Safety analysis TMSR-500 in terms of the temperature reactivity coefficient of the fuel and the moderator using the MCNP6 software

F R L Manik\(^1\), Suharyana\(^1\), F Anwar\(^1\), Riyatun\(^1\), and A 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), Jakarta Pusat, Indonesia

E-mail: suharyana61@staff.uns.ac.id

Abstract. TMSR-500 is a type of fourth-generation reactor that is technologically advanced with a full actinide recycling system and produces low fuel waste. This research focuses on calculating and analyzing the temperature reactivity coefficient of fuel and moderator in the TMSR-500 core designed by Martingale, Inc. All calculations performed using the MCNP6 software and the ENDF/B-VII.1 continuous energy nuclear data library. The fuel material for TMSR-500 is liquid salt NaF-BeF\(_2\)-ThF\(_4\)-UF\(_4\) with enrichment of U-235 of 19.75%, and the moderator material is graphite. The variation of temperature increase in fuel and moderator starts from 293.6 K to 2500 K. As the reactor temperature increases, the value of fuel reactivity decreased, the fuel temperature reactivity coefficient is negative (-2.4879 ± 0.42) pcm/K. At the stage of calculating the moderator temperature reactivity coefficient, the calculation results show a positive value (0.0019 ± 0.0016) pcm/K as the moderator temperature increases. Based on the study of the temperature reactivity coefficient of the fuel and the moderator, then the reactor is in a safe state in terms of the overall calculation results, which indicate the total temperature reactivity coefficient is negative (-2.4883 ± 0.42) pcm/K.

1. Introduction

The development of the use of fossil fuels as electricity generators has a negative potential for the environment. The result of burning fossil fuels results in increased air pollution and the greenhouse effect, which has an impact on climate change. That is different from the use of nuclear energy for electricity generation, which does not produce a greenhouse effect and pollute the air [1, 2]. The nuclear reactor used for PLTN is called a power reactor [3].

The energy in PLTN generally comes from the fission of uranium is U-235 as the primary fuel in a nuclear reactor. However, the amount of U-235, which is easily fissioned by thermal neutrons in nature, is limited to only 0.7% of natural uranium. The largest concentration is U-238 at 99.3%, which can only fission with fast neutrons. According to the estimate by calculation, as much as 1 kg of U-235 will produce thermal energy of 25.5-gigawatt-hours, that is equivalent to the thermal energy from burning 3 million kg of coal [4, 5]. Based on this calculation, the PLTN has the potential as a new energy source.

Oak Ridge National Laboratory has been developing a nuclear reactor since 1950 called the Molten Salt Reactor (MSR). The reason MSR has survived until now is that it has the advantage of a
closed fuel system, which means that its spent fuel can be recycled [6]. MSR is a type of IV generation reactor that is technologically advanced with a full actinide recycling system and produces low fuel waste. The fuel is in the form of liquid salt based on UF₄ and ThF₄, so it also functions as a coolant, while the moderator is from solid graphite. The reactor operates at high temperature with pressures approaching atmospheric pressure [7, 8]. MSR has a variety of design concepts, one of which is the TMSR-500 issued by Martingale, Inc., which has a modular MSR design that operates continuously for four years. The main components of this reactor are the moderator, Can, and shield, which must replace every four years. The design of the TMSR-500 consists of several modules where one module produces 250 MWe of electricity [9, 10].

The aspects of nuclear safety available in the installation system serve to achieve reactor safety standards are inherent safety, passive safety, and fail-safe. The inherent safety feature is to save itself if something goes wrong with the reactor, it happens, when the temperature increases, then the reactor can reduce the power. In inherent conditions, the value of the reactivity feedback system must be negative. Passive safety functions to cool the reactor core. The fail-safe mode is useful in case of a failure in the reactor system or components. The existence of a protection system in the reactor is a facility that can make a scrammed reactor [11, 12].

One way to determine the reactor safety standard is by calculating the temperature reactivity coefficient using MCNP software. Monte Carlo is a method used in MCNP as a form of solving particle transport problems statistically, namely by tracing the traces of particles that appear first until they disappear. MCNP is a code on a computer that can simulate the probability of a neutron, photon, and electron [13]. This study focuses on the calculation and analysis of the temperature reactivity coefficient on fuel and the moderator in the TMSR-500 core to determine the effect of temperature variations on the temperature reactivity coefficient, which is associated with inherent safety aspects.

2. Experimental
2.1 Materials and methods
The reactor core design refers to Martingale, Inc., which consists of a pot, shield, reflector, and core, which contains 85 hexagonal logs and control rods. The type of melted fuel NaF-BeF₂-ThF₄-UF₄ with enrichment of U-235 is 19.75%. Na material in fuel to avoid tritium (T) abundant such as MSRE [14]. The shielding material in the form of B₄C, Reflector, and Moderator Material is solid graphite. The control rod is divided into a regulating rod using graphite material and a shutdown rod using gadolinium material.

The core geometry of the TMSR-500 can see in Figure 1. Dark blue is the pot, light blue is the protector, green is the reflector and moderator, and yellow is the fuel. This calculation uses MCNP6 software and makes use of the ENDF / B-VII. I continuous nuclear data library. The variation from room temperature is 293.6 K to 2500 K.

![Figure 1. TMSR-500 core geometry model.](image-url)
Reactivity is a quantity that states the change in the multiplication factor of the reactor core. Reactivity can occur due to physical effects, such as temperature increases in fuel and moderators [15]. Increasing temperature causes the $k_{\text{eff}}$ value and density to decrease. The decrease in the $k_{\text{eff}}$ value means that the fission chain reaction in the core produces a decreasing number of neutrons [16,17]. Decreasing density is the result of the material expanding at a constant mass. In this condition, the atoms vibrate rapidly and make the distance between the atoms increase.

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}}$$

The fuel temperature coefficient or Doppler effect is the change in reactivity ($\rho$) per unit change in fuel temperature [18]. The widening of the neutron resonance region in the neutron energy cross-section simultaneously increases the temperature of the fuel. Determine the resonance region with a very important effect on the absorption of the neutron resonance [19].

The moderator temperature reactivity coefficient is the change in reactivity per change in temperature in the moderator element. The moderator temperature reactivity coefficient is a function of ($N_m / N_f$), meaning the ratio of the moderator atomic density to the density of the fuel. The optimal $N_m / N_f$ value in the reactor core reduces the $k_{\text{eff}}$, and the value of the moderator temperature reactivity coefficient is negative. Moderator temperature changes without density changes will increase the probability of escape resonance and reproductive factors ($\eta$) [20]. The temperature change in the reactor causes a change in the $k_{\text{eff}}$ value, meaning that the reactivity value will also affect. This effect can affect the safety of the reactor operation so that the magnitude of the change in reactivity value due to temperature changes is as follows [21].

$$\alpha_T = \frac{\Delta \rho}{\Delta T}$$

### 3. Results and discussions

TMSR-500 operates at a temperature of 977 K. Perform calculations on the geometry of the TMSR-500 to get the $k_{\text{eff}}$ value. The $k_{\text{eff}}$ value at operating temperature determines whether this reactor is in a critical condition or not. The result of the TMSR-500 $k_{\text{eff}}$ value is $1.01794 \pm 0.00008$.

#### 3.1. Fuel Temperature Reactivity

Variations in fuel temperature ranging from room temperature 293.6 K to 2500 K, while another material temperature is kept constant at a temperature of 293.6 K. Any variation obtained $k_{\text{eff}}$ value, which will be useful to calculate the change in reactivity, as in Table 1.
Table 1. $k_{\text{eff}}$ value and reactivity changes for variations in fuel temperature.

| Temperature (K) | $k_{\text{eff}}$ (pcm) $10^5$ | $\Delta\rho$ (pcm) $10^5$ |
|----------------|-------------------------------|---------------------------|
| 293.6          | $1.05205 \pm 0.00008$         | $0 \pm 0$                |
| 600            | $1.03312 \pm 0.00008$         | $-0.01742 \pm 0.0016$    |
| 900            | $1.02120 \pm 0.00008$         | $-0.02871 \pm 0.0016$    |
| 1200           | $1.01275 \pm 0.00008$         | $-0.03689 \pm 0.00017$   |
| 2500           | $0.9948 \pm 0.00008$          | $-0.05909 \pm 0.00016$   |

The results of the fuel temperature reactivity coefficient at TMSR-500 are (-2.4879 0.42) pcm/K. This value is the result of the linear regression gradient equation in Figure 3.

Figure 3. Reactivity changes with temperature in the fuel.

3.2. Reaktivitas Temperatur Moderator
Reactivity changes also occur in the moderator, which is the effect of increasing temperature. The results of changes in reactivity can see Table 2.

Table 2. $k_{\text{eff}}$ value and reactivity change for the moderator temperature variation.

| Temperature (K) | $k_{\text{eff}}$ (pcm) $10^5$ | $\Delta\rho$ (pcm) $10^5$ |
|----------------|-------------------------------|---------------------------|
| 293.6          | $1.05197 \pm 0.00003$         | $0 \pm 0$                |
| 600            | $1.05195 \pm 0.00003$         | $-0.00002 \pm 0.00006$   |
| 900            | $1.05191 \pm 0.00003$         | $-0.00005 \pm 0.00006$   |
| 1200           | $1.05196 \pm 0.00004$         | $-0.00001 \pm 0.00007$   |
| 2500           | $1.05200 \pm 0.00004$         | $0.00003 \pm 0.00007$    |

The results of the moderator temperature reactivity coefficient are positive, namely (0.0019 0.0016) pcm/K. These results are the results of the gradient graph using linear regression.
Increasing temperature in the moderator causes a spike in the increase and decrease in the $k_{\text{eff}}$ value, which affects the reactivity value, as shown in Figure 4.

![Figure 4. Reactivity changes with temperature in the moderator.](image)

4. Discussion
TMSR-500 operates at a temperature of 977 K. The cross-sections of the available nuclear data are 900 K and 1200 K, so to obtain the $k_{\text{eff}}$ value at 977 K, one has to perform calculations using linear interpolation equations. The TMSR-500 condition is still in a critical condition, the critical value requirement if the $k_{\text{eff}}$ value is equal to 1 with a criticality tolerance limit of $\pm 0.02$ [22].

TMSR-500 is said to be safe if it meets safety aspects. One way to determine if a reactor meets safety aspects is to calculate the temperature reactivity coefficient. This calculation is carried out on the fuel and moderator areas only with temperature variations referring to the availability of ENDF/B-VII. I continuous energy nuclear data.

4.1. Fuel Temperature Reactivity
The results of the fuel reactivity coefficient have a negative value. This value is the result of the Doppler effect phenomenon. Doppler broadening causes the cross-sectional view of the absorption of the fuel to increase, but not along with the number of neutrons that escape in the resonant region at a certain energy level. Increasing the temperature causes the number of neutrons that escape in the resonant region to decrease so that the thermal neutrons absorbed in the fuel become less. The temperature coefficient value determines the safety factor in the reactor so that a negative temperature reactivity coefficient will fulfill the safe design of the reactor.

4.2. Moderator Temperature Reactivity
The temperature of 293.6 K to 900 K, the reactivity changes decreases, then at a temperature of 1200 K, the reactivity changes to an increase. The increase in temperature makes the reactivity in the moderator less stable, but not very significant because it is still in the $k_{\text{eff}}$ 1.05000 range. The moderator temperature reactivity coefficient is positive. This result is the effect of using graphite material. The main effect of heating graphite is to increase thermal neutron energy. In the thermal neutron energy region, the cross-section of Th-232 slows down faster, and the neutron energy of U-233 increases. The effect of the hot graphite material affects the hardening of the spectrum and causes
Th-232 to change to U-233 [23]. The reactor is in a safe condition and has reviewed the overall calculation results, which shows a negative total temperature reactivity \((-2.4883 \pm 0.42)\) pcm/K.

5. Conclusion

The values of the fuel and moderator temperature reactivity coefficients are \((-2.4879 \pm 0.42)\) pcm/K, and \((0.0019 \pm 0.0016)\) pcm/K. The overall calculation results show that the total temperature reactivity coefficient is negative \((-2.4883 \pm 0.42)\) pcm/K. TMSR- 500 is in a safe condition and meets inherent safety aspects.

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