

Conceptual Core Analysis of Long Life PWR Utilizing Thorium-Uranium Fuel Cycle

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Abstract. Conceptual core analysis of long life PWR utilizing thorium-uranium based fuel has conducted. The purpose of this study is to evaluate neutronic behavior of reactor core using combined thorium and enriched uranium fuel. Based on this fuel composition, reactor core have higher conversion ratio rather than conventional fuel which could give longer operation length. This simulation performed using SRAC Code System based on library SRACLIB-JDL32. The calculation carried out for (Th-U)O₂ and (Th-U)C fuel with uranium composition 30 - 40 % and gadolinium (Gd₂O₃) as burnable poison 0,0125%. The fuel composition adjusted to obtain burn up length 10 – 15 years under thermal power 600 – 1000 MWt. The key properties such as uranium enrichment, fuel volume fraction, percentage of uranium are evaluated. Core calculation on this study adopted R-Z geometry divided by 3 region, each region have different uranium enrichment. The result show multiplication factor every burn up step for 15 years operation length, power distribution behavior, power peaking factor, and conversion ratio. The optimum core design achieved when thermal power 600 MWt, percentage of uranium 35%, U-235 enrichment 11 – 13 %, with 14 years operation length, axial and radial power peaking factor about 1.5 and 1.2 respectively.

1. Introduction

Nuclear energy is one of the most used as an electric source especially for developed countries. The utilizing of nuclear energy as an electric source has run more than 50 years [1]. Pressurized water reactor has the most used as a nuclear reactor for produce electricity. Conventional pressurized water reactor use enriched uranium as a fuel with enrichment 1.5 – 2.5 %, the operation time 1.5 years for one fuel batch loading [2]. Now day's many research has conducted to build long life nuclear reactor. Small long life pressurized water reactor based on thorium fuel cycle is one of the most researched in the world.

Thorium is a fertile isotope which can converted to U-233 as a fissile isotope if absorb one neutron. The abundant of Th-232 in earth crust has three times greater than natural uranium. Thorium based fuel has several advantages than uranium in reason [1, 3–9]:

- The abundant of thorium can provide long term supply of nuclear fuel,
- Higher conversion ratio which can provide longer operation time of reactor,
- The fissile product of Th-232 (U-233) has higher thermal fission factor (η),
- Reduce plutonium in spent fuel,
- ThO₂ has 50% higher thermal conductivity rather than UO₂, etc.



The present study intends to evaluate thorium-uranium based fuel in pressurized water reactor. The design arranged to provide 10 – 15 years operation time of the reactor which fulfill required design such as percentage of uranium lower than 40%, enrichment of U-235 lower than 15%, power distribution, and power peaking factor. The study conducted to oxide and carbide fuel type.

2. Theoretical Background

2.1. Neutron Diffusion Equation

Basic theoretical concept used to nuclear reactor design are neutron diffusion equation, multiplication factor, conversion ratio, depletion equation to fuel burn up evaluation [2].

Neutron diffusion equation used to evaluate neutron distribution and behavior in reactor core during reactor operation. The equation written bellow.

$$-\nabla \cdot D_g \nabla \phi_g + \sum_{Rg} \phi_g = \frac{\chi_g}{k_{eff}} \sum_{g^i} \nu_{g^i} \sum_{fg^i} \phi_{g^i} + \sum_{g^i} \sum_{sg^i g} \phi_{g^i} \phi_g \quad (1)$$

- D : diffusion constant,
 Σ_i : macroscopic cross section in i reaction,
 $\nu \Sigma_f$: fission reaction probability per second,
 ϕ_g : neutron flux,
 k_{eff} : effective multiplication factor.

2.2. Multiplication Factor

Multiplication factor defined as number of neutron in one generation divided to number of neutron in preceding generation. This parameter to determine nuclear reactor state ($k > 1$ supercritical, $k = 1$ critical, $k < 1$ subcritical).

$$k = \frac{\text{number of neutron in one generation}}{\text{number of neutron in preceding generation}} \quad (2)$$

2.3. Conversion Ratio

Conversion ratio (CR) defined as ratio of average rate of fissile atom production to average rate of fissile atom consumption.

$$CR = \frac{\text{average rate of fissile atom production}}{\text{average rate of fissile atom consumption}} \quad (3)$$

If $CR > 1$ this quantity also referred to as *breeding ratio* (BR).

2.4. Depletion Equation

The materials in reactor core will have depleted during reactor operation. Depletion equation can describe fuel behavior before and after reactor operation and the amount of minor actinide as a fission production. The equation shown as,

$$\frac{dN_A}{dt} = -\lambda_A N_A - \left[\sum_g \sigma_{ag}^A \phi_g \right] N_A + \lambda_B N_B + \left[\sum_g \sigma_{cg}^C \phi_g \right] N_C \quad (4)$$

- N_A : atomic density isotope A
 λ_A : radioactive decay constant of isotope A
 ϕ_g : neutron flux in group g
 σ_{ag}^A : absorption cross section A in group g
 σ_{cg}^C : capture cross section C in group g

2.5. Power Distribution

Diffusion equation can describe power distribution profile from neutron flux behavior in reactor core. Power distribution profile in reactor core formulated with this equation,

$$q'''(r) = \sum_i w_f^{(i)} N_i(r) \int_0^\infty dE \sigma_f^{(i)}(E) \phi(r, E) \quad (5)$$

3. Reactor Design Parameter

In order to fulfill required specification, the design of reactor has evaluated. The basic reactor core design parameter are shown in **Table 1**. The reactor core design parameter based on the conventional pressurized water reactor [2], but the total power output varied to 600 – 1000 MWt. The reactor core dimension adjusted to 362.88 cm height, 337.68 cm diameter and 15.12 cm reflector inn radial and axial direction. The pin pitch of reactor is definitely similar to typical PWR 1.26 cm. the pin diameter adjusted to optimum design as a function of fuel volume fraction.

Table 1. Reactor design parameter

Parameter		
Thermal power output	600 - 1000	MWt
Active core diameter	337.68	cm
Active core height	362.88	cm
Reflector	15.12	cm
Fuel	(Th-U)O ₂ and (Th-U)C	
UO ₂ and UC percentage	35%	
U-235 enrichment	9 – 13 %	
Burnable poison	Gd ₂ O ₃	
BP percentage	0.0125%	
Pin pitch	1.26	cm
Fuel volume fraction	35 – 50%	
Clad thickness	0.057	cm
Temperature		
Fuel	900	K
Cladding	600	K
Coolant	600	K

The geometry of reactor core used cylindrical R-Z geometry and divided into 3 region in radial direction. Volume of each region arranged to small different value.

The fuel of reactor system used (Th-U)O₂ and compared to (Th-U)C. Percentage of uranium composition adjusted to found out optimum result, it is evaluated from 25% to 40%. Enrichment of U-235 in uranium composition adjusted to 9 - 11% in inner region, 10 - 12% in middle region, 11 - 13% in outer region. To decrease multiplication factor value in a beginning of life, 0.0125% Gd₂O₃ as burnable poison in every fuel pin was implemented for this study.

4. Calculation Method

Cell calculation carried out by PIJ to found out multiplication factor, conversion ratio, fission product, neutron flux, microscopic and macroscopic cross section data of each material in reactor core [10]. Data of cell calculation saved in user library data. Core calculation carried out by CITATION module to found out effective multiplication factor (k_{eff}), average power density, power distribution in axial and radial direction, power peaking factor.

Reactor core geometry adopted 2D cylindrical R-Z geometry divided into 3 region in radial direction. The shape of core reactor geometry shown in **figure 1**.

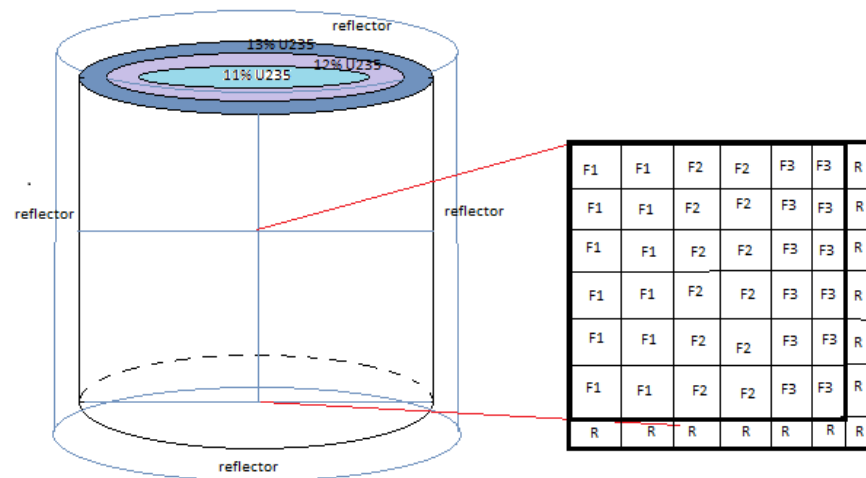


Figure 1. Reactor core geometry, $\frac{1}{4}$ cylindrical R-Z geometry

5. Result and Discussion

The present study has evaluated composition of uranium composition in total fuel. The obtained results of fuel composition are shown this section. Isotopic fissile product in end of life (EOL) also analysed in cell calculation. Core calculation performed to analyse core performance such as power distribution and reactor operation time in one fuel batch. The calculation conducted to thermal power output 600 – 1000 MWt, 35 – 50% fuel volume fraction, 25 – 40% uranium composition in whole fuel.

The effect of fuel volume fraction to k-eff value given in **fig. 3** in a beginning of life (BOL). Higher fuel volume fraction give an impact to lower k-eff.

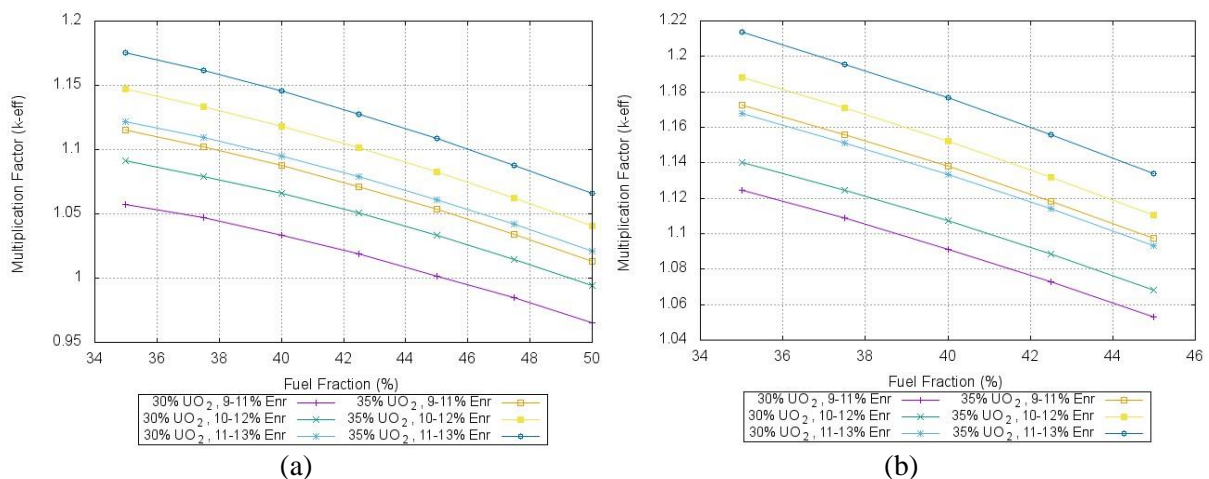


Figure 2. Effect of fuel volume fraction change to k-eff of oxide fuel (a) and carbide fuel (b) in a beginning of life (BOL)

To evaluate the impact of fuel volume fraction to criticality period, the multiplication factor evaluated in each burn up step. See **fig. 3** and **fig. 4** for thermal power output 1000 MWt and 600 MWt, respectively. Higher fuel volume fraction value impacted to lower k-eff, this result caused by moderation performance in high fuel volume fraction decreased because moderator/coolant volume fraction decreased as long as fuel volume fraction increased. Moderator is an important parameter in thermal reactor to provide thermal neutron as a fission reaction trigger. In lower moderator fraction, moderation performance decrease and impacted to reduction number of thermal neutron. In the other perspective, higher fuel volume fraction impacted to higher conversion ratio. Higher conversion ratio can provide

slower reduction of multiplication factor in sequence burn up step and impacted to longer operation time.

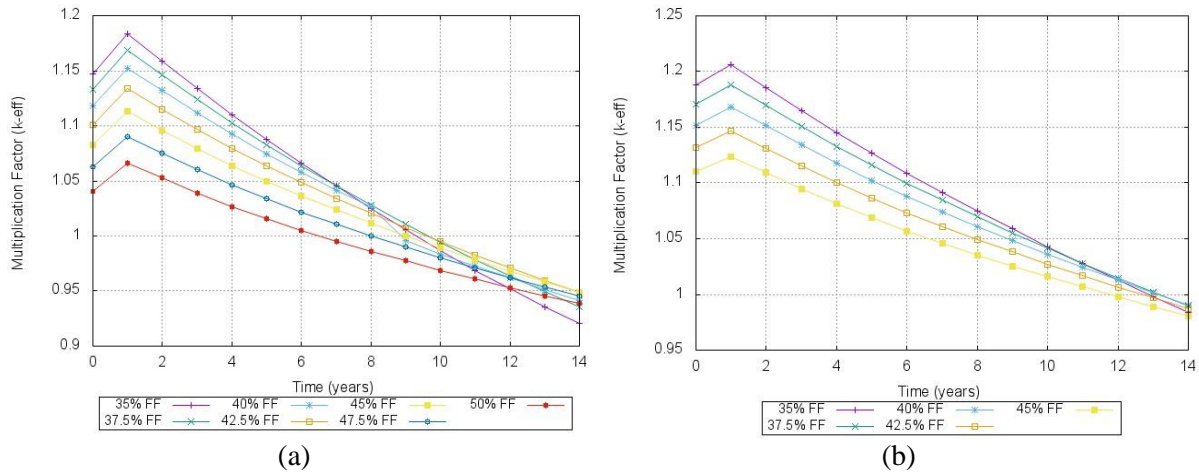


Figure 3. Effect of fuel volume fraction change to k_{eff} vs time of oxide fuel (a) and carbide fuel (b) at 1000 MWt, 35% UO_2 , 10 – 12% enrichment U-235

Higher thermal power output or power level impacted to progressively decrease on k_{eff} in sequence next burn up step. It is caused by higher burn up rate as long as higher power level [7]. Effective multiplication factor at 1000 MWt has lower operation time compared to 600 MWt. at 45% fuel volume fraction and 9-11% enrichment, 600 MWt power output has longer operation time compared to 1000 MWt, k_{eff} at 600 MWt become less than 1 after 14 years, k_{eff} at 1000 MWt become less than 1 after 8 years.

The different of carbide and oxide fuel in this study show just in reactor operation time, carbide has longer operation time rather than oxide. It is caused by mass density of carbide has higher value than oxide. The reactor will have more fuel fissile material to be burn so that can maintain its criticality for a longer time. Lower effect of burnable poison in carbide fuel caused by atomic density has higher value, therefore lower neutron absorbed to fissile isotope.

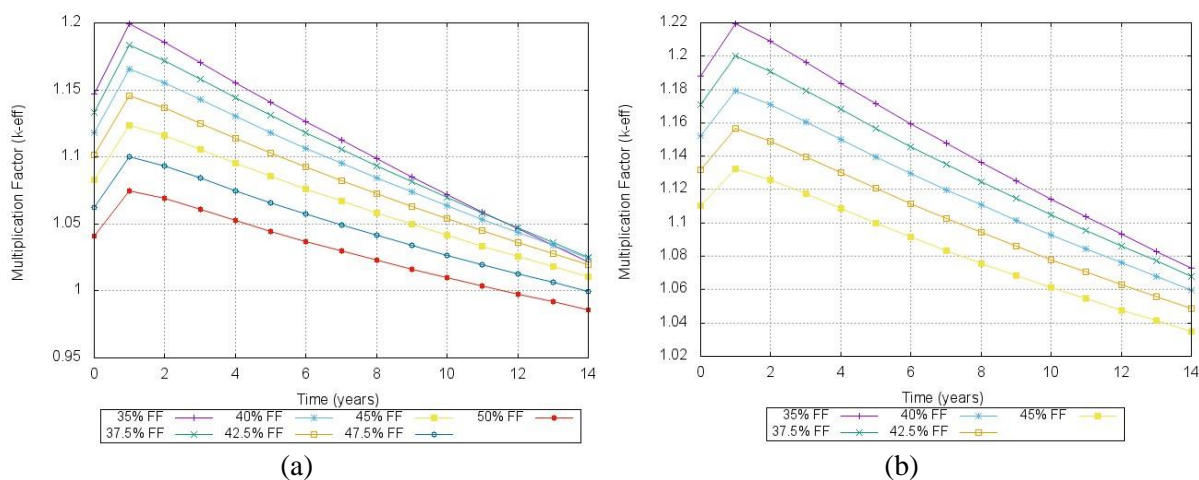


Figure 4. Effect of fuel volume fraction change to k_{eff} vs time of oxide fuel (a) and carbide fuel (b) at 600 MWt, 35% UO_2 , 10 – 12% enrichment U-235

Effective multiplication factor evaluation in the scope of thermal power output given in **fig. 5** as a function of time. According to this result, carbide fuel has longer operation time compared to oxide fuel. The longest operation time in carbide fuel obtained at 600 MWt for more than 14 years, and at 1000 MWt has 10 years operation time. In an oxide fuel, reactor operation time at 600 MWt has obtained 14 years, meanwhile at 1000 MWt just 8 years.

The optimum result obtained at 45% fuel volume fraction for both oxide and carbide fuel. In this fuel volume fraction value, there has lower peak of k_{eff} (burn up step 1) for optimum operation length time (criticality > 1).

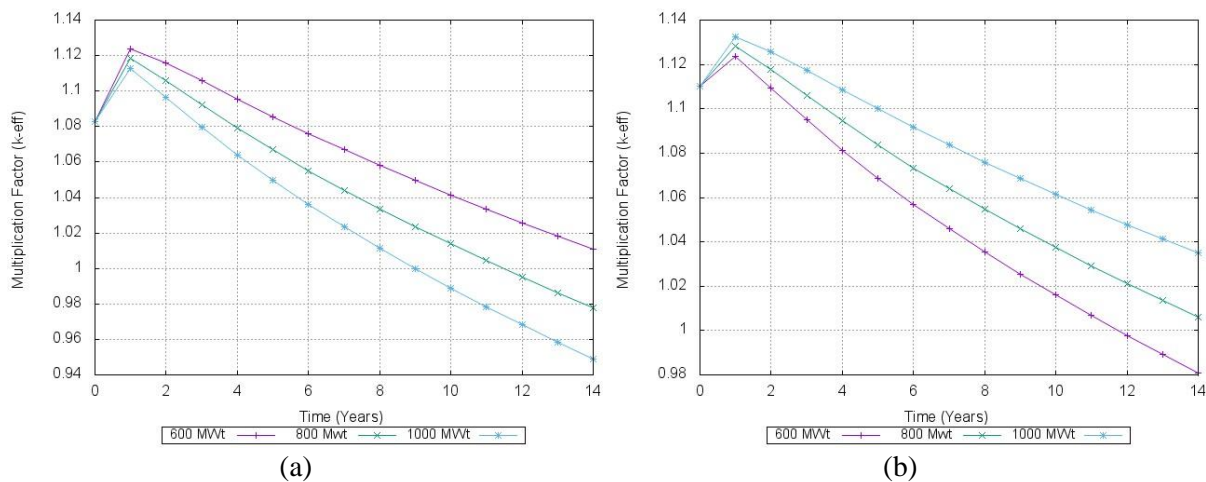


Figure 5. Effective multiplication factor of oxide fuel (a) and carbide fuel (b) at 600-1000 MWt, fuel volume fraction 45%, 35% uranium composition, 10 – 12% enrichment U-235

The power distribution in radial direction also investigated to evaluate core performance. The obtained result of radial power distribution shown in **fig. 6** as a function of radial mesh, respectively. The power distribution in radial direction more flat than axial direction, it is an impact of different enrichment in each region for radial direction. Outer region has higher enrichment than inner region for equalize power distribution. In axial direction, there is no different region, so the power distribution not as flat as radial distribution. The power peaking factor in radial direction almost 1.2, meanwhile in axial direction almost 1.5. There is no different in power distribution for carbide and oxide fuel.

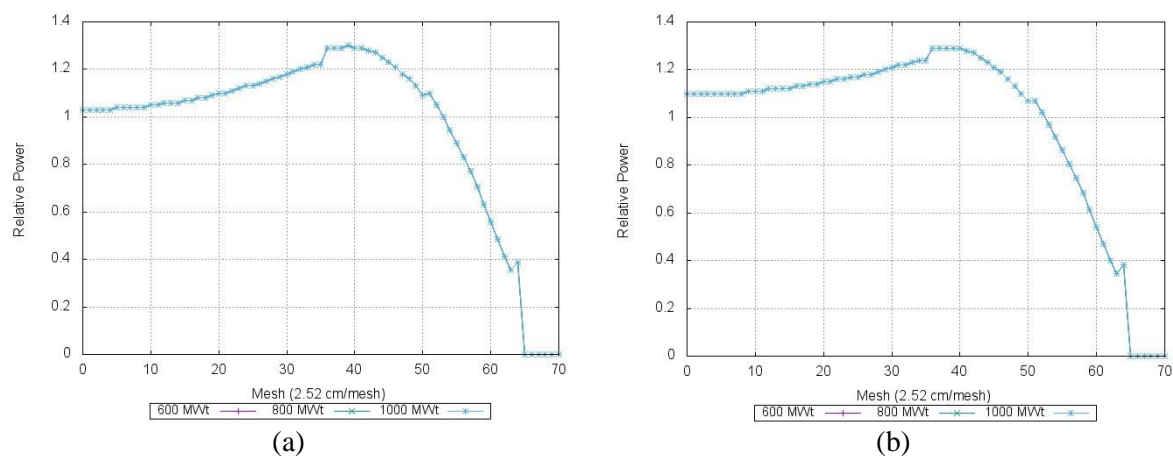


Figure 6. Radial power distribution at beginning of life (BOL) (a) and carbide fuel (b) at 600-1000 MWt, fuel volume fraction 45%, 35% uranium composition, 10 – 12% enrichment U-235

6. Conclusion

The thorium-uranium based fuel has been applied in this study to design long life pressurized water reactor at thermal power output 600 – 1000 MWt. The optimum design has obtained at 45% fuel volume fraction and 35% uranium composition at enrichment U-235 10% in inner region, 11% in middle region, 12% in outer region. Calculation results show that the longest operation time in carbide fuel obtained at 600 MWt for more than 14 years, and at 1000 MWt has 10 years operation time. In an oxide fuel, reactor operation time at 600 MWt has obtained 14 years, meanwhile at 1000 MWt just 8 years. Power peaking factor in axial and radial direction 1.5 and 1.2 respectively.

Higher fuel volume fraction value impacted to lower k-eff, this result caused by moderation performance in high fuel volume fraction decreased because moderator/coolant volume fraction decreased as long as fuel volume fraction increased. In lower moderator fraction, moderation performance decreased and impacted to reduction number of thermal neutron. In the other perspective, higher fuel volume fraction impacted to higher conversion ratio. Higher conversion ratio can provide slower reduction of multiplication factor in sequence burn up step and impacted to longer operation time.

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References

- [1] Sidik P 2007, Journal of Nuclear Science and Technology (Atomic Energy Society of Japan), Vol. 44, No. 7, p. 946 – 957.
- [2] Duderstadt J. J., and Hamilton L. J. 1976, Nuclear Reactor Analysis (John Wiley & Sons, Inc., New York), p. 74 – 88.
- [3] Michael L, Otto G 1998, “Perspective of the thorium fuel cycle,” *Nucl. Eng. Des.*, 180[2], 133.
- [4] Tucker L. P, Alajo A, Usman S 2015, “*Thorium-based mixed oxide fuel in a pressurized water reactor: A beginning of life feasibility analysis with MCNP*,” *Annals of Nuclear Energy* 76 p. 323-334.
- [5] Iyos S, Asril P, Rida S.N.M, Zaki S, Sapta R. E, Nurul S. M, Topan S, Astuti Y, Soentono S 2008, “The utilization of thorium for long-life small thermal reactors without on-site refueling,” *Progress in Nuclear Energy* 50, p. 152-156D.
- [6] Shengyi S, “Roadmap Design for Thorium-Uranium Breeding Recycle in PWR”, Shanghai, China, IAEA-CN-164-5S09
- [7] Irwanto D and Zaki S 2005, “Design Study of Long Life Thorium-based Pressurized Water Reactor (PWR) Using Annular Fuel System and Protactinium as Burnable Poison”, *Proceedings of Asian Physics Symposium, Bandung*, p. 366-370.
- [8] Yulianti Y 2005, “Design and Thermal Hydraulic Analysis of Long-Life Thorium-Uranium Fueled Boiling Water Reactor”, *Proceedings of Asian Physics Symposium, Bandung*, p. 307-313.
- [9] Shawgeraus E, Volasky D, Friedman E 2008, “High Conversion Thorium Fuel Cycle for PWRs”, *IYNC*, Paper p. 151.
- [10] Okumura K., et al. 2002, SRAC version 2002, Japan Atomic Energy Research Institute (JAERI) report.