ANALYSIS OF FUEL REJUVENATION TIMES IN A FUSION BREEDER REACTOR FUELLED WITH A MIXTURE OF URANIUM-THORIUM OXIDES FOR THE CANDU REACTOR

by

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This study presents the determination of fuel rejuvenation times in a D-T fusion breeder reactor fuelled with a mixture of $^{nat}UO_2$ and ThO_2 for multi-reuse of nuclear fuels in CANDU-37 reactors. To determine the effect of thorium on the fuel enrichment and rejuvenation times, neutronic analyses are performed by increasing the percentage of ThO_2 in the fuel mixture from 10 to 35. The time-dependent neutronic calculations are carried out in three stages. In the first stage, which is the fuel enrichment or rejuvenation process in the fusion breeder reactor, the subcritical calculations of the fusion breeder reactor fuelled with the fuel mixtures are performed by using the MCNPX 2.7/CINDER under a fusion neutron wall loading of 1 MWm^{-2}, corresponding to neutron flux of $4.444 \cdot 10^{13}$ cm^{-2}s^{-1} (energy of every fusion neutron is 14.1 MeV). In the second stage, which is the thermal reactor analysis, the fuel rods enriched at the end of the first stage are placed in the CANDU-37 reactor, and the critical calculations of this reactor are performed by using MCNPX 2.7 and MONTEBURNS codes separately. The numerical results show that the neutronic values obtained from both codes are very near each other. The third stage is the two-year cooling process of CANDU spent fuels. The values obtained by numerical calculations show that this fusion breeder reactor is self-sufficient in terms of tritium and has a high performance in terms of energy multiplication as well as fuel rejuvenation and thorium utilization.

Key words: fusion breeder reactor, fissile breeding, fuel enrichment, fuel rejuvenation, thorium utilization, CANDU reactor

INTRODUCTION

Canada deuterium uranium (CANDU) thermal reactors, using natural uranium (0.005 % ^{234}U, 0.711 % ^{235}U, and 99.284 % ^{238}U) [1], have been operated widely for over 50 years to convert nuclear energy to electric energy. CANDU and other thermal reactors (such as light water reactors, LWR) can utilize only 1 % of natural uranium [2]. Unfortunately, the remaining spent fuels, which include abundant amounts of fertile fuel, cannot be used for energy generation as is. Moreover, there are large amounts of hazardous radioactive nuclear waste in these spent fuels. Managing of nuclear spent fuels, therefore, is one of the most crucial problems of the nuclear energy industry. Currently, many countries prefer to bury the nuclear spent fuels placed in concrete containers underground. Furthermore, thorium is also an attractive nuclear fertile fuel, and its reserves are estimated to be approximately three times larger than natural uranium [3]. On the other hand, a fusion breeder reactor (HYBRID reactor) operating safely in sub-critical mode can rejuvenate spent fuels and enrich natural uranium and thorium fuels by means of high energetic neutrons released in fusion reactions as well as energy production. In the near future, the HYBRID reactors, therefore, will be an alternative method for natural uranium enrichment, spent fuel rejuvenation, nuclear waste transmutation and also thorium utilization.

Many time-dependent burn calculations have studied CANDU reactors fuelled with various fuel mixtures. Yang *et al*., developed a fuel cycle scheme for thorium-uranium (^{232}Th-^{233}U) breeding recycle in CANDU reactors [4]. The results of this study show that such a recycling can be technically applicable in existing CANDU reactors. Mohamed and Badawi use thorium-plutonium MOX fuels by placing them in the inner fuel rods of CANDU fuel bundles [5]. Numerical analyses are performed by using MCNP6. The numerical results show that uranium demand can be reduced approximately by 27 % by placing the thorium-plutonium MOX fuels in the inner fuel rods. Mirvakili *et al*.,

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analyzed the neutronic effects of ThO_2 by placing it in 6 of the 37 fuel rods in fuel bundles of the CANDU 6 reactor [6]. Neutronic calculations are performed by using MCNPX 2.6 and CINDER90. The computational results show that at the end of one year burn-up, 18.38 kg of ^{233}U and 31.84 kg of ^{239}Pu can be produced via this method. Nuttin *et al*. comparatively analyzed the conversion performances of CANDU and PWR reactors loaded with a mixture of thorium and plutonium by slightly modifying them [7]. Saldideh *et al*. calculated the neutronic values of a CANDU reactor fuelled with various mixtures of thorium, uranium and plutonium by using Monte Carlo techniques [8]. They point out that with such fuel compositions, the infinite neutron multiplication factor (k) can be above 1.04 during over 8 years of burn operation. Bergelson *et al*. studied on the self-sufficient thorium fuel cycle for CANDU reactors [9, 10]. The results of these studies confirm that a self-sufficient thorium mode is possible for a CANDU reactor without the need for a new technology.

Furthermore, the rejuvenation of spent fuel and the enrichment of uranium-thorium fuel are performed in HYBRID reactors by many researchers. Azizov *et al*. studied the transmutation of long-lived actinides in a TOKAMAK fusion reactor cooled with different coolants by using the Monte Carlo method [11]. Francois *et al*. analyzed the transmutation of LWR spent fuel in a fusion-fission HYBRID system based on the TOKAMAK concept by considering mixed oxide fuel and inert matrix fuel [12]. They used the MCNPX code for the neutronic analyses. Noack *et al*. considered a mirror HYBRID, which is based on the TOKAMAK fusion reactor to incinerate the transuranic (TRU) elements from spent nuclear fuel and to amplify fusion energy [13]. This HYBRID reactor is operated at $k_{eff} = 0.95$, and the MCNP5 code together with the JEFF-3.1 nuclear data library are used for neutronic calculations. Acir and Ubeyli investigated the reduction of the reactor grade (RG) plutonium in a HYBRID reactor fuelled with a mixture of PuO_2 and ThO_2 [14]. This study shows that a substantial amount of RG-plutonium can be burned in the investigated HYBRID reactor in a short period. Ubeyli investigates the effects of a fuel zone coolant, Flinabe, $Li_{20}Sn_{80}$, natural lithium and Flibe, on the neutronic performance of a HYBRID reactor rejuvenating the CANDU spent fuel [15]. The results of this study show that Flibe and Flinabe have the best neutronic properties for spent fuel rejuvenation. Furthermore, Ubeyli studied the enrichment and rejuvenation of nuclear fuels and the fission power flattening in the fuel zone in ARIES-RS Fusion Breeder Reactors fuelled with various fuel compositions [16, 17].

In our previous works, rejuvenation and transmutation of nuclear spent fuels (extracted from LWR or CANDU reactors), enrichment of nuclear fuels and transmutation of long-lived fission products in various HYBRID reactors are investigated [18-31]. The results of these works indicate that the considered HYBRID reactors have a high performance in terms of energy multiplication as well as rejuvenation, transmutation and enrichment of nuclear fuels. In this study, fuel rejuvenation times in a HYBRID reactor fuelled with a mixture of uranium-thorium oxides are analyzed for multi-reuse of nuclear fuels in CANDU reactors.

FUSION BREEDER REACTOR

A D-T fusion breeder reactor operating in sub-critical mode can produce fissile fuel from fertile materials (such as ^{232}Th and ^{238}U) as well as fission energy by using high energetic fusion neutrons. It also produces the necessary tritium for self-sustainment. Hence, a fusion breeder reactor is a HYBRID system in which both fusion and fission reactions occur. It is also named as a HYBRID reactor. In this study, the HYBRID reactor used in [29] is considered by modifying sizes. The sketch of a vertical cross- section view of one-quarter of the modified HYBRID reactor is plotted in fig. 1. As apparent from this figure, the reactor consists essentially of two parts: (1) a fusion chamber in which the D-T fusion reactions occur and (2) a blanket with four zones surrounding this fusion chamber. The blanket zones are as follows.

- First wall (FW) is made of a SiC composite.
- Fuel zone (FZ), in which the fission and fissile fuel breeding reactions occur, contains containing CANDU fuel rods placed as a hexagonal arrangement. A mixture of $^{nat}UO_2$ and ThO_2 is used as fuel. This zone is conceptually divided into four subzones and is cooled with either helium or natural liquid lithium. Volume fractions of fuel, clad and coolant are 0.60, 0.085, and 0.315, respectively. In the cases of $^{nat}UO_2$ fuel mixed with ThO_2, natural liquid lithium is used instead of helium as a coolant to provide a tritium breeding ratio (TBR) above 1.1.
- Tritium breeding zone (TBZ): One of the main parameters of fusion breeder reactors is the TBR, and for a fusion breeder to be self-sufficient in terms of tritium, this ratio must be greater than or equal to 1.1. Since tritium can be produced from lithium, this region contains Li_2O. Furthermore, this zone is designed in a sandwich form along with the reflector zone to increase TBR.
- Reflector zone (RZ): This Zone, which is made of graphite, returns neutrons coming from the TBZ.

In addition, atomic percentages and mass densities of materials used in the considered HYBRID are given in tab. 1.

CANDU-37 REACTOR

As is known, the CANDU-37 reactor [1], which is a thermal reactor and operates in critical mode, uses $^{nat}UO_2$ (0.711 % ^{235}U, 0.005 % ^{234}U and 99.284 %

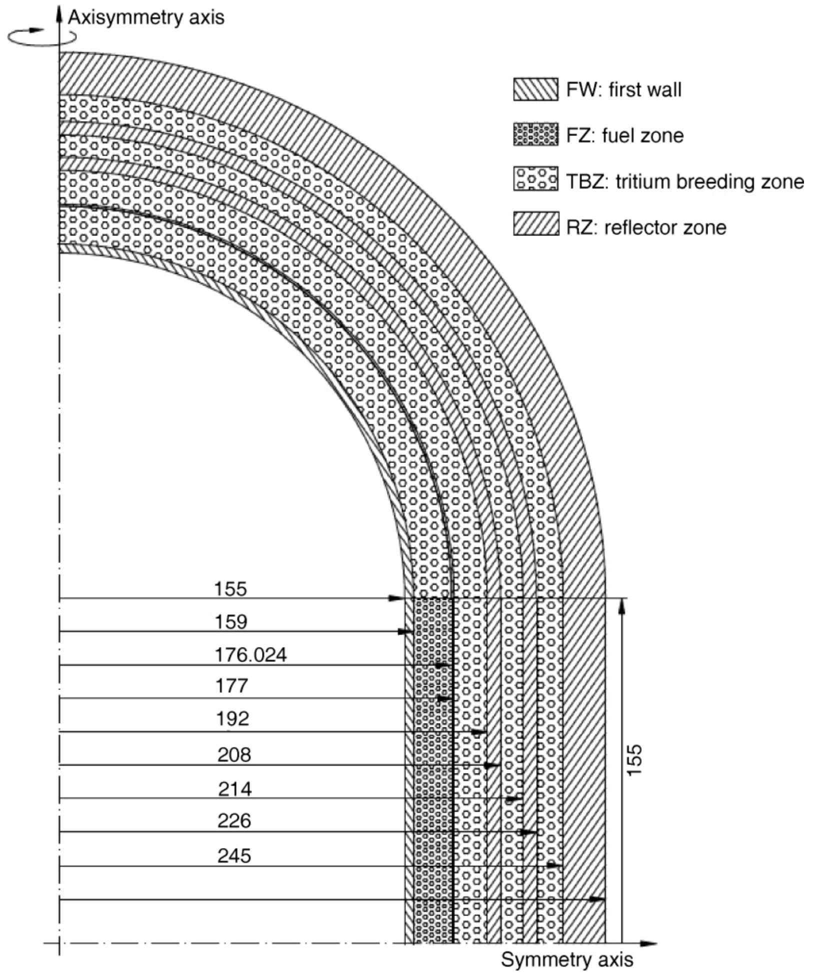

Figure 1. Vertical section view of one-quarter of the HYBRID reactor (dimensions are in cm) [29]

Table 1. Materials used in the HYBRID reactors

Zone		Volumetric percentage	Material	Density [gcm^{-3}]	Isotope	Atomic percentage
First wall		100	SiC	3.2	^{14}Si	50
					^{12}C	50
Fuel	Fuel	60	UO_2 (100 to 35 %)	10.54	^{234}U	0.005
					^{235}U	0.711
					^{238}U	99.284
			ThO_2 (0 to 65 %)	9.88	^{232}Th	100
	Clad	8.5	Zircaloy-4	6.56	^{24}Cr	0.1
					^{26}Fe	0.21
					^{40}Zr	98.23
					^{50}Sn	1.45
					^{72}Hf	0.01
	Coolant	31.5	Helium	0.00715	^{4}He	100
			Natural liquid lithium	0.534	^{6}Li	7.5
					^{7}Li	92.5
Tritium breeding		100	Li_2O	2.013	^{6}Li	7.5
					^{7}Li	92.5
Reflector		100	Graphite	2.1	^{12}C	100

^{238}U) [1] pellets placed in thin cylindrical zircaloy-4 rods. Figure 2 shows the radial cross-section view of one-quarter of a CANDU-37 fuel channel with a length of 595 cm. In the CANDU-37 reactor, there are 380 fuel channels, which are placed as a square lattice with a pitch of 28.575 cm, each fuel channel contains 12 fuel bundles fitted longitudinally (end-to-end). Each fuel bundle with a length of 49.53 cm includes 37

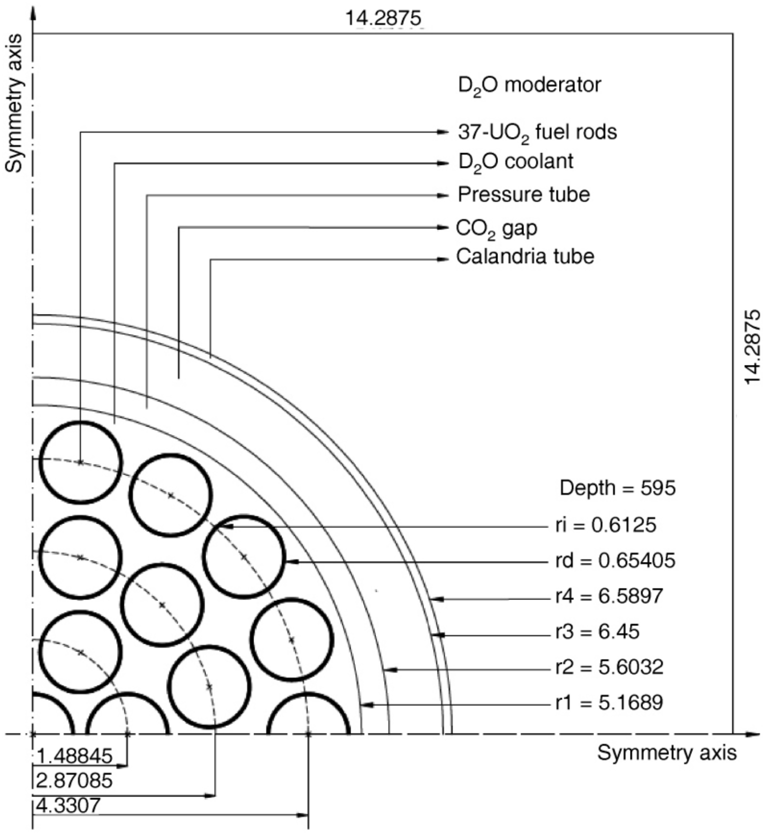

Figure 2. Cross-section view of one-quarter of a heterogeneous CANDU-37 fuel channel (dimensions are in cm and the dimensions except the height and width of the fuel channel are in scale) [1]

fuel rods arranged in the form of four rings as shown in fig. 3. The CANDU reactor uses heavy water (D_2O) as a coolant and moderator, and its total fission power is 2156 MW.

Moreover, atomic percentages and mass densities of materials used in the CANDU-37 reactor are presented in tab. 2.

NUMERICAL RESULTS

Calculation procedure

In this study, the fuel rejuvenation, enrichment and burn processes are carried out in three stages as: (1) the fuel rejuvenation and enrichment processes in the HYBRID reactor, (2) the fuel burn process in the CANDU reactor, and (3) the two-year cooling process of CANDU spent fuels. In the fuel rejuvenation process, CANDU-37 fuel rods filled with the a mixture of $^{nat}UO_2$ and ThO_2 are hexagonally placed in the subzones of the fuel zone of the fusion breeder reactor to increase their cumulative fissile fuel enrichment (CFFE). According to the dimensions of these two reactors, only about one-third of the total fuel mass of a CANDU-37 reactor can be placed in the fuel zone of the HYBRID reactor. The time-dependent sub-critical calculations of this reactor have been performed by us-

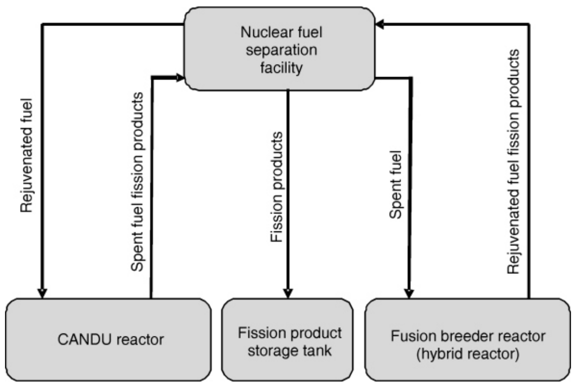

Figure 3. One fuel cycle of CANDU-spent fuel

ing MCNPX 2.7 [32] and CINDER [33] codes under a fusion neutron wall loading of 1 MWm^{-2}, corresponding to a D-T fusion neutron flux of $4.444 \cdot 10^{13}$ $cm^{-2}s^{-1}$ (energy of each fusion neutron is 14.1 MeV). The neutron density is obtained as $2.68335 \cdot 10^{19}$ fusion neutrons per second by multiplying this flux value and FW area ($6.03814 \cdot 10^5$ cm^2). According to these values, the fusion power wall loading is calculated as 60.38 MW. In the fuel burn process, the fuel rods, which reach the enough cumulative fissile fuel enrichment (CFFE) in the fuel rejuvenation and enrichment processes for the CANDU reactor, are placed in the bundles of the CANDU-37 reactor. The fuel rods in each sub-zone

Table 2. Materials used in the CANDU-37 reactor

Zone	Volumetric percentage	Material	Density [gcm^{-3}]	Isotope	Atomic percentage
Calandria tube	100	Zirc2.5Nb	6.53	^{40}Zr	97.5
				^{41}Nb	2.5
Gap	100	CO_2		^{12}C	100
Pressure tube	100	Zircaloy-2		^{24}Cr	0.1
			6.56	^{26}Fe	0.135
				^{28}Ni	0.055
				^{40}Zr	98.25
				^{50}Sn	1.45
				^{72}Hf	0.01
Moderator	100	D_2O	1.1	^{2}H	100
Clad	100	Zircaloy-4	6.56	^{24}Cr	0.1
				^{26}Fe	0.21
				^{40}Zr	98.23
				^{50}Sn	1.45
				^{72}Hf	0.01
Fuel	100	UO_2	10.54	^{234}U	0.005
				^{235}Uf	0.711
				^{238}U	99.284

are placed in the same numbered ring of the bundle of the CANDU reactor, from the inside out. The time-dependent heterogeneous critical burn calculations of this reactor are carried out by using MCNPX 2.7 (with a BURN TIME option) and MONTEBURNS [34] codes for a total thermal power of 2156 MW. Interface computer codes named XBURN [35], CBURN [36] and MBURN [37] are developed to accurately evaluate the MCNPX, CINDER and MONTEBURNS outputs, respectively. The numerical results indicate that the neutronic values of the burn processes obtained from both MCNPX 2.7 and MONTEBURNS codes are almost the same. In the following sections, the fuel rejuvenation or enrichment process together with the fuel burn process will be called as one fuel cycle. The stages of one fuel cycle are shown in detail in fig. 3. As apparent also from this figure, the nuclear fuels and fission products from both reactors are separated from one another in the Nuclear Fuel Separation Facility so that both reactors are loaded with only nuclear fuels at the beginning of all fuel cycles.

NEUTRONIC ASSESSMENTS

Case of only $^{nat}UO_2$ fuel

The fissile fuel atomic percentage of natural uranium is 0.711 %, and this fuel can be burned in the CANDU reactor until k_∞ decreases to 1.06-1.05. During this process, its burn time is calculated as about 180 days. The 180-day duration is adopted as the effective burn time for the CANDU reactor, and in the following sections, it will be known as the effective burn time. Firstly, $^{nat}UO_2$ fuel is burned in the CANDU reactor during the effective burn time. The burned fuel is subjected to a cooling process for two years, and the cooled fuel rods are rejuvenated in the blanket of the HYBRID reactor until they become re-burnable in the CANDU reactor during the effective burn time. In the following sections, the time required for the spent fuel to become available again in the CANDU reactor will be called as the rejuvenation time. This time is calculated as about 90 days.

Figure 4 shows the decrease and the subsequent increase of CFFE in the CANDU and HYBRID reactors during each fuel cycle (the effective burn time (left subfigure) and the subsequent rejuvenation time (right subfigure)) in the case of only $^{nat}UO_2$ fuel. In addition, the variations of k in each fuel cycle depending on the effective burn time are plotted in fig. 5. As is apparent from these figures, at the beginning of the first fuel cycle, CFFE of 0.7 % is sufficient for the effective burn time, but requires a higher CFFE at the beginning of the fuel cycles as the number of the fuel cycles increases. Hence, the highest value of CFFE is at the beginning of the fifth fuel cycle and its value is about 1.034. Values of k , which are in the range of 1.12 and 1.28 at the beginning of fuel cycles, decrease to about 1.07 at the end of all fuel cycles.

The tritium breeding ratio (TBR), which is one of the main parameters of fusion breeder reactors, can be obtained from the following reactions

$$^{6}\text{Li} \quad \text{n} \quad ^{4}\text{He} \quad \text{T} \qquad (1a)$$

$$^{7}\text{Li} \quad \text{n} \quad ^{4}\text{He} \quad \text{T} + \text{n} \qquad (1b)$$

The calculated values of TBR are greater than 1.1 (in the range of 1.15 and 1.17) during the fuel rejuvenation processes of all fuel cycles. This means that

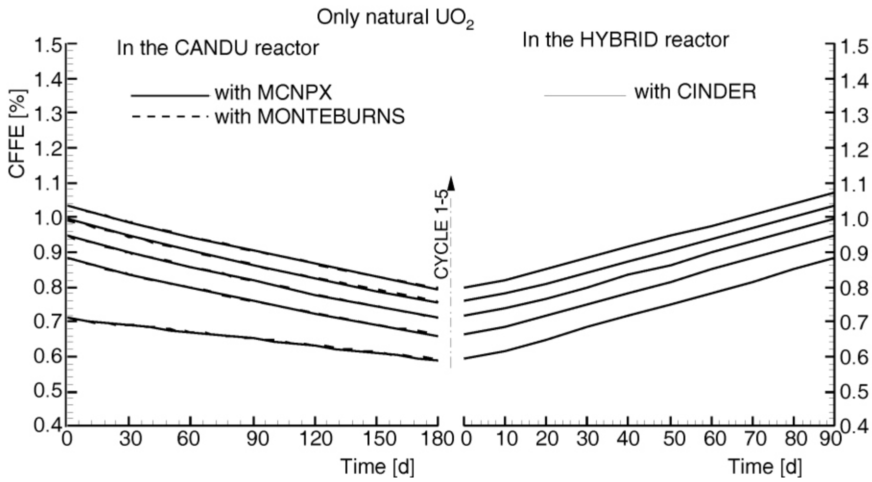

Figure 4. Decrease and subsequent increase of CFFE during each fuel cycle (the effective burn time (left subfigure) and the subsequent rejuvenation time (right subfigure))

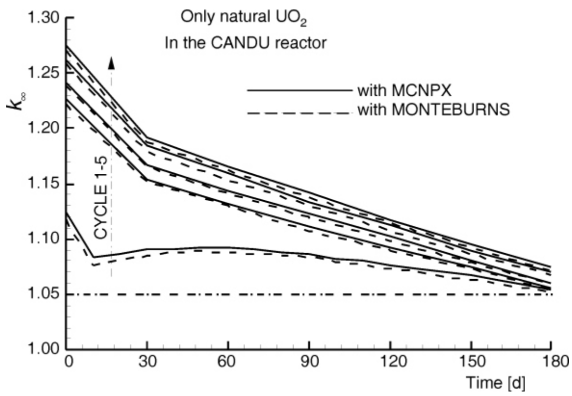

Figure 5. Variations of the infinite neutron multiplication factor in each fuel cycle during the effective burn time

the considered fusion breeder reactor is self-sufficient in terms of tritium.

Another main parameter is the energy multiplication factor (M), and it can be calculated with the following equation

$$M \quad \frac{R_{\mathrm{f}} 200 \quad {}^{6}\mathrm{Li}(n,\gamma)\ 4.784 \quad {}^{7}\mathrm{Li}(n,\gamma)\ 2.476 \quad 14.1}{14.1} \tag{2}$$

where R_f is the number of fission reactions per fusion neutron, ^{6}Li(n,γ) – the tritium breeding reaction from ^{6}Li (see eq. 1a) and ^{7}Li(n,γ) – the tritium breeding reaction from ^{7}Li (see eq. 1b). The mean value of M calculated with this equation is 4.22. In other words, the fusion power wall loading of 60.38 MW can be increased up to 255 MW in the blanket during the fuel rejuvenation process. These values show that the considered fusion breeder reactor has a high performance in terms of energy multiplication as well as fuel rejuvenation.

In nuclear reactors, fuel burn-up (BU), which is also known as fuel utilization, is described as the produced total fission energy per the mass of initial fuel. It is can be calculated with the following equation

$$\mathrm{BU}(t \quad \Delta t) \quad \mathrm{BU}(t) \quad \frac{\text{Fission power}}{\text{MTU}} \Delta t \tag{3}$$

where t is the process time, MTU – the metric ton of uranium and Δt – the time interval.

Total BU, with an average value of 4.60 GWd per MTU at the end of each fuel cycle, reaches 22.99 GWd per MTU at the end of the fifth fuel cycle. 15.56 % of the total BU belongs to the enrichment and rejuvenation processes in the HYBRID reactor.

Case of ${}^{nat}UO_2$ fuel mixed with ThO_2

In the cases of ${}^{nat}UO_2$ fuel mixed with ThO_2, firstly, the cumulative fissile fuel enrichment (CFFE) values of the fuel mixture must be increased to a value necessary for the effective burn time in the CANDU reactor by fuel enrichment in the HYBRID reactor. Therefore, the fuel cycles begin with the fuel enrichment process in the HYBRID reactor.

The CFFE values and the fuel enrichment times necessary for the effective burn times versus the percentages of ThO_2 are plotted in fig. 6. Since the fission and capture cross-sections of ^{232}Th are lower than those of ^{238}U, when the percentage of ThO_2 is increased, the CFFE values and the fuel enrichment

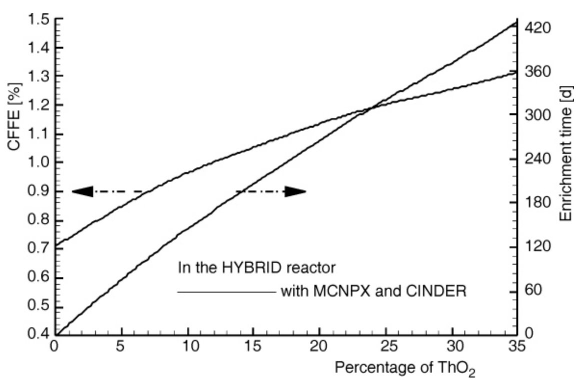

Figure 6. Variations of the fuel enrichment times and cumulative fissile fuel enrichments (CFFE) necessary to effectively burn the fuel in the CANDU-37 reactor depending on the percentage of ThO_2

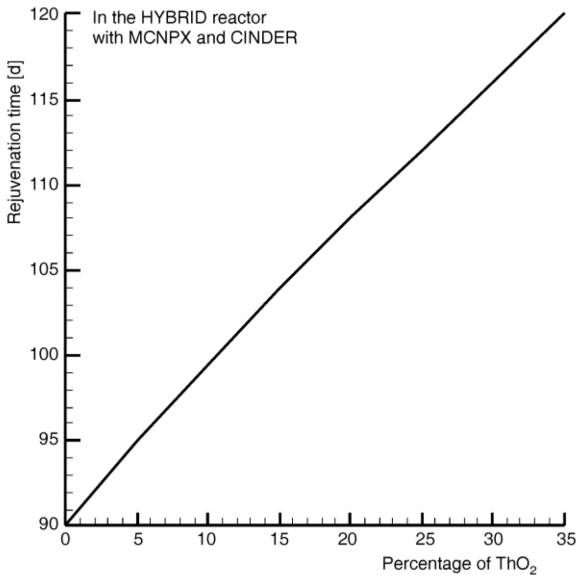

Figure 7. Variation of the fuel rejuvenation time necessary to effectively burn the fuel mixture in the CANDU-37 reactor depending on the percentage of ThO_2

times, which depend on CFFE, also increase. The numerical calculations show that when the ThO_2 percentage is greater than 35, the value of TBR decreases under 1.1 Therefore, the cases of the ThO_2 percentages only in the range of 10 and 35 are investigated. When the percentage of ThO_2 is raised from 10 to 35, the CFFE values at the beginning of the fuel cycle increase from 0.9651 % to 1.3136 % and the fuel enrichment times also increase from 145 days to 425 days. In other words, for instance, $^{nat}UO_2$ fuel mixed with 35 % ThO_2 can be used in the CANDU reactor during the effective burn time only after 425 days of an enrichment process.

Figure 7 exhibits the increase of the fuel rejuvenation time in the HYBRID reactor necessary to effectively burn the fuel mixture in the CANDU-37 reactor depending on the percentage of ThO_2. The fuel rejuvenation times linearly increase from 90 days to 120 days depending on the increase of the ThO_2 percentage. This means that, for instance, in the case of a percentage of 35 % ThO_2, CANDU spent fuel can be rejuvenated in the HYBRID reactor in 120 days for an effective burn time.

The increase and subsequently the decrease of the CFFE values during the fuel enrichment and subsequent burning processes in the HYBRID and CANDU reactors are plotted in fig. 8 for various ThO_2 percentages. Furthermore, the variations of k in the cases of these fuels mixed with ThO_2 during the effective burn time are presented in fig. 9. As apparent from these figures, the enriched fuel mixtures in the HYBRID reactor can be effectively burned for 180 days in the CANDU reactor. The enrichment times increase from 145 days to 425 days when the percentage of ThO_2 is raised from 10 to 35. At end of the effective burn time, k decreases to 1.06 in all fuel cases. These results indicate that the enriched fuel mixtures can be burned effectively in the CANDU reactor during the effective burning time.

Case of $^{nat}UO_2$ fuel mixed with a 35 % ThO_2

Figure 10 shows in the case of $^{nat}UO_2$ fuel mixed with a 35 % ThO_2 the increase and the subsequent decrease of CFFE in the HYBRID and CANDU reactors during the fuel cycle for five fuel cycles. Figure 11 indicates the variations of k in these fuel cycles during the effective burn time. As apparent from fig. 10, in the first fuel cycle, the CFFE of the fuel mixture is increased from 0.47 % to 1.3 % by the enriching process in the HYBRID reactor for 425 days, and the enriched fuel is burned in the CANDU reactor during the effective burn time. In the second and subsequent fuel cycles, the rejuvenation times of CANDU spent fuels are only 120 days. For instance, in the fifth fuel cycle, the CFFE value is increased from 1.24 % to 1.44 % in 120 days, and the rejuvenated fuel can be burned in the CANDU reactor during the same effective burn time (180 days). At the beginning of the fuel cycles, the val-

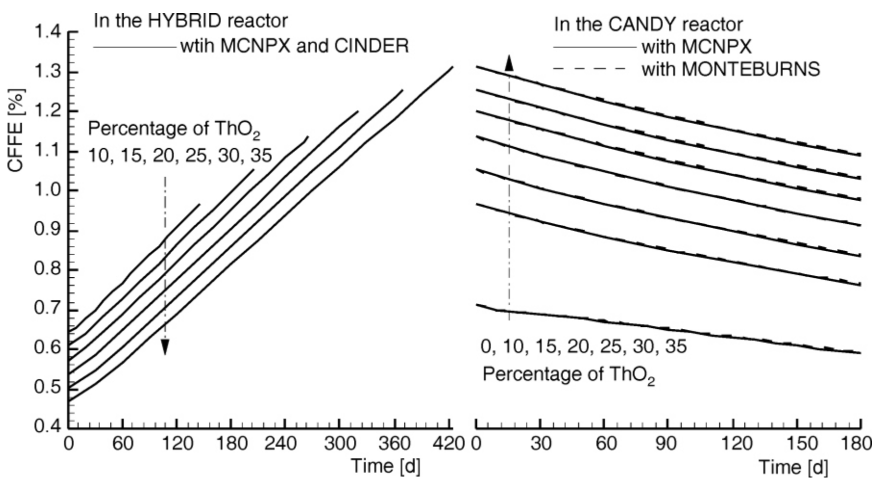

Figure 8. In the cases of the various percentages of ThO_2, increase and subsequent decrease of CFFE during the first fuel cycle

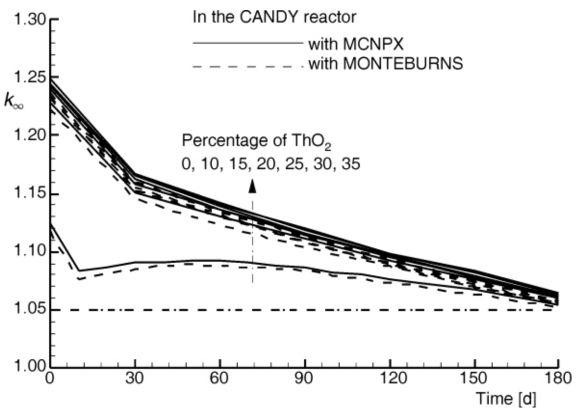

Figure 9. Variations of the infinite neutron multiplication factor in the case of the various percentages of ThO_2 during the effective burn time

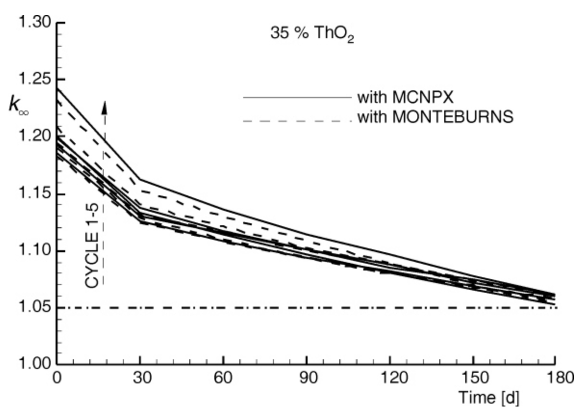

Figure 11. Variations of the infinite neutron multiplication factor in each fuel cycle during the effective burn time

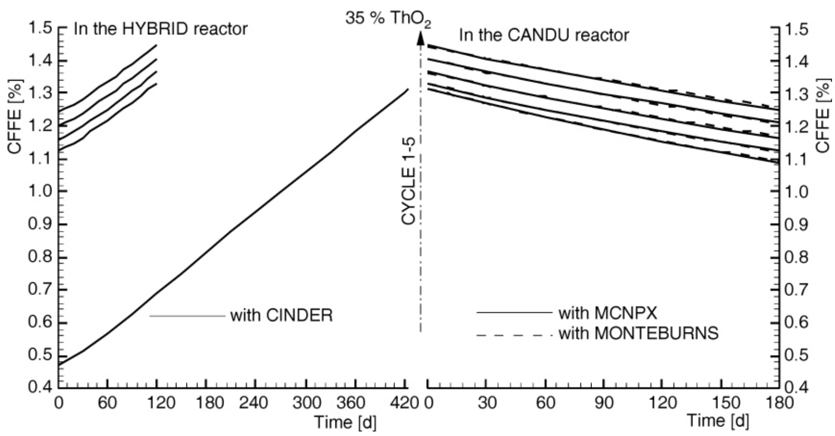

Figure 10. Increase and subsequent decrease of CFFE during each fuel cycle (the rejuvenation time (left subfigure) and the subsequent effective burn time (right subfigure))

ues of k_∞ are in the range of 1.19 and 1.24, and at the end of the burning, they decrease to about 1.06.

The calculated values of TBR are greater than or equal to 1.1 (in the range of 1.10 and 1.16) during the fuel rejuvenation processes of all fuel cycles. This means that the considered fusion breeder reactor fuelled with the mixture fuel is self-sufficient in terms of tritium. The *M* values are in the range of 3.2 and 3.7 (mean 3.45). Thus, the mean heat power released in the blanket is 208 MW during the fuel enrichment process. These values confirm that the considered fusion breeder reactor has a high performance in terms of energy multiplication as well as fuel enrichment. Total BU, with an average value of 5.24 GWd per MTU at the end of each fuel cycle, reaches 26.20 GWd per MTU at the end of the fifth fuel cycle. 15.31 % of the total BU occurs in the enrichment and rejuvenation processes in the HYBRID reactor.

The masses of isotopes at the beginning of the first fuel cycle (BOC) and the end of the fifth fuel cycle (EOC) in the CANDU reactor are given in tab. 3 for both fuel cases in grams.

CONCLUSIONS

One way of rejuvenation of nuclear fuels is to use HYBRID reactors with a high-energetic neutron source. Several time-dependent calculations are carried out to obtain the most suitable neutronic data by using MONTEBURNS, MCNPX 2.7 and CINDER computer codes. Some important results are briefly presented as follows.

– In the first fuel cycle, the fuel enrichment times in the HYBRID reactor increase from 145 days to 425 days depending on the ThO_2 percentages in the mixture.
– In the case of only $^{nat}UO_2$ fuel, total BU, with an average value of 4.60 GWd per MTU at the end of each fuel cycle, reaches 22.99 GWd per MTU at the end of the fifth fuel cycle.
– In the case of $^{nat}UO_2$ fuel mixed with ThO_2, with an average of 5.24 GWd per MTU at the end of each cycle, the BU value reaches 26.20 GWd per MTU at the end of the fifth cycle. Correspondingly, its value can only be 52.40 GWd per MTU at the end of the tenth fuel cycle.

Table 3. Masses of isotopes at the beginning of the first fuel cycle (BOC) and the end of the fifth fuel cycle (EOC) in the CANDU reactor in grams

CASE	Only UO_2		$^{nat}UO_2$ fuel mixed with 35 % ThO_2	
Isotope	BOC	EOC*	BOC	EOC*
^{232}Th	–	–	7.72540E+04	7.43800E+04
^{233}Pa	–	–	5.42400E+01	–
^{233}U	–	–	5.27510E+02	1.32460E+03
^{234}U	1.23261E+01	8.67120E+00	9.95590E+00	1.78680E+02
^{235}U	1.76017E+03	1.73032E+02	1.04291E+03	1.85037E+02
^{236}U	–	2.85900E+02	5.31380E+01	2.27493E+02
^{238}U	2.48938E+05	2.42025E+05	1.52468E+05	1.48658E+05
^{237}Np	–	1.19274E+02	1.13414E+02	1.58972E+02
^{236}Pu	–	1.86810E–03	1.01080E–03	5.34540E–03
^{238}Pu	–	5.07720E+01	1.86200E+00	7.57910E+01
^{239}Pu	–	1.08525E+03	1.03004E+03	6.82800E+02
^{240}Pu	–	8.97540E+02	6.21730E+00	6.30200E+02
^{241}Pu	–	1.71554E+02	2.89580E–02	1.27201E+02
^{242}Pu	–	1.16522E+02	7.05700E–05	9.24990E+01
^{241}Am	–	3.33210E+01	4.08390E–04	2.80430E+01
^{243}Am	–	1.08794E+01	1.48300E–07	9.51420E+00
^{244}Cm	–	2.13819E+00	2.38500E–10	1.74356E+00
TOTAL	2.50710E+05	2.44980E+05	2.32561E+05	2.26761E+05
^{16}O	3.36947E+04	3.36809E+04	3.15842E+04	3.15815E+04
TOTAL	2.84405E+05	2.78661E+05	2.64146E+05	2.58342E+05

*At the end of burn of 180 days and then cooling of 2 years

The time-dependent numerical calculations have been performed for a fusion neutron wall loading of 1 MWm^{-2} (60.38 MW) and the obtained enrichment and rejuvenation times are, therefore, valid for one-third of the total fuel mass of a CANDU-37 reactor. The fusion neutron wall loading must be 3 MWm^{-2} (181.143 MW) so that the same obtained times can be valid when the total mass is considered.

In conclusion, the considered fusion breeder reactor has a high performance in terms of energy multiplication as well as fuel rejuvenation.

AUTHORS' CONTRIBUTIONS

Theoretical and numerical analyses were carried out by H. Yapici, and G. Bakir analyzed and discussed the results. The manuscript was written and the figures were prepared by all authors.

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АНАЛИЗА ВРЕМЕНА ОБНАВЉАЊА ГОРИВА У ОПЛОДНОМ ФУЗИОНОМ РЕАКТОРУ СА МЕШАВИНОМ ГОРИВА УРАНИЈУМ-ТОРИЈУМ ОКСИДА НАМЕЊЕНИХ CANDU РЕАКТОРИМА

Ова студија приказује одређивање времена обнављања код D-T оплодног фузионог реактора који као гориво користи мешавину природног UO_2 и ThO_2 за вишеструку употребу нуклеарног горива у CANDU-37 реакторима. Како би се одредио утицај торијума на обогаћење горива и време обнављања, спроведене су неутронске анализе повећањем ThO_2 у мешавини горива од 10-35 %. Временски зависни неутронски прорачуни изведени су у три фазе. У првој фази, која обухвата обогаћење горива или процес обнављања у оплодном фузионом реактору, извршени су прорачуни у поткритичном режиму оплодног фузионог реактора са горивном мешавином применом програмског пакета MCNPX 2.7/CINDER при оптерећењу зида суда фузионим неутронима од 1 MWm^{-2}, што одговара флуксу неутрона од 4.444 10^{13} $cm^{-2}s^{-1}$ (енергија сваког фузионог неутрона 14.1 MeV). У другој фази, термичкој анализи реактора, обогаћене горивне шипке са краја прве фазе постављају се у CANDU-37 реактор и врши се прорачун критичности реактора независном применом програмских пакета MCNP 2.7 и MONTEBURNS. Нумерички резултати показују да су неутронке вредности добијене помоћу оба програмска пакета међусобно веома блиске. Трећа фаза је двогодишње хлађење CANDU истрошеног горива. Вредности добијене нумеричким прорачунима показују да је овај оплодни фузиони реактор самоодржив у погледу трицијума и има високе перформансе у погледу енергетске мултипликације, као и обнављања горива и искоришћења торијума.

Кључне речи: оплодни фузиони реактор, фисиона оплодња, обогаћење горива, обнављање горива, искоришћење торијума, CANDU реактор