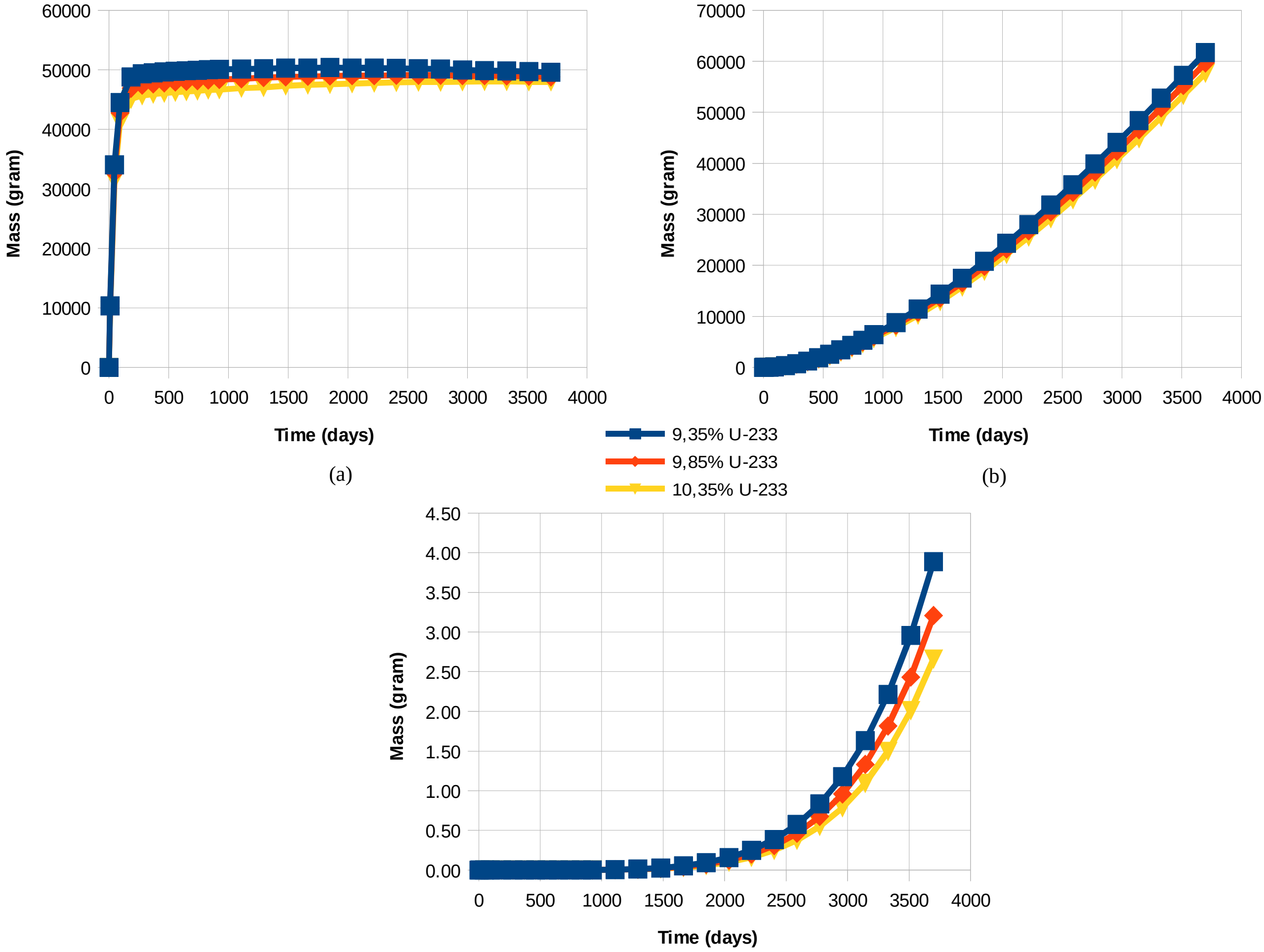

(c)

Fig 6. (a) Mass variation of ^{233}Pa. (b) Mass variation of ^{235}U. (C) Mass variation of fissile plutonium (^{239}Pu + ^{241}Pu)

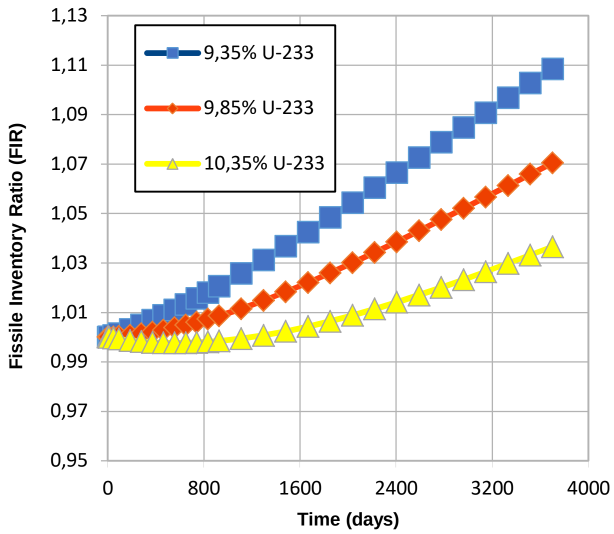

Fig 7. Variation of fissile inventory ratio (FIR)

IV. Conclusions

For the improvement of sustainable nuclear energy, a 1000 MWt thorium fueled reduced moderation boiling water reactor (RBWR) was studied. The core burnup calculations were carried out on this reactor to evaluate the neutronic behavior. The impact of the initial fissile fuel content in the fissile zone on the reactor characteristics related to neutronic behavior such as the core burnup, fissile breeding and fissile inventory ratio (FIR) was analyzed.

The analysis indicated that the change in initial fissile fuel content in the fissile zone resulted in the opposite impact on the core burnup and fissile breeding. The low initial fissile fuel content in the fissile zone led to the low core burnup and high fissile breeding, and the opposite results were obtained with the high initial fissile fuel content in the fissile zone. The initial fissile fuel used in this study was ^{233}U. In all ^{233}U content cases applied in this study, the FIR values of above 1 were obtained. It means that a fuel-self-sustaining system was achieved in this study. The targets of high fuel burnup and fuel-self-sustaining design were achieved with ^{233}U content in the fissile zone of 10.35%. Even though in the 9.35% and 9.85% ^{233}U content cases the FIR values are higher than that in the 10.35% ^{233}U content case, but the fuel burnup of these configurations were smaller than that of the 10.35% configuration.

The results of inventory analysis indicated that ^{233}Pa is a major factor in the fissile breeding of the thorium fuel cycle as it accumulates in the fuel in a considerable amount. By waiting for the entire ^{233}Pa contained in the discharged fuel to undergo a beta decay to become ^{233}U during the cooling period before the reprocessing can take place, the amount of fissile fuel in the reprocessed fuel can be maximized. It also was found that the fissile plutonium (^{239}Pu and ^{241}Pu) inventory in the core was very small and much smaller than that of uranium (^{233}U and ^{235}U) and ^{233}Pa. From this result, there are two possible options for fissile plutonium utilization in the thorium fuel cycle: it can be safely disposed of as waste since its inventory in the discharged fuel is considerably less than that in UO_2 spent fuel, or it can be recycled back to the core along with the uranium fissile. However, to maximize the sustainability and minimize the proliferation and radiotoxicity, recycling back the fissile plutonium to the core is a more likely excellent option.

From these results, it was confirmed that it is feasible to create a self-sustaining fuel cycle system using thorium fueled reduced moderation boiling water reactor (RBWR). However, there is a trade-off between the core burnup and fissile breeding that can be a significant challenge in the development of this system. Evaluating the other design variables may be considered to address this challenge. The further study to analyze the safety performances of the core is required to arrive at a safe and reliable reactor system.

References

[1] F. Ganda, F. J. Arias, J. L. Vujic, and E. Greenspan, "Self-Sustaining Thorium Boiling Water Reactors", *Sustainability*, vol. 4, pp. 2472-2497, 2014.

[2] P. M. Gorman, J. L. Vujic, and E. Greenspan, "Trade-Off Studies for the Fuel-Self Sustaining RBWR-Th Core" *Nuclear Technology*, vol. 191, pp. 282-294, 2015.

[3] T. Hino, M. Ohtsuka, K. Moriya and M. Matsura, "Light Water Reactor System Designed to Minimize Environmental Burden of Radioactive Waste", *Hitachi Review,* Vol. 63, No. 9, 2014.

[4] Nuclear Energy Agency, *Perspectives on Use of Thorium in the Nuclear Fuel Cycle*, NEA No. 7228, 2015.

[5] H. Y. Choi, and C. J. Park, "Conceptual Design of Thorium Based Epithermal Spectrum Reactor", *Annals of Nuclear Energy*, vol. 109, pp. 61-68, 2017.

[6] D. Medina-Castro, P. L. Hernandez-Adame, C. L. de Leon, L. Sajo-Bohus, H. R. Vega-Carrillo, "Designing a Heterogeneous Subcritical Nuclear Reactor with Thorium-Based Fuel", *Annals of Nuclear Energy*, vol. 96, pp. 455-458, 2016.

[7] B. J. Lewis, E. N. Onder, and A. A. Prudil, *Fundamentals of Nuclear Engineering*, Chichester, West Sussex, United Kingdom: John Wiley & Sons, Inc., 2017.

[8] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavita, and T. Kaltiaisenaho, "The Serpent Monte Carlo Code: Status, Development and Applications in 2013", *Annals of Nuclear Energy*, Vol. 82, pp. 142-150, 2015.

[9] J. Leppänen, M. Pusa, and E. Fridman, "Overview of Methodology for Spatial Homogenization in the Serpent 2 Monte Carlo Code", *Annals of Nuclear Energy*, Vol. 92, pp. 126-136, 2016.

[10] Neil E. Todres and Mujid S. Kazimi, *Nuclear System I: Thermal Hydraulic Fundamentals*, 2nd ed., Boca Raton, USA: CRC Press, 2011.

[11] M. Pusa, *Numerical Methods for Nuclear Fuel Burnup Calculations*, PhD Thesis, Aalto University, 2013.

[12] A. Isolato, *Computational Methods for Burnup Calculations with Monte Carlo Neutronics*, PhD thesis, Aalto University, 2013.

[13] D. Kotlyar and E. Shwageraus, "On the Use of Predictor-Corrector Method for Coupled Monte Carlo Burnup Codes", *Annals of Nuclear Energy*, vol. 58, pp. 228-237, 2013.

[14] A. Isotalo and V. Sahlberg, "Comparison of Neutronics-Depletion Coupling Schemes for Burnup Calculations", *Nuclear Science and Engineering*, vol. 179, pp. 434-459, 2015.

[15] M. Pusa, "Higher-Order Chebyshev Rational Approximation Method and Application to Burnup Equations", *Nuclear Science and Engineering*, vol. 182, pp. 297-318, 2017.

[16] V. Valtavirta, and J. Leppänen, "Coupled Burnup Calculations with the Serpent 2 Monte Carlo Code". In. *Proc of M&C 2017,* Jeju, Korea, 2017.