https://doi.org/10.48048/tis.2023.6937

Optimization of Core Regions and Fuel Fractions for Better Power Peaking Factor of 150, 450 and 1,000 MWth Molten Salt Reactor

Marisa Variastuti[1], Dwi Irwanto[1,2,*],
Mohamad Nurul Subkhi[3] and Piyatida Trinuruk[4]

[1]Department of Nuclear Science and Engineering, Faculty of Mathematics and Natural Science, Bandung Institute of Technology, West Java 40132, Indonesia
[2]Nuclear Physics and Biophysics Research Group, Department of Physics, Faculty of Mathematics and Natural Sciences, Bandung Institute of Technology, West Java 40132, Indonesia
[3]Physics Department, Faculty of Science and Technology, State Islamic University of Sunan Gunung Djati Bandung, West Java 40614, Indonesia
[4]Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand

([*]Corresponding author's e-mail: dirwanto@itb.ac.id)

Received: 7 April 2023, Revised: 14 May 2023, Accepted: 21 May 2023, Published: 15 September 2023

Abstract

The power peaking factor (PPF) is an important parameter that needs to be considered to maintain the reactor's stability, safety and efficiency. The present study discusses the power density distribution in the reactor core by calculating the PPF to increase the reactor safety margin and minimize the possibility of a high power density at a certain point causing core failure in the Molten Salt Reactor (MSR), which is one of the Generation-IV reactors with fuel and coolant dissolved in molten salt. Important parameters discussed in the present study are the distribution of the reactor core region and the fuel composition in each region during the reactor operation time of 2,000 days. Analysis was performed for 3 different thermal power: 150, 450 and 1,000 MWth as a representative to determine the behavior of PPF at small to large power by taking the reference design of the FUJI U3 reactor developed by ITMSF (International Thorium Molten-Salt Forum) Japan. FliBe (Lithium and Beryllium Fluoride) is used as the coolant, and the fuel mixture is 233UF4-ThF4. The calculation was conducted using SRAC2006 with PIJ and CITATION modules that solve the neutron diffusion equation providing power distribution values and effective multiplication factors. As a result, the MSR with 4 core regions produces a more balanced power distribution, a better PPF value, and a good effective multiplication factor for 2,000 days of operation time compared to the reference design.

Keywords: Effective multiplication factor, Molten salt reactor, Power distribution, Power peaking factor, Thermal power

Introduction

Alternative energy is needed at this time, considering the increasing population and increasing use of electrical energy [1]. It is also used as an effort to reduce the reliance on fossil fuels. Nuclear energy is a long-term alternative that can produce significant amounts of energy [2]. Nuclear power plants have undergone developments since 1950, starting from as Generation I to the current development of generation IV, which is planned to begin operation in 2030 [3]. Generation IV nuclear power plants are sought to improve passive and inherent safety features with a simple, more economical design besides it and produce less waste [4-6]. There are 6 types of nuclear power plants or nuclear reactors included in Generation IV, namely GFR (Gas-cooled Fast Reactor), LFR (Lead-cooled Fast Reactor), MSR (Molten Salt Reactor), SFR (Sodium-cooled Fast Reactor), SCWR (Supercritical Water-cooled Reactor) and VTHR (Very High-Temperature Reactor). Several studies related to the development of generator IV, especially GFR and VHTR reactors, have been carried out previously [7-10]. In addition, MSR (Molten Salt Reactor) operates at low pressure with fuel dissolved in the molten salt coolant [11,12]. The MSR has several advantages over current LWR designs due to the liquid nature of the fuel, low salt vapor pressure and high operating temperatures. Online refueling and chemical processing are also possible within MSR operations. However, there are some challenges, such as liquid fuels which affect the physical properties of other solid components because they interaction, and corrosion problems which also need to be considered [13,14].

This research was conducted with a focus on increasing the safety factor in the MSR design from the aspect of equal distribution of power distribution on the core so as not to allow system failure on the core due to high power at certain points. The consistency of power distribution at any time while the reactor is operating is indicated by the PPF value. PPF is the ratio between the peak value of the thermal power in the reactor core and the thermal average in the entire reactor core [15,16]. Several factors, including the non-uniform geometry in the reactor core, the non-uniform fuel distribution or the presence of non-uniform absorption of neutrons in the reactor core, influence the value of the PPF [17,18]. PPF values that are getting smaller and more evenly distributed indicate better reactor conditions because it does not allow overheating at 1 point, and an even distribution of the neutron flux will provide a long life for the use of graphite [19-21]. To achieve an optimized PPF value, the reactor core area and the fuel composition are divided into several parts while maintaining the reactor's operation periods for 2,000 days. The 2,000 days are the Effective Full Power Days (EFPD), a cycle period of chemical processing fuel carried out as in the reference design. The study focused on the PPF value in the radial direction, which takes into account the peak power value and the average power in the reactor core aling the radial axis. The analysis will also be carried out on 3 different reactor thermal power states, namely 150, 450 and 1000 MWth. The MSR design refers to the FUJI U3 developed by ITMSF (International Thorium Molten-Salt Forum) Japan [22-24]. The Th-232 and U-233 cycles are used as fuel, producing a very small amount of Pu and Minor Actinida compared to the conventional Uranium cycle [25]. The fuel was dissolved in FLiBe molten salt cooler with a pitch of 20 cm. The research will be conducted using SRAC2006 (Standard Reactor Analysis Code) with PIJ (Collision Probability Method) and CITATION modules for cell and core calculations developed by the Japan Atomic Energy Agency (JAEA). The analysis will focus on an even distribution of power, a small and even PPF value, and a good Effective Multiplication Factor value so that the reactor can operate critically for 2,000 days.

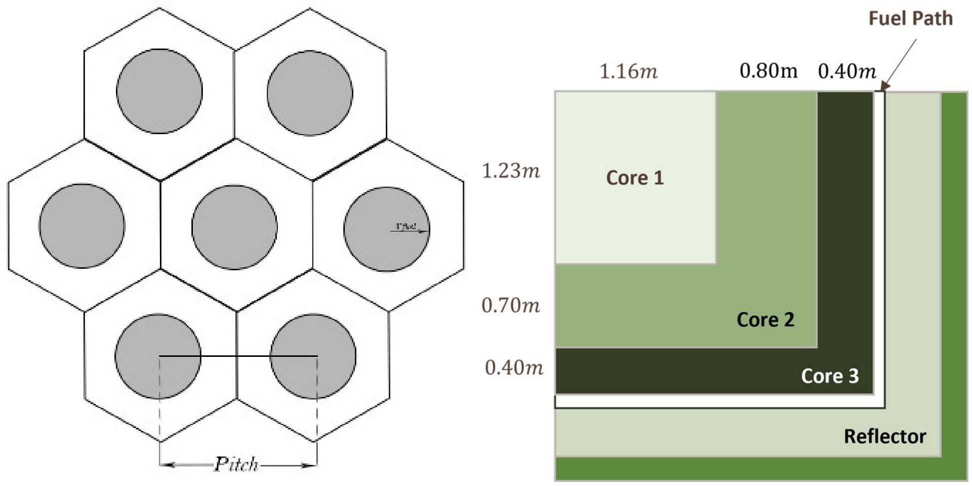
Materials and methods

The FUJI U3 design is used as a reference for this study and its specifications are presented in **Table 1**. The Molten Salt Reactor FUJI U3 is designed with an active core divided into 3 core areas, reflector and fuel path. The fuel salt used is 0.24 % $^{233}UF_4$, 12 % ThF_4, 16 % BeF_2 and 71.76 % LiF. Fluoride is a stable salt compound that can eliminate the risk of releasing radioactive material from the reactor building, so it is used in this design. Flibe is used as a coolant with BeF_2, which has a balanced melting temperature but a high viscosity, so it is mixed with LiF to lower the viscosity [26,27].

Table 1 Specification of MSR FUJI U3 [28,29].

Parameters	Specification
Electric Output	200 MWe
Thermal Output	450 MWth
Thermal Efficiency	44.4 %
Reactor Vessel	
Diameter/Height	5.40 m/5.34 m
Core 1	
Radius/Height	1.16 m/1.23 m
Core 2	
Radius/Height	0.80 m/0.70 m
Core 3	
Radius/Height	0.40 m/0.45 m
Fuel Path	
Width/Fuel vol Frac	0.04 m/90 vol %
Reflector	
Thickness/Fuel vol Frac	0.45 m/0.5 vol %
Temperature In/Out	833 K/973 K
Fuel Salt	
Composition	LiF, BeF_2, ThF_4 and UF_4
Mol %	71.76, 16, 12 and 0.24

The fuel cell geometry used is shown in **Figure 1(a)**, and the core geometry is shown in **Figure 1(b)**. The fuel cell geometry is hexagonal, containing a cylinder filled with fuel salt flow and coated with a solid-shaped moderator. Graphite is utilized as a moderator and reflector due to its ability to withstand very high temperatures [28].



(a) (b)

Figure 1 The geometry of the fuel cell and core of the FUJI U3.

In the present study, the FUJI U3 design was modified by dividing the active core into 4 core areas to equalize the power distribution on the core. Besides modifying 450 MWth reactor power, a new reactor core was designed for different powers of 150 and 1,000 MWth to determine the PPF characteristics at lower and higher power compared to the reference while maintaining the same reactor core volume. The radius and height of each core are shown in **Table 2**. While the division of the core geometry for 450 MWth is shown in **Figure 2**.

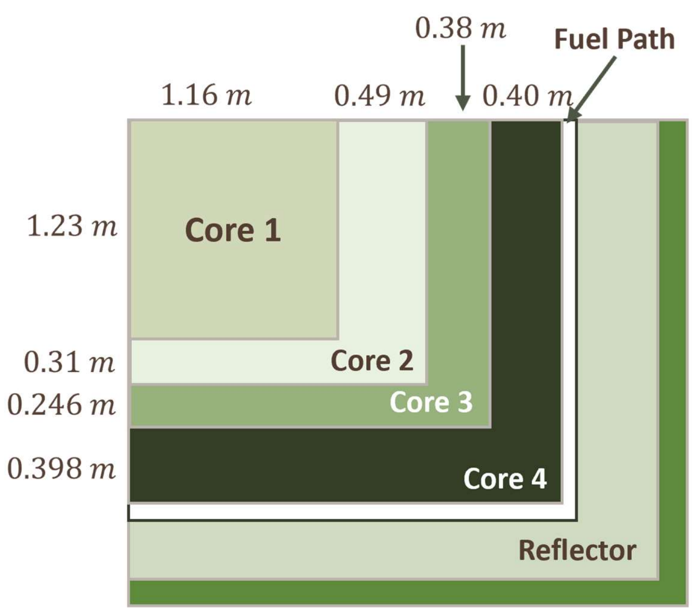


Figure 2 FUJI U3 450 MWth modified core geometry.

Table 2 Specification modified core geometry for 150 and 1,000 MWth.

Active core	150 MWth	1,000 MWth
Volume Core	81.5 m^3	81.5 m^3
Core 1		
Radius/Height	1.16 m/1.23 m	1.82 m/ 0.975 m
Core 2		
Radius/Height	0.49 m/0.31 m	0.49 m/ 0.235 m
Core 3		
Radius/Height	0.38 m/0.246 m	0.31 m/ 0.195 m
Core 4		
Radius/Height	0.40 m/0.398 m	0.262 m/ 0.145 m

The fuel fraction in each core area is varied until it reaches critical conditions at 2,000 days of reactor operation and obtains an even distribution of power and a good PPF value. The simulation uses the SRAC2006 code with the PIJ module based on the Collision Probability Method. The PIJ module is used to perform calculations of neutron transport and fuel burnup at the cell level. A fuel cell is a collapsed fuel made homogeneous with several groups of neutron energies using the collision probability matrix method. The calculations were carried out using the CITATION (Multi-D Diffusion) module in SRAC2006. This module performs multi-dimensional diffusion calculations by inputting the reactor core geometry with cell data obtained from the PIJ module [30,31].

Results and discussion

Power peaking factor of 450 MWth

This analysis emphasizes the equal distribution of power on the core to increase the reactor's safety factor. The consistency of the power distribution will be shown in the PPF value. In addition to reviewing the power distribution, it is also important to analyze the effective multiplication factor variable, which shows the criticality level of the reactor during operation so that more than one effective multiplication factor value is needed so that the reactor is critical. The FUJI U3 design was modified by dividing the core active area into 4 areas with reference to the reference design, and the volume remained the same. The division of 4 core areas shows a more even distribution of radial power compared to the division of 3 core areas. The radial power distribution shown in **Figure 3** shows a more even power distribution than the original FUJI U3 design using 3 core areas.

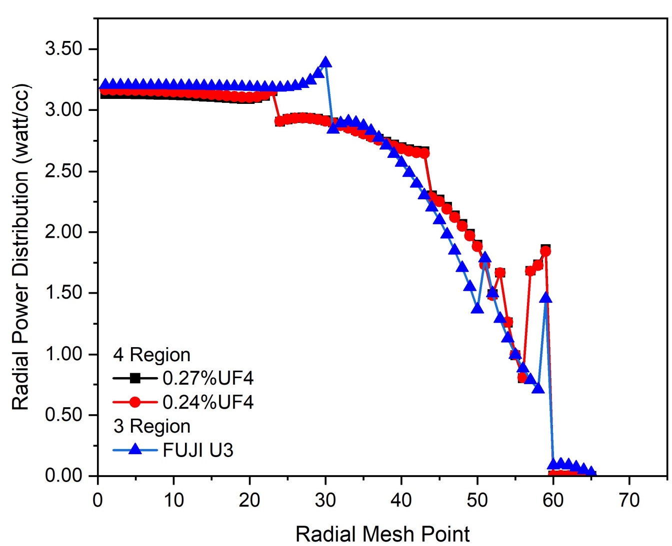


Figure 3 Radial power distribution for the reference FUJI U3 reactor with 3 core regions and the modified FUJI U3 reactor with 4 core regions.

Apart from PPF, the effective multiplication factor is also an important neutronic parameter in this study. As shown in **Figure 4**, to achieve an operating time of 2,000 days, as in the reference, the composition of 0.24 % $^{233}UF_4$ cannot be used. Using 0.27 % of $^{233}UF_4$ shows a better multiplication factor with a BOL (Begin of Life) value of 1.054 and an EOL (End of Life) of 1.002 so that the target operation period of 2,000 days can be met. The power distribution shows the same trend, which is better than using 3 regions of the reactor core.

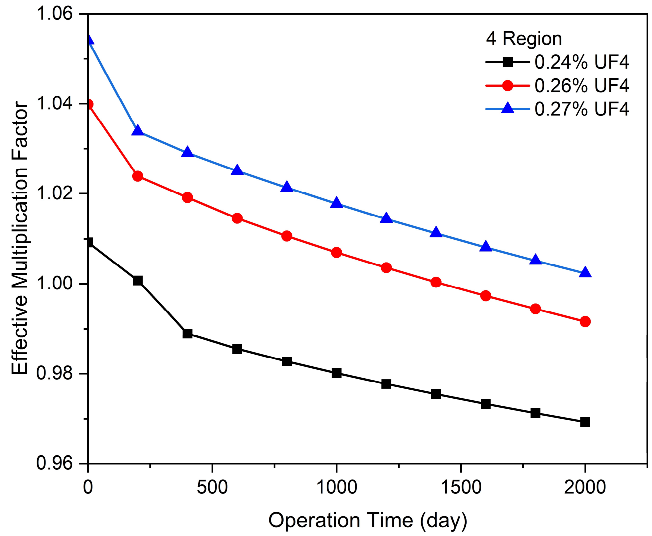


Figure 4 Effective multiplication factor for modified FUJI U3 reactor with 4 core regions.

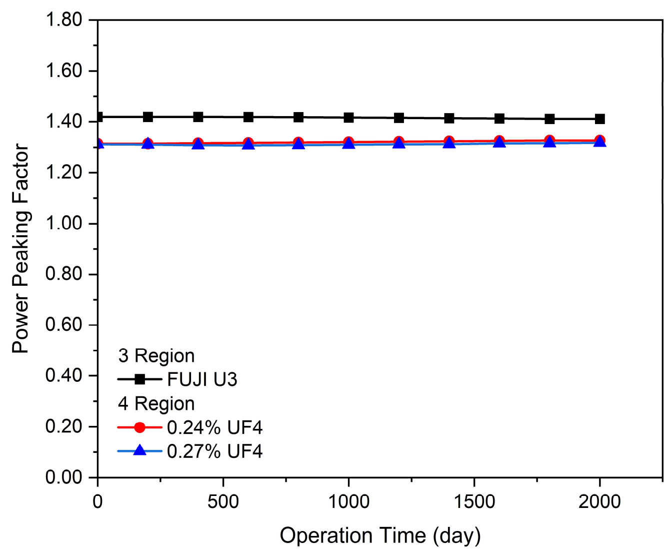


Figure 5 Power peaking factor for the reference FUJI U3 reactor with 3 core regions and the modified FUJI U3 reactor with 4 core regions.

Figure 5 shows the value of the PPFrad, obtained from a comparison of the maximum power value in the radial direction with the average radial power distribution on the core. The PPF of the FUJI U3 shows a higher value with BOL 1.42 and EOL 1.41. The modified design using 4 core areas offers a smaller PPF value than the original FUJI U3 design, which is 1.313 on the BOL for a composition of 0.24 % $^{233}UF_4$. A smaller PPF is obtained when the uranium composition is increased to 0.27 % with a PPF BOL value of 1.31. The addition of uranium from 0.24 to 0.27 % only resulted in a small difference in the PPF value, namely the difference of 0.19 % in BOL from the 2 uranium compositions. This small difference is due to the composition changes in all regions, and the PPF value is obtained from the ratio between the peak value and the average power density in all cores. The improved uranium composition increases the value of the effective multiplication factor while adjusting the number of core regions, resulting in a more uniform power distribution leading to smaller PPF. Increasing the composition of ^{233}U will increase the reactor's criticality. This is because the number of fission reactions on the core increases, thereby increasing the criticality level of the reactor. The trends obtained are identical in the 3 conditions by showing uniform values at each point until the reactor operates for 2,000 years which shows good consistency of the radial power distribution on the core.

Power peaking factor of 150 MWth

Analysis was also carried out on the new Molten Salt Reactor design with a power of 150 MWth using specifications based on the modified references design using 4 core regions. The fractions of fuel and moderator were adjusted to achieve even power distribution values and a good multiplication factor, ensuring the critical reactor can operate for 2,000 days. **Figure 6** shows the radial power distribution for 3 and 4 core regions with fuel fractions of 39%-33%-27%-45% and 39%-30%-27%-45% in each area. The division of 4 core regions shows a more even radial power distribution compared to the 3 regions. Equal power distribution on the core increases the safety factor that strives for no increased power at a point on the core, which can cause core failure. Core failure can occur when overheating occurs at a certain point in the reactor core. The high thermal power at that point can be affected reactor core stability, which can cause structural failure and lead to radioactive leakage. It can also affect the increase in pressure drop in the reactor core. Furthermore, it can increase corrosion in the MSR cooling system, which will impact pipe blockages and obstacles to the flow of molten salt. The fuel fraction in region 2 is lowered to increase the reactor's criticality. The reduced fuel fraction causes an increase in the moderator fraction so that more neutrons are moderated to become thermal neutrons and carry out fission reactions which increase the reactor's criticality. **Figure 7** shows the effective multiplication factor for the reactor operating time with the value in the division of 3 regions having a subcritical effective multiplication factor value since the reactor is in operation. The fuel fraction of 39%-30%-27%-45% shows a better effective multiplication factor value with a BOL of 1.017 and an EOL of 1.004.

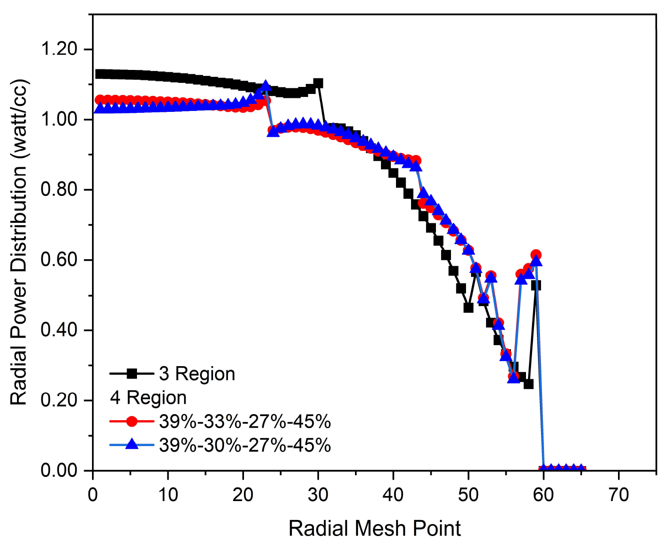


Figure 6 Radial power distribution for a modified 150 MWth MSR.

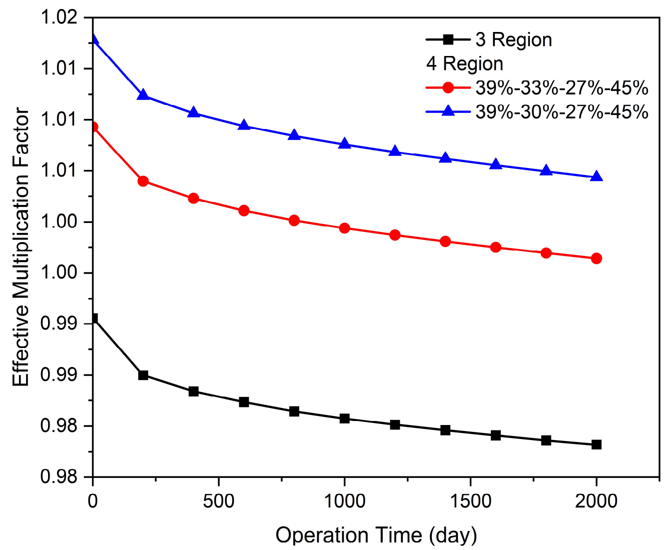


Figure 7 Effective multiplication factor for a modified 150 MWth MSR.

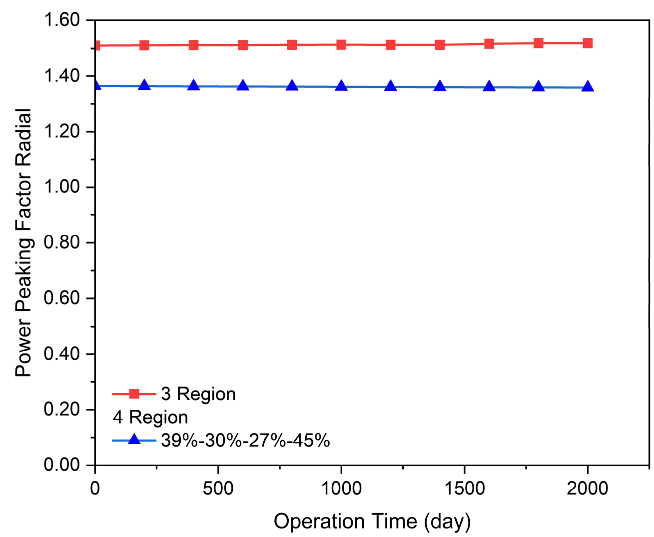


Figure 8 Power peaking factor for a modified 150 MWth MSR.

Figure 8 shows the value of the PPF for a modified 150 MWt Molten Salt Reactor using 3 and 4 regions. The obtained values of PPF show a stable trend evenly in the reactor core operating for 2,000 days, and the PPF for 4 core regions is better than for 3 core regions. In the 3 core regions, PPF obtained at the BOL was 1.51 and 1.518 for EOL; meanwhile, for 4 regions, it was 1.36 for BOL and 1.359 for EOL.

Power peaking factor of 1,000 MWth

Further analysis was carried out for the modified 1,000 MWth MSR design. In order to make a fair comparison, this design utilizes the same total volume as the previous 1, but with modifications made to the volume in each core area. The results of the core configuration shown in **Table 2**.

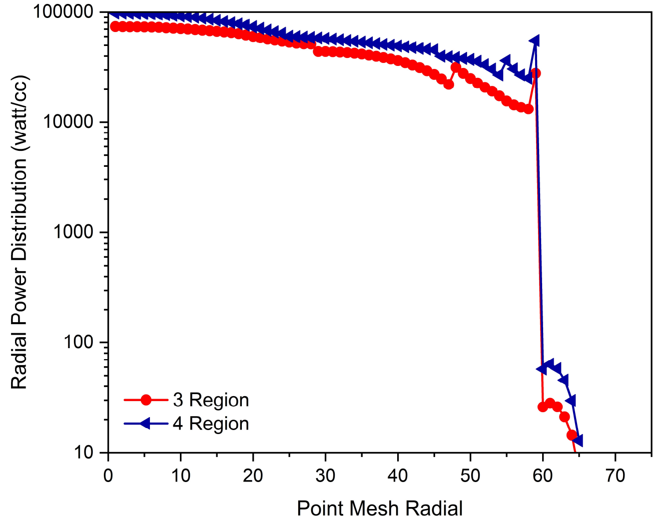


Figure 9 Radial power distribution for a modified 1,000 MWth MSR.

Figure 9 shows the power distribution for 3 and 4 core regions. The division of 4 core regions shows a more even power distribution compared to the 3 core regions. The fractions of fuel and moderator were also optimized for this modified 1,000 MWth MSR design because using the same volume as the reference design with higher power resulting a non-critical state for 2,000 days of operation time. The effective multiplication factor of the various fuel fractions is shown in **Figure 10**. The fuel fractions in regions 1, 2 and 3 need to be reduced to obtain the reactor's criticality level for 2,000 days. Fuel configurations of 30%-25%-20%-45% can provide critical conditions to the reactor during 2,000 days of operation time. The reduced fuel fraction and the increased moderator in the 3 core regions cause more fission reactions because more neutrons energy is moderated so that the criticality level in the reactor increases.

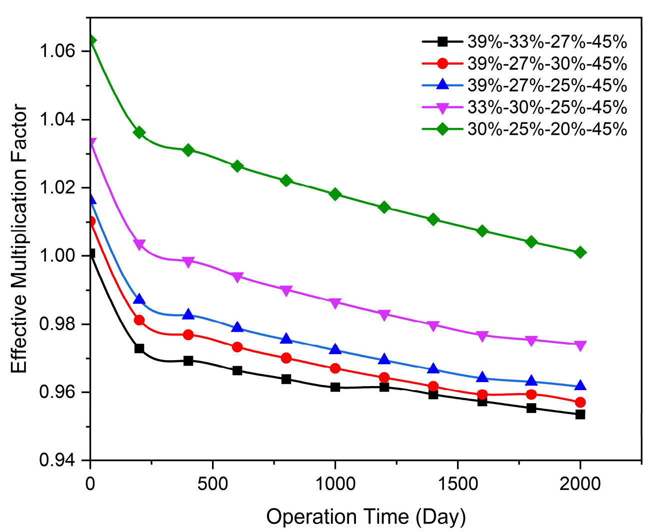


Figure 10 Effective multiplication factor for a modified 1,000 MWth MSR.

The obtained PPF is shown in **Figure 11**. Several other fuel fraction variations show inconsistent PPF values, and it increases with the length of time the reactor has been operating. The fuel fraction variation of 39 % in the core area shows an unstable PPF value where around 350 days the reactor operates. The PPF value will continue to increase, which means that the power distribution on the core is uneven and does not show a good safety factor. Unequal power distribution on the core can cause system failure due to high power at a certain point. In addition, the value of the non-critical effective multiplication factor for 2,000 days is shown in this variation. Efforts were made to obtain an even PPF value by lowering the value of the fuel fraction and repositioning the distribution mesh points in areas 1, 2 and 3 of the reactor core. The analysis indicates that the fuel fraction of 30%-25%-20%-45% offers a more stable PPF value and a better value than the 3 reactor core regions.

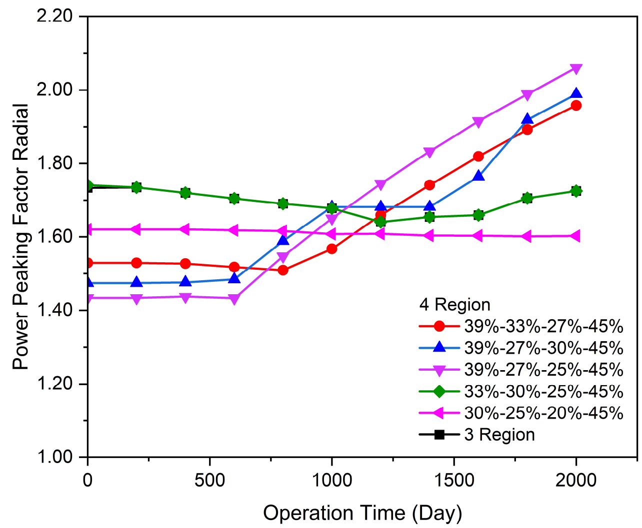


Figure 11 Power peaking factor at 1,000 MWth.

Figure 12 shows the radial power distribution at 150, 450 and 1,000 MWth. The 3 radial power distributions have slightly different patterns, with the largest radial power observed for 1,000 MWth, followed by 450 and 150 MWth, according to the amount of power used in each reactor. This radial power distribution will affect the PPF value for each power. **Figure 13** shows the effective multiplication factor, which describes the critical condition of the reactor at each power level during the operational period. This research aims to ensure the reactor remains in a critical state for 2,000 days, after which the fraction of fuel in each area is varied to achieve equal distribution of radial power and the desired PPF value. Calculations show that a reactor design with greater power and the same fuel will have a higher PPF value due to the increase in power distribution shown in **Figure 14**. A similar PPF pattern results from 150 and 450 MWth power due to the same core geometry modification pattern used for both designs.

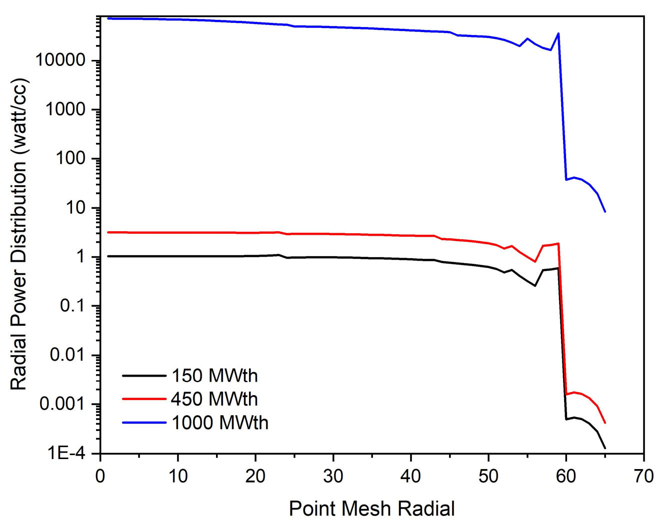


Figure 7 Radial power distribution at 150, 450 and 1,000 MWth.

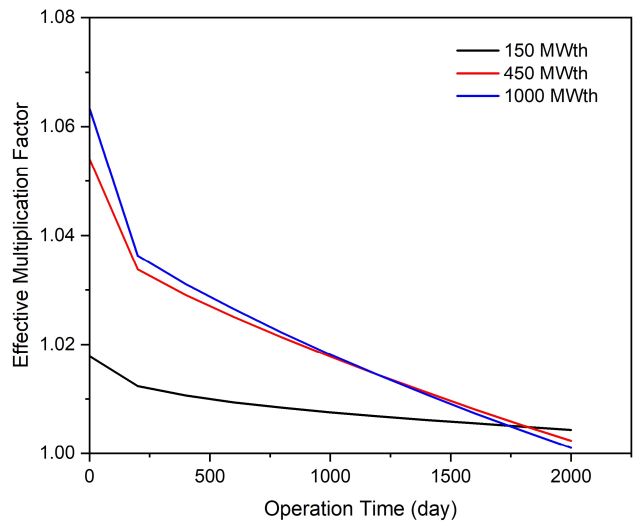


Figure 8 Effective multiplication factor at 150, 450 and 1,000 MWth.

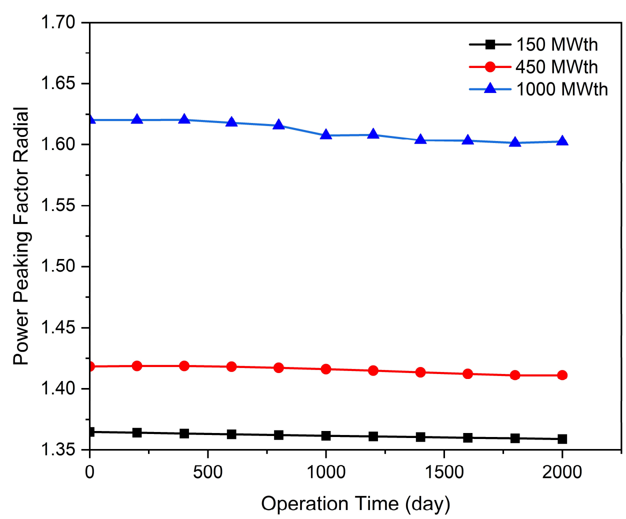


Figure 9 Power peaking factor at 150, 450 and 1,000 MWth.

The required fuel fraction will have a smaller value with increasing power due to an increase in the moderator fraction, which will cause an increased number of thermal neutrons so that the fission reaction will also increase. This will make the reactor more critical, and the effective multiplication factor value will be higher.

Conclusions

In the present study, more evenly distributed power in the core are achieved by optimizing the number of core regions using different fuel fraction and composition. It is shown from the calculations that 4 core regions produce a better power distribution than the 3 core regions, as in the references. The value of the PPF for reference FUJI U3 design is 1.42, while after optimization, the PPF value could be reduced to 1.31. For a modified 150 and 1,000 MWth Molten Salt Reactor design, the obtained PPF values after optimization are 1.36 and 1.62, respectively. It is shown from this study that a better PPF, which is an important safety parameter so that no power increases at a point so as not to trigger a reactor accident, could be obtained by optimizing the number of core regions using different fuel fractions and compositions.

Acknowledgements

The authors would like to express their gratitude for the support from Institut Teknologi Bandung (ITB), Indonesia, and the Faculty of Mathematic and Natural Sciences - ITB, through the scheme of Research, Community Service, and Innovation (PPMI).

References

[1] T Sekher. *World population day-2022 symposium & launch of united nations world population prospects-2022.* Columbia University, New York, 2022.
[2] FI Petrescu, A Apicella, RV Petrescu, S Kozaitis, R Bucinell, R Aversa and T Abu-Lebdeh. Environmental protection through nuclear energy. *Am. J. Appl. Sci.* 2019; **13**, 941-6.
[3] A Lokhov, V Sozoniuk, G Rothwell, M Cometto, H Paillere, M Crozat, P Genoa, TJ Kim, M McGough, D Ingersoll, R Rickman, D Stout, G Halnon, J Chenais, FX Briffod, S Perrier, F Shahrokhi, B Kaufer, A Wasylyk, D Shropshire, S Danrong and R Swinburn. *Small modular reactors: Nuclear energy market potential for near-term deployment*. OECD, Paris, France, 2016.
[4] I Pioro. *Handbook of generation IV nuclear reactors: A guidebook*. Woodhead Publishing, Sawston, 2022.
[5] RA Knief. *Nuclear engineering: Theory and technology of commercial nuclear power*. American Nuclear Society, Illinois, 2008.
[6] J Wu, J Chen, X Cai, C Zou, C Yu, Y Cui, A Zhang and H Zhao. A review of molten salt reactor multi-physics coupling models and development prospects. *Energies* 2022; **15**, 8296.
[7] RD Syarifah, Y Yulianto, Z Su'ud, K Basar and D Irwanto. Design study of 200 MWth gas cooled fast reactor with nitride (un-pun) fuel long life without refueling. *MATEC Web Conf.* 2016; **82**, 03008.
[8] RD Syarifah, Z Su'ud, K Basar, D Irwanto, SC Pattipawaej and M Ilham. Comparison of uranium plutonium nitride (U-Pu-N) and thorium nitride (Th-N) fuel for 500 MWth gas-cooled fast reactor (GFR) long life without refueling. *Int. J. Energ. Res.* 2018; **42**, 214-20.
[9] D Irwanto, S Permana, A Pramutadi and S Pramuditya. Preliminary design study of small power 30-50 MWt experiment power reactor based on high temperature pebble bed gas cooled reactor technology. *J. Phys. Conf. Ser.* 2019; **1127**, 012024.
[10] H Raflis, M Ilham, Z Su'ud, A Waris and D Irwanto. Neutronic analysis of modular gas-cooled fast reactor for 5 - 25 % of plutonium fuel using parallelization MCNP6 code. *J. Phys. Conf. Ser.* 2020; **1493**, 012008.
[11] PL Kirillov and GP Bogoslovskaya. Generation IV supercritical water-cooled nuclear reactors: Realistic prospects and research program. *Nucl. Energ. Tech.* 2019; **5**, 67-74.
[12] MB Schaffer. Abundant thorium as an alternative nuclear fuel: Important waste disposal and weapon proliferation advantages. *Energ. Pol.* 2013; **60**, 4-12.
[13] SE Creasman, V Pathirana and O Chvala. Sensitivity study of parameters important to molten salt reactor safety. *Nucl. Eng. Tech.* 2023; **55**, 1687-707.
[14] CE Moss, O Chvála, H Reisinger, AM Wheeler and D Moser. Neutronics and fuel cycle modeling of a thorium-fueled two-fluid molten salt iso-breeder reactor. *Ann. Nucl. Energ.* 2022; **177**, 109299.
[15] IH Bae, MG Na, YJ Lee and GC Park. Calculation of the power peaking factor in a nuclear reactor using support vector regression models. *Ann. Nucl. Energ.* 2008; **35**, 2200-5.
[16] X Zhou, Y Tang, Z Lu, J Zhang and B Liu. Nuclear graphite for high temperature gas-cooled reactors. *New Carbon Mater.* 2017; **32**, 193-204.
[17] T Surbakti, S Pinem and L Suparlina. Dynamic analysis on the safety criteria of the conceptual core design in MTR-type research reactor. *Atom. Indonesia* 2018; **44**, 89-97.
[18] A Erfaninia, A Hedayat, SM Mirvakili and MR Nematollahi. Neutronic-thermal hydraulic coupling analysis of the fuel channel of a new generation of the small modular pressurized water reactor including hexagonal and square fuel assemblies using MCNP and CFX. *Progr. Nucl. Energ.* 2017; **98**, 213-27.
[19] DY Cui, XX Li, Y Dai, G Hu, XZ Cai, Y Zou and JG Chen. An improved core design of a 50 kWth heat pipe cooled micro molten salt reactor (micro-MSR). *Progr. Nucl. Energ.* 2022; **151**, 104326.
[20] X Kang, G Zhu, J Wu, R Yan, Y Zou and Y Liu. Core optimization for extending the graphite irradiation life-span in a small modular molten salt reactor. 2023, DOI: 10.2139/ssrn.4374087.
[21] A Waris and S Permana. Design concept of small long-life PWR using square and hexagonal thorium fuel. *ARPN J. Eng. Appl. Sci.* 2016; **11**, 830-2.
[22] K Furukawa, K Arakawa, LB Erbay, Y Ito, Y Kato, H Kiyavitskaya, A Lecocq, K Mitachi, R Moir, H Numata, JP Pleasant, Y Sato, Y Shimazu, VA Simonenco, DD Sood, C Urban and R Yoshioka. A

road map for the realization of global-scale thorium breeding fuel cycle by single molten-fluoride flow. *Int. Conf. Emerg. Nucl. Energ. Syst.* 2007; **49**, 1832-48.

[23] D Zhang, QIU Suizheng, LIU Changliang and SU Guanghui. Steady thermal hydraulic analysis for a molten salt reactor. *Nucl. Sci. Tech.* 2008; **19**, 187-92.

[24] T Yamamoto, K Mitachi and T Suzuki. Steady state analysis of small molten salt reactor* (effect of fuel salt flow on reactor characteristics). *JSME Int. J.* 2005; **48**, 610-7.

[25] International Atomic Energy Agency. *Thorium fuel cycle-potential benefits and challenges.* International Atomic Energy Agency, Austria, 2005.

[26] C Wulandari, A aris, S Pramuditya and PAM Asril. Study on utilization of super grade plutonium in molten salt reactor FUJI-U3 using citation code. *J. Phys. Conf. Ser.* 2017; **877**, 012021.

[27] K Mitachi, T Yamamoto and R Yoshioka. Three-region core design for 200-MW (electric) molten-salt reactor with thorium-uranium fuel. *Nucl. Tech.* 2007; **158**, 348-57.

[28] SQ Jaradat and AB Alajo. Studies on the liquid fluoride thorium reactor: Comparative neutronics analysis of MCNP6 code with SRAC95 reactor analysis code based on FUJI-U3-(0). *Nucl. Eng. Des.* 2017; **314**, 251-5.

[29] C Wulandari, A Waris and S Permana. Comparatives studies in molten salt reactor FUJI-U3 with various power. *J. Phys. Conf. Ser.* 2021, **1772**, 012027.

[30] K Okumura. *Introduction of SRAC for reactor physics analyses.* Japan Atomic Energy Agency, Ibaraki, Japan, 2007.

[31] K Shibata, T Kawano, T Nakagawa, O Iwamoto, J Katakura, T Fukahori, S Chiba, A Hasegawa, T Murata, H Matsunobu, T Ohsawa, Y Nakajima, T Yoshida, A Zukeran, M Kawai, M Baba, M Ishikawa, T Asami, T Watanabe, … H Takano. Japanese evaluated nuclear data library version 3 revision-3: JENDL-3.3. *J. Nucl. Sci. Tech.* 2002; **39**, 1125-36.