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BURNUP CHARACTERISTICS OF $\text{PuO}_2\text{+ZrO}_2$, $\text{PuO}_2\text{+ThO}_2$
AND MOX FUELED LWRs

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Burnup Characteristics of PuO₂+ZrO₂, PuO₂+ThO₂ and MOX Fueled LWRs

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To compare the burnup characteristics of U-free fuels in LWRs for once-through use, plutonium transmutation was investigated for various types of fuels such as PuO₂+ZrO₂ (Rock-like oxide fuel: ROX), PuO₂+ThO₂ (Thorium oxide fuel: TOX) and conventional MOX fuels, with soft to hard neutron spectrum core (a moderator to fuel volume ratio Vm/Vf is from 0.5 to 3.0). Furthermore, radiotoxicity hazards were studied by calculating minor actinide (MA) and long life fission product (LLFP) production buildup. From the viewpoint of reactor safety analysis, fuel temperature and void coefficients were also studied.

From the result of the cell burnup calculation, ROX fuel transmutes 90% of net initial loaded weapons-grade Pu, and 2.5% of initial loaded Pu is converted to MAs when Vm/Vf is 2.0 and the discharge burnup in EFPD is equivalent to that of 33 GWd/t in MOX fuel. Reactor-grade Pu based ROX fuel transmutes 80% of net initial loaded Pu and 6.7% of initial loaded Pu converts to MAs with the same condition as the weapons-grade Pu ROX fuel. TOX fuel also has a good Pu transmutation capability, but ²³³U production amount is approximately a half of fissile Pu transmutation amount. MA production amount in TOX fuel is lower than that in MOX and ROX fuels. LLFP production amount in ROX fuel is lower than that in MOX and TOX fuels. Radiotoxicity hazard of ROX spent fuel is low compared to that in TOX and MOX spent fuels. The major drawback of ROX fuel is its fuel temperature and void coefficients. If the reactivity coefficient problem can be improved, ROX fuel has excellent performance as a once-through fuel.

Keywords: Inert-Matrix Fuel, Rock-like Oxide Fuel, Thorium Oxide Fuel, Once-through Fuel, MOX, Plutonium, Minor Actinide, Long Life Fission Product, Transmutation, Fuel Temperature Coefficient, Void Coefficient, Radiotoxicity Hazard

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PuO₂+ZrO₂、PuO₂+ThO₂及びMOX燃料軽水炉の燃焼特性

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ウラニウムを含まない(U-free)プルトニウム燃料の、軽水炉におけるワنسスルー燃料としての燃焼特性を比較するために、PuO₂+ZrO₂(岩石型酸化物燃料: ROX)、PuO₂+ThO₂(トリウム酸化物燃料: TOX)及び通常のMOX燃料という異なるタイプの燃料を、軟スペクトルから硬スペクトルの軽水炉心(減速材対燃料体積比Vm/Vfが0.5から3.0)に装荷した時のプルトニウム燃焼を検討した。さらに、これらの燃料中のマイナーアクチニド(MA)や長寿命核分裂生成物(LLFP)の生成蓄積量を求め、使用済燃料中の放射能の毒性を評価した。原子炉の安全性の観点から、燃料温度係数とボイド係数の検討も行った。

セル燃焼計算の結果より、例えばVm/Vf=2.0、取り出し燃焼度を33GWd/tのMOX燃料と同じ日数(EFPD)に取った場合、ROX燃料中で兵器級Puの初装荷量の90%を消滅でき、そのうち初装荷Puの2.5%はMAに変換することがわかった。原子炉級Puの場合は80%が消滅し、6.7%がMAに変換する。TOX燃料もPu消滅特性は良いが、核分裂性Puの消滅量の半分程度の量の²³³Uが生成する。MA生成量は、TOXがMOXやROX燃料より少ない。また、ROX燃料中のLLFP生成量がMOXやTOX燃料に比べ少ない。ROX使用済燃料中では放射能の毒性もTOXやMOXと比べて低くなる。ROX燃料の主な欠点は燃料温度係数及びボイド係数である。反応度係数の問題が改善されれば、ROX燃料はワنسスルー燃料として優れた特性を持っている。

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1. Introduction

At the present day increasing amount of excess plutonium from nuclear weapons and reactor-spent fuels becomes a formidable challenge for the nuclear power industry. It is reasonable to recycle these plutonium in MOX fueled LWR by using conventional technology and systems. The build-up of Pu from U in MOX, however, remains disadvantageous for inventory reduction and also enhances the need for a multiple recycling. The plutonium contained within the spent fuel presents a significant proliferation and waste disposal problem. Thus, it is important to consider the possibility of using U-free Pu fuels with an inert matrix for Pu transmutation. For the disposition of excess plutonium, Japan Atomic Energy Research Institute (JAERI) has been studying on rock-like oxide (ROX; $\text{PuO}_2\text{-(Zr,Y)O}_2\text{-MgAl}_2\text{O}_4$) fuel system and its once-through burning process^{1,2}. Now, France³, USA⁴, Switzerland⁵ and Italy⁶ are doing research on inert matrix fuels.

From the viewpoint of Pu transmutation, uranium-free fuels such as ROX have a very good performance in conventional LWRs². It has been reported another U-free fuel for Pu transmutation, thorium oxide Pu based ($\text{PuO}_2+\text{ThO}_2$) fuel, also has good transmutation capability⁶. But a comparison between these U-free fuels has not been studied in detail.

Some of the minor actinide (MA) nuclides (^{244}Cm , ^{241}Am , ^{243}Am , ^{237}Np , ^{231}Pa , ^{227}Ac etc.) raise a serious problem because of a long-term radiotoxicity. Long life fission product (LLFP) nuclides (^{79}Se , ^{93}Zr , ^{99}Tc , ^{107}Pd , ^{126}Sn , ^{129}I and ^{135}Cs) also make a long-term radiotoxicity. MA and LLFP production amounts and their radiotoxicity hazards are important from the viewpoint of once-through use of the fuels.

The main disadvantage of ROX fuel is its reactivity coefficients², while thorium oxide fuel has good reactivity coefficients⁶ in conventional LWRs. A detail analysis is necessary to understand the difference of the reactivity coefficients between these fuels, for the improvement of the reactivity coefficients of ROX fuel.

This report describes the calculated results of burnup characteristics of LWRs with ROX and thorium oxide (TOX) fuels. MOX is considered as a reference case. The composition of ROX in this report is taken as $\text{PuO}_2+\text{ZrO}_2$ for simplicity. Detailed parametric survey has been carried out on Pu transmutation, MA production, LLFP production, radiotoxicity hazard, fuel temperature coefficient, and void coefficient in ROX, TOX and MOX fuels. A series of calculations were performed by changing grade of Pu, discharge burnup, and moderator to fuel volume ratio (V_m/V_f). From these calculations we can compare the burnup characteristics between U-free ROX and TOX fuels in LWRs as a once-through fuel.

2. Calculation Condition

Cell burnup calculations were done on the ROX, TOX, and MOX fueled cell models based on a 17×17 type PWR. The following conditions are assumed:

1. Fuel pin diameter is 0.95 cm, and cladding thickness is 0.0572 cm. Fuel-cladding gap was smeared to the fuel region. Linear power density is 180 W/cm.
2. Smeared density of MOX fuel is 10.02 g/cm³, that of TOX fuel is 9.188 g/cm³, and the molecular density of ROX is fixed at 0.029812×10^{24} molecules/cm³, which, for example, corresponds to 5.843 g/cm³ for 4 a/o fissile Pu in reactor-grade Pu ROX.
3. Hexagonal geometry cell is used. The geometrical buckling is fixed for all the calculation cases at 2.7742E-4 cm⁻². Corresponding core diameter is 337 cm, and height is 366 cm.
4. Vm/Vf values are 0.5, 2.0, and 3.0, and corresponding fuel element pitches are 1.0652 cm, 1.4437 cm, and 1.6484 cm, respectively.
5. Discharge burnups of 33 GWd/t, 45 GWd/t and 60 GWd/t for MOX are considered and the corresponding effective full power days to these discharged burnups are commonly used for ROX and TOX.
6. Reactor-grade and weapons-grade Pu are considered individually (Table 1).
7. In ROX fuel, small amount of Er₂O₃ and Gd₂O₃ are added to decrease excess reactivity when Vm/Vf is 2.0 and 3.0.
8. For a nominal case, fuel temperature 887K, cladding temperature 623K and moderator temperature 573K are assumed.

The calculations were done by using SRAC95⁷ based on JENDL-3.2⁸ nuclear data library.

Table 1: Isotopic composition of reactor- and weapons-grade Pu fuels.

Pu-Grade	²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu	²⁴¹ Am
Reactor-grade (a/o) [†]	2.32	58.2	20.8	11.561	5.95	1.17
Weapons-grade (a/o) ⁹	0.012	93.84	5.78	0.347	0.022	0.0

[†] 46 GWd/t burnup, 4.5w/o ²³⁵U in UO₂ fuel, 5-year-cooling and 2-year-reprocessing are assumed.
(Results of cell calculation by SRAC95 based on JENDL-3.2 nuclear data.)

3. Burnup Calculations

To get criticality at the end of cycle (EOC) by three batch refueling scheme, the enrichment of fissile Pu in MOX fuel is first adjusted for three kinds of discharge burnup 33, 45, and 60 GWd/t. As a result of the adjustment, we get criticality unity in the average value of the effective multiplication factors (k -effs) at 1/3, 2/3 and 3/3 of the discharge burnup. Corresponding effective full power days (EFPD) to 33, 45, and 60 GWd/t in MOX fuel are 887.6, 1210.4, and 1613.8 days, respectively, and they are used as discharge burnup values for ROX and TOX fueled LWRs to search the enrichment of fissile Pu. Table 2 shows the enrichment of fissile Pu for reactor- and weapons-grade Pu fuels for all the discharge burnups and V_m/V_f values.

Table 2: Enrichment of fissile Pu in ROX, TOX and MOX fueled LWRs

V_m/V_f	Reactor			Weapons		
	ROX(a/o)	TOX(a/o)	MOX(a/o)	ROX(a/o)	TOX(a/o)	MOX(a/o)
	33GWd/t			33GWd/t		
0.5	2.90	8.10	7.10	2.74	7.10	6.67
2.0	2.44	4.10	2.80	2.75	3.60	2.39
3.0	2.49	3.90	2.50	2.79	3.60	2.39
45GWd/t				45GWd/t		
0.5	4.00	8.50	7.70	3.75	7.059	7.27
2.0	3.28	5.10	3.80	3.71	4.47	3.29
3.0	3.33	4.70	3.30	3.75	4.58	3.19
60GWd/t				60GWd/t		
0.5	5.25	9.40	8.40	5.96	8.27	8.17
2.0	4.34	6.30	5.10	5.22	5.54	4.28
3.0	4.38	5.90	4.40	5.25	5.64	4.28

The excess reactivity of ROX fueled LWRs is very high at BOL when V_m/V_f is 2.0 or 3.0 but not so high when V_m/V_f is 0.5. To decrease the excess reactivity of ROX fueled LWRs, firstly we searched the molecular percentage (mol%) of Er_2O_3 , which can reduce the excess reactivity at the beginning of life (BOL) although has a little at the end of life (EOL). After that, we adjusted the mol% of Gd_2O_3 to decrease the excess reactivity only at BOL. After searching, we fixed the amounts of these burnable poisons at 0.3 mol% for Er_2O_3 and 0.01 mol% for Gd_2O_3 when V_m/V_f are 2.0 and 3.0 for both weapons- and reactor-grade Pu. The effect of Er and Gd is shown in Fig. 1 until 800 EFPD burnup of reactor-grade Pu ROX fuel when V_m/V_f is 3.0. By adding Er_2O_3 and Gd_2O_3 , k -eff

decreases about $0.1 \Delta k$ at BOL for both reactor- and weapons-grade Pu fuels. We did not add Er_2O_3 and Gd_2O_3 in the case that V_m/V_f is 0.5, partly because of the excess reactivity of ROX fuel cell is smaller than V_m/V_f is 2.0 or 3.0. Another reason is the reactivity effect of these poisons is very small at BOL, moreover that of Er_2O_3 remains up to EOL more than that in V_m/V_f 2.0 or 3.0.

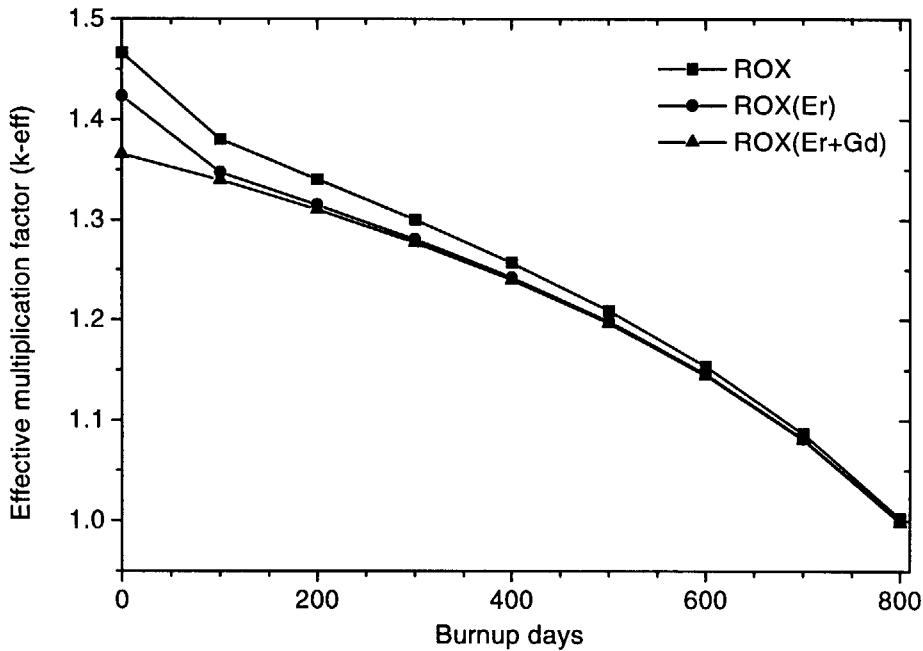


Fig. 1: Effect of Er and Gd to decrease excess reactivity in reactor-grade Pu ROX fuel when discharge burnup is 33 GWd/t and V_m/V_f is 3.0.

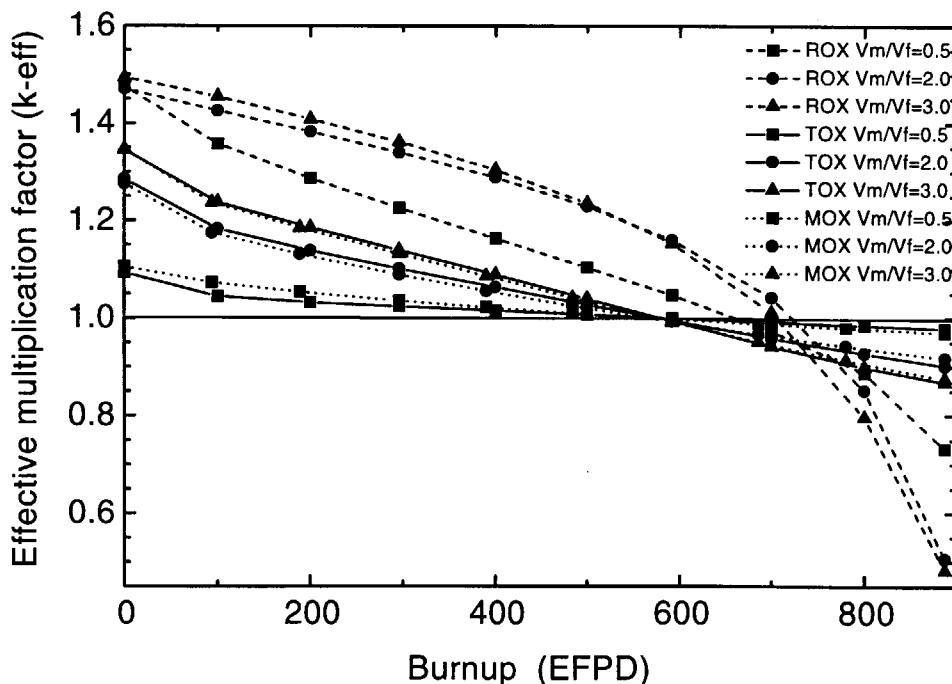


Fig. 2: Burnup reactivity changes of weapons-grade Pu fuels in 33 GWd/t discharge burnup.

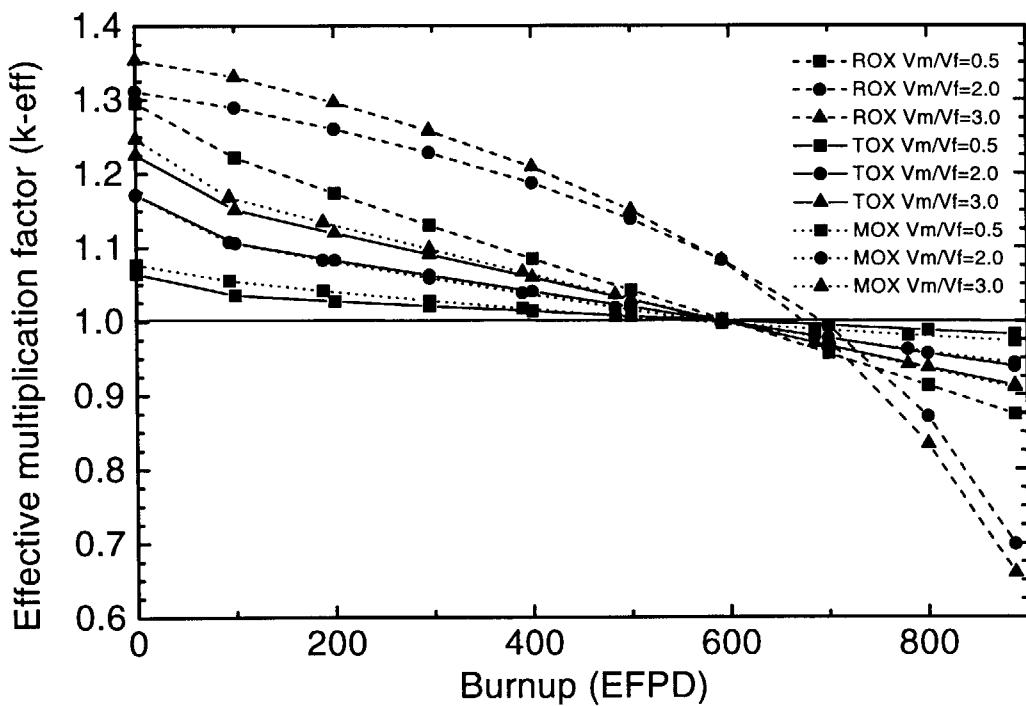


Fig. 3: Burnup reactivity changes of reactor-grade Pu fuels in 33 GWd/t discharge burnup.

After adjusting mol% of Er and Gd and enrichment (a/o) of fissile Pu, the burnup reactivity changes of weapons- and reactor-grade Pu fuels are shown in Figs. 2 and 3 for 33 GWd/t discharge burnup. From these Figures, we can see weapons- and reactor-grade Pu fuels have similar burnup reactivity change tendency, although in reactor-grade Pu, k_{eff} decreases slowly with burnup compared to the weapons-grade Pu case.

4. Plutonium Transmutation

The net Pu transmuted amount and transmutation percentage in ROX, TOX and MOX fueled LWRs are calculated for different V_m/V_f and discharge burnups. Figures 4 and 5 respectively show V_m/V_f dependent transmuted amount of net Pu and ^{239}Pu in ROX, TOX and MOX fueled LWRs based on weapons-grade Pu. The net Pu transmuted amount is normalized to the unit electric power output GWe and also divided by total burnup year. From the viewpoint of Pu transmutation, ROX fuel is not so sensitive to V_m/V_f and discharge burnup. ROX fuel can transmute 1.1 ton/GWe per year of net Pu and 1.2 ton/GWe per year of ^{239}Pu . Transmutation and production amount of all Pu isotopes are contained in Appendix I for weapons- and reactor-grade Pu fuels.

TOX fueled LWRs can transmute 0.85 ton/GWe/year of net Pu when V_m/V_f is 2.0 and discharge burnup is 33 GWd/t, and net transmuted amount decreases with decreasing V_m/V_f and discharge burnup. In TOX fuel ^{233}U is produced by the conversion from ^{232}Th and contributes to a power generation. Therefore, Pu transmutation decreases according to fissions of ^{233}U , because the total number of fissions is almost constant for all the cases. Figure 6 shows that the uranium production amounts in weapons-grade Pu based TOX fuels for different discharge burnups and V_m/V_f s. When V_m/V_f is 0.5, ^{233}U production amount is highest due to lower neutron absorption of ^{233}U . Production amount

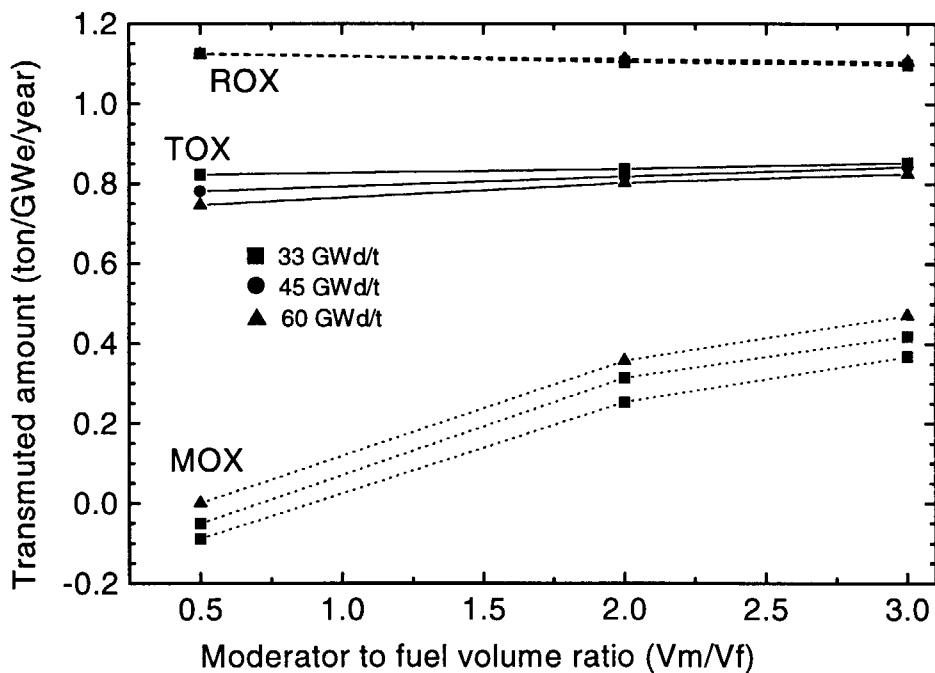


Fig. 4: Net Pu transmuted amount (per year) in weapons-grade Pu fuels.

of ^{233}U in TOX fuel is approximately a half of ^{239}Pu transmuted amount. Therefore, net fissile material transmuted amount in TOX fuel is approximately the same as MOX fuel. Another problem of the thorium fuel use, is the radioactivity by 72-year half-life ^{232}U , and its daughters accompanied with very energetic and penetrating gamma dose. So, gamma shielding is required to handle the TOX spent fuels. However, the gamma dose rate can be considered as an asset rather than a drawback, for the non-proliferation of a good nuclear weapon material ^{233}U .

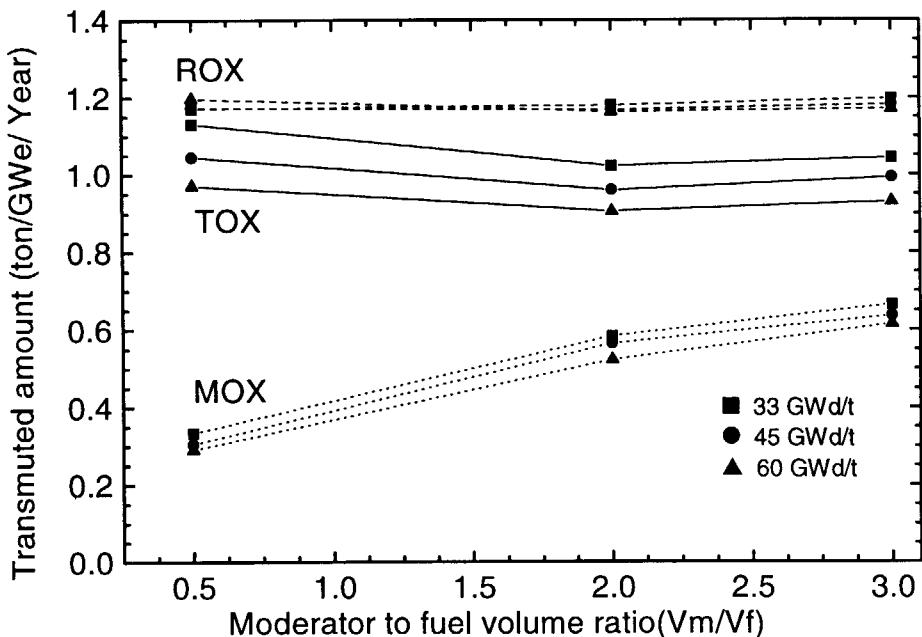


Fig. 5: ^{239}Pu transmuted amount (per year) in weapons-grade Pu fuels.

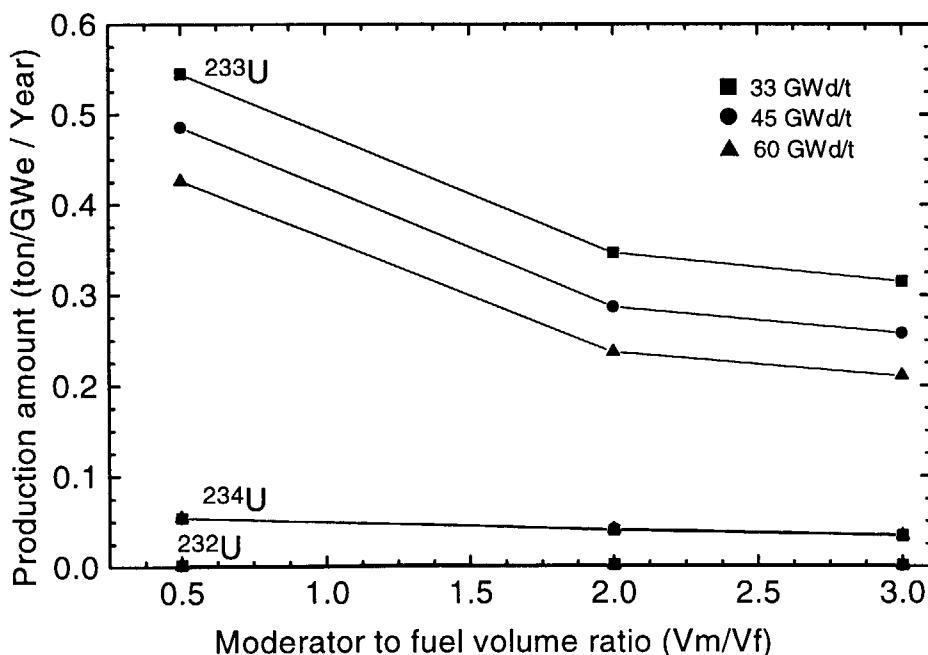


Fig. 6: U production amount (per year) in weapons-grade Pu TOX fuels.

MOX fuel can transmute –0.08 to 0.47 ton/GWe per year of net Pu, and 0.3 to 0.70 ton/GWe per year of ^{239}Pu in the weapons-grade Pu (Figs. 4 and 5). The Pu transmuted amount of MOX fuel increases with the increasing discharge burnup and Vm/Vf, because conversion rate from ^{238}U to ^{239}Pu decreases with increasing discharge burnup and Vm/Vf. Moreover, the fissions of ^{238}U decrease with increasing discharge burnup and Vm/Vf, and result in the increase of Pu fission.

Figures 7 and 8 respectively, show the percentage of net Pu and ^{239}Pu transmutation in weapons-grade Pu fuels. ROX fuel can transmute 90% of initial loaded Pu and this transmutation percentage does not depend on Vm/Vf and discharge burnup. In TOX fuel, Pu transmutation percentage increases with increasing Vm/Vf, and discharge burnup. The net Pu transmutation percentage in TOX fuel varies from 40% to 80%. In MOX fuel, the transmutation percentage of Pu also increases with increasing Vm/Vf and discharge burnup. This percentage varies from about –5% to 60%. From Fig. 8, we can see ^{239}Pu transmutation percentage in ROX fuel is more than 99%. Transmutation percentage of ^{239}Pu in TOX fuel increases with increasing discharge burnup and Vm/Vf. This percentage varies from 53% to 99% of initial loaded ^{239}Pu . The transmutation percentage of ^{239}Pu in MOX fuel also highly depends on discharge burnup and Vm/Vf, because conversion rate of ^{238}U decreases with increasing Vm/Vf from 0.5 to 3.0. The transmutation rate of ^{239}Pu in MOX fuel ranges from 13% to 87% of initial loaded ^{239}Pu .

Figures 9 and 10 respectively show the net reactor-grade Pu transmuted amount and Pu transmutation percentage of ROX, MOX and TOX fuels. From Fig. 9, we can see net Pu transmuted amount increases in reactor-grade Pu fuels compared to weapons-grade Pu fuels. Transmuted amount of ^{239}Pu is smaller in reactor-grade Pu fuels than that in weapons-grade Pu fuels. Smaller ^{239}Pu transmuted amount in reactor-grade Pu fuels is compensated by a larger transmuted and smaller production amount of higher Pu isotopes. For example, in weapons-grade Pu ROX fuel ^{241}Pu is produced, on the contrary in reactor-grade Pu ROX fuel ^{241}Pu is transmuted. Transmutation and production amount of the Pu isotopes are compared in Appendix I between weapons- and reactor-grade Pu fuels. Net Pu transmutation percentage in reactor-grade Pu fuels (Fig. 10) is lower than that in weapons-grade Pu fuels. Net Pu transmutation percentage in reactor-grade ROX fuel is higher when Vm/Vf is 2.0 compared to 0.5 and 3.0 for all the discharge burnups, because resonance absorption of ^{241}Pu and ^{243}Am increases when Vm/Vf is 2.0.

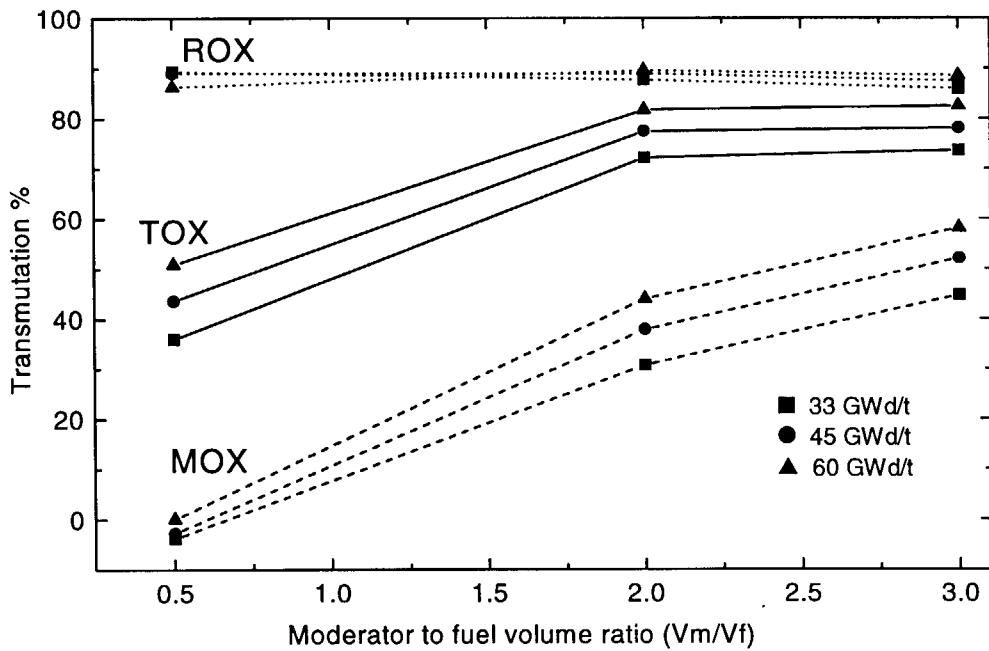


Fig. 7: Percentage of net Pu transmutation in weapons-grade fuels.

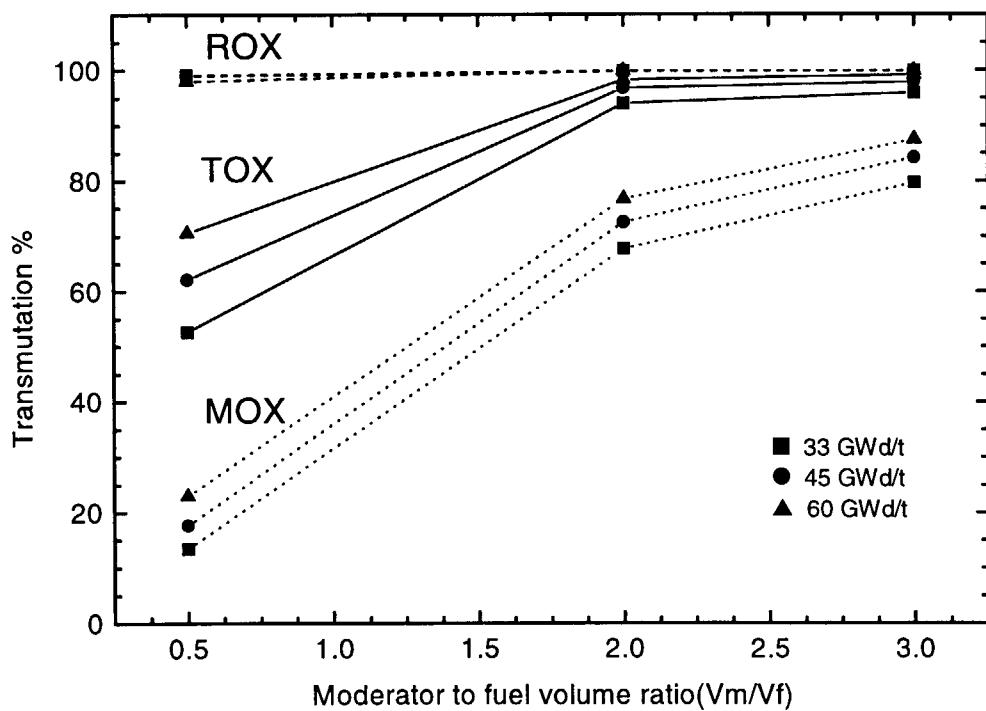


Fig. 8: Percentage of ^{239}Pu transmutation in weapons-grade fuels.

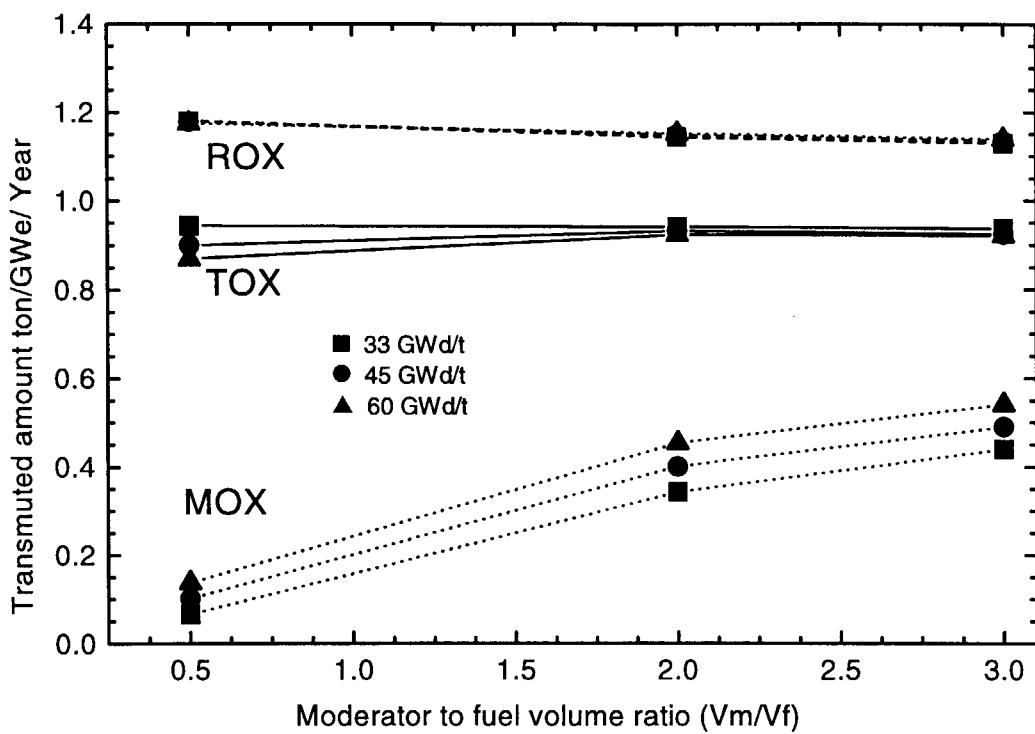


Fig. 9: Net Pu transmuted amount (per year) in reactor-grade Pu fuels.

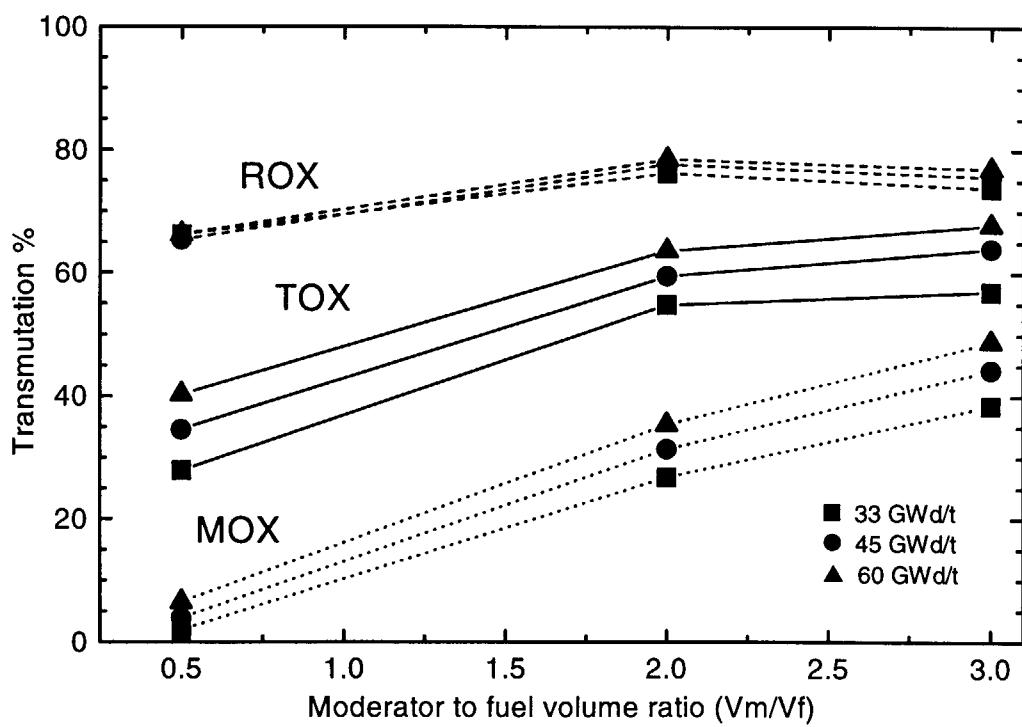


Fig. 10: Percentage of net Pu transmutation in reactor-grade fuels.

5. Minor Actinide Production

Figure 11 shows the net minor actinide (MA) production amount per year in ROX, MOX and TOX fuels for weapons-grade Pu. As MA we considered americium (Am), curium (Cm), and neptunium (Np) isotopes. MA production in ROX fuel is higher than that in TOX and MOX fuels especially when V_m/V_f is 0.5, because of higher flux level of ROX fuel. Figures 12 and 13 show the neutron spectra of ROX, MOX and TOX fuels at BOL and EOL, respectively. Here, neutron flux is normalized in order to get unit neutron production reaction rate. Burnup calculation was done under constant power condition and power is approximately proportional to the neutron production reaction rate. From Fig. 12 we can see, at BOL, flux level of ROX fuel is nearly equal to TOX and MOX fuels. But from Fig. 13, we can see the flux level of ROX fuel is higher than that in MOX and TOX fuels at EOL.

ROX fuel contains only Pu as actinides, while MOX and TOX contains U and Th, respectively. In ROX fuel, fissile materials are burnt rapidly. While in TOX and MOX fuels, secondary fissile material is produced from ^{232}Th and ^{238}U . For these reasons, the density of fissile materials becomes very low in ROX fuel compared to that in TOX and MOX fuels. Under constant power condition, higher flux level of ROX fuel is necessary to keep constant neutron production reaction rate. From Fig. 14 we can see, higher flux level of ROX fuel increases the capture reaction rate of Pu than that in TOX and MOX fuels. Therefore, the MA production in ROX fuel is higher than that in TOX and MOX fuels.

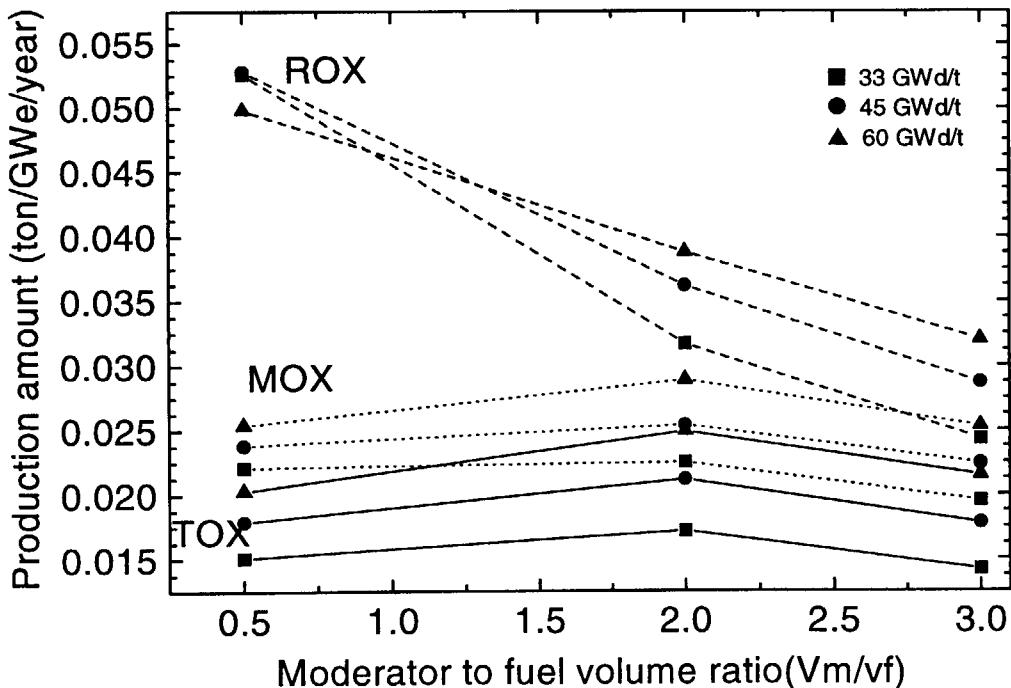


Fig. 11: Net MA production amount (per year) in weapons-grade Pu fuels.

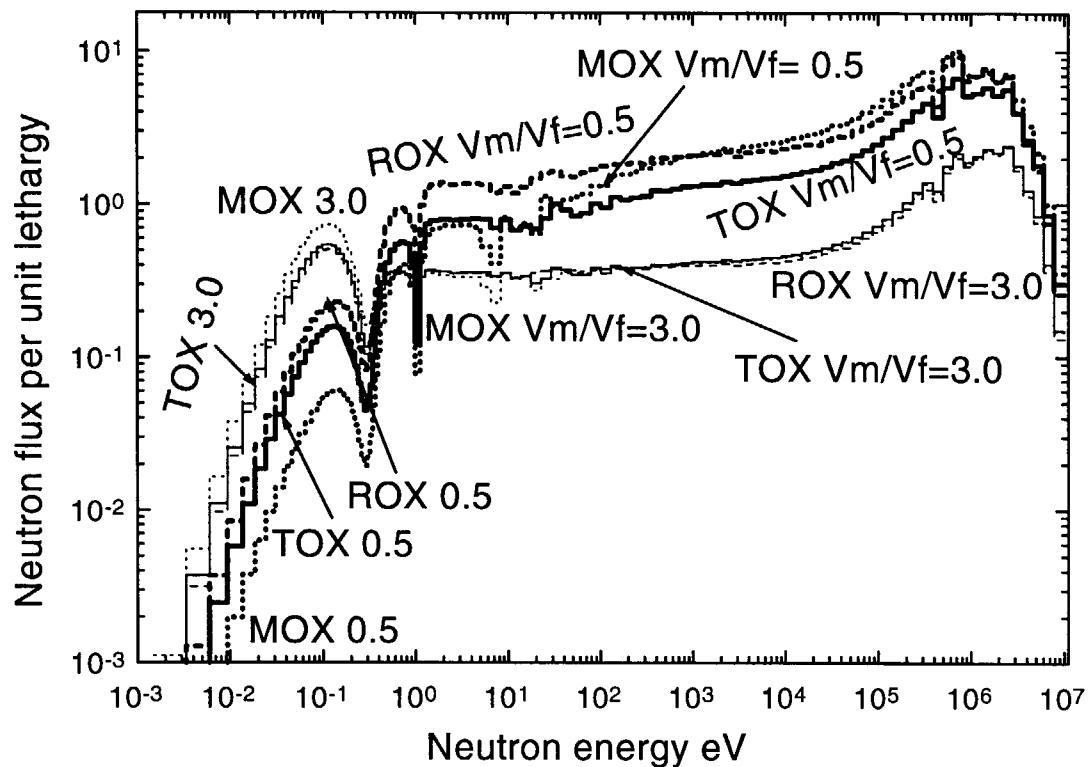


Fig 12: Neutron spectra at BOL of weapons-grade Pu fuels for 33GWd/t discharged burnup.

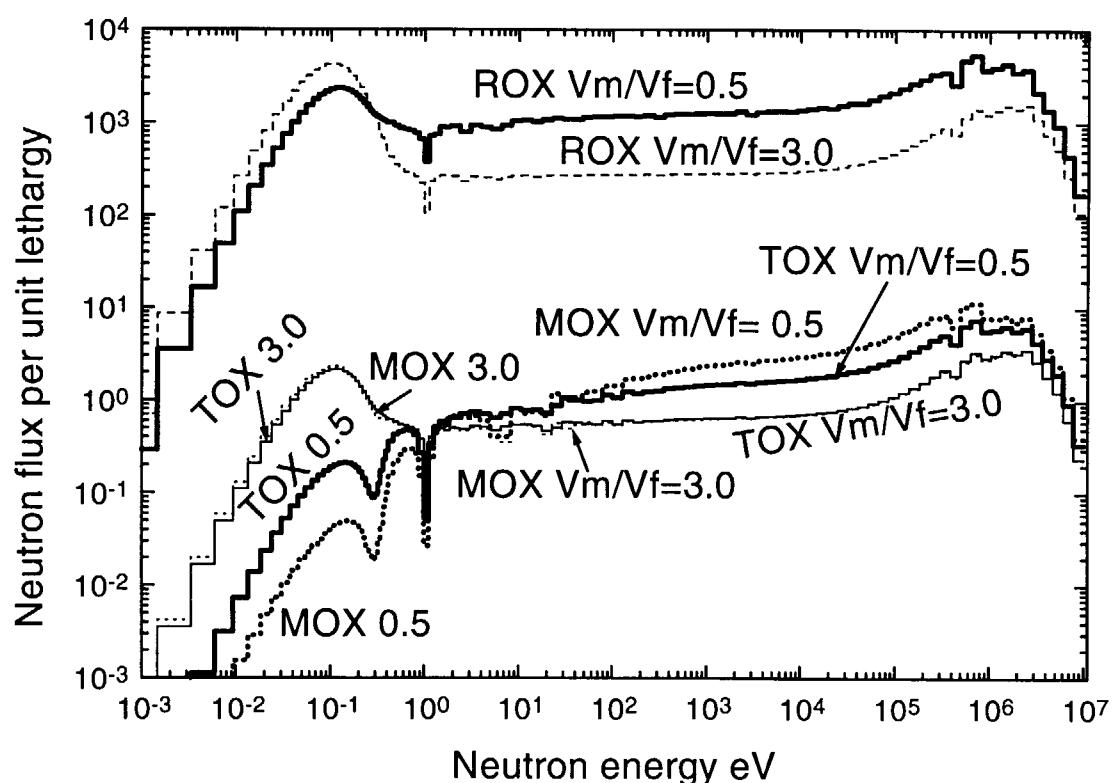


Fig 13: Neutron spectra at EOL of weapons-grade Pu fuels for 33GWd/t discharged burnup.

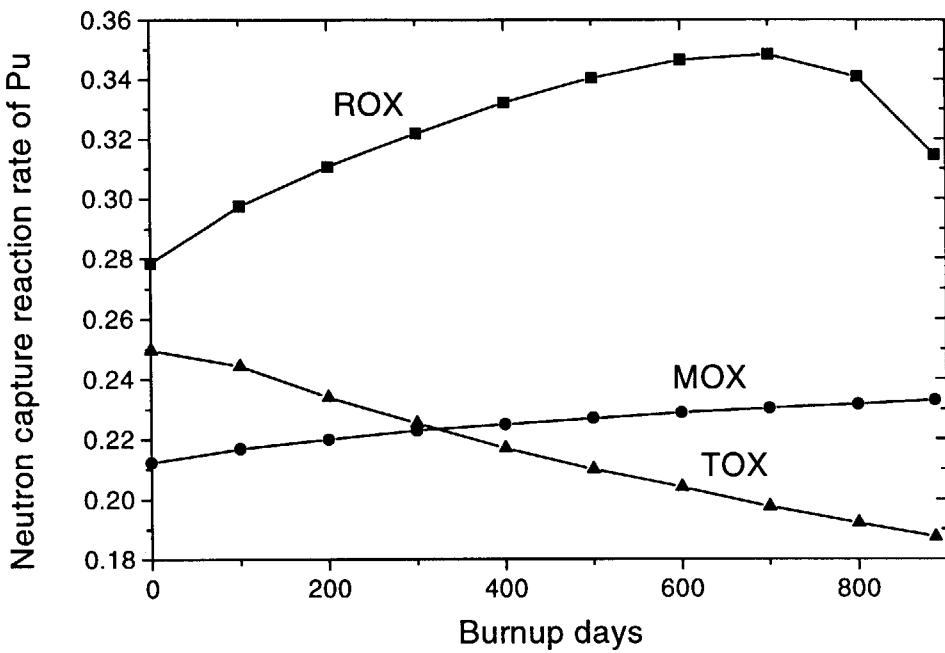


Fig. 14: Burnup dependent neutron capture reaction rate of Pu in W-Pu fuels when V_m/V_f is 0.5 and discharge burnup is 33 GWd/t.

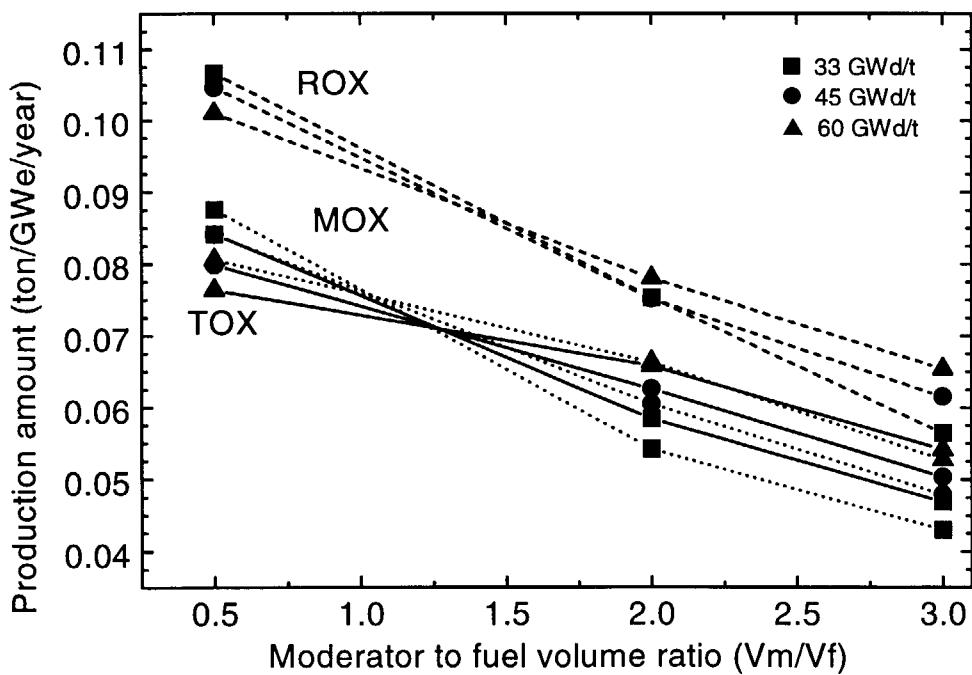


Fig. 15: Net MA production amount (per year) in reactor-grade Pu fuels.

MA productions are 2.5% in ROX fuel, 1.5% in TOX and 2.7% in MOX of initial loaded weapons-grade Pu when V_m/V_f is 2.0 and discharge burnup is 33 GWd/t.

Figure 15 shows the MA production amount in reactor-grade Pu fuels. In this case, MA productions are 6.7%, 4.0%, and 4.7% of initial loaded Pu in ROX, TOX and MOX fuels, respectively, when V_m/V_f is 2.0 and discharge burnup is 33 GWd/t. MA production in reactor-grade Pu fuels is higher than that in weapons-grade Pu fuels as a result of higher ^{240}Pu , ^{241}Pu and ^{242}Pu contents.

Tables 3 to 5 represent net Am, Cm and Np production amounts, respectively, in the unit of ton/GWe/year in reactor-and weapons-grade Pu fuels. As explained above, the amount of Am and Cm are very high in ROX fueled LWRs especially when V_m/V_f is 0.5 compared to TOX and MOX fueled LWRs for both reactor and weapons-grade Pu cases (Table 4 and 5). Np is produced from the capture reaction of ^{235}U and $(n, 2n)$ reaction of ^{238}U . So, Np production in MOX fuel is higher than that in ROX and TOX fuels. In weapons-grade Pu ROX fuel, 2.5% of initial loaded Pu is converted to net MA. Within this 2.5% of MA production, 1.5% is converted to Am, 1.0% to Cm, and 5.6E-4% to Np. At the same condition as ROX fuel, the net MA conversion in TOX fuel is 1.5% of initial loaded Pu and within this 1.5%, 1.1% converted to Am, 0.4% converted to Cm, and 2.5E-3% converted to Np. The net MA production in MOX fuel is 2.7% and within this 1.4% converted to Am, 0.5% converted to Cm, and 0.8% converted to Np.

In reactor-grade Pu ROX fuel, net MA production is 6.7 % of initial loaded net Pu and within this percentage 3.9 % converted to Am, 2.8 % converted to Cm, and 2.1E-3 % converted to Np when V_m/V_f is 2.0 and 33GWd/t discharge burnup. In TOX fuel net MA production is 4.0 % of initial loaded Pu and within this 2.5 % converted to Am, 1.5 % converted to Cm and 4.1E-3 % converted to Np. In MOX fuel 4.7 % of initial Pu converts to MA, 2.6 % to Am, 1.7 % to Cm and 0.5 % to Np.

Appendix II contains the nuclide-wise Am, Cm and Np production amount per year in weapons-grade and reactor-grade Pu fuels for different discharge burnup and V_m/V_f .

Table 3: Net AM production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	3.230E-2	5.653E-2	5.377E-2	2.154E-2	1.224E-2	1.111E-2
2.0	2.871E-2	3.198E-2	2.699E-2	1.883E-2	1.243E-2	1.182E-2
3.0	2.504E-2	2.663E-2	2.118E-2	1.571E-2	1.060E-2	1.032E-2
45GWd/t				45GWd/t		
0.5	3.147E-2	5.115E-2	5.032E-2	2.025E-2	1.394E-2	1.326E-2
2.0	2.812E-2	3.237E-2	2.986E-2	1.993E-2	1.432E-2	1.419E-2
3.0	2.559E-2	2.631E-2	2.330E-2	1.736E-2	1.256E-2	1.258E-2
60GWd/t				60GWd/t		
0.5	2.996E-2	4.732E-2	4.676E-2	1.916E-2	1.520E-2	1.511E-2
2.0	2.690E-2	3.199E-2	3.233E-2	1.994E-2	1.560E-2	1.623E-2
3.0	2.535E-2	2.656E-2	2.501E-2	1.812E-2	1.411E-2	1.443E-2

Table 4: Net CM production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	7.422E-2	2.752E-2	2.534E-2	3.103E-2	2.842E-3	2.312E-3
2.0	4.179E-2	2.638E-2	2.116E-2	1.282E-2	4.726E-3	4.302E-3
3.0	3.134E-2	2.024E-2	1.642E-2	8.566E-3	3.572E-3	3.529E-3
45GWd/t				45GWd/t		
0.5	7.309E-2	2.853E-2	2.663E-2	3.255E-2	3.890E-3	3.288E-3
2.0	4.698E-2	3.008E-2	2.562E-2	1.627E-2	6.821E-3	6.110E-3
3.0	3.588E-2	2.387E-2	2.018E-2	1.130E-2	5.175E-3	5.240E-3
60GWd/t				60GWd/t		
0.5	7.094E-2	2.885E-2	2.773E-2	3.064E-2	4.988E-3	4.266E-3
2.0	5.107E-2	3.366E-2	2.980E-2	1.883E-2	9.228E-3	8.340E-3
3.0	4.000E-2	2.745E-2	2.406E-2	1.384E-2	7.285E-3	7.104E-3

Table 5: Net NP production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	4.346E-5	1.726E-4	8.517E-3	7.957E-6	6.162E-5	8.631E-3
2.0	3.167E-5	6.966E-5	6.073E-3	6.988E-6	2.698E-5	6.343E-3
3.0	3.433E-5	6.105E-5	5.359E-3	6.513E-6	1.687E-5	5.668E-3
45GWd/t				45GWd/t		
0.5	6.523E-5	2.006E-4	7.179E-3	1.196E-5	1.096E-4	7.211E-3
2.0	4.357E-5	9.321E-5	5.003E-3	1.073E-5	4.695E-5	5.134E-3
3.0	4.658E-5	7.390E-5	4.388E-3	1.013E-5	2.837E-5	4.583E-3
60GWd/t				60GWd/t		
0.5	9.035E-5	2.448E-4	6.141E-3	1.904E-5	1.772E-4	6.073E-3
2.0	6.019E-5	1.249E-4	4.214E-3	1.601E-5	7.713E-5	4.272E-3
3.0	6.314E-5	9.736E-5	3.643E-3	1.512E-5	4.684E-5	3.741E-3

6. Long Life Fission Product Production

Figures 16 and 17 show the net LLFP production in reactor- and weapons-grade Pu fuels, respectively. As for LLFP, we considered ^{79}Se , ^{93}Zr , ^{99}Tc , ^{107}Pd , ^{126}Sn , ^{129}I , and ^{135}Cs . The net LLFP production amount in ROX fuel is lower than that in MOX and TOX fuels especially when Vm/Vf is 0.5 for both weapons- and reactor-grade Pu cases. The total number of fission is nearly same for ROX, MOX, and TOX fuels, therefore the FP production amounts in three fuels are assumed to be almost same. Among all the FPs, Table 6 shows the yield of LLFPs. From this table we can see the total yield of LLFP from U isotopes is slightly smaller than that from Pu isotopes. It means the FP yield is not the cause of the higher LLFP production amounts in the U containing TOX and MOX fuels.

From Table 6, it can be seen that ^{135}Cs , ^{99}Tc , ^{93}Zr and ^{107}Pd are the main components of LLFPs. Table 7 shows the effective one group capture cross-sections of LLFP nuclides in weapons grade Pu fuels. The capture cross-section of ^{135}Cs , ^{99}Tc , ^{93}Zr and ^{107}Pd in ROX fuel is higher when Vm/Vf is 0.5 than in MOX and TOX fuels. For this reason the net LLFP production amount in ROX fuel is lower than that in MOX and TOX fuel when Vm/Vf is 0.5.

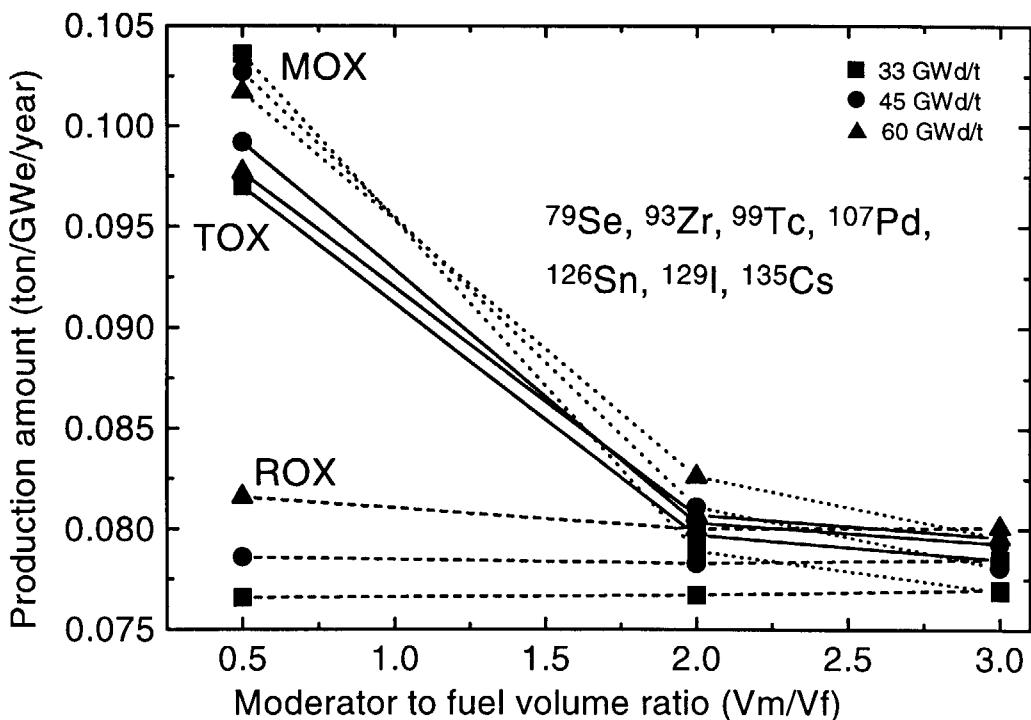


Fig. 16: Net production amount of LLFP (per year) in weapons-grade Pu fuels.

Net LLFP production amount of TOX and MOX fuels decreases very rapidly when the V_m/V_f increase from 0.5 to 3.0 and becomes nearly equal to that of ROX fuel. Figures 18 to 21 show ^{135}Cs , ^{99}Tc ^{93}Zr and ^{107}Pd production amounts in weapons-grade Pu fuels. From Fig. 18 we can see the production amount of ^{135}Cs is about 40% of the total LLFP production amount when V_m/V_f is 0.5, and it decreases very rapidly with increasing V_m/V_f because of the increase in capture cross section. This is the main cause of the decrease of net LLFP production amount in TOX and MOX fuels with increase of V_m/V_f . In ROX fuel, though the yield of ^{135}Cs from Pu is higher than that from U isotopes, the capture cross-section of ^{135}Cs is also higher than that of MOX and TOX fuels especially when V_m/V_f is 0.5. So the change in ^{135}Cs production amount with V_m/V_f value in ROX fuel is smaller than that in TOX and MOX fuels.

The production amount of ^{99}Tc is higher in MOX fuel than in TOX and ROX fuels (Fig. 19) and about 25-30% of the total LLFP production amount. Production amount of ^{99}Tc in ROX fuel increases largely with increasing the V_m/V_f from 0.5 to 3.0, while in MOX and TOX fuels it is almost constant with V_m/V_f . It seems this is due to the particularly large capture cross-section of ^{99}Tc in ROX fuel compared to that in TOX and MOX fuel when V_m/V_f is 0.5.

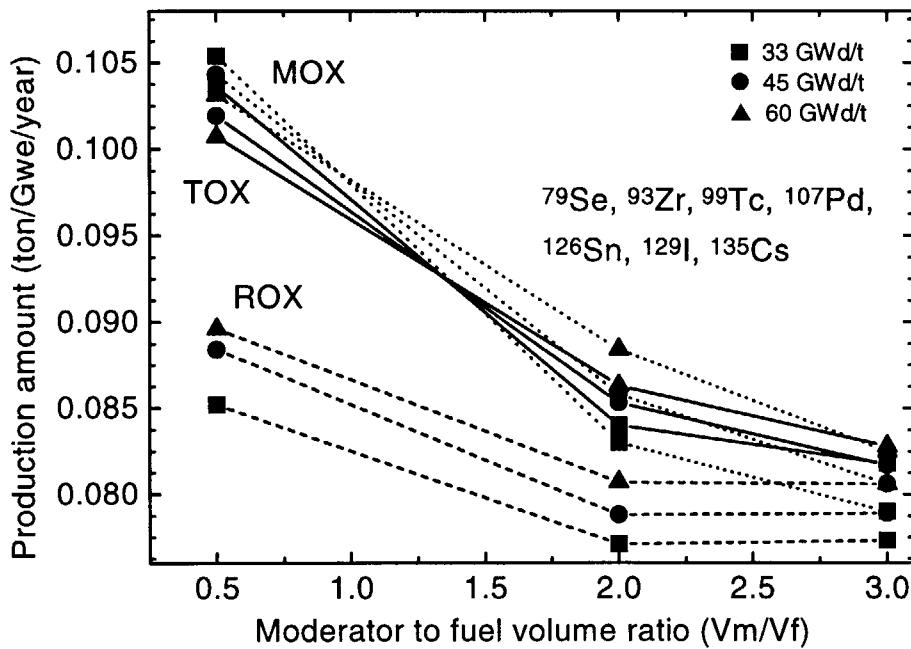


Fig. 17: Net production amount of LLFP (per year) in reactor-grade Pu fuels.

The production amount of ^{93}Zr in TOX fuel is higher than in MOX and ROX fuels and it is about 20% of the total LLFP production amount (Fig. 20). The yield of ^{93}Zr from ^{233}U is very high and also the capture cross-section of ^{93}Zr in TOX fuel is low compared to that in ROX fuel.

The production amount of ^{107}Pd in ROX fuel is higher than in MOX and TOX fuels for all Vm/Vf (Fig. 21), because the yield of ^{107}Pd from Pu is higher than that from U isotopes and the capture cross-section of ^{107}Pd does not differ very much in ROX fuel from that in TOX and MOX fuels.

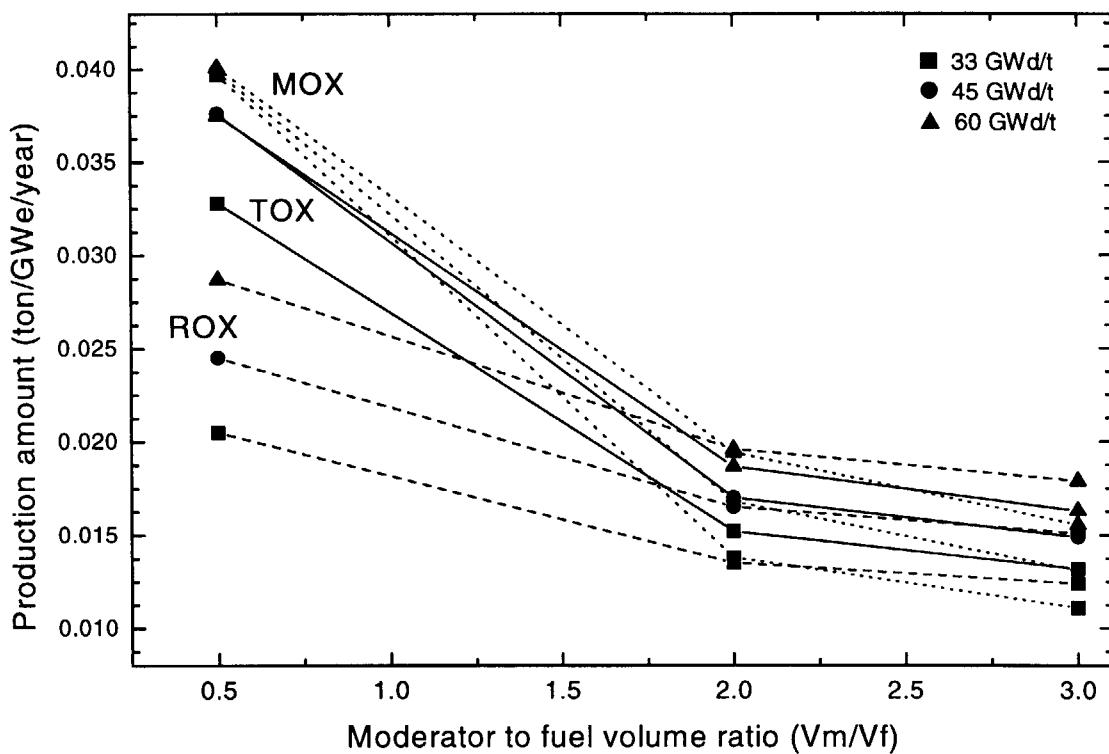
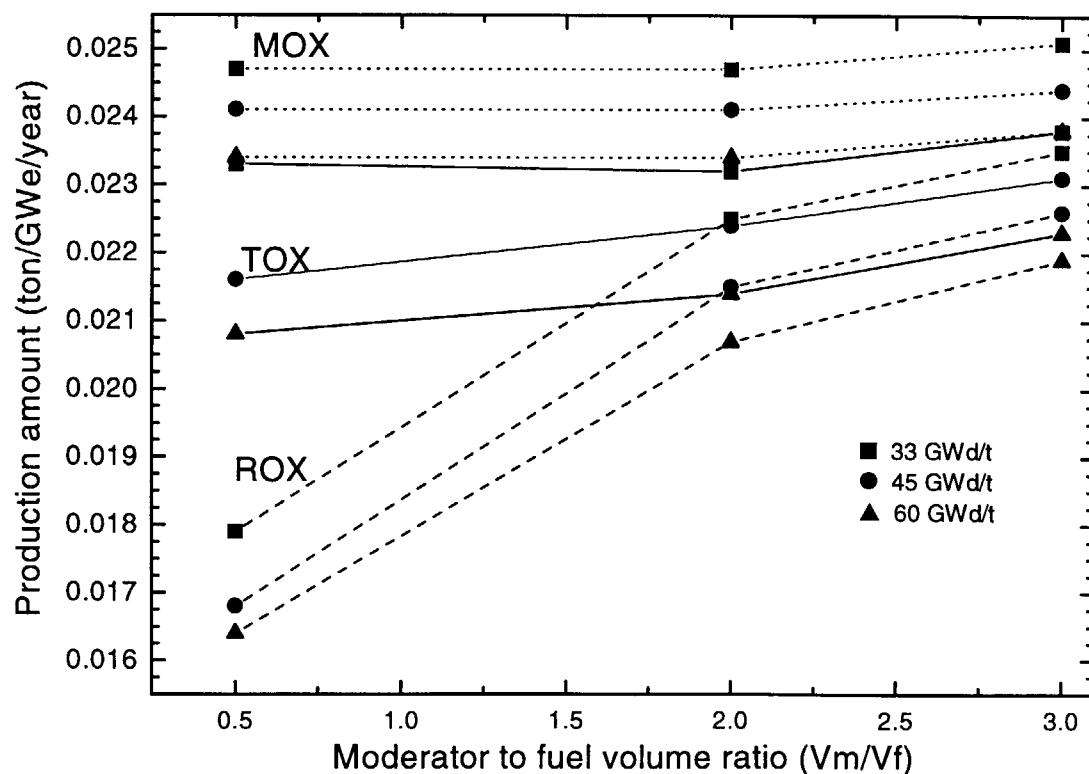
Appendix III contains the nuclide-wise LLFP production both from reactor- and weapons-grade Pu spent fuel.

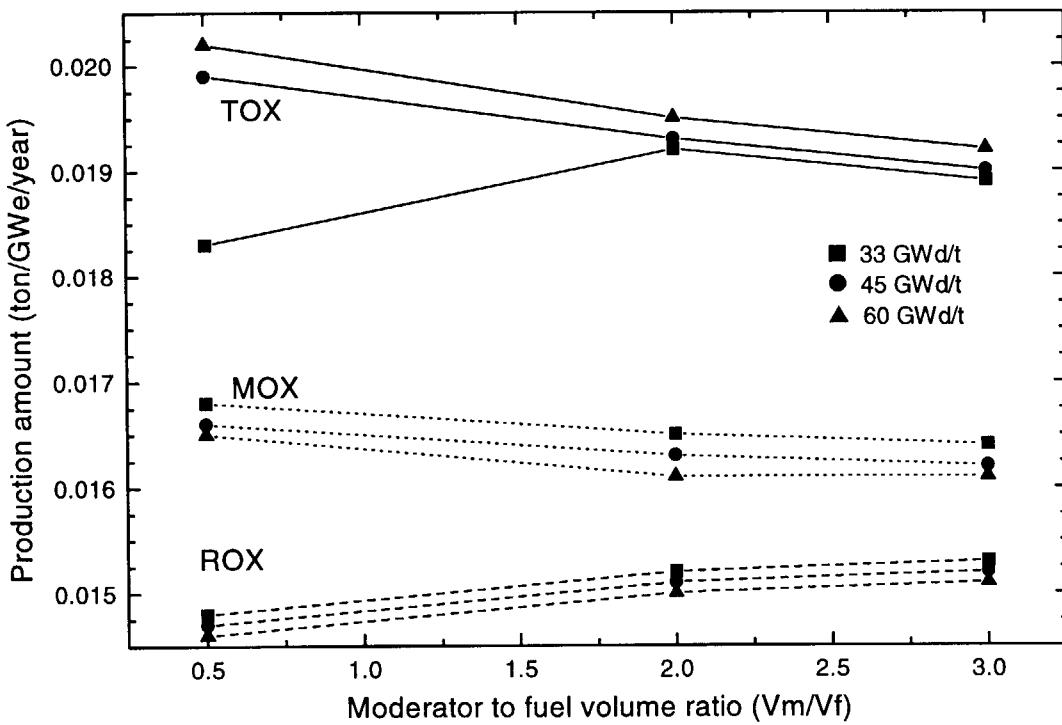
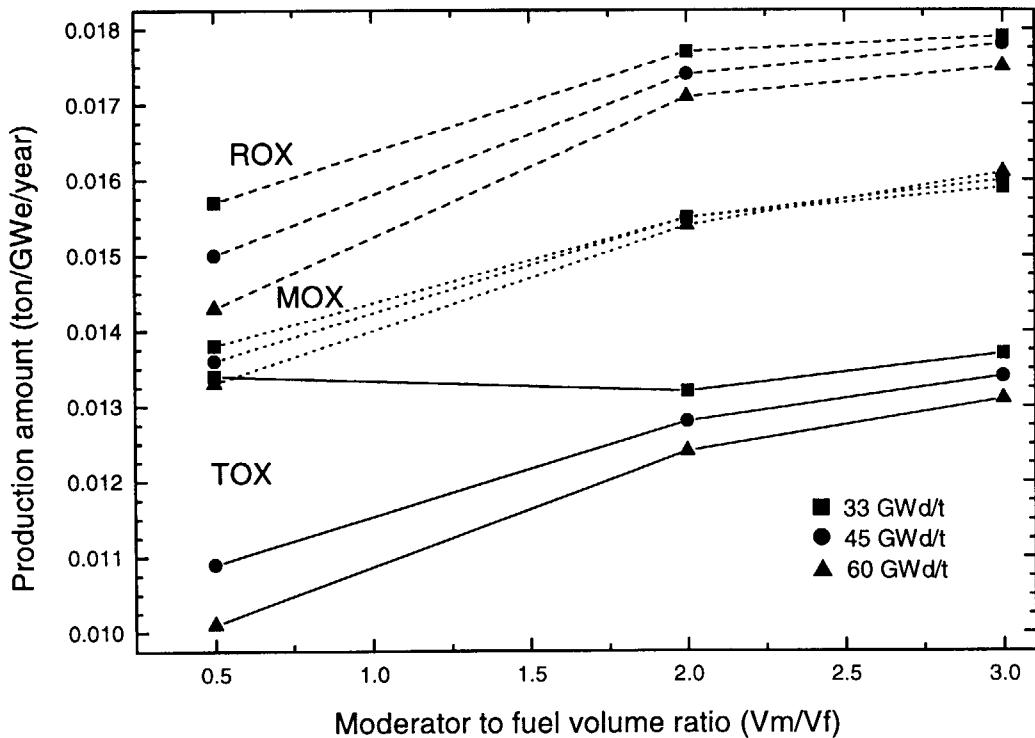
Table 6: Yield of long life fission product (LLFP) for different nuclides.

Nuclide name	^{79}Se	^{93}Zr	$^{99}\text{Mo} + ^{99}\text{Tc}$	^{107}Pd	^{126}Sn	^{129}I	$^{135}\text{I} + ^{135}\text{Xe} + ^{135}\text{Cs}$	Total LLFP Yield
^{232}Th	8.49E-4	6.76E-2	2.87E-2	5.17E-4	4.96E-4	3.72E-3	5.35E-2	1.55E-1
^{233}U	1.51E-3	7.02E-2	4.87E-2	1.17E-3	2.40E-3	1.51E-2	6.21E-2	2.01E-1
^{235}U	4.53E-4	6.39E-2	6.11E-2	1.40E-3	5.49E-4	7.18E-3	6.53E-2	2.00E-1
^{236}U	1.05E-3	5.70E-2	5.87E-2	9.23E-3	2.45E-3	9.83E-3	5.78E-2	1.96E-1
^{238}U	3.35E-4	5.00E-2	6.20E-2	1.30E-2	6.30E-4	1.00E-2	6.81E-2	2.04E-1
^{237}Np	5.80E-4	5.14E-2	6.16E-2	1.69E-2	1.63E-3	1.40E-2	7.54E-2	2.22E-1
^{239}Pu	4.70E-4	3.87E-2	6.14E-2	3.36E-2	2.66E-3	1.39E-2	7.62E-2	2.27E-1
^{240}Pu	5.08E-4	3.78E-2	5.97E-2	4.15E-2	2.78E-3	1.05E-2	7.45E-2	2.27E-1
^{241}Pu	1.53E-4	3.09E-2	6.23E-2	5.20E-2	7.56E-4	7.36E-3	7.28E-2	2.26E-1
^{242}Pu	3.56E-4	3.14E-2	5.36E-2	5.01E-2	1.76E-3	8.23E-3	7.15E-2	2.17E-1

Table 7: Effective capture cross-section (barn) of weapons-grade Pu fuels at middle of life (MOL).

Nuclide name	ROX			MOX			TOX		
	Vm/Vf 0.5	Vm/Vf 2.0	Vm/Vf 3.0	Vm/Vf 0.5	Vm/Vf 2.0	Vm/Vf 3.0	Vm/Vf 0.5	Vm/Vf 2.0	Vm/Vf 3.0
^{79}Se	2.78	11.00	13.04	1.43	3.79	6.30	1.42	3.83	5.44
^{93}Zr	0.74	0.70	0.72	0.55	0.65	0.69	0.53	0.63	0.66
^{99}Tc	8.82	9.94	10.01	3.94	7.99	8.61	5.05	9.02	9.40
^{107}Pd	4.34	3.77	3.54	3.34	3.63	3.41	3.39	3.67	3.49
^{126}Sn	0.009	0.022	0.026	0.008	0.011	0.015	0.008	0.011	0.013
^{129}I	1.34	2.35	2.99	0.935	2.19	3.07	0.93	1.98	2.61
^{135}Cs	2.28	2.40	2.49	1.57	2.27	2.44	1.60	2.24	2.36

Fig. 18: ^{135}Cs production amount in weapons-grade Pu fuels.Fig. 19: ^{99}Tc production amount in weapons-grade Pu fuels.

Fig. 20: ^{93}Zr production amount in weapons-grade Pu fuels.Fig. 21: ^{107}Pd production amount in weapons-grade Pu fuels.

7. Radiotoxicity Hazard

The radioactive fission products (FPs) and actinides are generated in the fuel during reactor operation. Net fission product amount in spent fuels are approximately same for all cases; although the presence of heavy metal (HM) varies from one fuel to another. Therefore, the difference in the radiotoxicity hazards among spent fuels depends mainly on HMs. ROX fuel contains only Pu as a heavy metal and weight of Pu in unit of metric ton is much less than that of TOX and MOX spent fuels. Because, MOX and TOX fuel contains Pu and large amount of fertile materials ^{238}U and ^{232}Th , respectively. Therefore we considered the hazard with corresponding volume to one metric ton of fresh MOX fuel for all type fuels. Ingestion radioactivity concentration limit of nuclides, which has been approved by ICRP¹⁰, is used to calculate the toxicity index of the nuclides.

Figures 22, 23 and 24 show the ingestion radiotoxicity hazard per one metric ton fresh MOX fuel volume equal to volume of ROX, TOX, and MOX spent fuels from LWRs, respectively. In ROX spent fuel, the hazard index of ^{244}Cm has a large value compared to TOX and MOX fuels. Succeeding (n, γ) reaction of ^{242}Pu and ^{243}Am produce more ^{244}Cm in ROX fuel than that in TOX and MOX fuels, because the production amount of ^{242}Pu (Table A.I.5 in Appendix I) in ROX fuel is higher than that in TOX and MOX fuels. In TOX fuel, the hazard indexes of ^{231}Pa , ^{227}Ac and ^{229}Th have very large values compared to those of ROX and MOX fuels, because ($n, 2n$) reaction of ^{232}Th produces ^{231}Pa , α -decay of ^{231}Pa and ^{233}U produce ^{227}Ac and ^{229}Th , respectively. In MOX fuel, hazard index of ^{237}Np is higher than that in ROX and TOX LWRs spent fuels, because (n, γ) reaction of ^{235}U and ($n, 2n$) reaction of ^{238}U produce ^{237}Np .

Figure 25 shows the comparison of ingestion radiotoxicity hazard index of TRU+Pu+FP for ROX, TOX and MOX LWRs spent fuels. Up to 10 cooling years, the hazard index of ROX spent fuel is higher than that of MOX and TOX fuels when V_m/V_f is 0.5, because of higher MA production amount especially ^{244}Cm . When V_m/V_f is 2.0 or 3.0, however, ROX fuel radiotoxicity hazard is lower than TOX and MOX fuels from initial cooling time. The half-life of ^{244}Cm is only 18 years, and after that ^{244}Cm decreases and ^{241}Am increases by the decay of ^{241}Pu (half-life 14.35 years). From 10^2 to 10^3 years cooling time, ^{241}Am (half-life 433 years) is dominant for the radiotoxicity hazard. In ROX spent fuel ^{241}Am production amount is lower than that in MOX and TOX spent fuels, because the number density of ^{241}Pu at EOL in ROX fuel is lower than that in MOX and TOX fuels. After 10^4 cooling years in TOX fuel, ^{229}Th , a daughter of ^{233}U (half-life 1.59×10^5 years), and ^{237}Np (half-life 2.14×10^6 years) are dominant in the radiotoxicity hazard. On the other hand, in ROX and MOX LWR spent fuels only ^{237}Np is dominant. The radiotoxicity hazard index of ^{237}Np in ROX fuel is smaller than that in TOX and

MOX fuels because ^{237}Np comes from the α -decay of ^{241}Am whose quantity in ROX fuel is low.

Radiotoxicity hazard of reactor-grade Pu spent fuel has similar tendency to weapons-grade Pu spent fuel, but is higher than that in weapons-grade Pu fuels because of lower Pu transmutation-and higher MA production amounts in reactor grade fuels.

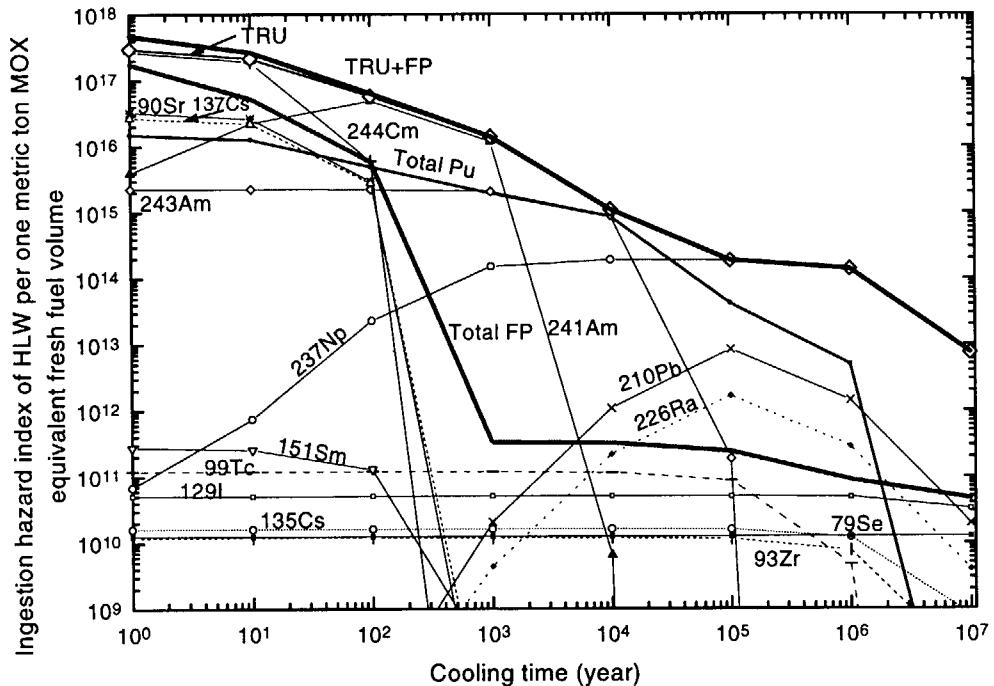


Fig. 22: Hazard indexes of weapons-grade ROX spent fuel in 33GWd/t discharged burnup and Vm/Vf 2.0

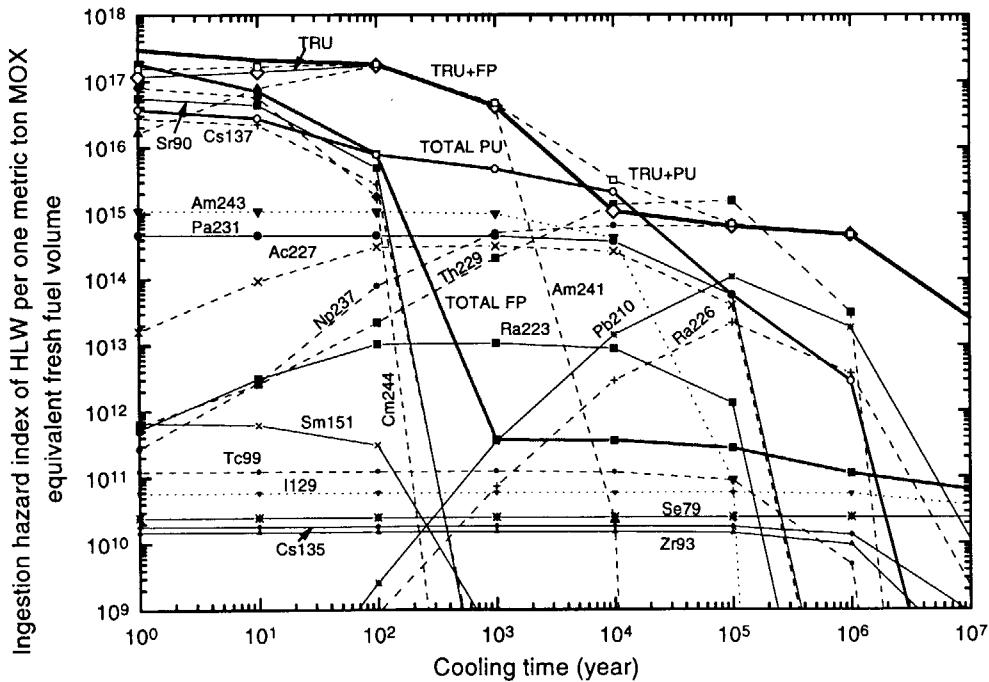


Fig. 23: Hazard indexes of weapons-grade TOX spent fuel in 33GWd/t discharged burnup and Vm/Vf 2.0.

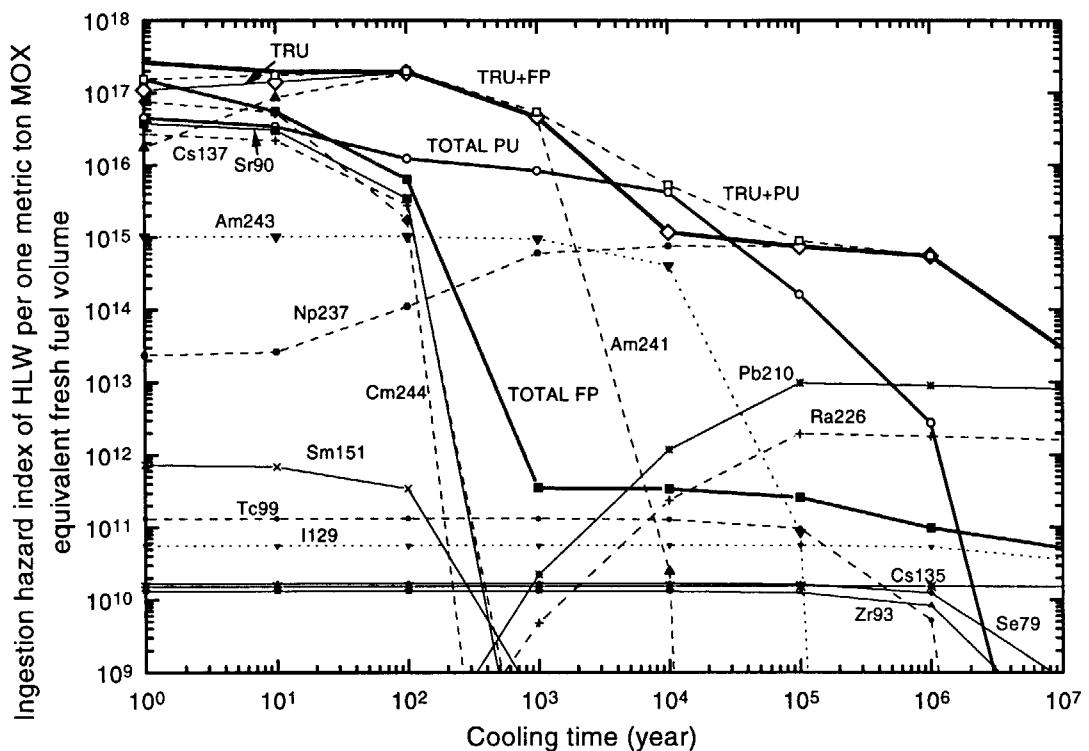


Fig. 24: Hazard indexes of weapons-grade Pu MOX spent fuel in 33GWd/t discharged burnup and V_m/V_f 2.0

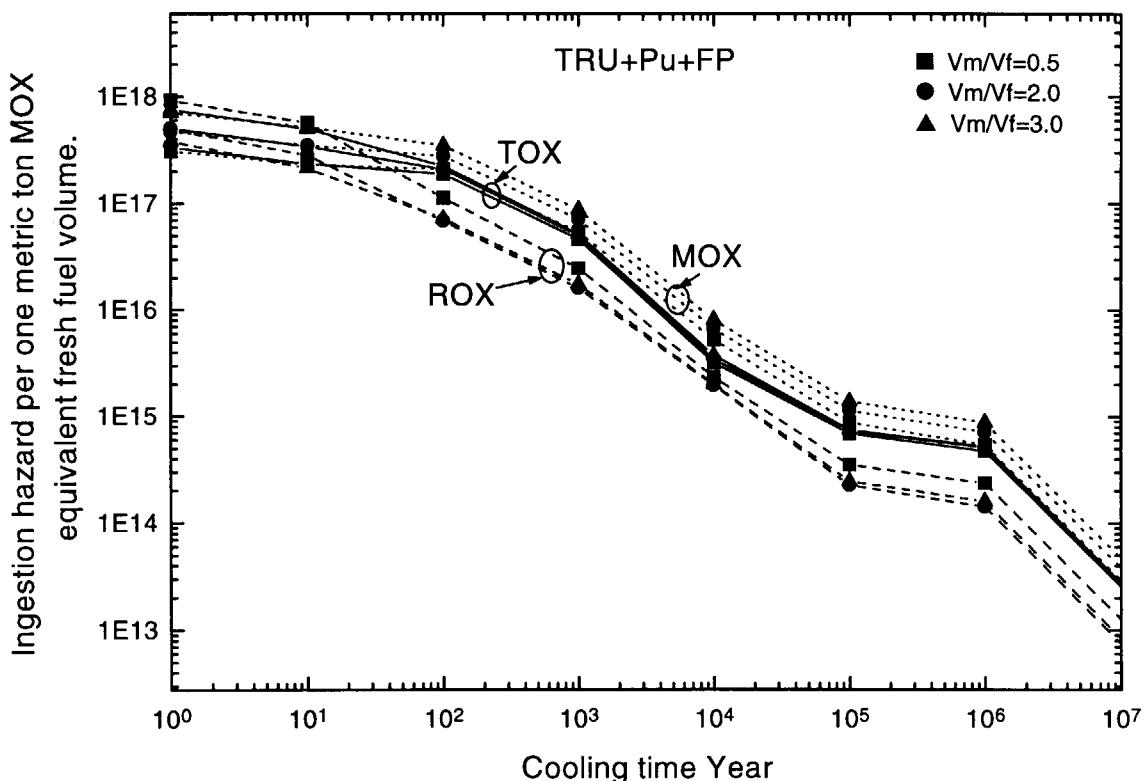


Fig. 25: Hazard indexes of weapons-grade Pu spent fuels in 33 GWd/t discharged burnup and V_m/V_f 2.0

8. Fuel Temperature Coefficient

The fuel temperature coefficient depends on both the effects of thermal neutron spectrum shift and resonance absorption change according to temperature change. The nominal fuel temperature 600°C is increased to 900°C for fuel temperature coefficient calculation. Figure 26 shows the burnup dependent fuel temperature coefficient of weapons-grade Pu ROX, MOX, and TOX fuels, when discharge burnup is 33 GWd/t. ROX fuel has small negative fuel temperature coefficient at BOL for all V_m/V_f s. The coefficient becomes positive at EO. When V_m/V_f is 0.5, the fuel temperature coefficient of ROX fuel is more negative at BOL and less positive at EOL. In MOX and TOX fuels the fuel temperature coefficient is more negative at BOL than in ROX fuel and changes slightly with burnup for all the V_m/V_f s. TOX fuels have more negative fuel temperature coefficient than MOX fuels for all the V_m/V_f s.

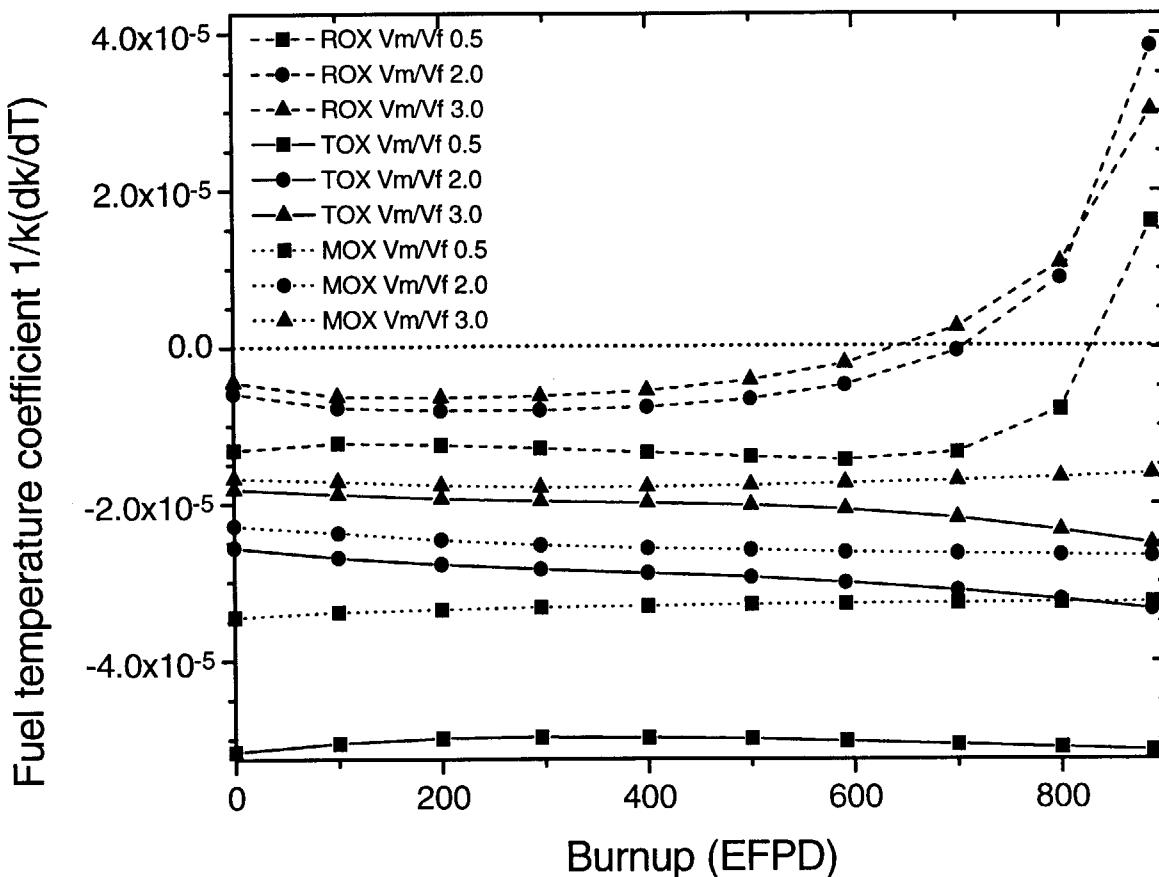


Fig. 26: Fuel temperature coefficient of weapons-grade Pu fuels for 33 GWd/t discharge burnup.

Figures 27 and 28 show the nuclide-wise reactivity contribution to the fuel temperature coefficient at BOL and EOL, respectively, when V_m/V_f is 2.0 and discharge burnup is 33 GWd/t. Fertile materials ^{238}U and ^{232}Th have a large resonance neutron absorption, which makes the fuel temperature coefficient largely negative at BOL and EOL in MOX and TOX fuels. On the contrary, ROX fuel contains only Pu as actinides; moreover the negative reactivity contribution of ^{239}Pu is less than that in TOX and MOX fuels at BOL. At EOL we can see from Fig. 26, ^{239}Pu and ^{241}Pu behaviors in ROX fuel are opposite to those in MOX and TOX fuels. The production reaction rate of ^{241}Pu in ROX fuel increases largely with increasing the temperature and makes the fuel temperature coefficient large positive value. The fission product (FP) also becomes an important contributor to the positive fuel temperature reactivity in the ROX fuel. The negative contribution of ^{239}Pu at BOL in ROX fuel is going to positive direction with burnup. Neutron resonance peak of ^{239}Pu and ^{241}Pu is present between 0.1 to 1 eV neutron energy region. The behavior of ^{239}Pu and ^{241}Pu in ROX fuel indicates that thermal neutron energy region in ROX fuel is important to understand the difference of ROX fuel from TOX and MOX fuels.

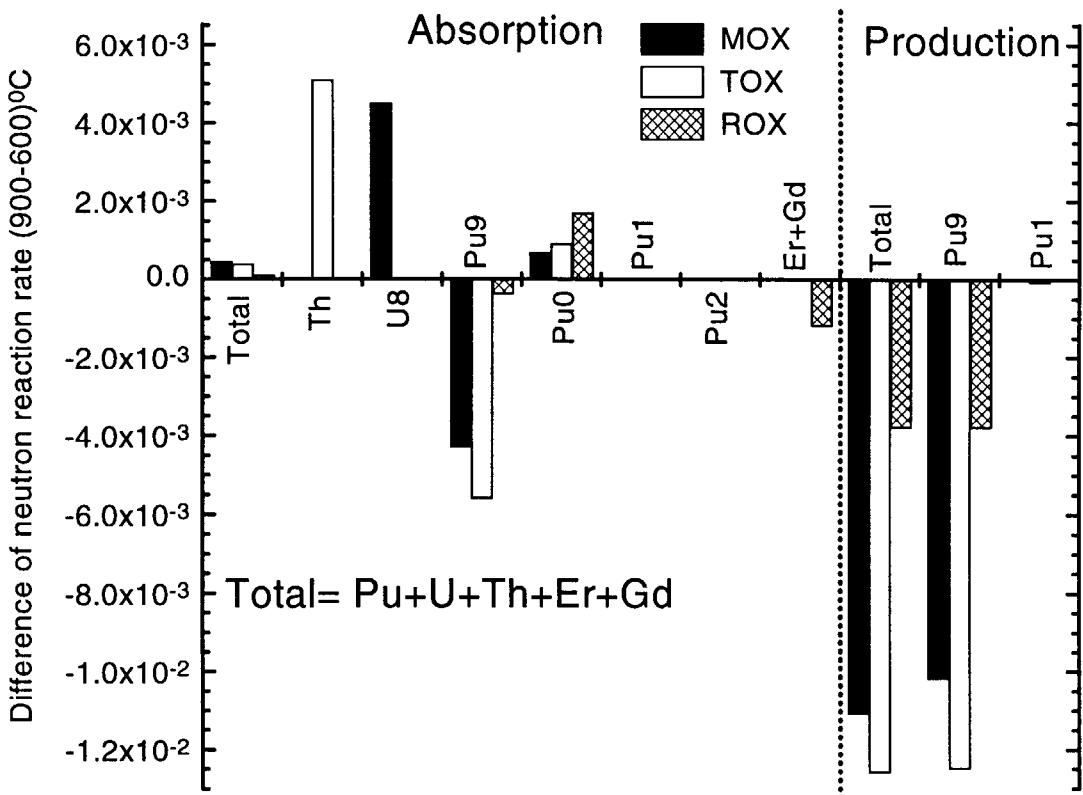


Fig. 27: Fuel temperature reactivity contributor nuclides of weapons-grade fuels at BOL when discharge burnup is 33 GWd/t and V_m/V_f is 2.0.

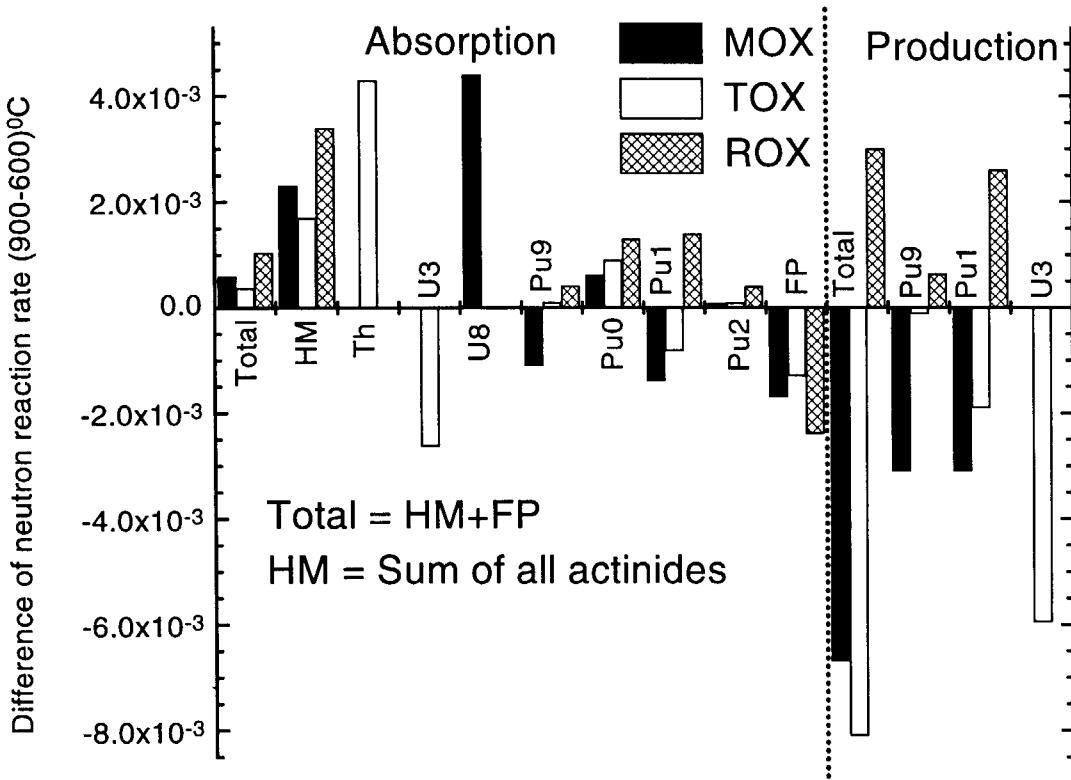


Fig. 28: Fuel temperature reactivity contributor nuclides of weapons-grade fuels at EOL when discharged burnup is 33 GWd/t and Vm/Vf is 2.0.

Figure 29 shows the burnup dependent fuel temperature coefficient of reactor-grade Pu ROX, MOX and TOX fuels when discharge burnup is 33GWd/t. The fuel temperature coefficient of reactor-grade Pu fuels has similar tendency to weapons-grade Pu fuels, though more negative value at BOL and less positive at EOL. When Vm/Vf is 0.5, the fuel temperature coefficient of ROX fuel is negative from BOL to EOL.

Figures 30 and 31 show the nuclide-wise reactivity contribution in reactor-grade Pu fuels at BOL and EOL, when Vm/Vf is 2.0 and discharge burnup is 33 GWd/t. Reactivity contributor nuclides in reactor-grade Pu fuels have similar tendency to the nuclides in weapons-grade Pu fuels. Production reaction rate of ^{241}Pu in reactor-grade Pu fuels has more negative reactivity contribution at BOL, has less positive reactivity contribution at EOL, than in weapons-grade Pu fuels.

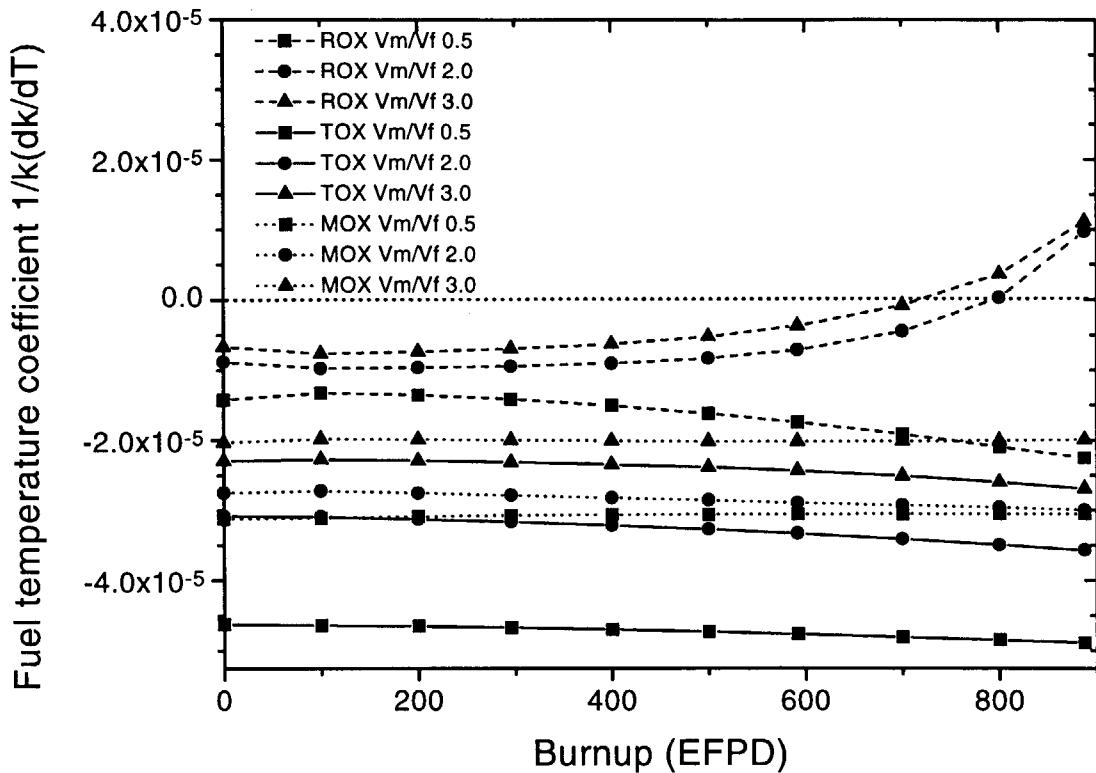


Fig. 29: Fuel temperature coefficient of reactor-grade Pu fuels for 33 GWd/t discharged burnup.

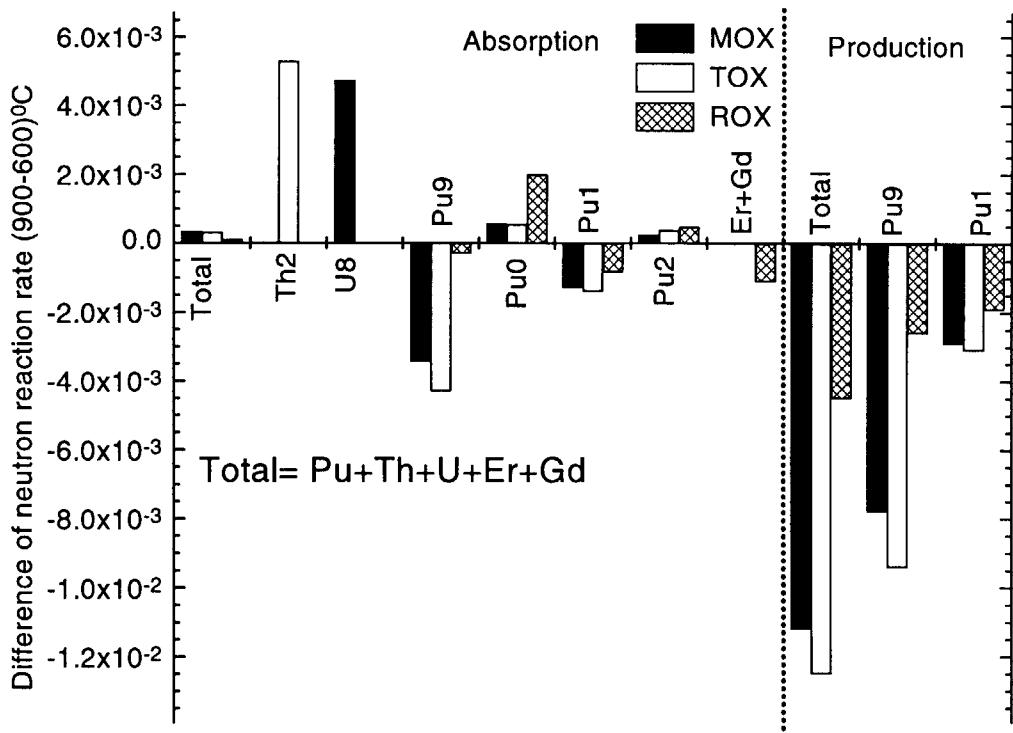


Fig. 30: Fuel temperature reactivity contributor nuclides of reactor-grade fuels at BOL when discharge burnup is 33 GWd/t and V_m/V_f is 2.0.

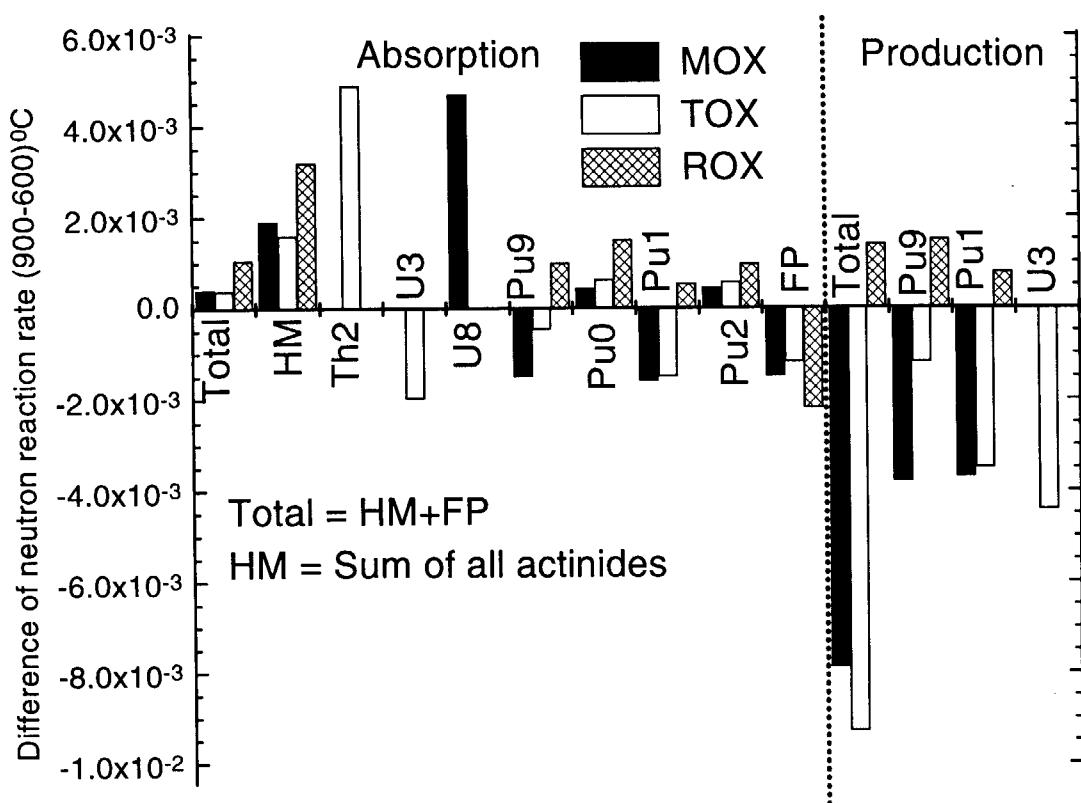


Fig. 31: Fuel temperature reactivity contributor nuclides of reactor-grade fuels at EOL when discharge burnup is 33 GWd/t and V_m/V_f is 2.0.

9. Void Coefficient

Figure 32 compares burnup dependent void coefficients among weapons-grade Pu ROX, TOX, and MOX fuel cells of 33 GWd/t discharge burnup. For void coefficient calculation, We increased the void fraction from 0% to 40%. From this figure we can see, void coefficient of ROX fuel is negative at BOL and becomes positive after about 800 EFPD when V_m/V_f is 3.0 or 2.0. When V_m/V_f is 0.5, the void coefficient of ROX fuel is nearly zero at BOL and going to negative direction with burnup. TOX and MOX fuels have large negative void coefficient from BOL to EOL compared to that in ROX fuel. MOX fuel has more negative void coefficient value than TOX fuel when V_m/V_f is 2.0 or 3.0, but when V_m/V_f is 0.5, it has less negative void coefficient than TOX fuel.

Figures 33 and 34 show the nuclide-wise reactivity contribution to void coefficient at BOL and EOL, respectively. At BOL, a similar tendency to the fuel temperature reactivity case can be seen. In ROX fuel ^{239}Pu has less negative contribution to void reactivity coefficient than that in MOX and TOX fuels. In TOX fuel, ^{232}Th has less negative void reactivity contribution than ^{238}U in MOX fuel. The void reactivity contribution of ^{239}Pu in TOX fuel is lower than in MOX fuel cell.

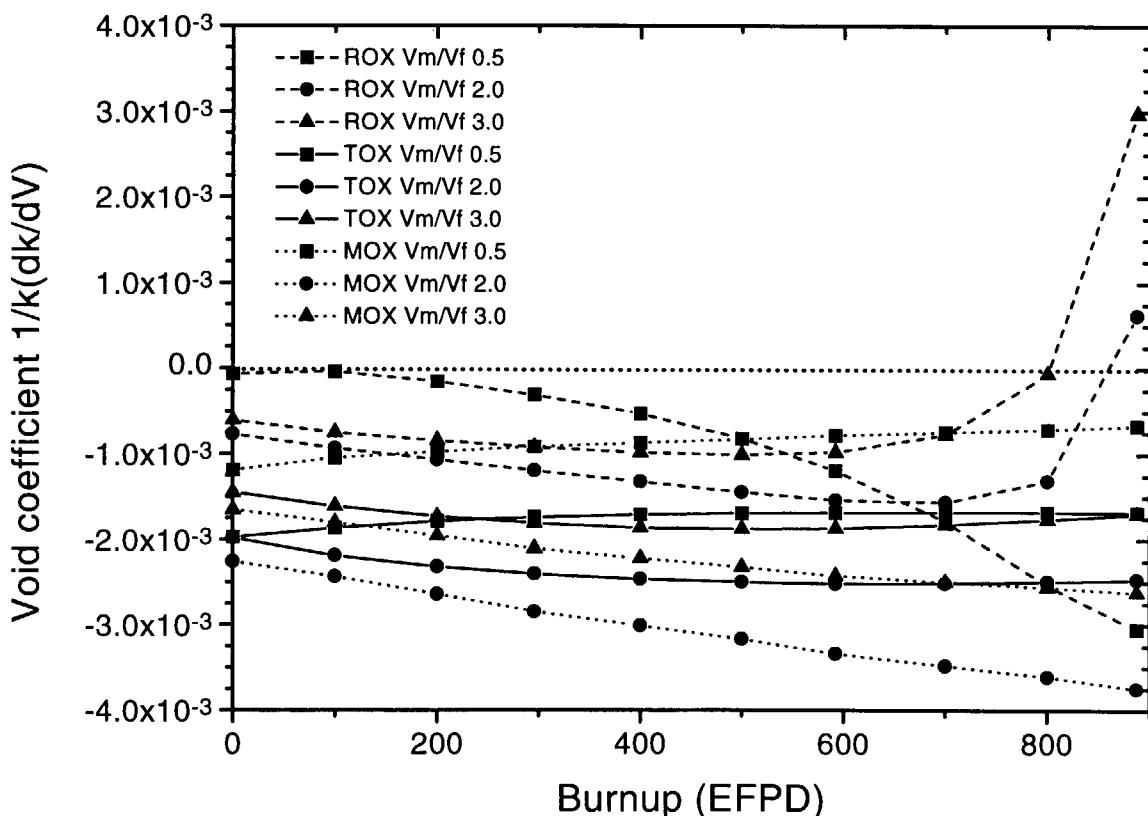


Fig. 32: Void coefficient in weapons-grade Pu fuels when discharge burnup is 33 GWd/t.

At EOL, void reactivity contributions of ^{239}Pu and ^{241}Pu are negligible in ROX fuel, and FP has negative contribution. The main cause for positive void coefficient in ROX fuel is ^1H at EOL. Neutron absorption reaction rate of ^1H decreases very rapidly with increasing void fraction. In TOX and MOX fuels, ^1H has small positive void reactivity contribution compared to ROX fuel. Large positive void reactivity contribution of ^1H in ROX fuel indicates that thermal neutron energy region is more important in ROX fuel than TOX and MOX fuels for the void reactivity coefficient problem.

TOX fuel has much more negative void coefficient than MOX fuel when Vm/Vf is 0.5, because ^{232}Th has more negative void reactivity contribution compared to ^{238}U in MOX fuel cells.

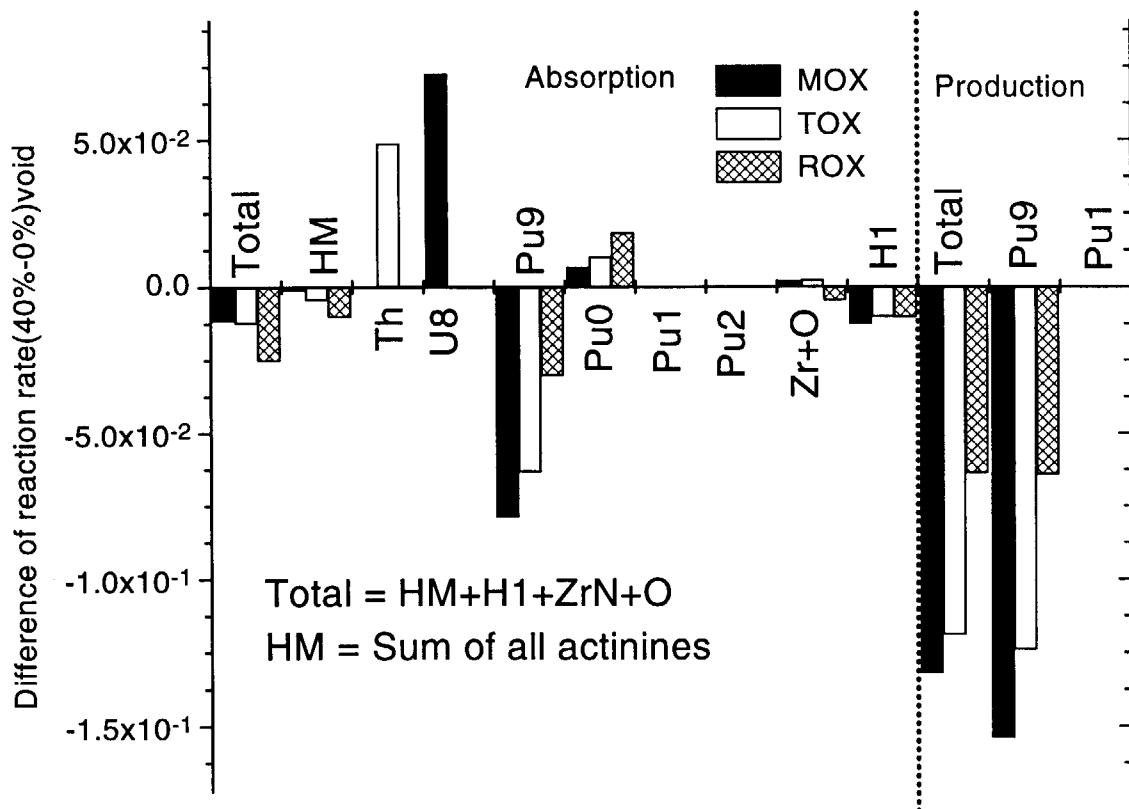


Fig. 33: Void coefficient contributor nuclides in weapons-grade Pu fuels at BOL when discharge burnup is 33 GWd/t and Vm/Vf is 2.0.

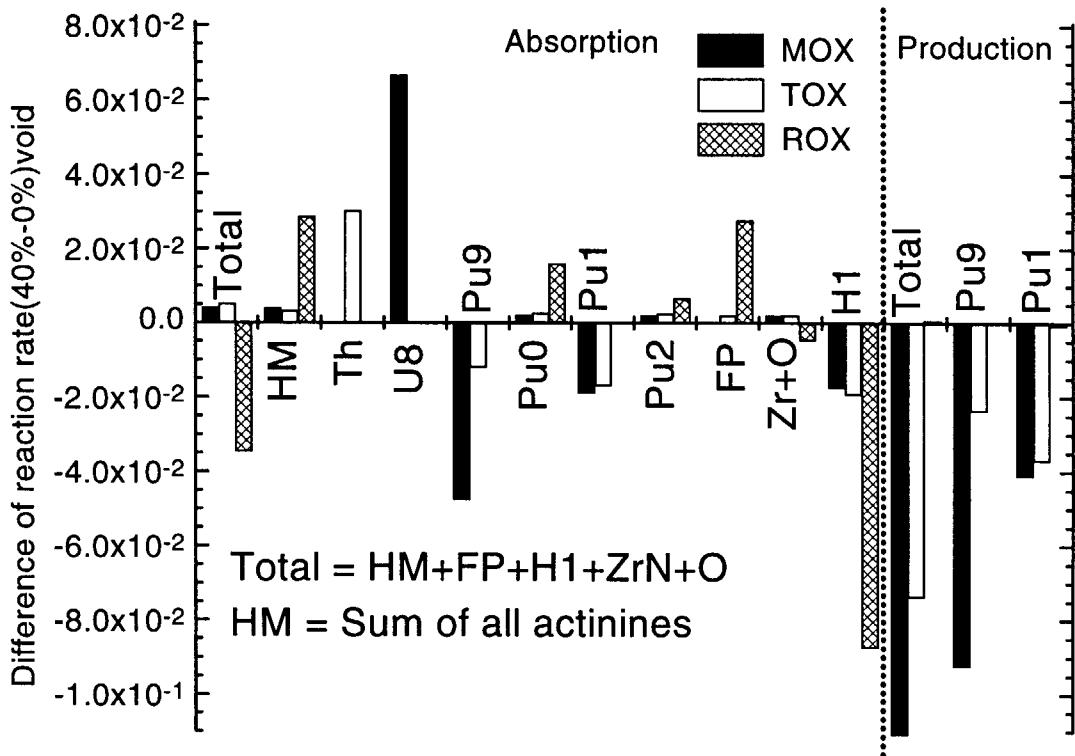


Fig. 34: Void coefficient contributor nuclides in weapons-grade Pu fuels at EOL when discharge burnup is 33 GWd/t and V_m/V_f is 2.0.

Figure 35 shows the burnup dependent void coefficient in reactor-grade Pu fuels when discharge burnup is 33 GWd/t. Void coefficient of reactor-grade Pu fuels has similar tendency to weapons-grade Pu fuels. The void coefficient of ROX fuel at EOL is improved compared to with weapons-grade Pu fuels when V_m/V_f is 2.0 or 3.0. When V_m/V_f is 0.5, the void coefficient of ROX fuel is positive at BOL, and going to negative direction with burnup but less negative than that in weapons-grade Pu fuels. The void coefficient of MOX and TOX fuel has similar tendency to weapons-grade Pu fuels, when V_m/V_f is 0.5 the void coefficient shifted to less negative value from BOL up to EOL.

Figures 36 and 37 show nuclide-wise void reactivity contribution at BOL and EOL, respectively, when V_m/V_f is 2.0 and discharge burnup is 33 GWd/t. At BOL void reactivity contributor nuclides in the reactor-grade Pu have similar tendency to nuclides in the weapons-grade Pu fuels. When V_m/V_f is 2.0, void coefficient of reactor-grade Pu fuel is negative from BOL to EOL, while in weapons-grade Pu fuel is positive at EOL. The negative void reactivity contribution of ^{241}Pu in ROX fuel increases and positive contributor ^1H decreases in Reactor-grade Pu fuels in comparison with in weapons-grade Pu fuels cell at EOL. At EOL, TOX and MOX fuel nuclides have similar tendency to the nuclides in weapons-grade Pu fuels.

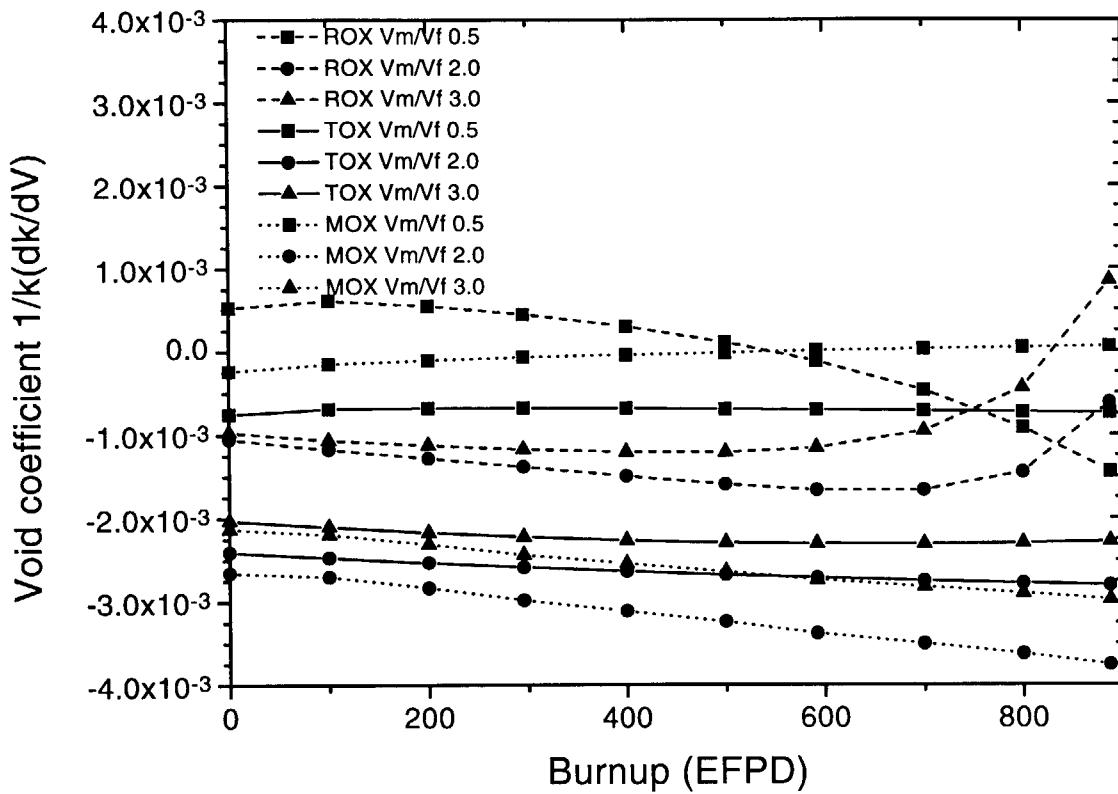


Fig. 35: Void coefficient of reactor-grade Pu fuels for 33 GWd/t discharge burnup.

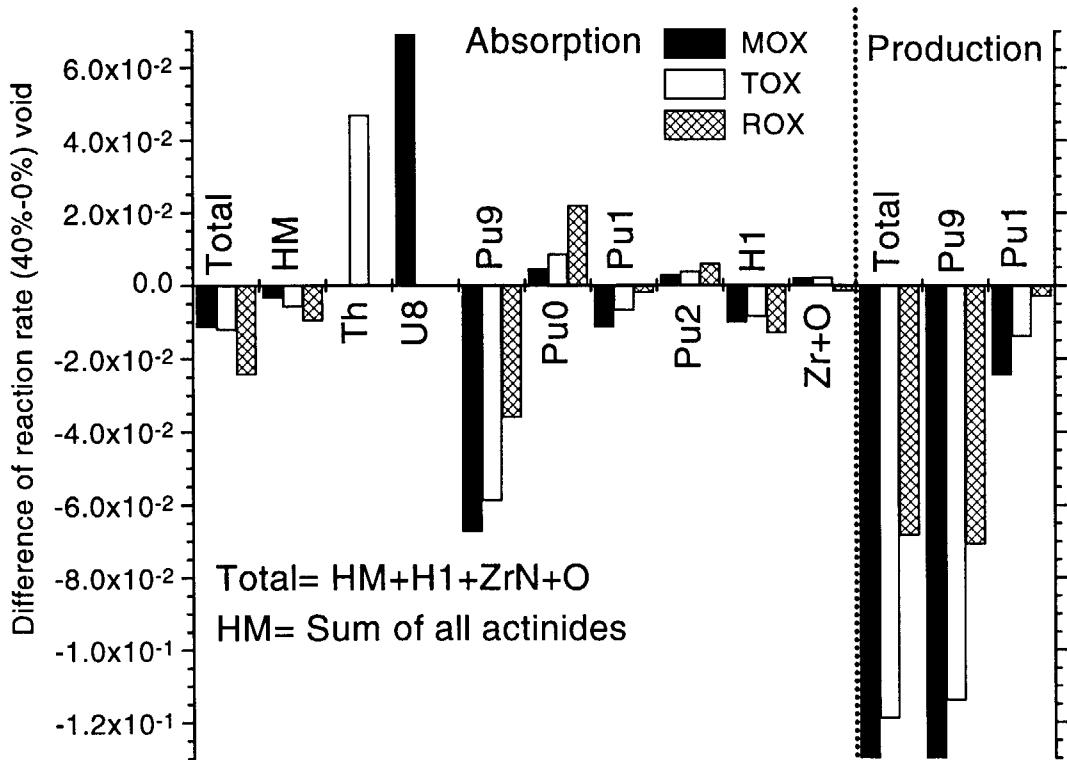


Fig. 36: Void coefficient contributor nuclides in reactor-grade Pu fuels at BOL when discharge burnup is 33 GWd/t and V_m/V_f is 2.0.

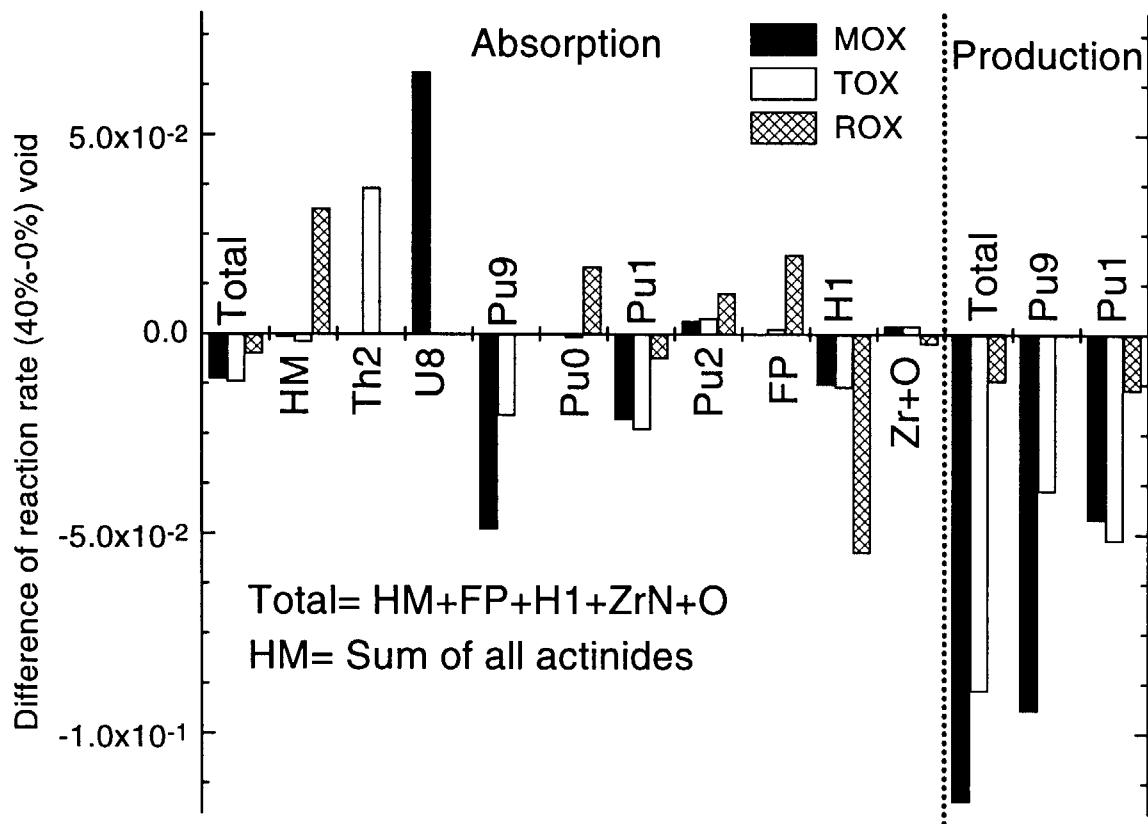


Fig. 37: Void coefficient contributor nuclides in reactor-grade Pu fuels at EOL when discharge burnup is 33 GWd/t and V_m/V_f is 2.0.

10. Conclusion

From the parametric survey of U-free inert matrix fuels, $\text{PuO}_2\text{+ZrO}_2$ (ROX) and $\text{PuO}_2\text{+ThO}_2$ (TOX), in comparison with conventional MOX fuel, we can remark the following:

1. ROX fueled LWRs can transmute ~99.8% ^{239}Pu in weapons- and ~88% in reactor-grade Pu, but the net Pu transmutation of weapons-grade Pu is ~90% and reactor-grade Pu is ~80%. This transmutation of Pu is not sensitive to V_m/V_f and discharge burnup. TOX fuel also has a good Pu transmutation ability in higher V_m/V_f and transmutation amount decreases with decreasing V_m/V_f and discharge burnup. TOX fueled LWRs can transmute 74% of net initial loaded Pu when V_m/V_f is 3.0 and discharged burnup 33GWd/t. ^{233}U production amount in TOX fuel compensates the transmutation amount of Pu, moreover this fuel produces γ -active ^{232}U . Transmuted amount of Pu isotopes; ^{239}Pu and ^{241}Pu in MOX fueled LWRs is limited especially at lower V_m/V_f by the production of secondary Pu from the uranium. Comparing with MOX fuel, the quality of Pu in ROX and TOX spent fuels is very poor.
2. Net minor actinide production percentage in weapons-grade Pu fuels are 2.5%, 1.5%, and 2.7% of initial loaded Pu in ROX, TOX, and MOX fueled LWRs, respectively, when V_m/V_f is 2.0 and discharge burnup is 33 GWd/t. In reactor-grade Pu fuels, net MA production percentages are 6.7%, 4.0% and 4.7% of initial loaded Pu in ROX, TOX, and MOX fuels, respectively, for the same V_m/V_f and discharge burnup as weapons-grade Pu fuels. MA productions in TOX and MOX fuels increase slightly with decreasing the V_m/V_f from 2.0 to 0.5; on the contrary increases largely in ROX fuel due to higher flux level both for reactor- and weapons-grade Pu.
3. Production amount of net LLFP in ROX fueled LWRs is lower when V_m/V_f is 0.5 or 2.0 than to that of TOX and MOX fueled LWRs because of higher effective neutron capture cross-sections of LLFPs in ROX. In TOX and MOX fuels, LLFP production amount decreases rapidly, and in ROX fuel slightly, with increasing V_m/V_f . When V_m/V_f is 3.0, net LLFP production amounts for all fuels become almost same. LLFP production amounts in reactor-grade Pu fuels are nearly equal to those of the weapons-grade Pu fuels.
4. Radiotoxicity hazard of ROX spent fuel is lower when V_m/V_f are 2.0 and 3.0 than that of TOX and MOX spent fuels. When V_m/V_f is 0.5, the radiotoxicity hazard of ROX spent fuel is higher than that of TOX and MOX fuels at the beginning of cooling time but after 18 years cooling time becomes lower according to decay of ^{244}Cm . TOX fuel has lower radiotoxicity hazard than MOX fuel. Radiotoxicity

hazard in reactor-grade Pu spent fuels is a little bit higher than that in weapons-grade Pu fuels.

5. Fuel temperature coefficient of ROX fuel is negative at BOL, but less than a half of that of TOX and MOX fuels. But at EOL it becomes positive, mainly due to large positive reactivity contribution of ^{241}Pu and FP in both reactor- and weapons-grade Pu. When Vm/Vf is 0.5, the fuel temperature coefficient of reactor-grade ROX fuel is negative from BOL to EOL. TOX fuel has more negative fuel temperature coefficient than MOX fuel for all the Vm/Vfs .
6. Void coefficient of weapons-grade Pu ROX fuel is less negative than that of TOX and MOX fuels at BOL for higher Vm/Vf . But at EOL, void coefficient of ROX fuel becomes positive, because of large positive void reactivity contribution of ^1H . When Vm/Vf is 0.5, the void coefficient of weapons-grade Pu ROX fuel is nearly zero at BOL and becomes negative at EOL. Reactor-grade Pu ROX fuels has negative void coefficient BOL to EOL when Vm/Vf is 2.0. TOX fuel has less negative void coefficient than MOX fuel when Vm/Vf is 2.0 or 3.0.

If reactivity coefficient problem can be improved, ROX fuel has excellent performance as a once through fuel, because of higher Pu transmutation and lower radiotoxicity hazard. From the study of reactivity coefficient, it is indicated thermal neutron energy region is important in ROX fuel for reactivity coefficient problem. Further study is devoted to understand the reactivity coefficient problem of ROX fuel, especially the behavior in thermal neutron energy region. TOX fuel has no reactivity coefficient problem. As a once-through fuel, Pu transmutation capability of TOX fuel is good and radiotoxicity hazard is less than that in MOX fuel. We need to pay attention, however, to the production of ^{233}U and ^{232}U in TOX fuel.

Acknowledgement

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Appendices

Appendix I: Nuclide wise Pu production and transmutation in reactor and weapons-grade Pu fuels.

Table A. I 1: ^{238}Pu transmuted amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	7.842E-3	6.096E-3	5.301E-3	-2.034E-3*	-1.378E-3	-2.428E-3
2.0	1.629E-2	3.387E-3	2.330E-3	-1.040E-3	-1.439E-3	-2.285E-3
3.0	1.780E-2	5.581E-3	5.548E-3	-8.681E-4	-1.210E-3	-1.819E-3
45GWd/t				45GWd/t		
0.5	7.082E-3	4.625E-3	3.712E-3	-3.048E-3	-1.758E-3	-3.325E-3
2.0	1.453E-2	1.666E-3	3.617E-4	-1.635E-3	-2.340E-3	-3.291E-3
3.0	1.654E-2	5.107E-3	4.375E-3	-1.355E-3	-1.993E-3	-2.613E-3
60GWd/t				60GWd/t		
0.5	6.797E-3	3.646E-3	2.369E-3	-4.356E-3	-2.551E-3	4.291E-3
2.0	1.202E-2	-9.882E-5	1.934E-3	-2.472E-3	-3.406E-3	4.569E-3
3.0	1.471E-2	3.734E-3	2.728E-3	-1.977E-3	-2.886E-3	3.596E-3

*Negative symbol means production

Table A. I 2: ^{239}Pu transmuted amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	9.383E-1	8.744E-1	8.082E-2	1.171E+0	1.131E+0	2.914E-1
2.0	8.706E-1	8.665E-1	4.002E-1	1.180E+0	1.023E+0	5.233E-1
3.0	8.887E-1	8.669E-1	4.721E-1	1.197E+0	1.043E+0	6.153E-1
45GWd/t				45GWd/t		
0.5	9.384E-1	8.179E-1	1.116E-1	1.173E+0	1.046E+0	3.052E-1
2.0	8.591E-1	8.240E-1	4.319E-1	1.168E+0	9.601E-1	5.650E-1
3.0	8.731E-1	8.022E-1	4.908E-1	1.181E+0	9.917E-1	6.360E-1
60GWd/t				60GWd/t		
0.5	9.291E-1	7.752E-1	1.429E-1	1.197E+0	9.703E-1	3.344E-1
2.0	8.524E-1	7.863E-1	4.611E-1	1.163E+0	9.065E-1	5.841E-1
3.0	8.618E-1	7.686E-1	5.145E-1	1.170E+0	9.304E-1	6.656E-1

Table A. I 3: ^{240}Pu transmuted amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	2.181E-1	1.888E-2	-4.089E-2*	4.850E-2	-1.572E-1	-2.198E-1
2.0	2.185E-1	9.933E-2	-2.119E-3	2.425E-2	-5.812E-2	-1.314E-1
3.0	1.954E-1	8.079E-2	-1.231E-4	5.422E-3	-7.139E-2	-1.258E-1
45GWd/t				45GWd/t		
0.5	2.011E-1	2.755E-2	3.007E-2	4.591E-2	-1.319E-1	-2.077E-1
2.0	2.27E-1	1.180E-1	1.659E-2	3.322E-2	-2.929E-2	-1.146E-1
3.0	2.088E-1	1.160E-1	2.400E-2	1.892E-2	-4.181E-2	-1.002E-1
60GWd/t				60GWd/t		
0.5	1.883E-1	3.250E-2	-4.228E-2	3.193E-2	-1.091E-1	-1.978E-1
2.0	2.315E-1	1.338E-1	3.246E-2	3.749E-2	-5.979E-3	-9.603E-2
3.0	2.178E-1	1.362E-1	4.403E-2	2.810E-2	-1.153E-2	-8.113E-2

*Negative symbol means production

Table A. I 4: ^{241}Pu transmuted amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	3.216E-2	4.661E-2	2.194E-2	-3.974E-2	-1.35E-1	-1.441E-1
2.0	1.218E-1	1.985E-2	-1.374E-2	-2.166E-2	-8.380E-2	-9.460E-2
3.0	1.240E-1	4.431E-2	2.214E-2	-2.476E-2	-7.113E-2	-7.144E-2
45GWd/t				45GWd/t		
0.5	4.180E-2	5.193E-2	3.007E-2	-4.305E-2	-1.143E-1	-1.302E-1
2.0	1.244E-1	3.377E-2	-7.578E-3	-1.732E-2	-6.473E-2	-9.025E-2
3.0	1.280E-1	6.274E-2	3.000E-2	-1.909E-2	-5.590E-2	-6.220E-2
60GWd/t				60GWd/t		
0.5	5.663E-2	6.011E-2	3.669E-2	-5.873E-2	-9.585E-2	-1.161E-1
2.0	1.250E-1	4.635E-2	-3.735E-4	-1.537E-2	-4.827E-2	-8.245E-2
3.0	1.305E-1	7.268E-2	3.686E-2	-1.511E-2	-3.927E-2	-5.568E-2

Table A. I 5: ^{242}Pu transmuted amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	-1.666E-2	-1.937E-3	-1.197E-3	-5.244E-2	-1.555E-2	-1.349E-2
2.0	-8.359E-2	-4.787E-2	-4.315E-2	-7.641E-2	-4.306E-2	-4.173E-2
3.0	-9.632E-2	-6.085E-2	-5.916E-2	-7.907E-2	-4.625E-2	-4.835E-2
45GWd/t				45GWd/t		
0.5	-9784E-3	-1.436E-3	-1.063E-3	-4.741E-2	-1.652E-2	-1.494E-2
2.0	-7.628E-2	-4.574E-2	-4.004E-2	-7.337E-2	-4.519E-2	-4.293E-2
3.0	-9.113E-2	-6.242E-2	-5.859E-2	-7.781E-2	-4.936E-2	-5.186E-2
60GWd/t				60GWd/t		
0.5	-5.199E-3	-7.710E-4	-6.823E-4	-4.296E-2	-1.700E-2	-1.587E-2
2.0	-6.874E-2	-4.295E-2	-3.651E-2	-7.053E-2	-4.575E-2	-4.405E-2
3.0	-8.528E-2	-6.037E-2	-5.685E-2	-7.608E-2	-5.130E-2	-5.360E-2

Appendix II: Nuclide wise MA production in reactor and weapons-grade Pu fuels.

Appendix II (A) contains the nuclide-wise Am production in reactor- and weapons-grade Pu fuels. ^{243}Am produced from the (n,γ) reaction of ^{242}Pu is dominant in both reactor and weapons-grade Pu ROX fuels. On the other hand in MOX and TOX fuels ^{241}Am is dominant, which is produced from the β -decay of ^{241}Pu . With increasing Vm/Vf, ^{241}Am and ^{243}Am productions decrease.

Appendix II (B) contains nuclide-wise Cm production, which is produced from (n,γ) reaction and β -decay of Am isotopes. Within Cm, ^{244}Cm is dominant in all fuels, which is produced from (n,γ) reaction of ^{243}Am . In ROX fuel, ^{243}Am production is higher, so ^{244}Cm production is also higher than that in TOX and MOX fuels.

Appendix II (C) contains nuclide-wise Np production, which is produced from (n,γ) reaction of ^{235}U , $(n, 2n)$ reaction of ^{238}U and α -decay of Am. Neptunium production in MOX fuel is higher than that in ROX and TOX fuels.

Appendix II (A): Americium (Am) production:**Table A. II 1: ^{241}Am transmuted amount in ton/GWe/year**

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	1.230E-2	-8.947E-3	-1.053E-2	-1.025E-3	-7.259E-3	-7.260E-3
2.0	1.493E-2	5.036E-3	3.228E-3	-6.350E-4	-3.586E-3	-3.549E-3
3.0	1.501E-2	6.328E-3	5.822E-3	-6.839E-4	-3.001E-3	-2.539E-3
45GWd/t				45GWd/t		
0.5	1.060E-2	-8.636E-3	-1.099E-2	-1.326E-3	-7.923E-3	-8.402E-3
2.0	1.460E-2	4.231E-3	1.577E-3	-6.350E-4	-3.519E-3	-4.351E-3
3.0	1.478E-2	7.079E-3	5.355E-3	-6.540E-4	-2.996E-3	-2.752E-3
60GWd/t				60GWd/t		
0.5	9.278E-3	-8.955E-3	-1.106E-2	-2.278E-3	-8.351E-3	-9.425E-3
2.0	1.410E-2	3.710E-3	-3.529E-4	-7.247E-4	-3.250E-3	-4.905E-3
3.0	1.445E-2	6.971E-3	4.679E-3	-6.566E-4	-2.594E-3	-3.037E-3

Table A. II 2: ^{242}M Am production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	3.419E-4	1.999E-3	1.963E-3	2.595E-5	2.030E-4	1.944E-4
2.0	4.102E-5	3.072E-4	2.244E-4	8.368E-6	6.003E-5	5.520E-5
3.0	4.058E-5	2.144E-4	1.122E-4	8.251E-6	4.239E-5	3.286E-5
45GWd/t				45GWd/t		
0.5	4.784E-4	1.769E-3	1.837E-3	3.867E-5	2.554E-4	2.610E-4
2.0	4.459E-5	2.988E-4	2.744E-4	8.758E-6	6.159E-5	7.312E-5
3.0	4.058E-5	1.636E-4	1.170E-4	8.140E-6	4.395E-5	3.707E-5
60GWd/t				60GWd/t		
0.5	5.715E-4	1.656E-3	1.726E-3	7.792E-5	3.026E-4	3.289E-4
2.0	5.274E-5	2.916E-4	3.412E-4	1.030E-5	5.878E-5	8.763E-5
3.0	4.311E-5	1.530E-4	1.329E-4	8.326E-6	3.887E-5	4.249E-5

Table A. II 3: ^{243}Am production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	4.420E-2	4.553E-2	4.122E-2	2.047E-2	4.763E-3	3.654E-3
2.0	4.355E-2	3.667E-2	2.996E-2	1.818E-2	8.769E-3	8.202E-3
3.0	3.997E-2	3.270E-2	2.686E-2	1.500E-2	7.551E-3	7.740E-3
45GWd/t				45GWd/t		
0.5	4.156E-2	4.072E-2	3.747E-2	1.887E-2	5.752E-3	4.595E-3
2.0	4.265E-2	3.628E-2	3.115E-2	1.928E-2	1.073E-2	9.760E-3
3.0	4.031E-2	3.320E-4	2.852E-2	1.669E-2	9.515E-3	9.779E-3
60GWd/t				60GWd/t		
0.5	3.864E-2	3.669E-2	3.396E-2	1.679E-2	6.536E-3	5.353E-3
2.0	4.092E-2	3.539E-2	3.162E-2	1.919E-2	1.228E-2	1.122E-2
3.0	3.973E-2	3.335E-2	2.954E-2	1.744E-2	1.147E-2	1.134E-2

Appendix II (B): Curium (Cm) production:**Table B. II 4:** ^{242}Cm production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	6.752E-3	6.042E-3	5.858E-3	2.581E-3	9.080E-4	8.357E-4
2.0	6.556E-3	5.691E-3	4.212E-3	2.239E-3	1.479E-3	1.267E-3
3.0	6.698E-3	5.532E-3	3.931E-3	2.028E-3	1.360E-3	1.199E-3
45GWd/t				45GWd/t		
0.5	6.112E-3	4.715E-3	4.731E-3	2.667E-3	1.033E-3	9.943E-4
2.0	5.957E-3	5.068E-3	4.033E-3	2.497E-3	1.678E-3	1.515E-3
3.0	6.070E-3	4.794E-3	3.636E-3	2.293E-3	1.571E-3	1.413E-3
60GWd/t				60GWd/t		
0.5	5.450E-3	3.856E-3	3.888E-3	2.686E-3	1.102E-3	1.093E-3
2.0	5.452E-3	4.550E-3	3.913E-3	2.666E-3	1.740E-3	1.685E-3
3.0	5.518E-3	4.282E-3	3.480E-3	2.465E-3	1.620E-3	1.570E-3

Table B. II 5: ^{243}Cm production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	4.946E-4	4.272E-4	3.849E-4	1.350E-4	3.758E-5	3.132E-5
2.0	2.231E-4	2.107E-4	1.590E-4	6.204E-5	3.491E-5	2.974E-5
3.0	1.934E-4	1.640E-4	1.215E-4	4.885E-5	2.657E-5	2.412E-5
45GWd/t				45GWd/t		
0.5	5.029E-4	4.055E-4	3.747E-4	1.606E-4	5.453E-5	4.719E-5
2.0	2.273E-4	2.191E-4	1.768E-4	7.780E-5	4.993E-5	4.375E-5
3.0	1.946E-4	1.684E-4	1.295E-4	6.188E-5	3.839E-5	3.497E-5
60GWd/t				60GWd/t		
0.5	4.945E-4	3.796E-4	3.553E-4	1.816E-4	7.135E-5	6.300E-5
2.0	2.321E-4	2.241E-4	1.945E-4	9.036E-5	6.355E-5	5.903E-5
3.0	5.518E-3	1.719E-4	1.394E-4	7.231E-5	4.931E-5	4.603E-5

Table B. II 6: ^{244}Cm production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	5.231E-2	1.833E-2	1.698E-2	2.331E-2	1.677E-3	1.313E-3
2.0	3.243E-2	1.843E-2	1.524E-2	9.934E-3	2.984E-3	2.807E-3
3.0	2.312E-2	1.349E-2	1.158E-2	6.227E-3	2.075E-3	2.200E-3
45GWd/t				45GWd/t		
0.5	5.084E-2	1.971E-2	1.867E-2	2.357E-2	2.398E-3	1.995E-3
2.0	3.725E-2	2.187E-2	1.902E-2	1.278E-2	4.653E-3	4.176E-3
3.0	2.774E-2	1.733E-2	1.516E-2	8.513E-3	3.349E-3	3.579E-3
60GWd/t				60GWd/t		
0.5	4.888E-2	2.014E-2	1.986E-2	2.124E-2	3.149E-3	2.697E-3
2.0	4.084E-2	2.498E-2	2.234E-2	1.484E-2	6.671E-3	5.935E-3
3.0	3.179E-2	2.079E-2	1.859E-2	1.067E-2	5.217E-3	5.118E-3

Table B. II 7: ^{245}Cm production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	1.305E-2	2.627E-3	2.046E-3	4.089E-3	2.119E-4	1.287E-4
2.0	1.874E-3	1.881E-3	1.418E-3	4.327E-4	2.105E-4	1.823E-4
3.0	9.626E-4	9.494E-4	6.913E-4	1.970E-4	9.959E-5	9.428E-5
45GWd/t				45GWd/t		
0.5	1.393E-2	3.553E-3	2.751E-3	5.064E-3	3.894E-4	2.439E-4
2.0	1.528E-3	2.647E-3	2.177E-3	6.608E-4	3.943E-4	3.417E-4
3.0	1.330E-3	1.373E-3	1.083E-3	3.134E-4	1.905E-4	1.851E-4
60GWd/t				60GWd/t		
0.5	1.424E-2	4.252E-3	3.460E-3	5.512E-3	6.353E-4	3.963E-4
2.0	3.170E-3	3.461E-3	3.038E-3	8.551E-4	6.548E-4	5.926E-4
3.0	1.694E-3	1.853E-3	1.562E-3	4.300E-4	3.360E-4	3.133E-4

Table B. II 8: ^{246}Cm production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	1.585E-3	8.00E-5	5.892E-5	9.124E-4	6.119E-6	3.371E-6
2.0	6.982E-4	1.585E-4	1.235E-4	1.500E-4	1.843E-5	1.579E-5
3.0	3.539E-4	9.878E-5	9.495E-5	6.474E-5	1.052E-5	1.162E-5
45GWd/t				45GWd/t		
0.5	1.707E-3	1.444E-4	1.044E-4	1.092E-3	1.453E-5	8.227E-6
2.0	1.021E-3	2.748E-4	2.090E-4	2.574E-4	4.543E-5	3.333E-5
3.0	5.542E-4	2.062E-4	1.776E-4	1.194E-4	2.610E-5	2.832E-5
60GWd/t				60GWd/t		
0.5	1.878E-3	2.167E-4	1.692E-4	1.014E-3	2.997E-5	1.672E-5
2.0	1.369E-3	4.386E-4	3.166E-4	3.833E-4	9.903E-5	6.797E-5
3.0	8.036E-4	3.459E-4	2.894E-4	1.974E-4	6.297E-5	5.665E-5

Appendix II (C): Neptunium (Np) production:**Table C. II 9: ^{236}Np production amount in ton/GWe/year**

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	1.077E-10	7.345E-10	2.259E-8	7.908E-12	1.372E-10	1.954E-8
2.0	1.609E-11	1.046E-10	4.731E-9	2.417E-12	2.065E-11	3.369E-9
3.0	1.363E-11	6.289E-11	2.180E-9	1.819E-12	9.400E-12	1.635E-9
45GWd/t				45GWd/t		
0.5	2.217E-10	1.028E-9	2.729E-8	1.706E-11	3.159E-10	2.342E-8
2.0	2.825E-11	1.640E-10	5.875E-9	4.599E-12	4.138E-11	3.974E-9
3.0	2.256E-11	8.008E-11	2.488E-9	3.383E-12	1.794E-11	1.753E-9
60GWd/t				60GWd/t		
0.5	3.945E-10	1.496E-9	3.163E-8	4.120E-11	3.149E-11	2.681E-8
2.0	4.887E-11	2.537E-10	7.152E-9	7.948E-12	7.612E-11	4.435E-9
3.0	3.617E-11	1.180E-10	2.860E-9	5.621E-12	6.426E-10	1.873E-9

Table C. II 10: ^{237}Np production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	4.340E-5	1.725E-4	4.921E-3	7.935E-6	6.159E-5	4.724E-3
2.0	3.162E-5	6.960E-5	3.216E-3	6.577E-6	2.697E-5	3.112E-3
3.0	3.428E-5	6.100E-5	2.633E-3	6.499E-6	1.686E-5	2.547E-3
45GWd/t				45GWd/t		
0.5	6.519E-5	2.006E-4	4.624E-3	1.194E-5	1.096E-4	4.424E-3
2.0	4.353E-5	9.318E-5	3.023E-3	1.072E-5	4.694E-5	2.880E-3
3.0	4.654E-5	7.387E-5	2.472E-3	1.012E-5	2.837E-5	2.356E-3
60GWd/t				60GWd/t		
0.5	9.031E-5	2.447E-4	4.283E-3	1.903E-5	4.683E-5	4.059E-3
2.0	6.015E-5	1.249E-4	2.818E-3	1.599E-5	7.712E-5	2.643E-3
3.0	6.310E-5	9.733E-5	2.298E-3	1.510E-5	1.772E-4	2.150E-3

Table C. II 11: ^{239}Np production amount in ton/GWe/year

Vm/Vf	Reactor			Weapons		
	ROX	TOX	MOX	ROX	TOX	MOX
	33GWd/t			33GWd/t		
0.5	4.143E-8	4.008E-8	3.592E-3	2.159E-8	4.709E-9	3.907E-3
2.0	3.884E-8	3.198E-8	2.854E-3	1.654E-8	7.841E-9	3.231E-3
3.0	3.519E-8	2.839E-8	2.724E-3	1.327E-8	6.605E-9	3.121E-3
45GWd/t				45GWd/t		
0.5	3.977E-8	3.613E-8	2.554E-3	2.079E-8	5.970E-9	2.786E-3
2.0	3.866E-8	3.187E-8	1.979E-3	1.818E-8	9.817E-9	2.254E-3
3.0	3.594E-8	2.902E-8	1.915E-3	1.516E-8	8.425E-9	2.227E-3
60GWd/t				60GWd/t		
0.5	3.788E-8	3.283E-8	1.857E-3	1.816E-8	1.034E-8	2.014E-3
2.0	3.755E-8	3.137E-8	1.396E-3	1.844E-8	1.158E-8	1.630E-3
3.0	3.581E-8	2.935E-8	1.346E-3	1.618E-8	7.148E-9	1.591E-3

Appendix III: Nuclide wise LLFP production from weapons-and reactor-grade Pu fuels.

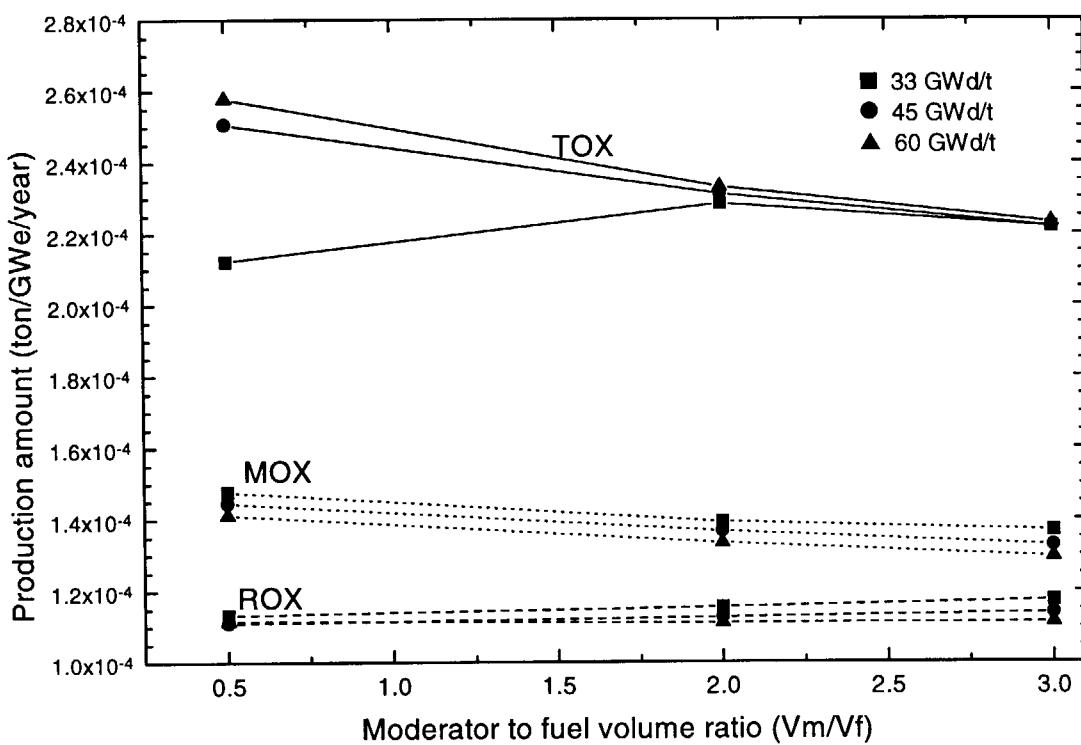


Fig. A. III. 1: ^{79}Se production amount in weapons-grade Pu fuels.

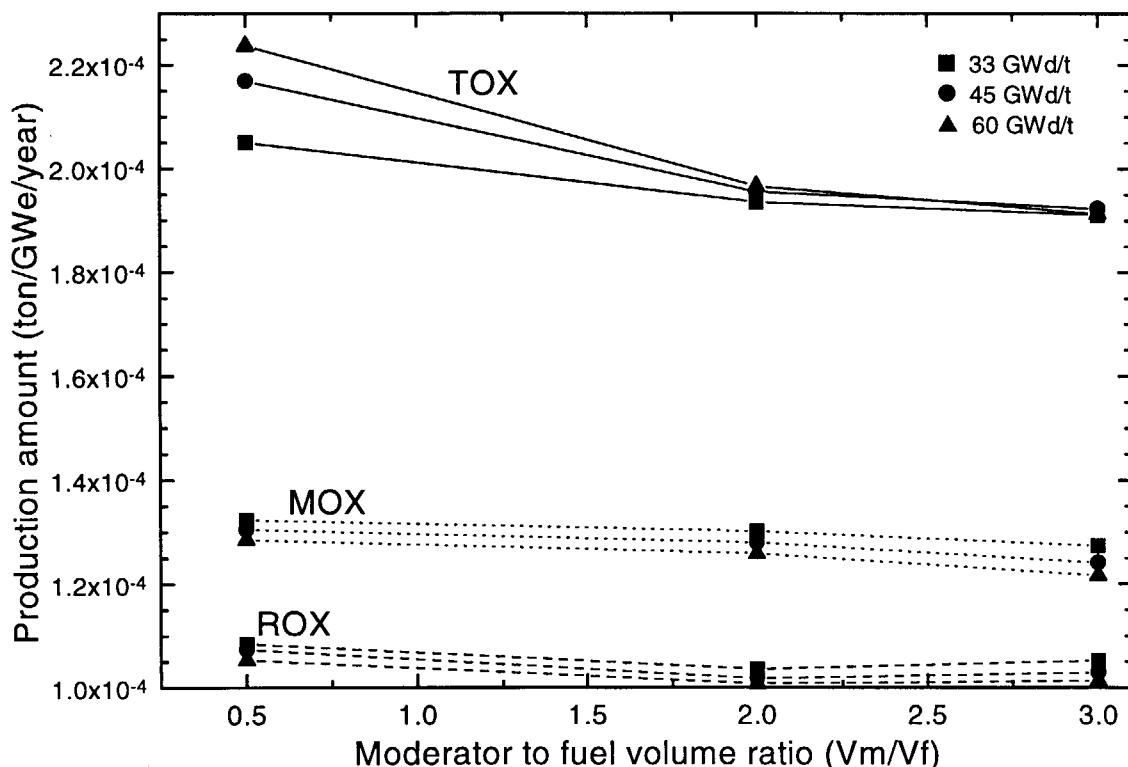
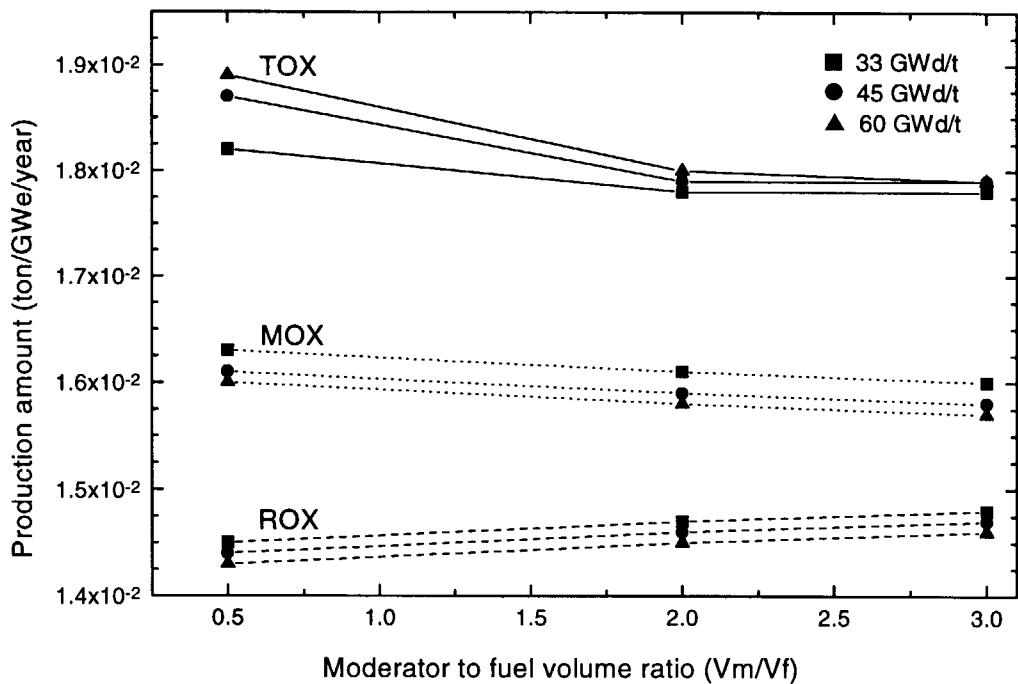
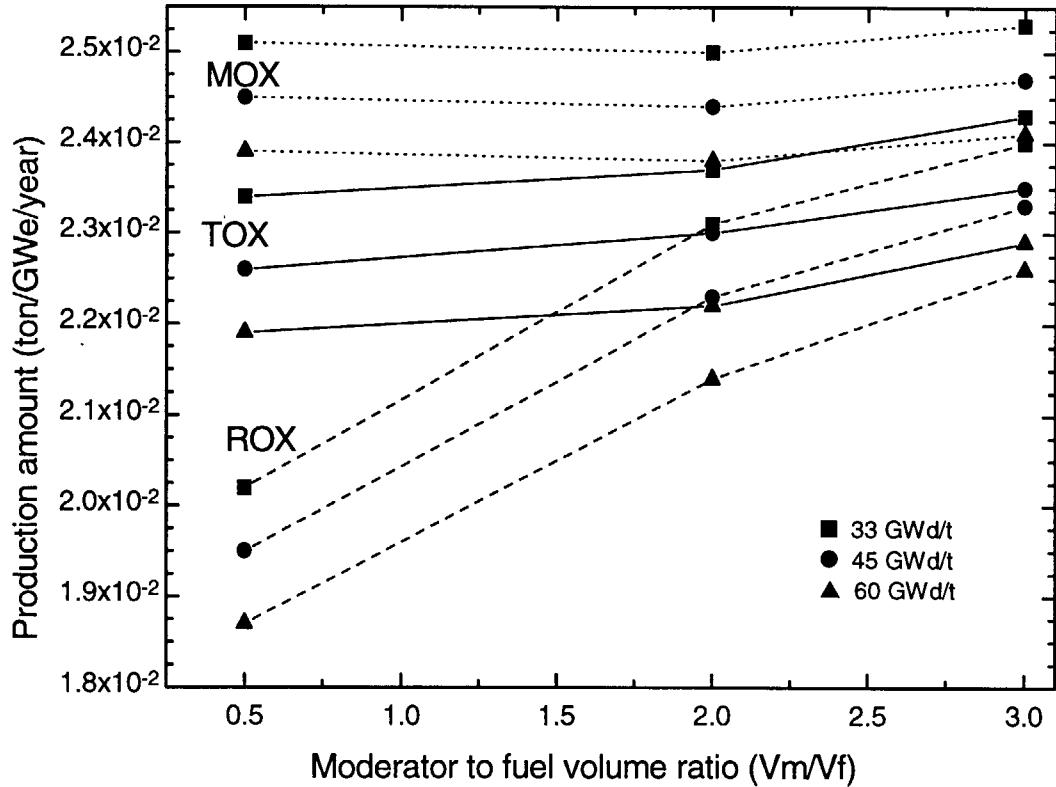
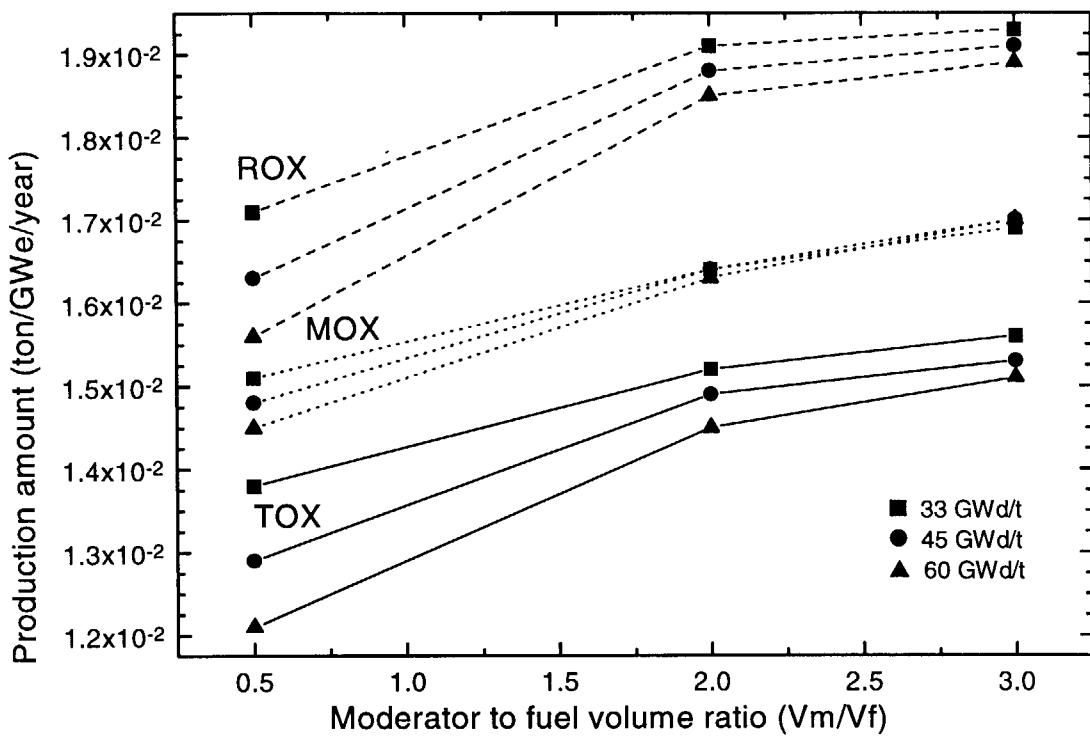
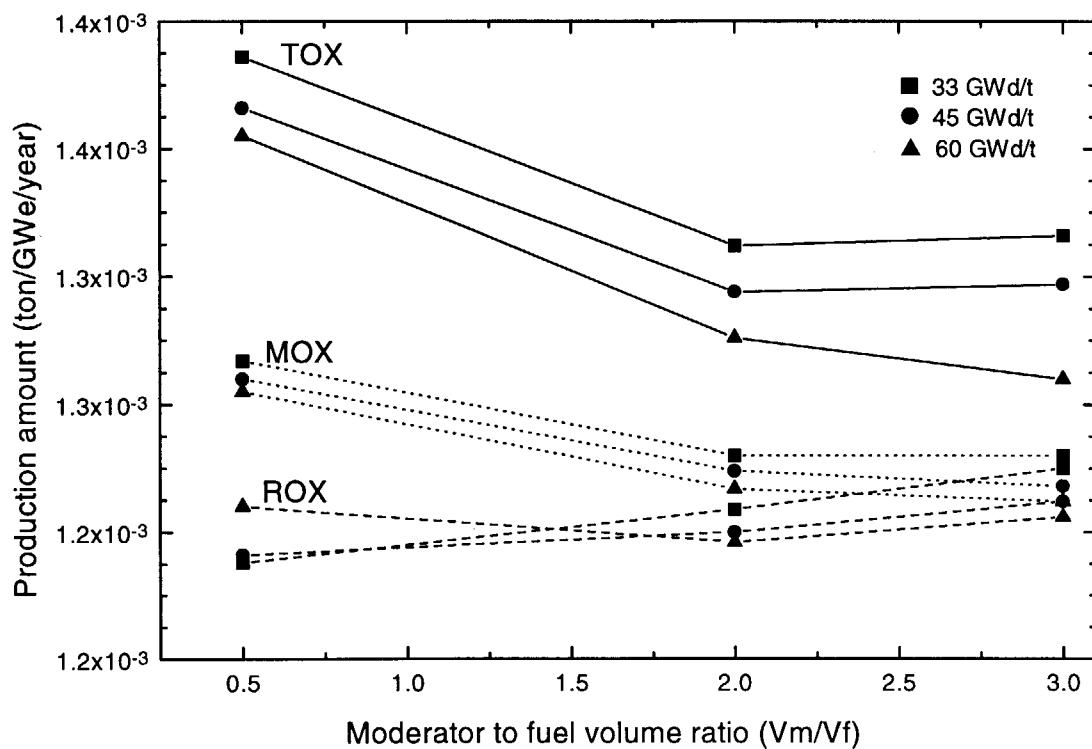
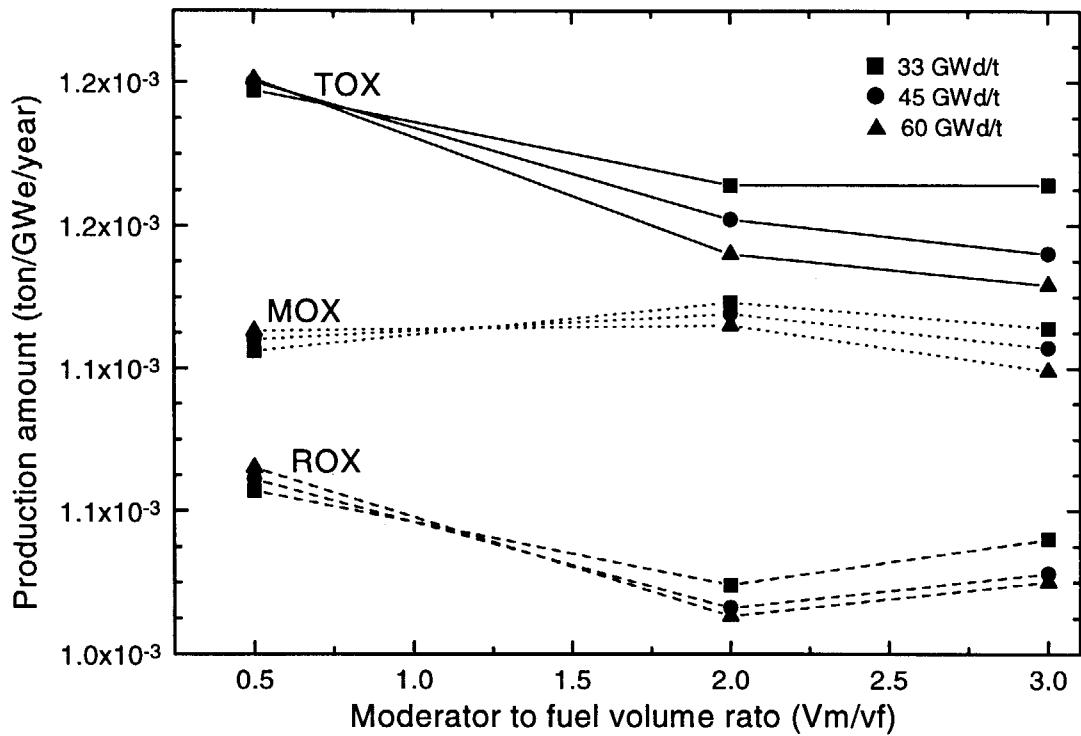
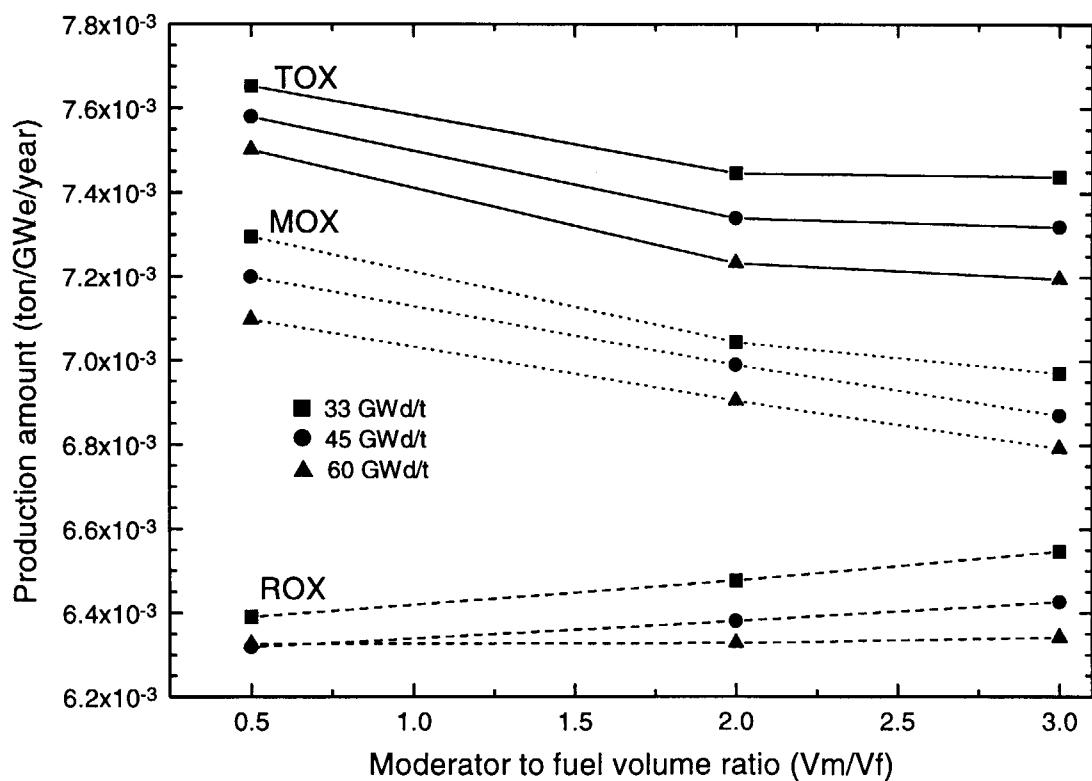
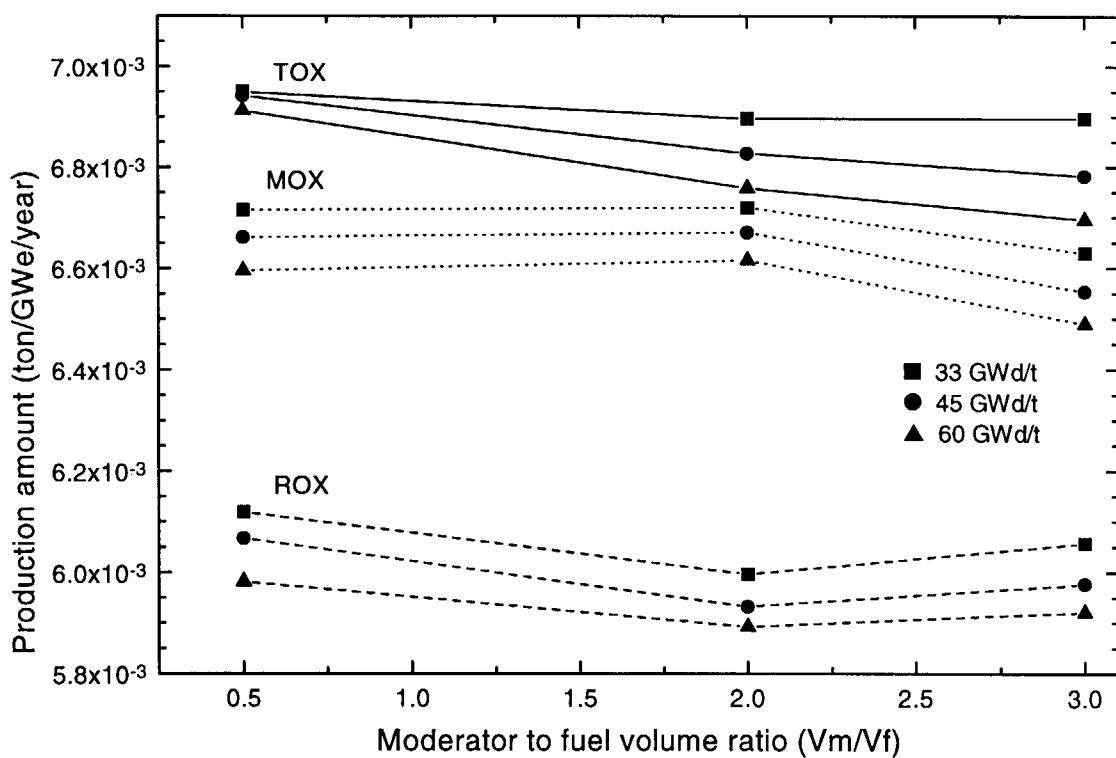
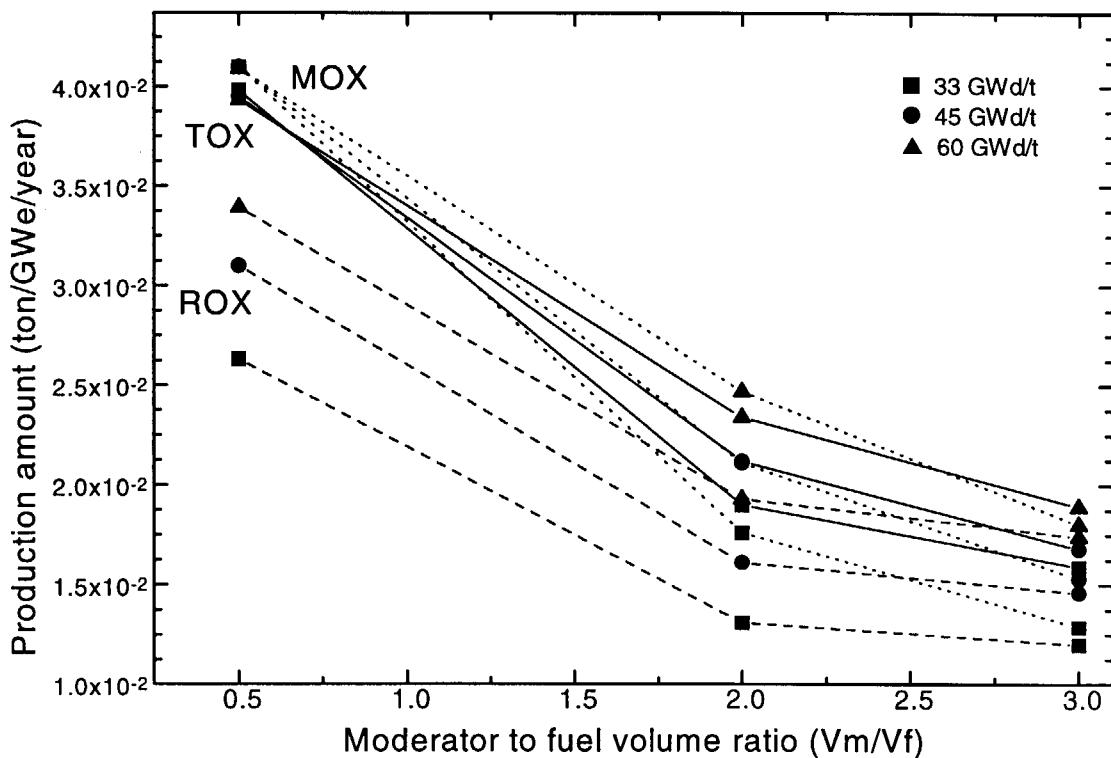


Fig. A. III. 2: ^{79}Se production amount in reactor-grade Pu fuels.

Fig. A. III. 3: ^{93}Zr production amount in reactor-grade Pu fuels.Fig. A. III. 4: ^{99}Tc production amount in reactor-grade Pu fuels.

Fig. A. III. 5: ^{107}Pd production amount in reactor-grade Pu fuels.Fig. A. III. 6: ^{126}Sn production amount in weapons-grade Pu fuels.

Fig. A. III. 7: ^{126}Sn production amount in reactor-grade Pu fuels.Fig. A. III. 8: ^{129}I production amount in weapons-grade Pu fuels.

Fig. A. III. 9: ^{129}I production amount in reactor-grade Pu fuels.Fig. A. III. 10: ^{135}Cs production amount in reactor-grade Pu fuels.

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国際単位系(SI)と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s ⁻¹
力	ニュートン	N	m·kg/s ²
圧力、応力	パスカル	Pa	N/m ²
エネルギー、仕事、熱量	ジュール	J	N·m
工率、放射束	ワット	W	J/s
電気量、電荷	クーロン	C	A·s
電位、電圧、起電力	ボルト	V	W/A
静電容量	ファラード	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束密度	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m ²
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	°C	
光束度	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m ²
放射能	ベクレル	Bq	s ⁻¹
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表2 SIと併用される単位

名 称	記 号
分、時、日	min, h, d
度、分、秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$$

$$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$$

表4 SIと共に暫定的に維持される単位

名 称	記 号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリ	Ci
レンントゲン	R
ラド	rad
レム	rem

$$1 \text{ Å} = 0.1 \text{ nm} = 10^{-10} \text{ m}$$

$$1 \text{ b} = 100 \text{ fm}^2 = 10^{-28} \text{ m}^2$$

$$1 \text{ bar} = 0.1 \text{ MPa} = 10^5 \text{ Pa}$$

$$1 \text{ Gal} = 1 \text{ cm/s}^2 = 10^{-2} \text{ m/s}^2$$

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$$

$$1 \text{ rad} = 1 \text{ cGy} = 10^{-2} \text{ Gy}$$

$$1 \text{ rem} = 1 \text{ cSv} = 10^{-2} \text{ Sv}$$

表5 SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^9	ギガ	G
10^6	メガ	M
10^3	キロ	k
10^2	ヘクト	h
10^1	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

(注)

- 表1～5は「国際単位系」第5版、国際度量衡局1985年刊行による。ただし、1eVおよび1uの値はCODATAの1986年推奨値によった。
- 表4には海里、ノット、アール、ヘクタールも含まれているが日常の単位なのでここでは省略した。
- barは、JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
- EC閣僚理事会指令ではbar、barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換 算 表

力	N(=10 ⁵ dyn)	kgf	lbf
1	0.101972	0.224809	
9.80665	1	2.20462	
4.44822	0.453592	1	

$$\text{粘度 } 1 \text{ Pa}\cdot\text{s} (\text{N}\cdot\text{s}/\text{m}^2) = 10 \text{ P(ポアズ)} (\text{g}/(\text{cm}\cdot\text{s}))$$

$$\text{動粘度 } 1 \text{ m}^2/\text{s} = 10^4 \text{ St(ストークス)} (\text{cm}^2/\text{s})$$

圧力	MPa(=10 bar)	kgf/cm ²	atm	mmHg(Torr)	lbf/in ² (psi)
力	1	10.1972	9.86923	7.50062×10^3	145.038
0.0980665	1	0.967841	735.559	14.2233	
0.101325	1.03323	1	760	14.6959	
1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}	
6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1	

エネルギー・仕事・熱量	J(=10 ⁷ erg)	kgf·m	kW·h	cal(計量法)	Btu	ft · lbf	eV	1 cal = 4.18605 J(計量法)
1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}		= 4.184 J(熱化学)
9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}		= 4.1855 J(15 °C)
3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}		= 4.1868 J(国際蒸気表)
4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}		仕事率 1 PS(仏馬力)
1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}		= 75 kgf·m/s
1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}		= 735.499 W
1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1		

放射能	Bq	Ci
1	2.70270×10^{-11}	
3.7×10^{10}	1	

吸収線量	Gy	rad
1	100	
0.01	1	

照射線量	C/kg	R
1	3876	
2.58×10^{-4}	1	

線量当量	Sv	rem
1	100	
0.01	1	

(86年12月26日現在)

BURNUP CHARACTERISTICS OF $\text{PuO}_2\text{-ZrO}_2$, $\text{PuO}_2\text{-ThO}_2$ AND MOX FUELED LWRs