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Research Article

Performance Analysis of MOX and Thorium Dioxide Fuels in Accelerator-Driven Systems

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ABSTRACT

Accelerator-Driven Systems (ADS) utilize high-energy particle beams to provide innovative solutions in fields such as medical radioisotope production, nuclear waste transmutation, and clean energy generation. ADS is expected to play a significant role in solving future challenges in healthcare and energy. In this study, plutonium dioxide (PuO_2) and thorium dioxide (ThO_2) fuels were mixed in different ratios and placed in the fuel region of the ADS. The PuO_2 fuel used in this system was extracted from MOX fuel, which is a byproduct of thermal reactors. The other fuel type, thorium, reacts with neutrons released from the target region of the ADS, converting into uranium-233 (^{233}U), which contributes to energy production. Thus, waste generated by thermal reactors is reutilized in *Accelerator-Driven Systems (ADS), reducing environmental harm while also contributing to additional energy production. The neutron multiplication factor, a crucial parameter for the efficient operation of ADS, was maintained at approximately 0.98. Neutronic analyses were performed using the MCNPX 2.7 code and its integrated CINDER 90 program.*

Keywords: *ADS, MOX, MCNPX 2.7, Thorium dioxide*

Hızlandırıcı Sürücülü Sistemlerde MOX ve Toryum Dioksit Yakıtlarının Performans Analizi

ÖZ

Hızlandırıcı sürücülü sistemler (HSS), yüksek enerjiye sahip parçacık demetlerini kullanarak tıbbi radyoizotop üretimi, nükleer atık dönüşümü temiz enerji üretimi gibi alanlarda yenilikçi çözümler ortaya koyan sistemlerdir. HSS'ler gelecekte sağlık ve enerji alanlarındaki problemlerin çözümlenmesinde önemli bir rol oynayacaktır. Çalışmada, HSS'in yakıt bölgesine plütonyum dioksit (PuO2) ve toryum dioksit (ThO2) yakıtları farklı oranlarda karıştırılarak konulmuştur. Buradaki PuO2 yakıtı termal reaktörlerden atık olarak ortaya çıkan MOX yakıtı içerisinden alınmıştır. Sisteme konulan diğer yakıt türü toryum ise, HSS'in hedef bölgesinden açığa çıkan nötronlarla reaksiyona girerek 233U izotopuna dönüşmekte ve bu süreç de enerji üretimine katkıda bulunmaktadır. Böylelikle termal reaktörlerin

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çalışması sonucu açığa çıkan atıklar, Hızlandırıcı Sürücülü Sistemlerde (HSS) yeniden değerlendirilerek hem çevresel zararın azaltılmasına hem de sistemin ek enerji üretimine katkı sağlamaktadır. HSS'in verimli bir şekilde çalışmasında önemli bir parametre olan nötron çoğaltma faktörü 0.98 civarında tutulmuştur. Nötronik analizlerin gerçekleştirilmesinde MCNPX 2.7 ve onunla entegre bir şekilde çalışan CINDER 90 programlarından faydalanılmıştır.

Anahtar Kelimeler: *HSS, MOX, MCNPX 2.7, Toryum dioksit*

I. INTRODUCTION

With the development of industry and technology, along with the increasing population, there has been a significant rise in energy demand. Due to the reliance on fossil fuels in traditional energy production, environmental degradation and irreversible damage to natural ecosystems have occurred. This situation has created the need for environmentally friendly, sustainable, and efficient energy production methods. Considering environmental and other factors, energy production systems utilizing renewable energy sources, nuclear power plants, and accelerator-driven systems have come to the forefront. Nuclear power plants (NPPs) stand out as an alternative energy source due to their low carbon emissions, continuous, and reliable energy production. Additionally, conventional nuclear power plants are self-sustaining systems based on a chain fission reaction. In NPPs, the fission reaction, once initiated in a controlled manner, can continue without external intervention. In Accelerator-Driven Systems (ADS), however, the chain reaction is initiated by high-energy protons from a particle accelerator. When the accelerator is turned off, the reaction stops, meaning the system is not self-sustaining. Furthermore, since ADS operates in a subcritical state, it is considered safer and plays a significant role in the disposal of nuclear waste generated in conventional reactors.

In recent years, numerous studies have been conducted on nuclear waste transmutation and fissile fuel production in Accelerator-Driven Systems (ADS). In the studies conducted by Barros et al., the reuse of thorium and spent fuels as fuel in ADS has been investigated. The research evaluates fuel transmutation and neutronic parameters in a lead-cooled ADS. A fuel composed of plutonium and minor actinides extracted from spent fuel using the GANEX method, mixed with thorium or spent uranium fuel, was used. Calculations were performed using the Monteburns 2.0 (MCNP/ORIGEN 2.1) code [1, 2]. Vu and Kitada [3] stated in their study that the inclusion of thorium fuel in the core is an effective method for the transmutation of plutonium and minor actinides (MA), and that energy can be obtained from this process. Abánades and Pérez-Navarro [4] examined nuclear waste transmutation in a gas-cooled ADS. The study focused on the design of a subcritical reactor cooled with helium and moderated by graphite. Tsujimoto et al. [5] used a lead-bismuth-cooled ADS reactor for minor actinide (MA) transmutation and performed neutronic calculations. The results indicated that when the effective neutron multiplication factor is 0.97, ADS designs can transmute MA more efficiently. Yapıcı et al. [6] analyzed the neutronic behavior of infinite target environments driven by high-energy protons. In their study, neutron production properties of target materials such as lead-bismuth eutectic (LBE), mercury, tungsten, uranium, thorium, chromium, copper, and beryllium were evaluated under the influence of isotropic point-source protons with an energy of 1000 MeV. Bakır et al. [7] demonstrated that high neutronic performance can be achieved for ADS design and fuel compositions in nuclear waste transmutation, fissile fuel production, and energy generation. Cho et al. [8] examined the numerical design of a 20 MW lead-bismuth eutectic (LBE) spallation target for ADS. For an ADS driven by a 1 GeV proton beam, a spallation target design was proposed for a system with 1000 MW of thermal power. Şahin et al. [9] conducted a comprehensive study on the feasibility of using plutonium and/or minor actinides mixed with thorium as fuel. Attom et al. [10] compared homogeneous and heterogeneous thorium fuel combinations in long-life high-temperature reactors (HTR) and showed that plutonium-driven MOX blocks have a higher burnup rate. An Accelerator-Driven System consists of a particle accelerator that produces high-energy protons. These protons interact with a spallation target to generate neutrons. The spallation target is located at the center of a subcritical core containing nuclear fuel. The nuclear fuel may consist of transuranic elements, materials used to convert long-lived fission products into shortlived isotopes, or mixtures such as uranium-thorium (U + Th) and plutonium-thorium (Pu + Th) [11]. One effective way to reduce plutonium stocks is to use it as fuel in reactors. Since plutonium is a highly efficient nuclear fuel, its combination with thorium enables the direct production of new fissile material within the reactor.

In this research, the feasibility of a fuel cycle based on PuO_2 and ThO_2 fuel mixtures was analyzed. The analyzed parameters include the effective neutron multiplication factor and energy gain values. Various fuel regions were created by altering the thorium and plutonium ratios for four different MOX fuel types. Fuel regions predominantly containing thorium (%100 Th - %0 Pu) were used for MOX11, MOX12, MOX21, and MOX22, while additional regions included combinations where plutonium content varied between 10% and 25%. This diversification was aimed at evaluating the impact of different fuel mixtures on reactor performance. The keff values for different proposed cases were calculated using the MCNPX code. The calculation results for different fuel ratios (10%, 15%, 20%, 25%, and 30%) are presented.

II. MATERIAL AND METHOD

A. ACCELERATOR-DRIVEN SYSTEM DESIGN

In this paper, an accelerator-driven system design is examined, and a reactor has been designed. The system, as illustrated in figure 1, consists of four main regions: the spallation neutron target, the fuel region, the coolant region, and the graphite region. Each of these regions has been designed with specific characteristics to enhance the overall performance and safety of the reactor.

A. 1. Spallation Neutron Target

In accelerator-driven systems, high-energy protons must interact with the target material to generate neutrons. This process leads to the release of high-energy neutrons through spallation reactions. Typically, lead-bismuth eutectic (LBE) alloy is preferred as the spallation target due to its high thermal conductivity and excellent neutron production capacity [12].

A. 2. Fuel Region

Four different MOX types (MOX11, MOX12, MOX21, and MOX22) have been evaluated in the reactor's fuel region. In addition to the PuO_2 component in the MOX composition, thorium dioxide (ThO_2) has been added in specific proportions to create a heterogeneous fuel mixture. This approach aims to achieve a more efficient fission process while also facilitating fuel transmutation.

A. 3. Coolant Region

Helium gas has been used as the coolant in the reactor. Helium stands out as a suitable coolant for nuclear reactors due to its low neutron absorption cross-section and inert nature.

A. 4. Graphite Region

In this region, graphite material, which has neutron moderating properties, radiation resistance, and high thermal stability, has been preferred. The lightweight structure and high-temperature resistance of graphite allow this component to be effectively used in the shielding region.
These sections have been designed to ensure the safe and efficient operation of the reactor, highlighting the potential of ADS for sustainable energy production and radioactive waste transmutation.

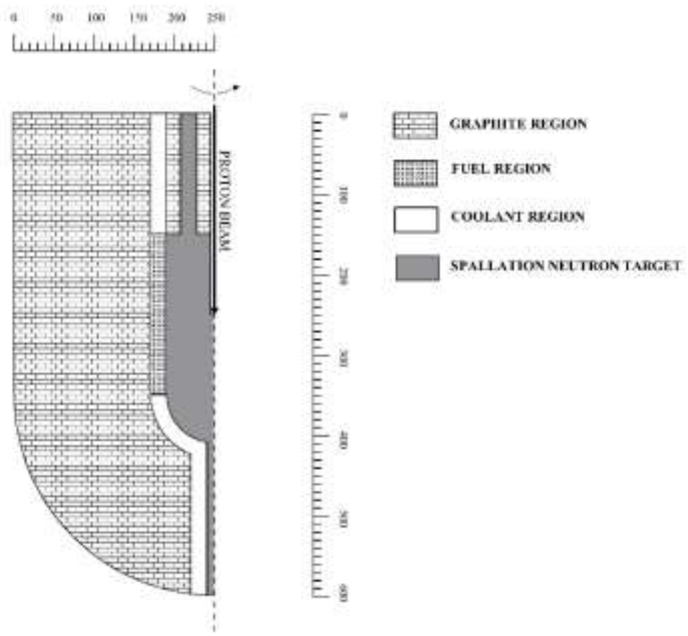

Figure 1. *Half-Section view of the Accelerator-Driven System* [13]

III. NEUTRONIC CALCULATIONS

Neutronic analyses were performed using proton beams with an energy of 1000 MeV, aiming to achieve maximum energy gain. In the study, four different types of MOX (MOX11, MOX21, MOX12, and MOX22) were considered, and the performance differences of these fuels were analyzed in detail. For each MOX fuel, calculations were performed by mixing plutonium dioxide (PuO_2) and thorium dioxide (ThO_2) in varying proportions from 0% to 90%. The effects of these fuel combinations on the neutron multiplication factor (k_{eff}) and energy gain have been comprehensively evaluated. For accelerator-driven systems to operate reliably, the neutron multiplication factor (k_{eff}) must not exceed a value of 1. Neutronic analyses were carried out using the MCNPX 2.7 [14] nuclear simulation code. Additionally, for sub-critical system calculations, the CINDER 90 [15] program, which works in coordination with the MCNPX simulation code, was utilized.

A. NUMERICAL RESULTS

A. 1. Neutron Multiplication Factor

This factor plays a critical role in expressing the operational state of a reactor. Especially in sub-critical reactors such as accelerator-driven systems (ADS), it is essential for k_{eff} to be close to 1 but not exceed 1 for safety reasons.

$$keff = \frac{Number\ of\ neutrons\ in\ the\ next\ generation}{Number\ of\ neutrons\ in\ the\ previous\ generation} \quad (1)$$

A. 2. Energy Gain

It is defined as the ratio of the total energy produced from fission reactions to the energy spent on accelerating proton beams into the system. This parameter plays a critical role in determining the energy efficiency of an ADS and is used as a key criterion to assess how much energy the system can produce compared to the energy spent.

$$G = \frac{R_f E_f}{E_p} \tag{2}$$

Here; E_p is the proton energy, and E_f is the energy released per fission.

In Tables 1, 2, 3, and 4, the percentages of fuels placed in the fuel region are shown. The neutron multiplication factors and energy gain values obtained based on these usage amounts are also presented.

Table 1. *The placement ratios of thorium dioxide and plutonium dioxide by region in the MOX 11 fuel condition (For the MOX 11 fuel condition, when the fuels are placed in this way into 10 fuel regions : k_{eff} = 0.98974, Gain = 155.798 (MeV))*

Number of Fuel Regions	**ThO_2** *(%)*	**PuO_2** *(%)*
4	100	0
1	95	5
1	85	15
1	80	20
2	75	25

When the k_{eff} values obtained in table 1 are examined, it can be seen that the MOX11 fuel has the highest k_{eff} value (0.98974), indicating that the neutron multiplication factor is better maintained in regions with higher thorium content. The MOX11 fuel contains plutonium ratios ranging from 0% to 25%, and it can be said that k_{eff} values are relatively higher, especially in regions with low plutonium content. This can be explained by the potential of thorium to convert into U-233, which undergoes fission with thermal neutrons. The highest energy gain value, 155.798 MeV, was obtained for MOX11. This can be attributed to the fact that the neutron multiplication factor of MOX11 is higher compared to other fuel types. As a thorium-based fuel, MOX11 provides an advantage in U-233 production, resulting in a higher energy gain value.

Table 2. *The placement ratios of thorium dioxide and plutonium dioxide by region in the MOX 12 fuel condition (For the MOX 11 fuel condition, when the fuels are placed in this way into 10 fuel regions: k_{eff} = 0.98659, Gain = 104.450 (MeV))*

Number of Fuel Regions	**ThO_2** *(%)*	**PuO_2** *(%)*
3	100	0
5	90	10
2	80	20

When table 2 for the MOX12 fuel is examined, it can be seen that with a keff value of 0.98659, it has a lower neutron multiplication factor compared to MOX11. Plutonium ratios ranging from 0% to 20% were used in this fuel type. This decrease can be attributed to the effect of increasing plutonium content on neutron economy and the more pronounced neutron losses in the fuel region design of MOX12. MOX12 shows a lower energy gain value of 104.450 MeV compared to MOX11. This decrease is due to the different distribution of plutonium ratios in MOX12 compared to MOX11, and the resulting changes in the neutron spectrum.

__Table 3.__ The placement ratios of thorium dioxide and plutonium dioxide by region in the MOX 21 fuel condition (For the MOX 11 fuel condition, when the fuels are placed in this way into 10 fuel regions : k_{eff} = 0.98615, Gain = 103.342 (MeV)

Number of Fuel Regions	ThO_2 (%)	PuO_2 (%)
4	100	0
1	90	10
2	85	15
2	80	20
1	70	30

When looking at table 3 for the MOX21 fuel case, the k_{eff} value is 0.98515, which shows a slightly lower neutron multiplication factor compared to MOX11 and MOX12. This fuel type has plutonium ratios ranging from 0% to 30%. Although increasing the plutonium content somewhat increases fission efficiency, the change in the neutron spectrum due to the high plutonium content and the resulting decrease in thorium's potential to produce U-233 causes the k_{eff} value to decrease. The MOX21 fuel case shows a value of 103.342 MeV for energy gain, which is quite close to MOX12. The variation in plutonium content from 0% to 30% causes the neutrons to be directed towards higher energy regions, resulting in the energy gain remaining at a certain level.

__Table 4.__ The placement ratios of thorium dioxide and plutonium dioxide by region in the MOX 22 fuel condition For the MOX 11 fuel condition, when the fuels are placed in this way into 10 fuel regions : keff = 0.98804, Gain = 91.200 (MeV)

Number of Fuel Regions	ThO_2 (%)	PuO_2 (%)
3	100	0
2	95	5
1	85	15
1	80	20
1	75	25
1	70	30

In the evaluation of the MOX22 fuel case in table 4, it can be seen that with a k_{eff} value of 0.98804, it has a relatively higher neutron multiplication factor compared to MOX12 and MOX21. Plutonium ratios ranging from 0% to 30% were used in this fuel type. The fact that the k_{eff} value of MOX22 is higher than that of MOX21 can be explained by the more balanced distribution of the fuel's heterogeneous structure and the thorium-plutonium ratios distributed across different regions, which provides a more balanced neutron economy. The energy gain of MOX22 has been calculated as 91.200 MeV. This value represents the lowest energy gain among the fuels evaluated in the study. This decrease can be explained by the effect of the heterogeneous fuel structure on the neutron flux and the fact that, although the fuel content is similar to MOX21, it exhibits a different distribution.

IV. CONCLUSION

The findings obtained from this study are as follows:

- The highest k_{eff} and energy gain values of MOX11 highlight the advantages of thorium-based fuels. However, increasing the plutonium content in MOX21 and MOX22 caused the k_{eff} values to remain at certain levels.

- Although the k_{eff} value of MOX22 is higher than that of MOX21, its energy gain is the lowest, emphasizing the impact of the heterogeneous fuel structure on neutron distribution.
- The MOX11 case, characterized by a more homogeneous and thorium-rich structure, achieved the highest energy gain among all cases with 155.798 MeV. This outcome can be attributed to thorium's low neutron absorption cross-section, which allows for more efficient utilization of available neutrons in the system.
- The MOX11 case, the k_{eff} value was calculated as 0.98974. This indicates a high level of sustainability of chain reaction, likely due to the balanced distribution of plutonium within the fuel, which enhances neutron production efficiency.

This study demonstrates that thorium-based fuels offer significant advantages in terms of neutron economy, proliferation resistance, and environmental impact, consistent with previous research. Thorium enables high neutron efficiency through the production of 233^{233}233U, facilitating a fuel cycle with enhanced proliferation resistance and reduced environmental footprint. Additionally, the abundance of thorium resources and its low radiotoxicity contribute importantly to sustainable energy policies. In the design phase, careful optimization of thorium-plutonium ratios is required, as localized plutonium accumulation may adversely affect energy gain and disrupt neutron flux balance. Therefore, future studies should focus on more gradual and balanced plutonium distributions. Furthermore, it is crucial to integrate neutronic analyses with thermal-hydraulic calculations, evaluate long-term fuel consumption, and investigate advanced moderator and reflector materials to improve neutron economy. In conclusion, this study highlights the potential of Accelerator-Driven Systems (ADS) technology for nuclear waste management and sustainable energy production, contributing to the effective utilization of thorium-based fuels within these systems.

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V. REFERENCES

[1] G. P. Barros, C. Pereira, M. A. F. Veloso and A. L. Costa, "Thorium and reprocessed fuel utilization in an accelerator-driven system," *Annals of Nuclear Energy*, vol. 80, pp. 14–20, 2015.

[2] G. P. Barros, C. Pereira, M. A. F. Veloso and A. L. Costa, "Study of an ADS loaded with thorium and reprocessed fuel," *Science and Technology of Nuclear Installations*, vol. 2012, 2012, Art. no. 934105.

[3] T. M. Vu and T. Kitada, "Transmutation strategy using thorium-reprocessed fuel ADS for future reactors in Vietnam," *Science and Technology of Nuclear Installations,* vol. 2013, 2013, Art. no. 674638.

[4] A. Abánades and A. Pérez-Navarro, "Engineering design studies for the transmutation of nuclear wastes with a gas-cooled pebble-bed ADS," *Nuclear Engineering and Design*, vol. 237, no. 3, pp. 325–333, 2007.

[5] K. Tsujimoto, T. Sasa, K. Nishihara, H. Oigawa and H. Takano, "Neutronics design for lead-bismuth cooled accelerator-driven system for transmutation of minor actinide," *Journal of Nuclear Science and Technology*, vol. 41, no. 1, pp. 21–36, 2004.

[6] H. Yapıcı, G. Genç and N. Demir, "Neutronic limits in infinite target mediums driven by high energetic protons," *Annals of Nuclear Energy*, vol. 34, no. 5, pp. 374–384, 2007.

[7] G. Bakır, B. S. Selçuklu, G. Genç and H. Yapıcı, "Neutronic analysis of LBE–uranium spallation target accelerator driven system loaded with uranium dioxide in TRISO particles," *Acta Physica Polonica A*, vol. 129, no. 1, pp. 30–32, 2016.

[8] C. H. Cho, T. Y. Song and N. I. Tak, "Numerical design of a 20 MW lead–bismuth spallation target for an accelerator-driven system," *Nuclear Engineering and Design*, vol. 229, no. 2–3, pp. 317–327, 2004.

[9] S. Şahin, K. Yıldız, H. M. Şahin and A. Acır, "Investigation of CANDU reactors as a thorium burner," *Energy Conversion and Management*, vol. 47, no. 13–14, pp. 1661–1675, 2006.

[10] A. M. Attom, J. Wang, J. Huang, C. Yan and M. Ding, "Comparison of homogeneous and heterogeneous thorium fuel blocks with four drivers in advanced high temperature reactors," *International Journal of Energy Research*, vol. 44, no. 7, pp. 5713–5729, 2020.

[11] C. García et al., "Evaluation of uranium–thorium and plutonium–thorium fuel cycles in a very high temperature hybrid system," *Progress in Nuclear Energy*, vol. 66, pp. 61–72, 2013.

[12] H. Ding, G. Quan, L. Hao, J. Song and W. Yican, "Verification and application of SuperMC3.3 to lead–bismuth-cooled fast reactor," *Nuclear Technology and Radiation Protection*, vol. 34, no. 2, pp. 122–128, 2019.

[13] A. B. Arslan, I. Yılmaz, G. Bakır and H. Yapıcı, "Transmutations of long-lived and medium-lived fission products extracted from CANDU and PWR spent fuels in an accelerator-driven system," *Science and Technology of Nuclear Installations*, vol. 2019, 2019, Art. no. 4930274.

[14] D. B. Pelowitz, et al. MCNPX^{TM} User's Manual, Version 2.7.0. Los Alamos National Laboratory Tech. Rep. LA-CP-11-00438. Los Alamos, NM, USA, 2011.

[15] W. B. Wilson, S. T. Cowell, T. R. England, A. C. Hayes and P. Moller, "A manual for CINDER'90 Version 07.4 codes and data," Los Alamos National Laboratory report LA-UR-07-8412, Version 07.4.2, 2008.