DOI: 10.15669/pnst.8.58

Progress in Nuclear Science and Technology
Volume 8 (2025) pp. 58-63

ARTICLE

Analysis of the Necessity and Usefulness of MA Temporary Storage Technology for the Sustainable Nuclear Fuel Cycle

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The separation of minor actinides (MA) from high-level radioactive waste (HLW) represents a critical technology for the sustainable utilization of nuclear energy, and the impact is higher the earlier it is introduced. Nevertheless, the advent of fast reactors (FR), indispensable for the transmutation of recovered MA, is projected to materialize no earlier than the latter half of this century. The temporal gap could span several decades, contingent on the timing of MA separation implementation. To address this gap, the temporary storage technology of MA has become a crucial element. In this study, four future nuclear power generation scenarios were considered, and the impact of implementing MA separation and temporary storage technologies on MA inventory, the number of vitrified waste canisters, and the footprint of geological repository were evaluated using the dynamic nuclear fuel cycle simulator NMB4. In the envisioned future nuclear power generation scenarios, the total generating capacity from 2030 onward is set at 36 GWe. Multiple scenarios have been defined—LWR cycle, LWR/FR coexistence, FR transition, and FR delayed transition—each differing in the type of reactor introduced when replacing existing reactors or constructing new ones. The results demonstrated the necessity and effectiveness of introducing MA separation and temporary storage technologies.

KEYWORDS: nuclear fuel cycle simulation, NMB4, MA separation, MA temporary storage technology, geological disposal

I. Introduction

The Japanese government has formulated a policy entitled "The Basic Policy for the Realization of GX," which outlines a strategy for transitioning towards an economic and social structure based on clean energy.[1)] The policy provides a detailed framework for the government's approach to nuclear energy, with a focus on enhancing the utilization of existing nuclear resources, promoting R&D of advanced reactors, and the nuclear fuel cycle.

It is anticipated that the replacement of Japan's existing boiling water reactors (BWR) and pressurized water reactors (PWR) with innovative light water reactors (LWR) will represent a fundamental milestone in the coming decades. By the mid-21st century, the deployment of a demonstration sodium-cooled fast reactor (FR) is planned, thereby paving the way for a transition to an FR cycle in the latter half of this century to the early part of the next. The capability of FR to transmute minor actinides (MA) presents a significant opportunity to reduce the burden of final disposal when combined with the separation of MA from high-level radioactive waste (HLW).

The MA separation has been a primary consideration in the context of reprocessing for spent MOX fuel, which is known to contain a higher concentration of MA. It was believed to be ineffective for HLW derived from UO_2 fuel, where the concentration of MA is lower. However, to comply with the new regulatory standards introduced after the accident at the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station, the minimum cooling period for spent fuel to be reprocessed at the Rokkasho Reprocessing Plant has been changed from the conventional 4 years to at least 15 years. This prolonged cooling period affects the thermal property of the vitrified waste through the increased presence of the heat-emitting radionuclide Am-241, as well as the decay of Sr-90 and Cs-137. Furthermore, according to an analysis examining the spent fuel to be reprocessed during the 40 years following the startup of the Rokkasho Reprocessing Plant, the spent fuel—both already existing and to be generated in the future—that will total 32,000 tons reprocessed between 2025 and the subsequent 40-year period is projected to have an average cooling period of about 40 years.[2)] Consequently, relatively high Am-241 content is expected in the resulting HLW. This indicates that the deployment of MA separation techniques could notably diminish the disposal burdens associated with UO_2 fuel. To minimize these burdens, MA separation must be introduced at the earliest possible stage. However, considering Japan's timeframe for replacing LWR, it is predicted that FR capable of transmuting recovered MA will only become commercially widespread from the latter half of the 21st century into the 22nd century. Consequently, if MA separation is introduced at an early stage, a temporary gap between the supply and demand of MA will arise.

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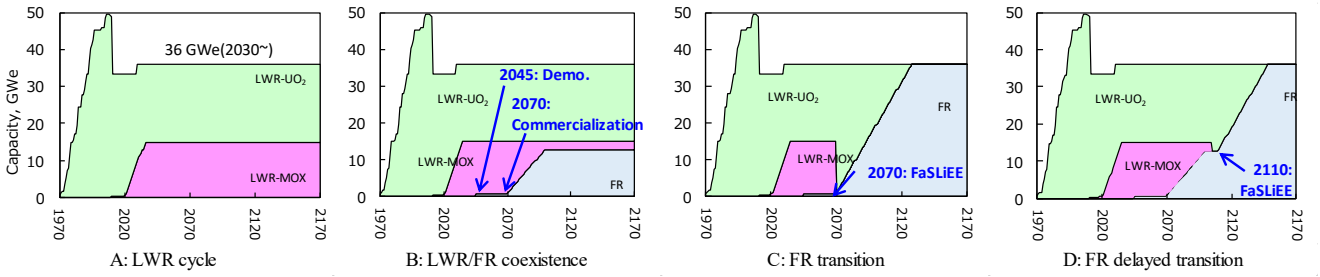

Fig.1 Assumed four scenarios for the future of nuclear power generation in Japan

The aforementioned gap must be bridged through the introduction of a temporary storage solution for the recovered MA. In the absence of temporary storage, the recovered MA would have to be mixed and loaded directly into FR fuels, rendering the recovery amount contingent on the rate of FR deployment. In contrast, the introduction of temporary storage permits the recovery of MA to occur independently of the timelines associated with FR deployment.

Various organizations have conducted simulations of nuclear fuel cycles involving the separation and transmutation of MA to date.[3] Among these, several studies have focused on temporary storage. Regarding MA temporary storage technology, Yamamura et al.[4] proposed an MA separation and temporary storage process based on evaluations of potential storage media and related technologies. Similarly, to enhance the effectiveness of MA separation and transmutation, a concept has been proposed[5] in which high-level radioactive liquid waste is evaporated and dried or denitrated—converting it into nitrates or oxides—then stored until separation and transmutation technologies become feasible. A common feature of these concepts is that they aim to reduce, as far as possible, the quantity of MA in HLW destined for geological disposal, thereby alleviating the disposal burden. However, none of these studies have conducted dynamic simulations of the nuclear fuel cycle, indicating a need for a more detailed discussion of their effectiveness. Therefore, in this study, based on Japan's nuclear power generation scenario, we use a dynamic nuclear fuel cycle simulator to quantitatively clarify the impact of early MA separation from HLW and the introduction of an MA temporary storage process—as a buffer until fast reactors are introduced in the latter half of the 21st century—on mitigating the burden of final disposal.

1. Nuclear Fuel Cycle Simulator: NMB4.0

In this study, the open-source nuclear fuel cycle simulator NMB4 was employed as the analytical tool.[6] The simulator encompasses a comprehensive range of nuclear fuel cycle scenarios, extending from the front end to the back end. This simulator models the processes of reprocessing, storage, transport, and geological disposal, making it suitable for detailed back-end scenario evaluations. In light of the complex scenarios under evaluation and the paramount significance of back-end analysis, NMB4 was selected as a suitable simulator for this study. For a detailed description of NMB4's methodology, please refer to the official manual included in the publicly available NMB4 package.

2. Nuclear Power Generation Scenarios

This study assesses four scenarios for the future of nuclear power generation in Japan, as shown in **Fig. 1**. The analysis period spans 200 years, from 1970, when Japan's first commercial nuclear power plant was commissioned, to 2170. Operating data for individual nuclear power plants were derived from publicly available information provided by electricity utilities. Future nuclear power generation was modeled based on the "Long-term Energy Demand and Supply Outlook".[7] According to this plan, nuclear power generation is assumed to maintain a capacity of 36 ± 1.0 GW until 2030, which is 22% of an estimated total annual power generation of about 1.1×10^3 TWh. In reality, it is unlikely that nuclear power generation capacity will remain constant in the future, and there are inherent uncertainties. However, the purpose of this paper is to evaluate whether the introduction of MA separation and temporary storage yields benefits under all scenarios in which the number of newly introduced LWR and FR differs. Therefore, to simplify the scenarios, we assume that power generation remains constant.

The four assumed scenarios are summarized as follows. In Scenario B to D, which excludes the LWR cycle in Scenario A, it was assumed that an FR demonstration plant (0.6GW) will begin operating in 2045 and that the deployment of commercial FR will begin in 2070. A key metric introduced in this study set FaSLiEE (FR is Superior to LWR including Economic Evaluation), which serves as a decision-making criterion for transitioning from the LWR fuel cycle to the 100% FR fuel cycle. In Scenario B, FaSLiEE is not achieved, and in Scenarios C and D, it is assumed that FaSLiEE is achieved at different times. Since no economic evaluation is conducted in this study, the adoption of FaSLiEE is treated as one assumption for determining when to begin the transition to the FR cycle.

Scenario A (LWR cycle): This scenario assumes LWR multi-recycling, in which Pu recovered from reprocessing of UO_2 and MOX fuels burned in LWR is used again as MOX fuel in LWR.

Scenario B (LWR/FR coexistence): This scenario assumes the coexistence of LWR and FR. It is assumed that MA generated mainly by LWR is transmuted in FR, and the deployed capacity of FR is assumed to be 12 GWe, one-third of the total power generation capacity.

Scenario C (FR transition): This scenario assumes that FsSLiEE is achieved by 2070, leading to a complete replacement of 36 GWe of LWR with FR. The replacement period is set to begin in 2070 and span 60 years.

Scenario D (FR delayed transition): This scenario

assumes that FaSLiEE is achieved during the coexistence period of LWR and FR, leading to a policy change towards a full transition to FR. After 60 years of operation of a demonstration reactor, a policy change is planned for 2105, with starting the full transition from 2110.

It was assumed that the reprocessing plant would begin operations in 2025, followed by the start of MOX fuel production. In this context, MOX fuel is loaded into 25 and 33% of the core assemblies in PWR and BWR, constrained by reactor design limits. It was assumed that any recovered Pu not allocated to FR would be used for pluthermal generation (i.e., employing MOX fuel made from Pu in LWR), in line with Japan's policy of not retaining surplus Pu beyond operational requirements. Accordingly, pluthermal generation is used throughout Scenario A and during the pre-FaSLiEE phases of Scenarios B, C, and D. Pluthermal generation varies depending on the amount of MOX fuel loaded into LWR. Using NMB4's functionality, the MOX fuel loading is dynamically adjusted based on the Pu supply-demand balance within each reactor's core constraints.

The operational lifespan of the reactor is set at a baseline of 80 years. In Scenarios B to D, to maintain generation capacity and a consistent FR deployment pace, reactor lifespans are dynamically adjusted within a range of 60–90 years. Newly constructed reactors are assumed to have capacities of 0.9 GWe and 1.2 GWe for LWR and 0.6 GWe for FR. During the LWR/FR coexistence period preceding FaSLiEE in Scenarios B and D, FR construction is set at a rate of 0.4 GWe per year. For the future introduction of reactors, it is assumed that a new LWR will be introduced with advanced BWR and PWR in approximately a 50:50 ratio. For the FR, we assumed a sodium-cooled FR that employs multiple recycling of TRU oxide fuel, as examined in the FaCT project,[8] and MA transmutation is carried out in all FR. ORLIBJ40[9] was used for the nuclear data library.

3. Reprocessing Plant Operation Scenarios

The reprocessing plant operation was assumed to start in 2025 and operate for 40 years. Throughput is gradually increased to a maximum processing capacity of 800 tHM per year by 2031. A minimum spent fuel cooling period of 15 years is assumed, with U and Pu recovery rates of 99%.

Future reprocessing plants are modeled to begin operating every 40 years starting in 2065. The maximum annual reprocessing capacity is set at 800 tHM for all scenarios. In Scenario A, up to 5% of this capacity is allocated to reprocessing LWR-MOX fuel. In other scenarios, 600 tons per year are allocated to UO_2 fuel and 200 tHM per year to a combination of UO_2, LWR-MOX, and FR-MOX fuels. The minimum cooling period for spent fuel is four years. Uranium and plutonium recovery rates are maintained at 99%, with 10% of neptunium recovered alongside plutonium. The introduction of MA separation is assumed in 2065 or 2045, with a 99% recovery rate for MAs (Np, Am, Cm).

4. Temporary Sorage of Minor Actinides (MA)

To evaluate the impact of MA separation and temporary storage, the following definitions have been established:

With Temporary Storage: All recovered MA is immobilized and stored until they can be used in FR.

Without Temporary Storage: Recovered MA is immediately loaded into FR-MOX fuel, and any MA not loaded into FR-MOX fuel is vitrified with other FPs as HLW for geological disposal. In other words, without temporary storage, all MA is not recovered before FR is deployed, and after deployment, only those MA that can be transmuted are recovered, while the remainder is vitrified as HLW.

5. Vitrification and Geological Disposal

The vitrification assumes the following limiting conditions:

- ✧ **Waste Loading**: The waste content in the vitrified product, excluding Na components, is set at 25 wt%.
- ✧ **Heat Generation**: Heat generation is limited to 2.3 kW for maintaining the production quality and the requirements for the vitrified waste storage facility at the Rokkasho Reprocessing Plant.
- ✧ **Buffer Material Temperature**: The temperature of the buffer material during geological disposal is maintained below 100°C.

These constraints determine the waste content incorporated into the vitrified waste.

The produced vitrified waste is categorized based on the presence or absence of MA separation and the subsequent management of recovered MA (either transmutation in FR or immobilization and geological disposal).

The categories were assumed to be regular vitrified waste and MA-free type (vitrified waste without MA). It was assumed that regular vitrified waste would be stored for 50 years between vitrification and disposal and then disposed of using the PEM method.[10] In addition, it was assumed that MA base type waste would be stored as a temporary storage body for 120 years, then vitrified, and immediately disposed of using the PEM method. For MA-free vitrified waste, a storage period of 120 years—longer than usual—has been set to allow for the decay of Sr and Cs, thereby maximizing the benefits of MA separation. This allows for the adoption of a Multi-loaded PEM disposal method, where multiple vitrified waste canisters are stacked within a single PEM.[11]

III. Results and Discussion

In determining the necessity and effectiveness of temporary storage of MA separation, two evaluation periods were set: ① 1970-2170 "entire evaluation period" and ② 2045-2104 "period affected by the decision to introduce MA temporary storage." In ①, the effects of MA separation and temporary storage were compared with a scenario in which there was no MA separation, and in ②, the effects of MA temporary storage were compared with a scenario in which there was no MA temporary storage. In ②, for evaluating the impact of the presence or absence of MA temporary storage, the following approach was taken: the "time when MA can be recovered at the earliest" (2045) to "the time when the maximum amount of MA loaded into FR exceeds the amount of MA recovered in all scenarios B to D" (2104).

In addition, Scenario A is not included in the evaluation for evaluation period ② because FR is not introduced. The

results of the evaluation of various quantities for each evaluation period are shown below.

As a reference for comparing the number of vitrified waste and the footprint of the geological repository, it was assumed that one disposal site corresponds to 40,000 vitrified waste occupying an area of 1.75 km², as estimated by NUMO[10].

1. MA inventory (Evaluation period: 1970-2170)

To confirm the changes in the MA stream when MA separation and temporary storage are introduced, the amount of MA in each process at the end of the evaluation period (2170) is shown in **Figure 2**.

Scenario A: In Scenario A, the LWR multi-recycle without FR for MA transmutation results in the accumulation of MA in temporary storage. The temporary storage amount reaches approximately 177 tHM with MA separation introduced in 2065 and 207 tHM with its introduction in 2045.

Regarding the transition of MA to waste, without MA separation, 235 tHM would be allocated to geological disposal. However, the adoption of MA separation and temporary storage reduces this amount to about 57 tHM (2065 introduction) or 29 tHM (2045 introduction).

Additionally, approximately 100 tHM of MA is retained within the LWR cycle, primarily contained in spent LWR MOX fuel. To prevent the degradation of Pu quality, which would inhibit the production of MOX fuel through multi-recycling, the annual reprocessing of spent MOX fuel was limited to 5% of the total reprocessing capacity. As a result, spent MOX fuel in the LWR cycle remains by 2170, containing approximately 100 tHM of MA.

Scenario B: The total MA amount in the case of both MA separation from 2065 and 2045 is reduced to approximately 130 tHM, which is roughly half of the amount without MA separation due to transmutation in FR. The amount of temporary storage was about 10 tHM (introduced in 2065) or 30 tHM (introduced in 2045) since an FR for the amount of transmutation capacity as the amount of recovered MA was introduced. For geological disposal, without MA separation, 281 tHM of MA is allocated. This amount is reduced to approximately 60 tHM (2065 introduction) or 30 tHM (2045 introduction).

Scenario C: With MA transmuted in FR, the total MA amount decreases significantly to approximately 107 tHM (2065 introduction) or 81 tHM (2045 introduction). As the transmutation capacity of MA in FR exceeds the recovery amount, temporary storage is effectively eliminated. For geological disposal, 281 tHM of MA is allocated without MA separation. The adoption of MA separation and temporary storage reduces this to approximately 58 tHM (2065 introduction) or 32 tHM (2045 introduction).

Scenario D: The total MA amount is reduced to 109 tHM (2065 introduction) or 85 tHM (2045 introduction) through transmutation in FR. For geological disposal, without MA separation, 249 tHM of MA is allocated. With MA separation and temporary storage, this is reduced to approximately 59 tHM (2065 introduction) or 33 tHM (2045 introduction).

The MA inventory at each process in 2170 varies greatly depending on the presence or absence of MA separation and temporary storage. Nevertheless, all scenarios demonstrate that introducing MA separation and temporary storage significantly reduces the amount of MA allocated to waste. Specifically, compared to no separation, the implementation of MA separation and temporary storage achieves a reduction of approximately 70% (2065 introduction) and 80% (2045 introduction) in the amount of MA allocated to geological disposal. However, under Scenario A, approximately 200 tHM of MA temporary storage would remain, which would need to be addressed.

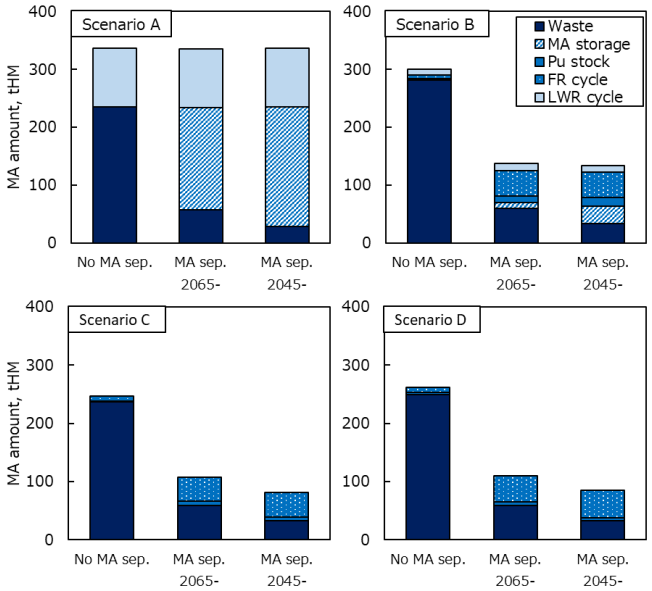

Fig. 2 MA inventory at the end of the evaluation period (2170) for each process

2. HLW Amount (Evaluation period: 1970-2170)

This study aims to clarify how the introduction of MA separation and temporary storage impacts disposal burdens, such as the number of vitrified waste and the footprint of the geological repository. **Figures 3** and **4** illustrate the number of vitrified waste and the footprint for each scenario at the end of the evaluation period. Note that, mainly in Scenario A, it is assumed that MA temporary storage units and spent MOX fuel remaining at the end of the analysis period of 2170 will eventually be used as fuel and are not included in the amount of waste to be disposed of or in the footprint of repository shown thereafter.

The introduction of MA separation and temporary storage results in a reduction in the number of vitrified waste across all scenarios. The reduction rate is approximately 50% or more, corresponding to a decrease of about 85,000–100,000 canisters. Additionally, an early implementation of MA separation (20 years earlier) contributes to a further reduction of about 10% in the number of vitrified waste, as demonstrated by comparing MA separation introductions in 2045 and 2065.

Similar to the impact on vitrified waste, MA separation, and temporary storage also significantly reduce the required footprint across all scenarios. Without MA separation, a repository three times larger than the one for the reference scenario would be necessary. However, the introduction of

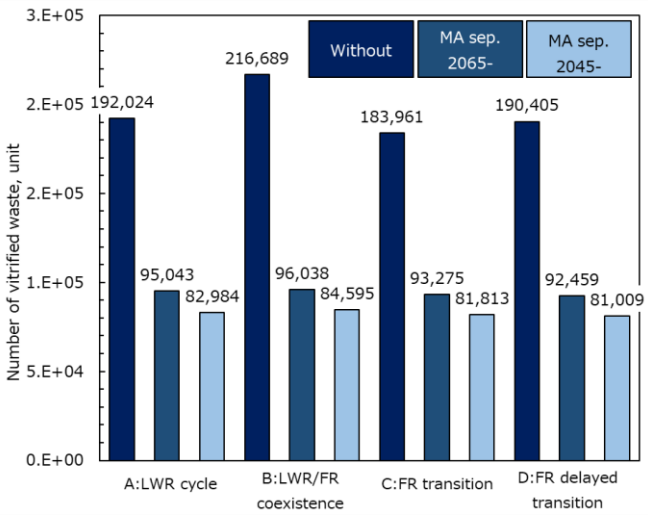

Fig. 3 Number of vitrified waste during the evaluation period: 1970-2170

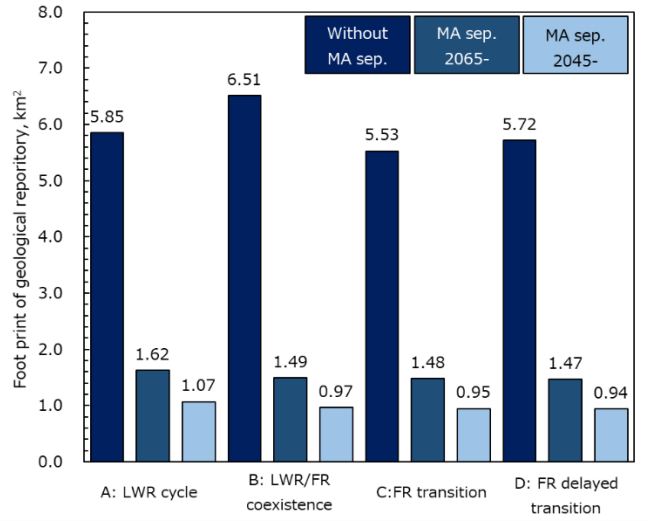

Fig. 4 Footprint for vitrified waste generating at the evaluation period: 2045-2104

MA separation and temporary storage can reduce to approximately one repository site or less. An early implementation (20 years earlier) further decreases the repository area by approximately 25%.

While MA decays to some extent during temporary storage, a significant quantity remains in the stored material, leading to increased MA transfer to the repository. Consequently, the repository area required for vitrifying and disposing of these MAs increases by approximately 66% compared to the Scenario A results in Fig. 4. However, compared to the no-separation condition, the footprint is reduced by approximately 25%.

Regardless of the presence or pace of FR deployment, MA separation and temporary storage contribute to reducing disposal burdens. Furthermore, in scenarios where FR is operational, the effectiveness of MA separation and temporary storage—especially with early implementation—on reducing disposal burdens was clearly demonstrated.

3. Impact of MA Temporary Storage (Evaluation period: 2045-2104)

The extent to which temporary storage of MA suppresses allocation of MA to the waste side and affects disposal burden, including the number of vitrified waste and the footprint, are evaluated as shown in **Figs. 5** and **6**.

First, with respect to the number of vitrified waste, the introduction of MA separation showed a reduction effect even without MA temporary storage. The reduction was approximately 40%, corresponding to a reduction of approximately 28,000-37,000 canisters. Furthermore, comparing the scenarios with and without MA temporary storage, reductions of about 20% and 40% were observed for MA segregation introduced in 2065 and 2045, respectively.

Similarly, for the footprint of the geological repository, the introduction of MA separation resulted in a reduction of more than 50%, even without MA temporary storage. When comparing the scenarios with and without MA temporary storage, reductions of about 33% and 82% were observed for

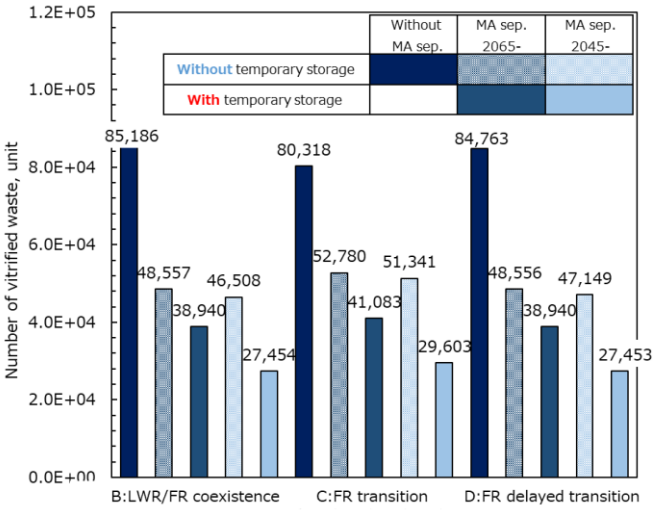

Fig. 5 Number of vitrified waste during the evaluation period: 2045-2104

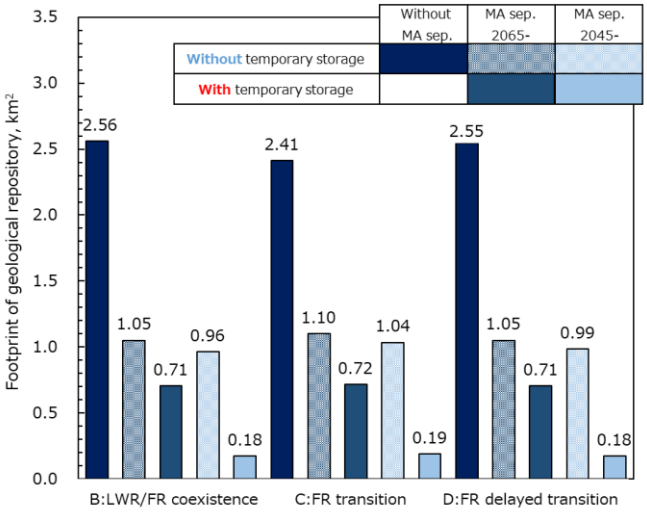

Fig. 6 Footprint for vitrified waste generating at the evaluation period: 2045-2104

the MA separation introduced in 2065 and 2045, respectively.

Thus, the effectiveness of MA temporary storage is evident. Compared to conditions without temporary storage, the introduction of MA separation in 2065 resulted in reductions of about 20% in vitrified waste and 33% in footprint. For the 2045 introduction, the reductions were about 40% and 82%, respectively.

IV. Conclusion

In this study, we evaluated how introducing MA separation and temporary storage technologies would affect the burden of final disposal of HLW through the evaluation of MA inventory, the number of vitrified waste packages, and the footprint of the geological repository in four potential future nuclear power generation scenarios in Japan. The findings highlight the necessity and effectiveness of introducing MA separation and temporary storage technologies as follows:

- ✧ The introduction of FR enables significant reductions in vitrified waste canisters and repository areas. In all scenarios involving FR (Scenarios B–D), the implementation of MA separation and temporary storage halved the number of vitrified waste canisters and reduced repository areas by 70–80%. Even in Scenario A, which does not require FR, vitrified waste and geologic repository area will be reduced by the introduction of MA separation and interim storage technology. On the other hand, since FR is not introduced, spent MOX fuel and MA temporary storage remain unconsumed.
- ✧ Compared to scenarios without temporary storage, introducing MA separation in 2065 reduced vitrified waste by approximately 20% and repository areas by about 33%. Early implementation in 2045 resulted in reductions of approximately 40% and 82%, respectively.

Thus, the temporary storage process effectively suppresses MA migration into HLW during the period between the early introduction of MA separation and the widespread adoption of FR, reducing the burden of final disposal. Moreover, temporary storage allows for setting MA recovery volumes independently of the power generation capacity of FR. On the other hand, if the FR is not introduced, MOX fuel and MA temporary storage will remain without being consumed, which will need to be addressed.

Acknowledgment

This work was supported by MEXT Innovative Nuclear Research and Development Program Grant Number JPMXD0223812958. We would like to express our gratitude to Dr. Nishihara and Mr. Abe in the Japan Atomic Energy Agency for their invaluable advice on NMB4.0 scenario analysis. Their insights significantly enhanced the quality of our research.

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