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Assessment of TMSR-500 Shutdown Capability

A. Khakim[1*]**, F. R. Firmanda**[1]**, Y. Pramono**[1]**, Suharyana**[2]

[1]*Nuclear Energy Regulatory Agency (BAPETEN), Jl. Gajah Mada No. 8 Jakarta 10120, Indonesia*
[2]*Physics Department, Faculty of Mathematics and Natural Sciences, Sebelas Maret University, Jl. Ir. Sutami 36A Kentingan Jebres Surakarta 57126, Indonesia*

A R T I C L E   I N F O

A B S T R A C T

The molten salt reactor (MSR) is a generation IV reactor with liquid fuel having nearly zero excess reactivity. Due to the very low excess reactivity, it requires a small number of control rods worth to shut down the reactor. However, as it operates at high temperatures, the core reactivity increases as the fuel temperature cools down during shutdown. In such a case, the control rods might not be able to keep the reactor at a subcritical state, and consequently, the fuel must be removed from the core for long-term shutdown into a fuel drain tank (FDT) below the core. This paper is intended to assess the shutdown capability of the first active shutdown system and fuel drain tank of ThorCon MSR by doing neutronic calculations with MCNP6. The results indicated that the control rods having reactivity worth -1.699 %dk/k are unable to maintain the core at a subcritical state as the core excess reactivity increases to +7.760 %dk/k when the fuel reaches room temperature. Therefore, the fuel must be drained to FDT to be cooled down and kept subcritical. Evaluation for various cases of FDT produced the highest multiplication factor of 0.57008 ± 0.00004 at the most conservative condition. The multiplication factor is well below the critical state of 1.0. The evaluations suggest that soon after the control rods shut the reactor down, the fuel has to be drained to FDT to maintain shutdown condition and dissipate the decay heat.

INTRODUCTION

The molten salt reactor (MSR) has been classified as a generation IV (Gen-IV) nuclear reactor concept due to its favorable features compared to the conventional light water reactor (LWR). Gen-IV nuclear reactors feature four characteristics, namely sustainability, economic competitiveness, high level of safety and reliability, and proliferation resistance and physical protection. The safety and reliability features imply that Gen-IV reactor designs will excel in safety and reliability, and will have a very low probability and degree of reactor damage. Those features have recently attracted renewed interest among nuclear researchers and industries. Several start-up companies on MSR design have emerged over the period of 2011-2015, such as Moltex Energy (UK), Terrestrial Energy (Canada), Transatomic Power (USA), FLiBe Energy (USA), ThorCon (USA), and Elysium Industries (USA) [1].

MSRs operate at high temperatures with low or nearly atmospheric pressure that eventually eliminates a significant number of expensive components. MSRs offer many of the ideal goals of nuclear energy, such as improved sustainability, inherent safety with a strong negative temperature coefficient of reactivity, stable coolant, low-pressure operation which eliminates expensive containment, ease of control, passive decay heat cooling, and the unique characteristics of actinide burning and waste reduction [2]. As the fuel circulates, some delayed neutrons are generated outside at the less important region of the core [3], leading to a reactivity loss. The faster the fuel flows, the greater the reactivity loss becomes. In addition, reactivity loss depends on the fuel recirculation time within the primary circuit. The longer the recirculation time is, the more the core loses its reactivity [4].

An important advantage of liquid fuel is that the volatile fission products, Xe and Kr gases, are continuously removed from the core, minimizing their leakage in case of an accident, and saving neutrons from being absorbed by Xe. Removing neutron poison means minimizing the necessary amount of fissile material to achieve the desired excess core reactivity.

To compensate for fissile material depletion, new fuel can be injected into the core at any time or continuously at power operation. As such, the excess reactivity can be maintained sufficiently small, and it consequently requires much smaller control rods in terms of reactivity worth and necessary space than those of LWR. The core can be more compact with a higher power density as more spaces are occupied by the fuel.

Unlike conventional solid-fueled reactors, the MSR operates with circulating molten fluid serving as both fuel and primary coolant. The primary fluid works under a low and close-to-atmospheric pressure. During normal operation, the core has a very low, close to zero excess reactivity, reducing the scale of reactivity insertion accidents. The primary circuit is equipped with an off-gas system to separate gaseous, strongly neutron-absorbing fission products from the core.

The ThorCon Molten Salt Reactor of 500 MW (TMSR-500) is a thermal MSR projected to be deployed in Indonesia [5]. The reactor has a central log, a house of three absorber rods and one regulating rod, serving as the first shutdown system. The second shutdown system is a fuel drain tank (FDT), right below the reactor core connected by a fuse valve. If by chance the fuel heats up, the fuse will open up the valve and drain the fuel to the tank. The fuel is cooled down and kept subcritical in the tank. Therefore, the capability of these two systems to bring the fuel into a subcritical state needs to be assessed, both in hot and cold conditions. The assessment is to ensure that the reactor can be shut down at any condition including at the most reactive core condition.

This paper is intended to assess the shutdown capability of TMSR-500 based on open literature. Assessment is done by performing neutronic calculations with MCNP6 code on parallel processors of HPC (High-Performance Computing)-BAPETEN. The study also evaluates the second shutdown system of the fuel drain tank to ensure the fuel goes to a subcritical state at any condition.

The calculations on ThorCon MSR have been carried out by T. Fei et al. It is intended to confirm a newly developed PROTEUS code application on MSR [6].

CALCULATION TOOLS

The eigenvalue calculations were performed with MCNP6 Monte Carlo code with nuclear data ENDF/B-VII.1. The code is installed for parallel computation on BAPETEN's high-performance computing (HPC).

MCNP6 working on a continuous neutron energy spectrum is used to calculate static neutronic parameters. The code is a three-dimensional simulation software package capable of simulating neutron, photon, and electron particles for calculating criticality, shielding, dosimetry, detector response, and many other applications. The latest version of the ENDF/B-VII.1 nuclear data set consists of 423 nuclides processed to seven temperatures suitable for reactor calculations. Neutron interaction data is available up to 20 MeV. Recent thermal neutron scattering data, $S(\alpha,\beta)$, are available for 21 materials [7], including graphite material which is very important for thermal MSR. The code is also capable of performing depletion calculations.

In this study, most of the calculations were carried out by simulating 300 cycles in which the first 35 cycles were skipped. Each cycle simulated one million particles. They produced results with standard deviations in the order of 10^{-5}. Since calculations with the Monte Carlo method take a long time, to speed up the process, the code was installed and run on the High-Performance Computing (HPC). The machine ran on 172 cores on a free Linux platform of CentOS. Since calculations were carried out during the COVID-19 pandemic and most people worked from home, data exchange was performed through PSFTP protocol by remote access, which allowed the users to perform calculations anywhere with an internet connection.

METHODOLOGY

The ThorCon MSR core refers to version 1.09 year 2015 [8]. The core parameters are described in Table 1. ThorCon MSR is a molten salt thermal reactor producing 250 MWe of electric power or 557 MWt, which is a scaled-up design of

the Molten Salt Reactor Experiment (MSRE). The ThorCon MSR core consists of 84 fuel logs and one central control log made of graphite serving as a moderator. Graphite material also forms radial and axial reflectors. Graphite contributes 90 % of the core material. The fuel salt flows into the reactor at a temperature of 564 ℃ and leaves the core at a temperature of 704 ℃. The fuel salt, so-called NaBe, is composed of $NaF-BeF_2-ThF_4-UF_4$ with a mole ratio of 76/12/9.5/2.5 enriched to 19.75 % in U-235 [8]. The fuel has a density of 3.11 g/cm^3 [9]. Table 2 details the isotopic composition of fresh fuel. As U-235 fissile material is consumed, U-233 and Pu-239 fissile materials will be produced, but they are not sufficient to replace the burning fuel. Since the reactor has nearly zero excess reactivity, refueling is done continuously. As the inlet and outlet fuel temperatures are 564 ℃ and 704 ℃ respectively, the calculations employed ENDF/B-VII at average temperature of 627 ℃ (900 K), which is by chance available from the original MCNP6 package. The calculations were done at stationary condition (no drift effects) which will produce higher multiplication factor leading to a more conservative approach.

Table 1. Core parameters of TMSR-500.

Core parameters	Descriptions
Number of fuel log	84
Inlet/outlet temperature	564/704 °C
Fuel salt composition	$NaF-BeF_2-ThF_4-UF_4$
Mole fraction	76/12/9.5/2.5
U-235 enrichment	19.5 %
Active core height	3780 mm
Moderator	Graphite
Reflector	Graphite
Radial shielding	B_4C
Pot material	Stainless steel

Table 2. The isotopic fresh fuel composition.

Isotope	Atomic Fraction
U-235	2.0114E-03
U-238	8.0695E-03
Th-232	3.8306E-02
Be-9	4.8387E-02
F-19	5.9677E-01
Na-23	3.0645E-01

Figure 1 shows the TMSR-500 core configuration [8] and its MCNP6 geometrical model consisting of 84 hexagonal fuel logs, a central control log, graphite reflector, and neutron shielding of B_4C powder [8]. A detail of the hexagonal fuel log [8] and its geometrical model is shown in Fig. 2. A moderately high power density core of 16 MW/m^3 produces high neutron fluence in the graphite moderator. Therefore, the whole core will be replaced every four years. The shield segment containing boron powder reduces the neutron flux at the outer wall by about a factor of 100 [8].
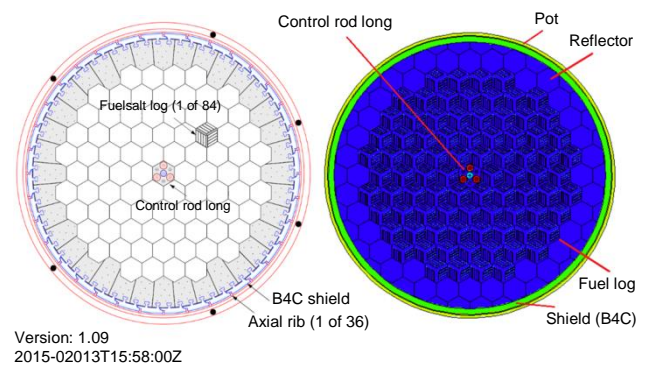
Fig. 1. TMSR-500 core configuration and MCNP6 geometrical model.
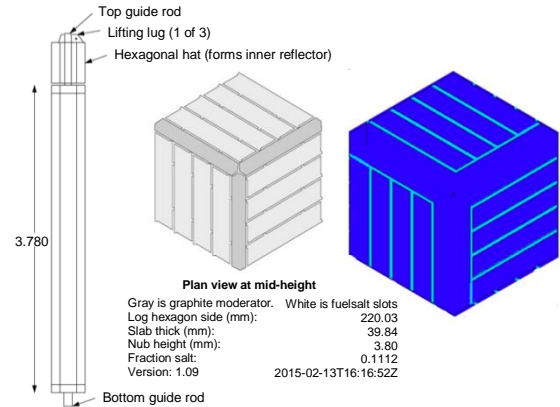
**Fig. 2.** Hexagonal fuel log and its MCNP6 geometrical model.

The central log consists of three absorber rods of Gd_2O_3 and one graphite regulating rod. Several gadolinium isotopes are strong neutron absorbers, and when inserted into the core, the control rods reduce core reactivity. The graphite regulating rod slows down the neutron energy from fast into the thermal region. Therefore, its presence in the core increases the reactivity.

The central log serves as the first shutdown system in hot condition. If by chance the fuel heats up, a fuse valve under the core will open to drain the fuel into a fuel drain tank (FDT). The fuel will be cooled down in the tank located directly below the can.

Figure 3 exhibits a fuel drain tank located under the reactor can and is filled with cast iron serving as a heat sink [8]. The axial and radial section of its MCNP6 geometrical model is shown in Fig. 4. Salt fuel is shown in yellow, while white indicates voids or air. The blue color is cooling water that takes radiant heat from molten salt fuel. Concrete silos are indicated by the green color, while the red color represents the heat storage made of cast iron.
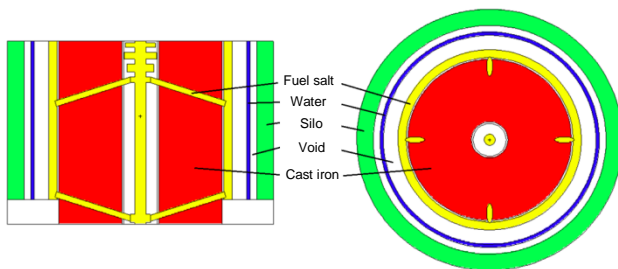

(a)
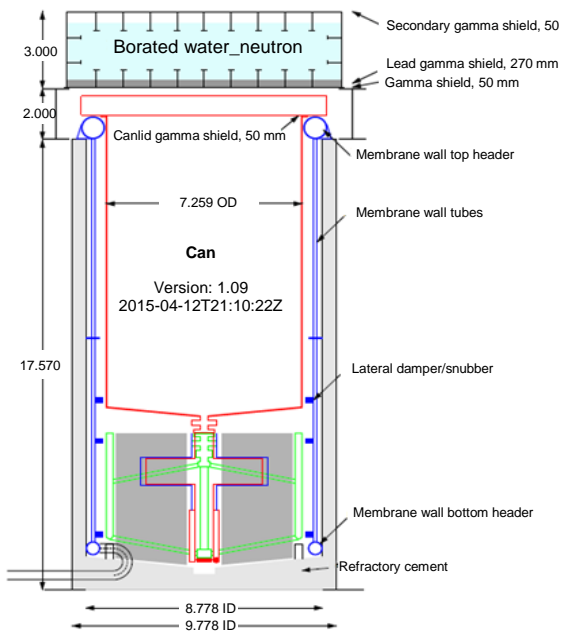
(b)

Fig. 3. Fuel drain tank layout and dimension.


(a)   (b)

Fig. 4. MCNP geometrical model of the fuel drain tank.

RESULTS AND DISCUSSION

MCNP code has been widely used by researchers, the academia, and nuclear regulators for calculating static neutronic parameters. The code has been benchmarked for the first criticality of Indonesian MTR-type research reactor RSG-GAS resulting in a very good agreement [10].

The calculations of the shutdown capability of the TMSR-500 control rods have been carried out using the MCNP6 code on High-Performance Computing (HPC)-BAPETEN. The control log of TMSR-500 is located in the central log which consists of three absorber rods and one regulating rod. The three absorber rods are made of gadolinia (Gd_2O_3), while the regulating rod is made of graphite. During normal operation, the three absorbers are fully up, while the regulating rod is fully inserted into the core. The insertion of the absorbers into the core will provide negative reactivity, while the insertion of the regulating rod will provide positive reactivity. The reactor scram is effected by releasing the grip of the four control rods so that the three absorbers with a higher density (7.07 g/cc) than the fuel salt (3.11 g/cc) will fall into the core, while the graphite regulating rod having a lower density (1.86 g/cc [11]) will float to the top. Therefore, during shutdown conditions, the three absorbers will be inserted into the core and the regulating rod is fully withdrawn from the core.

Figure 5 indicates the position of the four control rods under normal operation where the three absorber rods are in the fully up position, while the regulating rod is fully inserted. The absorber rods are indicated by a red color, while the regulating rod in the middle is dark blue. Light blue is the fuel salt.
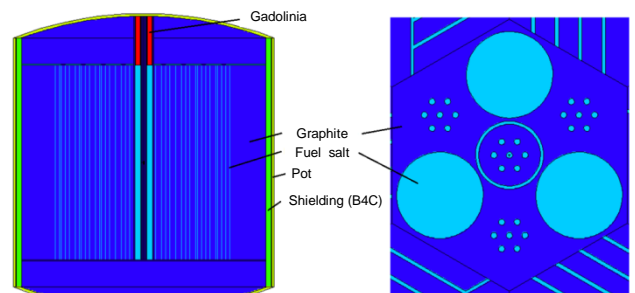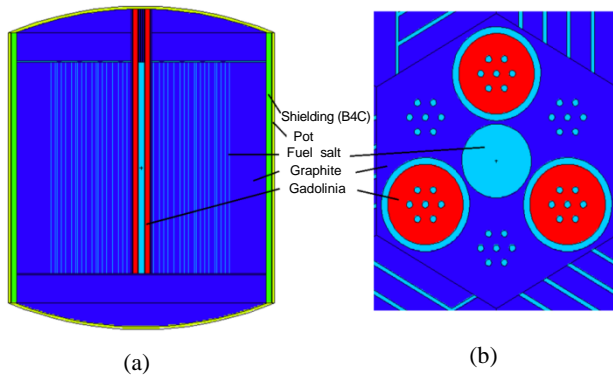

(a)   (b)

Fig. 5. Control rotableds position during normal operation.

Figure 6 shows the position of the four control rods at shutdown conditions where the three absorbers are fully inserted while the regulating rod is fully up.

(a)   (b)

Fig. 6. Control rods position during shutdown.

The calculation results of the TMSR-500 control rods capability are presented in Table 3. From the table, it can be seen that the TMSR-500 reactor has an excess reactivity of 1.33 %dk/k ($k_{eff} = 1.01346 \pm 0.00004$) at operating conditions (temperature 900 K). This worth is comparable to

the benchmark calculation carried out by Shen *et al.* [12] using the SERPENT code for the MSRE reactor under stationary and isothermal conditions, which is $k_{eff} = 1.01276$ ($\pm$ 10 pcm). The total experimental uncertainty with regards to k_{eff} is 478 pcm. The reactivity losses due to salt flow calculated by Shen *et al.* and MSRE researchers were -224 $\pm$ 7 pcm and -212 pcm, respectively. TMSR-500 is designed to have nearly zero excess reactivity during normal operation. Thus, to get more reactivity that is close to zero during operation, it requires a core excess reactivity of around 1.2-1.3 %dk/k at stationary conditions. The excess reactivity worth is to compensate for the reactivity loss of delayed neutrons due to circulating fuel, entrained gas, power coefficient (the increase of graphite temperature), Xe poisoning, Sm transient, burnup, the margin for the operation of control rods, and calculation uncertainties. In comparison, MSRE required 1.9 %dk/k of excess reactivity to compensate for those losses [11].

Table 3. Calculation results of TMSR-500 control rod worth.

No.	Condition	k_{eff}	Std Deviation	ρ (%dk/k)	Remarks
1.	Hot[*], all absorbers up, Reg. Rod down	1.01346	0.00004	1.328	Core excess reactivity at the hot and stationary condition
2.	Absorber No.1 down, two other absorbers up, Reg. Rod down	1.00426	0.00004	0.904	Reactivity worth of absorber No. 1
3.	Absorber No.2 down, two other absorbers up, Reg. Rod down	1.00418	0.00004	0.912	Reactivity worth of absorber No. 2
4.	Absorber No.3 down, two other absorbers up, Reg. Rod down	1.00419	0.00004	0.911	Reactivity worth of absorber No. 3
5.	Hot shutdown (3 absorbers down, Reg. Rod up)	0.99630	0.00004	-0.371	Reactor subcritical state at margin of 0.371 %dk/k (<0.5 %dk/k)
				1.699	Total control rods reactivity worth
6.	Cold[**], shutdown (3 absorbers down, Reg. Rod up)	1.06465	0.00004	6.072	Super-critical state: all control rods unable to keep the reactor subcritical at cold condition
7.	Reg. Rod stuck at hot condition	0.99625	0.00004	-0.376	Reactor subcritical with margin of 0.376 %dk/k (<0.5 %dk/k)
8.	Absorber No.1 stuck at hot condition	0.99925	0.00004	-0.075	Reactor subcritical with margin of 0.075 %dk/k (<0.5 %dk/k)
9.	Hot, all absorbers and Reg. rod up	1.01250	0.00004	0.094	Reactivity worth of regulating rod
10.	Reg. Rod stuck at cold condition	1.08084	0.00004	7.479	Reg. rod stuck, the reactor at super-critical state: all three absorbers unable to shut down the reactor at cold state
11.	Absorber No.1 stuck at cold condition	1.06772	0.00004	6.342	One absorber stuck, the reactor at a super-critical state. Two absorbers and one Reg. rod unable to shut down at cold state
12.	Shutdown at fuel temp. 600 K	1.02484	0.00004	2.424	The reactor attains a critical state when temperature down from 900 K to 600 K

[*]Operating temperature = 900 K;
[**]Room temperature = 293.6 K

The average worth of the three Gd_2O_3 absorbers is 0.909 %dk/k. Meanwhile, the reactivity worth of the graphite regulating rod is 0.094 %dk/k. The reactor can be brought to subcritical state by inserting all three absorbers and withdrawing the regulating rod, and the reactor has a shutdown margin of 0.371 %dk/k. However, the margin is still lower than 0.5 %dk/k, which is the minimum worth usually required for research reactors.

If the regulating rod is stuck while trying to shut down, the reactor can still be subcritical with a margin of 0.376 %dk/k. Meanwhile, if one of the absorber rods is stuck, the reactor can also be brought to a subcritical state with a lower margin, 0.075 %dk/k. In both cases, the shutdown margin of the one-struck rod is still lower than 0.5 %dk/k.

The four control rods have a total negative reactivity worth of -1.699 %dk/k. However, the reactivity worth is not able to shut down the reactor if the fuel stays in the core until it cools down to room temperature. At cold shutdown conditions, the reactor core still has a positive reactivity which is quite large, +6.072 %dk/k. When the reactor shutdown in cold conditions with a regulating rod and an absorber rod is assumed to be stuck, the reactor core still has quite large positive reactivities, which are +7.479 and +6.342 %dk/k, respectively. From Table 3, it is also seen that the reactor will reach a critical condition when the fuel temperature drops by 300 ºC, from 900 K to 600 K. Thus, during long shutdowns the fuel salt has to be removed from the core to avoid undesired criticality accident, as the control rods cannot bring the core to the subcritical condition when the fuel temperature goes down. The fuel may be drained to the FDT for cooling and maintaining a subcritical state. In the case of an accident, the fuse valve has to work reliably, as its failure may produce a criticality accident in the core. Therefore, its failure rate has to be quantitatively estimated [13].

One may have to consider increasing the excess reactivity to 1.9 %dk/k, the worth required by MSRE to compensate the reactivity losses. In such a case, the TMSR-500 control rods will not be able to bring the reactor to subcritical condition, as the total rods worth is only -1.699 %dk/k, even at a hot fuel state.

As the FDT is the ultimate shutdown system to ensure that the reactor system can be brought to a subcritical state at any condition, criticality analyses are performed for several selected cases.

Table 4 presents the results of the FDT criticality calculations for the five selected cases. For the most realistic conditions, Case 1, the FDT system only reaches a k_{eff} of 0.33551 ± 0.00003. For Case 2, which is a more conservative condition assuming all material is in cold conditions (293 K), the k_{eff} value only slightly increases to 0.34594 ± 0.00003. In Case 3, the void space of Case 2 is replaced with air. By comparing Case 2 and Case 3, one can draw the fact that air absorbs more neutrons than void. Thus, replacing voids with air would slightly decrease the neutron multiplication factor by 0.00152. With the assumption that external events such as floods or tsunamis cause the FDT to be flooded, there will be an increase in the k_{eff} to 0.50195 ± 0.00003 due to the increase in neutron moderation by water. Although Case 5 is extremely conservative, the calculation results show the fact that the presence of water and even graphite, with a geometry that is not the same as that of the core, will not cause FDT to attain criticality. Only with a graphite geometry like fuel log can the FDT become critical, and it requires a graphite reflector as well. The result of the Case 5 calculation also shows there is a very large margin between the results of the maximum k_{eff} calculation (0.57008 ± 0.00004) and the critical condition $k_{eff} = 1.0$. Thus, it can be concluded that at any conditions the FDT geometric design will not cause criticality.

Table 4. Results of FDT criticality calculations for five cases.

No.	Case	Condition	Multiplication factor (k_{eff})
1.	Case 1	The fuel temperature is the same as operating temperature, 900 K, and other materials are treated to be at room temperature of 293 K	0.33551 ± 0.00003
2.	Case 2	All materials at the same temperature, at room temperature of 293 K	0.34594 ± 0.00003
3.	Case 3	All materials at room temperature 293 K, and void replaced with air	0.34442 ± 0.00003
4.	Case 4	All materials at room temperature 293 K, and the void is flooded with water	0.50195 ± 0.00003
5.	Case 5	All materials at room temperature 293 K, the void space is flooded with water, and the solid heat sink is treated as if made of graphite	0.57008 ± 0.00004

CONCLUSION

Calculations on shutdown capability of control rods and second shutdown system of FDT have been carried out using MCNP6 taking advantage of HPC. The first shutdown system of control rods cannot work independently, as it can only shut the reactor down at a hot fuel state. Soon after the reactor shutdown, the fuel salt has to be removed from the core to avoid reactivity increase due to fuel temperature drop. Their total rods worth

is only -1.699 % dk/k. The criticality analysis of the second shutdown system of the FDT has confirmed that it will not produce a critical state and provided a large margin at any condition even if it is assumed to be flooded with water.

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AUTHOR CONTRIBUTION

Azizul Khakim is the main contributor to this paper. He developed the input file, conducted the calculations, and wrote the manuscript. All other authors read and approved the final version of the paper.

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