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ARTICLE

Impact of Fast Reactor Fuel Type on Backend Processes in the Nuclear Fuel Cycle

Kenji TAKESHITA[1*], Tomohiro OKAMURA[1], Masahiko NAKASE[1], Takumi ABE[2] and Kenji NISHIHARA[2]

[1] Institute of Science Tokyo, 2-12-1 Ookayama, Meguro-ku, 152-0033, Tokyo, Japan
[2] Japan Atomic Energy Agency, 2-4, Shirakata, Tokai-mura, Naka-gun, Ibaraki, 319-1106, Japan

This study analyzed minor actinide (MA) inventory in scenarios assuming demonstration and subsequent commercialization of fast reactor (FR) in the mid-21st century, focusing on the characteristics of reprocessing processes in oxide and metal fuel FR cycles. At the end of the evaluation period defined in this study, the transition of MA to waste was 138 tons in the oxide fuel FR cycle without an MA separation process, requiring a footprint of geological repository of 3.01 km². In contrast, in the metal fuel FR cycle, when only spent fuel discharged from the FR was subjected to pyro-reprocessing, the MA transition to waste was nearly identical to that of the oxide FR cycle. However, when spent MOX fuel discharged from light water reactor (LWR) was also reduced to metal and processed by the pyro-reprocessing, the MA transition decreased to 93 tons, with a correspondingly reduced footprint of 2.12 km². The results show a strong link between MA transition to waste and repository footprint, highlighting the potential of metal fuel FR cycles which can reduce demand of final disposal by the metallization and pyro-reprocessing of spent MOX fuel from the LWR fuel cycle.

KEYWORDS: oxide or metal fuel fast reactor cycle, PUREX, pyro-reprocessing, final disposal

I. Introduction

The Japanese policies for utilizing nuclear energy and promoting the nuclear fuel cycle were announced in the 5th Green Transformation Implementation Council held in December 2022. Following the announcement in the Ministry of Economy, Trade and Industry (METI) Advanced Reactor WG, which indicated the aim to demonstrate a fast reactor (FR) by 2050, it is expected that R&D related to FR and its nuclear fuel cycle will be accelerated.

The demonstration FR, planned to be constructed by 2050, has been selected as a sodium-cooled FR, leveraging the accumulated technical expertise in this field. However, the decision regarding its fuel type—either oxide or metal—will be finalized by 2026. In this selection process, multiple aspects of performance will be considered, such as reactor operation, fuel supply, economic factors, as well as the feasibility of achieving a nuclear fuel cycle for long-term nuclear energy utilization.

Figure 1 show the overview of oxide and metal fuel FR cycles. Aqueous reprocessing based on the PUREX method is introduced for the oxide-fuel FR cycle (Fig.1 (1)), while pyro-reprocessing for the metal-fuel FR cycle (Fig.1 (2)). As shown in Fig. 1 (1), in the oxide-fuel FR cycle, the spent MOX fuel generated in the LWR cycle is transferred to the PUREX reprocessing plant in the FR cycle, and the highly decontaminated MOX powder (described as "Highly decon. MOX" in Fig.1) recovered at the PUREX reprocessing plant in the LWR cycle is transferred to the MOX fuel fabrication process in the FR cycle. The produced MOX fuel is burned in the FR. On the other hand, as shown in Fig. 1 (2), in the metal fuel FR cycle, the spent MOX fuel is metallized in the electrolytic reduction process and transferred to the pyro-reprocessing plant, and the highly decontaminated MOX powder is also metallized and transferred to the fuel fabrication process of the FR cycle.

The reprocessing method introduced in the FR cycle, PUREX or Pyro-reprocessing, results in significant

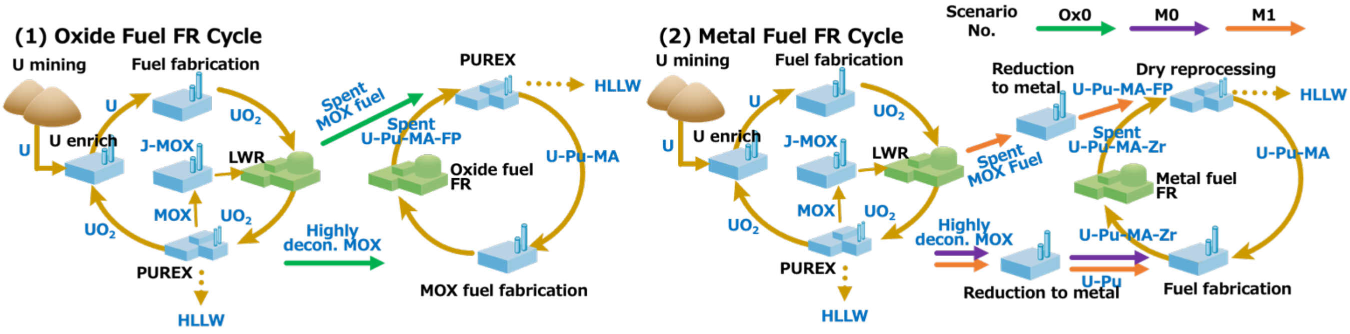

Fig. 1 Overview of Oxide and Metal fuel FR cycle

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*Corresponding author, E-mail: takeshita.k.1f97@m.isct.ac.jp

differences in the types of elements recovered as fuel and in the quantities and inventories of radioactive waste generated. Particularly the transition of minor actinides (MA) has a significant impact on the amount of final disposal waste generated from high-level radioactive waste (HLW) and the footprint of the geological repository. In the PUREX process, to prevent the transition of MA to the waste side, it is required to additionally introduce an MA separation process. An aqueous process named SELECT method is developing now for effective MA separation from HLW in Japan Atomic Energy Agency (JAEA)1) and will be applicable practically in the future. On the other hand, in the pyro-reprocessing, Pu and MA, which have similar chemical properties, are recovered simultaneously, so while it is difficult to increase the purity of Pu, it is possible to suppress the transition of MA to the waste side. In previous nuclear fuel cycle simulation studies, the effects of introducing oxide fuel FR and MA separation processes have been examined.2-4) In these reports, the following benefits that can be obtained by the separation of MA from HLW are described. ① The time to reduce the toxicity of HLW below that of natural uranium is shortened from more than 100,000 years in the case of direct disposal to hundred years. ② As the decay heat of HLW is reduced significantly by the separation of MA, the storage period of vitrified waste required for geological disposal as well as the disposal site area can be reduced. On the other hand, the effects of pyro-reprocessing in the metal fuel FR cycles have not been evaluated, and it is necessary to expand nuclear fuel cycle simulation studies to select future FR cycle technologies.

This study employs a dynamic nuclear fuel cycle simulator, NMB4,5) which was co-developed by Institute of Science Tokyo (formerly Tokyo Institute of Technology) and Japan Atomic Energy Agency. Using NMB4.0, we conduct a mass balance analysis, especially MA inventory, to assess the introduction of either oxide-fueled or metal-fueled FR cycle and clarify their impacts on the footprint of the geological repository as the volume of HLW.

II. Scenarios & Conditions

1. Nuclear Power Generation Scenarios

Figure 2 shows the assumed trends in nuclear power generation capacity up to the year 2105 in Japan (total generation capacity of 33±1 GWe). As LWRs are assumed to be implemented in the future, they remain predominantly until the end of this century. FR (0.6 GWe) would be implemented as a demonstration reactor in 2045, with the gradual introduction at the time of reactor replacement starting from 2065. For replacement with the advanced LWRs, large reactors with capacities of 1.2 GWe or 1.5 GWe were considered. In the case of replacement with FR, a capacity of 0.6 GWe was assumed. As shown in Fig.1 (1), LWR-MOX was used solely to consume the Pu recovered at PUREX reprocessing. Multi-recycling of Pu in LWR was not considered. The calculation period was set from 1970 to 2105.

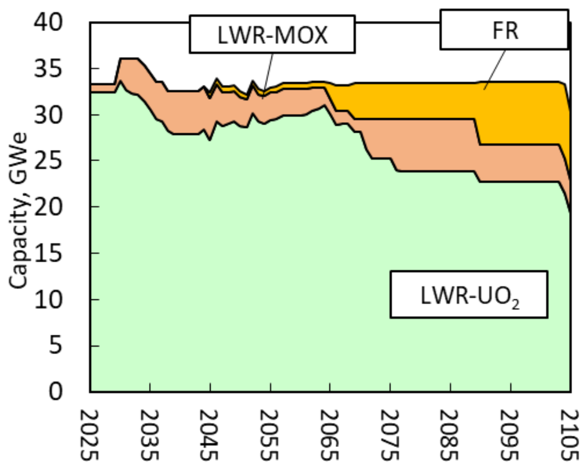

Fig. 2 Assumed nuclear power generation

2. Fuel Cycle Scenarios

In this study, the operation of reprocessing plants was assumed to span 80 years, divided into two distinct phases:

1. **2025–2064:** During the initial 40 years, the plants process 800 t-HM/y of UO_2 fuel.
2. **2065–2104:** For the latter 40 years, the plants prioritize MOX fuel reprocessing at a maximum capacity of 200 t-HM/y, supplementing with UO_2 fuel to maintain an overall throughput of 800 t-HM/y.

The reprocessing and waste conditions were assumed based on oxide or metal fuel FR cycle.

(1) Scenario of Oxide Fuel FR Cycle Implementation

Fig. 1 (1) illustrates the conceptual flow of the oxide fuel FR cycle. In this scenario, spent UO_2 fuel from LWR undergoes PUREX reprocessing and the recovered Pu is used as MOX fuel in LWR. Spent MOX fuel is transferred to the FR cycle and reprocessed in the PUREX plant of the FR cycle. The FR cycle assumes no Pu breeding and Pu recovered from LWR-PUREX reprocessing is used as a FR fuel. The PUREX method is assumed for reprocessing with recovery rates of U and Pu set at 99.588% and 99.452%, respectively.5) Noble gases, such as Kr and Xe, are not captured and released to the atmosphere. One of volatile fission products (FP), iodine, is entirely captured, while other FPs are recovered as HLW and vitrified5). This scenario is designated as "Ox0."

(2) Scenario of Metal Fuel FR Cycle Implementation

Fig. 1 (2) shows the metallic fuel FR cycle, involving two distinct scenarios, M0 and M1. In the “M0” scenario, the highly decontaminated MOX powder from the LWR-PUREX plant is metallized electrically and transferred to the fuel fabrication process in the metal fuel FR cycle. The produced metal fuel is burned in the FR. In the “M1” scenario, besides highly decontaminated MOX powder, spent MOX fuel is metallized and transferred to the pyro-reprocessing plant. The metal fuel discharged from the FR is also reprocessed by the pyro-reprocessing. The conditions for pyro-reprocessing are based on a report by the Central Research Institute of Electric Power Industry (CRIEPI),7) and the recovery rates of U, Pu and MA are assumed as shown in **Table 1**. Metallic wastes and FP-based sodalite matrices are assumed to be waste forms.

Table 1 Recovery ratios in pyro-reprocessing

Major Elements	*Minor Elements*	*Recovery Ratio*
U	U	99.80%
Pu	Np	99.80%
	Pu	99.80%
	Am	99.50%
	Cm	99.50%

3. Waste Production and Geological Disposal

The conditions for producing HLW, particularly the radioactive content of the waste form, are determined dynamically based on the inventory of radioactive materials and three constraints: ① Waste content limit, ② Heat generation limit, ③ Buffer material temperature limit during geological disposal.

For vitrified waste from PUREX, the maximum radioactive material content is set at 25 wt% excluding sodium components. For sodalite matrices from pyro-reprocessing, the content limit is 10 wt%. The heat generation limit is 2.3 kW, based on storage facility constraints at the Rokkasho Reprocessing Plant, and the buffer material temperature is capped at 100°C. The waste forms are assumed to be stored for 50 years prior to geological disposal.

As shown in **Fig. 3**, the disposal method assumes a multiple waste canister PEM (MPEM)-3 system, where three waste forms are loaded into each PEM container. This concept was created based on several report published by NUMO.6,8)

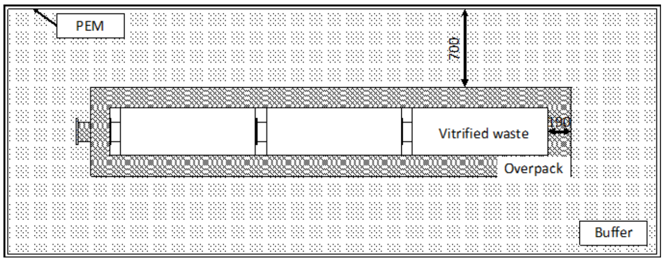

Fig. 3 MPEM-3 concept

III. Results and Discussion

1. Reprocessing of Spent Fuels and These Storage Amounts

In order to grasp the overview of the fuel cycle operation from the NMB4.0 calculation results obtained under the calculation conditions of the previous section, we show the reprocessing amounts of spent fuels, such as UO_2 fuel, LWR-MOX, and FR-MOX, and the storage amounts of these spent fuels. **Figure 4** shows the change in the reprocessing amounts of these spent fuels. The UO_2 fuel is reprocessed at the PUREX reprocessing plant in the LWR fuel cycle, and spent LWR-MOX and FR-MOX are reprocessed at the 200t-HM/y MOX fuel reprocessing plant after 2065. We assume that the spent UO_2 fuel instead of spent MOX fuels is reprocessed in the case that the total amount of spent MOX fuels is below 200 t-HM/y.

Figure 5 shows the change in the amounts of spent fuels stored. LWR-MOX is initially accumulate, but when the MOX fuel reprocessing plant is operational in 2065, the storage amount of LWR-MOX decreases, and almost zero after 2085. These results suggest that the planned reprocessing capacity is sufficient, and stable fuel cycle operation is possible. We discuss the effects of the introduction of the MA separation process and the MA transmutation in FRs in the next section.

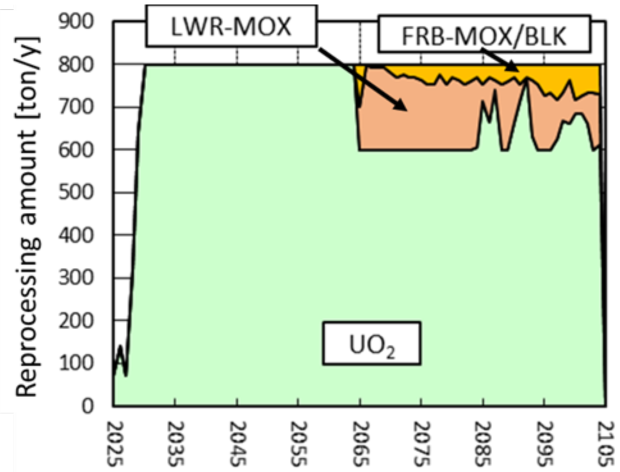

Fig. 4 Change in the reprocessing amounts of spent fuels

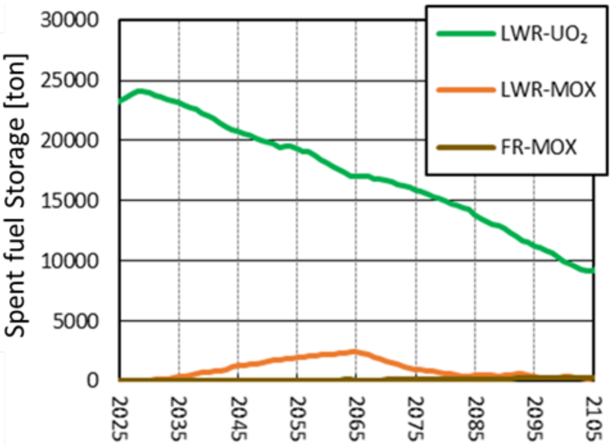

Fig.5 Change in storage amounts of spent fuels.

2. MA Inventory

A significant difference between oxide fuel and metal fuel FR cycles is the ability of pyro-reprocessing to transfer MA into the fuel cycle along with Pu. In the oxide fuel cycle, MA cannot be recovered without an additional MA separation process, particularly in conventional PUREX processes. To assess the behavior of MA within each nuclear fuel cycle facility, the MA amount was evaluated for both oxide and metal FR cycle scenarios, focusing on the proportion of MA transferred to waste.

Figure 6 illustrates the MA inventory in the nuclear fuel cycle. In the Ox0 scenario, approximately 85% (138 t) of the MA is transferred to waste by 2105. In the M0 scenario, although pyro-reprocessing allows MA to be retained within the FR cycle, this MA originates within the FR cycle itself and its amount corresponds only a negligible fraction of the total

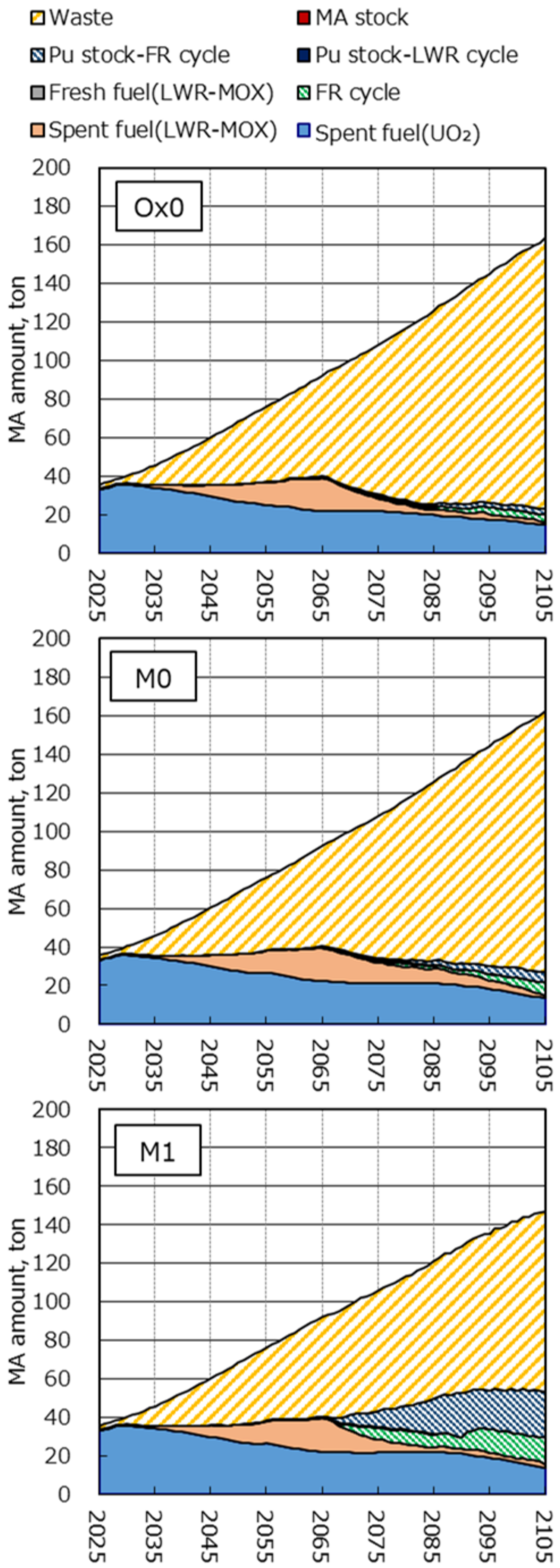

Fig. 6 MA inventory in the nuclear fuel cycle

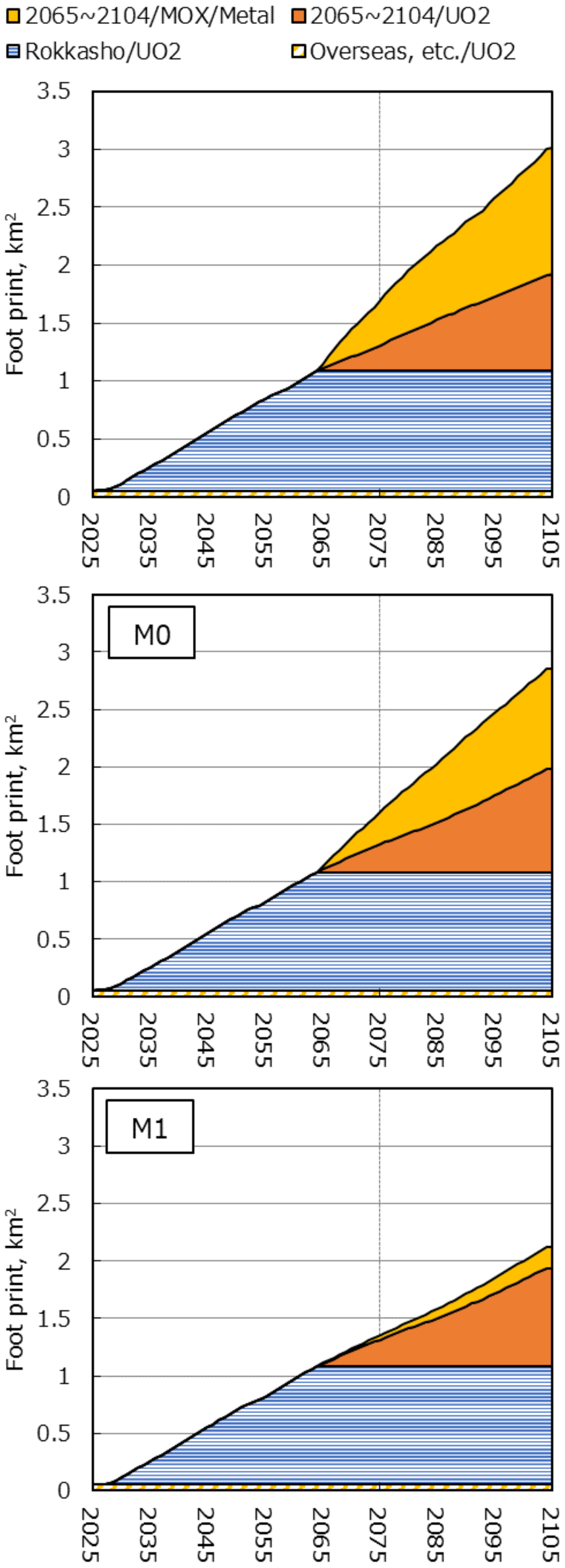

Fig. 7 Footprint for each scenario

inventory. Therefore, the amount of MA going to vitrified waste is not reduced. Consequently, the proportion of MA going to vitrified waste in the M0 scenario is 83% (133 t), which is almost identical to that of the Ox0 scenario. Conversely, in the M1 scenario, the MA contained in spent LWR-MOX fuel is transferred to the FR cycle, where it undergoes transmutation. The total MA amount is reduced by about 10% compared to those of the Ox0 and M0 scenarios. In addition, the retention of MA in the FR cycle reduces the amount of MA transferred to vitrified waste to 63% (93 t), which corresponds to the reduction of 33% compared to that of the Ox0 scenario. Therefore, in the oxide fuel and metal fuel FR cycles, the total amount of MA transferred to vitrified waste is almost the same, but by utilizing electrolytic reduction and pyrochemical reprocessing of spent LWR-MOX fuel, the amount of MA transferred to vitrified waste can be effectively reduced without the additional MA separation process.

3. HLW Volume and Geological Disposal

Based on the above MA inventory transitions, an evaluation of the footprint of the geological repository was performed. **Figure 7** shows the footprint for each scenario: 3.01 km^2 for the Ox0 scenario, 2.85 km^2 for the M0 scenario, and 2.12 km^2 for the M1 scenario. The reduction in the footprint for the M0 scenario, which is about 5% less than that for the Ox0 scenario, results from the reduced waste output from the FR cycle. The M1 scenario, as noted above, achieves about 33% reduction in MA transferred to waste, which translates into 30% reduction in footprint.

These results indicate a strong correlation between the MA content in waste and the required footprint of the geological repository. Under the nuclear power generation scenarios assumed in this study, the metal fuel FR cycle demonstrates the ability to reduce the transfer of MA to waste through the characteristics of pyro-reprocessing. This allows a significant reduction in the required footprint, especially when applied to spent LWR-MOX fuel.

IV. Conclusion

This study utilized the dynamic nuclear fuel cycle simulator NMB4.0 to investigate the mass balance of MA within oxide and metal fuel FR cycles. The analysis assumed the demonstration of FR in the mid-21st century, followed by the deployment of commercial FR.

In the oxide fuel FR cycle, PUREX reprocessing necessitates the addition of an MA separation process to retain MAs within the cycle. In contrast, the pyro-reprocessing characteristic of the metal fuel FR cycle inherently causes MA to accompany Pu chemically, making the separation of Pu challenging. However, this enables the retention of MA within the cycle.

At the end of the evaluation period, the fraction of total MA transferred to waste was 85% (138 t) in the oxide fuel FR cycle (Ox0 scenario), 83% (133 t) in the metal fuel FR cycle (M0 scenario), and 63% (93 t) in the metal fuel FR cycle with pyro-reprocessing applied to LWR-MOX fuel (M1 scenario). While the M0 scenario prevents the transfer of MA generated within the FR cycle to waste, the reduction in quantity was similar to the Ox0 scenario. The M1 scenario, however, achieved a 33% reduction in MA transferred to waste.

This MA transfer to waste significantly impacts the required footprint of the geological repository. The footprint for each scenario was estimated as 3.01 km^2 for the Ox0 scenario, 2.85 km^2 for the M0 scenario, and 2.12 km^2 for the M1 scenario. A strong correlation was observed between the amount of MA in waste and the footprint of the geological repository. Notably, this effect is pronounced when applied to spent LWR-MOX fuel.

Introducing an MA separation process into the oxide fuel FR cycle could achieve similar results to the M1 scenario in this study. Given the current advancements in the research and development of MA separation technologies, the differences between oxide and metal fuel FR cycles may diminish. However, the inherent characteristic of pyro-reprocessing, where Pu and MA are simultaneously recovered, offers a straightforward approach to suppress MA transfer to waste, thereby reducing the burden on final disposal.

The scenarios evaluated in this study assumed that FRs would account for approximately 20% of nuclear power generation in the latter half of the 21st century. It is anticipated that differences between oxide and metal fuel FR cycles will become more pronounced with the large-scale deployment of FRs in the 22nd century.

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