# INCREASING PLUTONIUM DISPOSITION RATE IN THE THERMAL REACTORS (VVER AND RBMK)

S. DAWAHRAH
Nuclear Engineering Department, Atomic Energy Commission
Damascus, Syria
saldawahrah@aec.org.sy

**Abstract**

Several countries reuse MOX fuel (reactor-grade (RG) and weapons-grade (WG) Pu) in the thermal reactors, but within no more than 30% of the total core loading. Many years of operational experience with MOX-fuelled cores along with well-developed technologies in the management of MOX fuel demonstrate possibilities in extending MOX fuel share in commercial nuclear power plants. Therefore, this paper deals increasing weapons-grade plutonium disposition rate ($m_{Pu}$) in the thermal reactors using differenced methods as: reducing the burnup, reducing the residence time of the MOX assemblies in the reactor, increasing the fraction of MOX assemblies in the core, and reducing the plutonium enrichment in the MOX fuel. The results showed at EOC for 100% MOX fuel that the $m_{Pu}$ were: 1320 and 930 kg/year and the $^{240}$Pu fractions were: 31 and 45% for VVER and RBMK respectively. The $m_{Pu}$ was increased: 930, 985, 1076 and 1590 when the plutonium enrichment was reduced: 1.8, 1.6, 1.4, 1.0 % respectively. The $m_{Pu}$ was increased by 45% when using four $UO_2$ fuel cycles and one MOX cycle instead of three $UO_2$ fuel cycles and one MOX cycle.

## 1. INTRODUCTION

The mixed oxide (MOX) fuel is one of the most important fuels for the advanced reactors in the future. It is flexible to be applied either in the thermal reactor like pressurized water reactor (PWR) or in the fast reactor (FR). The closed fuel cycle becomes more and more attractive in the fast development of nuclear industry. Many countries have executed or decided to execute such strategy. By using the reprocessed plutonium, the utilization efficiency of uranium, which is defined as the mass of uranium consumed duo to per kilowatt hour electricity production, is significantly increased. The previous studies have shown that utilizing of MOX fuel in the thermal reactors can increase the utilization efficiency by 20%–30% [1]. If it is applied in the fast reactors (FRs), the efficiency can be increased by 20 times [2].

Studying the effects which effect on increasing disposition plutonium rate in thermal reactors (VVER and RBMK) was conducted in this paper. The disposition plutonium rate of the reactor for weapons-grade plutonium is determined by the amount $m_{Pu}$:

$$m_{pu} = X_{pu} \frac{W}{Pt} \tag{1}$$

Where: W is the reactor power, Pt is the fuel burnup, $X_{Pu}$ is the fraction of plutonium in the loaded fuel.

Therefore, with the condition of the same power, the reactors with the highest fuel loading, which ensures the criticality of the reactor, have the highest disposition plutonium rate. Fast reactors have the biggest critical loading (~ 20%). Thus, at 100% MOX loading on the basis of weapon-grade plutonium, the $m_{Pu}$ of fast reactors is 3–4 times greater than that of thermal ones. The $m_{Pu}$ of thermal reactors can be increased by reducing the burnup, however, since this reduces the critical fuel concentration $X_{Pu}$, the $m_{Pu}$ with a decrease in burnup will indeed increase if the ratio $X_{Pu}$/Pt increases.

For a batch fuel cycle, reducing the burnup means shorter fuel cycle length. This method of increasing $m_{Pu}$ is difficult from an economic point of view, since the refueling requires stopping the reactor. The experience gained so far in working with MOX fuel for VVER reactors shows that, the share of plutonium in the fuel loading of a light-water reactor should be about 30% without any changing in the reactor construction [3]. Obviously, the highest $m_{Pu}$

in such conditions (the time of one cycle remains the same for a reactor with uranium fuel ~ 1 year) can be achieved by reducing the residence MOX assemblies time to two or one year. When using MOX fuel in mixed loading, the efficiency of plutonium fuel increases due to the softening of the neutron spectrum as compared to 100% plutonium loading. This leads to the need to reduce the enrichment of plutonium and, accordingly, reduce the $m_{Pu}$. Under these conditions, plutonium loading can be increased by increasing the burnup in uranium fuel assemblies by switching to a four-cycle overload scheme for uranium fuel assemblies.

Channel-type reactors have great potential for increasing the $m_{Pu}$ of weapons-grade plutonium, due to the system of continuous refueling, which can significantly reduce the fuel cycle length. This also applies to reactors with 100% MOX fuel loading and mixed loading. Of course, the reduction of the fuel cycle length is not infinite here; it is limited by the capabilities of the reloading machine. In addition, the limited time for the burning of MOX fuel based on weapons-grade plutonium is associated with the concept of "standard of irradiated fuel", according to which the plutonium–240 content in the discharged fuel should not be less than a certain value.

## 2. METHODOLOGY

The GETERA code was used to calculate the fuel burnup and radioactive inventory of important isotopes. The GETERA code has been used to solve the one dimensional neutron transport for research and power reactors [4]. It is intended for calculation of neutron space-energy distribution in nuclear reactor cells and polycells (cluster) and various neutron flux functional by the collision probability method in multigroup approximation [5]. For the present analysis, 93 groups neutron cross section library BNAB-90 (based on the ENDF/B-IV and JENDL-2 nuclear data) was used. The 93-group GETERA library was collapsed to produce a four-group cross-section data set for researcher reactors as MNSR (Miniature Neutron Source Reactor) (the upper energy boundary limits were used as: 10 MeV, 0.82 MeV, 5.53 keV and 0.625 eV) and a two groups for power reactors such as RBMK and VVER (with a 0.625 eV cutoff for the thermal group). The GETERA is a modern code and its library was updated to have 135 isotopes [5]. The code calculates the absorption, the cell-averaged diffusion coefficients, fission cross sections, the unit cell infinite multiplication factor. The code solves the burnup equations for fuel and fission products for a given specific power and then calculates the isotopic compositions and concentrations of important isotopes present in the reactor core. For the present analysis, collision probability method option was used. The GETERA code also performs calculations for the important fission product chain and various absorber event chain reactions. Figure 1 shows the RBMK fuel channel (1-a) and the VVER fuel unit cell (1-b) modeling by the GETERA code. Figure 2 shows the RBMK fuel bundle (1-a) and the VVER fuel assembly (1-b) modeling by the MCNP code [6].

In this work, three types of the fuel cores were studied: 1- the Core with $UO_2$ fuel, 4.4 and 2% enriched for the VVER and RBMK reactors respectively. The fuel cycle length is one year. The average burnup is 15 and 25 MW.d/kg for the VVER and RBMK reactors respectively; 2- the Core with 100% of the MOX fuel. The uranium used in the MOX fuel is depleted with a $^{235}U$ content of 0.2 wt %. The weapons-grade plutonium isotopes are 93.0 % $^{239}Pu$, 6.5% $^{240}Pu$ and 0.5% $^{241}Pu$.; 3- the Core with mixed assemblies (MOX and $UO_2$). The MOX ratio in the core is 30%. The effect of cycles number on the $m_{Pu}$ was studied for two cases: 3 cycles of $UO_2$+one cycle of MOX and 4 cycles of $UO_2$+ one cycle of MOX fuel (The fuel cycle length is one year). The Pu enrichments in MOX fuel were 4% and 1.8% for the VVER and RBMK reactors respectively.

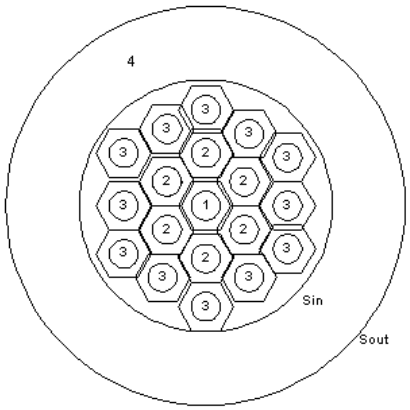


*FIG. 1. (a) RBMK fuel bundle modeling by the GETERA code. Where:1- Zr cell, 2 and 3- fuel cells, 4- graphite.*

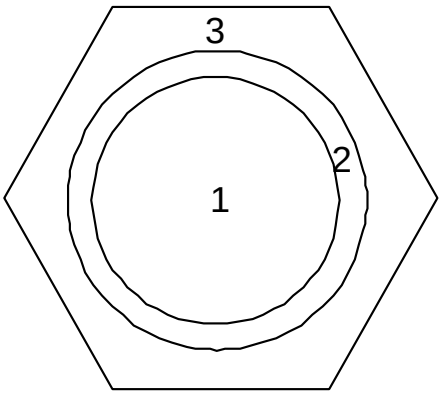


*FIG. 1. (b) VVER fuel cell modeling by the GETERA code. Where: 1- fuel, 2- clad, 3- water.*

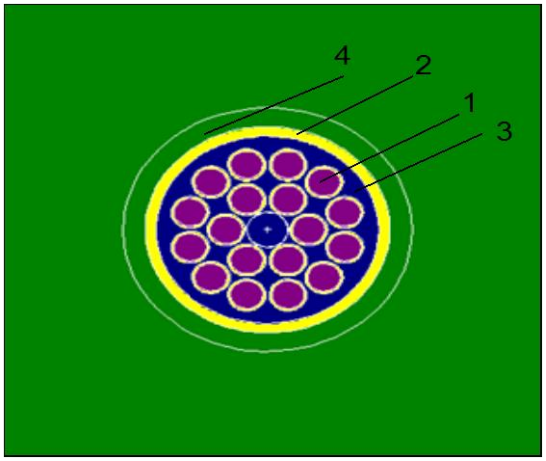


*FIG. 2. (a) RBMK fuel assembly using MCNP code; where: 1- fuel element, 2- fuel channel tube, 3- coolant water,.4 – graphite.*

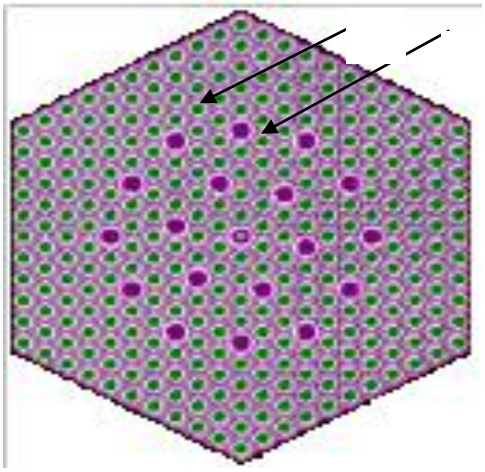

*FIG. 2. (b) VVER fuel assembly using MCNP code; where:, 1- water tube, 2- fuel element.*

## 3. RESULTS AND DISCUSSION

The differences in neutron-physical characteristics of the VVER and RBMK reactors when replacing the uranium fuel with plutonium were conducted. Table 1 shows the group cross sections for U and Pu isotopes and spectrum hardness $\Phi_F/\Phi_{Th}$ for the VVER and RBMK reactors. Because the thermal cross sections are larger for plutonium than for uranium, the thermal flux in the MOX assemblies is significantly lower than that of the $UO_2$ assemblies. As can be seen from this Table, a significant change in cross sections was accrued and increasing the spectrum hardness $\Phi_F/\Phi_{Th}$ when transition to the plutonium fuel.

TABLE 1. SPECTRUM HARDNESS ΦF/ΦTH AND ONE GROUP CONSTANT FOR UO2 AND MOX IN VVER AND RBMK REACTORS

| | VVER | RBMK | VVER | RBMK | VVER | RBMK |
|---|---|---|---|---|---|---|
| Fuel in assembly | $\Phi_F/\Phi_{Th}$ | $\Phi_F/\Phi_{Th}$ | $\sigma_a^9$ | $\sigma_a^5$ | $\sigma_a^9$ | $\sigma_a^5$ |
| $UO_2$ | 5.5 | 1.85 | 175 | 90 | 530 | 225 |
| MOX | 13.0 | 4.0 | 93 | 45 | 300 | 130 |

Figure 3 shows the variation of the infinite multiplication factor ($k_{inf}$) versus the burnup value calculated for $UO_2$ and MOX fuels by the GETERA code using the model shown in Figs. 1 and 2. The $k_{inf}$ first decrease abruptly and then slowly as can be seen in Fig. 3. The initial fast decrease in the $k_{inf}$ is due to the consumption of $^{235}U$ and build-up of xenon and samarium and other fission products in the core.

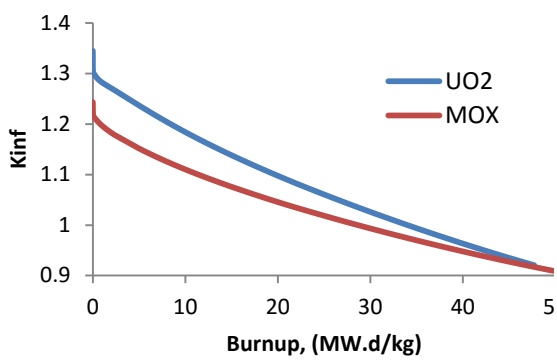


*FIG. 3. (a). Infinite multiplication factors as a function of burnup for VVER reactor.*

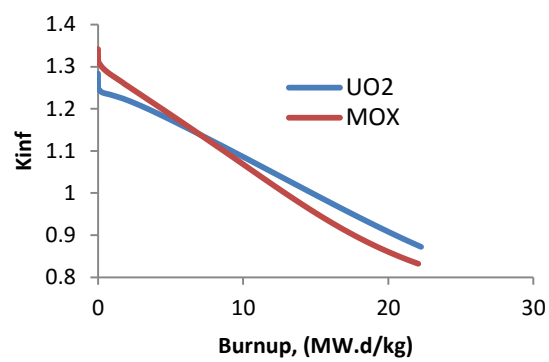


*Fig. 3 (b) Infinite multiplication factors as a function of burnup for RBMK reactor.*

The infinite multiplication factors as a function of burnup for three cycles of fuel reloading in the VVER reactor for $UO_2$ and MOX fuels can be seen in Fig. 4. The burnup of $UO_2$ and MOX fuel reached the same value in the EOC.

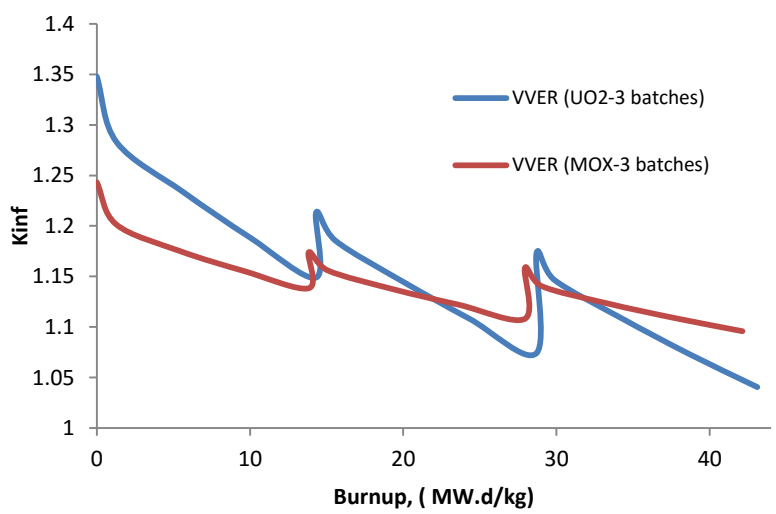


*FIG. 4. Infinite multiplication factors as a function of burnup for three cycles of fuel reloading in the VVER reactor.*

The atom densities of $^{235}U$ as a function of burnup for the $UO_2$ and MOX fuels of the VVER and RBMK reactors are shown in Fig. 5. As can be seen, the concentrations of $^{235}U$ in $UO_2$ fuel for two reactor types are decreased faster than the concentrations of $^{235}U$ in MOX fuel.

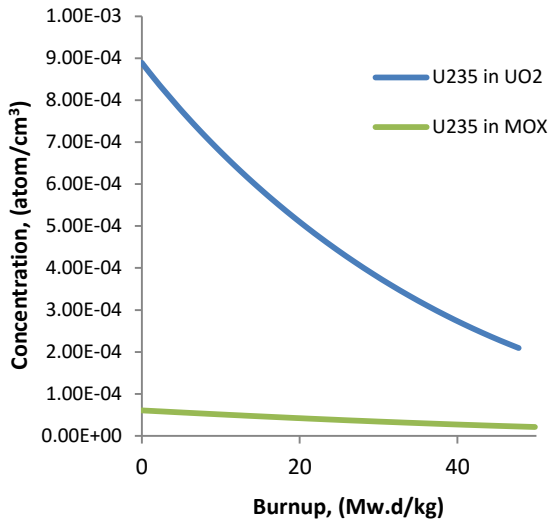


*FIG. 5. (a) $^{235}U$ concentration as a function of burnup for VVER reactor.*

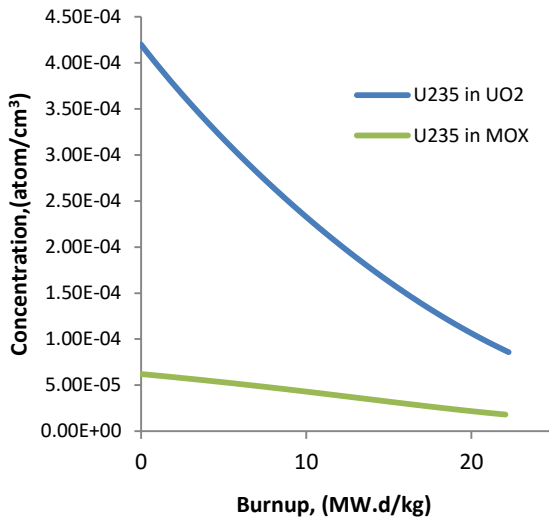


*FIG. 5. (b) $^{235}U$ concentration as a function of burnup for RBMK reactor.*

The atom densities of $^{239}Pu$ and $^{240}Pu$ as a function of burnup for the $UO_2$ and MOX fuels of VVER and RBMK reactors are shown in Fig. 6. As can be seen, the concentrations of $^{239}Pu$ in MOX fuel for the two reactor types are decreased due to burnup of the MOX fuel.

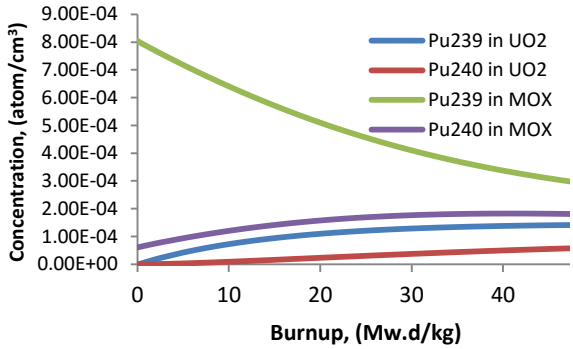


*FIG. 6. (a) $^{239}Pu$ and $^{240}Pu$ concentrations as a function of burnup for VVER reactor.*

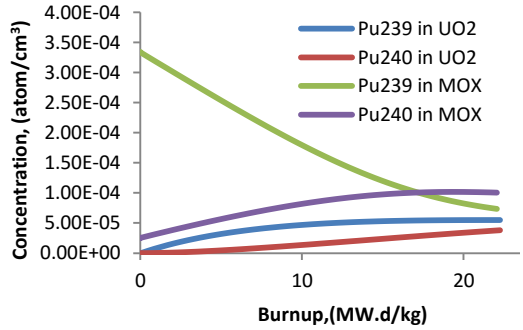


*FIG. 6. (b) $^{239}Pu$ and $^{240}Pu$ concentrations as a function of burnup for RBMK reactor.*

Figure 7 shows the thermal neutron spectrum for the $UO_2$ and MOX fuels of VVER and RBMK reactors. As can be seen from this Fig, for both the reactors: the thermal neutron spectrum for the MOX fuel is lower than the thermal neutron spectrum for $UO_2$ fuel (due to the high thermal cross sections of the plutonium).

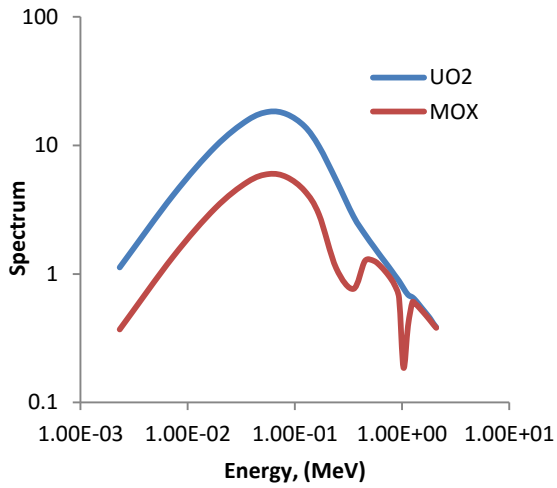


*FIG. 7. (a) Thermal neutron spectrum for VVER reactor.*

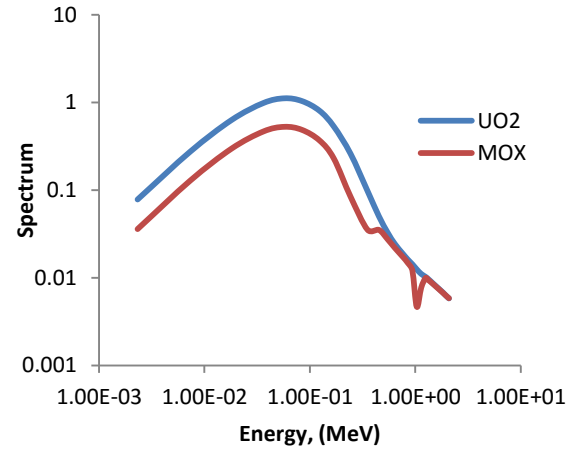


*FIG. 7. (b) Thermal neutron spectrum for RBMK reactor.*

A comparison of the infinite multiplication factors and its components for a uranium assembly and a WG MOX assembly are shown in Tables 2 and 3. From the Table 2, the infinite multiplication factor for MOX assemblies in the VVER reactor is lower than $UO_2$ assemblies. Therefore, the matching of the MOX and uranium core designs must consider this difference to obtain the fuel cycle lengths that are similar. In general this requires that the lifetime-averaged reactivities must match, rather than just the beginning-of-life or end-of-life reactivities. From the Table 3, the infinite multiplication factor for MOX assemblies in the RBMK reactor is higher than $UO_2$ assemblies.

TABLE 2. INFINITE MULTIPLICATION FACTOR FOR THE MOX AND UO2 ASSEMBLIES IN THE VVER REACTOR

| Fuel in assembly | $K_{inf}$ | ε | p | f | η |
|---|---|---|---|---|---|
| $UO_2$ | 1.3448 | 1.8806 | 0.91423 | 1.2477 | 0.62689 |
| MOX | 1.2433 | 1.5990 | 0.96316 | 1.3283 | 0.60777 |

TABLE 3. INFINITE MULTIPLICATION FACTOR FOR THE MOX AND UO2 ASSEMBLIES IN THE RBMK REACTOR

| Fuel in assembly | $K_{inf}$ | ε | p | f | η |
|---|---|---|---|---|---|
| $UO_2$ | 1.2837 | 1.7037 | 0.84308 | 1.0797 | 0.82774 |
| MOX | 1.3417 | 1.6535 | 0.90806 | 1.0840 | 0.82434 |

Calculating and comparing the $m_{Pu}$ (100% MOX) for the VVER and RBMK reactors while maintaining the refueling conditions characteristic of uranium loads can be seen in Table 4. The calculated results of $m_{Pu}$ (kg/year) for two types of the reactors with a thermal power is W = 3000 MW are showed, that the $m_{Pu}$ for the VVER is 1320 kg/year, and for the RBMK is 930 kg/year.

TABLE 4. PLUTONIUM DISPOSITION RATE FOR 100% MOX FUEL

| Type of reactor | VVER | RBMK |
|---|---|---|
| Volume density $MW/m^3$ | 119.0 | 4.2 |
| Fuel cycle length year | 2.7 | 4.2 |
| Burnup MW.d/kg | 43 | 22 |
| Fissile enrichment % | 4.7 | 1.8 |
| Plutonium disposition rate kg/year | 1320 | 930 |

Table 5 shows the plutonium isotopes (%) at EOC for the two reactors. It can be seen that in the VVER reactor the amount of $^{240}Pu$ in spent fuel lower than in the RBMK type reactor.

TABLE 5. PLUTONIUM ISOTOPES IN SPENT FUEL FOR RBMK (X%=1.8 AND 22 MW.D/KG) AND VVER (X%=4.7 AND 43 MW.D/KG)

| Isotope\Reactor | VVER | RBMK |
|---|---|---|
| 239 | 50 | 34 |
| 240 | **31** | **45** |
| 241 | 15 | 13 |
| 242 | 4 | 8 |
| $Pu_{fissile}/Pu_{total}$ % | 65 | 47 |

The dependence of the $m_{Pu}$ on the initial enrichment of MOX fuel for RBMK type reactor can be seen in Table 6. The $m_{Pu}$ was increased by reducing the initial MOX enrichment.

TABLE 6. EFFECT OF THE INITIAL MOX ENRICHMENT ON THE PLUTONIUM DISPOSITION RATE

| Enrichment $X_{fissile}$ % | 1.0 | 1.4 | 1.6 | 1.8 |
|---|---|---|---|---|
| Fuel cycle length (year) | 1.36 | 2.8 | 3.5 | 4.2 |
| $^{240}Pu/Pu$ % | 40.0 | 43.0 | 44.7 | 45.0 |
| $m_{Pu}$ kg/year | 1590 | 1076 | 985 | 930 |

The $m_{Pu}$ can be increased by irradiating the $UO_2$ fuel assemblies for four cycles instead of 3 cycles, and reducing the residence MOX assemblies time to two or one year. Investigation of $m_{Pu}$ for the VVER reactor with mixed loading of uranium and MOX can be seen in Table 7. In this core design the disposition rate increased from 825 kg/year to 1195 kg/year.

TABLE 7. PLUTONIUM DISPOSITION RATE AT DEFERENCE REFUELING CYCLE NUMBER (UO2: MOX=2:1)

| Type of fueling | 3 cycles of $UO_2$+1 cycle of MOX | 4 cycles of $UO_2$+1 cycle of MOX |
|---|---|---|
| Fuel cycle length, year | 1.0 | 1.0 |
| $X_{fissile}$ $UO_2$ % | 4.4 | 4.4 |
| $X_{fissile}$ MOX % | 3.0 | 4.4 |
| $m_{Pu}$ kg/year | 825 | 1195 |

## 4. CONCLUSION

Studying the effects on the Plutonium disposition rate ($m_{Pu}$) for thermal reactors (VVER and RBMK) was investigated in this paper. The results show that an increase the $m_{Pu}$ can be achieved through differenced options. For the VVER reactor, the highest $m_{Pu}$ in such conditions (the time of one cycle remains the same for a reactor with uranium fuel ~ 1 year) can be achieved by reducing the residence MOX assemblies time to two or one year and increasing the burnup in uranium fuel assemblies by switching to a four-cycle overload scheme for uranium fuel assemblies. For the RBMK reactor, Channel-type reactors have great potential for increasing the $m_{Pu}$ of weapons-grade plutonium, due to the system of continuous refueling, which can significantly reduce the fuel cycle length. The neutron spectrum resulting from MOX fuel is harder than that from $UO_2$ fuel. This harder spectrum reduces the worth of the soluble boron and control rod absorbers. The worth of absorber materials (boron and gadolinium) used in the soluble boron, burnable absorbers, and control rods is lower in MOX cores. This results in the increase in the soluble boron concentration, increased use of burnable absorbers, and a modification to the control rods to use enriched boron. The recycling of plutonium as MOX fuel derives additional energy from this resource; however, it does not speedily reduce growing plutonium inventories. Therefore, the use of another option as inert matrix fuel (IMF) in the reactors would provide a means of reducing plutonium inventories. The reduction of the accumulated plutonium by the use of IMF is a subject of great interest in the future.

## ACKNOWLEDGEMENT

The author thanks Professor I. Othman, Director General of the Syrian Atomic Energy Commission, for his encouragement and support.

## REFERENCES

[1] BERNARD, P., “French experiences and perspectives on plutonium recycling in the existing power fleet,” AREVA-COGEMA Recycling Business Unit, vol. 49, no. 8, pp. 583–588, 2007.

[2] GU, Z. AND G. YE., “Recent developments in studies of advanced nuclear fuel cycle system,” Atomic Energy Science and Technology, vol. 36, no. 2, pp. 97–104, 2002.

[3] GEHIN, J. C., CARBAJO, J. J., ELLIS, R. J., Issues in the use of Weapons-Grade MOX Fuel in VVER-1000 Nuclear Reactors: Comparison of UO2 and MOX Fuels. ORNL/TM-2004/223.

[4] DAWAHRA, S., KHATTAB, K., SABA, G., Calculation of fuel burnup and radionuclide inventory in the 10 MW MTR type research reactor using the GETERA code Annals of Nuclear Energy; 2015; 78: 89–92.

[5] BELOUSOV, N., BICHKOV, S., MARCHUK, Y., The code GETERA for cell and policell calculations model capability, Russia (1990).

[6] BRIESMEISTER, J.F., (Ed.) (2000) MCNP – A General Monte Carlo N-Particle Transport Code, Version 4C, LA-13709-M, USA.