IMPACT OF MA TEMPORARY STORAGE PROCESS ON THE REDUCTION OF FINAL DISPOSAL BURDEN IN THE ADVANCED NUCLEAR FUEL CYCLE

Tomohiro Okamura[1]*, *Masahiko* Nasase[1], Kenji Takeshita[1], Takashi Shimada[2,3], Yuki Konishi[4], Keisuke Nishimura[4], Hitomi Ishida[4] and Tomoo Yamamura[4]

1 Tokyo Institute of Technology, Institute of Innovative Research, Laboratory for Zero-Carbon Energy, 2-12-1 Ookayama, Meguro-ku, Tokyo, Japan
2 Mitsubishi FBR systems, 33-11, Shiba 5-chome, Minato-ku, Japan
3 Kyoto University, Institute for Integrated Radiation and Nuclear Science, 2, Asashiro-Nishi, Kumatori-cho, Sennan-gun, Osaka, Japan
4 Mitsubishi Heavy Industry, 108-8015, 33-11, Shiba 5-chome, Minato-ku, Tokyo, Japan
* Corresponding author

Abstract. Separating minor actinides (MA) from high-level radioactive waste (HLW) is an effective option for reducing the burden of final disposal. However, the recovered MA must be transmuted in fast reactors (FR) or similar technologies. The widespread deployment of FR is expected in the latter half of the 21st century. In this study, we evaluated the introduction of a temporary MA storage process to bridge the time gap between the early introduction of MA separation and the deployment of FR with adequate transmutation capacity. The results showed that the MA temporary storage process effectively mitigates the burden of final disposal and MA temporary storage allows the amount of recovered MA to be managed independently of the FR capacity.

1. Introduction

In pursuit of a sustainable society, there is a global demand to secure stable and developing energy sources while achieving carbon neutrality. In Japan, the "GX (Green Transformation) Basic Policy," aimed at transforming the economic and social structure through clean energy, was established by the GX Implementation Council. In this Council, government policies such as "Maximise the use of nuclear power", "Promotion of the development and construction of next-generation advanced reactors", "Replacement of decommissioned reactors", "Extension of operating periods for existing reactors", and "Promotion of the nuclear fuel cycle" were outlined [1]. While nuclear power generation would continue to primarily rely on light-water reactors (LWR), the goal is to achieve commercialization of fast reactors (FR) by the mid-21st century and transition to FR cycle in the latter half of the century.

FR is capable of transmuting minor actinides (MA), and combining this with the separation of MA from high-level radioactive waste (HLW) has the potential to significantly reduce the burden of final disposal. To minimize the disposal burden, it is effective to introduce MA separation as early as possible. However, even if an early introduction of MA separation is achieved, FR capable of transmuting MA is expected to become widespread in the latter half of the 21st century, and it is necessary to bridge this temporal gap.

Figure 1 shows the conceptual diagrams of the nuclear fuel cycle process with and without the MA temporary storage process. In the absence of the MA temporary storage process, the MA recovered during the reprocessing stage is mixed with fuel for FR and loaded into the reactors. In this case, the amount of MA that can be recovered depends on the rate of FR introduction. On the other hand, when the MA temporary storage process is in place, MA recovery can proceed without being dependent on the pace of FR introduction.

To date, various organizations have conducted nuclear fuel cycle simulations related to MA separation and transmutation [1]. Among the studies on this subject, several have focused on temporary storage. Regarding temporary storage technology for MA, Yamamura et al. [2] proposed an MA separation and temporary storage process based on the evaluation of the storage medium and relevant technologies. Similarly, to enhance the effectiveness of MA separation and nuclear transmutation, another proposed concept involves evaporating and solidifying high-level radioactive liquid waste, or converting it to nitrates or oxides by denitration, and then storing these forms until separation and transmutation technologies become feasible [3]. A common feature of these concepts is the aim to reduce, as much as possible, the amount of MA in HLW destined for geological disposal, thereby mitigating the disposal burden. However, none of these studies have conducted dynamic nuclear fuel cycle simulations, indicating the need for a more detailed discussion of their effectiveness. Therefore, in this study, based on Japan's nuclear power generation scenario, we aim to quantitatively clarify the effects of early MA separation from HLW and the introduction of the MA temporary storage process, which serves as a buffer until the introduction of FR in the second half of the 21st century, on the reduction of the final disposal burden using a dynamic nuclear fuel cycle simulator.

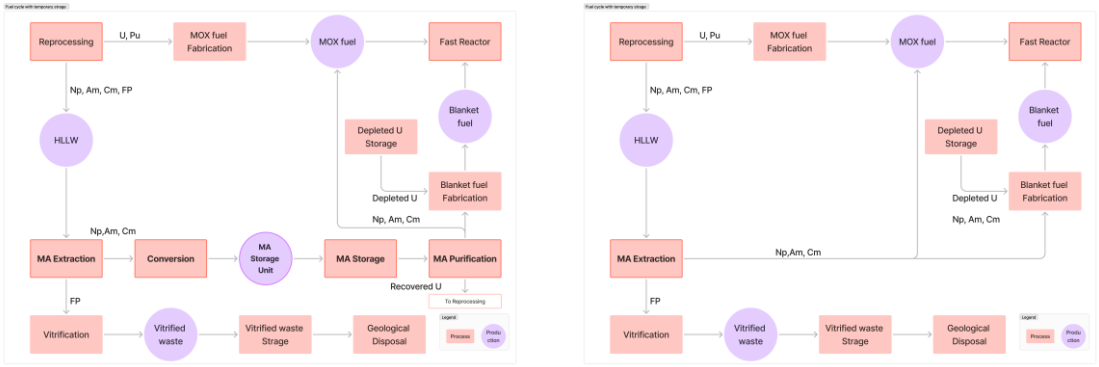

Fig. 1. The conceptual diagrams of the nuclear fuel cycle process with and without the MA temporary storage.

2. Scenario & Conditions

2.1 Nuclear Fuel Cycle Simulator: NMB4.0

In this study, we conducted an analysis using the nuclear fuel cycle simulator, Nuclear Material Balance analysis code version 4.0 (NMB4.0), jointly developed and freely published by Tokyo Institute of Technology and Japan Atomic Energy Agency (JAEA) [4]. This simulator models a wide range of processes from the front- to the backend of the nuclear fuel cycle, with a particularly comprehensive scenario analysis function for the backend. Therefore, it is an appropriate simulator for this study, which evaluates the generation scenarios of high-level waste.

2.2 Nuclear power generation scenarios

The nuclear power generation scenarios from the past to the future were established based on information disclosed by Japan's electric power companies. The three energy generation scenarios assumed in this study are shown in Figure 2. The analysis period spans 200 years, from 1970, when Japan's first commercial nuclear power plant began operation, to 2170. The future nuclear power generation is based on the "Long-term Energy Demand Outlook" presented at the General Energy Council on July 16, 2015 [5], assuming that the nuclear power generation capacity would be maintained at 36 ±1.0 GW from 2030 onward. This corresponds to 22% of the total annual power generation in 2030 (approximately 1.1 × 10^3 TWh). The demonstration FR (0.6 GW) is expected to start operation in 2045 and the introduction of commercial FR is assumed to begin in 2070. The concepts behind both scenarios are described below. As an indicator for the commercialization of FR, we introduced "FaSLiEE: Fast Reactor is Superior to LWR Including Economic Evaluation."

A. LWR/FR coexistence scenario: It is assumed a situation where FR cannot be FaSLiEE, and the minimum required (12 GWe, based on various evaluations) FR are introduced over 30 years to transmute MA.

B. LWR/FR transition scenario: It is assumed that FR become FaSLiEE, leading to a full transition to FR starting with the first commercial reactor in 2070 based on the knowledge gained from the development and operation of demonstration FR. For a full transition, LWR-MOX will be discontinued to supply Pu to the FR

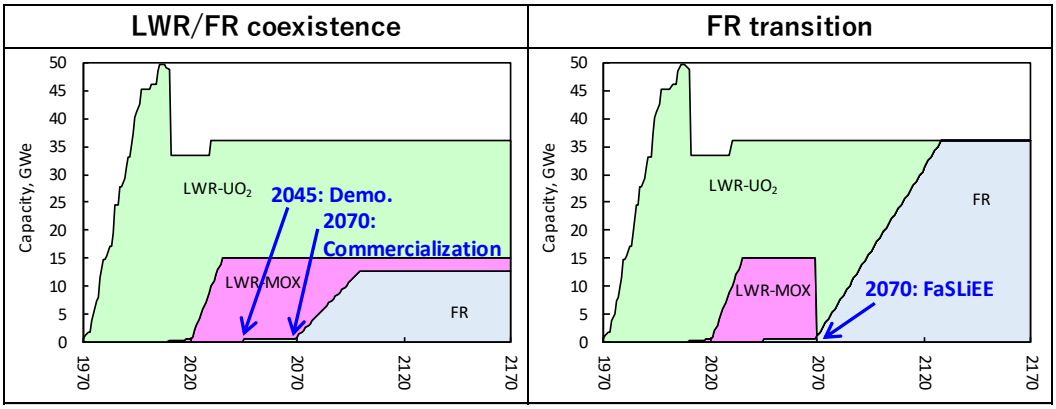

Fig. 2. Nuclear power generation scenarios.

2.2.1 Nuclear power plant operation and replacement

The operational period of reactors is set at 80 years in principle. The priority is given to the pace of FR introduction and maintaining nuclear energy capacity, with adjustments made in the range of 60 to 90 years. The operational period of nuclear fuel cycle facilities is fixed at 40 years. Nuclear power plant capacity that is newly constructed is set at two levels for LWRs: 0.9 GWe/unit and 1.2 GWe/unit, while FR are set at 0.4 GWe/unit for LWR/FR coexistence scenario and 0.6 GWe/unit for FR transition scenario. The transmutation capacity, balanced with the amount of MA generated during reprocessing, was set based on various evaluations. The transmutation capability of FR is set at 125 kg/GWe-year, corresponding to the case where 5% MA is loaded into the reactor core.

2.2.2 Reprocessing plant operation

It is assumed that after the present Reprocessing Plant starts operation in 2025, pluthermal power generation would commence. Pluthermal power generation refers to the use of mixed oxide (MOX) fuel recovered from reprocessing plants to generate electricity in LWR. Pluthermal power generation is expected to use Pu stockpiles, with a maximum of 25% and 33% core assemblies in PWR and BWR reactors, respectively. The Pu obtained from reprocessing that is not used in FR would be used for pluthermal operations, and in principle, excess recovered Pu, aside from the necessary buffer for operation, would not be held within the cycle. Therefore, pluthermal operations would be carried out, with the capacity determined by subtracting the Pu amount used in FR from the recovered Pu.

2.3 Backend scenario

2.3.1 Reprocessing

The assumptions for the backend are based on the Japanese geological disposal program [6]. The present reprocessing plant is assumed to operate for 40 years starting from 2025. The processing capacity is expected to gradually increase, reaching its maximum capacity of 800 t/year by 2031. The minimum cooling period for spent fuel is set at 15 years, and the recovery rate of U and Pu is assumed to be over 99%.

The future reprocessing plant is assumed to operate from 2065 to 2104, with a processing capacity of 600 t/year for LWR UO_2 fuel and 200 t/year for a combination of LWR -UO_2, -MOX, and FR fuels. The minimum cooling period for spent fuel is set at 4 years, with U and Pu recovery rates above 99% and Np recovery at 10%.

2.3.2 MA separation and temporary storage

The introduction of MA separation is assumed to be introduced in either 2065 or 2045. The recovery rate of MA stored and retrieved at the reprocessing plant is shown in Table 1. The final destination of MA, depending on whether MA separation and temporary storage are implemented, is shown in Table 2.

2.3.3 Vitrification and Geological Disposal

In the vitrification process, the waste loading, thermal power, and buffer temperature on the geological repository are the limitation factors that determine the waste loading at the vitrification. The following limits are set: 25 wt% (excluding 10 wt% Na component), 2.3 kW, and 100°C respectively.

The storage period from vitrification to geological disposal is categorized based on whether MA separation is performed from HLW. For typical vitrified waste that does not recover MA, the storage period is set at 50 years, while for vitrified waste that does recover MA, it is set at 120 years. This is to enhance the effectiveness of MA separation by allowing the decay of the main heat sources, Cs and Sr, in the non-MA-containing vitrified waste.

Furthermore, the method of placing the waste package in the geological repository is also categorized based on the presence or absence of MA separation. The Prefabricated Engineered Barrier System Module (PEM) and Multi-loaded PEM (MPEM) methods [7] are used for typical and MA-recovered vitrified waste.

2.4 Evaluation period

The purpose of this study is to clarify the differences between scenarios with and without temporary storage of MA. Therefore, the evaluation period is set from 2045 to 2104 as the "period affected by the decision-making regarding the introduction of MA temporary storage". This period is established considering the following:

- ✧ The disposal burden during the equilibrium phase, in which all MA recovered from reprocessing can be transmuted by the introduced FRs, remains unchanged regardless of the presence of temporary storage. (However, positive effects due to the decay of MA during temporary storage are expected, but since this impact is small, it is not considered here.)
- ✧ If the decision to introduce MA separation is made now and construction of the necessary facilities begins, the earliest operational start would be in 2045, meaning that the disposal burden before this period remains unchanged regardless of the presence of temporary storage.

Table 1. The recovery rate of MA stored and retrieved at the reprocessing plant.

Plant	Recovery ratio	Notes
Present	Np：99% Am：99% Cm：99%	MA separation is introduced during the mid-term of plant's operational period.
Future	Np：90% Am：99% Cm：99%	10% of Np is transferred to the U/Pu product side during reprocessing.

Table 2. The final destination of MA, depends on whether MA separation and temporary storage are implemented.

No.	Introduction Timing (Plant)	Presence or Absence of Temporary Storage	Destination of MA
1	No Introduction	Absent	MA remains in HLW
2-1	From 2065 (Future Plant)	Presence	MA is recovered from HLW and stored until transmutation in FR.
2-2		Absent	Only the portion of MA that can be transmuted in FR is recovered, while the remainder is vitrified.
3-1	From 2045 (Present Plant)	Presence	Same as 2-1
3-2		Absent	Same as 2-1

3. Result & Discussion

3.1 MA inventory analysis

The evaluation focuses on the transfer of MA, which significantly impacts the disposal burden, to geological disposal. Figure 3 shows the amount of MA transferred to HLW in 2104 for each scenario. MA separation alone, even without the introduction of temporary storage, could reduce the amount of MA transferred to HLW in 2104 by 60%. When temporary storage for MA was introduced, the reduction compared to the scenario without temporary storage was approximately 30% and 90% for the scenarios where MA separation was introduced in 2065 and 2045, respectively. Additionally, when comparing the timing of the introduction of temporary storage, the amount of MA transferred to HLW was reduced by about 85%. Therefore, MA separation with temporary storage has a suppressive effect on the transfer of MA to HLW, and this effect is enhanced by earlier implementation.

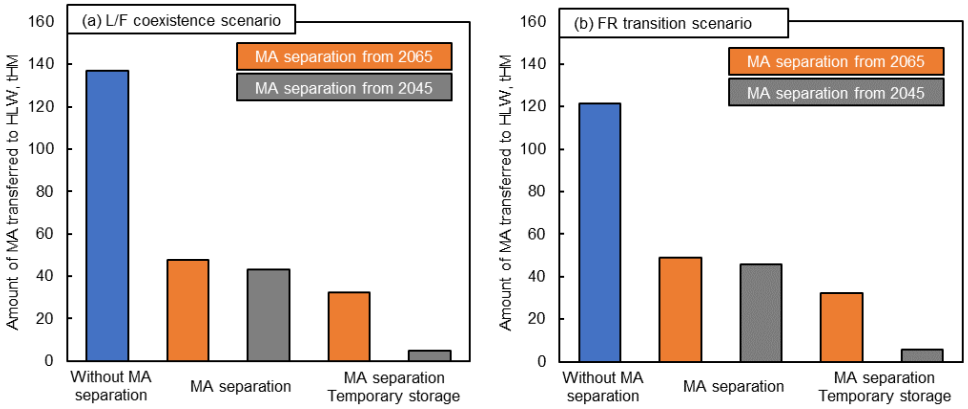

Fig. 3. Amount of MA transferred to HLW

3.2 Vitrified waste amount and foot-print of geological repository

This study aims to clarify the extent to which temporary storage of MA suppresses the migration of MA to disposal sites and how this impacts disposal burdens, including the number of vitrified waste canisters and the footprint of geological repository. Figures 4 and 5 show the number of vitrified waste canisters and the footprint of geological repository at the end of the evaluation period for each scenario. The footprint of geological repository is determined by the product of the number of vitrified waste canisters and the area required for one waste package unit (occupied area). The occupied area differs for each emplacement method were shown in 2.3.3.

First, regarding the number of vitrified waste canisters, it was revealed that the introduction of MA separation produces a reduction effect even under conditions without temporary storage of MA. The reduction amounted to approximately 40% (around 28,000 to 37,000 canisters). Additionally, when

comparing scenarios with and without temporary storage, a reduction of about 20% and 40% was observed with the introduction of MA separation in 2065 and 2045, respectively.

Similarly, the footprint of geological repository was reduced by over 50% through the introduction of MA separation, even under conditions without temporary storage. When comparing scenarios with and without temporary storage, the disposal area was reduced by approximately 33% and 82%, with the introduction of MA separation in 2065 and 2045, respectively. Thus, the effectiveness of temporary storage can be demonstrated by comparing it with scenarios without temporary storage: the introduction of MA separation in 2065 resulted in a reduction of about 20% in the number of vitrified waste canisters and about 33% in the foot-print of the geological repository, while the introduction in 2045 achieved reductions of approximately 40% and 82%, respectively.

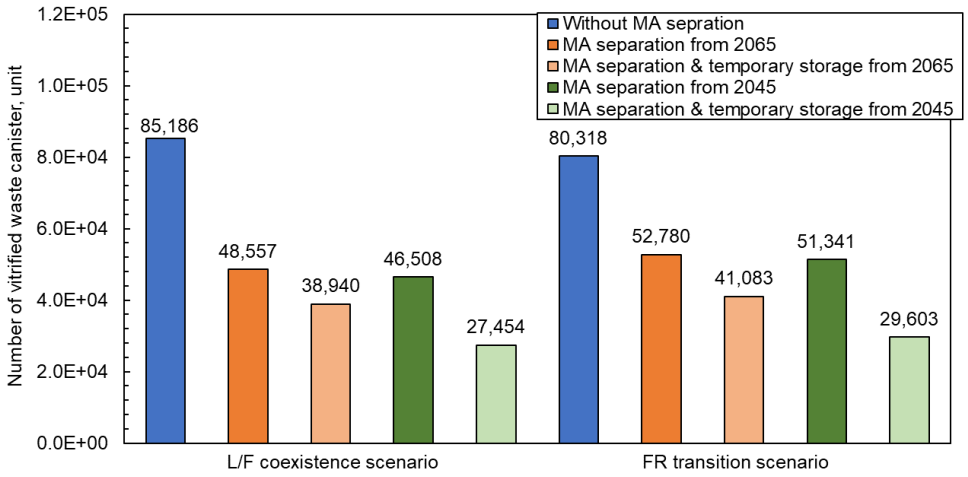

Fig. 4. Number of vitrified waste canisters in each scenario.

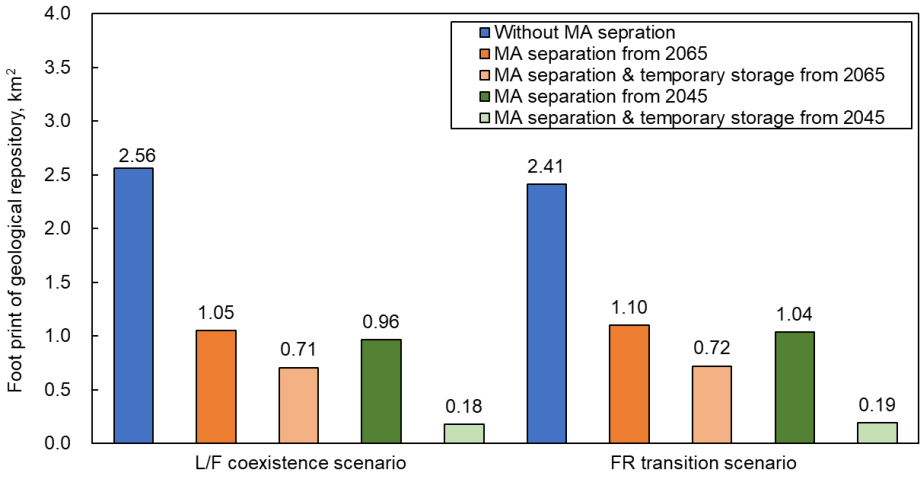

Fig. 5. Foot print of geological repository in each scenario.

4. Conclusion

In this study, using the nuclear fuel cycle simulator NMB4.0, we evaluated the impact of MA separation and transmutation on the amount of MA transferred into HLW, the number of vitrified waste canisters, and the required footprint of geological repositories under Japan's nuclear energy scenario. The analysis compared scenarios with and without the introduction of an MA temporary storage process. The results showed that implementing the MA temporary storage process could reduce the amount of MA transferred into HLW by approximately 30% and 90%, depending on whether MA separation was introduced in 2065 or 2045, respectively. Additionally, introducing MA separation in 2065 could reduce

the number of vitrified waste canisters by about 20% and the foot-print of the geological repository by 33%, while a 2045 introduction could achieve reductions of 40% and 82%, respectively. Therefore, the MA temporary storage process effectively mitigates the burden of final disposal during the gap between early MA separation and the widespread deployment of FR. Furthermore, MA temporary storage allows the amount of recovered MA to be managed independently of the FR capacity.

Acknowledgments

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