Void Reactivity Coefficient Analysis for Safety of TMSR-500 Using MCNP6

Atika Nur Mufidah[1], Suharyana[1], Riyatun[1], and Azizul Khakim[2]

[1]*Department of Physics, Faculty of Mathematics and Natural Science, Sebelas Maret University, Surakarta, Indonesia*
[2]*Nuclear Energy Regulatory Agency of Indonesia (BAPETEN)*
Gajah Mada Street No. 8 Central Jakarta

Corresponding author: suharyana61@staff.uns.ac.id

Abstract. *Thorium Molten Salt Reactor* (TMSR-500) is one of the developments of the generation IV reactor which has various advantages over the type of reactor in the previous generation because it can produce high resources and long lasting. This reactor uses liquid salt as fuel as well as coolers and moderators made from graphite. The main fuel used is NaF-BeF_2-ThF_4-UF_4. Void reactivity is a very important parameter to calculate the safety level of the reactor. Voids can be formed due to heating the fuel to the boiling point of the fuel which causes bubbles to occur in the fuel and decreases the fuel density. This reported study simulates and calculates the void reactivity coefficient due to a decrease in fuel density expressed by the void fraction. Simulations are carried out using the MCNP6 when voids have not formed (0%), formed 10%, 20%, 30%, and 40%. The results of this study indicate that the TMSR-500 is a reactor that operates in the thermal energy spectrum with a temperature of 977K. The criticality of TMSR-500 was obtained with the value of $k_{eff} = (1.01804 \pm 0.00008)$, and the void reactivity coefficient was positive at (0.068±0.003) %Δk/k/%void due to the undermoderated condition of the reactor so it was safe.

Keyword: TMSR-500, MCNP6, thermal spectrum, void reactivity coefficient, safety

INTRODUCTION

Molten Salt Reactor (MSR) or liquid salt-fueled reactors, is one of the resource technologies that are suiTABLE to be a renewable energy solution. *Thorium Molten Salt Reactor* (TMSR-500) is one of the generation IV reactors which has various advantages over the type of reactor in the previous generation because it can produce high resources, long-lasting, but lower costs. This reactor operates at high temperatures, but low pressure approaches atmospheric pressure [1-2].

The power produced by the TMSR-500 is 1000 MWe which is divided into 4 modules (in the form of pots) with 250Mwe each. The pot module is one of the 3 core components of the TMSR-500, the other two are the primary heat exchanger and the primary strand pump. Each module in it has a reactor that can be replaced in a closed silo can. Can contain a moderator made from graphite and salt fuel with a mixture of NaF, BeF2, ThF4, UF4 [3]. In this study the percentage of moles used for each fuel component was 76% / 12% / 9.8% / 2.2% with 19.75% enrichment of U^{235} [4]. In the liquid salt fuel, there is graphite that plays a very important role as moderators for thorium-based nuclear reactors.

One aspect of safety for nuclear reactors is void reactivity. Voids in liquid salt reactors occur due to reactor operations whose temperature is close to saturation temperature, causing bubbles to form on the reactor core. The saturation temperature is the temperature at which the vapor pressure of a liquid is equal to the pressure of the environment surrounding the liquid [5]. Voids in MSR can also occur due to the formation of fission products in the gas phase. The formation of voids also causes a reduction in fuel density. The higher the fuel temperature, the higher the voids in the core. The presence of voids will affect the performance of the reactor, this condition can be seen from the estimated value of the criticality. The reactor's criticality is expressed in terms of the magnitude of $k_{eff.}$

This study aims to obtain the void reactivity coefficient value of the TMSR-500 as one of the aspects of reactor safety. The method used is a variation of the void fraction assumed with a variation of the reduction in fuel density by 0%, 10%, 20%, 30%, and 40%. The calculations are carried out using the MCNP6 program which works with the Monte Carlo method.

The value of the void reactivity coefficient can be positive or negative depending on the nuclear system overmoderated or undermoderated. If undermoderated, the results of the void reactivity coefficient are positive, and vice versa [6].

METHODOLOGY

In this study, the core design of the TMSR-500 is based on a model from Devanney [4] using Vised software and version 6 of the MCNP (Monte Carlo N-Particle) program for the running process of k_{eff} calculation. The TMSR-500 core consists of pots, shields, reflectors, moderators, fuels, and control rods which can be seen in **FIGURE 1**.

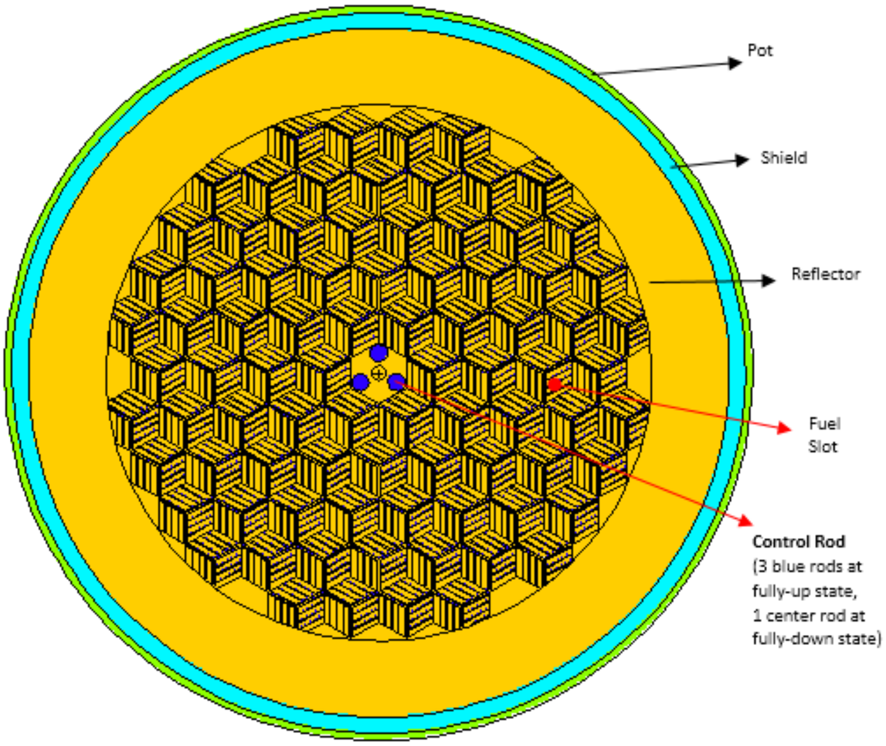

FIGURE 1. Core of TMSR-500

The core design of the TMSR-500 has 2 types of control rods, shutdown rods (which is blue) using gadolinium and regulating rods (the center one) using graphite. When the TMSR-500 operates the shutdown rod is in a fully-up state, while the regulating rod is in a fully-down state. The outermost layer pot or reactor core vessel uses SUS316H (316H Stainless steel) material, the next layer is a shield made from B_4C. The material used for moderators is graphite, as well as reflector materials. Liquid salt that functions as the main fuel as well as the coolant uses a mixture of NaF, BeF_2, ThF_4, and UF_4 [4].

The geometry that has been compiled on running using a PC with 200,000 neutron histories were tracked takes ± 20 hours for each run. The criticality of the TMSR-500 designed in this research was calculated by the MCNP6 program. The multiplication factor of neutrons or keff from the output produced shows the criticality of the reactor design that has been made. For the TMSR-500, the reactor design is declared in critical condition if the value is $1.00 < k_{eff} < 1.02$ [7].

In addition to calculating the keff value to determine the criticality of the design, validation of the geometry is also needed by analyzing the neutron energy spectrum on the TMSR-500. The neutron energy spectrum can be determined by calculating the value of the neutron flux in the fuel and moderator. To calculate the flux in cells from geometry, MCNP6 requires a tally flux card (F4) and an En tally card to obtain flux values in the specified energy range [8]. The range of neutron energy used is thermal neutron energy, epithermal neutron, and fast neutrons.

Bubbles or voids can occur due to the formation of fission products in gases which causes the reduced density of the fuel [5]. Therefore, this study uses variations in the void fraction with assumed variations in the reduction in fuel density. The variation in the reduction in fuel density used is 0%, 10%, 20%, 30%, and 40% with a void of 0% is the value of the fuel density during normal conditions.

The reactivity value is obtained from the value of k_{eff} with Equation 1.

$$\rho = \frac{\Delta k_{eff}}{k_{eff}} = \frac{k_{eff-1}}{k_{eff}} \qquad (1)$$

where k_{eff} is a neutron multiplication factor, the output of the MCNP6 program.

Then for k_{eff} of each void variation, the reactivity value was calculated. From the results of the void reactivity can be obtained the coefficient of void reactivity using Equation 2.

$$\alpha = \frac{\partial \rho}{\partial \phi} \quad (2)$$

where :
α = void reactivity coefficient
ρ = reactivity
ϕ = void fraction

RESULT AND ANALYSIS

Based on the results of running using MCNP6 at 977K, the value of k_{eff} was obtained $1.00 < k_{eff} < 1.02$. The k_{eff} value at 977K was obtained through the interpolation of the k_{eff} at 900K and 1200K, valued at 1.01804 ± 0.00008. **TABLE 1** displays the k_{eff} values from the simulations carried out at 900K and 1200K, and the k_{eff} obtained at the reactor operating temperature is 977 K.

TABLE 1. Values of k_{eff} at 977K from interpolation between 900K and 1200K

Temperature (K)	k_{eff}
900	1.02039±0.00008
977 (Interpolate)	1.01804±0.00008
1200	1.01124±0.00009

The results in **TABLE 1.** show that the simulation design of the TMSR-500 when operating at 977K was in a critical state.

Next is the evaluation of the energy spectrum as validation for the design geometry of the TMSR-500 that has been made. The neutron flux calculation can be done by the MCNP program by adding an F4 tally card (flux in cells). Cells whose neutron flux values are calculated are fuel cells and moderators, results can be seen in **TABLE 2** where neutron energy is only divided into thermal energy and fast energy.

TABLE 2. Neutron flux values of thermal and fast energy in fuel cells and moderators

Position	**Neutron Flux ($n.cm^{-2}/s$)**	
	Thermal Energy (10^{13})	Fast Energy (10^{12})
Fuel	2.0469 ± 0.0002	8.5209 ± 0.0002
Moderator (at fuel log)	2.5648 ± 0.0002	8.4983 ± 0.0002
Moderator (at rod log)	3.3651 ± 0.0014	8.9343 ± 0.0019

TABLE 3. k_{eff} values and reactivity change for each void fraction variation

Void (%)	k_{eff}	**Reactivity Change (%Δk/k)**
0	1.01804±0.00008	0
10	1.02641±0.00008	0.00801
20	1.03436±0.00007	0.01549
30	1.04140±0.00007	0.02203
40	1.04700±0.00007	0.02717

Based on **TABLE 2.** it can be seen that the value of thermal energy flux is greater than the value of fast energy flux, applicable to all three positions. This proves that the TMSR-500 is a thermal reactor, which means the reactor operates on thermal neutron energy. The moderator made from graphite has the role of slowing down the speed of neutron energy rapidly into thermal is also one of the factors why the TMSR-500 reactor is a thermal reactor [9]. A comparison of neutron flux values from the three positions is more clearly seen in **FIGURE 2**.

On the thermal reactor core, the maximum thermal neutron flux value is in the moderator and the maximum fast neutron flux value is in the fuel. As the edge of the neutron flux value decreases, it gets smaller, so that the highest thermal flux value is in the moderator cell (at rod log), where the log is in the center of the reactor core. The highest fast neutron flux value is in the fuel [10]. From the data in **TABLE 2**, it has been proven that it is in accordance with the literature.

Based on **FIGURE 3**, the void reactivity coefficient obtained from the data in **TABLE 3** using Equation (2) is positive (0.068 ± 0.003) %Δk/k/%void. The value of k_{eff} from each void fraction shows that when the void fraction increases, the reactivity value also increases. However, the TMSR-500 is an under-moderated reactor so the void reactivity is positive [6]. In previous studies [11] the MSR Fuji-12 reactor also had a positive void reactivity value.

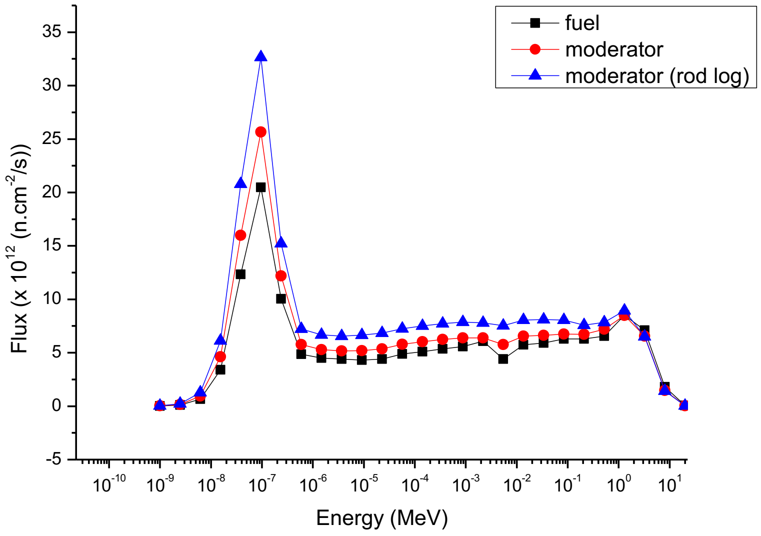

FIGURE 2. Graph of neutron energy spectrum in the fuel and moderator of the TMSR-500

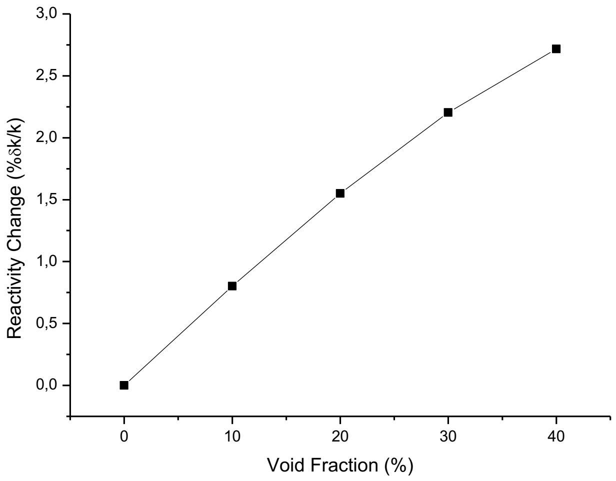

FIGURE 3. Graph of void fraction versus reactivity change

CONCLUSION

From the results of this research, it can be concluded that the design of the TMSR-500 operating at 977K is in a critical condition with a keff value of (1.01804 ± 0.00008). With a graphite based moderator whose role is to slow the rate of neutron energy rapidly into thermal, the neutron energy spectrum of the TMSR-500 is a thermal neutron spectrum. The coefficient of void reactivity obtained is positive value of (0.068 ± 0.003) %Δk/k /%void. Positive void reactivity is assumed to be caused by the condition of the TMSR-500 reactor which is under-moderated, then TMSR-500 declared safe. These results can be considered for further research analyzing other aspects of reactor safety, such as the coefficient of temperature reactivity and engineered safety (defense in depth).

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