CHARACTERISTICS OF A HETEROGENEOUS TRU-LOADING CORE

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ABSTRACT

LMFBRs are considered to have the potentiality of transmuting the TRU nuclides effectively because of their hard neutron spectrum("TRU' means eventually minor actinide(MA) in the present study). Since MA loading considerably affects not only core characteristics but fuel material properties, it is necessary to investigate MA loading method taking into account the influence upon core characteristics and fuel material properties.

A heterogeneous MA-loading method, where a few number of subassemblies with concentrated MA fuel (target fuel subassemblies) are loaded in the core, can have an advantage in fabricating and managing the MA-loaded fuel since the number of the MA-loaded fuel subassemblies is smaller compared with the method loading MA homogeneously. A study has been carried out on the feasibility of the heterogeneous MA-loading in an oxide-fueled 1000MWe LMFBR core.

Based on the experimental data on fuel properties of MA fuel published up to now, it was found that MA loading significantly reduces the linear power limit almost proportionally to the MA loading ratio because of degradation of the thermal conductivity and the melting point. Furthermore, core analyses showed that heterogeneous MA-loading leads to a significant power deformation in the core if the design of target fuel subassemblies is the same as that of the normal fuel subassemblies with no MA fuel loaded. These cause a serious thermal problem.

An effort was made so as to make the heterogeneous method feasible. The fuel pin design and the loading pattern of the target fuel subassemblies were studied. It was found that reduction of the fuel pin diameter and the Pu enrichment is essential to reduce the power of MA-loaded fuel. It is concluded that the heterogeneous MA-loading method is feasible by optimizing fuel design, loading pattern and coolant flow of MA-loaded fuel subassemblies.

1. Introduction

LMFBRs are considered to have the potentiality of transmuting the minor actinides (MA) such as Np, Am and Cm effectively because of their hard neutron spectrum[1]. Since loading MA considerably affects not only core characteristics but fuel material properties, it is necessary to investigate the MA loading method taking into account the influence upon core characteristics and fuel material properties.

We have been investigating transmutation of minor actinides in oxide-fueled LMFBR cores[2]~[4]. One of the important items studied is MA loading methods in the core. Two typical loading methods are considered. One is the homogeneous MA-loading method (HO method) where the MA fuel is dispersed uniformly throughout the core. This method has the advantage of no serious influence on core characteristics. The other is the heterogeneous MA-loading method (HE method) where a few number of subassemblies with concentrated MA fuel (target fuel subassemblies) are loaded in the core. The HE method can have an advantage in fabricating and managing the MA-loaded fuel since the number of the MA-loaded fuel subassemblies is smaller than that of the HO method.

We carried out a core study[2] to compare neutronic and thermal characteristics between the two methods. As a result, we found that the HE method causes a serious thermal problem due to significant deformation of power distribution. However, there were no special design consideration for the HE method, so no optimization of the loading pattern and fuel design of the fuel loaded with MA was performed in the study.

The objective of the present study is to investigate the feasibility of the HE method in an oxide-fueled 1000MWe LMFBR core, optimizing loading pattern and fuel design of the fuel loaded with MA. The influence of loading MA upon fuel properties is taken into account in the optimization. Emphasis is placed on the improvement of the power deformation and the feasibility from thermal design was studied. Through the study, design considerations to make the method feasible are clarified.

Loading ratio of MA in a target fuel subassembly in the HE method was chosen to be 50%. The fraction of target fuel subassemblies in the core is assumed about 10%, so that whole core average of the loading ratio of MA is about 5%. For comparison, a reference core with no MA and a core loaded with MA homogeneously by 5% are also considered. It is not clear that the MA fraction of 50% in a fuel is feasible from the view point of fuel fabrication and irradiation, but it was chosen as a maximum limit to perform a conservative evaluation of the feasibility.

The fuel properties necessary for fuel design were estimated from the published experimental data on MA-loaded fuel. However, there are not enough data for fuel design and so some assumptions were employed to estimate the properties of the fuel designed. Therefore, it should be noted that the estimated properties include considerable uncertainty.

2. Estimation of properties of the fuel containing MA

The most influential property of the fuel containing MA is degradation of the melting point and the thermal conductivity because it leads to a reduction of linear power limit. The influence on the linear power limit was estimated based on the published data on the fuel properties of MA. Influences upon fuel design parameters other than the linear power limit were not taken into account. For example, the maximum allowed fuel discharge is assumed the same as that of the MOX fuel.

There are a few data published[5]~[12] on fuel properties of MA-loaded fuel in oxide form. However, the published data concerns only each isotope of MA or the mixture of U and MA (all in oxide form), so no data published for the mixture including all of Pu, U and MA in oxide form. Then, it was assumed that fuel properties of the mixture' including all of PuO_2, UO_2 and oxide of MA can be estimated by the linear combination of fuel properties of individual compound with a weight of its fraction. All the published data shows Am and Cm in oxide form have lower melting point and thermal conductivity compared with the mixture of PuO_2-UO_2. Therefore, the linear power limit for MA-loaded fuels would be lower than the conventional PuO_2-UO_2 fuel.

The estimated melting point and thermal conductivity are shown in Fig.1 and 2, respectively. Two compositions were assumed as fuel containing MA. One is the mixture of PuO_2, UO_2 and NpO_2. The other is the mixture of PuO_2, UO_2, NpO_2, AmO_2 and CmO_2. As shown in the figures, addition of all the MA to PuO_2-UO_2 degrades these properties considerably, whereas addition of only Np does not.

The linear power limit in normal operation was estimated as a function of loading ratio of MA. The estimation was carried out relatively assuming that the linear power limit is 430W/cm in normal operation for PuO_2-UO_2 fuel. The result is shown in Fig.3. This shows that the linear power limit decreases by about 30W/cm per 10% loading of MA. If MA is loaded by 50%, the peak linear power must be designed to be less than 300W/cm, which is about 30% smaller than that for fuel with no MA. The influence of irradiation on the linear power limit is not taken into account because of lack of data.

3. Description of core and fuel design

We assumed a 1000 MWe-class large FBR core with mixed oxide fuel as a reference. The design parameters are shown in Table 1. The core layout is shown in Fig.4. The fuel loaded in the core is assumed to come from LWR spent fuel with five-year cooling time before reprocessing. The isotopic composition of MA was calculated by the ORIGEN2 code[13]. Table 2 shows the composition.

The fuel design parameters are shown in Table 3. We consider three types of design which differ in pin diameter and number of pins in a assembly. They are designed so that the coolant pressure drop is equal to each other when the coolant flow rate is the same. The fuel with pin diameter of 8.3mm is designed for the reference core. The other two are designed for the target fuel which has lower linear power limit. They have smaller pin diameters than the fuel for the reference core, so that the linear power can be lower even if the power density is the same.

4. Description of calculational methods

Core analyses were performed by a burnup code on two-dimensional RZ and XY geometries. Burnup characteristics, power distribution and reactivity coefficients were obtained from the analyses. Cross sections were collapsed from JFS-3-J2 library[14] based on JENDL-2[15]. Seven-group effective cross sections were used in the calculation of burnup characteristics and power distribution. Reactivity coefficients were calculated using 18-group effective cross sections.

5. Results of core study

(1) Parametric survey

Parametric survey on fuel parameters was carried out for a typical loading pattern of target fuel subassemblies. The loading pattern of target fuel subassemblies is shown in Fig.5. The Pu enrichment and the fuel pin diameter of target fuels were varied as parameters. In each case, fuel parameters of normal fuel with no MA loaded are the same as those of the fuel in the reference core. The target fuel subassemblies loading MA by 50% are loaded in a dispersed manner in the core.

The peak linear power for each case is summarized in Table 4. If the Pu enrichment and the fuel pin diameter of target fuels are the same as those of the normal fuel, the peak linear power for the target fuel is about 30% higher than that of the normal fuel (Case1). In this case, the peak linear power for the normal fuel is within the design limit (430W/cm). Figure 6 shows the distribution of assembly power and the linear power at end of cycle for case 1. It is seen that the target fuels subassemblies have much larger power compared with the neighboring normal fuel subassemblies. This is attributed to burnup effect of minor actinides, most influential of which is the buildup of ^{238}Pu from ^{237}Np. Figure 7 shows dependency of specific heat of MOX fuel and oxide fuel of MA on burnup under constant neutron flux. It is seen that specific heat of oxide fuel of M-A increases remarkably with burnup, whereas that of MOX fuel decreases.

Use of lower Pu enrichment in the target fuel is considered helpful so as to reduce its power. The results of cases 1 to 5 show that the peak linear power of the target fuels decreases as the Pu enrichment of the fuels is reduced. However, even if the Pu enrichment is zero, the peak linear power of the target fuels is much higher than 300W/cm which is the estimated limit for fuels with 50% MA. Furthermore, the peak linear power of the normal fuel increases as the Pu enrichment of the target fuels decreases.

The results of cases 3, 3-1 and 3-2 show that use of smaller pin diameter is effective to reduce the peak linear power of the target fuels more. On the whole, the peak linear power decreases in proportion to the number of fuel pins in a assembly. For example, the peak linear power of the target fuels is about 325W/cm in case assemblies with 397 pins (6.7mm diameter) is employed.

From the results shown above, it can be said that the proper selection of the Pu enrichment and the fuel pin diameter in the target fuels makes the peak linear power close to its limit for both the normal and target fuels. Further reduction of the linear power is expected by adjusting Pu enrichment and optimizing loading position of target fuels.

(2) Optimized core and its characteristics

Based on the results of parametric survey, optimization of loading position, fuel pin diameter and Pu enrichment of target fuels was performed. The core layout is shown in Fig.8. Table 5 shows the core performances. For target fuels, the fuel pin diameter is 6.7mm (number of fuel pins in a assembly is 397), and the Pu enrichment is O% and 5.6% in the inner and outer cores, respectively. With this design of target fuels, the peak linear power is439W/cm and 310W/cm for normal and target fuels, respectively. For both fuels, the peak value exceeds its limit by a few percent. However, the result is similar in the homogeneouMA-loading core. The peak linear power of the core is431W/cm, which is about 4% higher than its limit for MA-loaded fuel with loading ratio of 5%(415W/cm as shown in Fig.3).

The. burnup reactivity loss, control rod worth, Doppler coefficient and coolant density coefficient are almost the same as those of the homogeneous MA-loading core. The burnup reactivity loss is smaller than that of the reference core by about 40%, which is advantageous in extending operation cycle length or reducing control rod worth requirement. The increase in the sodium density effect and the decrease in the absolute value of Doppler coefficient are not small. The influence on core safety should be evaluated. Table 6 shows mass balance of MA. The heterogeneous MA- loading core can burn MA by about 180Kg/cycle, which is almost equal to that of the homogeneous MA-loading core. The MA from 6 LWRs of 1000MWe each can be burned, since a typical 1000MWe LWR produces MA by 26Kg/year.

Table 7 shows the thermal characteristics. The required and design flow rate of each sub-region of the core and the resultant peak cladding temperature are compared with those of the reference core. The required flow rate is determined to assure simultaneously that the peak cladding temperature is less than 700°C and that the cumulative damage function of the cladding is less than 0.3. The required flow rates for both normal and target fuel subassemblies are larger than that for the fuel in the reference core. However, it is seen that the thermal design criteria can be met by adjusting the flow rate for each region. The cladding temperature is higher than that of the reference core in most of the regions by 5°C to 37°C. The peak cladding temperature for the whole core increases from 695°C to 700°C. The peak value can be reduced by a more detailed assignment of flow rate to each region. However, it should be noted that the thermal design margin is reduced compared with the reference core.

6. Summary and conclusion

A study has been carried out to investigate the feasibility of heterogeneous MA (minor actinides) loading method in an oxide-fueled 1000MWe LMFBR core. A loading method that satisfies thermal design criteria was sought taking into account the influence of loading MA upon fuel properties.

The linear power limit was evaluated for MA-1oaded fuel based on published experimental data. It was found that MA loading reduces the linear power limit almost in proportion to the MA loading ratio because of degradation of the thermal conductivity and the melting point. For example, the linear power limit for the fuel pin with 50% MA loading reduces about 30% compared with that of no MA-loaded fuel pin. It should be noted that the result includes considerable uncertainty because of insufficient experimental data.

Core. analyses were performed to study the influence of MA-loaded fuel upon core characteristics. The loading ratio of MA in a target fuel subassembly was assumed 50%. About 10% of the total core fuels are replaced with the target fuel subassemblies. Therefore, the average loading ratio of MA in the core is about 5%. It was found that the peak linear power and the assembly power of the target fuel is much higher than those of the fuels in the conventional core with no MA loaded, if there is *no* special consideration in fuel design of the target fuel subassembly.

A parametric survey was carried out on the fuel design of the target fuel subassembly and their loading pattern to improve serious power deformation. It was revealed that the peak linear power and the assembly power can be significantly decreased by reducing Pu enrichment and fuel pin diameter of the target fuels and the optimization of their loading pattern. The peak linear power in the optimized core is slightly (2%) larger than its design limit. The thermal design criteria can be met by optimizing flow design within the total design flow rate. The burnup reactivity loss, control rod worth, Doppler coefficient and coolant density coefficient are almost the same as those of the homogeneous MA-1oading core.

The conclusion is that the heterogeneous MA-loading is feasible if following design requirements are satisfied.

- Optimization of fuel design of the target fuel subassembly with MA (The optimization of the Pu enrichment and fuel pin diameter are essential.)
- Optimization of the coolant flow design to provide adequate coolant flow for target fuel subassemblies.
- Extra design margin of several percent in the peak linear power of the reference core for target fuel subassemblies to be loaded.

The last is required for not only the heterogeneous method but also the homogeneous method. Therefore, it is not a disadvantage peculiar to the heterogeneous method.

If the loading ratio of MA in a target fuel subassembly is less than 50%, the above requirements can be quantitatively mitigated according to the ratio.

It is necessary to accumulate and improve data on the thermal conductivity and the melting point of MA-1oaded fuel so as to reduce the uncertainty of the estimated linear power limits. It is also required to obtain more experimental data related to other fuel properties, irradiation characteristics and neutron cross sections.

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Table 1 Main Design Parameters of 1000MWe Reference LMFBR

Design Parameters	Data
1. Plant Parameters	
“Reactor Thermal Power	2517 MWt
“Coolant Temperature (Reactor Outlet /Inlet)	530 /375 ℃
“Operation Cycle Length	15 Months
2. Core parameters	
-Core Concept	2-region Homogeneous
“Average Fuel Burnup	91 GWd/t
“Linear Power Limit	430 W/cm
·Core Diameter /Core Height	368/100 cm
“Thickness of Axial Blanket (Upper/Lower)	20/20 cm
3. Core fuel parameters	
·Fuel Composition	$PuO_2 \cdot UO_2$
·Pu Isotopic Ratio (239/240/241/242)	58/24/14/4 (LWR Discharged)
-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 Composition of Minor Actinides *

Nuclide	Weight Fraction (%)
Np-237	49.1
Am-241	30.0
Am-242m	0.1
Am-243	15.5
Cm-243	0.05
Cm-244	5.0
Cm-245	0.3

*Discharged from PWR (35 GWd/t) and Cooled for 5 Years Before Reprocessing

Table 3 Fuel Design Parameters

Design Parameters	Number of fuel pins per assembly		
	271* (Reference)	331	397
Fuel pin diameter (mm)	8.3	7.44	6.73
Cladding thickness (mm)	0.45	0.425	0.405
Fuel pellet diameter (mm)	7.22	6.43	5.78
Fuel smeared density (%TD)	87.6	←	←
Wire spacer diameter (mm)	1.5	1.43	1.37
Duct inside flat-flat (mm)	165.8	←	←
Duct thickness (mm)	4.0	←	←
Gap between assemblies (mm)	6.0	←	←
Volume ratio			
Fuel	0.396	0.384	0.372
Gap	0.020	0.019	0.018
Structure	0.209	0.214	0.220
Coolant	0.375	0.383	0.390

*This is designed for the reference core.

Table 4 Peak Linear Power for Heterogeneous MA-Loading Core (MA: Minor Actinides)

Case Number	Pu enrichment in target fuel (w/o, Inner /Outer cores)	Number of pins per subassembly	Peak Linear Power of Normal Fuel (W/cm)		Peak Linear Power of Target Fuel (w/an)	
			Inner Core	outer Core	Inner Core	Outer Core
Reference*	(No target fuel loaded)	(No target fuel loaded)	419	420	.	
1	15.3/19.3	271(8.3)**	416	423	554	489
2	Case 1 X0.7	271(8.3)	408	431	508	453
3	Case 1 X0.5	271(8.3)	386	437	491	446
3-1	Case 1 X0.5	331(7.44)	388	437	390	354
3-2	Case 1 X0.5	397(6.73)	388	437	325	295
4	Case 1 X0.3	271(8.3)	390	445	468	431
5	0.0	271(8.3)	397	456	454	409

*)Pu enrichment: 15.3/19.3 w/o, Number of pins per subassembly: 271
**)Fuel pin diameter (mm)

Table 5 Comparison of Core Characteristics

	Reference Core (No MA*-loaded)	Homo. MA-Loading Core (5%)	Hetero. MA-Loading Core
Pu Enrichment (wt%) (Inner Core/Outer Core)	15.3/19.3	16.2/19.6	15.3/19.3(Normal) 0/5.6 (Target)
Peak Linear Power (W/cm)			(Normal/Target)
Inner Core	**419**	**431**	**428 / 310**
Outer Core	420	416	4391279
Burnup Reactivity Loss (%Δk/kk')	3.3	1.9	1.9
Control Rod Worth(%Δk/kk', 33cm Insertion of Primary Rods)	1.67 (1.00)**	1.46 (0.87)	1.50 (0.90)
Doppler Coefficient (Tdk/dT)	-10.5 X10-3	-7.1×10^{-3}	-7.4×10^{-3}
Coolant Density Coefficient (Δk/kk'/100%Density Change)	-1.73×10^{-2}	-2.50×10^{-2}	-2.60 x10-2

*) Minor Actinides
**) Relative Control Rod Worth

Table 6 Transmutation of Minor Actinides

	Isotope	Ref. Core (No MA)	Homo. MA-Loading Core	Hetero. MA-Loading Core
Inventory at BOEC* (kg)	Np	6	719	**721**
	Am	46	710	704
	Cm	4	142	140
	Total	55	1571	1565
Inventory at EOEC* (kg)	Np	11	590	593
	Am	82	624	613
	Cm	8	173	171
	Total	101	1387	1376
Trans-muted (kg/cycle)	Np	-5	129	128
	Am	-36	86	91
	Cm	-5	-31	-30
	Total	-46.	184	189
Transmutation Rate (%/cycle)	Np	-	18.0	17.7
	Am		12.2	12.9
	Cm	-	-22.1	-21.7
	Total	-	11.7	12.1

*BOEC : Beginning of equilibrium cycle,
EOEC : End of equilibrium cycle

Table 7 Thermal Characteristics of Hetero. MA-Loading Core (MA : Minor Actinides)

Region Number	Number of Fuels*	Reference Core: Max. Assembly Power (MW)	Reference Core: Required Flow Rate** (Kg/s.)	Reference Core: Design Flow Rate*** (Kg/s.)	Reference Core: Max. Cladding Temp. (°C)	Hetero. MA-Loading Core (Optimized): Max. Assembly Power (MW)	Hetero. MA-Loading Core (Optimized): Required Flow Rate** (Kg/s.)	Hetero. MA-Loading Core (Optimized): Design Flow Rate*** (Kg/s.)	Hetero. MA-Loading Core (Optimized): Max. Cladding Temp. (°C)
IC-1	13	9.65	33.3	34.4	690	9.66/9.84****	33.2/34.5	34.5	700
IC-2	24	9.08	33.9	34.4	695	9.25	34.5	34.5	700
IC-3	54(12)	8.57	32.0	34.4	677	8.79/8.30	32.8/30.9	34.5	684
IC-4	42	8.07	29.1	34.4	650	8.02	28.3	29.5	687
IC-5	48(6)	7.99	28.2	34.4	641	8.77/8.85	30.9/31.1	34.5	668
OC-1	42	8.87	31.7	34.4	674	9.23	33.0	34.5	686
OC-2	30(6)	8.06	29.8	34.4	657	8.27/7.47	30.6/30.0	34.5	663
OC-3	18	7.26	27.2	28.2	688	7.86	29.5	29.5	700
OC-4	12(12)	6.89	27.0	28.2	686	-/6.47	-/31.9	34.5	676
OC-5	12	6.17	25.8	28.2	672	6.15	25.6	29.5	657
OC-6	24	5.67	25.2	28.2	665	5.49	24.3	29.5	643
OC-7	30	5.08	22.7	28.2	637	5.11	22.8	29.5	626
Core total	355(42)		101$4.7	11616.8			10473.5	11617.5	

*Number in parentheses shows the number of target fuels in case of hetero. MA-loading core

**Max. Cladding Temp. ≦700°C and CDF≦(.3

***Core total normalized to 91.3% of total coolant flow in primary system

****Normal Fuel /Target Fuel with MA

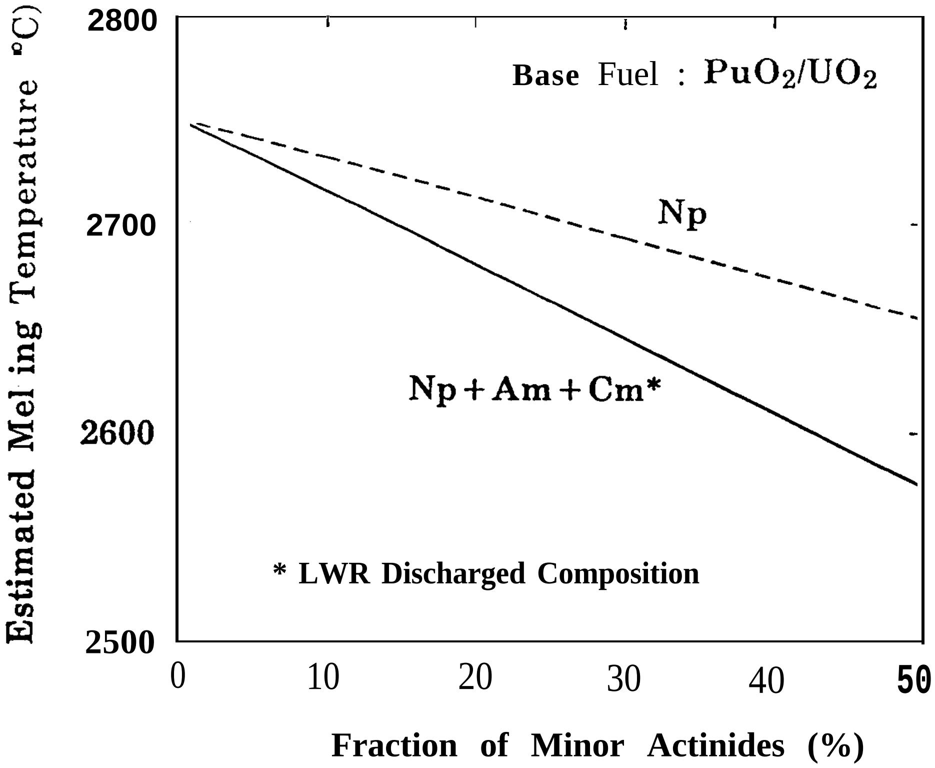


Fig. 1 Estimated Melting Temperature of Fuel Loaded with Minor Actinides

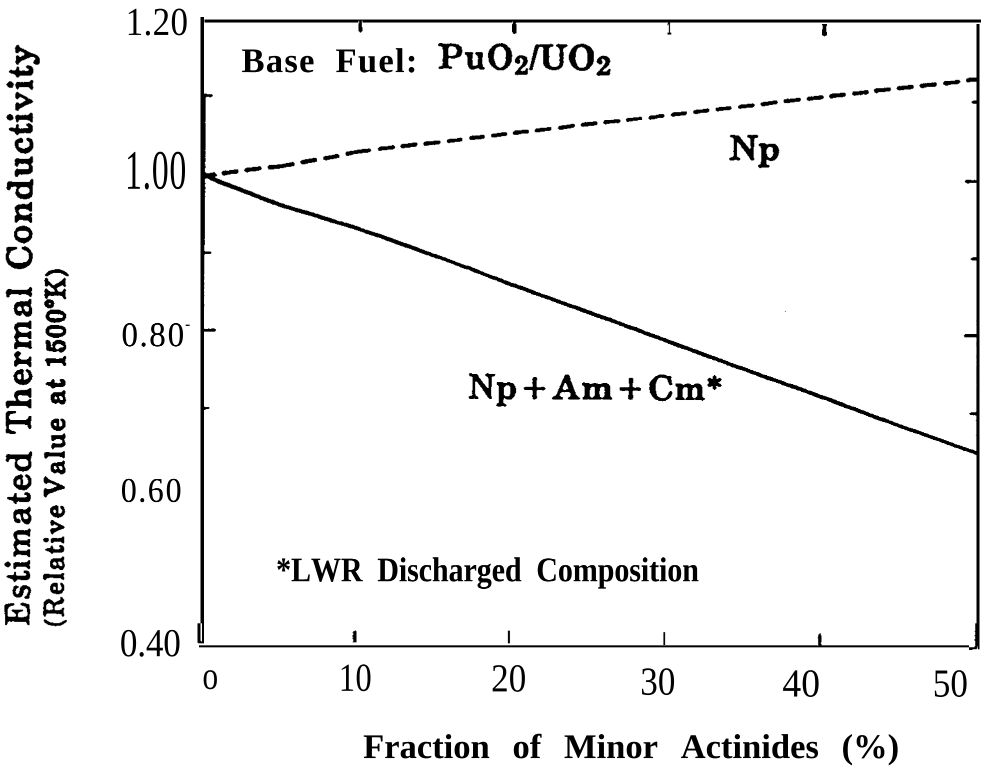


Fig. 2 Estimated Thermal Conductivity of Fuel Loaded with Minor Actinides

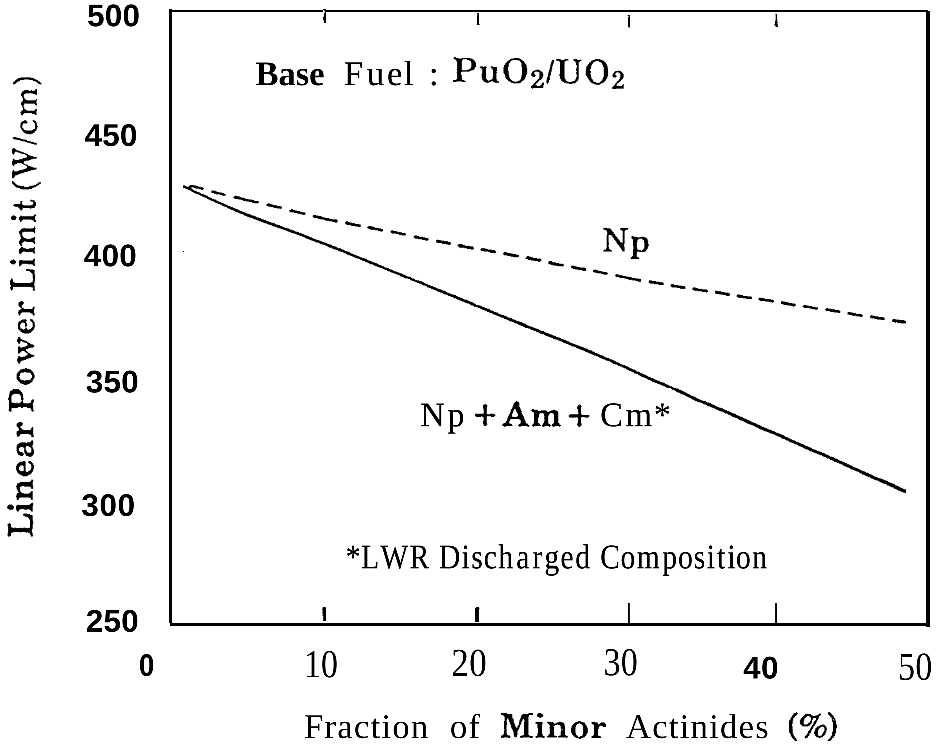


Fig. 3 Estimated Linear Power Limit of Fuel Loaded with Minor Actinides

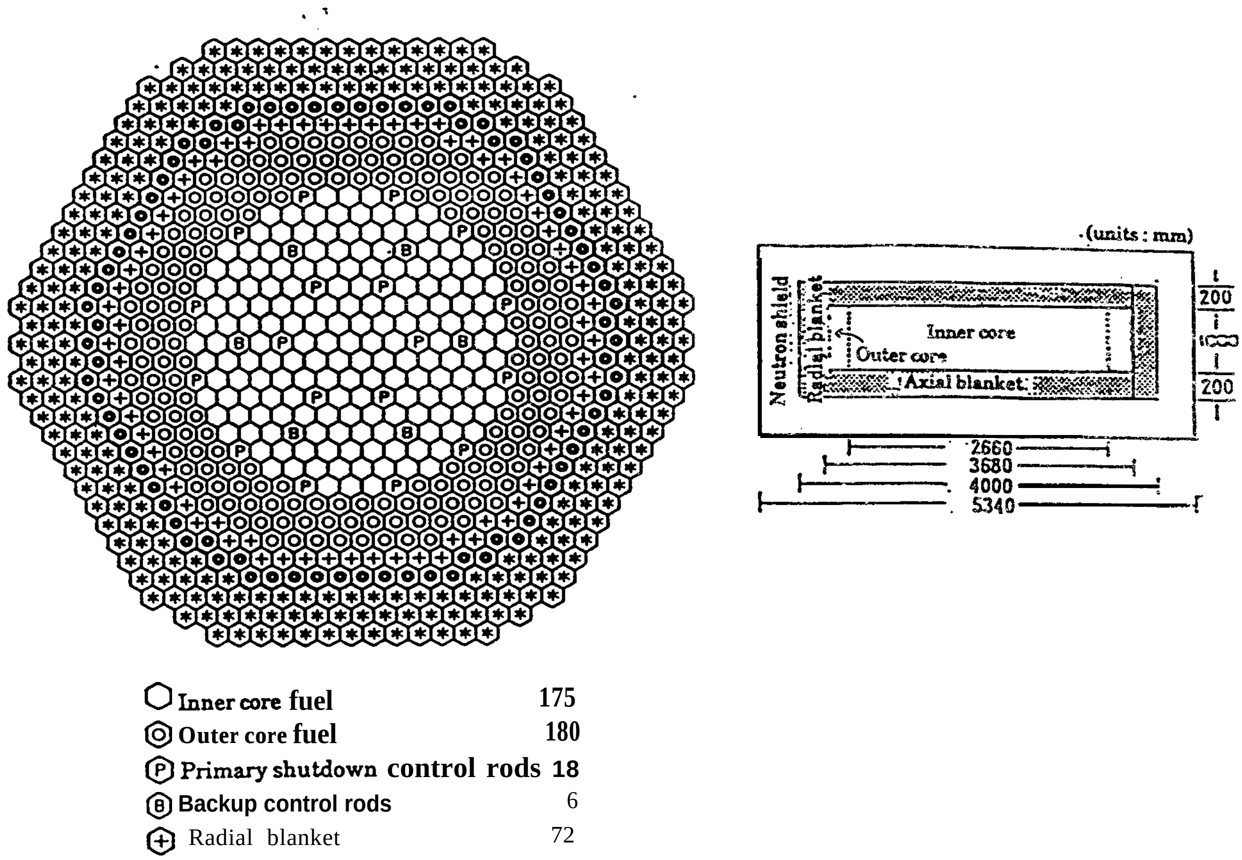
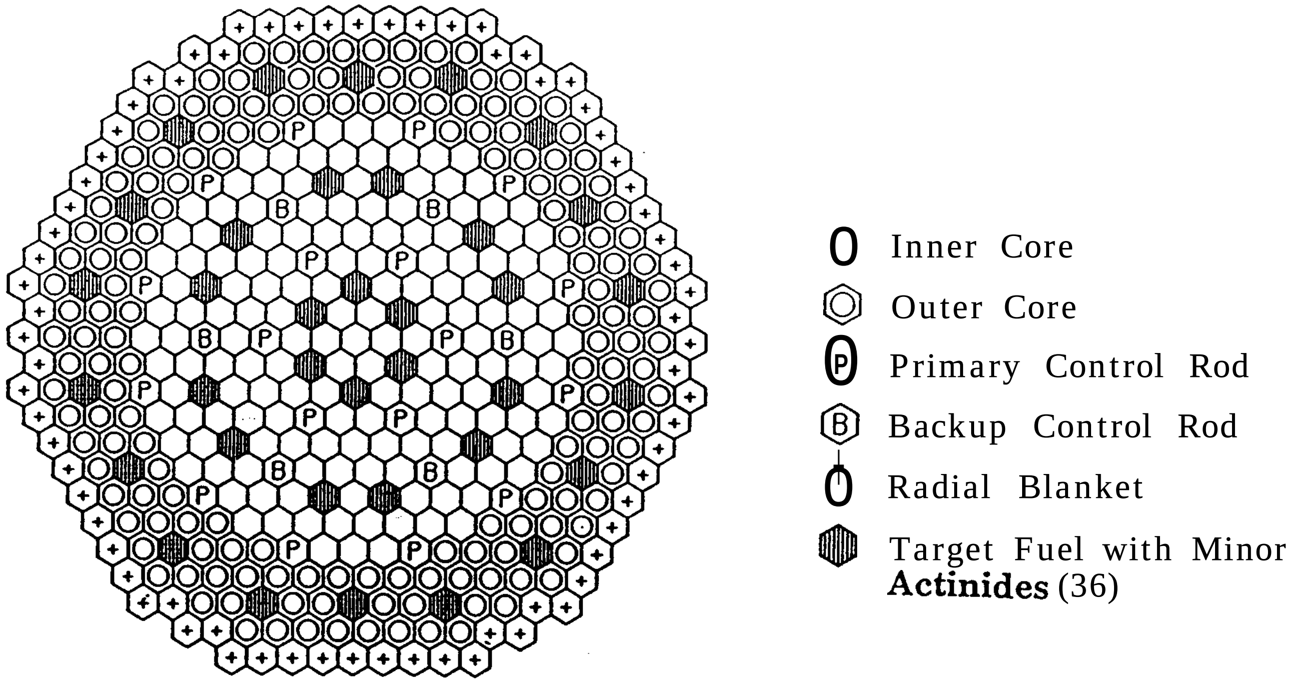


Fig. 4 1000MWe Reference Core Layout



. **Fraction of Target Fuels = 10% (36/ 355)**

Fig. 5 Typical Loading Pattern of Target Fuels

Upper: Assembly Power (Maximum for All Cycles, MW)
Lower: Linear Power (Maximum for All Cycles, W/cm)

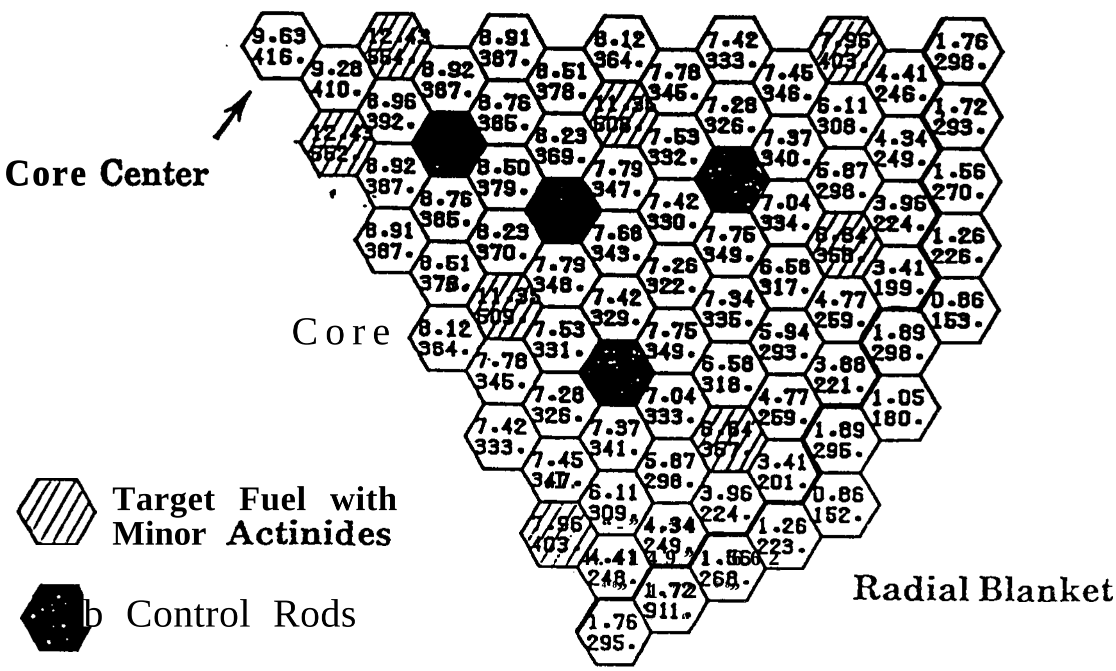


Fig. 6 Power Distribution in Hetero. MA-Loading Core
(at End of Cycle for Case 1 in Table 4)

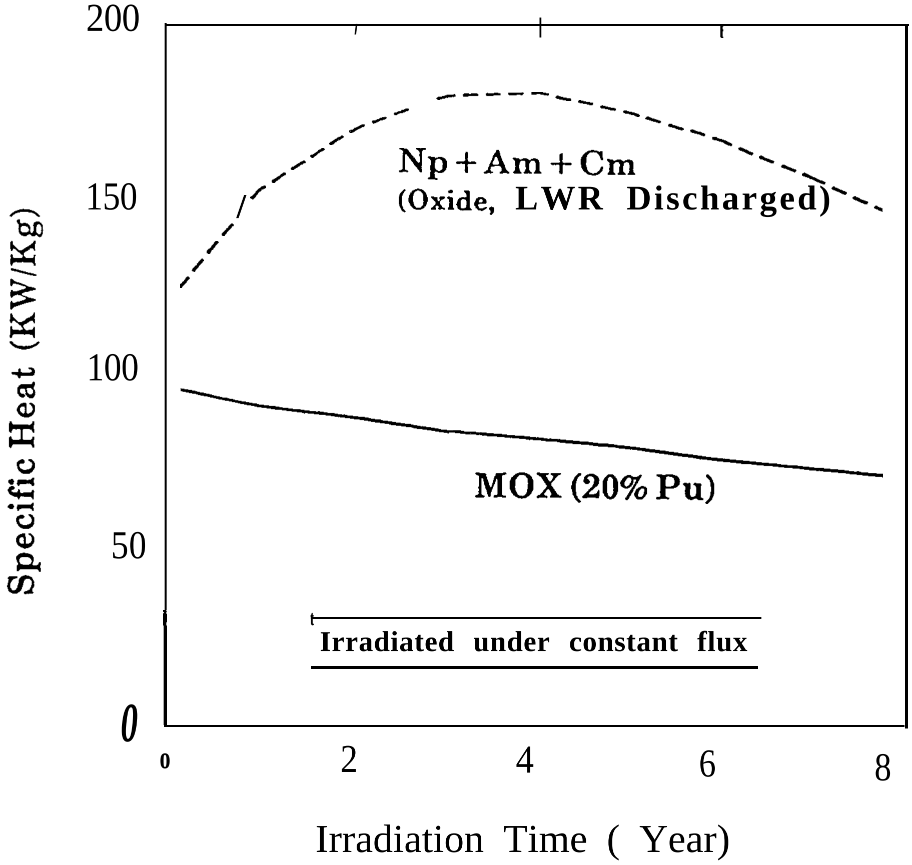
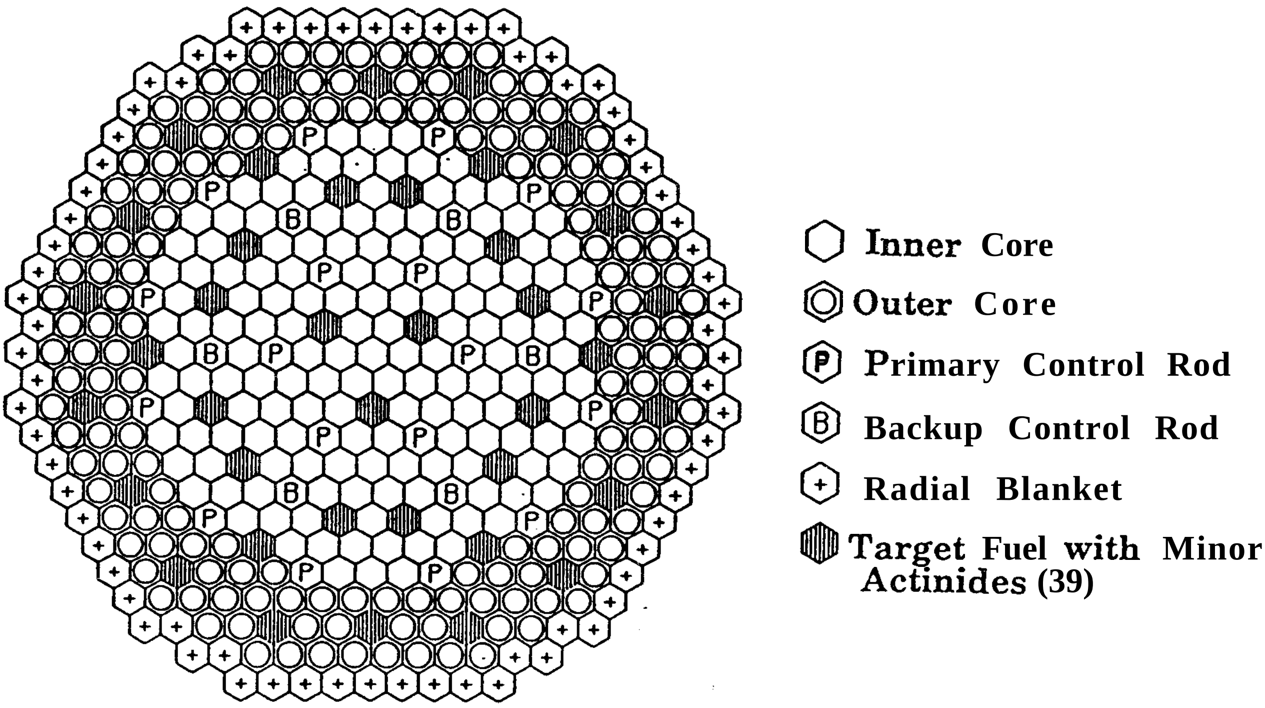


Fig. 7 . Dependency of Specific Heat of Fuel Loaded with Minor **Actinides on Burnup**



. Fraction of Target Fuels = 11% (39 / 355)

Fig. *8* Optimized Loading Pattern of Target Fuels