# ANALYSIS OF THORIUM AND TRANSURANIUM UTILIZATION IN A SMALL MODULAR REACTOR

by

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Scientific paper
https://doi.org/10.2298/NTRP2203175B

**This study presents neutronic analyses of a small modular reactor utilizing transuranium and thorium. Two different fuel cases are considered in the analyses as the transuranium extracted from PWR-MOX spent fuel (a form of a mixture of minor actinide and Pu isotopes) (Case A) and 4.5 % enriched $UO_2$ with $ThO_2$ (the form of separate fuel rods) (Case B). The total power of the considered small modular reactor containing 69 assemblies is 450 MW thermal. In both fuel cases, the time-dependent critical burnup calculations are carried out by using MCNPX 2.7 code until their effective neutron multiplication factors decrease to 0.99. The calculations bring out that the small modular reactor can operate for quite a long time without refueling and that a new fuel with a richness of 1.05 % can be obtained from $ThO_2$ as well as energy production.**

*Key words: thermal reactor, small modular reactor, transuranium fuel, PWR-MOX fuel*

## INTRODUCTION

Currently, commercial reactors mostly like Canada deuterium uranium reactor (CANDU) and pressure water reactor (PWR) generate electricity as a nuclear source. Nuclear waste includes high-level waste and minor actinides (MA) produced in commercial reactors. Spent fuel management is one of the biggest issues in the nuclear field. Nowadays, the *wait and see approach* is used for spent fuel management. In addition to this, spent fuels are a potential fissile fuel producer. Namely, they contain fertile fuel and can transmute to fissile fuel in a nuclear reactor. Fissile fuels can use directly in a nuclear reactor to generate energy. The spent fuels, which include MA can be used in small modular reactors (SMR). Thorium is a fertile fuel that can also be used in SMR to produce $^{233}$U which is a fissile fuel.

Many researchers have studied the transmutation of spent fuel in SMR. Hwang and Hong [1] examined the transmutation of transuranium (TRU) in a light water-cooled small modular reactor. The full ceramic micro-encapsulated (FCM) fuel rods in the SMR which include $UO_2$-$TRUO_2$ were set, hence, a big transuranium consumption ratio of 14.7 % was obtained in the results. Gul *et al*. [2] studied Unit-II (CNPP-II) core which is PWR type SMR fueled with 1/3rd Mixed Oxide (MOX) fuel and used ORIGEN2.2, as well as OpenMC (LOOP) for their burnup calculations. A linear reactivity model for the core and the same operation cycle length with $UO_2$ fuel was achieved. The results of the study show that all neutronics parameters except for the control rod and delayed neutron ratio were close to those of 100 % $UO_2$ core as well as that they were slightly reduced in the control rod and delayed neutron ratio parameters. Uguri *et al*. [3] investigated Westinghouse small modular reactor (W-SMR) to understand the impact of gadolinium burnable absorbers. The actinide and non-actinide content of nuclear waste were tackled, and the results exhibited that the net activity of $^{241}$Pu and $^{239}$Np were larger than that of plutonium and neptunium's other isotopes, respectively. Furthermore, the use of gadolinium absorbers enhanced the non-actinide substances of spent fuel. Zou *et al*. [4] investigated transuranium and thorium fuel in an SMR which is a thorium-based molten salt reactor. The fuel salt fraction and reprocessing time are selected as 18.4-27.4 % and 5-10 years, respectively. The results of the study exhibited that the largest amount of $^{233}$U breeding was achieved with the configuration with SF = 27.4 % and RP = 5 years. Hwang *et al*. [5] studied transuranium transmutation along with several core performance parameters in a light water-cooled SMR core. A 17 × 17 fuel assembly in the form of MOX rods for transuranium fuel is used in the study. The MA amount was decreased by 12.4 kg compared to the fresh fuel amount at the beginning of the cycle. Be-

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sides, 64.9 kg of TRU nuclides was consumed, which is equal to the 14.7 % consumption rate. Choi *et al*. [6] performed annular $UO_2$ and transuranic fuels in a PWR-based SMR. Their goals were net consumption of transuranium and electricity production with 22 months operation cycle life. A 16 % TRU consumption rate was achieved, which is a high value (*i. e*., 131.8 kg) for all discharged fuel assemblies. Also, the transmutation of spent fuel can be realized in an accelerator-driven system (ADS). As an example of this, Qaaod *et al*. [7] investigated nuclear waste transmutation for a one-year operation cycle in ADS inner and outer zone. The MA was transmuted effectively in the inner zone of the ADS.

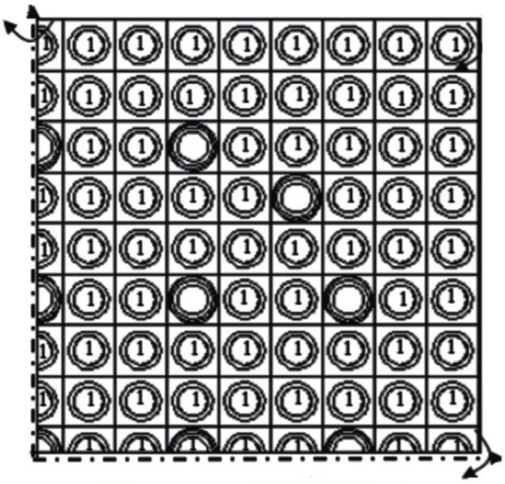
Thorium isotopes are around four times more abundant than uranium in nature. Thorium is a fertile fuel that can produce $^{233}U$ by neutron capture. Therefore, thorium is an attractive fuel for nuclear reactors. Recently, many researchers have worked on thorium utilization in SMR. Zou *et al*. [8] analyzed a thorium-based small modular reactor (molten salt type) to observe the transmutation of thorium. In the study, transuranium was used for starting fuel and several fuel fractions were considered in the thermal region to breed the required $^{233}U$ amount. When higher amounts of fuel fractions were used, the maximum $^{233}U$ isotope was obtained. Ali *et al*. [9] worked on Multi-application small light water reactoR and they modified the design to convert the SMR to use 50 % $ThO_2$, 50 % $UO_2$, or 100 % $ThO_2$ fuels. The MCNPX 2.7.0 and RELAP codes were used for their neutronic and thermal-hydraulic calculations, respectively. The longer cycle length and the bigger burn-up were obtained with thorium fuel usage. Uguru *et al*. [10] studied the outcome of the $^{238}U$ replacement with thorium in SMR with four different uranium enrichments. In the results, the replacement of $^{238}U$ with $^{232}Th$ with less than 17 % enriched uranium case decreased plutonium. Moreover, at the beginning of life, the reactivity of thorium was less than the reactivity of uranium, while at the end of the cycle it had a reverse situation. Jeyhouni *et al*. [11] used the SMR core fueled with uranium to be fueled with thorium. The study aimed to reduce burnable poison usage in the SMR with a longer length cycle. Their results showed that the $(Th/U)O_2$ fuel assemblies operate longer cycle lengths with less burnable poison. Dzianisau and Hah [12] used Th-Pu in an SMR and developed a new loading pattern. The 17 17 Westinghouse-type fuel assemblies were used. The results presented that the new Th-Pu model has a longer cycle length and good reactivity balance as well as satisfying design criteria inclusive of safety-related factors obtained. Permana [13] worked on thorium utilization in an SMR with 10 years of operation life. They performed various coolant types by using the SRAC-CITATION code. By using liquid metal coolant, higher burnup and power density were achieved than with water coolant types.

In our previous studies [14-18], the utilization of various nuclear-spent fuels and thorium fertile fuels were analyzed in several subcritical nuclear reactors to rejuvenate or enrich them. As for the present study, unlike them, the effective usability of PWR-MOX spent fuel and thorium fertile fuel in an SMR operating under critical mode is investigated in terms of energy generation.

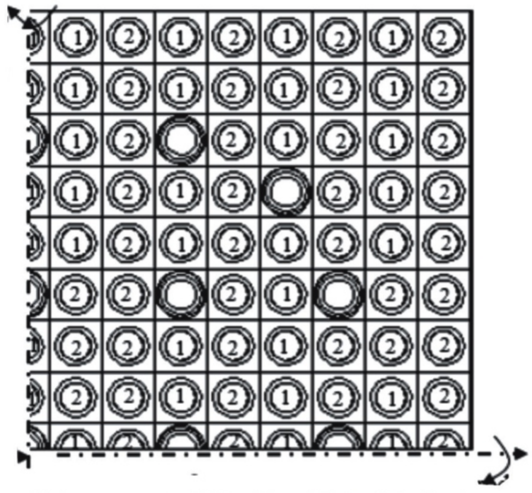
## THE SMR CORE DESIGN

In this study, the reactor core and fuel design of considered SMR includes a total of 289 rods (264 fuel rods, 24 control rods, and 1 water hole rod) positioned in a 17 17 square array [19]. Two different fuel cases are separately analyzed for this SMR as a mixture of MA and Pu isotopes taken from [20] (Case A) and 4.5 % enriched $UO_2$ plus $ThO_2$ (in separate fuel rods) (Case B).

In fig. 1, axisymmetric cross-section views of one-quarter of the considered SMR assembled are



(a) Arrangement of TRU (1) fuel rods



(b) Arrangement of $UO_2$ (1) and $ThO_2$ (2) fuel rods

**Figure 1. Axisymmetric cross-section view of one-quarter of the considered SMR assemble (white rod at the center is a water hole and other white rods are the control rods)**

**Table 1. Densities and fractions of isotopes used in the SMR**

| Material | | Density [gcm$^{-3}$] | Isotope | Fraction [%] |
|---|---|---|---|---|
| Case A:<br>TRU mixed fuel* | $NpO_2$ | 11.38 | $^{237}$Np | 26.31 |
| | | | $^{16}$O | |
| | $AmO_2$ | 11.50 | $^{241}$Am | 26.49 |
| | | | $^{243}$Am | 5.723 |
| | | | $^{16}$O | |
| | $CmO_2$ | 10.55 | $^{244}$Cm | 1.24 |
| | | | $^{16}$O | |
| | $PuO_2$ | 11.55 | $^{238}$Pu | 0.62 |
| | | | $^{239}$Pu | 24.31 |
| | | | $^{240}$Pu | 9.72 |
| | | | $^{241}$Pu | 3.57 |
| | | | $^{242}$Pu | 2.25 |
| | | | $^{16}$O | |
| Case B:<br>In separate fuel rods | $UO_2$ | 10.54 | $^{235}$U | 4.5 |
| | | | $^{238}$U | 95.5 |
| | | | $^{16}$O | |
| | $ThO_2$ | 9.88 | $^{232}$Th | 100 |
| | | | $^{16}$O | |
| | | | $^{16}$O | |
| Clad | Zr | 6.503 | $^{90}$Zr | 100 |
| Moderator | $H_2O$ | 0.660** | $^{1}$H | 100 |
| | | | $^{16}$O | |

*The MA and Pu isotopes denoted as MOX11 in tabs. 2, 3 in [20] are mixed by 1.18 and 0.82 times the percentages of MA and Pu, respectively. **At 600 K

plotted. Furthermore, in tab. 1, the densities and fractions of isotopes used in this SMR are given.

The ATOM core SMR assembly dimensions are the same for both fuel cases and these dimensions are taken from [19]. The size of height, width, and length of the considered assembly are 12.2655, 12.2655, and 200 cm, respectively. The radii of the inner gap and cladding of fuel rods are 0.40958, 0.41873, and 0.5476 cm, respectively. The pitch length of the fuel rods is 1.443 cm. The radii of the inner, interior clad, water guide tube, and clad guide tube are 0.41873, 0.5476, 0.6335, and 0.6746 cm, respectively, for control rods and water hole. The total power of the considered SMR containing 69 assemblies is 450 MW thermal.

## CALCULATION PROCEDURE

The considered SMR generating a total power of 450 MW thermal contains 69 assemblies. The power of one assembly produces 6.522 MW thermal. To decrease the computer processing time, time-dependent heterogeneous critical burn calculations are performed for one assembly. The calculations are conducted in the case of removed control rods. In both fuel cases, these calculations are carried out by using MCNPX 2.7 code [21] until their effective neutron multiplication factors $k_{\text{eff}}$ decrease to 0.99. In addition to this code, the XBURN [22] interface computer code is used to accurately evaluate the MCNPX output.

## NUMERICAL RESULTS

### Effective neutron multiplication factor

The effective neutron multiplication factor is one of the most significant parameters in nuclear reactors. It can be computed as follows

$$k_{\text{eff}} \quad \frac{\text{number of one generation neutrons}}{\text{number of previous generation neutrons}} \tag{1}$$

Figure 2 shows the variation of effective neutron multiplication factors in both fuel cases during the corresponding effective burn time of the case. The results of numerical calculations show that $k_{\text{eff}}$ values of fuel Cases A and B drop from around 1.03 to 0.99 after

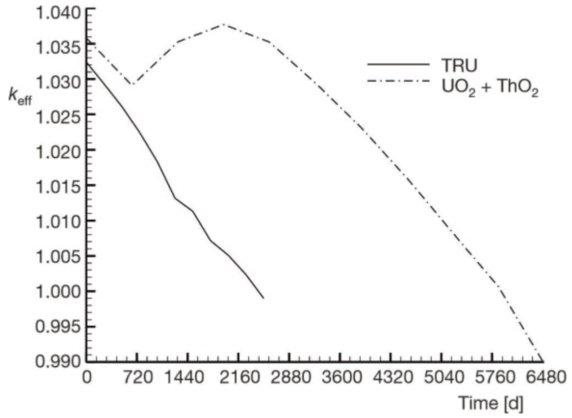


**Figure 2. Variations of effective neutron multiplication factors in both fuel cases during the corresponding effective burn time of the case**

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*pcm means the one-thounsandth of a percent

2520 and 6500 days, respectively. These times are defined in this study as the effective burn time. This means that the considered SMR fuelled with the $UO_2$ plus $ThO_2$ fuel operates without refueling longer than that fuelled with the TRU fuel.

As apparent from this figure, in the Case A, the value of $k_{\mathrm{eff}}$ rapidly decreases, relatively more than in the Case B. These decreases are from 1.032 to 0.99 and from 1.035 to 0.99 in the Cases A and B, respectively. Therefore, without using burnable poison, the excess reactivity swing is 3300 pcm and 3600 pcm in the Case A and B respectively.

## Cumulative fissile fuel enrichment

Fissile fuel richness is another of the most significant parameters in nuclear reactors. In a nuclear fuel core, the ratio of the total atomic density of fissile fuels to the total atomic density of all nuclear fuels is expressed as the cumulative fissile fuel enrichment. This ratio indicates the quality of nuclear fuel, and it can be calculated as follows

$$CFFE \quad \frac{N_{\mathrm{fissile}}}{N_{\mathrm{fuel}}} \, 100 \, [\%] \tag{2}$$

where $N$ is the atomic density of isotopes

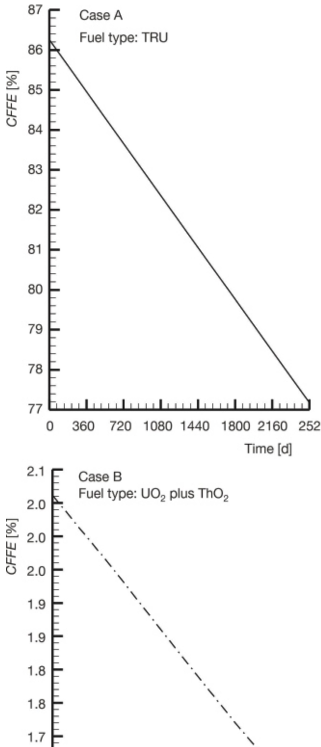

**Figure 3. Decreases in CFFE in both fuel cases during the corresponding effective burn time of the case**

The decreases in CFFE are plotted in fig. 3 for both fuel cases during the corresponding effective burn time of the case. In the Case of A, the CFFE values drop from 86 % to about 77 % in all fuel rods. In regards to Case B, the CFFE values are the volumetric weighted average of CFFE in the $UO_2$ and $ThO_2$ fuel rods. While the values of CFFE decrease from 4.5 % to about 2 % in the $UO_2$ fuel rods, they increase from 0 % to about 1.05 % in the $ThO_2$ fuel rods.

## Fuel burnup

Fuel burnup (FBU) is one of the most significant parameters in nuclear reactors showing the energy generation per used nuclear fuel. Namely, it is described as the produced nuclear energy per unit metric fuel mass loaded at the beginning of the cycle. Its time-dependent value can be computed as follows

$$FBU(t \quad t) \quad FBU(t) \quad \frac{\text{Fission power}}{MTU} \quad t \tag{3}$$

Generally, the unit of burnup is GWd/MTU or MWd/MTU, where MTU is metric ton uranium.

Figure 4 depicts the increases of burnup values in both fuel cases during the corresponding effective burn time of the case. One can see that both profiles linearly increase. Although the effective burn time in Case A is shorter than that in Case B, at the end of the cycle, the burnup value in Case A is about 3.4 times higher than in Case B. Namely, the burnup values reach up to 58 and 17 GWD/MTU in Cases A and B at end of the cycle (EOC), respectively.

## CONCLUSIONS

Analyses of the utilization of $ThO_2$ and TRU fuels in an SMR 17    17 are in detail investigated by considering two different fuel cases.

The $k_{\mathrm{eff}}$ values of fuel Cases of A and B decrease from about 1.03 to 0.99 after 2520 and 6500 days, re-

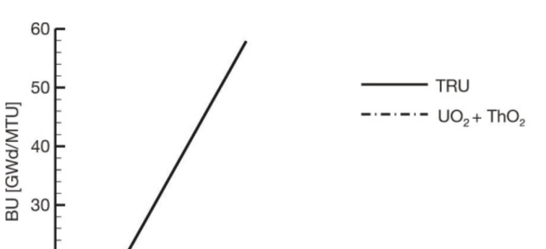

**Figure 4. Increases of burnup values in both fuel cases during the corresponding effective burn time of the case**

spectively. This means that the considered SMR can be operated for quite a long time in both fuel cases without refueling. Furthermore, without using burnable poison, the excess reactivity swing is 3300 pcm and 3600 pcm in the Case A and B, respectively. In the Case B, the values of CFFE drop from 4.5 % to about 2 % in the $UO_2$ fuel rods. On the contrary, these values increase from 0 % to about 1.05 % in the $ThO_2$ fuel rods. In Cases A and B at the EOC, the burnup values reach 58 and 17 GWD/MTU, respectively.

Consequently, this study brings out that an SMR can produce a significant amount of energy by utilizing the $ThO_2$ fertile fuel and the transuranium fuel extracted from PWR-MOX spent fuel.

## REFERENCES

[1] Hwang, D. H., Hong, S.G., Transition Cycle Analysis of Light Water-Cooled SMR Core Loaded with MOX (TRU) and FCM (TRU) Fueled PWR Assemblies, *Nuclear Engineering and Design, 375* (2021), 111103

[2] Gul, A., Ali, R. A., Neutronics Analysis of CNPP-II Loaded with 1/3$^{rd}$ MOX Fuel, *Annals of Nuclear Energy, 120* (2018), 120, pp. 839-844

[3] Uguri, E. H., *et al.*, Actinide and Non-Actinide Production from $UO_2$ Fuel in W-SMR: Effects of Gadolinium Burnable Absorber, *Annals of Nuclear Energy, 137* (2020), 107083

[4] Zou, C., *et al.*, Transition to Thorium Fuel Cycle in a Small Modular Molten Salt Reactor Based on a Batch Reprocessing Mode, *Annals of Nuclear Energy, 138* 2020),107163

[5] Hwang, D. H., *et al.*, TRU Transmutation in Light Water Cooled SMR Cores Loaded with Fuel Assemblies composed of MOX and FCM fuel rods, *Proceedings*, Transactions of the Korean Nuclear Society Autumn Meeting Gyeongju, Korea, October 26-27, 2017, p. 5

[6] Chio, J. Y., *et al.*, Conceptual Design of a Long Cycle Small Modular Reactor Core with Annular $UO_2$ and FCM (TRU) Fuels, *International Journal Energy Research, 45* (2020), 1, pp. 11957-11975

[7] Al Qaaod, A. A., *et al.*, Computational Study on Distribution Feasibility of Radioactive Waste Transmutation in Accelerator Driven System, *Nucl Technol Radiat, 35* (2020), 4, pp. 294-303

[8] Zou, C., *et al.*, Preliminary Study on TRU Utilization in a Small Modular Th-Based Molten Salt Reactor (smTMSR), *Nuclear Engineering and Design, 339* (2018), p. 75-82

[9] Ali, A. M. M., *et al.*, The Utilization of $ThO_2$ Fuel Discharged from an ADS in the Multi-Application Small Light Water Reactor (MASLWR), *Annals of Nuclear Energy, 161* (2021), 108449

[10] Uguru, E. H., *et al.*, Investigation on the Effect of $^{238}$U replacement with $^{232}$Th in Small Modular Reactor (SMR) Fuel Matrix, *Progress in Nuclear Energy, 118* (2020), 103108

[11] Jeyhouni, R. A., *et al.*, The Utilization of Thorium in Small Modular Reactors – Part I: Neutronic Assessment, *Annals of Nuclear Energy, 120* (2018), pp. 422-430

[12] Dzianisau, S., Hah, C. J., Nuclear Design Characteristics of Thorium-Plutonium Fueled Soluble Boron-Free Small Modular Reactor, *Proceedings*, Transactions of the Korean Nuclear Society Autumn Meeting Yeosu, Korea, October 25-26, 2018, p. 4

[13] Permana, S., Thorium Fuel Utilization Analysis on Small Long Life Reactor for Different Coolant Types, *Journal of Physics: Conference Series, 877* (2016), 012060

[14] Bakir, G., *et al.*, Time-Dependent Neutronic Analysis of a Power-Flattened Gas Cooled Accelerator Driven System Fuelled with Thorium, Uranium, Plutonium, and Curium Dioxides TRISO Particles, *Science and Technology of Nuclear Installations, 2016* (2016), https://doi.org/10.1155//2016/2612459

[15] Durmaz, B., *et al.*, Neutronic Analysis of an Ads Fuelled with Minor Actinide and Designed for Spent Fuel Enrichment and Fissile Fuel Production, *Nucl Technol Radiat, 36* (2021), 4, pp. 299-314

[16] Arslan, A. B., *et al.*, 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, 2019* (2019), https://doi.org/10.1155/209/4930274

[17] Bakir, G., Yapici, H., Analysis of Fuel Rejuvenation Times in a Fusion Breeder Reactor Fuelled with a Mixture of Uranium-Thorium Oxides for the CANDU Reactor, *Nucl Technol Radiat, 32* (2017), 3, pp. 193-203

[18] Bakir, G., Genc, G., Yapici, H., Study of a Conceptual Accelerator Driven System Loaded with Thorium Dioxide Mixed with Transuranic Dioxides in TRISO Particles, *Nucl Technol Radiat, 31* (2016), 3, pp. 197-206

[19] Nuguyen, H. N., *et al.*, Impact of ATF Cladding on Neutronic Performance of the Soluable-Boron-Free ATOM Core, *International Journal of Energy Research, 44* (2020), 1, pp. 8193-8207

[20] ***, NEA, Calculations of Different Transmutation Concepts an International Benchmark Exercise, Nuclear Science Committee, 2000

[21] Pelowitz, D. B., MCNPX User's Manual, Version 2.7.0, LA-CP-11-00438, Los Alamos Scientific Laboratory, 2011

[22] Yapici, H., XBURN Inter face Computer Code for Evaluation of Time-De pendent MCNPX 2.7 Outputs, Erciyes University, Turkey, 2017

Received on April 7, 2022
Accepted on November 3, 2022

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# АНАЛИЗА УПОТРЕБЕ ТОРИЈУМА И ТРАНСУРАНИЈУМА У МАЛОМ МОДУЛАРНОМ РЕАКТОРУ

У раду су приказане неутронске анализе малог модуларног реактора који користи трансуранијум и торијум. У анализама су разматрана два различита случаја горива: трансуранијум екстрахован из PWR-MOX ислуженог горива (у облику мешавине мањих актинида и плутонијумских изотопа, Случај А) и 4.5 % обогаћеног $UO_2$ са $ThO_2$ (као одвојене горивне шипке, Случај Б). Укупна снага разматраног малог модуларног реактора који садржи 69 склопова износи 450 MW термичких. У оба случаја, временско зависни прорачуни критичности реактора са изгарањем обављени су коришћењем MCNPX 2.7 кода, све док се њихови ефективни фактори умножавања неутрона не смање на 0.99. Прорачуни показују да мали модуларни реактор може да ради прилично дуго без допуњавања горива и да се из $ThO_2$ са производњом енергије може добити и ново гориво са обогаћењем од 1.05 %.

*Кључне речи: термички реактор, мали модуларни реактор,трансуранијумско гориво, PWR-MOX гориво*