Characteristics of TRU Transmutation in an LMFBR

M. Yamaoka, M. Ishikawa, and T. Wakabayashi

O-arai Engineering Center
Power Reactor and Nuclear Fuel Development Corporation
4002 Narita, O-arai-machi, Ibaraki-ken 311-13 JAPAN

ABSTRACT

It is generally acknowledged that LMFBRs would be superior TRU transmutation devices, mainly due to their hard neutron spectrum. In the present study, the characteristics of TRU transmutation in a 1000 MWe-class LMFBR with mixed-oxide(MOX) fuel were quantitatively investigated to substantiate the feasibility.

We considered here two typical methods transmuting TRU in the LMFBR core. One is the method dispersing TRU homogeneously throughout the entire core (homogeneous TRU-loading method). It was found that the homogeneous method had no serious penalties of TRU loading to the reactor core performance, and the TRU transmutation rate reached approximately 11% per cycle (15months) with the loading of the weight ratio of 5% TRU in MOX fuel. The amount of the TRU transmutation in the LMFBR is almost six times as much as that of the TRU production from a 1000 MWe-class LWR. As another desirable property, the TRU-loaded core was found to reduce the burnup reactivity loss by 40% compared with the reference core without TRU. It can be concluded that the TRU transmutation in an LMFBR has no serious problems from the viewpoint of the core performance, provided that the homogeneous method could be employed.

The other possible method is the use of small number of subassemblies (target S/As) which concentrate TRU in fuel (heterogeneous TRU-loading method). The weight ratio of 50% TRU fuel was assumed to be loaded in the target S/As. The calculated results showed that the swing of power peaking near the target S/As became quite severe and critical for the thermal design criteria, although the TRU transmutation rate and other reactor core performances of the heterogeneous method were roughly comparable to those of the homogeneous method. It seems from the present study that the heterogeneous method has a serious problem to be overcome and much effort would be needed to make the method feasible.

§1. Introduction

There is a strong social requirement not to leave the radiological hazardous material to future generations in utilizing the nuclear power. Most of fission products in the high level waste(HLW) from reprocessing have relatively short half-lives and decay to stable form within a few hundred years, while the transuraniums (TRU) like ^{237}Np and ^{243}Am have extremely long half-lives of over thousands of years and contribute to the long-term radiotoxicity of the HLW.

Power Reactor and Nuclear Fuel Development Corporation (PNC) has launched the project of the TRU transmutation study in LMFBRs from the view point of both reactor core characteristics and nuclear fuel cycle.

Because of their hard neutron spectrum, LMFBRs are considered to have the potentiality of transmuting the TRU nuclides effectively (Ref. 1). We studied the characteristics of TRU transmutation in a large LMFBR quantitatively to substantiate the feasibility. Two typical methods loading TRU fuel in the LMFBR core are considered in this study. One is the homogeneous TRU-loading method (HO method), where the TRU fuel is dispersed uniformly throughout the core. The HO method is expected not to affect the core characteristics seriously. The other is the heterogeneous one (HE method), where small number of subassemblies (S/As) with concentrated TRU fuel (target S/As) are loaded in the core. The HE method can have the advantage in manufacturing the TRU-loaded fuel since the numbers of TRU-loaded fuel pins and WAS are fewer than those of the HO method, although the core characteristics maybe affected locally because of the loading of the concentrated TRU fuel. We made comparison quantitatively between the two TRU-loading methods from the view point of the influence upon the core nuclear and thermal characteristics. The followings are the results of the study.

§2. Assumed Conditions and Method of Analysis

A 1000 MWe-class typical LMFBR core with MOX fuel was defined as the reference whose main parameters are shown in Table 2.1 and Fig. 2.1. The loaded-TRU material was assumed to come from LWR spent fuel with five-year cooling time before reprocessing. The isotopic composition of the TRU shown in Table 2.2 was calculated by the ORIGEN2 code (Ref. 2).

The nuclear characteristics of TRU-loaded cores were calculated by two-dimensional diffusion theory with depletion chain. The cross sections used were seven effective group constants condensed from the Japanese standard 70-group constant set, JFS-3-J2 (Ref. 3), which is based on an evaluated nuclear data library, JENDL-2 (Ref. 4).

§3 Parametric Study of TRU-loading Methods

In this section, we show the results of the parametric study of the TRU-loading methods. The effect of the loading mass and position of TRU upon reactor core characteristics was studied for each TRU-loading method.

3.1. Homogeneous TRU-loading Method

Figure 3.1 shows the relationship between the amount of TRU transmuted and that of loaded-TRU in the core. At least, one percent of TRU-loading to fuel would be needed to eliminate TRU, and the amount of TRU transmuted increases linearly with that of loaded-TRU.

As shown in Fig.3.2, the TRU-loading to core results in significant decrease of burnup reactivity loss mainly due to ^{238}Pu build-up. A proper amount of TRU-loading might be advantageous to the extension of reactor operation period.

Figure 3.3 shows the swing of power distribution between the beginning and the end of equilibrium cycle (BOEC and EOEC) with the parameter of TRU mass loaded in the outer core region. It could be possible to minimize the power swing by optimizing the ratio of loaded-TRU amount between the inner and the outer core regions.

3.2. Heterogeneous TRU-loading Method

The survey cases and the TRU transmutation rate calculated are summarized in Table 3.1.

As seen in cases A30 through AlOO, or B30 through B1OO of Table 3.1, the TRU transmutation rate increases with the amount of TRU loading, but the tendency is not always linear and also depends on the position of the target S/As. The TRU transmutation rate in the case where the target S/As are loaded at the periphery of the inner core is much larger than that in the case where they are loaded at the core center with roughly identical TRU mass. This means that the target S/As perform high transmutation rate when they are loaded in a dispersive manner to avoid the depression of neutron flux.

In addition, quite a surprising fact was found from the case AB50, in which the target S/As with 50% TRU were loaded at just the same positions with cases A50 and B50. The amount of TRU transmuted in the case AB50 was by 80% larger than the summed value transmuted in the cases A50 and B50. This curious behavior of TRU transmutation was found to be caused by the increase of flux level in each TRU-loaded region due to the positive interference effect between the two regions.

The case C50 shows the radial blanket region is another possibility to load TRU, since a large number of target S/As can be accepted there with almost no influence to core characteristics and transmute sufficient mass of TRU in spite of their low TRU transmutation rate.

Figure 3.4 shows the power distribution of the cases A30, A50 and A 1OO. That of the case REF with no TRU loaded is also shown in the figure for comparison.

The power of the TRU-loaded region in each case is quite depressed at BOEC and increases remarkably from BOEC to EOEC. The degree of the power swing tends to increase with the mass of loaded-TRU in the target S/As, but the dependency on the mass of loaded-TRU is quite non-linear, especially in the case AlOO. This marked non-linearity can be interpreted as the complicated effect of the dominant isotope ^{237}Np in TRU nuclides, which acts as both strong poison and fertile of active ^{238}Pu.

§4. Comparison of Homogeneous and Heterogeneous TRU-loading Methods

The HO and HE methods were compared from the view point of the influence upon the core nuclear and thermal characteristics. Based on the previous survey, a typical TRU-loading core was assumed for each of the HO and HE methods. The total mass of TRU loaded is set to be approximately identical between them, that is, 5% TRU in the whole core fuel in the case of the HO method, and 37 target S/As(about 107o of the core fuel S/As) which have 50% of TRU in fuel in the case of the HE method. Figure 4.1 shows the loading pattern of TRU-loaded S/As in the HE method. The reference core with no TRU loaded was also analyzed as the reference case.

4.1 Nuclear Characteristics

The basic nuclear characteristics was calculated by means of two-dimensional RZ diffusion-depletion theory. The three-dimensional power distribution and burnup compositions were obtained with the combination of two-dimensional RZ and XY calculation. The plutonium enrichment of each core was determined to sustain criticality at EOEC, where the control rods are all withdrawn from the core.

Table 4.1 summarizes the TRU inventory and transmutation rate of these three cores. There is almost no difference in TRU transmutation between the two TRU-loaded cores, and they can transmute TRU by 11～12%(180kg) per cycle

(15months). Since a 1000MWe-class LWR produces about 26 kg of TRU per year, an LMFBR with 5% TRU-loading can transmute the TRU mass from six LWRS in rough estimation. In detail, Np and Am were eliminated after depletion, but Cm increased on the contrary. This would be a problem from viewpoint of the fuel fabrication and transportation in fuel cycle.

Fig. 4.2 shows the spectra of neutron and adjoint flux in the three cores. It is found that the neutron spectrum gets harder and the high-energy importance becomes larger with TRU-loading.

Table 4.2 compares the calculated results about the nuclear characteristics of the TRU-loaded cores and the reference core.

The swing of region-integrated power in the inner and outer core and blanket is almost identical among these three cores. However, the power swing of the TRU-loaded region of the heterogeneous TRU-loaded core is much larger than that of the corresponding region of the homogeneous TRU-loaded core as shown in Fig.4.3. This power swing would be a great obstacle for thermal characteristics.

The control rod worth of the TRU-loaded cores decreases from the reference core by 1O-2O9'O. This maybe caused by the hardening of neutron spectrum.

Due to the production of ^{238}Pu from ^{237}Np in TRU, the burnup reactivity in the TRU-loaded cores is 40% smaller than that of the reference core.

The Doppler coefficients of the TRU-loaded cores are 20-3070 smaller in absolute value, and the sodium density reactivity coefficients are 50% larger than the reference core mainly because of the the spectrum hardening. Similarly, the values of prompt neutron life time in the TRU-loaded cores become shorter by 20% than that of the reference core.

4.2 Thermal Characteristics

The coolant flow distribution was optimized for the no TRU-loaded reference core, and the influence of TRU-loading was evaluated about the thermal characteristics. The results are shown in Table 4.3.

There are no serious thermal problems about the HO method, since the power distribution hardly changes from the reference core. On the other hand, the position where maximum temperature of cladding occurs in the heterogeneous TRU-loaded core moves from the reference core, and the hot spot temperature of the cladding is higher than that of the reference core by 40 degrees.

Although there might be rooms for optimization of the flow distribution, significant influence of power swing upon the thermal characteristics is inevitable for the HE method.

§5. Conclusions

The characteristics of TRU transmutation in a 1000 MWe-class LMFBR with MOX fuel were quantitatively investigated to substantiate the feasibility.

There would be two typical methods transmuting TRU in the LMFBR core. One is the homogeneous TRU-loading method. The TRU transmutation rate was found to be about 11% per cycle (15 months) with the homogeneous TRU-loading of 5% in the whole core. The amount of the TRU transmutation is almost six times as much as that of the TRU production from a 1000 MWe-class LWR. As another desirable property, the burnup reactivity loss was found to decrease by 40% compared with the reference core with no TRU loaded. This feature results from the enhanced internal breeding mainly due to the conversion of ^{237}Np to ^{238}Pu, which is advantageous in extending the operation cycle length. The power swing due to the fuel burnup and the maximum cladding temperature are almost the same as those of the reference core. It can be concluded that the TRU transmutation in the typical large LMFBR with oxide fuel has no serious problems from the viewpoint of the core performances, provided that the homogeneous method can be employed with the ratio of the TRU fuel of several percent.

The other possible method is the heterogeneous TRU-loading method, in which small number of target S/As with concentrated TRU fuel are loaded in the core. It was found that the swing of power peaking near the TRU loading S/As for the method becomes quite severe and critical for the thermal design criteria, although the TRU transmutation rate and other core performances are roughly comparable to those of the homogeneous method. It seems from the present study that the heterogeneous method has a serious problem to be overcome and much effort would be needed to make the method feasible.

The remaining issues of researches to accomplish the TRU transmutation in an LMFBR include: (1)accumulation of data related to material property and irradiation characteristics of TRU-loaded fuel, (2)improvement of nuclear data for TRU isotopes, (3)establishment of reactor core design method including uncertainties of nuclear and thermal data of TRU, (4) optimization of TRU loading method, and (5)consideration of FBR plant system to treat TRU fuel with high radioactivity, especially fuel handling system.

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3. H. Takano, et al.,"Revision of Fast Reactor Group Constant Set JFS-3-J2," Japan Atomic Energy Research Institute report, JAERI-M 89-141 (1989)
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Table 2.1 Main design parameters of the 1000 MWe-class reference LMFBR

Design parameters	Data
1. Plant parameters	
“Reactor thermal power	2517 MWt
“Coolant temperature (Reactor outlet /inlet)	530/ 375 °C
“Operation cycle length	456 days
2. Core parameters	
·Core concept	2-region homogeneous core
·Core layout	see Fig.2.1
“Number of core fuel S/As (inner/outer)	175 / 180
“Number of radial blanket S/As	72
“Number of control rods (primary /backup)	18/6
“Number of shielding (Stainless Steel / B4C)	78/277
·Core diameter /core height	3.68/1.00 m
“Thickness of axial blanket (upper/lower)	0.20/0.20m
3. Core fuel parameters	
·Fuel composition	$PuO_2 \cdot UO_2$
·Pu isotope ratio(239/240/241/242)	58/24/14/4
·Pu enrichment(inner / outer)	15.3 /19.3 Wt%
·Pattern of fuel exchange	3 dispersed batches
4. Blanket fuel parameters	
·Fuel composition	UO_2
·U isotope ratio(235 / 238)	0.3/ 99.7
·Pattern of fuel exchange	4 dispersed batches

Table 2.2 Isotopic composition ofloaded TRUfuel*

Isotopes	Weight ratio(%)
Np-237	49.14
Am-241	29.98
Am-242m	0.08
Am-243	15.50
Cm-242	
Cm-243	0.05
Cm-244	4.99
Cm-245	0.26

* Discharged from PWR (35 GWD/T) and
cooled for 5 years before reprocessing

Table 3.1 Effect of loading region and loaded amount of TRU upon the transmutation characteristics
(Heterogeneous TRU-loading Method)

Case name	Loading region of target S/As	Number of target S/As	TRU-loading ratio in target SIAS (%)	Amount of TRU transmuted (kg/cycle)	TRU transmutation rate* (%/cycle)
REF		o	0	-47	
A30	Center of the inner core	19	30	5	0.9
A50	Center of the inner core	19	50	18	1.9
AlOO	Center of the inner core	19	100	72	4.0
B30	Periphery of the inner core	18	30	25	4.8
B50	Periphery of the inner core	18	50	65	7.9
B1OO	Periphery of the inner core	18	100	153	9.5
AB50	Center and periphery of the inner core	37 (19 + 18)	50	147	8.7
C50	Radial blanket	72	50	153	2.3

*(Amount of TRU transmuted) / (TRU inventory at BOEC)

Table 4.1 Summary of TRU inventory and transmutation rate

Core	Isotope	Amount of TRU loaded (kg/cycle)	TRU inventory		Amount of TRU discharged (kg/cycle)	Amount of TRU transmuted (kg/cycle)	TRU transmutation rate* (%)
			BOEC(kg)	EOEC(kg)			
Reference core (no TRU loaded)	Np	0	6	11	5	-5	
	Am	0	46	82	36	-36	
	Cm	0	4	8	5	-5	
	Total	0	55	101	46	46	
Homogeneous TRU- loaded core	Np	289	719	590	160	129	18.0
	Am	268	710	624	182	86	12,2
	Cm	31	142	173	63	-31	-22.1
	Total	589	1571	1387	404	184	11.7
Heterogeneous TRU-loaded core	Np	302	769	647	180	122	15.8
	Am	280	752	669	197	83	11.0
	Cm	33	140	168	61	-28	-20.4
	Total	614	1660	1485	438	176	10.6

*(Amount of TRU transmuted) / (TRU inventory at BOEC)

Table 4.2 Comparison of nuclear characteristics of TRU-loaded cores

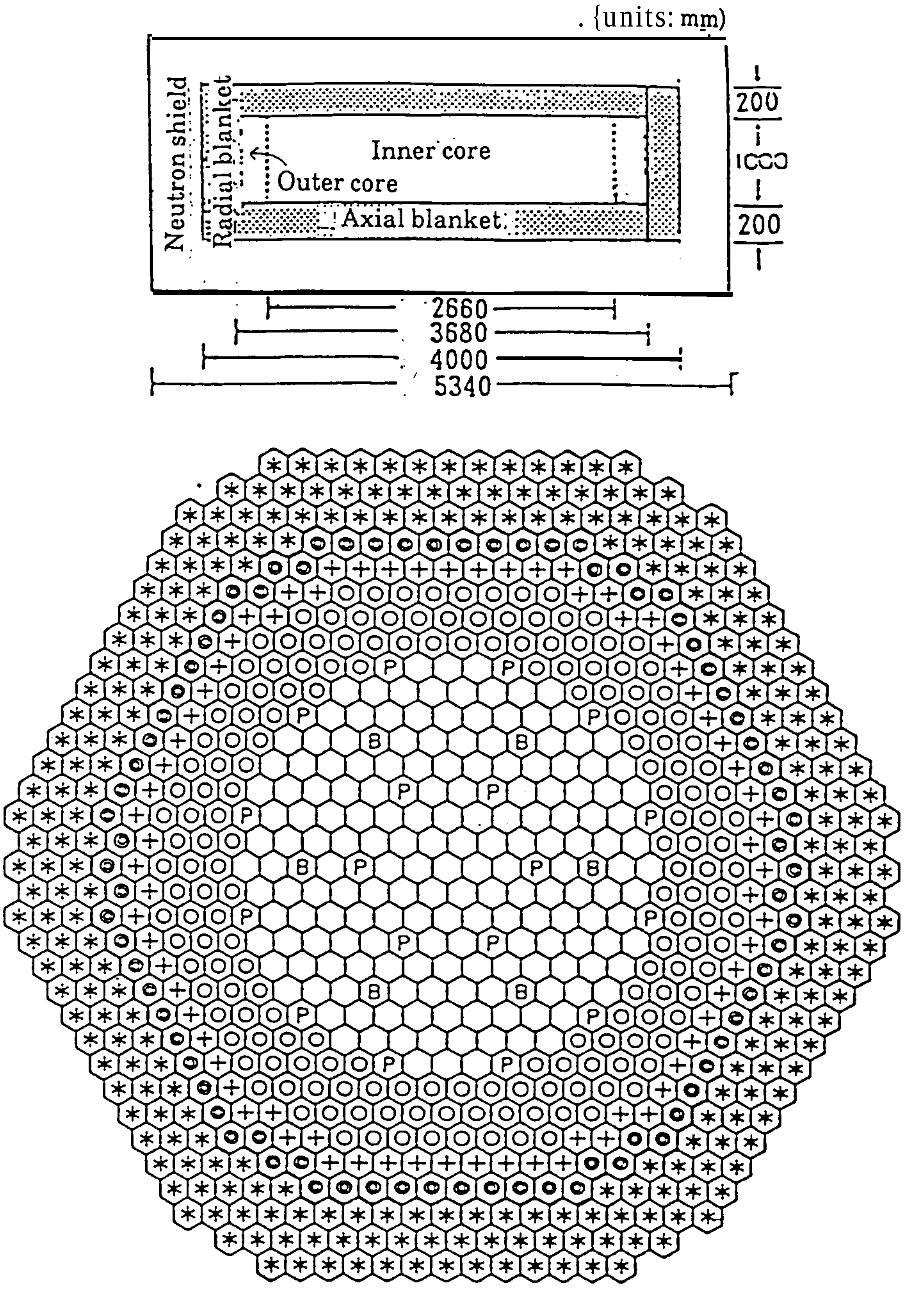
	Reference core (no TRU-loaded)	Homogeneous TRU-loaded core	Heterogeneous TRU-loaded core
Pu enrichment (inner core/outer core)	15.3/19.3 wt%	16.2/19.6 wt%	15.7/19.7 Wt%
Region-integrated power ratio (BOEC/EOEC) Inner core Outer core Radial and axial blankets	 46.8/50.9 % 47.6/41.8 % 5.6/7.4 %	 49.9/53.5 % 44.7/39.5 % 5.3/7.0 %	 48.8/53.6 % 45.4/38.9 % 5.8/7.5 %
Max.linear heat rate (BOEC/EOEC) Inner core Outer core	 380/419 w/cm 420/357 w/cm	 376/43 1 w/cm 416/355 w/cm	 391/419 w/cm 411/332 w/cm
Control rod worth (BOEC、33cm insertion of primary rods)	1.7 $\%\Delta k/kk'$ (1.00)*	1.5 $\%\Delta k/kk'$ (0.87)*	1.4 $\%\Delta k/kk'$ (0.81)*
Neutron spectrum (core center)	see Fig.4.2	←	←
Burnup reactivity loss	3.3 $\%\Delta k/kk'$	1,9 $\%\Delta k/kk'$	2.2 $\%\Delta k/kk'$
Doppler coefficient	-1.05×10^{-2} Tdk/dT	-7.08×10^{-3} Tdk/dT	-8.35 × 1O-3 Tdk/dT
Density reactivity coefficient of Coolant ($\Delta\rho/\rho$/100%density change)	-1.73 x1 O-Z	-2.5 OX1O-Z	-2.67×10^{-2}
β_{eff}	3.71 X1 O-3	3.47 X1 O-3	3.31 x 10”3
Prompt neutron life time	0.406 μsec	0.338 μsec	0.326 μsec

*) Value in parentheses denote relative control rod worth

Table 4.3 Comparison of thermal characteristics of TRU-loaded cores

Core	Max. assembly power*	Magnitude of relative change ofmax. hot spot cladding temperature from that of the reference core
Homogeneous TRU- loaded core		
. Inner core(EOEC)	9.89 MW (9.65 MW)	+9 °C
● outer core(BOEC)	8.84 MW (8.87 MW)	- I ” c
Heterogeneous TRU- loaded core		
. Inner core(EOEC)	9.86 MW (9.08 MW)	+32 °C
● Outer core(BOEC)	8.98 MW (8.06 MW)	+43 “C

*) The value in parentheses denotes the power for the assembly at the same position as in the reference core



@ 179.8m

⊛ I 181.2m

○	Inner core fuel	175
◎	Outer core fuel	180
Ⓟ	Primary shutdown control rods	18
Ⓑ	Backup control rods	6
⊕	Radial blanket	72
◉	Neutron shield (Stainless Steel)	78
⊛	Neutron shield (B_4C)	277
		(total 799)

Fig. 2.1 Core layout of 1000 MWe-class reference LMFBR

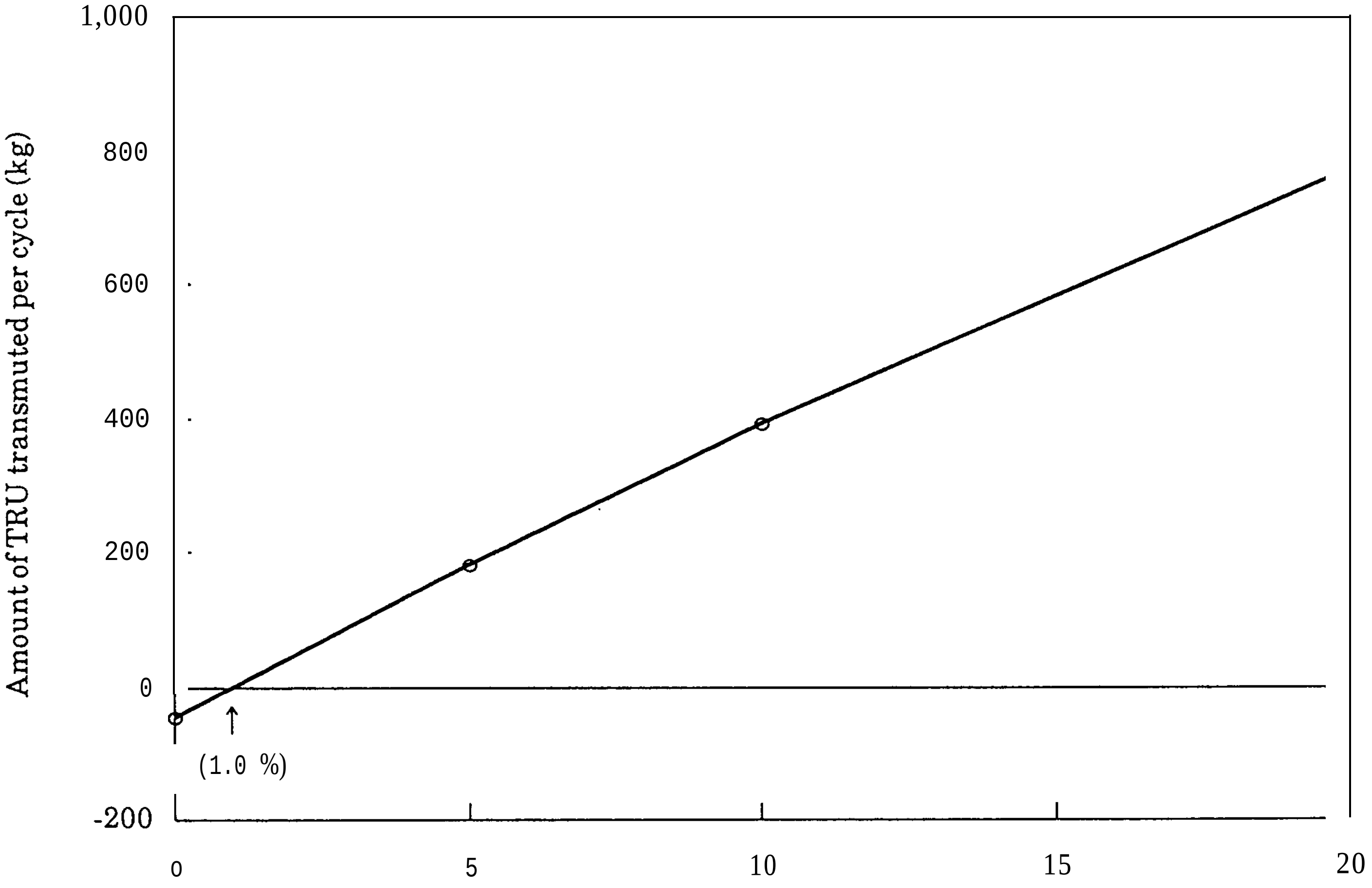


Fig. 3.1 Relationship between amount of TRU transmuted and ratio of TRU amount loaded in fuel (Homogeneous TRU-loading method)

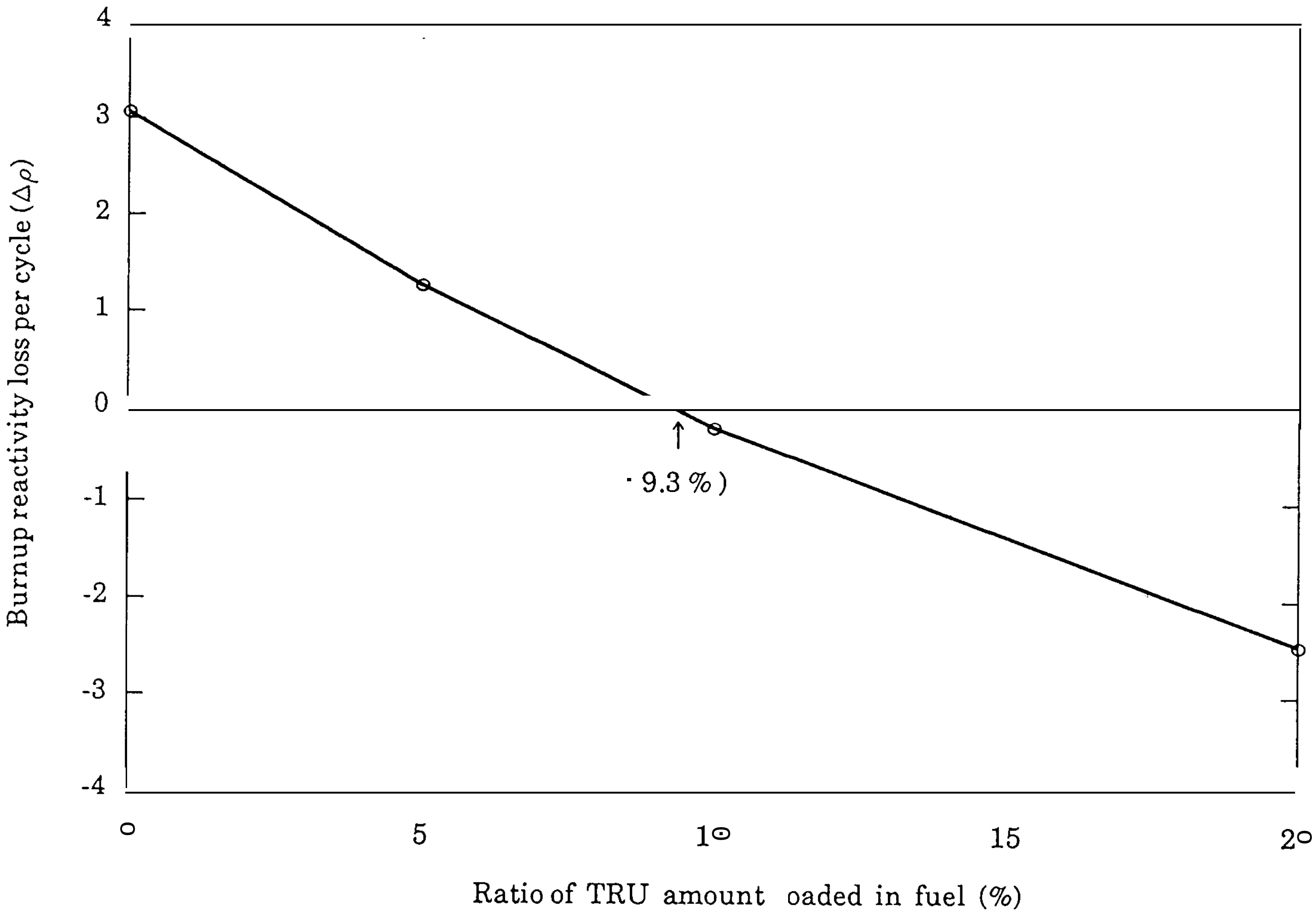


Fig. 3 2 Relationship between burnup reactivity loss and ratio of TRU amount loaded in fuel (Homogeneous TRU-loading method)

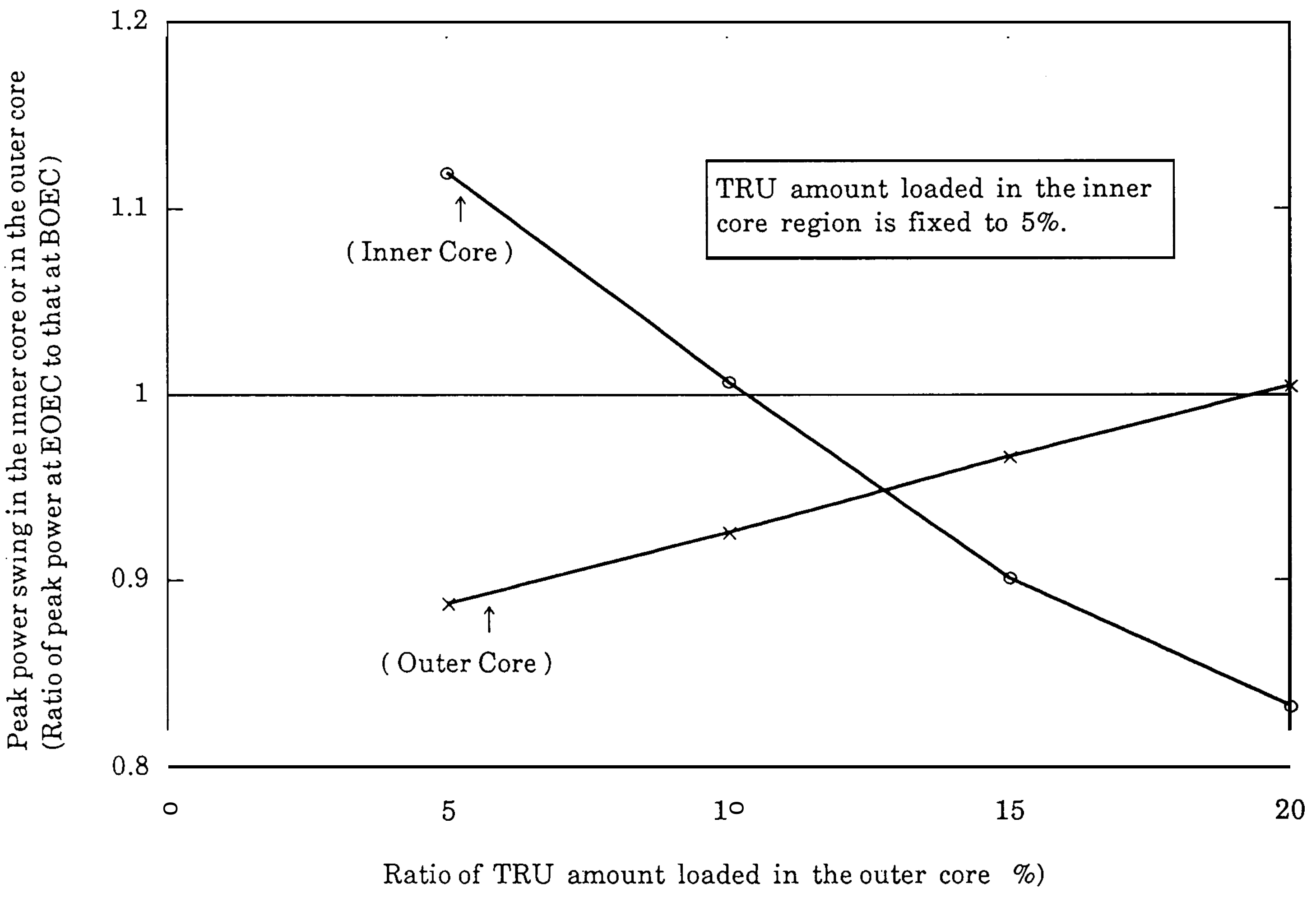
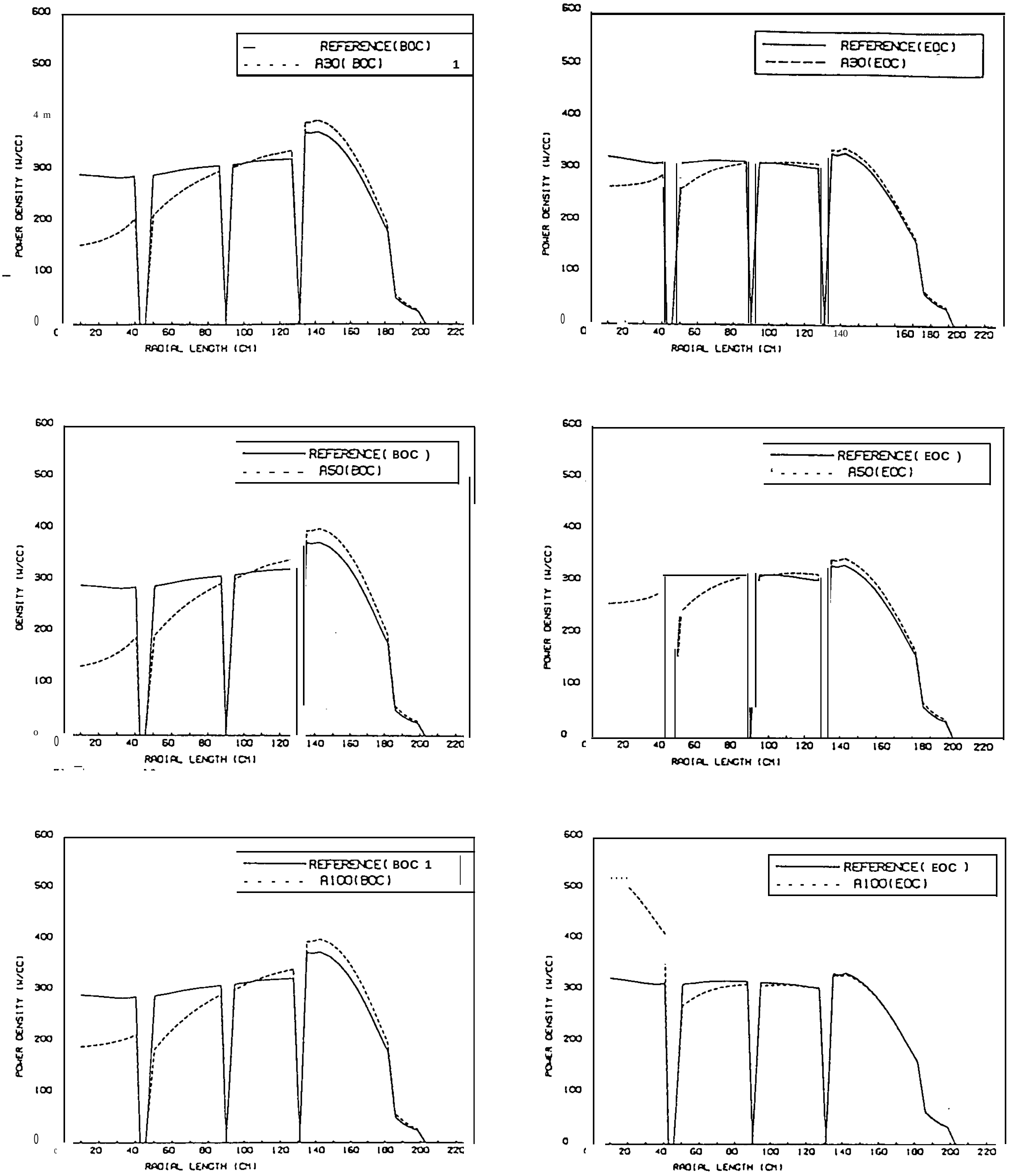


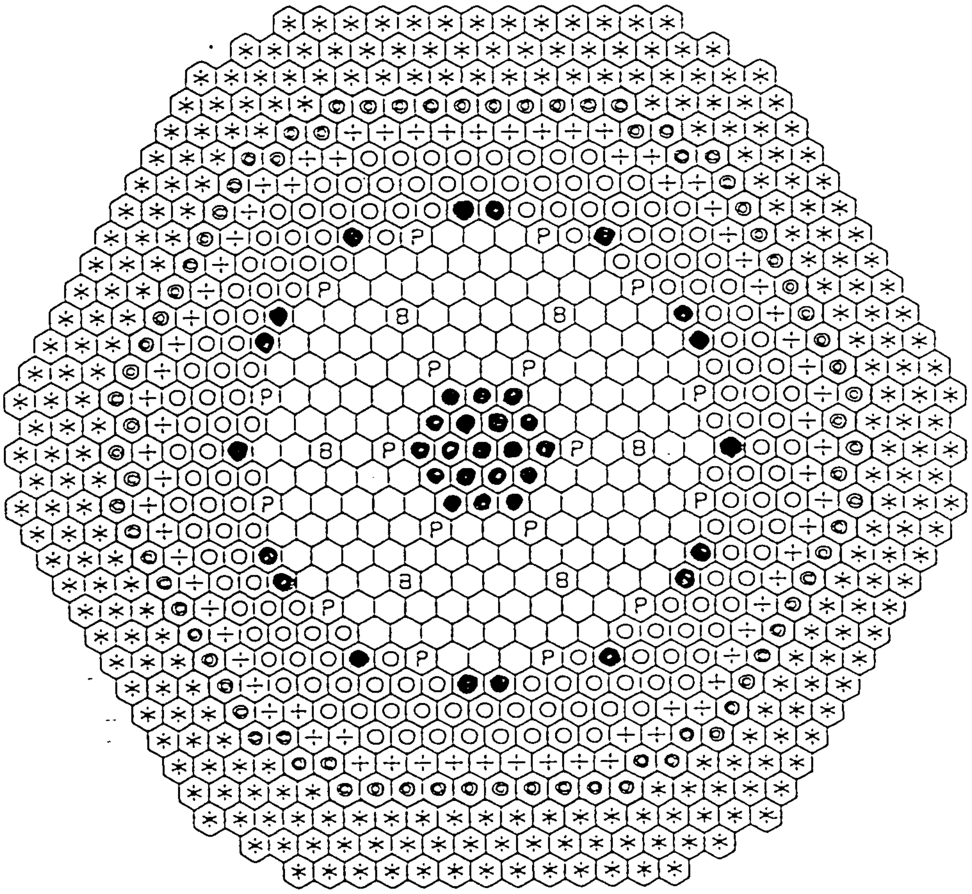
Fig. 3.3 Relationship between peak power swing and ratio of TRU amount loaded in the outer core with fixed TRU amount in the inner core (Homogeneous TRU-loading method



(Beginning of Equilibrium Cycle)

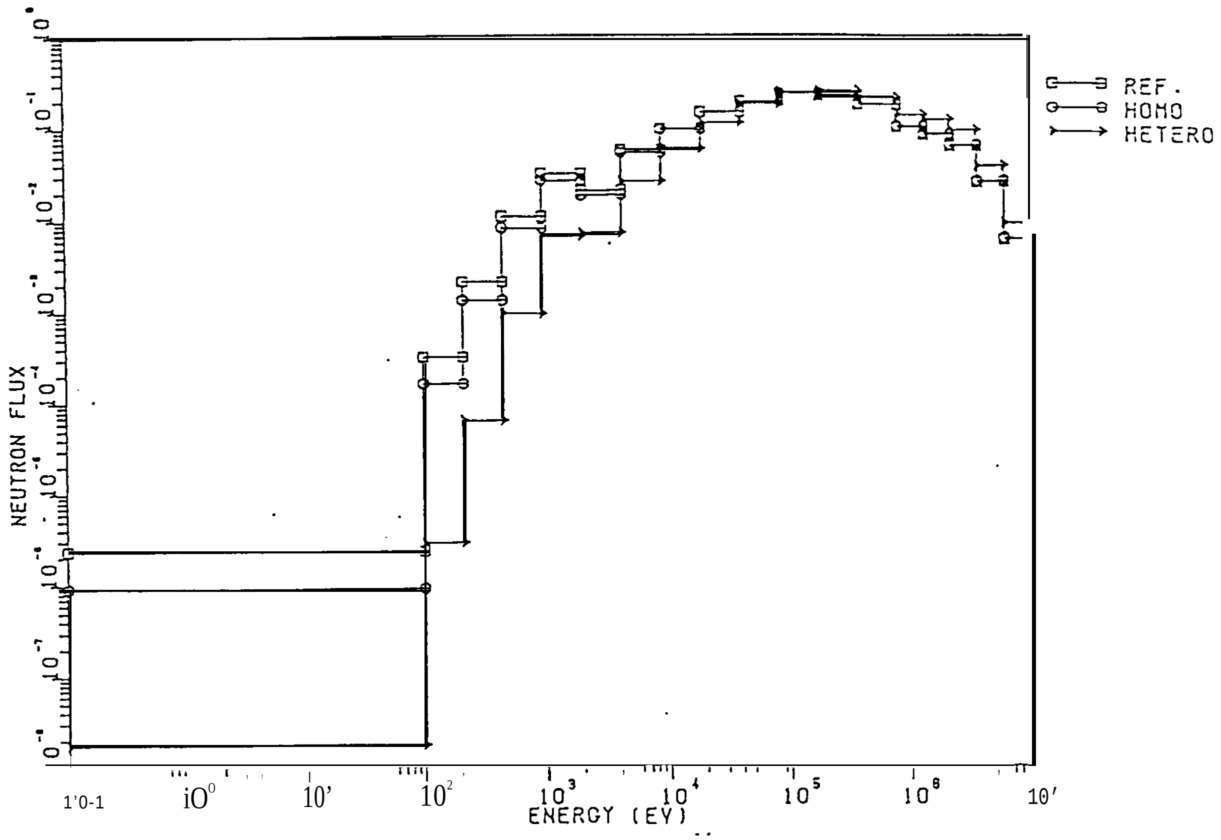
(End of Equilibrium Cycle)

Fig. 3.4 Power distribution of heterogeneous TRU-loaded cores

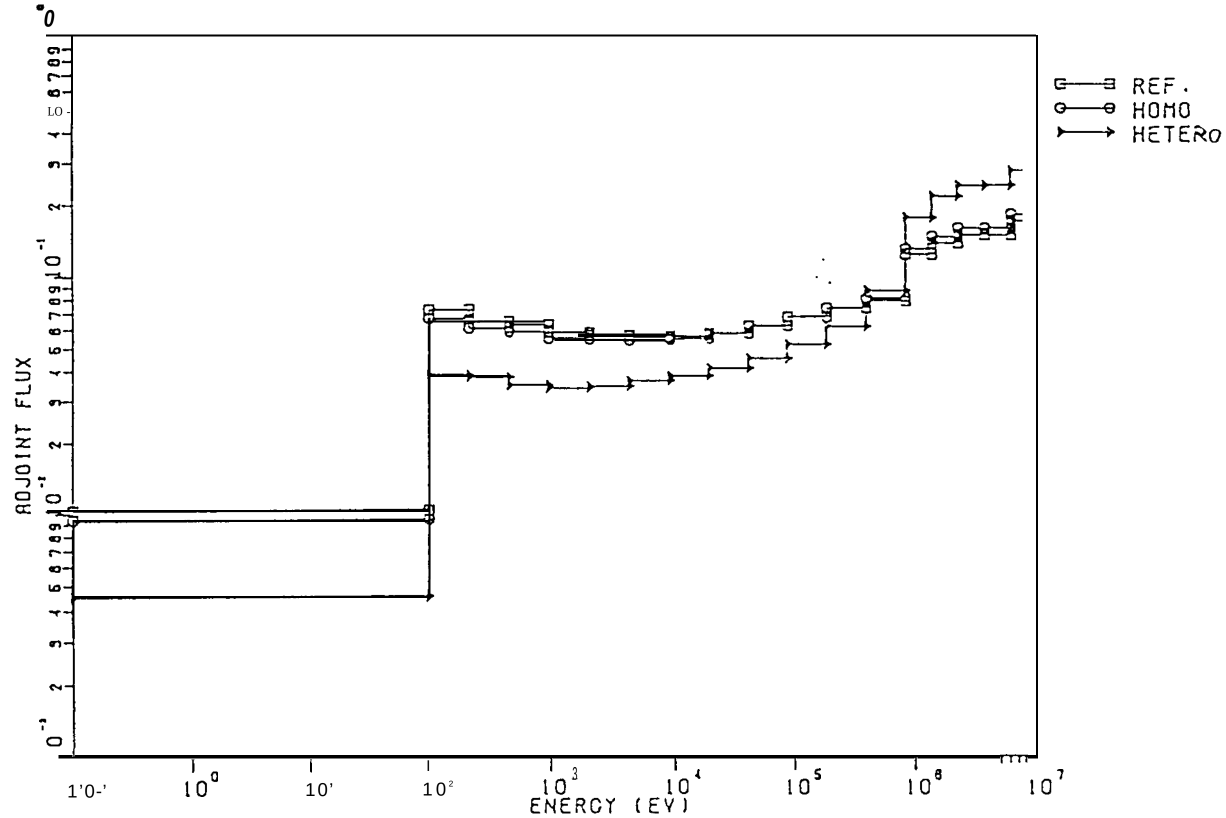


◉ Target S/A including TRU

Fig.4.1 Loading pattern of target S/As
(Heterogeneous TRU-loaded core)

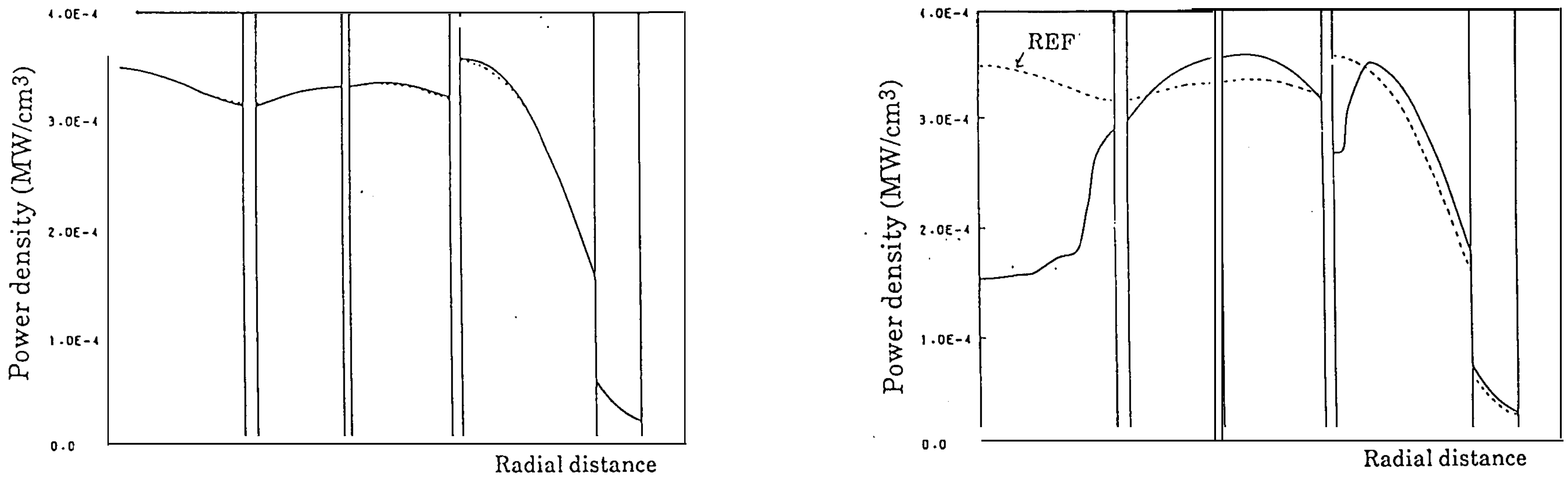


Neutron spectrum at EOEC in the core center (relative value)



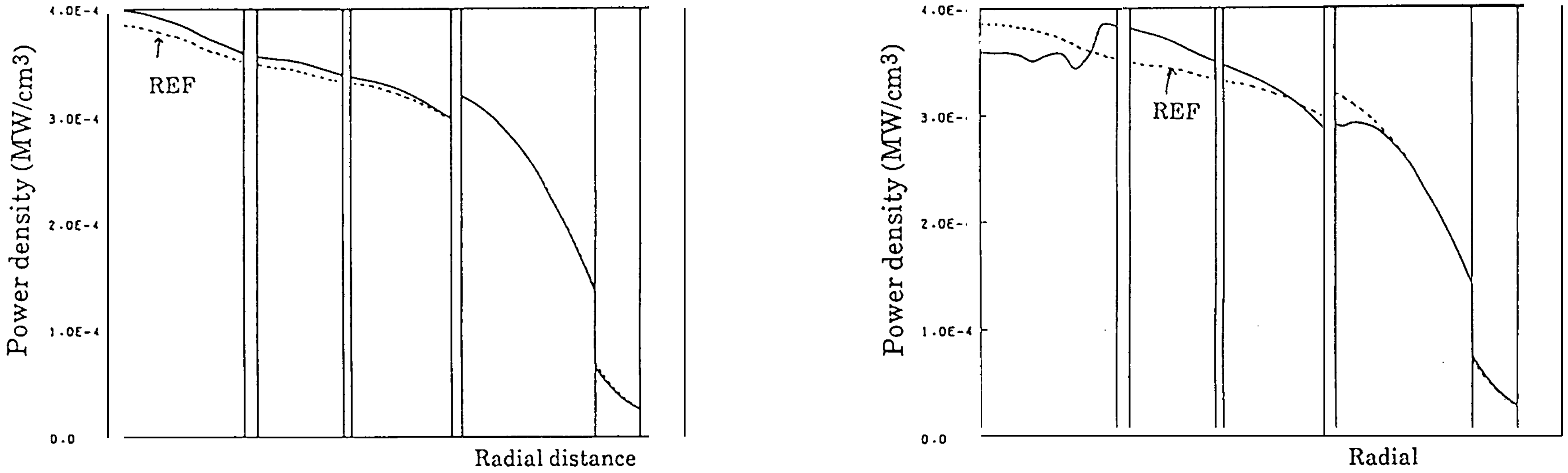
Adjoint spectrum at EOEC in the core center (relative value)

Fig. 4.2 Neutron and adjoint spectrum in the TRU-loaded cores



Radial power distribution of homogeneous TRU-loaded core at BOEC
(Primary control rods partially inserted)

Radial power distribution of heterogeneous TRU-loaded core at BOEC
(Primary control rods partially inserted)



Radial power distribution of homogeneous TRU-loaded core at EOEC
(Primary control rods fully withdrawn)

Radial power distribution of heterogeneous TRU-loaded core at EOEC
(Primary control rods fully withdrawn)

Fig. 4.3 Radial power distribution of TRU-loaded cores