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Investigation of Minor Actinide-Contained Thorium Fuel Impacts on CANDU-Type Reactor Neutronics Using Computational Method

S. A. H. Feghhi, Z. Gholamzadeh, Z. Alipoor, C. Tenreiro

Abstract**—**Currently, thorium fuel has been especially noticed because of its proliferation resistance than long half-life alpha emitter minor actinides, breeding capability in fast and thermal neutron flux and mono-isotopic naturally abundant. In recent years, efficiency of minor actinide burning up in PWRs has been investigated. Hence, a minor actinide-contained thorium based fuel matrix can confront both proliferation resistance and nuclear waste depletion aims. In the present work, minor actinide depletion rate in a CANDU-type nuclear core modeled using MCNP code has been investigated. The obtained effects of minor actinide load as mixture of thorium fuel matrix on the core neutronics has been studied with comparing presence and non-presence of minor actinide component in the fuel matrix. Depletion rate of minor actinides in the MA-contained fuel has been calculated using different power loads. According to the obtained computational data, minor actinide loading in the modeled core results in more negative reactivity coefficients. The MA-contained fuel achieves less radial peaking factor in the modeled core. The obtained computational results showed 140 kg of 464 kg initial load of minor actinide has been depleted in during a 6-year burn up in 10 MW power.

Keywords**—**Minor actinide burning, CANDU-type reactor, MCNPX code, Neutronic parameters.

I. INTRODUCTION

RECENTLY depleting of minor actinide waste obtained in a nuclear reactor in critical reactors under one-cycle or multiple-cycle strategy has been evaluated. Sahin et al. have been theoretically investigated load of a thorium fuel mixture contained some fractions of transuranic (TRU) elements in CANDU reactor. As their results shows, the modeled core can depletes 100 kg/y of the loaded wastes [1] Romanello et al. have been compared TRU burning ability in accelerator driven and critical systems. According to their results, the fast investigated reactors need to a 30-40% power more than accelerator driven systems for burning of TRUs [2]. Perko et al. have been studied burn up of a TRU-contained fuel in two VVER and PWR modeled reactors. As their theoretical calculations shows, the modeled VVER and PWR cores can deplete TRU fraction of the loaded fuel with a rate of 73 kg/y and 88 kg/y respectively [3]. According to the carried out study by Ikeda et al., burn up of TRU in an ARR modeled reactor achieves 34 kg/TW$_{th}$h americium depletion. They used an americium nitrate (AmN) blanket in the ARR modeled core [4]. Atomic Energy of Canada Ltd (AECL) have carried out very extensive studies which demonstrate the flexibility of CANDU heavy water reactors (HWRs) to burn fuels with different materials compositions. Two recent studies have investigated the potential of CANDU HWRs for MA-TRU burning [5], [6]. Hyland et al. modeled the depletion behavior of two different types of fuel rods containing TRU in the CANFLEX advanced fuel assembly bundle. The first fuel type was MOX fuel comprised of TRU in a conventional UO_2 matrix. The second rod type was an Inert Matrix Fuel (IMF) comprised of TRU in an inert matrix. The MOX fuel showed a worthwhile decrease in TRU inventory of 40% at discharge, while the IMF fuel achieved a reduction of 71%. Hyland et al. investigated the potential of CANDU HWRs and LWRs for burning americium. The HWR analysis modeled the irradiation of CANFLEX bundles in a CANDU reactor, with fuel rods containing various initial fuel compositions of uranium and americium. In some of the examined cases the americium was assumed to be homogeneously distributed in the fuel, while in two cases a centre pin consisting of a 3.7 or 7.0 w/o americium in zirconia was used. The various cases showed transmutation fractions for the americium ranging from 46% to 79%. These are slightly higher than the transmutation fractions achieved in the LWR variants, the highest of which was 71%. This indicates that HWRs have the potential to burn minor MA-TRU slightly more efficiently than PWRs.The presence of MA-TRU fuels in the core will have an impact on the nuclear design behavior of the core [6]. Tomas et al. reported a recent study of americium-curium targets loaded in a PWR core. According to their obtained results, loading of 100 kg of minor actinides could be accommodated in a PWR while satisfying the normal nuclear design limits. Their results shows presence of minor actinides in the core depresses core reactivity, requiring a compensatory increase in initial fissile loading. For a uranium fuelled core, this implies increased uranium ore and enrichment procurement costs which can be evaluated with reasonable confidence [7].

Hence, in this work investigation of consequent effects of TRU burning in a CANDU-type reactor on the nuclear core neutronic performance eusing computational method has been proposed.

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II. MATERIAL AND METHODS

MCNPX has been used as a powerful particle transport code with ability of calculation of steady-state reaction rates, normalization parameters, neutronic parameters as well as fuel burn up using CINDER90 to calculate the time-dependent parameters [8].

A square-arranged 64-assembly core has been modeled using MCNPX 2.6 code. Heavy water has been used as coolant and moderator for the assemblies. Graphite has been considered as moderator of the modeled core. A 3D neutronic model was set up using MCNPX 2.6 code in cold zero power situations by means of ENDF/B-VI continuous-energy cross section. The fuel and heavy water temperature was assumed to be 20°C. The cross sections S(α, β) have been used for BeO reflector material and heavy water. KCODE with 15000 initial neutrons, 150 effective cycles and 50 ineffective cycles has been used for neutronic parameter calculations. 37 concentric fuel pins have been considered in any assembly with CANDU6 [1] assembly characteristics according to the mentioned dimensions and materials in Table I.

TABLE I
CORE MATERIAL AND DIMENSIONS MODELED USING MCNPX

Core components (w%)-Dimensions	
Th-U	2.5% ^{235}U, 97.5% Th
Th-U+MA	11.52% ^{235}U, 83.47% Th, 0.625%^{237}Np, 2.5% ^{241}Am, 1.25%^{243}Am, 0.625% ^{244}Cm
Fuel clad	Zrcaloy-4
Pressuretubeclad	Zrcaloy-2
Calandria clad	Zr-Nb
Gap	Co_2
Moderator/Coolant/Reflector	Graphite/ D_2O/ BeO
Fuel dimension	1.2243×135 cm
Fuel number in assembly	37
Assemblynumber	64
Core dimension	330×310 cm
Fissile mass in Th-U fuel	218.407 kg
Fissile mass in Th-U+MA fuel	1070.456 kg
Total mass of MA	464 kg

A 5 cm BeO cylindrical reflector has been considered as external reflecting layer to minimize neutron leakage outside the core (Fig. 1).

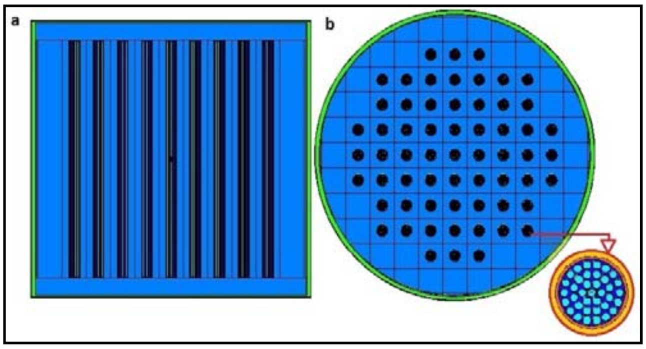

Fig. 1 Schematic view of the modeled core, a) axial view, b) cross sectional view

To investigate impacts of minor actinide-contained thorium based fuel matrix on neutronic performances of the modeled core, two thorium based fuel matrixes have been loaded in the core separately. The components of two different fuel matrixes have been selected in such a way that achieve a fairly-close multiplication factor to each other in cold zero power condition. Radial neutron flux, radial peaking factor, reactivity coefficients of fuel and moderator have been calculated and compared for the two different fuel loads. Fuel burn up has been calculated in 1 MW power for the different fuel matrixes separately for 335 days. Depletion rate of MA in different power insertions has been investigated.

III. RESULTS AND DISCUSSION

According to the obtained computational data, radial peaking factor of the modeled core fed MA-contained fuel was 1.29 which is 9% less than the core fed^{235}U-Th fuel matrix with peaking factor of 1.42 (Fig. 2).

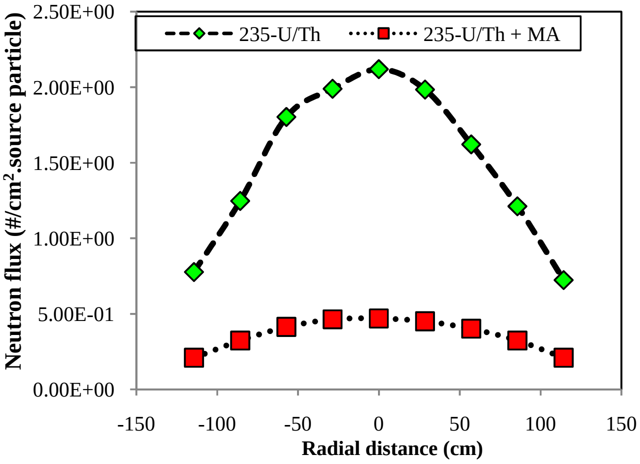

Fig. 2 Comparison of radial neutron flux obtained by two different fuel matrixes' loads

Temperature reactivity coefficients' calculations for coolant and moderator have been presented at Table II. As the obtained data show, the MA-contained fuel load in the modeled reactor can achieve negative reactivity coefficients for both coolant and moderator during temperature transit of 293 K to 599 K. However, the MA-contained fuel load in the modeled reactor obtain less delayed neutron fraction in comparison with U-Th loads.

TABLE II
COMPARISON OF SOME NEUTRONIC PARAMETERS OF THE TWO DIFFERENT FUEL LOADS IN THE CANDU-TYPE MODELED CORE

Fuel	Neutron generation tim((μs)	Delayed neutron fraction (pcm)	Moderator reactivity coefficient $\left(\frac{\mathrm{pcm}}{^{\circ}\mathrm{K}}\right)$	Coolant reactivity coefficient $\left(\frac{\mathrm{pcm}}{^{\circ}\mathrm{K}}\right)$
Th-U	323	813	4.29	2.64
Th-U+MA	376	614	-5.62	-0.61

Gas or buble formation inside the heavy water coolant can change the reactor reactivity. Calculations show reactivity variations consequent of void formation inside the coolant for the modeled core fed MA-contained fuel is positive while modeled core fed U-Th fuel experience negative reactivity coefficient during void percentage enhancement. The reactivity coefficient is +8.89 pcm/% void for the modeled core fed MA-contained fuel and the coefficient is -5.12 pcm/% void for the modeled core fed the other fuel matrix (Fig. 3).

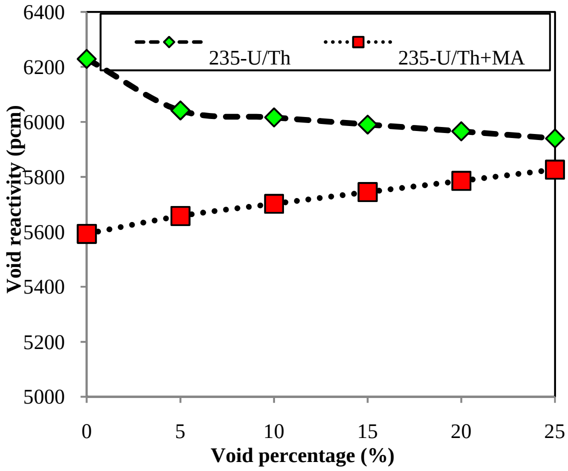

Fig. 3 Comparison of void reactivity variations for the two different fuel loads in the modeled reactor

Temperature reactivity coefficient calculation of the two different fuel matrixes loaded in the modeled core showed the MA-contained fuel experience more negative reactivity coefficients during temperature enhancement, there is a -58 pcm/K during fuel temperature transient of 293 K to 599 K while in case of the other fuel the coefficient is -18 pcm/K (Fig. 4).

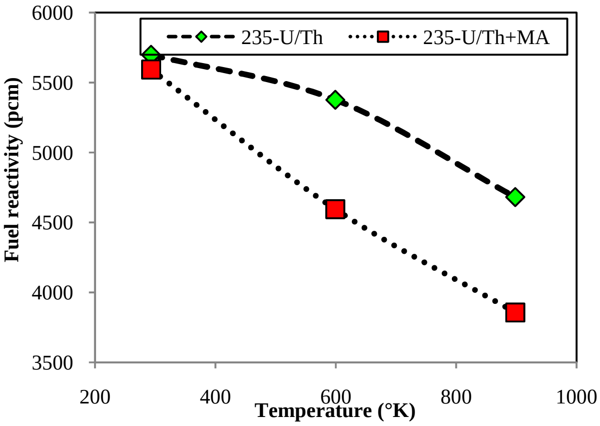

Fig. 4 Comparison of fuel reactivity variations for the two different fuel loads in the modeled reactor

Burn up calculations show ^{135}Xe and ^{149}Sm concentration production is noticeably higher for the MA-contained fuel matrix than the other one. As Table III shows, the produced mass of ^{233}U after 235 days burn up in 1 MW power is 2.67 Kg in case of U-Th fuel matrix while 3 kg of Th and 1.9 Kg of ^{235}U have been consumed. The MA-contained fuel matrix burn up in 335 MWd obtains 1.35 kg of ^{233}U while depletes 5 kg of ^{235}U and 1 kg of Th.

TABLE III
COMPARISON OF THE PRODUCED CONCENTRATIONS OF SOME IMPORTANT ISOTOPES AFTER 335 MWD BURN UP FOR THE TWO DIFFERENT FUEL LOADS

Fuel	^{135}Xe (g)	^{149}Sm (g)	^{233}U (g)	^{239}Pu (g)	$K_{eff(start)}$	$\Delta k_{eff}/k_{eff}$ (pcm)
Th-U	0.096	6.76	2670	0.00	1.05032	-692
Th-U+MA	0.246	21.8	1350	3.04	1.05476	-940
Ratio	2.55	3.22	0.50	–	–	–

Minor Actinide depletion rate during fuel burn up in different powers has been investigated. The obtained results show by doubling the power, depletion rate will be clearly doubled. After 6-year burn up in 10 MW power, 140 kg of the loaded waste as a mixture with the reactor fuel will be depleted (Table IV).

TABLE IV
COMPARISON OF THE PRODUCED CONCENTRATIONS OF SOME IMPORTANT ISOTOPES AFTER DIFFERENT BURN UP TIMES AND POWERS

Time (year)	Power (MW)	Depletion (kg)				Inventory (kg)		
		^{243}Am	^{241}Am	^{237}Np	^{235}U	^{232}Th	^{233}U	^{239}Pu
1	5	1.9	9	0.26	27	8	7.216	0.038
1	10	3.8	17.3	0.88	53.5	16	14.45	0.119
4	10	13.8	61.3	3.25	197	65	57.37	2.587
6	10	25.4	107	7.64	352	135	108.2	8.916

However, the neutron spectra are useful for $^{241/243}$Am and ^{237}Np transmutation but the modeled core available neutron spectra is not suitable for ^{244}Cm isotope so that after 6 years there is 5.83 kg additional value than its initial load (Fig. 5). As it is seen in the Fig. 6, after the 6-year burn up time the effective multiplication factor is steel higher than 1.03 because of converting ability of the thorium fed nuclear core which compensates ^{235}U depletion by ^{233}U inventory.

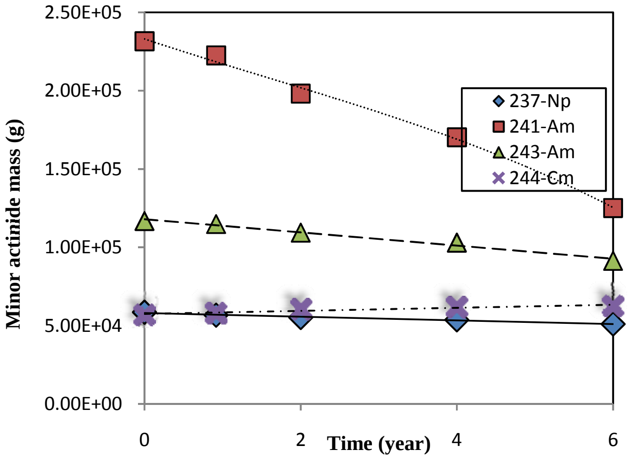

Fig. 5 Comparison of MAs depletion rate during the burn up time in 10 MW power

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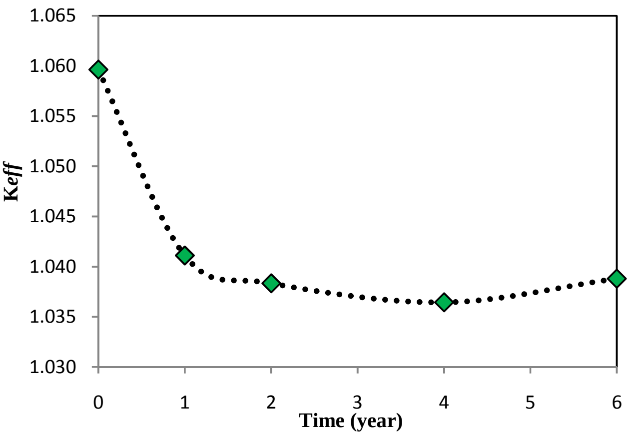

Fig. 6 Effective multiplication variations during the burn up time using 10 MW power

IV. CONCLUSION

Nuclear waste radiotoxicity reduction before sending them to disposal areas is a major concern for nuclear energy user countries. Minor actinide transmutation idea via fast neutron spectra produced using an accelerator driven system has been presented in last decades. High costs of an accelerator have been motivated researchers to investigate minor actinide burning in fast and thermal critical reactors. As the obtained data in the present work show, the modeled CANDU-type thermal reactor can efficiently burn the loaded long-half life alpha emitter wastes except ^{244}Cm because of ^{244}Am decay to it after 10.1 h. So, accumulation of ^{244}Am in the fuel during the burn up process will increase ^{244}Cm concentration. However minor actinide loading in thorium-based fuel matrix provides faster power transits for the modeled core because of the delayed neutron fraction reduction, but higher negative reactivity coefficients provided as a result of minor actinide loading offers a positive weight on safety concerns of a nuclear reactor. Overall to keep critically level of a nuclear core which is to be a minor actinide burner, higher initial enrichments are needed. Hence, an economic comparison between minor actinide incineration using accelerator driven systems and critical reactors should be carried out as complementary conceptual design of such nuclear waste transmuting systems.

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