# CHARACTERISTICS OF AN LMFBR CORE LOADED WITH MINOR ACTINIDE AND RARE EARTH CONTAINING FUELS

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## ABSTRACT

Systematic parameter survey calculations were performed to investigate basic characteristics (burnup reactivity loss, Doppler coefficient, sodium void reactivity , control rod worth , power distribution, transmutation rate, breeding ratio etc.) of an LMFBR core loaded with minor actinide (MA) fuels which contain rare earths (RE) and also to establish MA and RE loading method which has no serious influence on core design. It was found that the homogeneous loading of MA and RE has no serious penalties to the reactor core performance , provided that the amount of MA and RE in the fuel is less than 5 and 10wt%, respectively.

## 1. INTRODUCTION

While it is essential to consider all actinide containing wastes in a total actinide recycling scheme, the high-level waste(HLW) certainly presents the most difficult partitioning problem. Especially, separation of the trivalent minor actinides (Am, Cm, and higher products) from rare earths (RE) is notoriously difficult. Several methods have been successfully applied to isolating an actinides/RE fraction from the HLW. Although feasibility studies of MA transmutation have been implemented to establish MA transmutation technology by LMFBRs[1~6], it is necessary to investigate the impact of maximum tolerable amount of RE in minor actinide(MA) containing fuels from a viewpoint of core performance to establish MA transmutation technology in consideration of the total MA recycling system.

In the present study, systematic parameter survey calculations were implemented to investigate basic characteristics (burnup reactivity loss, Doppler coefficient, sodium void reactivity, control rod worth, power distribution, transmutation rate, breeding ratio etc.) of LMFBR cores loaded with MA fuels which contain RE and also to establish MA and RE loading method which has no serious influence on core design.

## 2. CALCULATIONAL METHOD

A 1000MWe homogeneous core with two enrichment zones was employed as a reference core. The main specifications of the reference core of MOX fuel are shown in Table 1.

The following items are selected as parameters;

(1) Content of MA in fuel and blanket: O - 20%

(2) Content of RE in fuel and blanket: O - 30%

(3) Fuel materials : oxide and nitride

(4) Configuration of MA and RE containing fuels : homogeneous loading method that MA and RE fuels are dispersed uniformly throughout the core, MA and RE loading method in the axial and/or radial blanket.

When adding MA and RE in the core, these new isotopes were homogeneously distributed all over the fuel , in replacement of heavy nuclides of uranium and plutonium . The fuel enrichment in $PuO_2$ was adjusted to get the same cycle length and overall fuel residence time and the same reactivity at the end of equilibrium core.

Ten nuclides of RE which have effect on core performance were selected in the study as shown in Table 2.

The nuclear characteristics of RE- loaded core were calculated by a burnup code on two-dimensional RZ geometries. Burnup characteristics, power distribution and reactivity coefficients were obtained from the analyses. Cross sections were collapsed from JFS-3-J2 library[7] based on JENDL-2[8]. 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.

The core confirmations of the reference core of MOX and nitride are shown in Fig. 1.

**Table 1 Main Design Parameters of the 1000MWe Reference LMFBR**

| Design Parameters | Data |
|---|---|
| **1. Plant Parameters** | |
| Reactor Thermal Power | 2517 MWt |
| Coolant Temperature (ReactorOutlet/inlet) | 530/ 375 ℃ |
| Operation Cycle Length | 15 Months |
| 2. Core parameters | |
| ·Core Concept | 2-region Homogeneous |
| Average Fuel Burnup | 91 GWD/T |
| ·Max. Linear Heat Rate | 430 w/cm |
| ·Core Diameter/Core Height | 3.6 8/1.00 m |
| Thickness of Axial Blanket (Upper/Lower) | 0.20/0.20 m |
| 3. Core fuel parameters | |
| ·Fuel Composition | $PuO_2 \cdot UO_2$ |
| ·Pu Isotope Ratio (239/240/241/242) | 5812411414<br>(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 One-Grouped Absorption Cross Section and Mass of Selected Rare Earth Nuclides in Spent Fuel

| Nuclides | Absorption Cross Section (barns) | Mass (g/t) |
|---|---|---|
| $^{153}Eu$ | 2.16 | 187 |
| $^{145}Nd$ | 0.32 | 1043 |
| $^{143}Nd$ | 0.29 | 1103 |
| $^{141}Pr$ | 0.15 | 1827 |
| $^{144}Nd$ | 0.09 | 2315 |
| $^{154}Eu$ | 2.58 | 62 |
| $^{150}Sm$ | 0.39 | 406 |
| $^{146}Nd$ | 0.12 | 1207 |
| $^{147}Sm$ | 0.77 | 161 |
| $^{148}Sm$ | 0.33 | 330 |

## 3. RESULTS AND DISCUSSION

### 3-1. MOX Fuel Core

The nuclear characteristics of the RE-loaded cores are shown in Tables 3, 4 and 5.

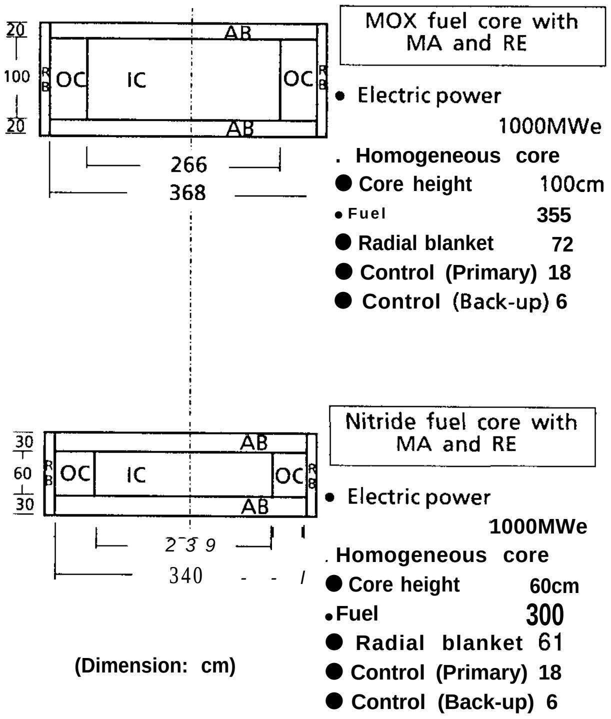

**Fig .1 MOX and Nitride Fuel Cores with MA and RE.**

The plutonium enrichment of RE- loaded cores is increased by -20% at the introduction of 10% RE due to neutron absorption of RE.

The MA loading to core results in significant decrease of burnup reactivity loss mainly due to the production of $^{238}Pu$ from $^{237}Np$ in fuels. On the other hand, the burnup reactivity loss increases by the introduction of RE. The maximum amount of RE would be limited to 10% from the aspect of reactor operation . In the case of adding MA and RE in the axial and radial blanket region, the burnup reactivity loss can be kept up -3% Δk/kk’ at the introduction of 20% RE.

The maximum linear heat rate of each RE- loaded core is not so much different with that of the MA- loaded core without RE. Concerning to the swing of power distribution between the beginning and the end of equilibrium cycle , it is possible to minimize the power swing by optimizing the plutonium enrichment ratio between inner and outer core region.

The RE- loaded cores can transmute MA by 10-11% , and there is not large difference between the MA- loaded cores with and without RE. Since a 1000MWe-class LWR produces about 26 kg of MA per year , an LMFBR with 5?70 MA-loading can transmute the MA mass from six LWRS in rough estimation. Minor actinides are transmuted at a rate of 6% per cycle in the axial and radial blanket region.

The control rod worth of the RE- loaded core is almost the same as the value of the MA- loaded core without RE.

The Doppler coefficient of the RE -loaded core is -16% smaller in absolute value, and the sodium void reactivity is -7% larger than the MA- loaded core without RE because of the spectrum hardening.

The breeding ratio decreases as the increase of the content of RE in the core fuel due to neutron absorption of RE. The impact of RE in the axial and radial blanket on breeding ratio is very small.

It was found that the homogeneous loading of MA and RE in the MOX fuel core has no serious penalties to the reactor core performance , provided that the amount of MA and RE in the fuel is less than 5 and 10wt%, respectively. It is pssible to insert ~5wt% of MA and -20wt% of RE in the axial and radial blanket from the viewpoint of core performance.

**Table 3 Core Performance of the MOX Fuel Core with MA and RE**

| Item | Case-1 | Case-2 | Case-3 | Case-4 |
|---|---|---|---|---|
| RE(wt%) | 0 | 10 | 30 | 10 |
| MA(wt%) | 5 | 5 | 5 | 20 |
| Pu Enrichment (wt%) | 16.6( Inner)<br>20.1(Outer) | 20. 0(Inner)<br>24.2( Outer) | 29.2( Inner)<br>35.4( Outer) | 21.9( Inner)<br>26.5( Outer) |
| Burnup Reactivity (% Δk/kk') | 2.12 | 3.71 | 6.40 | 0.69 |
| Maximum Linear Heat Rate (W/cm) | 407 | 413 | 433 | 416 |
| Breeding Ratio | 1.07 | 0.95 | 0.74 | 0.94 |
| MA Transmutation Rate(%) | 10.9 | 10.3 | 9.7 | 11.3 |

**Table 4 Core Performance of the MOX Fuel Core with MA and RE**

| Item | Case-5 | Case-6 | Case-7 |
|---|---|---|---|
| RE(wt%) | 20 (Axial Blanket) | 20 (Radial Blanket) | 20(Radial & Axial Blanket) |
| MA(wt%) | 5 (Axial Blanket) | 5 (Radial Blanket) | 5(Radial & Axial Blanket) |
| Pu Enrichment (wt%) | 15.4( Inner)<br>18.6( Outer) | 15 .4( Inner)<br>18.6( Outer) | 15.4( Inner)<br>18.6(Outer) |
| Burnup Reactivity (% Δk/kk') | 3.00 | 2.79 | 3.01 |
| Maximum Linear Heat Rate (W/cm) | 428 | 430 | 436 |
| Breeding Ratio | 1.07 | 1.08 | 1.05 |
| MA Transmuta-tion Rate in Blanket(%) | 6.9 | 4.7 | 6.0 |

**Table 5 Reactivity Coefficients and Control Rod Worth of the MOX Fuel Core with MA and RE**

| Item | Case-l | Case-2 |
|---|---|---|
| RE(wt%) | 0 | 10 |
| MA(wt%) | 5 | 5 |
| Doppler Coefficient (x10$^{-3}$Tdk/dT) | -4.3 | -3.6 |
| Na Void Reactivity (% Δk/kk') | 2.7 | 2.9 |
| Control Rod Worth (%Δk/kk') | 1.50 | 1.47 |

## *3-2.* Nitride Fuel Core

Nitride fuel offers a number of advantages as compared with MOX fuel : high density and high thermal conductivity yield superior breeding performance, allow high specific powers, and promise reduced costs for fuel cycle and plant capital investments for LMFBR. From the parameter survey calculations[9] of the core characteristics of the nitride fuels , it was found that we can design the nitride fuel cores having low burnup reactivity and low sodium void reactivity because of their high breeding ratios and high linear heat rate leading to the small core size. The nitride fuel is considered to be one of the attractive FBR fuels in future owing to its good core characteristics and thermal performances.

The nuclear characteristics of the RE-loaded core using the excellent properties of nitride fuel were investigated . In view of bundle pressure drop, the core height of the nitride fuel was reduced from 100cm of MOX fuel core to 60 cm. For the suppression of increasing burnup reactivity according to lower core height, the pin diameter was selected by 8.5mm.

The nuclear characteristics of the RE-loaded nitride fuel cores are shown in Tables 6 and 7.

The plutonium enrichment of RE-loaded nitride fuel core is increased by - 16% at the introduction of 10% RE because of neutron absorption of RE.

The burnup reactivity loss of RE-loaded nitride fuel decreases by ~2%Δk/kk' in comparison with that of RE-loaded MOX fuel core. It is possible to insert RE in the nitride fuel more than 10%.

The maximum linear heat rate of RE-loaded nitride fuel core is not so much different with that of the MA- loaded core without RE.

The RE- loaded nitride fuel cores can transmute MA by - 13% , and there is no difference between the MA- loaded cores with and without RE. The transmutation rate is higher in nitride fuel core than in MOX fuel core because of the hard neutron spectra.

The Doppler coefficient of the RE- loaded core is - 14% smaller in absolute value than that of the MA- loaded core without RE. The sodium void reactivity of the MA- loaded core containing 10?6 RE is nearly equal to the value of the MA- loaded core without RE.

The impact of RE in the nitride fuel core on breeding ratio is small.

It was found that the nitride fuel core has potential to transmute MA containing RE while keeping high core performances and low sodium void reactivity.

**Table 7 Reactivity Coefficients of the Nitride Fuel Core with MA and RE**

| Item | Case-1 | Case-2 | Case-3 |
|---|---|---|---|
| RE(wt%) | 0 | 0 | 10 |
| MA(wt%) | 0 | 5 | 5 |
| Doppler Coefficient (x10 $^{3}$Tdk/dT) | -4.2 | -2.9 | -2.5 |
| Na Void Reactivity (%Δk/kk') | 1.9 | 2.3 | 2.4 |

**Table 6 Core Performance of the Nitride Fuel Core with MA and RE**

| Item | Case-1 | Case-2 | Case-3 |
|---|---|---|---|
| RE(wt%) | 0 | 0 | 10 |
| MA(wt%) | 0 | 5 | 5 |
| Pu Enrichment (wt%) | 12.8(Inner)<br>17.5(Outer) | 12.9(Inner)<br>17.5(Outer) | 15.0(Inner)<br>20.3(Outer) |
| Burnup Reactivity (%Δk/kk') | 1.52 | 0.13 | 1.42 |
| Maximum Linear Heat Rate (W/cm) | 767 | 759 | 764 |
| Breeding Ratio | 1.38 | 1.41 | 1.34 |
| MA Transmutation Rate(%) | - | 12.6 | 12.7 |

## 5. CONCLUSION

As a result of the study , it was found that the homogeneous loading of MA and RE has no serious penalties to the reactor core performance , provided that the amount of MA and RE in the MOX fuel is less than 5 and 10wt% respectively. The MA transmutation rate reaches approximately 10% per cycle with the loading of the ratio of 5wt% MA in a 1000MWe MOX fuel LMFBR. The amount of the MA transmutation is almost six times as much as that of the MA production from a 1000MWe-class LWR. In the case of adding MA and RE in the axial and radial blanket region , it is possible to insert ~5wt% of MA and ~20wt% of RE in the axial and radial blanket assemblies from the viewpoint of core performance. Minor actinides are transmuted at a rate of 6% per cycle in the axial and radial blanket region. The nitride fuel core has potential to transmute MA containing RE while keeping high core performances and low sodium void reactivity.

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