DOI: 10.15669/pnst.8.154

Progress in Nuclear Science and Technology
Volume 8 (2025) pp. 154-159

ARTICLE

Study of Scenarios for Minor Actinide Transmutation by Deployment of Metal-Fueled Fast Reactor in Japan

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For future domestic implementation of minor actinide transmutation, the deployment scenario and the core concept of metal-fueled fast reactor were designed consistent with oxide fuel cycle proceeded in Japan. Three core concepts were designed according to the composition of recycled fuel from various spent fuels, and the feasibility and effectiveness of fast reactor deployment were indicated based on the fuel cycle parameter study.

KEYWORDS: fast reactor, metal fuel, reprocessing, minor actinide transmutation, scenario

I. Introduction

Future deployment of fast reactor (FR) is under consideration in Japan. Effective use of resources and decreasing environmental burden of radioactive waste disposal by Pu and minor actinides (MAs) recycling are indicated as the value of the FR deployment. On the other hand, recycling of spent fuel (SF) of light water reactors (LWRs) is currently in progress in Japan. Therefore, it is important to investigate FR deployment consistent with present domestic fuel cycle using LWRs.

This study focused on MA transmutation, and the deployment scenario of FR into Japan was investigated. The structure of fuel cycle investigated in this study is shown in **Fig. 1**. LWR fuel cycle using oxide fuel and PUREX reprocessing is progressed in Japan. The recovered Pu by reprocessing is recycled as mixed oxide (MOX) fuel and used in LWRs. For adapting the FR deployment to this LWR fuel cycle, we considered that the fuel material and MA are fed to the FR fuel cycle from the LWR fuel cycle as the recovered material by reprocessing or the spent MOX fuel itself.

Metal-fueled FR are being developed in the U.S.. We referenced the small metal-fueled FR (PRISM) investigated in U.S.[1,2] And pyro-reprocessing with the molten salt electrolysis method[3] was employed for the FR fuel cycle. The combination of a metal-fueled FR and pyro-reprocessing has the advantage of high proliferation resistance because, in principle, Pu is not recovered alone and recovered with MAs (Np, Am, and Cm) in pyro-reprocessing. Additionally, MA recovery ability of pyro-reprocessing is useful for MA recycle. For smaller reprocessing facilities, pyro-reprocessing was evaluated to be more economical than wet-reprocessing.[4]

In this study, the specifics of material flow of FR fuel cycle and the FR deployment pace were investigated as the fuel cycle scenario study. Furthermore, the FR core designs

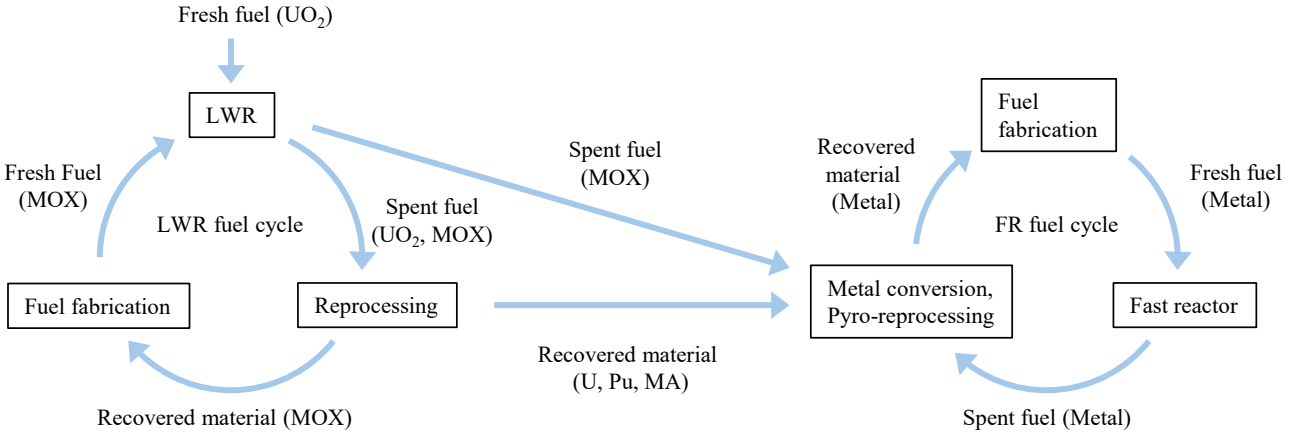

Fig. 1 The structure of fuel cycle investigated in this study

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suitable for the FR fuel cycle were investigated based on the composition of recycled SF. Lastly, the fuel cycle parameter study was carried out, and the feasibility and the effectivity of the FR fuel cycle were evaluated.

II. Evaluation Methods

1. Fuel Cycle Scenario Investigation

The specification of material flow of FR fuel cycle was detailed based on the fuel cycle structure shown in Fig. 1. In this fuel cycle, three species of SF are generated: LWR UO_2-SF, LWR MOX-SF, and FR metal-SF. Since Pu recovered by reprocessing of SF is used as ingredient of FR fresh fuel, three types of FR core and reasonable material flow of fuel cycle were investigated based on the nuclide composition of SF.

The pace of FR deployment was also investigated. The following points was considered:

- Japanese government assumption that introducing FR in the mid-21st century and the further operation of FRs in the latter half of this century
- The deployment status of domestic LWRs
- 60 years of the nuclear power plant lifespan
- Replace of LWR to LWR before the large-scale deployment of FR

2. FR Core Analysis

The FR core concept was designed referencing small metal-fueled FR (PRISM) investigated in U.S.[1] Thermal power generation is 840 MWt and electric power generation is 311 MWe. U-Pu-Zr fuel and U-Zr fuel are used for core fuel and blanket fuel, respectively. The reference core had passive safety systems of Gas Expansion Module (GEM) to automatically increase neutron leakage for the loss of coolant flow accident.

Burnup characteristics and reactivity coefficients were calculated by MARBLE[5] based on diffusion theory using a two-dimensional R-Z model. The reactivity of GEMs was evaluated using SN neutron transport calculation with three-dimensional TRI-Z model to improve the accuracy of neutron leakage evaluation.

The fresh fuel and SF composition of UO_2 and MOX fuels and the reprocessing performance were determined based on reported values.[3] Especially, the fresh fuel and SF composition of metal fuel were evaluated newly in this study, and the SF composition was calculated using ORIGEN code.[6]

3. Fuel Cycle Parameter Study

The fuel cycle parameter study was carried out using spreadsheet software. Input conditions were as follows:

- The nuclear power generation capacity toward future was determined based on the domestic estimations such as the 2030's energy use prediction and the MOX fuel utilization plan in Japan.
- Compositions of fresh fuel and SF of LWR UO_2-fuel and MOX-fuel were referenced from the reported values.[7] Then, the SF amount ratio of boiling water reactor (BWR) to pressurized water reactor (PWR) was assumed as 1:1 for UO_2-fuel and about 3:1 for MOX-fuel.
- For the LWR fuel cycle, the recovery ratio of U and Pu was set to 99.9%, and the recovery ratio of MA was set to 99.5%.
- Material balance in the pyro-reprocessing was evaluated based on the previous research[3]. The recovery ratio for U, Pu, and MA is greater than 99%.
- Three species of FR core were investigated in this study as indicated in section III. Therefore, the ratio of FR core was evaluated to balance and decrease the accumulated SF amount.
- Fuel fabrication and reprocessing pace needed were automatically determined by FR deployment pace and FR specification.

III. Results and Discussion

1. FR Deployment Scenario

(1) FR Fuel Cycle Structure and Material Flow

The material flow of the FR fuel cycle is shown in **Fig. 2**. Three types of FR core (core-D, B, and E) were investigated in this study. Core-D uses the recycling fuel of LWR

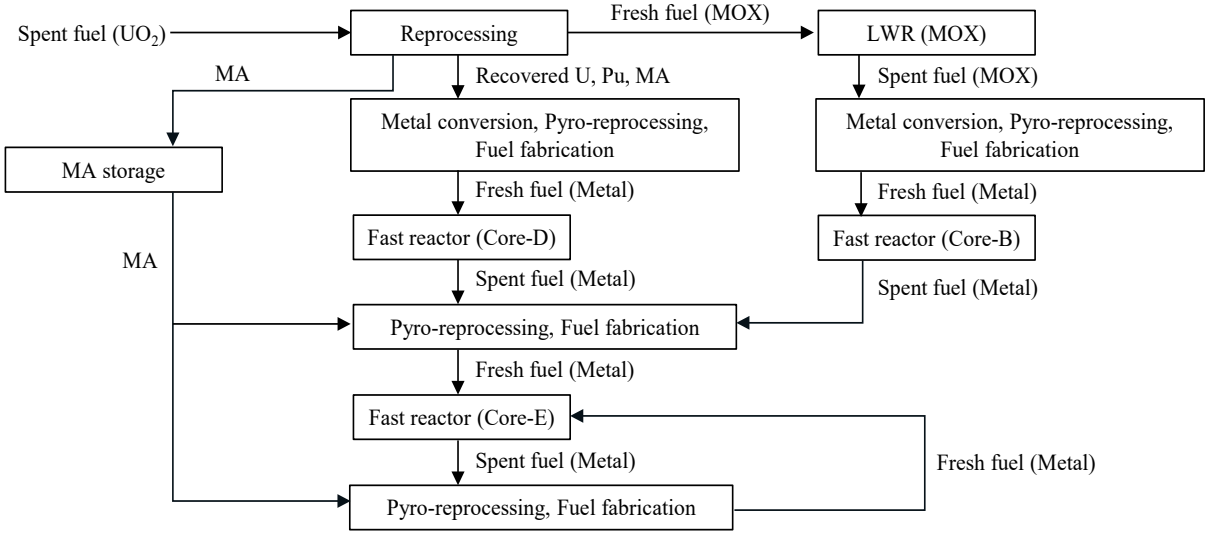


Fig. 2 The material flow of FR fuel cycle

UO_2-SF. Core-B uses the recycling fuel of LWR MOX-SF which has relatively low Pu fissile (Puf) composition. Core-E is used for recycling of metal-SF.

The MA recovery in the reprocessing of LWR UO_2-SF was assumed to start at 2060 because MA recovery method is in development stage. It was assumed that MA would not be recovered until 2060 and would migrate into high-level radioactive waste. On the other hand, because of limitation of MA concentration in metal fuel, all amount of the recovered MA could not be added to fresh metal fuel of Core-D in early stage of FR deployment. MA concentration was considered as below 5% in this study as mentioned in part III. 2. (1). Therefore, temporary MA storage and future MA feeding to fuel fabrication were assumed in this study. On the other hand, Pu and MA are co-recovered in the pyro-reprocessing, all recovered MA was assumed to be recycled as metal fuel without the temporary storage.

(2) FR Deployment Pace

Nuclear power generation capacity and its ratio of each plant are shown in **Fig. 3**. Following points were considered:

- Construction of the first FR (core-D without MA until 2060) in 2040, followed by gradual construction of FRs.
- The large-scale FR deployment (replace to FR from LWR reached end of their lifespan) started after about 2090. All nuclear power reactors will be replaced with FRs eventually.
- Total nuclear power generation by MOX-fuel was set to about 5 GWe. MOX-fuel use in LWRs stopped at the start timing of large-scale FR deployment because of supplying Pu to FR fuel fabrication.
- The ratio of FR core-D, B to E was determined to balance and decrease the accumulated SF amount. It was evaluated that about 10 modules of core-D and B were necessary to recycle LWR UO_2-SF and LWR MOX-fuel. And it was indicated that core-E should be introduced as the other FR.
- Total nuclear power generation capacity was set to about 30 GWe. That was slightly decreased in the future because the FR was assumed to have a relatively higher facility utilization ratio.

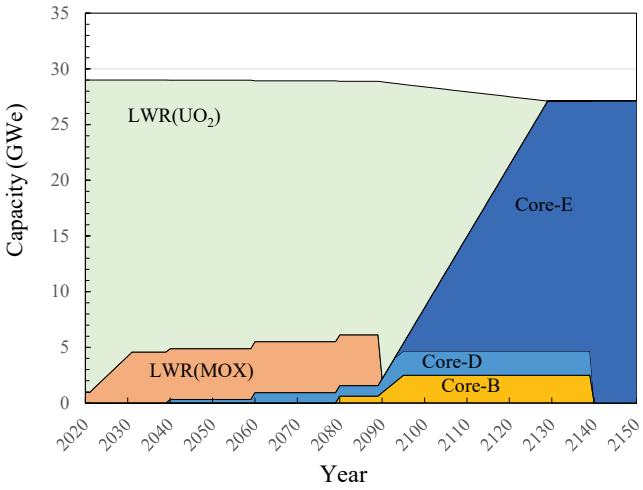


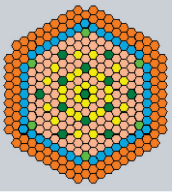
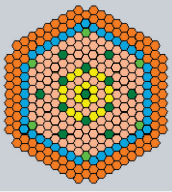
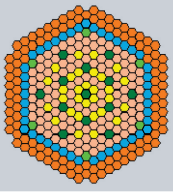
Fig. 3 FR deployment pace

2. Fast Reactor

(1) Core Configuration

Fast reactor core configuration is shown in **Table 1**. Core fuel, inner blanket (IB) and radial blanket (RB) were used as fuel. The number of core components depended on the type of core. Core fuel was U-Pu-MA-Zr alloy and blanket fuel was U-Zr alloy. Pu concentration was assumed as ≤ 25%, and MA concentration was assumed as ≤ 5% in this study; these concentrations were determined by taking into account the extensive range of experimental study.[8] Puf/Pu ratio was determined by the composition of recycled SF. For core-E, Puf/Pu ratio increased by multi-recycle; the biggening Puf/Pu ratio was evaluated as 58 %. The Pu surviving ratio, which means ratio of Pu amount in the fed fuel to the

Table 1 Fast reactor core configuration and fuel specifications

Items		Core-D	Core-B	Core-E
Core configuration (Horizontal section)				
Number of core components	Core fuel	120	132	120
	Inner blanket	30	18	30
	Radial blanket	45	45	45
	Control rod	13	13	13
	GEM	6	6	6
	Reflector and shield	177	177	177
Core fuel (Values used evaluation)	Pu source	Recovered Pu from spent UO_2 fuel reprocessing	Recovered Pu from spent MOX fuel pyro-reprocessing	Recovered Pu from spent metal fuel pyro-reprocessing
	Pu	23 %	24 %	≤ 25 %
	Puf/Pu	62 %	49 %	> 58 %
	MA	4.2%	4.2 %	4.2 %
Pu surviving ratio		1.05	1.01	1.13

removed fuel, was over 1; each core was shown to be capable of Pu breeding. Incidentally, we used Pu surviving ratio to evaluate the material balance of Pu element in this study.

MA-free U-Pu-Zr fuel was used in Core-D until 2060, when MA recovery would not be implemented. The Pu concentration at that time was assumed to be 24%.

In Core-B, the ratio of Puf in Pu was low because spent MOX fuel was recycled. Therefore, the blanket fuel was reduced and the core fuel was increased, and the Pu concentration in the fuel was set slightly higher to maintain reactor criticality within the Pu concentration limit.

(2) Fuel Exchange

Fuel exchange specification is shown in **Table 2**. The calculations were performed with Effective Full Power Day (EFPD) set to meet the design conditions of core configuration and Pu enrichment ratio shown in Table 1, and average discharge burnup of 106.3 GWd/t. The number of core fuel assemblies (core fuel) in Core B was increased compared to Core D and E. Therefore, the power sharing ratio of one core fuel assembly decreased, and the operation period (EFPD) was increased to adjust the average burnup of the core fuel withdrawal to the target value. Fuel exchange pace could be evaluated by inventory, batch number, and fuel cycle length. Fuel density was assumed as 15.8g/cc. The volume of the fuel in the core was calculated from the shape of the fuel rods, referring to literature,[2] and the total weight of the fuel was calculated from the volume and density of the fuel. Fuel cycle length was determined by EFPD and regular inspection period determined referencing that of LWRs.

Table 2 Fuel exchange specifications

Parameters		FR core		
		D	B	E
Power generation MWt		840	←	←
EFPD (day)		583	611	576
Fuel cycle length (day)		681	709	674
Average burnup (GWd/t)		106.3	←	←
Batch number	Core	3	←	
	IB	2	←	←
	RB	2	5	2
Fuel exchange (t/batch)	Core	3.69	4.06	3.69
	IB	3.05	1.83	3.05
	RB	3.05	1.83	3.05

(3) Pu and MA behavior for core-D and B

The changes in Pu and MA concentrations in core fuel before and after burnup are shown in **Table 3**; in Core-D and Core-B, both Pu and MA concentrations decreased due to burnup. In this study, as shown in Figure 2, the spent metal fuels from Core-D and Core-B are recycled to Core-E, and the new fuels from Core-D and Core-B are produced by recycling spent UO_2 fuel and spent MOX fuel. Therefore, the scenario does not take into account changes due to repetition, as in the case of multi-recycling in Core-E, which is described below.

Table 3 Pu and MA concentration changes for core-D and B

Parameters		Fresh fuel	Spent fuel
Concentration for core-D (%)	Pu	23	20
	MA	4.2	3.3
Concentration for core-B (%)	Pu	24	21
	MA	4.2	3.4

(4) Pu Behavior in FR Multi-Recycle using core-E

In the case of multi-recycle with core-E, Pu concentration and Puf/Pu ratio in SF changes by recycle. Therefore, we decided to control Pu concentration in fresh fuel for balancing fuel parameters. Pu concentration in fresh fuel (our setting value) and Puf/Pu ratio (automatically determined by SF composition) are shown in **Fig.4**(a) and (b). In the initial stage, the Puf concentration was low, so the Pu concentration was set to a relatively high value as approximately 24%. By repeating the recycling process, the Puf concentration gradually increased, so it was decided to gradually decrease the Pu concentration. In this study, the Pu concentration was balanced at approximately 22% and the Puf concentration at approximately 70%.

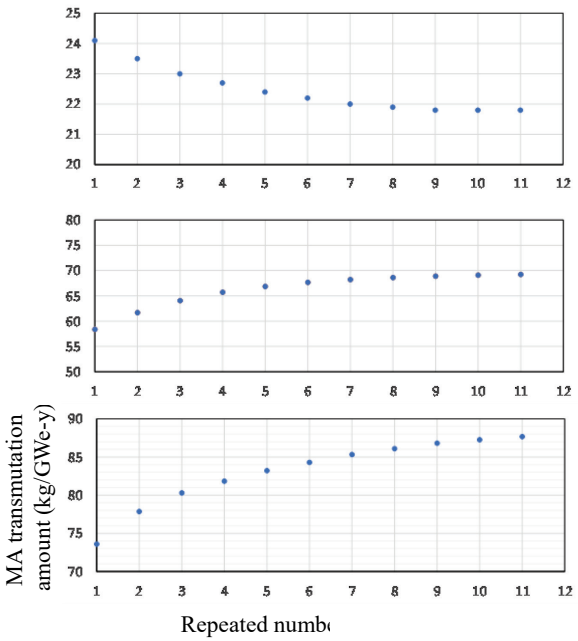


Fig. 4 Pu and Puf concentration and MA transmutation behavior in multi-recycle of metal fuel; (a) Pu concentration in fresh core fuel, (b) Puf/Pu in fresh core fuel, (c) MA transmutation amount

(5) MA Behavior in FR Multi-Recycle using Core-E

MA transmutation amount was evaluated by the difference in MA amount between fuel loading and fuel removal. The change of MA transmutation amount is shown in Fig. 4(c). The MA transmutation amount was about 80

kg/GWe-y and gradually increased, and finally a tendency towards convergence was observed. The reason for the change in MA transmutation amount was due to the change in MA composition in the fuel. Initially, the ratio of Am in MA was higher. However, the proportion of Np, which is easily combustible, increased by the recycle.

3. Fuel Cycle Parameter Study

(1) Spent Fuel Accumulation

Spent fuel accumulation amount is shown in **Fig. 5**(a). Total amount decreased toward future, it means that MOX use in LWR and FR deployment were effective to reduce SF storage amount in Japan. And it appeared that SF as Pu source was enough for FR deployment, therefore, the feasibility of FR deployment pace shown in Fig. 3 was confirmed.

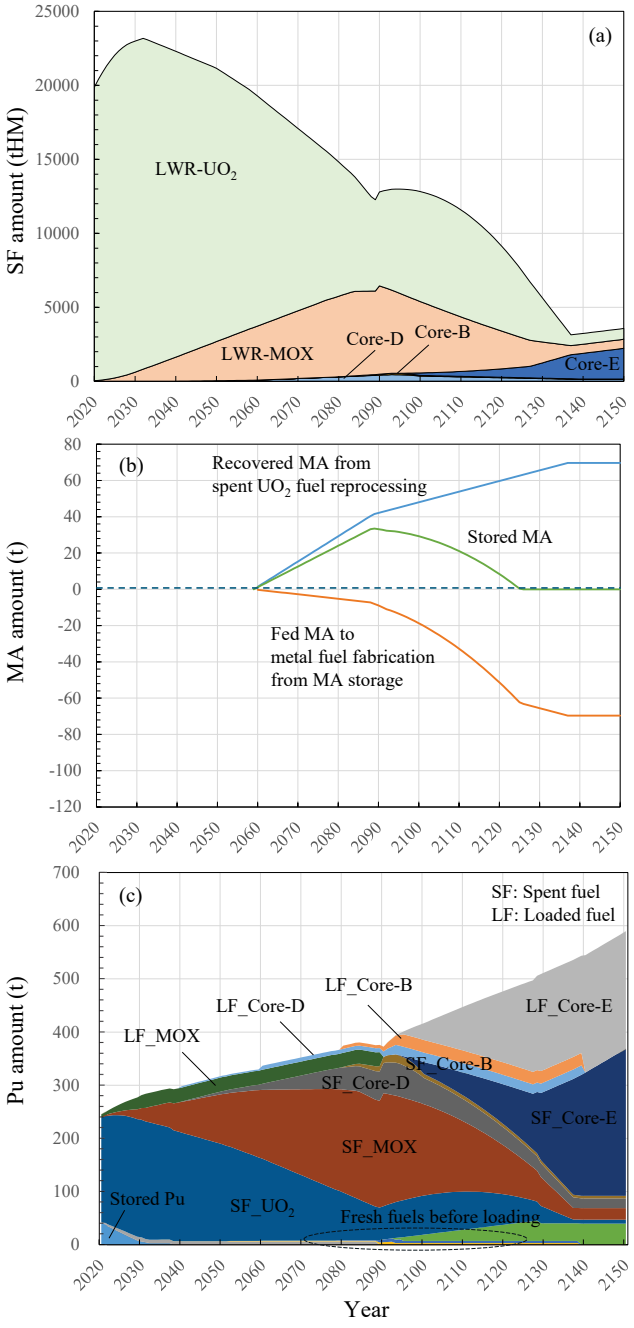


Fig. 5 Results of the fuel cycle parameter study; (a) SF accumulation amount behavior, (b) MA amount behavior, (c) Pu amount behavior

The accumulated SF amount did not become zero in Fig.5(a). We considered that the amount of oxide SF could be closer to zero by adjusting the scenario such as operation of core-D and core-E. And we also considered that the amount of metal SF could be closer to zero by introducing Pu burner core; that was not investigated in this study, but burner core was investigated in previous research.[1)]

(2) MA Accumulation

MA accumulation amount is shown in Fig. 5(b). The stored MA was evaluated by the difference between the recovered MA from the reprocessing of UO_2-SF and the fed MA to metal fuel fabrication from MA storage. In the early stage of FR deployment, the stored MA amount increased because the fed MA amount to fuel fabrication was small. In the large-scale FR deployment stage, the trend of stored MA amount turned to decrease, and the stored MA amount reached to zero. Therefore, it was indicated that all MA recovered could be recycled in the fuel cycle.

(3) Pu Accumulation

Pu amount in fresh fuel, loaded fuel (LF), and SF is shown in Fig. 5(c). In the early stage, Pu existed in oxide SF mainly. Gradually Pu existing was transferred into metal fuel. Pu amount in LF was relatively small in the early stage, however, the amount increased gradually. For example, Pu amount in LF of core-E became almost same amount to Pu amount in SF of core-E at 2150. On the other hand, Pu amount in fresh fuel before loading was relatively small.

In this study, the amount of Pu required for power generation at FR muti-recycle phase was evaluated as Fig. 5. The total amount of Pu increased toward the future, however, the Pu was contained in fresh fuel, loaded fuel, and spent fuel, and the separated Pu amount was not increased because of controlling the reprocessing amount. As mentioned in the introduction, Pu was co-recovered with MA by pyro-reprocessing using electrolysis method. It means FR fuel cycle using metal-fueled FR and pyro-reprocessing has high nuclear nonproliferation ability. Furthermore, we considered that investigation of the burner core was effective to prevent increasing total Pu amount toward future.

IV. Conclusion

Domestic FR deployment scenario and metal-fueled FR core were investigated for future MA transmutation. Designs of core-D for UO_2-SF recycling, core-B for MOX-SF recycling, and core-E for metal fuel recycling were constructed. By the fuel cycle parameter study, feasibility of domestic FR deployment in the viewpoint of Pu and SF amount balance was confirmed. It was also evaluated that all recovered MA could be consumed as the FR fuel by the large-scale FR deployment; this implied almost all of the MA could be recycled in the FR fuel cycle.

Acknowledgment

This research used resources of "Program to Support the Development of Innovative Nuclear Power Technologies in Response to Society's Needs" of the Ministry of Economy, Trade and Industry.

Thanks to Dr. Tsuyoshi Murakami of CRIPEI for advising on this research.

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