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Utilization of the thorium of the holos-quad micro-reactor concept

Holos-quad mikro-reaktör konseptinde toryumun kullanımı

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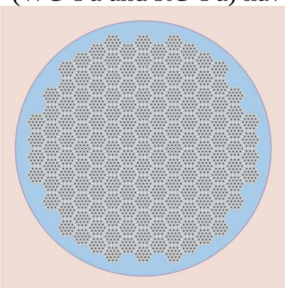
Holos-Quad Mikro-Reaktör konseptinde toryumun kullanımı

Highlights

- *3D heteregeneous reactor analysis*
- *Burnup analyses of the Holos-Quad micro-reactor for different fuels*
- *Use of thorium fuel in the Holos-Quad micro-reactor.*
- *Using RG-Pu and WG-Pu together with Th as fuel*

Graphical Abstract

In this study, utilization of the thorium of the Holos-Quad micro-reactor concept with alternative fuels (WG-Pu and RG-Pu) have been performed with a 3D heterogeneous full core model



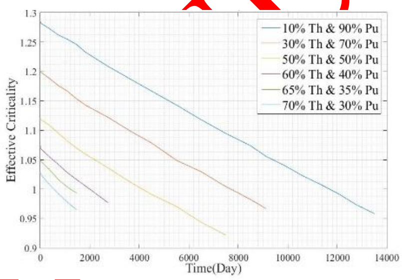


Figure: a-) Horizontal view of the Holos-Quad full core model **b-)** Time-dependent variation of the criticality for Holos-Quad fuel core with $(Th+WG\text{-}Pu)O_2$ fuel.

Aim

3D heterogeneous modeling of Holos-Quad micro reactor and demonstration of usability of Thorium as fuel and examination of fuels with different ratios / Holos-Quad mikro reaktörünün 3D heterojen modellenmesi ve Toryumun yakıt olarak kullanılabilirliğinin gösterilmesi ve farklı oranlardaki yakıtların incelenmesi

Design & Methodology

The Holos-Quad microreactor is modeled as a 3D heterogeneous in the Serpent code./ Holos-Quad mikroreaktör Serpent kodunda 3 boyutlu heterojen olarak modellenmiştir.

Originality

Thorium was used as fuel in the Holos-Quad micro-reactor/ Toryum, Holos-Quad mikro reaktöründe yakıt olarak kullanıldı.

Findings

The usability of Thorium as a fuel has been demonstrated in the Holos-Quad micro-reactor. / Holos-Quad mikro reaktöründe toryumun yakıt olarak kullanılabilirliği gösterilmiştir.

Conclusion

The criticality, effective full power year and burning thorium amount with increasing volume of the WG-Pu or RG-Pu has been increased./ WG-Pu veya RG-Pu'nun artan hacimle birlikte kritikliği, etkin tam güç yılı ve yanan toryum miktarı artırılmıştır.

Declaration of Ethical Standards

We declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Utilization of the Thorium of the Holos-Quad Micro-Reactor Concept

Research Article / Araştırma Makalesi

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ABSTRACT

In this study, the criticality and burnup analyses have been performed for Holos-Quad micro nuclear reactor as a thorium burner which has 15 ton reactor mass and 22 MW_{th} full core geometry by using continuous-energy multi-purpose three-dimensional Serpent and OpenMC Monte Carlo particle transport code with ENDF/ B-VII data libraries. As nuclear fuel, reactor grade (RG) and weapon grade (WG) Pu mixed with ThO_2 in different proportions have been used. Firstly, effective criticality for RG-Pu and WG-Pu for operation period have been determined. In addition, since each of the 4 subcritical power modules must be subcritical due to the structure of the Holos-Quad reactor, the criticality analysis of the power modules has been performed. The criticality, burnup and fissile fuel production of the Holos-Quad micro nuclear thorium-burner have been calculated with different fuel fraction depending on the fuel type. Finally, thorium mixed fuels with 35% WG-Pu or 75% RG-Pu would allow burn up levels of ~ 25 GWd/ton and ~15 GWd/ton with reactor operation periods ~3.5 years without fuel change, respectively.

Keywords: Monte Carlo, Micro reactor concept, Thorium, Burnup analysis, HTGR

Holos-Quad Mikro-Reaktör Konseptinde Toryumun Kullanımı

ÖZ

Bu çalışmada, 15 ton reaktör kütlesi ve 22 MW_{th} tüm çekirdek geometrisine sahip Holos-Quad mikro nükleer reaktör için toryum brülörü olarak kritiklik ve yanma analizleri, sürekli enerjili çok amaçlı üç boyutlu Serpent ve OpenMC Monte Carlo parçacık taşıma kodu ve ENDF/B-VII veri kütüphaneleri kullanılarak gerçekleştirilmiştir. Nükleer yakıt olarak, reaktör sınıfı (RG) ve silah sınıfı (WG) Pu ile farklı oranlarda ThO_2 karışımı kullanılmıştır. Öncelikle, RG-Pu ve WG-Pu için işletme periyodu için etkin kritiklik belirlenmiştir. Ayrıca, Holos-Quad reaktörünün yapısı gereği 4 alt kritik güç modülünün her biri kritik altı olması gerektiğinden, güç modüllerinin kritiklik analizi gerçekleştirilmiştir. Holos-Quad mikro nükleer toryum brülörünün kritikliği, yanma ve fisil yakıt üretimi, yakıt türüne bağlı olarak farklı yakıt oranlarıyla hesaplanmıştır. Son olarak, %35 WG-Pu ve %75 RG-Pu içeren toryum karışımlı yakıtlar, yakıt değişimi yapılmadan reaktör işletme süreleri ~3,5 yıl olacak şekilde sırasıyla ~25 GWd/ton ve ~15 GWd/ton yanma seviyelerine olanak sağlamıştır.

Anahtar Kelimeler: Monte Carlo, Mikro reaktör konsepti, Toryum, Yanma analizi, HTGR

1. INTRODUCTION

Small Modular Reactors (SMR) stand out compared to Light Water Reactors due to their low investment costs and small size. In addition to being portable, it also provides great advantages that they have fast installation. With the energy crisis in the world, there are studies on energy poverty in countries that are dependent on foreign energy, and energy efficiency has become important for existing resources, and academic studies have been published on these issues. (YAĞCI, B. E. et. al. 2023; Tamer, E. M. R. E. et. al. 2019) This has shown that diversity should be provided in energy production in countries that are dependent on foreign energy. There are multi-criteria conditions in the evaluation of investment alternatives when making a choice, and there are studies on this issue. (Özcan, N. A. et. al. 2022) Depending on these, Innovative studies have also begun to be carried out and developed in the nuclear field. (Çifci, A et. al.2023) The number of studies about SMRs in the literature has increased relatively rapidly. There are many SMRs in the design phase or in operation. All SMRs are nuclear fission reactors operating in the thermal neutron region or fast neutron region. Coolant systems can use natural convection to eliminate pumps that sometimes fail and cause refrigerant loss accidents. Thus, after the reactor is turned off, it does not need any additional cooling for the heat released as a result of decomposition. Some SMR designs have an active cooling system to back up the passive system. Negative temperature coefficients in moderators and fuels keep the fission reactions under control, causing the reaction to slow down when the temperature increases. Some SMR designs may bury the reactor and spent fuel storage ponds underground due to their small size (Vuji´c et. al., 2012;

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Iyer et. al., 2014; Moore, 2016; Ingersoll, 2009; Michaelson and Jiang, 2021). Recently, micro nuclear reactors are being developed as a type of reactor that can be placed in difficult locations for long-term electricity supply in emergencies, natural disasters and remote areas (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017; Firoozabadi, 2022). Micro nuclear reactors are a type of reactor suitable for rapid deployment to locations where there is poor or no external power grid in terms of power ratio and physical size. This type of reactor is preferred with a power rating of less than 20 MWe, a high level of passive safety and an autonomous reactor control system with all components assembled and tested. Because of these advantages of micro nuclear reactors, in recent years, Holos-Gen LLC has developed the Holos-Quad micro reactor concept, a very innovative high temperature gas-cooled reactor (HTGR) concept using four Subcritical Power Modules (SPM) (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017). A Holos-Quad micro-reactor concept has been proposed by Holos Gen LLC to produce 22 MWt for civilian applications with 3.5 and 8.3 effective full power years (EFPY). The design is a very innovative reactor type using four Subcritical Power Modules (SPM) based on the concept of a high temperature gas cooled reactor that fits in a commercial 40 ft transport ISO container. It adopts an unconventional primary reactivity control mechanism where the criticality is achieved by bringing the four SPMs closer together and turned off by moving the SPMs away from each other (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017). This concept uses TRISO fuel dispersed in graphite hexagonal blocks and cooled by helium gas. This reactor Effective full power years of the Holos-Quad is approximately 3.5 years and 8.3 years for nearly 15 and 26.7 tons core weight, respectively (Stauff et. al., 2021b). These types reactors can be used for a variety of applications to incineration of the nuclear waste and utilization of the thorium reserves as in the literature. Şahin et al., (2009) have performed the first criticality analysis using RG-Pu and WG-Pu with thorium in the Fixed Bed Nuclear Reactor (FBNR) which has innovative and small design. The criticality and burnup over plant operation of the FNBR have been examined by the same authors as given Ref. (Şahin et. al, 2010). Shamanin et. al., (2018) have been investigated low power HTGR type reactors which has different pellet sizes and fuel assemblies have been usually analysed by the reactor core cell method and in another study (Shamanin et. al., 2015), HTGR used in the calculations is based on a 78-channel fuel assembly by using neutronic computer codes of the MCU-5 series.

In this study, the neutronic potentials of alternative fuels for Holos-Quad thorium micro-reactor full core geometry, which has WG-Pu and RG-Pu plutonium in mixed oxide fuel form with thorium, has been performed with by using Monte Carlo calculation method. In this study, the SERPENT (Leppanen, 2015) which has Monte Carlo Reactor Physics Burnup Calculation Code is the main code used for full geometry design and analysis with ENDF/VII data libraries. OpenMC (Paul et. al., 2015; Romao et. al., 2022) Monte Carlo Neutron and Photon Transport Simulation Code were used for the distribution of TRISO fuel spheres in fuel channels in this study. The criticality, burnup and fissile fuel production have been calculated for alternative fuel fraction and compared with literature.

2. METHOD and CALCULATIONS

Holos-Quad critical nuclear reactor is a deployable modular reactor with enhanced safety features. Holos-Quad cores due to special configurations can be portable and deployed in time to provide emergency electricity and process heat for disaster areas and inaccessible remote locations (Çifci, A., et. al. 2023). As shown in Figs. 1 and 2, a single transport container contains the whole operational generator for electric power generation of up to 13 MWe (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017). Also, Holos-Quad fuel cartridge and containment configuration has been given as illustrated in Fig 3.

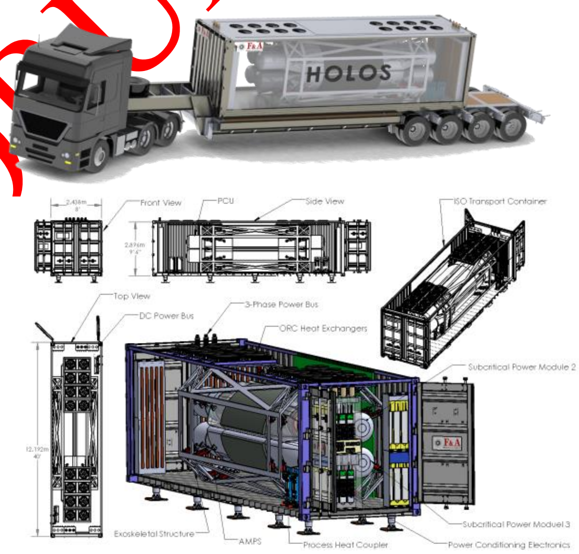

Fig. 1. 13 MWe Holos-Quad (4xsubcritical power modules) in transport ISO container (Filippone and Jordan, 2017)

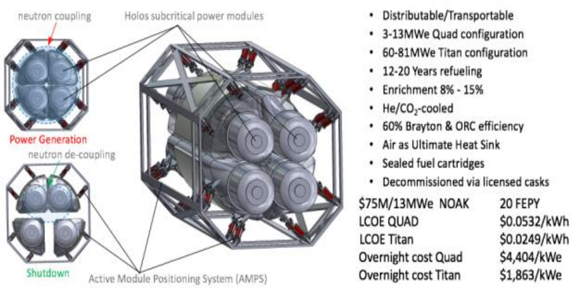

Fig. 2. Holos-Quad generator general characteristics (Filippone and Jordan, 2017)

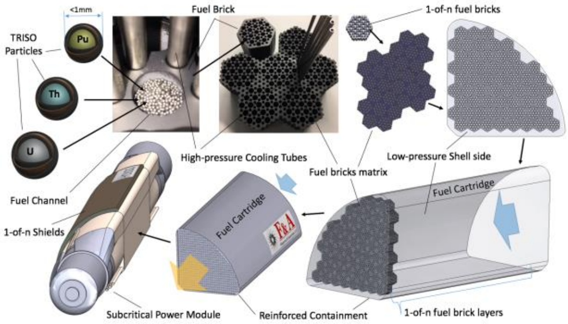

Fig. 3. Holos-Quad fuel cartridge and containment configuration (Filippone and Jordan, 2017)

The vertical and horizontal view of the Holos-Quad full core geometry obtained by using OpenMC and Serpent Monte Carlo nuclear code has been given in Figs. 4 and 5. There are 151 assemblies in the reactor. Each assembly consists of 19 fuel channels and 54 coolant channels. Each fuel channel contains about 2 million TRISO particles inside the sintered graphite.

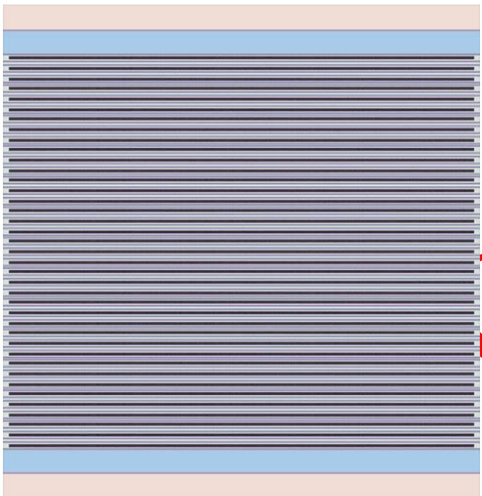

Fig 4. Vertical view of the Holos-Quad full core model

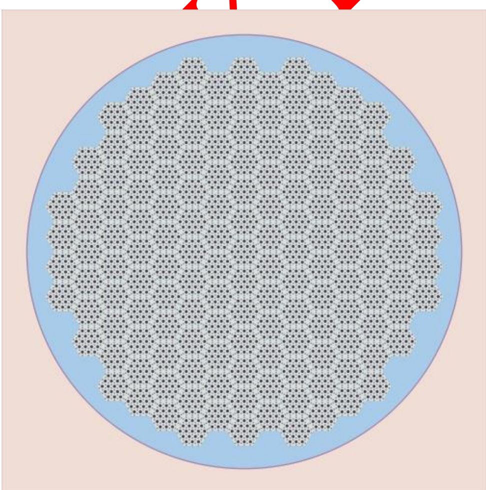

Fig. 5. Horizontal view of the Holos-Quad full core model

Technical specifications of the simulated Holos-Quad micro nuclear reactor have been presented in the Table 1 (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017).

Table 1. Technical data of simulated HOLOS-Quad core (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017)

Specification	Value
Thermal power (MWth)	22
Height of core (m)	3.9
Height of core with reflector (m)	4.0
Core radius with Zr-4 layer (m)	1.05
Zr-4 layer thickness (cm)	0.5
Fuel Form	$(Pu,Th)O_2$
Packing Fraction (%)	40
Radius of fuel hole (cm)	0.7
Radius of Coolant hole (cm)	0.3
Assembly flat to flat dimension (cm)	14.45
Number of fuel holes	19
Number of coolant holes	54

The densities of the materials used in the reactor are given in Table 2 (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017).

Table 2. Density of materials used in the calculations (Shamanin et. al., 2018)

Materials	Density (g/cm^3)
Graphite block (matrix)	1.806
Reflector block (Beryllium)	1.778
Coolant He	0.00365
Lead	10.253
Zircaloy-4 (Shell layer)	6.489
$(Th,Pu)O_2$	~10.4
Ti_3SiC_2	4.5
Pyrolytic Carbon	1.882
SiC	3.171

The layout of the fuel and coolant channels in the assembly and dimensions of the assembly are given in Fig. 6.

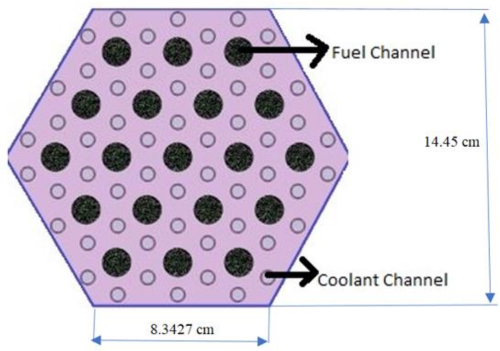

Fig. 6. Hexagonal assembly of the Holos-*Quad* full core model with dimensions

In this assembly, big black bores represent fuel channels, which has a radius of 0.7 cm. Small bores represent coolant channels , which has a radius of 0.3 cm. Flat to flat dimension of hexagonal bundle assembly is equal to

14.45 cm. TRISO particles used in fuel channels are given in Fig. 7 (Shamanin et. al., 2018).

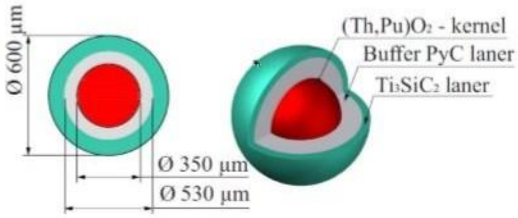

Fig. 7. TRISO fuel particles used fuel channel (Shamanin et. al., 2018)

Starting from the center, the layers used in the regions of this sphere are fuel, pyrolytic carbon and Ti_3SiC_2, respectively,. A mixture of RG-Pu or WG-Pu and Th was used as fuel. Since $(Pu,Th)O_2$ is used as fuel, sintered graphite is used in fuel channels and TRISO particles are dispersed on it (Shamanin et. al., 2018). In addition, SiC surface, which acts as a kind of clad, is used on the outer surface of the fuel channels. Fuel region in the pebble image consists of $(Pu,Th)O_2$. The fuel has produced with a different ratio of ThO_2 and PuO_2. The density of the fuel is nearly equal to 10.4 g/cm^3. The isotope ratio of Pu has been given in Table 3 (IAEA, 2003).

Table 3 The composition of the fissionable isotopes in the fresh fuel (IAEA, 2003)

Plutonium Composition (at%)	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Reactor Grade	1.8	59	23	12.2	4
Weapon Grade	0	94	5	1	0

The pitch distance of the fuel channels in the fuel assembly was found and accordingly the fuel assembly was formed. The fuel assemblies were placed in the reactor core in a suitable manner. Here, some operations have been made due to the preferred method in the SERPENT code. The centres of the fuel channels were found one by one and a TRISO particle distribution file specific to each fuel channel was created. When the TRISO particle dispersed on the sintered graphite in fuel channel, OpenMC Monte Carlo Neutron and Photon Transport Simulation Code was used. Using the packing fraction equation below, the total number of TRISO particle in a fuel channel was found and used in the relevant code.

$$P.F. = \frac{V_{Fuel\,Channel}}{V_{Triso} * N_{Total\,Triso}} = \frac{\pi R^2_{Fuel\,Channel} L_{Fuel\,Channel}}{\frac{4}{3}\pi R^3_{Triso} * N_{Total\,Triso}} \quad (1)$$

where, P.F. is the packing fraction, $V_{Fuel\ Channel}$ is the volume of the fuel channel, V_{Triso} is the volume of the TRISO particle, $N_{Total\ Triso}$ is the total number of TRISO Particles in one fuel channel. R is symbolized to radius and L symbolized to length. Then, the fuel channels found were subjected to translation process with MATLAB code according to their centres. Then these data are used as input in the SERPENT code. The reason for using OpenMC is that it approximates the porosity ratio in the fuel channels better than the SERPENT code. In addition, an OpenMC code was written for UCO for verification purposes. For the UCO fueled Holos-Quad reactor in the literature, the validation in this study was carried out and the reactor operated with a single loading for approximately 3.5 years for a core weight of 15 tons (Stauff et. al., 2021b).

In this study, $(Pu,Th)O_2$ fuel was used instead of UCO fuel studies given in the literature, fuel channels have been changed due to the fuel and TRISO used. Accordingly, TRISO particles were dispersed on sintered graphite. In addition, a SiC surface has been added to the outer surface of the fuel channels. Assembly analysis was performed, and the necessary geometric data were created. Thorium availability by volume was examined for RG-Pu and WG-Pu fuels used and how much this thorium was depleted. Apart from that, for fuels at different ratios, the number of years, the reactor has been operating at full power and the burnup values have been examined. A criticality analysis was performed for each case. The 3D heterogeneous full geometry method and the burnup code have been run in the Serpent Monte Carlo reactor physics burnup calculation code. Also, OpenMC Monte Carlo Neutron and Photon Transport Simulation Code was used for the distribution of TRISO particles. The neutronic calculations for heterogeneous 3D full core geometry, SERPENT Monte Carlo reactor physics burnup calculation code with ENDF/ B-VII cross sections have been performed.

3. RESULT and DISCUSSIONS

The neutronic analysis of the HOLOS-Quad thorium micro-reactor concept have been performed by using hybrid Serpent and OpenMC Monte Carlo calculation method. The main code used for full geometry design and analysis with ENDF/VII data libraries was Serpent whereas, OpenMC have been used for the distribution of TRISO fuel spheres in fuel channels. At first, the full core for HOLOS-Quad thorium micro-reactor concept have been modelled. In the calculations, UCO have been used as fuel form as given in the literature (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017) and compared with Ref. (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017, According to the 3D heterogeneous full core modeling results in this study, the reactor can be operated at full power for about 3.5 years with a core weight of 15 tons in the case of the reactor with UCO fuel. When the results obtained in the literature were compared, it was observed that the results obtained in this study and the results in Ref. (Stauff et. al., 2021b) were in acceptable agreement with each other. Neutronic results for alternative fuels are examined as weapon grade plutonium and reactor grade plutonium mixed thorium. In this evaluation, fuel channels of Holos-Quad were coated sintered graphite to provide more moderation for using $(Pu,Th)O_2$ type TRISO particle in Fig. 7 as differing Ref. (Shamanin et. al., 2018).

A large amount of high-quality plutonium has been accumulated in the nuclear warheads during the Cold War. In addition, due to the nuclear energy programs of countries in recent years, civilian plutonium isotopes have accumulated largely from nuclear energy. It is estimated that this ratio exceeds 1700 tons of the total amount of plutonium. It is of general interest to reduce stocks of both WG-Pu and RG-Pu (IAEA, 2003; Şahin et. al., 2006; 2010; 2012). Due to the highly radiotoxic content of this accumulated plutonium, its release to the environment and its abuse cause serious and political concerns in the world public opinion. The only way to alleviate serious and political concerns in the world public opinion is to reduce plutonium stocks by using it as fuel in nuclear reactors. Since weapon grade plutonium is a high quality nuclear fuel, incineration is one of the alternative methods for a fuel management and can be fuelled with thorium fuel (IAEA, 2003; Şahin et. al., 2006; 2010; 2012).

The neutronic analyses for heterogeneous full core have been performed with by using various vol. % fuel parameter. The criticality (k_{eff}) calculations have been performed with fuel compositions made of thorium (ThO_2) and WG-PuO_2, where PuO_2 varied from 30% to 90%, as shown in Fig. 8. The k_{eff}>1.0 has been achieved by 30% WG-PuO_2. As shown in Fig. 8, the k_{eff} at 35 % WG-PuO_2 will be remarkably high (k_{eff}=1.05). The k_{eff} will be rapidly increased with increasing with WG-PuO_2.

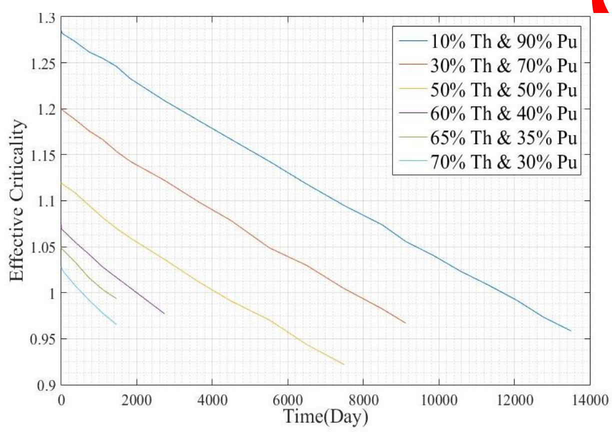

Fig. 8. Time-dependent variation of the criticality for Holos-Quad fuel core with (Th+WG-Pu)O_2 fuel.

As shown in Table 4., the burnup values increase with increasing PuO_2. The burnup values have computed as ~211 GWd/ton for a reactor operation time of 32 years at 10%ThO_2 + 90%PuO_2 fuel mixture. However, in this study, a reasonable fuel mixture of approximately 35 % WG- PuO_2 and 65 % ThO_2 can be suggested with k_{eff} = 1.20, corresponding to the original fuel reactor operating time of 3.5 years with a core weight of 15 tons as specified in the Ref. (Stauff et. al., 2021b). In the calculations made for the fuel mixture consisting of approximately 35% WG-PuO_2 and 65% ThO_2, the burnup value was calculated as ~25 GWd/ton.

Table 4. Burnup values and effective full power years for different Th+WG-Pu volumetric ratio.

Volumetric ratio of Fuel	Effective Full Power Years (EFPYs)	Burnup (GWd/ton)
(10% Th,90% Pu)O_2	~32	~211.313
(30% Th,70% Pu)O_2	~21	~131.670
(50% Th,50% Pu)O_2	~11	~67.500
(60% Th,40% Pu)O_2	~5.5	~32.074
(65% Th,35% Pu)O_2	~3.5	~25.660
(70% Th,30% Pu)O_2	~1.5	~9.500

On the other hand, the k_{eff} values have been carried out with thorium (ThO_2) and RG-PuO_2 fuel compositions, where PuO_2 varied from 65% to 90%, as shown in Fig. 9. The k_{eff}>1.0 has been achieved by 65% RG-PuO_2. As shown in Fig. 9, the k_{eff} at 70 % RG-PuO_2 will be remarkably high (k_{eff}=1.05). The k_{eff} with increasing with RG-PuO_2 will be rapidly rised.

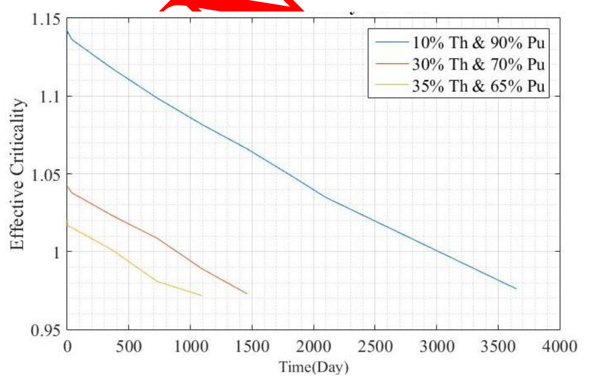

Fig. 9. Time-dependent variation of the criticality for Holos-Quad fuel core with (Th+RG-Pu)O_2 fuel.

As shown in Table 5., the burnup values the increasing with WG- PuO_2 is higher. In this study, fuel composition ratio can be suggested with k_{eff} = 1.20 as approximately 75 % RG-PuO_2 and 25 % ThO_2, corresponding to the original fuel reactor operating time of 3.5 years with a core weight of 15 tons as specified in the Ref. (Stauff et. al., 2021b). Fuel burnup values for this fuel compositions have been computed as ~ 15 GWd/ton. As a result, for both fuels, higher PuO_2 content is not recommended in order to benefit as much as possible from thorium fuel.

Table 5. Burnup values and effective full power years for different Th+RG-Pu volumetric ratio.

Volumetric ratio of Fuel	Effective Full Power Years	Burnup (GWd/ton)
(10% Th+90% RG-Pu)O_2	~9	~36.8333
(30% Th,70% RG-Pu)O_2	~2.5	~ 12.813
(35% Th,65% RG-Pu)O_2	~1	~6.4080

In addition, the Ref. (Stauff et. al., 2021b) calculated the reactor operating time as 8.3 years in the calculations made with the total core weight of 26.7 tons with UCO fuel. Considering the alternative fuels used in this study corresponding to these values, the reactor can be operated with 15 tons of fuel over approximately 8 effective full power years (EFPYs). As shown in Table 4 and 5, the fuel compositions at approximately 8.3 EFPYs have been found as 55 % ThO_2 + 45 % WG-PuO_2 and 10 % ThO_2 +90 % RG-PuO_2. This results obtained with alternative fuels will provide a great advantage in terms of core weight compared to the 26.7 tons given by the Ref. (Stauff et. al., 2021b).

The time-dependent density variations of fissionable isotopes for 10 % Th + 90% WG-PuO_2 fuel type have been investigated as presented in Figs. 10 and 11. The amount of ^{239}Pu tends to decrease rapidly. An increase in ^{233}U fuel is observed. In addition, other uranium isotopes increase very slowly compared to ^{233}U. The rise of ^{240}Pu and the rapid decline of ^{239}Pu reduce WG- plutonium to unproductive levels a few years later. In addition, other plutonium isotopes changes are very slowly compared to ^{240}Pu and ^{239}Pu changes.

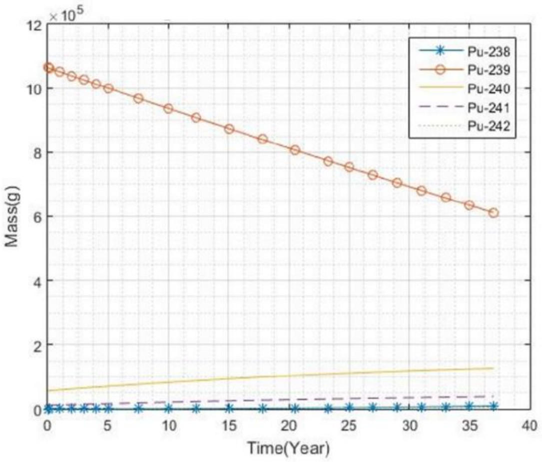

Fig. 10. Density variations of the main fissionable isotopes for Holos-Quad fuel core with (10 % Th + 90% WG-Pu)O_2 fuel

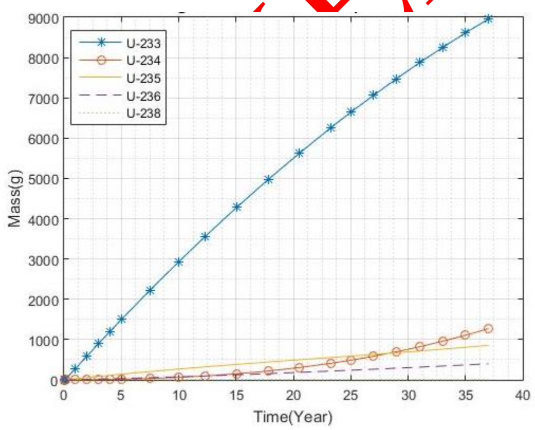

Fig. 11. Density variations of the main fissionable isotopes for Holos-Quad fuel core with (10 % Th + 90% WG-Pu)O_2 fuel

The time-dependent density changes of fissile isotopes for the 90% RG-PuO_2 plutonium fuel type are shown in Figs. 12 and 13. ^{239}Pu shows rapid a decreasing trend while ^{233}U shows an increasing trend. The other Uranium isotopes show slow increasing trend. Other plutonium isotopes, namely ^{240}Pu, ^{241}Pu and ^{242}Pu, maintain a stable level. This reduces plutonium to unusually low levels. This is a very important issue for reactor safety.

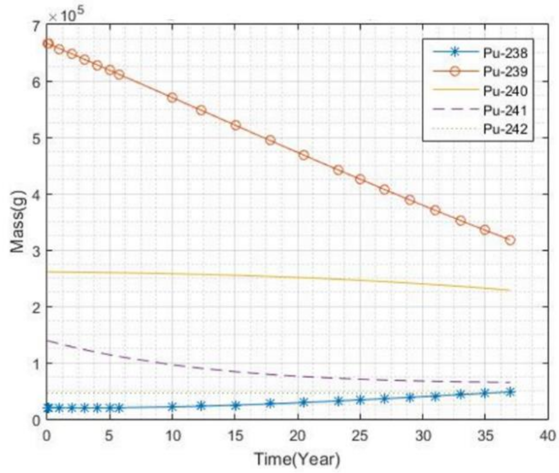

Fig. 12. Density variations of the main fissionable isotopes for Holos-Quad fuel core with (10 % Th + 90% RG-Pu)O_2 fuel

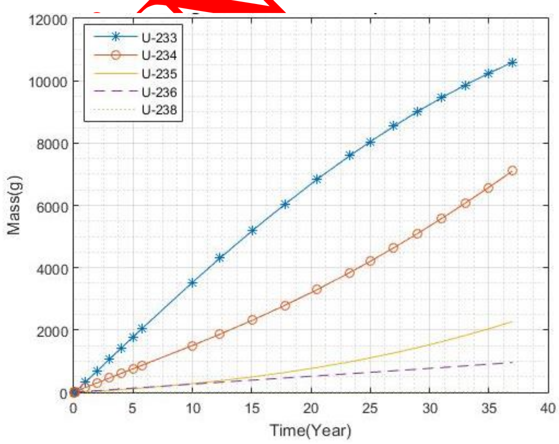

Fig. 13. Density variations of the main fissionable isotopes for Holos-Quad fuel core with (10 % Th + 90% RG-Pu)O_2 fuel

Finally, the Holos-Quad micro nuclear reactor has 4-subcritical power modules. For this reason, criticality calculation for a Holos-Quad is important in terms of reactor safety. The subcritical calculations a HOLOS-Quad single power module show that the k_{eff} with 10%Th and 90 %WG-PuO_2 is 0.95 in this study as determined in the Refs. (Stauff et. al., 2021a; 2021b; Filippone and Jordan, 2017; Firoozabadi, 2022). This showed that there was no contradiction to the structure of the reactor.

4. CONCLUSIONS

In this study, utilization of the thorium of the Holos-Quad micro-reactor concept with alternative fuels (WG-Pu and RG-Pu) have been performed with a 3D heterogeneous full core model. The following conclusions can also be drawn:

- The criticality, effective full power year and burning thorium amount with increasing volume of the WG-Pu or RG-Pu has been increased.
- Thorium mixed fuels with 35% WG-Pu or 75% RG-Pu would allow reactor operation periods ~3.5 years

without fuel change with burn up levels of ~ 25 GWd/ton and 15 GWd/ton, respectively.

- Thorium mixed fuels with 45% WG-Pu or 90% RG-Pu would allow reactor operation periods ~8.5 years without fuel change with burn up levels of ~ 50 GWd/ton and 36 GWd/ton, respectively.
- When 90% weapon grade Pu and 10% Th are used as fuel, it has been found that 4 power modules are subcritical as 0.95, so in other cases, each power module is subcritical and there is no situation contrary to the design.
- Finally, high burn up levels over reactor operation periods without fuel change will reduce total nuclear waste per unit energy output.

DECLARATION OF ETHICAL STANDARDS

We declare that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

AUTHORS' CONTRIBUTIONS

Ahmet ÇİFCİ: The author prepared the serpent code and ran it.

Adem ACIR: Literature review and interpretation of results

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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