ANALYSIS OF TRANSMUTATION RATES OF LONG-LIVED RADIONUCLIDES IN THE KOREAN MULTI-PURPOSE RESEARCH REACTOR

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ABSTRACT

Transmutation rates of Minor Actinides(MA) and long-lived fission products loaded in the irradiation thimble of the Korea Multi-purpose Research Reactor (KMRR) were estimated by using the "TRIFON" code. The transmutation rates of Np-237 and a mixture of Am and Cm calculated were 65% and 75 %, respectively, over the burning period of six fuel cycles (203 days) in the central flux trap of the KMRR. However, the net burning rates, which were offset by production rates of new transuranic nuclides, were 35 % and 27 %, respectively. The transmutation rates of long-lived fission products of Tc-99 and I-129 were estimated as 13 % and 9.5 %, respectively over the same burning period. In the cases of partially replacing six central fuel elements among the 36-element assembly of KMRR by Np-237 or a mixture of Am and Cm, the transmutation rate of Np-237 is 26 % for 17.5g replacement and 20 % for 52.4g replacement. The rate of Am-241 is 46 % for 17.5g replacement and 26 % for 52.4g replacement.

1. INTRODUCTION

Several types of reactors and/or accelerators are being suggested as practical transmutation facilities in several countries. For example, the actinide burner, hybrid system of a subcritical reactor combined with an accelerator or conventional power reactors are being considered for nuclear transmutation. However, the best way of transmutation is yet to be determined. Both economic and technical advantages or disadvantages should be taken into account to select the most suitable way of transmutation.

This study is focused on the estimation of long-lived radionuclide transmutation rates in the research reactor, KMRR which will be commissioned early next year. Since the neutron flux in the core of KMRR is higher than those of conventional PWR's, it may provide more favorable conditions for the transmutation of Minor Actinides which have lower fission cross sections than those of fissile uranium and plutonium.

The computer code, TRIFON, developed in Russian Institute of Theoretical and Experimental Physics (ITEP) was used to estimate the transmutation rates of MA and long-lived fission products such as Np-237, a mixture of Am and Cm, Tc-99 and I-129.

The fission products of Tc-99 and I-129 were assumed to be placed in the central flux trap. The minor actinides of Np-237 and a mixture of Am and Cm were assumed to be either placed in the central flux trap or partially mixed up into six central fuel elements among the 36-element assembly of KMRR. Both cases were assumed to be irradiated during the period of six fuel cycles (203 days).

2. REACTOR CORE AND IRRADIATION THIMBLES OF THE KMRR [1]

The reactor physics design was carried out to achieve the maximum neutron flux with the maximum available fuel enrichment, 20% LEU and proper heat removal. The core features a symbiosis of light water reactor lattices as well as heavy water reactor lattices. This combination provides extensive variety and flexibility of neutron quality in terms of its energy and spatial distributions. Table 1 shows the design concept of the KMRR core.

As shown in Fig. 1, the inner core, an assembly of light water reactor lattices, is enclosed by the corrugated parallelepiped inner shell of the reflector tank. The 8 out of 31 sites are assigned for residences of 4 control absorbers and 4 shut off shrouds. Each of them has 18-element fuel assembly and circular flow tube. The nominal core configuration allows 20 hexagonal flow tubes to accept 36-element fuel assemblies, and 3 vacant sites are reserved for capsule, rig, or loop installations.

The outer core is clustered with 8 circular flow tubes vertically passing through the reflector tank at the narrow sides of the inner core periphery. Loaded with 18-element fuel assemblies, the H_2O-cooled and D_2O-moderated outer core enhances total core excess reactivity. The outer core sites, used for irradiation purpose, provide high epithermal neutron fluence.

The central trap, one of the three flux traps in the inner core, has the highest flux, 5.3×10^{14} n/cm^2 s. It will be valuable to install the fuel and material test loop. The D_2O-filled reflector tank is equipped with a number of vertical irradiation thimbles. Their sizes and locations are optimized to maintain the required neutron quality and level without significant disturbance by the reactor operating condition changes and other near-by experiments.

One fuel cycle consists of 28 days' burning and 7 days' shutdown which is necessary for fuel exchange. Most of 36-element assemblies and all of 18-element assemblies are burned up for 6 fuel cycles, but part of the 36-element assemblies are used for 7 fuel cycles. Material and specifications of KMRR standard fuel are shown in Table 2.

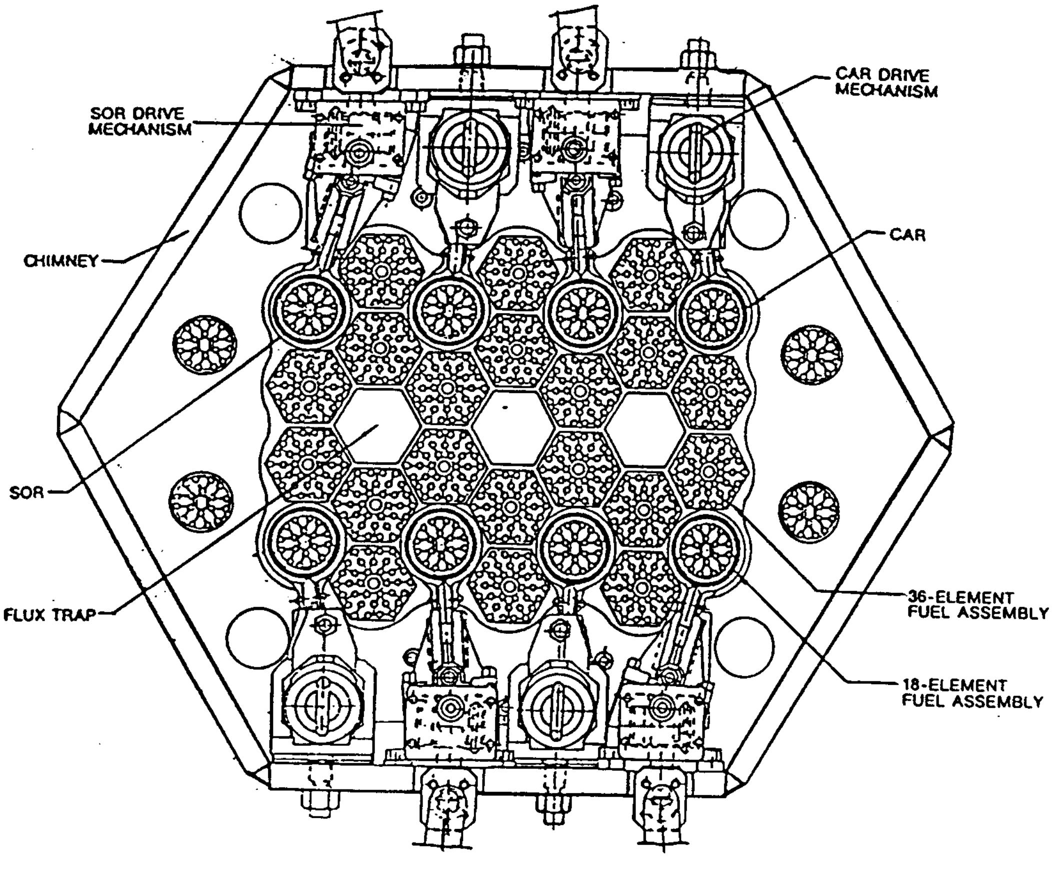


Fig.1 Schematic diagram of KMRR core

Table 1. Major design concept of KMRR

Reactor Type	Open-Tank-In-Pool, LWR/HWR Hybrid
Thermal Power	30 MWth
Fuel	U_3 Si-Al, 19.75 W/O ^{235}U Enriched
Coolant	H_2O
Moderator	H_2O/D_2O
Reflector	D_2O
Cooling Method	Convective Up-Flow
Secondary Cooling	Cooling Tower
Reactor Building	Confinement
Power Regulation and Xenon Poison Compensation	Four Hafnium Tubes Sliding over the 18-Element Fuel Assembly
Shutdown System	Four Hafnium Tubes Sliding over the 18-Element Fuel Assembly. Dropped by Gravity
Heat Generated in Reactor Fuel	27.5 MW
Heat Generated in Moderator and Structure	Approx. 2.5 MW
Total Fission Power	30.0 MW
Heat Removed by Primary Coolant System	27.5 MW

Table 2. Specifications of KMRR standard fuel

Composition Rates in Fuel Meat (W/O)	
^{235}U	11.7
^{238}U	46.9
Si	2.4
Al	39.0
Fuel Meat	
enrichment(w/o)	19.75
density(gr/cc)	5.4
diameter(mm)	6.35/5.5
length(mm)	700.0
mass of uranium(gr)	69.8/52.4
LEU density (gr/cc)	3.15
Cladding	
material	Al(co-extruded)
thickness(mm)	0.76/1.19
Fin	
number	8
height(mm)	1.02
width(mm)	0.76

3. TRIFON CODE [2]

The one-dimensional code TRIFON, which is based on the collision probability method was developed in ITEP, Russia. Neutron energy spectrum and spatial distribution of neutron flux can be computed with this model and transmutation rates of various nuclides can also be estimated. The cross section data, used in this code, are mainly from the Russian ABBN and also partly from the other additional information. They are composed of 26 group cross section data and resonance parameters.

ITEP validated this code by comparing the calculation results from other codes, as shown in Table 3 [3]. The results of this code are closer to the results of Monte-Carlo simulations than that of WIMS code. Also, the quantities of uranium and transuranium contained in LWR spent fuel were also calculated with this code. The comparison of the calculated results with experimental results is shown in Fig. 2. The agreement between the calculated and experimental results is quite good. On the basis of this demonstration, ITEP carried out transmutation studies with this code for the heavy water reactor, where high enriched uranium is used as fuel, as well as the thorium fuel cycle reactor[4,5].

Table 3. Comparison of the parameter values calculated from TRIFON and other codes

Lattice	Parameter	TRIFON	WIMS	EPRI-CELL	Monte Carlo(%SD)
NB-1, Low Enrichment	K_∞	1.1344	1.254	1.1449	1.1471(0.14)
	ρ_{28}	1.375	1.458	1.360	1.363(0.6)
	CR	0.804	0.829	0.796	0.798(0.4)
NB-2, (PU/U=0.02)	K_∞	1.1734	1.1640	1.1698	1.1748
	ρ_{28}	2.526	2.372	2.613	2.612
	CR	2.110	2.319	2.148	2.148
NB-4, PWR Type	K_∞	1.3363	-	1.3415	1.3424(0.26)
	ρ_{28}	2.666	-	2.632	2.654(0.6)
	CR	0.556	-	0.548	0.549(0.4)
NB-5. Hard Spectrum	K_∞	1.1302	-	1.1421	1.1456(0.15)
	ρ_{28}	8.452	-	8.534	8.503(0.4)
	CR	1.015	-	1.006	1.006(0.3)

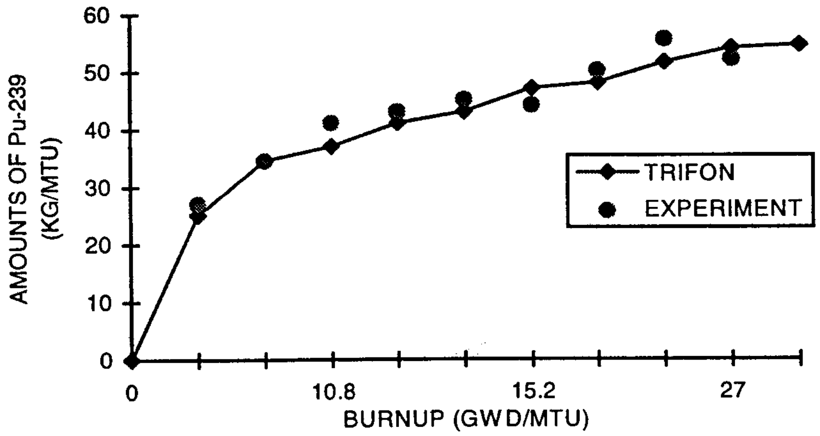


Fig. 2 Comparison of the experimental and calculated results for the amount of Pu-239 with burnup in PWR.

4. TRANSMUTATION RATE ANALYSIS IN THE KMRR

4.1. Calculation Model

For the convenience of calculation, in the transmutation study with the central irradiation thimble the shapes of hexagonal thimble, fuel assembly tubes, and surrounding moderator were assumed to be the annular rings with corresponding equivalent volumes. The schematic of the cell model reflected by these assumptions is illustrated in Fig. 3. The net current was assumed to be zero at the outer boundary of six assemblies around the central trap in the core.

In the transmutation study with minor actinides partially mixed up into six central fuel elements out of the 36-element fuel assembly as shown in Fig. 4, the central support rod, moderator, cladding, structure, and MA and fuel were also assumed to be the annular rings with corresponding equivalent volumes in the order of their locations.

4.2. Calculation and Results

The transmutation rate of Np-237 with burning time calculated by TRIFON code was compared, in Fig. 5, with that obtained from WIMS-KAERI code [6] which had been used in the design of KMRR. The two results were found to be in accordance within 7% error.

Small quantities of long-lived radionuclides were considered to be loaded as the target to minimize the impact on core behavior. The atomic number density of a target nuclide is fixed as $0.0001/\text{cm}^2$ barn. Since the code was developed on the basis of one dimension, the thermal power was converted to the power per unit length. As noted in previous section, one fuel cycle is composed of 28 days' burning and 7 days' shutdown in the KMRR. Thus the thermal power during the irradiation period of six fuel cycles is assumed as $30 \times (168/203)/70 \approx 0.355$ MW/cm.

Fig. 6 shows the transmutation rate of small quantity of Np-237 in the central flux trap. The transmutation rate was estimated as 64.6% and the net burning rate, offset by the production of new transuranium from the Np target, was 34.5%.

Fig. 7 illustrates the transmutation rates of a mixture of Am and Cm in the central flux trap with burning time when loaded as the same component ratio of the quantity as in typical PWR spent fuel at 10 year cooling time. The amount of Am-241 as well as Am-243 was found to decrease with time whereas that of total Cm nuclides increases due to the transmutation of Am into Cm by neutron capture and then β-decay during the irradiation. Consequently, the total net burning rate of Am and Cm was 27.3% during the irradiation period of six fuel cycles.

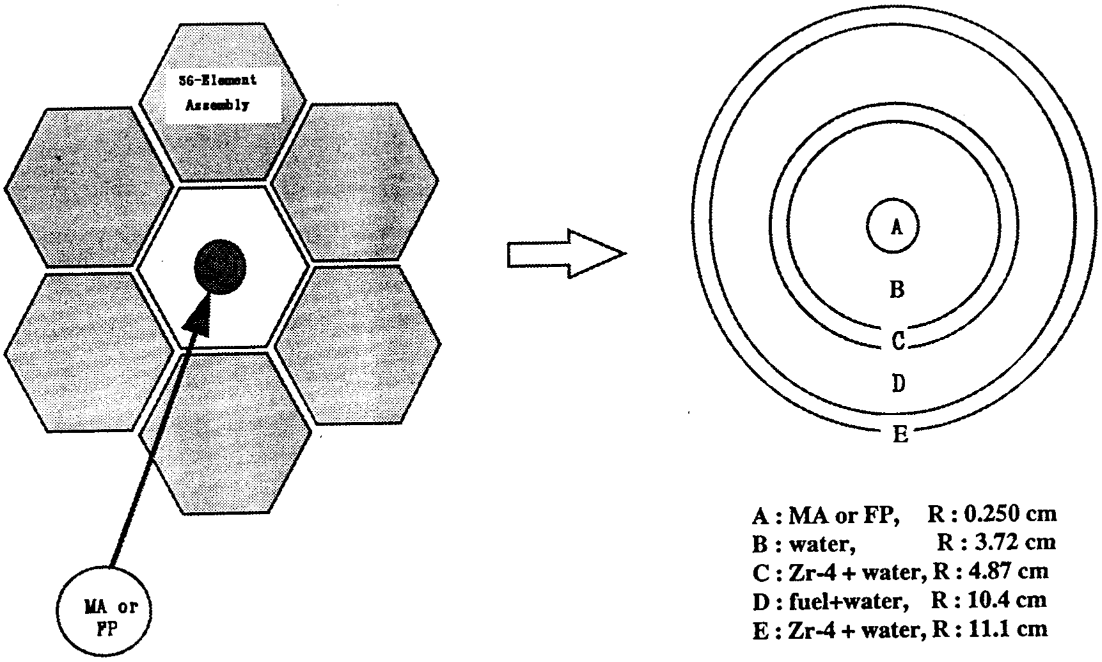
On the other hand, the transmutation rates of Tc-99 and I-129 loading in the central flux trap were 13% and 9.5%, respectively, as shown in Fig. 8. They were lower than those of minor actinides due to lower neutron cross sections of Tc-99 and I-129.

In the cases of partially mixing up Np-237 or a mixture of Am-Cm into six central fuel elements out of the 36-element assembly of KMRR fuel, the transmutation rate of Np-237 is 26 % for 17.5 g replacement and 20 % for 52.4 g replacement as shown in Fig. 9. The rate of Am-241 is 46 % for 17.5 g replacement and 26 % for 52.4 g replacement as shown Fig. 10. As the amounts of test materials inserted in the fuel assembly are increased, neutrons are captured in test materials considerably and the transmutation rates in such cases are decreased.

The estimated transmutation rates are much lower than those from the transmutation in the irradiation thimble because of the 4~5 times lower neutron flux.

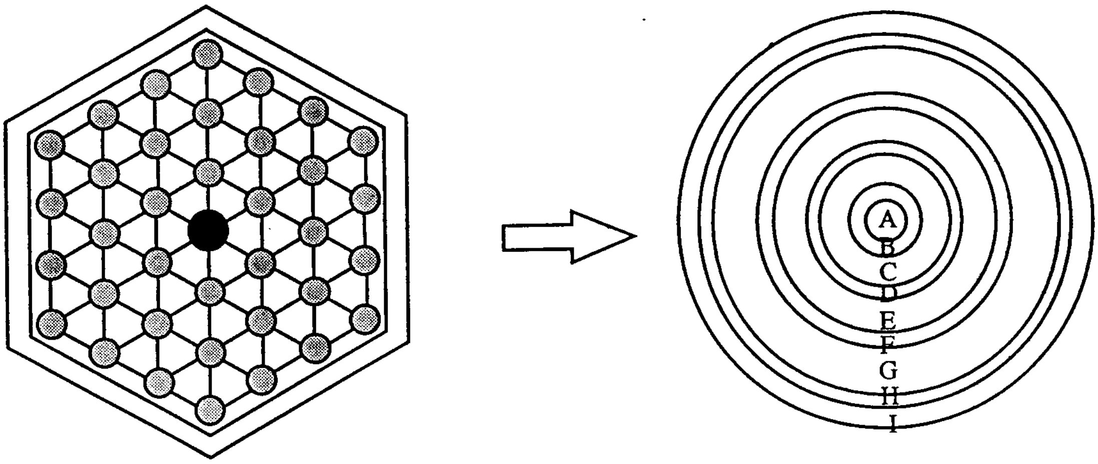
5. CONCLUSIONS

It was found that transmutation of minor actinides in the KMRR can be achieved to some extent, showing the possibility for using KMRR as a facility for transmutation test. The calculation results obtained from this study can also be used as basic information for target design or transmutation test.



A : MA or FP, R : 0.250 cm
B : water, R : 3.72 cm
C : Zr-4 + water, R : 4.87 cm
D : fuel+water, R : 10.4 cm
E : Zr-4 + water, R : 11.1 cm

Fig. 3. Cell calculation model of central flux trap and six 36-element Assemblies



● : Central support rod(zr-4

○ : fuel rod

A : Zr-4, R : 0.400 cm
B : water, R : 0.982 cm
C : MA + fuel, R : 1.33 cm
D : Al+water, R : 2.10 cm
E : fuel, R : 2.37 cm
F : Al+water, R : 3.08 cm
G : fuel, R : 3.42 cm
H : Al+water, R : 3.71 cm
I : Zr-4+water, R : 4.21 cm

Fig. 4. Cell calculation model of 36-element assembly with partly replacment of fuel by MA

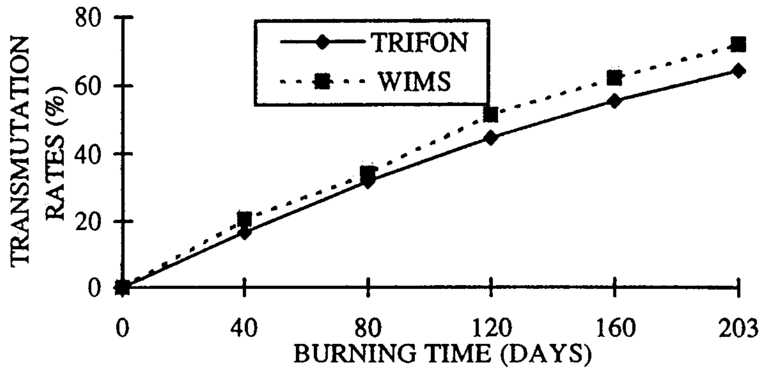


Fig. 5 Comparison of the calculated results of TRIFON and WIMS codes for transmutation rate of Np-237

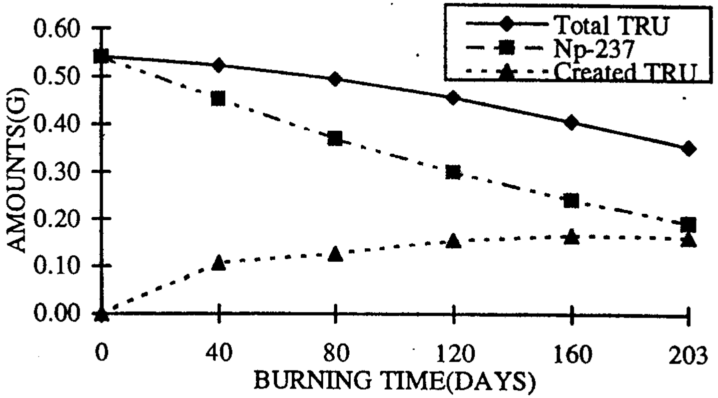


Fig. 6 The changes in the amounts of Np-237 and total TRU with burning time.

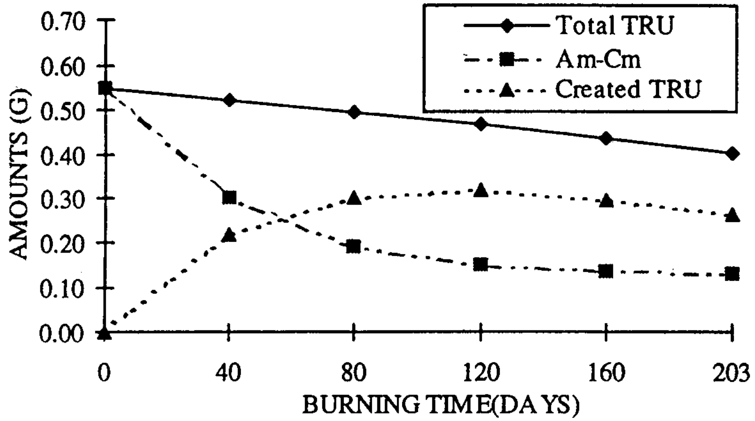


Fig. 7 The changes in the amounts of Am-Cm and total TRU with burning time.

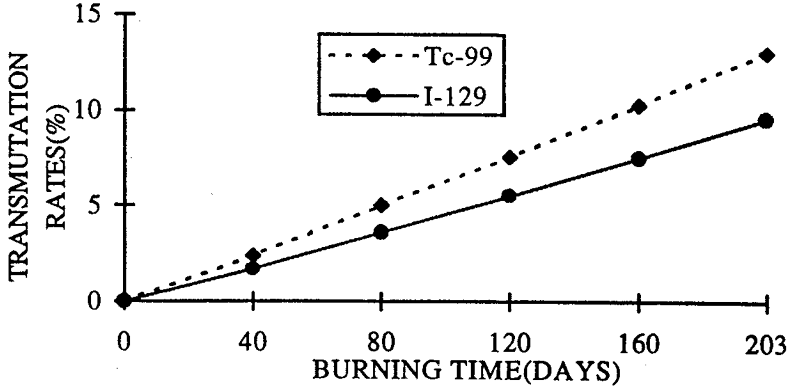


Fig. 8 Transmutation rates of Tc-99 and I-129 with burning time.

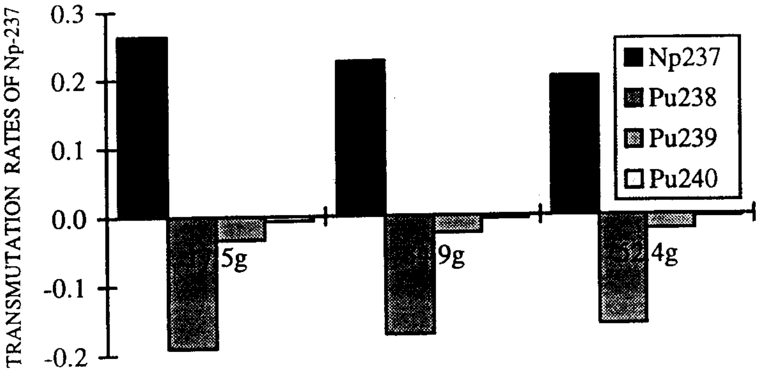


Fig. 9 Transmutation rate of Np-237 with loading quantity in the case of replacement of KMRR fuel

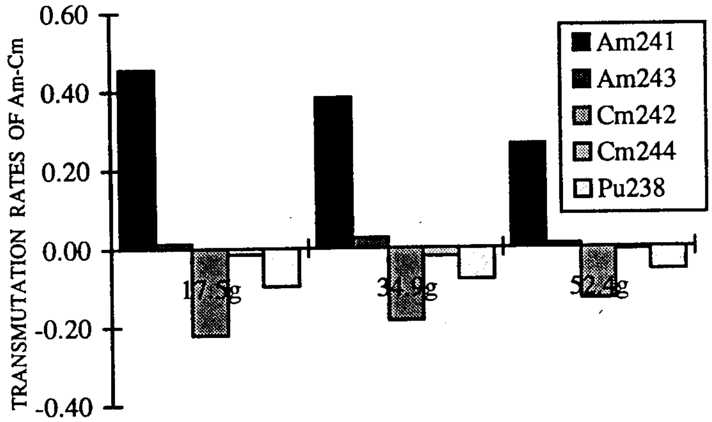


Fig. 10 Transmutation of Am-Cm with loading quantity in the case of replacment of fuel.

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