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The Effect of Nanofluid Coolant and Thorium-added Fuel on Burnup Dependent Isotopic Compositions in VVER-1000 Reactor

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VVER-1000 Reaktöründe Nanoakışkan Soğutucu ve Toryum İlaveli Yakıtın Yanmaya Bağlı İzotopik Kompozisyonlara Etkisi

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Abstract

Recently, the use of nanofluids has gained importance in studies aimed at increasing reactor efficiency while also addressing safety concerns in nuclear technology. Various studies have investigated the effects of adding nanoparticles of different types and proportions to the coolant water on the thermal and neutronic characteristics of power reactors using conventional UO_2 fuels. Given the abundance of thorium compared to uranium, research on thorium-based fuels has become increasingly significant. In this study, the criticality and isotope changes in a VVER-1000 reactor loaded with 5% ThO_2 and 95% UO_2 by mass as fuel, and 0.1% by volume of Al_2O_3, CuO, and TiO_2 nanoparticles as the coolant, were investigated. Neutronic analysis was performed using the MCNP5 and MONTEBURNS2.0 codes. The analysis results indicated that the operational lifespan of the reactor with only water coolant and thorium-based fuel was shortened due to the presence of nanoparticles. Furthermore, it was observed that while there was no significant change in the amount of fissile ^{235}U and fertile ^{238}U isotopes, the consumption of fertile ^{232}Th isotope in the reactor increased with the insertion of nanoparticles into the coolant.

Keywords: *VVER-1000; Criticality; Isotope; Nanoparticle; Thorium-based fuel*

Öz

Son zamanlarda nükleer teknolojide güvenlik faktörlerine dikkat edilerek reaktör verimliliğinin artırılmasına yönelik çalışmalarda nanoakışkanların kullanımı önem kazanmıştır. Geleneksel UO_2 yakıtlarını kullanan güç reaktörlerinde, soğutma suyuna farklı tür ve oranlarda nanopartiküller eklenerek termal ve nötronik karakteristikler üzerine etkilerinin incelendiği çalışmalar bulunmaktadır. Toryum kaynaklarının uranyum kaynaklarından çok daha fazla olduğu göz önüne alındığında toryum bazlı yakıtlara yönelik çalışmalar giderek önem kazanmaktadır. Bu çalışmada, yakıt olarak kütlece %5 ThO_2 ve %95 UO_2 ve soğutucu olarak hacimce %0,1 Al_2O_3, CuO ve TiO2 nanopartikülleri yüklenen VVER-1000 reaktöründeki kritiklik ve izotop değişiklikleri araştırılmıştır. Analizlerde MCNP5 ve MONTEBURNS2.0 nötronik analiz kodları kullanılmıştır. Analiz sonucu, nanopartiküllerin etkisiyle sadece su soğutucu ve toryum bazlı yakıtın bulunduğu reaktörün çalışma süresinin kısaldığını göstermiştir. Ayrıca ^{235}U ve ^{238}U izotop miktarında önemli bir değişiklik olmadığı ancak nanopartiküllerin soğutucuya eklenmesiyle reaktörde tüketilen ^{232}Th izotop miktarının arttığı gözlemlenmiştir.

Anahtar Kelimeler: *VVER-1000; Kritiklik; İzotop; Nanoparçacık; Toryum tabanlı yakıt*

1. Introduction

The known reserves of uranium, the main fuel component of nuclear power plants, are limited and expensive (Dungan et al. 2017), making the search for alternatives to uranium increasingly important. The fertile element thorium cannot be used alone as fuel in nuclear power reactors (Ünak 2020). Thorium-based fuels require fissile elements such as ^{235}U and ^{239}Pu isotopes to sustain nuclear chain reactions. However, recent attention has been focused on thorium for reasons such as its abundance, the potential to reduce enrichment needs in the fuel cycle, and the high conversion rate of fertile ^{232}Th to fissile ^{233}U in the thermal neutron spectrum (Lau et al. 2014, Mustafa et al. 2019). Thorium and its potential applications in nuclear technology were undervalued until recently, primarily due to the geographical distribution of thorium reserves. Thorium-based fuels offer promising compositions and could be utilized as thorium-based mixed oxide in many reactor cores without significant changes in reactor design (Mustafa et al. 2019, IAEA 2005).

Since the years when nuclear technology started to be used in the world, developed countries such as the USA, Germany, Canada, France, Japan and England have

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conducted nuclear fuel research programs based on thorium (Humphrey and Khandaker 2018). Researchers studying the present and future of the thorium fuel cycle are evaluating the developments related to thorium and examining the pros and cons of utilizing thorium-based nuclear fuels in commercial reactors. Dwiddar et al. in their study (Dwiddar et al. 2015), they mentioned the superiority of thorium in terms of safety measures and that thorium is an alternative as a fuel, they concluded that thorium is more useful because it produces less minor actinide compared to uranium fuel. They studied the effect of thorium as a part of nuclear fuel on the neutronic parameters of the VVER-1200 first core. Two different models, namely mixed thorium uranium fuel and seed blanket fuel, were compared. According to the amount of thorium placed, the position of the thorium assemblies in the reactor core, the effective multiplication factor has been found. It has been found that the best location is the location where thorium is placed around the core. They concluded that the use of uranium-thorium fuels would be advantageous, especially for a country with a high thorium reserve. Jan Frybort emphasized in his study that thorium fuel could be an alternative to uranium fuel in nuclear power plants. He stated that in U-Th fuel, the presence of small actinides in nuclear waste will be negligible. Thorium fuel consumption in VVER-1000 reactor with the help of MCNP code based on Monte Carlo methods is investigated. Dose values of calculated actinide compositions and gamma radiation were compared with uranium fuel and radiological damages were compared for two fuels (Fryort 2014). Substantial quantities of plutonium are produced within the nuclear waste of Light Water Reactors (LWRs) and CANDU reactors. Reactor-grade plutonium, in the configuration of a mixed ThO_2/PuO_2 fuel, can serve as supplementary fissile material within a CANDU fuel assembly, guaranteeing sustained reactor criticality. In their studies, researchers are investigating the possibilities of utilizing the rich thorium reserves in the world in CANDU reactors. In their study for two different fuel types, they examined the change in criticality. The reactor criticality will be sufficient provided that the fuel rods can be manufactured to withstand such high levels of burnup until most of the thorium fuel is burned. They conclude that fuel generation costs and nuclear waste mass for final disposal per unit energy can be greatly reduced (Şahin et al. 2006). In the final report of the Coordinated Research Project (CRP) on "The Potential of Thorium-Based Fuel Cycles to Limit Plutonium and Reduce Long-Term Waste Toxicity" initiated by IAEA in 1995, different fuel cycle options where plutonium can be recycled with thorium for incineration were investigated, and the potential of the thorium matrix was investigated by computer simulations. A comparison among various cycles has been conducted based on specific predefined criteria, such as the yearly decline in plutonium reserves. Research has delved into the radiotoxicity buildup and transformative capacity of thorium-based systems across current, cutting-edge, and pioneering nuclear power reactor designs (IAEA 2003). In many recent studies, the use of nanoparticles has gained importance and its effect has begun to be investigated in almost every field of science. In nuclear technology, water is commonly preferred as moderator and coolant in studies which thorium-based fuels are used as fuel however it is aimed to increase the thermal conductivity of the coolant by adding nanoparticles into the coolant and thus maximize the energy drawn from the system. In many studies, it has been tried to observe the effects of adding nanoparticle into the coolant in reactors fueled with UO_2 fuel (Ghazanfari et al. 2016, Hadad et al. 2010, Zarifi et al. 2013). However, in a reactor containing thorium fuel, the nanoparticle effect added to the coolant has not been studied yet.

This investigation focuses on conducting a neutronic analysis of the VVER-1000 reactor employing thorium-based fuel and utilizing nanofluid as a coolant. The primary objective is to assess the advantages and disadvantages associated with employing thorium in conjunction with nanofluid within this reactor system. Neutronic calculations were conducted by the help of MCNP5 code (Briesmeister 2000). As a result of neutronic calculations, effective multiplication factor and change of isotopes were obtained for thorium at varying rates and three nanofluidic coolant.

2. Materials and Methods

The born of Water-Water Energetic Reactor (WWER) or VVER (Voda-Vodyanoi Energetichesky Reaktor) type reactors originally designed and produced by Soviet Union dates back to the 1970s. VVER-440 V179 and VVER-440 V230 power reactors generating 440 MW electrical power are classified as the 1st generation reactors and have a distinctive design. All models of VVER-1000 power reactors except for Model V392, V428 and V412 are named as the 2nd generation of VVER and produces 1000 MWe power. Due to the fact that VVER-1000 Model V392, V428 and V412 have augmented control, safety and containment systems, these models are considered as 3rd generation. The latest model of VVER power reactor offering additional passive safety systems is named as VVER-1200 delivering 1200 MWe electrical output and categorized as generation 3+ reactor. Among the developed models of VVER reactor, VVER-1000 is the most preferred power reactors and today 31 units of it are operating around the world (Rosatom 2015). An image of a VVER reactor is shown in Figure 1 (Kanik et al. 2022).

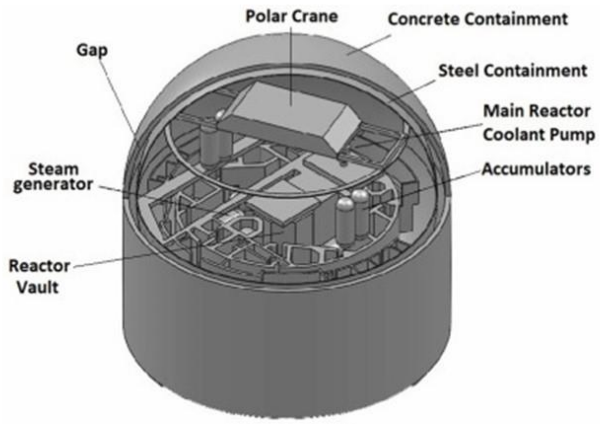

Figure 1. The design of the VVER-1000 containment

To briefly refer to the design parameters, VVER-1000 reactors contain 163 fuel assemblies in the core and 312 fuel rods per fuel assembly (Saadati et al. 2018, Nourollahi et al. 2018). The most important features that distinguish VVER-1000 reactors from the most widely used pressurized water reactors in the world are the hexagonal core structure and horizontal steam generators (Janos 2011). Other design features for the VVER-1000 reactor are shown in Table 1 (Acir et al. 2021).

Table 1. General characteristics of VVER-1000

Fuel assembly	
Lattice type	Hexagonal
Number of fuel assembly in the core	163
Pitch between the assemblies (mm)	23.6
Number of fuel rod in the fuel assembly	312
Fuel rod	
Fuel pellet outside diameter (mm)	7.57
Cladding inside diameter (mm)	7.73
Cladding outside diameter (mm)	9.1
Fuel pellet material	LEU + ThO_2
Cladding material	%98.97 Zr, %1 Nb, %0.03 Hf
Fuel rod pitch (mm)	12.75
Guide tube	
Number of guide tubes per F. A	18
Inside diameter / Outside diameter (mm)	10.9 / 12.6

Horizontal cross section MCNP model of VVER-1000 assembly is shown Figure 2 (Uzun et al. 2022). Figure 2 represents the horizontal cross section model obtained with MCNP, and according to the figure, the yellow shown is the fuel zone, while the pink (excluding guide tube) one represents the coolant.

Using the geometric features of VVER-1000 nuclear reactor presented in Table 1, the reactor fuel assembly was modeled with MCNP5 neutronic code and neutronic calculations were performed with the help of MCNP5 and Monteburns2.0 codes. The fuel pellet materials are fueled with homogeneously distributed fuel which is composed of 95% UO_2 (with 3.7% enrichment) and 5% ThO_2 by weight. As a base case, primary coolant is water. Then, three different nanoparticles with 0.1% volume fraction are added to the working fluid. The nanoparticles considered in this study were Al_2O_3, TiO_2 and CuO.

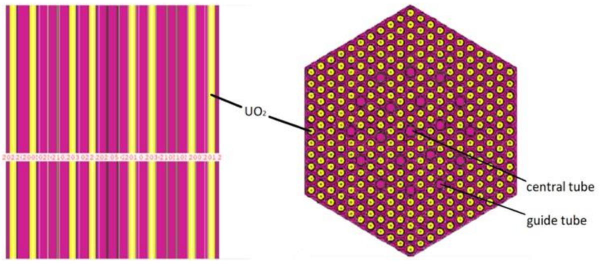

Figure 2. Horizontal cross section MCNP model of VVER-1000 assembly

3. Results and Discussions

3.1 Assessments of Criticality (keff)

In order to sustain fission reactions, which are the main components of energy production in nuclear power reactors, it is essential to produce at least one or more neutron that will continue the fission. Therefore, the effective multiplication factor, or criticality value (k_{eff}), which effectively defines all possible events during the interactions of a neutron, is very important. As long as the effective multiplication factor is in critical state, and power is generated in a controlled manner with the help of control rods, water-soluble and neutron-absorbing boron in power reactors. In Figure 3, the variations of criticality values at full power according to operating time for water and three different nanofluids as working fluid are compared. As can be seen in Figure 3, the operating time of the reactor with water as working fluid is determined to be approximately 930 days. However, it is determined that the addition of nanoparticles, regardless of what kind of nanoparticles is, to water reduces the criticality and operating life time of the reactor.

With addition of Al_2O_3, TiO_2 and CuO nanoparticles to water, the operating time of the reactor which can remain critical and generate power is reduced to 870, 690 and 660 days, respectively. It was observed that the reduction in k_{eff} values is higher for the fluid containing CuO and TiO_2 nanoparticles. The main reason for this is related to the higher absorption cross section of Cu and Ti nanoparticles when compared to the others.The fraction of hydrogen which has the highest scattering cross section in nanofluid decreases with the addition of nanoparticles into water. Thus, the total scattering cross section of water containing nanoparticles decreases but absorption cross section of nanofluid increases. As a result, the effective multiplication factor decrease, gradually (Kianpour and Ansarifar 2019).

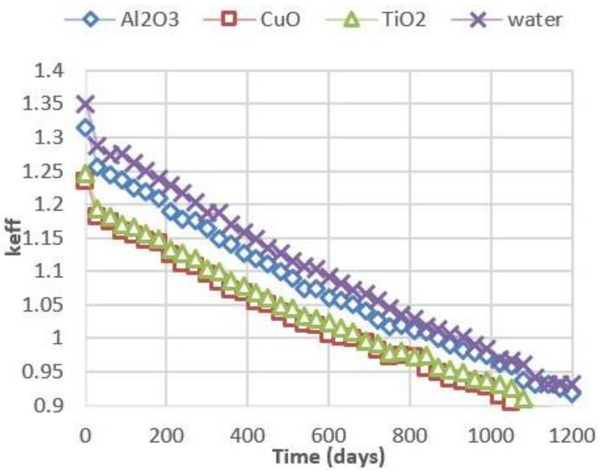

Figure 3. Criticality variations with nanoparticle coolant

3.2. Isotope Changes

The number of fission reactions or the operating time of the reactor highly depends on the amount of fissile and fertile isotopes present in the reactor fuel rods. Within the scope of this study, by using the predetermined homogeneously distributed fuel which is composed of 95% UO_2+ 5% ThO_2 by mass and coolant containing 0.1% of Al_2O_3, CuO and TiO_2 nanoparticles combination, it is aimed to determine how the amount of isotopes in the fuel assembly according to reactor operating time changes. Since ^{232}Th is the fertile material and it cannot be used as a nuclear fuel by itself. However, ^{232}Th isotope can be used as an alternative material instead of fertile ^{238}U isotope.

During the operation of reactor, the fertile ^{232}Th isotope capture a thermal neutron to transform into the ^{233}U fissile isotope, and then within 22.1 minutes ^{233}Th decay to ^{233}Pa (Protactinium-233) isotope before ^{233}Pa decay into ^{233}U after 27 days. The main conversion reaction of fertile ^{232}Th is shown in Eq.1 (Gosen and Tulsidas 2016).

$$^{232}\text{Th (fertile)} \xrightarrow{(n,\gamma)} {}^{233}\text{Th} \xrightarrow{\beta^-} {}^{233}\text{Pa} \xrightarrow{\beta^-} {}^{233}\text{U(fissile)} \quad (1)$$

In Figure 4, the variation of ^{232}Th isotope is presented for four different coolants. As can be seen in figure, it is observed that with the addition of nanoparticles to water the amount of ^{232}Th isotope spent in the reactor increases over time when compared to the case that water is used as a coolant only (Galahom 2020). It is estimated that the main reason for this case is the fact that with the addition of nanoparticles into the water, the density of nanofluidic coolant get higher and more fast neutrons are able to moderate when compared to water.

When considered operating time of reactor, it can be deduced that consumption rate of ^{232}Th isotope in reactor cooled with water, water containing Al_2O_3, TiO_2 and CuO is approximately 1.23, 1.32, 1.37 and 1.36 g/d, respectively.

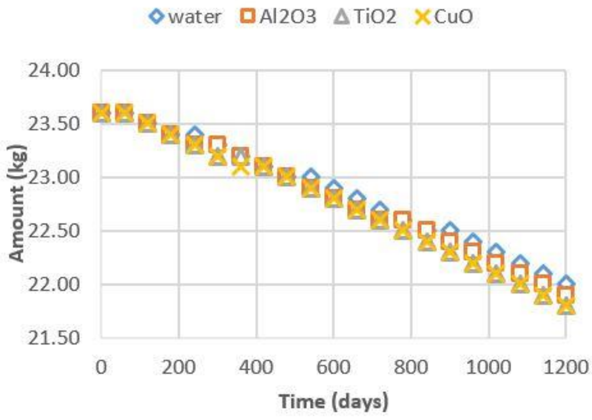

Figure 4. Variation of the ^{232}Th isotope

Figure 5 shows the formation of ^{233}Pa isotope. The ^{233}Pa isotope, which was initially absent in the reactor core, is produced upon capture of ^{232}Th isotope and exists in small amounts at the end of time of the reactor for water and nanofluidic coolant vary, during the operating time of the operating cycle of the reactor. Although operating reactor with water and water containing nanoparticles Al_2O_3, TiO_2 and CuO as coolant, respectively 55.35, 58.80, 56.70 and 55.30 g of ^{233}Pa was formed in the reactor.

Figure 6 represents the generation of fissile isotope ^{233}U according to operating time of the reactor. Accordingly, ^{233}U does not exist in the reactor core at the beginning. However, as a result of ^{233}Pa decaying to ^{233}U in the reactor, approximately 563 g of ^{233}U was formed in the reactor for the case that only water is used as coolant during the 960 days of operating time. Similarly, for Al_2O_3, TiO_2 and CuO nanofluidic coolants, approximately 596, 541 and 524 g of ^{233}U is produced, respectively. It is observed that with the effect of Al_2O_3 nanoparticles added to the coolant, ^{233}U generation increased a little bit. On the other hand, with the insertion of TiO_2 and CuO nanoparticles whose absorption cross section are much higher than Al_2O_3 into the water, operating time of reactor decreases significantly. Consequently, the amount of ^{233}U formed in the reactor reduces when compared to the case water is used as coolant.

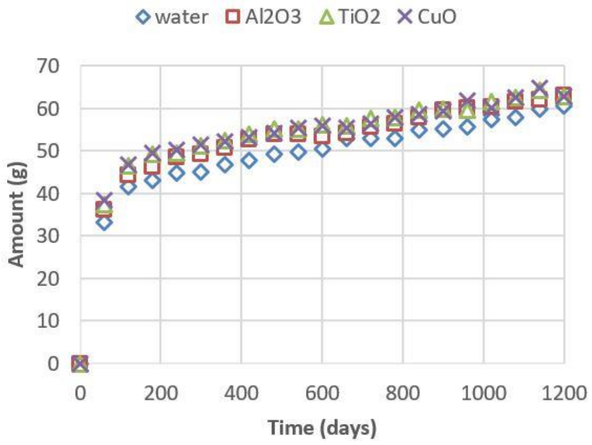

Figure 5. Variation of the ^{233}Pa isotope

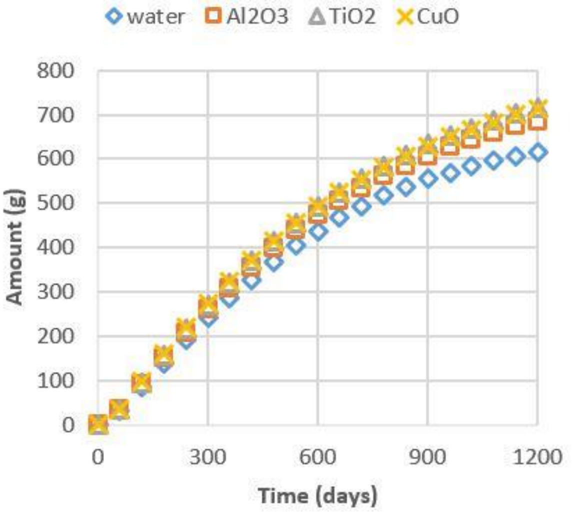

Figure 6. Variation of the ^{233}U isotope

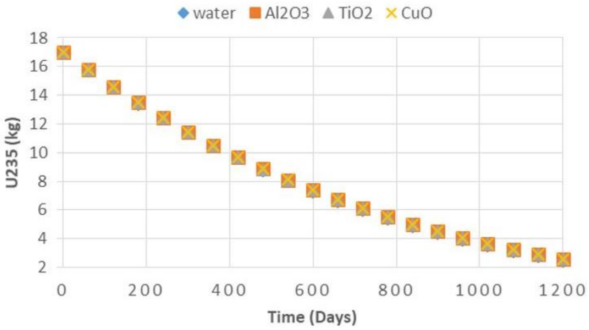

Figure 7. Variation of the ^{235}U isotope

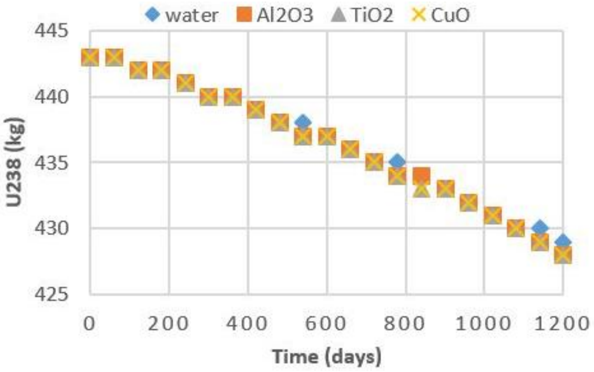

Figure 8. Variation of the ^{238}U isotope

The change of fissile isotope 235U, which is the main fuel material of the reactor, during the 1200 day operating period is shown in Figure 7. As can be seen in Figure 7, the amount of 235U isotope producing energy by fission decrease over time and no significant change has been observed with the utilization of nanofluidic coolant. In Figure 8, the change of 238U, the main fertile material in the reactor, is presented. As can be seen from the figure, all investigated cases have shown similar tendencies in the consumption of 238U and it is no noticeable change in the amount of 238U during the operating time of the reactor for all cases.

In nuclear reactors, the 238U isotope can turn into 239Pu by capturing neutrons as a result of burnup. This process plays an important role in the fuel cycle of nuclear reactors, and 239Pu is considered a fission material usable in nuclear energy production. The change of 239U isotope is shown in Figure 9.

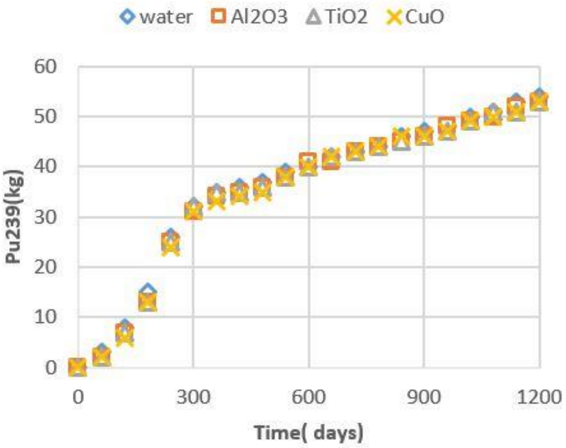

Figure 9. Variation of the ^{239}Pu isotope

4. Conclusions

In this study, criticality and burnup calculations have been performed for a reactor fueled with 5% ThO_2 and 95% UO_2 by mass as fuel and 0.1% by volume Al_2O_3, CuO and TiO_2 nanoparticles as the coolant. For each case, the effective multiplication factor value and the changes of the isotopes in the fuel composition according to the operating time were calculated and the results obtained were compared between each other in order to reveal their potential benefits or drawbacks.

- Since it reduces the criticality value less than other nanoparticles, the use of Al_2O_3 nanoparticle in the coolant gave more appropriate results.
- The criticality value decreased to approximately 0.97 for Al_2O_3 at the end of 930 days, this value is approximately 1 for water.

- It is observed that consumption of thorium isotope could be increased although the operating time of the reactor decreases due to the effect of nanoparticles adding into coolant.
- According to the results, it was concluded that ThO_2 added fuel and coolant containing nanoparticles decreases operating time of reactor, however it can be beneficial to use this fuel-coolant combination in terms of neutronic point of view.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, visualization and writing – original draft,
Author-2: Conceptualization, investigation, methodology and software, supervision and writing – review and editing,
Author-3: Supervision and writing – review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The authors declare that the main data supporting the findings of this work are available within the article.

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