [3]. Burnup calculation is a crucial element for neutronic evaluation therefore, it will be done in future work, separate from the presented study. The natural convective heat removal was assumed to be sufficient for removing the generated heat.

## MSTR LOW-POWER CONFIGURATION (MSTR-LPC)

The current MSTR designs was the base of the presented study. The MSTR low-power configuration (MSTR-LPC) involves several modification factors. For the proposed model (MSTR-LPC), criticality calculation was performed using the current MSTR fuel meat "$U_3Si_2$-Al" and showed subcritical core. Therefore, the first modification was changing the fuel meat type. The considered fuel meat type is uranium-10 wt% molybdenum metallic alloy (U-10Mo) with 19.75% $^{235}$U enrichment. The reasons for considering U-10Mo are due to; it's very high uranium density (16.09 $g/cm^3$), stability and predictable irradiation behavior [4, 5]. A thin zirconium layer of 25.4 $\mu$m-thick (1 mil) surrounded the U-10Mo meat, see Fig. 3. The reason of adding the zirconium layer is to prevent reaction between the aluminum and U10Mo foil [4, 5].

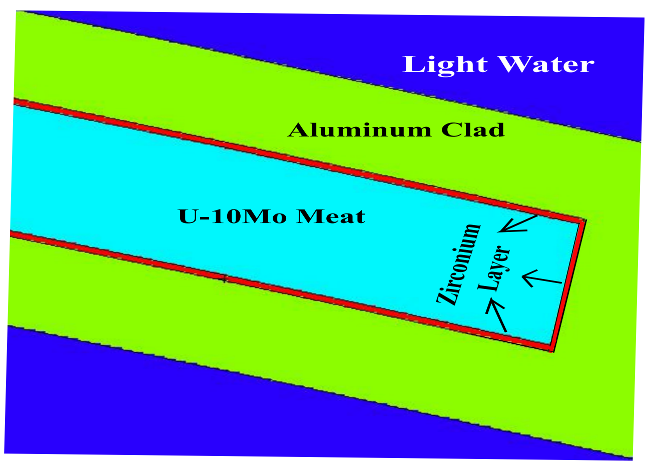


Fig. 3. Middle-Cut-View of a single fuel plate containing U-10Mo Meat surrounded by thin zirconium layer, aluminum clad and light water.

Second modification is the design of a flux trap (FT) facility. The FT is positioned at the central region of the reactor core. 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. In MSTR-LPC, the design of BRT and CRT remain unchanged. Both are the same in design of the ones in current MSTR. Third modification is the inclusion of additional irradiation facilities which are FT to be inside the graphite block (FT-GB), BRT to be inside the graphite block (BRT-GB) and CRT to be inside the graphite block (CRT-GB). The FT-GB is the same design of FT (explained previously) except the empty standard fuel element shell was filled with graphite. Same goes for BRT-GB and CRT-GB.

Forth factor is the reconfiguration of the reactor core, see Fig. 4. The design of grid plate was maximized to be 9×9 aluminum array. The core consists of eight fuel elements, four control rods and six irradiation facilities namely, FT, BRT, CRT, FT-GB, BRT-GB, CRT-GB. A graphite blocks is included in the left side of the core (see Fig. 4) to help reflecting neutrons back to the core. The control rods designs remain unchanged. The only changes in the control rods are the concentration of the boron in stainless steel. Boron concentration have been raised to 12.6% for an effective shutdown. The position of some components of the MSTR-LPC core were envisioned to remain unchanged in order to minimize shuffling requirements when switching to high-power core configuration.

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

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

Fig. 4. MSTR-LPC Core Configuration.

## MCNP SIMULATION

The model of MSTR-LPC (as of Fig. 4) was set up using MCNP5. The MCNP simulation was performed for neutronic evaluation which includes neutron multiplication factor ($k_{eff}$), void effects and the safety shutdown margin. Also, the neutron flux profile was determined. A KCODE criticality calculation was performed with 20,000 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 determination of $k_{eff}$ performed at room temperature (293.6 k) with control rods fully withdrawn. The determined $k_{eff}$ is 1.05568 with an estimated standard deviation of 0.00037. The determination of void effect is based on the ingress of water in places designed to be void. The following facilities have void places: FT, BRT, CRT, FT-GB, BRT-GB and CRT-GB. By water ingress to these facilities, $k_{eff}$ drop to 1.05219 with an estimated standard deviation of 0.00034. The reason for that drop is due to the introduction of additional absorption and moderation "water ingress". The negative effect of absorption overcome the positive effect of moderation.

A serval assumption has been applied for the safety shutdown margin; 1) two pair control rods are the shutdown control rods, 2) the third control rod is the extra shutdown control rod and 3) the fourth control rod is the regulating control rod. All the control rods positions (see Fig. 4) have been tested for the determination of optimum positions for the pair shutdown control rods, extra shutdown control rod and the regulating control rod. Full insertion of CR1 and CR2 was determined as the most effective pair shutdown control rods. The $k_{eff}$ in this case was 0.95910 with an estimated standard deviation of 0.00036. CR4 and CR3 were assigned to be the extra shutdown control rods and the regulating rod respectively. The control rod worth of CR1 and CR2 (the paired shutdown control rods) are plotted in Fig. 5.

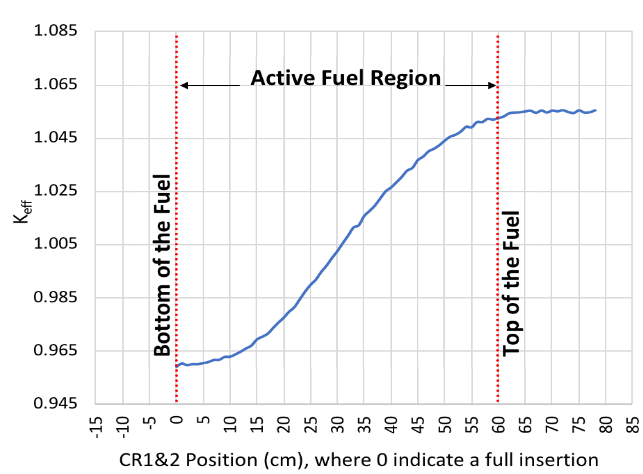


Fig. 5. The Worth of CR1 and CR2 (pair shutdown control rods).

## Neutron Flux Profile and Capabilities

Fig. 6 presented the neutron flux profile of the MSTR-LPC core. The picture of the actual core of MSTR-LPC is transparent over neutron flux profile for a better visualization. Fig. 6 showed a horizontal line of symmetry. This provides flexibility in positioning irradiation facilities either on the upper or lower sides of the core, considering XY-view. As can be seen in Fig. 6, the highest neutron flux region (in darkest red color) is the middle region of the core which is the FT region. At the FT region, the total neutron flux calculated by MCNP is $1.03\times10^{13} \pm 1.54\times10^{11}$ $n\ cm^2\ s^{-1}$. For the BRT and CRT, the total neutron flux calculated by MCNP are $6.41\times10^{12} \pm 5.83\times10^{11}$ $n\ cm^2\ s^{-1}$ and $3.22\times10^{12} \pm 4.12\times10^{11}$ $n\ cm^2\ s^{-1}$ respectively. For irradiation facilities in graphite block (FT-GB, BRT-GB and CRT-GB) the total neutron flux calculated by MCNP are $6.56\times10^{12} \pm 1.56\times10^{11}$ $n\ cm^2\ s^{-1}$, $7.09\times10^{12} \pm 6.63\times10^{11}$ $n\ cm^2\ s^{-1}$ and $4.91\times10^{12} \pm 5.01\times10^{11}$ $n\ cm^2\ s^{-1}$ respectively.

## SUMMARY AND CONCLUSION

The goal of the described work was the enhancement of the current traditional design of MSTR for supporting advance irradiation experiments and researches. This was achieved by considering a several of modification factors for the achievement of high neutron flux. Other consideration is increasing the number of irradiation facilities in the core to allow for

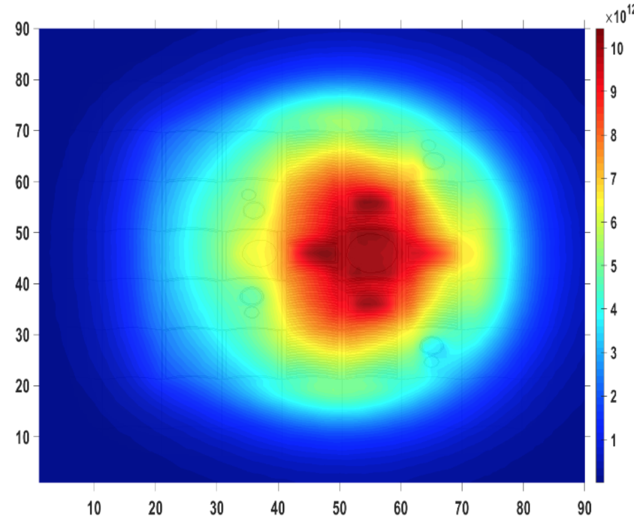


Fig. 6. Neutron Flux Profile for MSTR-LPC Core.

multiple irradiation facilities. A primer objective of the presented model (MSTR-LPC) is the adaptability and flexibility in core configuration which allow shifting from low-power to high-power core configuration by shuffling the reactor core components around the core alongside changing the reactor power level.

Neutronic evaluation results for the MSTR-LPC model showed that the reactor can sustain criticality. However, burnup calculation is a crucial element and it will to be evaluated in future work. For the safety shutdown margin, CR1 and CR2 were assigned to be the pair shutdown control rods and it showed an effective shutdown of the reactor. CR4 and CR3 were assigned to be the extra shutdown control and regulating control rods respectively. As of the neutron flux profile and capabilities, the MSTR-LPC model presented a horizontal line of symmetry which provides flexibility in positioning irradiation facilities. The presented MSTR-LPC model prove its capability and flexibility of supporting advance irradiation experiments and researches.

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