ANALYSIS OF INNOVATIVE U233-NP-TH CORE AS A NP-BURNER

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ABSTRACT

In this paper we have investigated how to transmute Np-237 by using U-233, Th-232 mixed oxide core with the usual PWR fuel pitch. At first, Np-237 has been uniformly mixed in the fuel rod as the same oxide. The both contents of U-233 and Np-237 have been changed as 10%, 12% and 15%. The void coefficients have been investigated for all the combination of U-233 and Np-237 contents. It was found that about 700kg of Np-237 could be transformed with a 100 ton-HM reactor in a year. However, a large number of Pu-238 have been newly produced from Np-237. Secondly, the recycling of the irradiated fuels has been investigated by adding U-233 every 5 years operation, which corresponds to the burn-up of 50 GWD/T. We have found that the recycling has been successfully done, and 10 tons of Np-237 has been incinerated below 1 ton including Pu-238 in the 80-years (16 cycles times 5 years) recycling .

1. INTRODUCTION

The maintaining of public confidence in the operations of the LWRs including MOX fuels and reprocessing plants will require the demonstration of a reliable technique for final disposal of the long-lived radioactive waste. During the irradiation of uranium and plutonium in LWRs, by-product actinides such as Np-237, as well as various Am and Cm isotopes are built-up. Whereas the fuel isotopes are going to be recovered in the reprocessing plant for further utilization, the by-product actinides remain in the waste stream. The largest part of the by-product is Np-237. Here, we have investigated how to incinerate Np-237. It is said that the thermal neutrons are not effective for the incineration of TRU. One of the reasons is due to their high capture to fission ratio. However, if we can recycle the irradiated fuels by using U-233, we have found that all the TRU can be transmuted to the almost stable U-234 and the small amounts of MA. The reason why we use Th-232 instead of U-238 is that Th fuel produce less higher actinide than uranium fuel, and moreover U-233 is superior to U-235 for maintaining the reactivity until 50GWD/T.

2. METHOD AND MATERIALS(1)

A unit cell model was assumed by using SRAC code[1], Pij routine. The usual PWR cell dimension was assumed, i.e. the cell radius: 0.6616cm, outer cladding radius: 0.475cm, cladding thickness: 0.057cm, fuel radius: 0.418cm.
The nine analyzed cores are called in this paper as follows; U10-10, U10-12, U10-15, U12-10,

U12-12, U12-15, U15-10, U15-12 and U15-15. The first number shows the contents of U-233 and the second number shows the contents of Np-237. The investigated burn-up steps are 30 GWD/T, 50 GWD/T and 70 GWD/T. The power density assumed is 179 W/cm, and the operation condition of reactors has been assumed 10 GWD/T in a year by using 100 ton HM-reactor. The void coefficients have also been investigated for the above nine cores. Here, we have defined the total void coefficient for k-infinity as a difference of k-infinity between 99% and 0% void ratio, and the instantaneous void coefficient for k-infinity as % Δk for 10% void change. The void coefficients have also been calculated for each burn-up step.

3. RESULTS AND DISCUSSIONS(1)

The calculated results are shown in Tables I to IX for the examined 9 cores. The first and second lines in these tables show the k-inf and k-eff change for each burn-up step. The fifth and sixth lines show the amount of Np-237 for each burn-up step. The instantaneous void coefficients for k-inf are also shown in these tables, which are defined as %Δk for 10% void change. The last two lines show the total void coefficients for k-inf and k-eff, which are defined as %Δk(99% Void –0% Void).

Table I. U10-10 (700kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.1889	1.0519	0.9892	0.9381
k-inf	1.2077	1.0685	1.0048	0.9530
Th-232	80(ton)	78.9(ton)	78.1(ton)	77.2(ton)
U-233	10(ton)	7.7(ton)	6.4(ton)	5.3(ton)
Np-237	10(ton)	7.9(ton)	6.6(ton)	5.4(ton)
Pu-238	0(ton)	1.8(ton)	2.7(ton)	3.4(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.27	-0.97	-0.78	-0.63
10-20(%)	-1.39	-1.08	-0.89	-0.73
20-30(%)	-1.50	-1.18	-1.00	-0.85
30-40(%)	-1.63	-1.32	-1.14	-0.99
40-50(%)	-1.75	-1.46	-1.29	-1.17
50-60(%)	-1.86	-1.59	-1.46	-1.36
60-70(%)	-1.88	-1.66	-1.59	-1.57
70-80(%)	-1.59	-1.49	-1.54	-1.64
80-90(%)	+0.04	-0.08	-0.38	-0.77
90-99(%)	+7.14	+6.90	+6.43	+5.79
*Total(k-inf)	-5.69	-3.93	-3.64	-3.92
*Total(k-eff)	-17.4	-15.9	-15.7	-16.1

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

In Table I, it is found that it existed 10 tons of Np-237 at first in the core, and it reduced to 7.9 tons at 30 GWD/T. It means that 2.1 tons of Np-237 was transformed for 3 years. It corresponds to 700 kg transformation for one year. As for Pu-238, it can be seen that 1.8 tons of Pu-238 have been newly produced for 3 years. It corresponds to 600 kg production for one year. It means that the net 100 kg (700 kg – 600 kg) of Np-237 has been incinerated for one year. Moreover, it can be seen from this table that the value of the instantaneous void coefficient are negative in the range of void ratio under 80%, however it changes to positive upper 80% void ratio. The total void coefficients for k-inf and k-eff are both negative in this case.

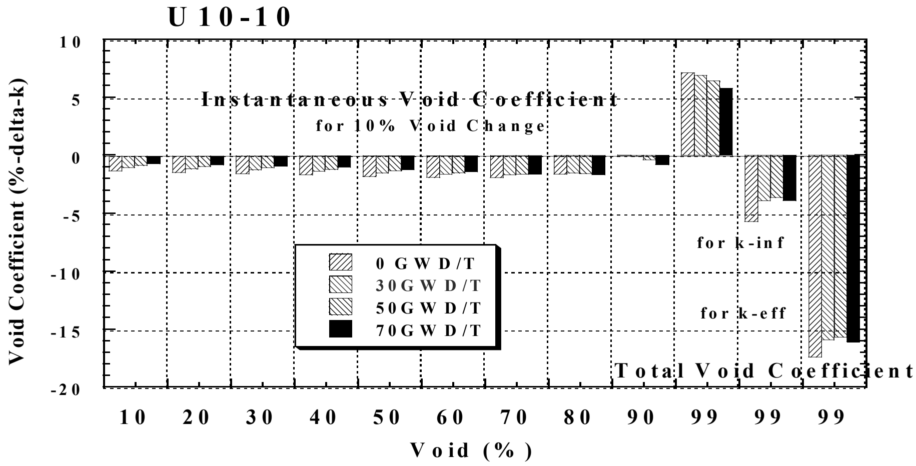

Figure 1. Change of Void Coefficients for U10-10 Core

Figure 1 shows a change of the instantaneous void coefficient as a function of burn-up and void ratio. We can see from this figure that the negative values of the coefficient become smaller in accordance with burn-up in the range of void ratio under 70%.

Table II. U10-12 (800kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30GWD/T	50 GWD/T	70 GWD/T
k-eff	1.1368	1.0103	0.9548	0.9114
k-inf	1.1546	1.0261	0.9698	0.9257
Th-232	78(ton)	76.9(ton)	76.1(ton)	75.2(ton)
U-233	10(ton)	7.7(ton)	6.5(ton)	5.4(ton)
Np-237	12(ton)	9.6(ton)	8.1(ton)	6.6(ton)
Pu-238	0(ton)	2.1(ton)	3.2(ton)	4.0(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.16	-0.84	-0.64	-0.51
10-20(%)	-1.25	-0.91	-0.72	-0.57
20-30(%)	-1.33	-0.99	-0.80	-0.66
30-40(%)	-1.42	-1.08	-0.89	-0.74
40-50(%)	-1.49	-1.15	-0.97	-0.85
50-60(%)	-1.51	-1.18	-1.03	-0.92
60-70(%)	-1.41	-1.13	-1.00	-0.96
70-80(%)	-0.89	-0.69	-0.67	-0.72
80-90(%)	+1.12	+1.17	+1.03	+0.77
90-99(%)	+8.70	+8.77	+8.60	+8.24
*Total(k-inf)	-0.64	+1.97	+2.91	+3.08
*Total(k-eff)	-12.1	-9.84	-9.16	-9.26

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

In Table II, it is found that it existed 12 tons of Np-237 at first in the core, and it reduced to 9.6 tons at 30 GWD/T. It means that 2.4 tons of Np-237 was transformed for 3 years. It corresponds to 800 kg transformation for one year. As for Pu-238, it can be seen that 2.1 tons of Pu-238 have been newly produced for 3 years. It corresponds to 700 kg production for one year. It means that the net 100 kg (800 kg – 700 kg) of Np-237 has been incinerated for one year. Moreover, it can be seen from this table that the value of the instantaneous void coefficient is negative in the range of void ratio under 80%, however it changes to positive upper 80% void ratio. The total void coefficient for k-inf is negative at 0 GWD/T, but it changes to positive from 30 GWD/T. The total void coefficient for k-eff is also negative in this case.

Figure 2 shows a change of the instantaneous void coefficient as a function of burn-up and void ratio. We can see from this figure that the total void coefficients for k-inf change to positive in accordance with the increase of burn-up, however, the total void coefficients for k-eff still remain in negative.

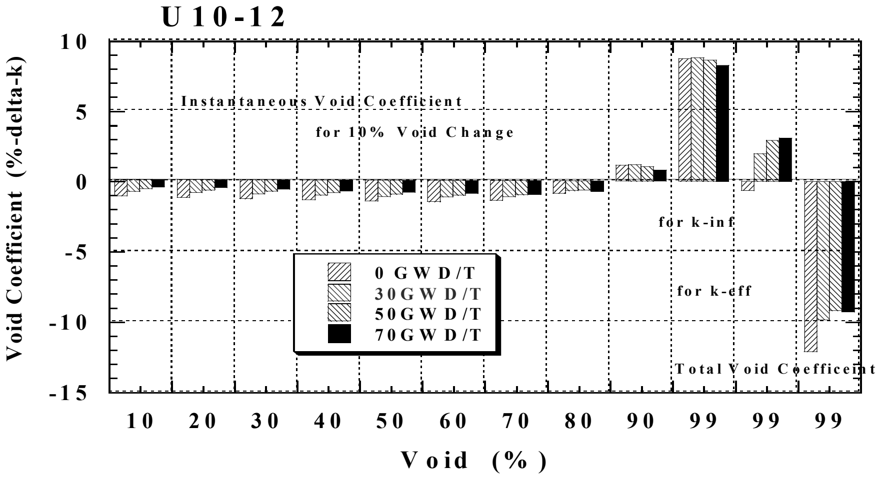

Figure 2. Change of Void Coefficients for U10-12 Core

Table III. U10-15 (960kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.0722	0.9600	0.9137	0.8794
k-inf	1.0889	0.9749	0.9279	0.8930
Th-232	75(ton)	73.9(ton)	73.1(ton)	72.3(ton)
U-233	10(ton)	7.8(ton)	6.6(ton)	5.5(ton)
Np-237	15(ton)	12.1(ton)	10.3(ton)	8.5(ton)
Pu-238	0(ton)	2.5(ton)	3.8(ton)	4.9(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.00	-0.64	-0.46	-0.32
10-20(%)	-1.04	-0.69	-0.49	-0.36
20-30(%)	-1.09	-0.71	-0.53	-0.39
30-40(%)	-1.12	-0.74	-0.54	-0.41
40-50(%)	-1.22	-0.73	-0.54	-0.41
50-60(%)	-1.03	-0.64	-0.46	-0.35
60-70(%)	-0.77	-0.39	-0.23	-0.15
70-80(%)	+0.02	+0.36	+0.46	+0.49
80-90(%)	+2.50	+2.79	+2.82	+2.71
90-99(%)	+10.55	+11.06	+11.22	+11.22
*Total(k-inf)	+5.90	+9.67	+11.25	+12.03
*Total(k-eff)	-5.32	-2.04	-0.84	-0.47

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

In Table III, it is found that it existed 15 tons of Np-237 at first in the core, and it reduced to 12.1 tons at 30GWD/T. It means that 2.9 tons of Np-237 was transformed for 3 years. It corresponds to 960 kg transformation for one year. As for Pu-238, it can be seen from this table that 2.5 tons of Pu-238 have been newly produced for 3 years. It corresponds to 830 kg production for one year. It means that the net 130 kg (960 kg – 830 kg) of Np-237 has bee incinerated for one year.

Table IV. U12-10 (600kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.2636	1.1362	1.0730	1.0155
k-inf	1.2833	1.1539	1.0897	1.0314
Th-232	78(ton)	77.0(ton)	76.3(ton)	75.5(ton)
U-233	12(ton)	9.5(ton)	8.1(ton)	6.8(ton)
Np-237	10(ton)	8.2(ton)	7.0(ton)	5.9(ton)
Pu-238	0(ton)	1.5(ton)	2.4(ton)	3.2(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.22	-1.02	-0.87	-0.73
10-20(%)	-1.31	-1.11	-0.96	-0.83
20-30(%)	-1.41	-1.21	-1.07	-0.93
30-40(%)	-1.50	-1.31	-1.18	-1.07
40-50(%)	-1.57	-1.41	-1.31	-1.20
50-60(%)	-1.61	-1.48	-1.40	-1.36
60-70(%)	-1.51	-1.45	-1.44	-1.45
70-80(%)	-1.00	-1.06	-1.18	-1.34
80-90(%)	+0.97	+0.71	+0.36	-0.06
90-99(%)	+8.31	+8.02	+7.60	+7.00
*Total(k-inf)	-1.85	-1.32	-1.45	-1.97
*Total(k-eff)	-14.2	-14.0	-14.3	-14.9

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

Table V. U12-12 (700kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.2129	1.0936	1.0358	0.9846
k-inf	1.2317	1.1106	1.0519	1.0000
Th-232	76(ton)	75.0(ton)	74.3(ton)	73.5(ton)
U-233	12(ton)	9.6(ton)	8.1(ton)	6.9(ton)
Np-237	12(ton)	9.9(ton)	8.5(ton)	7.2(ton)
Pu-238	0(ton)	1.8(ton)	2.8(ton)	3.7(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.12	-0.89	-0.73	-0.60
10-20(%)	-1.19	-0.95	-0.80	-0.66
20-30(%)	-1.25	-1.02	-0.87	-0.73
30-40(%)	-1.30	-1.08	-0.93	-0.81
40-50(%)	-1.33	-1.12	-1.00	-0.89
50-60(%)	-1.28	-1.10	-1.00	-0.92
60-70(%)	-1.07	-0.94	-0.88	-0.87
70-80(%)	-0.36	-0.32	-0.38	-0.47
80-90(%)	+1.95	+1.87	+1.65	+1.34
90-99(%)	+9.76	+9.72	+9.53	+9.20
*Total(k-inf)	+2.81	+4.17	+4.59	+4.59
*Total(k-eff)	-9.40	-8.34	-8.15	-8.37

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

It seems to be the best core for the transformation of Np-237. However, if we pay attention to the k-eff value of Table III, we can see that the excess reactivity is too small even at 0 GWD/T, and we cannot operate the reactor at 30 GWD/T. It means that the amount of Np-237 loaded seems to be too much in this case.

Table VI. U12-15 (830kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.1494	1.0413	0.9907	0.9475
k-inf	1.1671	1.0573	1.0060	0.9621
Th-232	73(ton)	72.0(ton)	71.4(ton)	70.6(ton)
U-233	12(ton)	9.6(ton)	8.2(ton)	7.0(ton)
Np-237	15(ton)	12.5(ton)	10.8(ton)	9.3(ton)
Pu-238	0(ton)	2.2(ton)	3.4(ton)	4.4(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-0.96	-0.70	-0.54	-0.40
10-20(%)	-1.01	-0.74	-0.57	-0.44
20-30(%)	-1.02	-0.76	-0.60	-0.46
30-40(%)	-1.03	-0.76	-0.60	-0.47
40-50(%)	-0.99	-0.72	-0.57	-0.46
50-60(%)	-0.83	-0.58	-0.46	-0.35
60-70(%)	-0.47	-0.24	-0.15	-0.10
70-80(%)	+0.49	+0.66	+0.69	+0.67
80-90(%)	+3.26	+3.36	+3.29	+3.16
90-99(%)	+11.47	+11.81	+11.89	+11.87
*Total(k-inf)	+8.91	+11.33	+12.38	+13.02
*Total(k-eff)	-2.99	-1.00	-0.26	+0.02

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

Table VII. U15-10 (500kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.3543	1.2404	1.1817	1.1244
k-inf	1.3752	1.2596	1.2000	1.1418
Th-232	75(ton)	74.2(ton)	73.6(ton)	72.9(ton)
U-233	15(ton)	12.4(ton)	10.8(ton)	9.3(ton)
Np-237	10(ton)	8.5(ton)	7.5(ton)	6.5(ton)
Pu-238	0(ton)	1.3(ton)	2.1(ton)	2.8(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.11	-1.00	-0.90	-0.81
10-20(%)	-1.16	-1.07	-0.99	-0.89
20-30(%)	-1.22	-1.14	-1.06	-0.98
30-40(%)	-1.27	-1.19	-1.14	-1.08
40-50(%)	-1.27	-1.23	-1.20	-1.16
50-60(%)	-1.18	-1.19	-1.20	-1.21
60-70(%)	-0.93	-0.99	-1.06	-1.16
70-80(%)	-0.16	-0.34	-0.53	-0.74
80-90(%)	+2.22	+1.89	+1.52	+1.07
90-99(%)	+9.67	+9.45	+9.12	+8.64
*Total(k-inf)	+3.59	+3.19	+2.56	+1.68
*Total(k-eff)	-9.65	-10.35	-11.17	-12.20

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

The other calculated results are tabulated in Tables IV, V and VI for U12-series and in Tables VII, VIII and IX for U15-series. The reason why the transformation rate of Np-237 is so small for U15-series will be due to the value of neutron flux. Table X shows the average neutron flux at 0 GWD/T for all the cores mentioned above. In this analysis, it is assumed that the power density is constant, that is, 179 W/cm. This means that the neutron flux becomes small when the amount of U-233 in the core is large. The amounts of U-233 in 100 ton-HM reactor are 10, 12 and 15 tons at first for U10, U12 and U15-series, respectively.

Table VIII. U15-12 (600kg/year Transformation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.3060	1.1980	1.1429	1.0900
k-inf	1.3261	1.2165	1.1605	1.1068
Th-232	73(ton)	72.2(ton)	71.6(ton)	70.9(ton)
U-233	15(ton)	12.4(ton)	10.8(ton)	9.3(ton)
Np-237	12(ton)	10.2(ton)	9.1(ton)	7.9(ton)
Pu-238	0(ton)	1.5(ton)	2.4(ton)	3.2(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-1.02	-0.88	-0.78	-0.67
10-20(%)	-1.06	-0.93	-0.83	-0.74
20-30(%)	-1.08	-0.97	-0.88	-0.78
30-40(%)	-1.09	-0.98	-0.91	-0.84
40-50(%)	-1.04	-0.96	-0.91	-0.85
50-60(%)	-0.90	-0.85	-0.82	-0.81
60-70(%)	-0.52	-0.53	-0.57	-0.62
70-80(%)	+0.42	+0.34	+0.21	+0.05
80-90(%)	+3.12	+2.93	+2.66	+2.33
99-99(%)	+10.94	+10.95	+10.80	+10.52
*Total(k-inf)	+7.77	+8.12	+7.97	+7.59
*Total(k-eff)	-5.19	-5.23	-5.61	-6.21

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff

Table IX U15-15 (700kg/year Transforation of Np-237 for 100ton-HM)

	0 GWD/T	30 GWD/T	50 GWD/T	70 GWD/T
k-eff	1.2447	1.1450	1.0949	1.0479
k-inf	1.2638	1.1625	1.1116	1.0639
Th-232	70(ton)	69.2(ton)	68.6(ton)	68.0(ton)
U-233	15(ton)	12.5(ton)	10.9(ton)	9.4(ton)
Np-237	15(ton)	12.9(ton)	11.5(ton)	10.1(ton)
Pu-238	0(ton)	1.8(ton)	2.9(ton)	3.9(ton)
Void Change	Instantaneous Void Coefficient for k-inf (%Δk / 10%-Void Change)			
0-10(%)	-0.88	-0.72	-0.60	-0.49
10-20(%)	-0.90	-0.73	-0.62	-0.51
20-30(%)	-0.88	-0.72	-0.62	-0.52
30-40(%)	-0.84	-0.70	-0.60	-0.51
40-50(%)	-0.73	-0.59	-0.51	-0.44
50-60(%)	-0.49	-0.38	-0.32	-0.27
60-70(%)	+0.03	+0.10	+0.11	+0.10
70-80(%)	+1.20	+1.23	+1.17	+1.09
80-90(%)	+4.28	+4.25	+4.13	+3.93
99-99(%)	+12.49	+12.77	+12.83	+12.81
*Total(k-inf)	+13.28	+14.51	+14.97	+15.19
*Total(k-eff)	+0.67	+1.45	+1.61	+1.52

*Total means total void coefficient, i.e.%Δk(99%Void-0%Void)for k-inf and k-eff.

Table X. Average Neutron Flux at 0 GWD/T (unit: x E+14 n/cm^{2}sec)

U10-10	U10-12	U10-15	U12-10	U12-12	U12-15	U15-10	U15-12	U15-15
2.83	2.93	3.07	2.62	2.71	2.82	2.39	2.46	2.56

Table XI. Summary Table for Transformation Rate of Np-237(Upper 700kg)

Core	Transformation rate for 1 year	Net Np-237 Reduction (- Pu-238 Production)	Total void coeff. for k-inf	Total void coeff. for k-eff	Inst. Void coeff.	Remarks
U10-10	700 kg	100 kg	negative	negative and large	negative except for 90% upper	OK
U10-12	800 kg	100 kg	positive	negative and large	negative except for 80% upper	Acceptable
U10-15	960 kg	130 kg	positive and large	negative but small	negative except for 70% upper	Limit for acceptable
U12-12	700 kg	100 kg	positive	negative and large	negative except for 80% upper	Acceptable
U12-15	830 kg	100 kg	positive and large	negative but small	negative except for 70% upper	Limit for acceptable
U15-15	700 kg	100 kg	positive and large	positive	negative except for 70% upper	Not acceptable

The transformation rate of Np-237 have been compared among the above nine cases, and the results are shown in Table XI only for the cases of the high transformation rate over 700 kg per year. In order to transform Np-237 as much as possible, we should mix it as much as possible. However, it depends on the concept of a safety margin for void coefficients. From this table we can conclude that the U10-10 core is the best choice for the transformation of Np-237, because of the negative void coefficients and the high transformation rate.

4. METHOD AND MATERIALS(2)

Secondly, we have investigated how to recycle the irradiated fuels included Pu-238. It was assumed that the one cycle period should be 5 years and the burn-up should be 50 GWD/T. The investigated core was determined to U10-10 core mentioned above. Therefore, the first cycle was started from 10 tons of U-233 and 10 tons of Np-237. After 5 years operation, it was assumed that all the FP should be removed from the core and all the TRU remained in the core. Moreover, the amount of U-233 was adjusted to 10 tons in every BOC (beginning of cycle), therefore, the amounts of the U-233 added depends on each cycle, which will be about 3 tons.

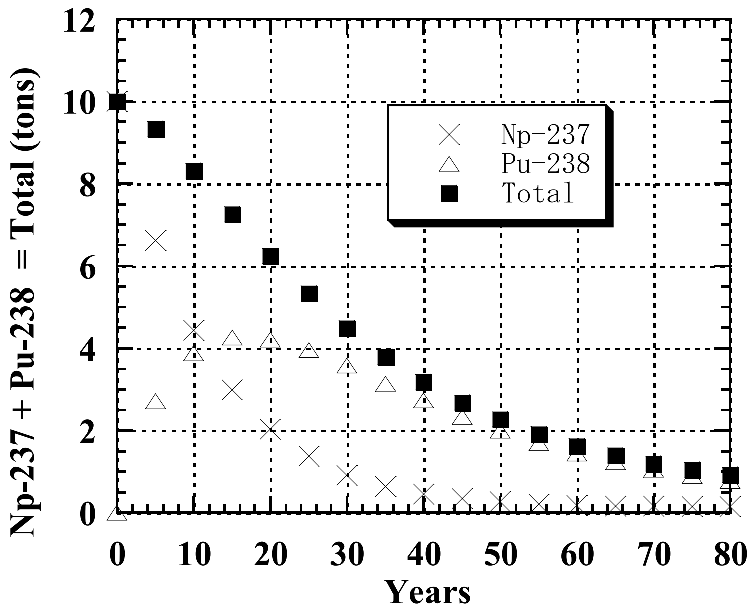

Figure 3. Incineration of Np-237 & Pu-238

5. RESULTS AND DISCUSSIONS(2)

Table XII shows the change of TRU amounts in the core from the first cycle to the 16th cycle.

Table XII. Change of TRU for Recycling by Using U-233

	1st-BOC	1st-EOC & 2nd-BOC	2nd-EOC & 3rd-BOC	3rd-EOC & 4th-BOC	4th-EOC & 5th-BOC	5th-EOC & 6th-BOC	6th-EOC & 7th-BOC	7th-EOC & 8th-BOC	8th-EOC & 9th-BOC
k-inf at 50GWD/T		1.0048	1.0881	1.1499	1.1968	1.2324	1.2614	1.2843	1.3023
Th-232	80 ton	78.091 ton	76.364 ton	74.773 ton	73.273 ton	71.864 ton	70.500 ton	70.545 ton	67.909 ton
Pa-231		9 kg	14 kg	16 kg	16 kg	16 kg	16 kg	16 kg	15 kg
Pa-233		62 kg	56 kg	52 kg	50 kg	48 kg	47 kg	46 kg	45 kg
U-232		4 kg	9 kg	14 kg	32 kg	35 kg	34 kg	31 kg	30 kg
U-233	10 ton	6.386 (10) ton	6.700(10) ton	6.864(10) ton	6.964(10) ton	7.018(10) ton	7.041(10) ton	7.059(10) ton	7.068(10) ton
U-234		0.6 ton	1.082 ton	1.494 ton	1.845 ton	2.145 ton	2.401 ton	2.619 ton	2.805 ton
U-235		87 kg	222 kg	357 kg	479 kg	586 kg	678 kg	755 kg	820 kg
U-236		4 kg	20 kg	45 kg	78 kg	114 kg	153 kg	194 kg	235 kg
Np-237	10 ton	6.623 ton	4.436 ton	2.991 ton	2.028 ton	1.385 ton	916 kg	644 kg	464 kg
Pu-238		2.714 ton	3.885 ton	4.266 ton	4.221 ton	3.951 ton	3.572 ton	3.145 ton	2.729 ton
Pu-239		212 kg	425 kg	547 kg	596 kg	597 kg	566 kg	517 kg	460 kg
Pu-240		24 kg	68 kg	106 kg	132 kg	146 kg	132 kg	138 kg	130 kg
Pu-241		17 kg	71 kg	123 kg	161 kg	185 kg	181 kg	186 kg	185 kg
Pu-242		1 kg	11 kg	27 kg	45 kg	63 kg	76 kg	86 kg	93 kg
Am-241		1 kg	5 kg	12 kg	20 kg	26 kg	29 kg	30 kg	31 kg
Am-243		0 kg	3 kg	9 kg	19 kg	30 kg	40 kg	49 kg	57 kg
Cm-244		0 kg	1 kg	2 kg	9 kg	17 kg	26 kg	37 kg	47 kg

Table XII.(Continued) Change of TRU for Recycling by Using U-233

	9th-EOC&10th-BOC	10th-EOC & 11th-BOC	11th-EOC & 12th-BOC	12th-BOC & 13th-EOC	13th-EOC & 14th-BOC	14th-BOC & 15th-BOC	15th-EOC & 16th-BOC	16th-EOC & 17th-BOC
k-inf at 50GWD/T	1.3181	1.3321	1.3449	1.3569	1.3679	1.3785	1.3882	1.3972
Th-232	66.682 ton	65.500 ton	64.182 ton	63.273 ton	62.182 ton	61.136 ton	60.136 ton	59.136 ton
Pa-231	15 kg	14 kg	14 kg	13 kg	13 kg	12 kg	12 kg	11 kg
Pa-233	45 kg	44 kg	43 kg	43 kg	42 kg	42 kg	41 kg	41 kg
U-232	28 kg	27 kg	26 kg	26 kg	25 kg	24 kg	24 kg	23 kg
U-233	7.073(10) ton	7.068(10) ton	7.064(10) ton	7.064(10) ton	7.059(19) ton	7.059(10) ton	7.064(10) ton	7.068(10) ton
U-234	2.963 ton	3.098 ton	3.214 ton	3.315 ton	3.462 ton	3.479 ton	3.547 ton	3.607 ton
U-235	874 kg	917 kg	952 kg	980 kg	1.002 ton	1.020 ton	1.035 ton	1.046 ton
U-236	276 kg	316 kg	355 kg	392 kg	428 kg	462 kg	494 kg	525 kg
Np-237	346 kg	270 kg	221 kg	191 kg	173 kg	163 kg	159 kg	158 kg
Pu-238	2.343 ton	1.999 ton	1.698 ton	1.441 ton	1.225 ton	1.044 ton	895 kg	774 kg
Pu-239	402 kg	347 kg	296 kg	252 kg	214 kg	182 kg	155 kg	133 kg
Pu-240	117 kg	102 kg	87 kg	73 kg	62 kg	52 kg	44 kg	37 kg
Pu-241	176 kg	162 kg	146 kg	129 kg	113 kg	98 kg	85 kg	74 kg
Pu-242	99 kg	101 kg	99 kg	96 kg	90 kg	83 kg	76 kg	68 kg
Am-241	30 kg	29 kg	26 kg	24 kg	21 kg	18 kg	15 kg	13 kg
Am-243	62 kg	67 kg	69 kg	70 kg	69 kg	67 kg	64 kg	60 kg
Cm-244	56 kg	64 kg	70 kg	75 kg	79 kg	81 kg	81 kg	79 kg

The first line shows the value of k-infinity at 50 GWD/T, which is increasing as the increase of cycles. It seems to be due to the decrease of Np-237 and the increase of U-235. It can be seen from this table that the amount of Pu-238 is increasing until the 3rd cycle, and after that, it is decreasing. Figure 3 shows the change of Np-237 and Pu-238. We have also noticed from Table XII that the amounts of U-234 and U-235 have been continuously increasing, and they have reached to 3.6 tons and 1 ton in 16th-EOC, respectively. It can be said that the production of U-235 should be the one of the merit of this recycling for maintaining the reactivity. We have found that the total amount of Np-237 and Pu-238 decreases from 10 tons to about 1 ton in the 80-years recycling. This means that about 9,000 kg (10 ton – 1 ton) of Np-237 can be incinerated during 80 years.

CONCLUSIONS

It was said that the thermal neutrons are not effective for the incineration of TRU, however, we have found that all the TRU can be transmuted to the almost stable U-234 and the small amount of MA by using U-233 recycling. At first, 10 tons of Np-237 has been uniformly mixed in the fuel rod by using U-233, Th-232 mixed oxide core with the usual PWR fuel pitch. We have found that about 700 kg of Np-237 can be transformed with a 100ton-HM reactor in a year. However, Pu-238 has been newly produced from Np-237. Secondly, the recycling of the irradiated fuels has been investigated by adding U-233 every 5 years operation, which corresponds to the burn-up of 50 GWD/T. We have found that the recycling has been successfully done and 10 tons of Np-237 has been transmuted below 1 ton including Pu-238 in the 80-years(16 cycles times 5 years) recycling. This means that about 9,000 kg of Np-237 can be incinerated during 80-years.

REFERENCES

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