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ARTICLE

Scenario analysis of future nuclear energy use in Japan: (3) Promotion of Plutonium utilization by RBWR-Backfit

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Japan has a policy of reprocessing spent fuel, reducing its volume, and disposing of it as vitrified waste, and a reprocessing plant is under construction. On the other hand, it is essential to utilize the plutonium separated by reprocessing to avoid accumulation. Hitachi-GE is conducting research and development of new fuel design named resource-renewable boiling water reactor-backfit (RBWR-BF) to enhance plutonium utilization in BWRs. In this study, the effects of installing RBWR-BF were estimated using the NMB code, a nuclear fuel cycle simulator, under the assumption of a future nuclear energy utilization scenario based on light water reactor (LWR) in Japan. As a result, it was shown that burden of MOX loading to LWRs can be minimized and fissionability of remaining plutonium in 2100 was improved by RBWR-BF introduction from 2040.

Keywords: RBWR-BF; Plutonium utilization; NMB; nuclear fuel cycle analysis

1. Introduction

The management of spent fuel (SF) is essential to the implementation of nuclear power generation. Japan has a policy of reprocessing SF, reducing its volume, and disposing of it as vitrified waste, and the Rokkasho Reprocessing Plant (RRP) is under construction. On the other hand, it is essential to utilize the plutonium separated by reprocessing to avoid accumulation. Plutonium will be used in light water reactors (LWRs) for the time being, and then be used as the main fuel of next-generation nuclear reactors such as fast breeder reactors (FBRs), which are capable of plutonium multi-recycling. However, it is expected to take 20 to 30 years to start introduction of such next-generation reactors, or even more for full-scale introduction, and the immediate issue is to efficiently utilize plutonium by then by existing technologies.

Hitachi-GE is conducting research and development of resource-renewable boiling water reactor-backfit (RBWR-BF) fuel to solve this issue (Hino et al. and Miwa et al. (2018-2021))[1-7]. RBWR-BF can accommodate more plutonium by using a tight-lattice fuel arrangement, maintaining an assembly shape similar to conventional one. Since fewer LWRs need to be loaded with MOX fuel, the economics of other LWRs loaded only with uranium fuel will be improved.

In this study, the effects of installing RBWR-BF were estimated using the NMB code (Okamura et al .(2021))[8], a nuclear fuel cycle simulator, under the assumption of a future nuclear energy utilization scenario in Japan.

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2. Assumptions

2.1. RBWR-BF

The RBWR is a technology including several concepts of plutonium-based MOX fuel assemblies that can be loaded into boiling water reactors (BWRs). Among them, RBWR-BF is a design that is more compatible with BWR and aims at the earliest commercialization. While other RBWR designs apply a hexagonal-shaped fuel assembly, the RBWR-BF, hereafter “BF”, uses a rectangular fuel assembly as same as the conventional MOX assembly in BWRs. However, the internal fuel pins are arranged with a narrow pitch in BF assembly, which decreases moderator-to-fuel ratio and increases the neutron energy. As a result, the core is not in the optimum moderation state in terms of criticality and the fuel composition is designed with high Pu enrichment. The higher Pu enrichment allows more plutonium to be contained in the fuel assembly, which promotes plutonium consumption. Furthermore, the higher neutron energy results in a higher conversion ratio that is a ratio of fissile plutonium in the spent fuel to that in the fresh fuel. The higher conversion ratio facilitates the use of plutonium contained in SF in the future introduction of FBRs.

Table 1 shows the core parameters of the BF incorporated in the NMB. The thermal efficiency to reactor life parameters were determined to reproduce advanced BWR (ABWR), although the electricity output in NMB depends on the

Table 1. Parameters of RBWR-BF.

Item	Value in Refs.	Value in NMB database
Thermal efficiency (%)	34.5	34.5
Load factor	92%	92%
Electricity output (MWe)	1356	NA
Batch length (day)	696.4	390.6
Batch number	3.4	6
Reactor life (year)	60	60
Averaged specific heat (MW/tHM)	23.2	23.2
Burn-up (GWd/tHM)	55	54.3
Maximum Pu enrichment (%)	13.4	15

scenario. The values for burnup and other parameters were taken from Ref. [7]. Some parameters have been adjusted to suit the calculations in the NMB. The batch length was set to 13 months, equivalent to current light water reactors, and the number of batches was set to 6, since it must be an integer. The resulting burnup of 54.3 GWd/tHM is almost the same as the reference value and does not significantly affect the results. The maximum Pu enrichment was set to 15% with a margin to 13.4% of the design value, since the enrichment is automatically adjusted inside the NMB according to the isotopic composition of the raw material so that the infinite multiplication factor of unloaded fuel is a predefined value. NMB is capable to solve the burn-up equation using database of one-group section for fuel with different isotopic compositions.

2.2. Nuclear Energy Utilization Scenarios

Table 2 shows assumptions on three scenarios. All scenarios are based on the continued use of LWRs at about 32 GWe corresponding to the 20 to 22% of total electricity supply in 2030 planned in the Sixth Strategic Energy Plan by Japanese government. In the past, 56 LWRs and one gas cooled reactor (GCR) was constructed, of which 33 LWRs are still in operation and 23 LWRs and a GCR was shut down. Now, 2 ABWRs, Shimane-3 and Ohma, are under construction and we have assumed that they will be operational in 2022 and 2028, respectively. All of the 33 operating LWRs and 2 ABWRs are assumed to operate for 60 years, while most of the current LWRs are not yet licensed to operate beyond 40 years. After shut down of these LWRs, they will be replaced by advanced PWR (APWR) or ABWR to keep the electricity capacity around 32 GWe.

The load factor of LWR in FY2021 in Japan was 22%. It was assumed to recover by 5% per year after 2022 and to reach a constant value at 75% after 2031. The load factor is reflected on analysis result such as production of spent fuels.

The RRP will be implemented with a maximum throughput of 800 tHM/year, depending on the plutonium consumption in LWRs. Reprocessing of MOX or BF SF and transition to FBRs are not envisioned. In Japan, large-scale replacement of LWRs could occur in the 2040s. Assuming a reactor life of 60 years, the next large-scale replacement is expected to occur around 2100. Therefore, the analysis will cover the period up to 2100 assuming transition to FBRs at around 2100.

In the Minimum scenario, the 4 pressurized water reactors (PWRs) that have permitted to use MOX fuel with 33% loading and Ohma Full-MOX reactor (the 2nd ABWR) will be used for MOX applications, while Shimane-3 (the 1st ABWR) is not used for MOX. In this scenario, the amount of reprocessing is limited to 500 tHM/year to avoid accumulation of separated Pu.

In the LWR12 scenario, MOX fuel is used in a total of 12 reactors (6 PWRs, 5 BWRs, and a Full-MOX reactor) referring to a target of the Federation of Electric Power Companies of Japan on 2020/12/17 that aims to use MOX fuel in 12 reactors in 2030. Adding to the 4 PWRs in the Minimum scenario, we have assumed that MOX will be used in 2 PWRs and 5 BWRs that have planned to use MOX before the Fukushima accident. The RRP will be operated at maximum capacity, 800tHM/year.

In RBWR2 scenario, plutonium is used in 4 PWRs and 2 ABWRs. Plutonium use as MOX fuel in PWRs is

Table 2. Assumptions on scenarios.

Scenario	Minimum	LWR12	RBWR2
LWR capacity	Constant at 32 GWe assuming replace		
Reprocessing before RRP	5600 t of LWR(UO_2) and 1500 t of GCR fuel in oversea, 1139 t in Tokai reprocessing plant		
Reprocessing of UO_2 SF after 2027[*1] (t/year)	500	800	800
Reprocessing of MOX SF	NA		
MOX loading to conventional reactors (GWe[*2])	PWR 3.81 BWR 0	PWR 5.882 BWR 4.982	PWR 3.81 (~2039) BWR 0
1st ABWR (2022~) 1.373GWe	100% UO_2	100% UO_2	100%UO_2 (2022~2027) 100%MOX (2028~2039) 100% BF(2040~)
2nd ABWR (2028~) 1.383GWe	100% MOX	100% MOX	100%MOX (2028~2039) 100% BF(2040~)

[*1] 70 t in 2023, 170 t in 2024, 170 t in 2025, 390 t in 2026 [*2] 33% of the electricity capacity is provided by MOX fuel.

stopped in 2039, and the 2 ABWRs start using the BF fuel in 2040. The RRP will be operated at maximum capacity, 800tHM/year.

3. Result and consideration

3.1. Overall result

In order to confirm the overall picture of the various quantity evaluation results, the results mainly for the RBWR2 scenario which BF fuel assemblies are loaded in 2 ABWRs are shown in this section. **Figures 1(a)** to **1(c)** show generation capacities of Minimum to RBWR2 scenario where the generation capacity remains constant at around 32 GWe since 2011. Three figures differ in the generation capacity by MOX or BF fuel. In RBWR2 scenario, MOX use in PWRs and BWRs will continue until 2043 with a transition to BF fuel beginning in 2040 at about 3 GWe.

In the RBWR2 scenario, reprocessing will reach a maximum of 800 tHM/y in the 2020s and remain constant thereafter (**Figure 1(d)**). Since the annual UO_2 SF generation is about 600 tHM, the amount of SF storage will decrease by 200 tHM/year (**Figure 2(a)**). On the other hand, MOX and BF SF will be generated, but in smaller

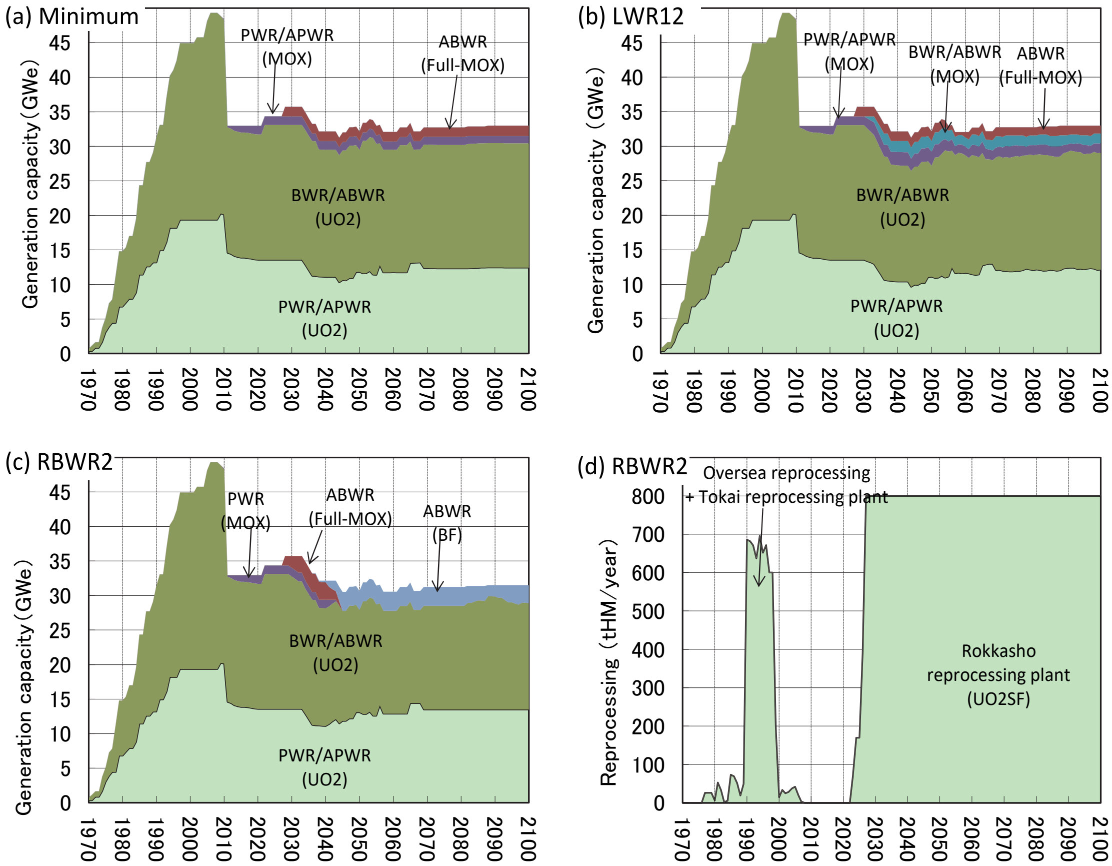

Figure 1. (a)-(c) Electricity generation capacity for Minimum, LWR12 and RBWR2 scenario, (d) Annual reprocessed amount (RBWR2 scenario).

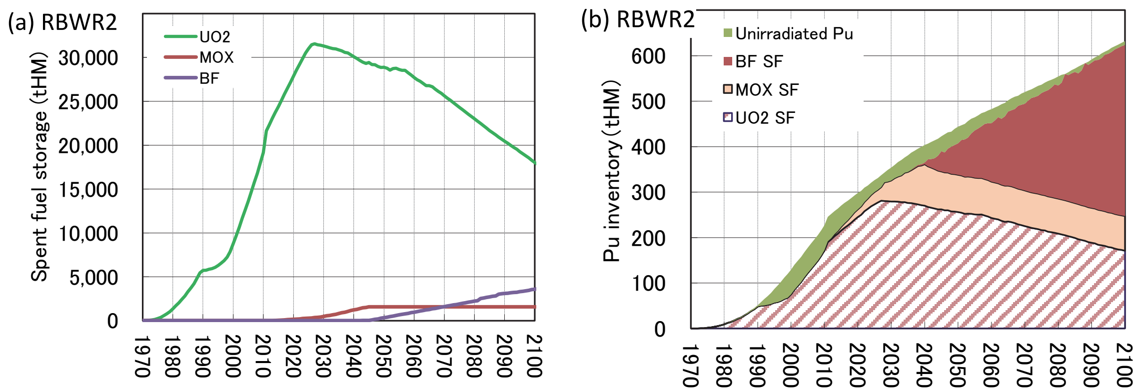

Figure 2. (a) SF storage, (b) Pu inventory (RBWR2 scenario).

quantities than the amount of UO_2 SF.

All generated Pu is used as MOX or BF fuel, and separated and unirradiated Pu is sufficiently suppressed (Figure 2(b)). The total amount including irradiated Pu continues to accumulate in the BF SFs.

3.2. Comparison among scenarios

For each scenario, the generation capacity from MOX and BF fuel is shown in **Figure 3(a)**. The LWR12 scenario has the largest power generation capacity, while the Minimum and RBWR2 scenarios have the smaller capacity. Since the Minimum scenario has only 500 tHM/year of reprocessing, the amount of Pu generated is 5/8 of those in the LWR12 and RBWR2 scenarios. Therefore, the generation capacity by MOX of the Minimum scenario is smaller than that of the LWR12 scenario. On the other hand, the RBWR2 scenario has less power generation capacity because the Pu enrichment of the BF fuel is greater than that of MOX fuel in the LWR12 scenario.

Figure 3(b) shows the power generation capacity of reactors fully or partly loaded with either MOX or BF fuel, including the power generation capacity of UO_2. Figure 3(b) shows larger value than Figure 3(a) because it is assumed that MOX fuel can only be loaded up to 33% in most LWRs. In the Minimum scenario, MOX fuel is loaded in 4 PWRs and one full-MOX ABWR corresponding to 5 GWe of nuclear power plants. On the other hand, in the LWR12 scenario, a total of 12 LWRs will be loaded with MOX fuel, which means that about 10 to 12 GWe of reactors will need to accept MOX fuel. In the RBWR2 scenario, 2 ABWRs are to be used for BF fuel, so only 2.9 GWe reactors are required to accommodate BF fuel. The 2 ABWRs will operate exclusively by BF fuel for much period after 2040, but will partially operate with UO_2 fuel near 2090 due to a shortage of Pu as shown in Figure 2(b).

In general, additional costs are incurred to load MOX or BF fuel into a reactor because of the need for plant system customization, permits from the regulator, and explanations to local authorities. Fewer reactors loaded with MOX or BF fuel will contribute to improving the economics of light water reactors.

Next, accumulation of SF is compared. In the Minimum scenario, UO_2 SF continues to increase because the amount of reprocessing is smaller by 100 tHM/year than the amount of UO_2 SF generated (**Figure 4(a)**). On the other hand, in other scenarios, the amount of UO_2 SF decreases by about 200 tHM/year because the amount of reprocessing is 800 tHM/year. MOX SF of 90 tHM/year is generated in the LWR12 scenario, which is the largest amount (**Figure 4(b)**). In RBWR2 scenario, only about 65 tHM/year is generated

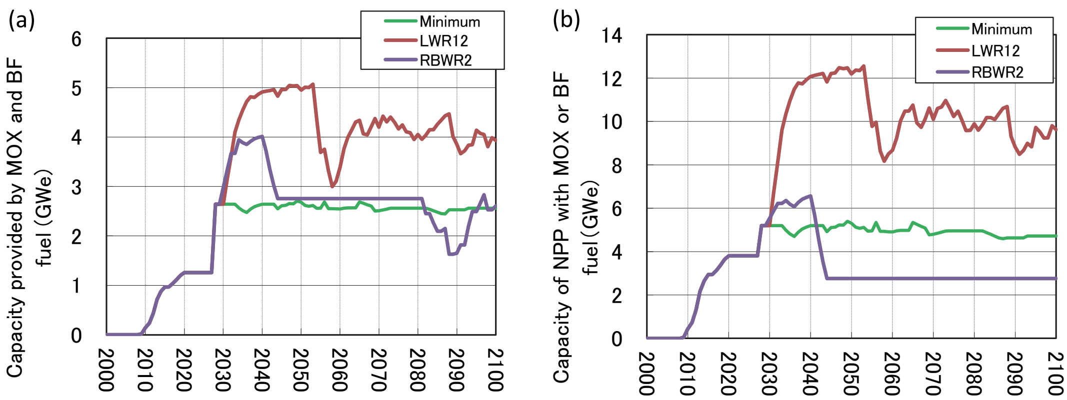

Figure 3. (a) Capacity provided by MOX and BF fuel, (b) Capacity of NPP accommodating MOX or BF fuel.

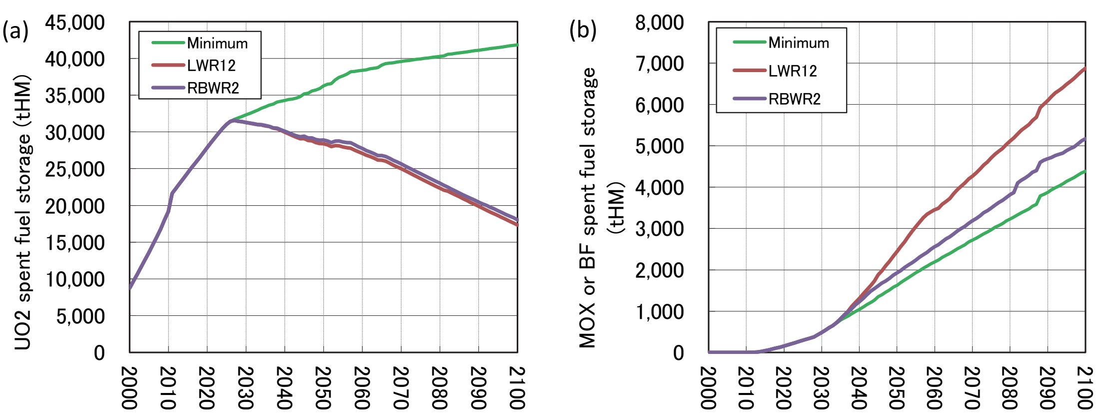

Figure 4. (a) UO_2 SF in storage, (b) MOX or BF SF in storage.

due to the small amount of BF fuel assembly utilization. The Minimum scenario generates a minimum MOX SF of about 55 tHM/year due to the smallest amount of separated Pu generation.

The amount of separated and unirradiated Pu is below 40 tPu in all scenarios after 2020s, as shown in **Figure 5**, and no Pu supply-demand issue has occurred. The Japanese government declared not to increase the amount of separated and unirradiated Pu more than the level in 2018 that is 47 tPu including 4.6 tPu for the research activities.

The Pu inventory, which includes Pu in storage, fresh fuel and spent fuel, increases monotonically in all scenarios

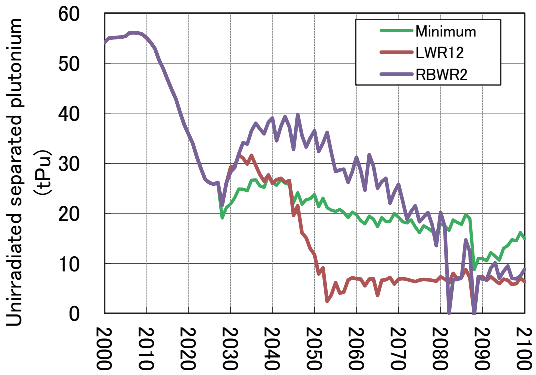

Figure 5. Separated and unirradiated plutonium including fresh MOX and BF fuel.

and reaches above 600 tons in 2100 (**Figure 6(a)**), until when FBRs are assumed to be installed in full-scale. In terms of the fissile Pu fraction of the whole Pu inventory (**Figure 6(b)**), the Minimum scenario is the largest at 58.3% in 2100. This is due to the large proportion of Pu in UO_2 SF that is not irradiated as MOX fuel. In the LWR12 scenario, in which a large amount of Pu is used as MOX fuel, the ratio drops to 55.6% in 2100. On the other hand, in the RBWR2 scenario, the ratio is 57.5% due to its higher neutron energy and higher conversion ratio, and does not decrease significantly compared to the Minimum scenario. The high fissile Pu fraction of plutonium will allow the introduction of FBRs with less plutonium handling in the future.

A comparison of the quantities at the cross section in 2100 is summarized in **Table 3**.

4. Conclusion

In this study, the effects of installing RBWR-BF concept were estimated using the NMB code, a nuclear fuel cycle simulator, under the assumption of a future nuclear energy utilization scenario based on LWR technology in Japan. The scenario was set up to continue using LWRs with a capacity of 32 GWe and reprocessing of 800 tHM/year at maximum.

As a result, the followings were found:

- By maximizing the reprocessing capacity of the RRP (LWR12 and RBWR2 scenarios), the UO_2 SF storage can be gradually decreased after peaking at 32,000 tons

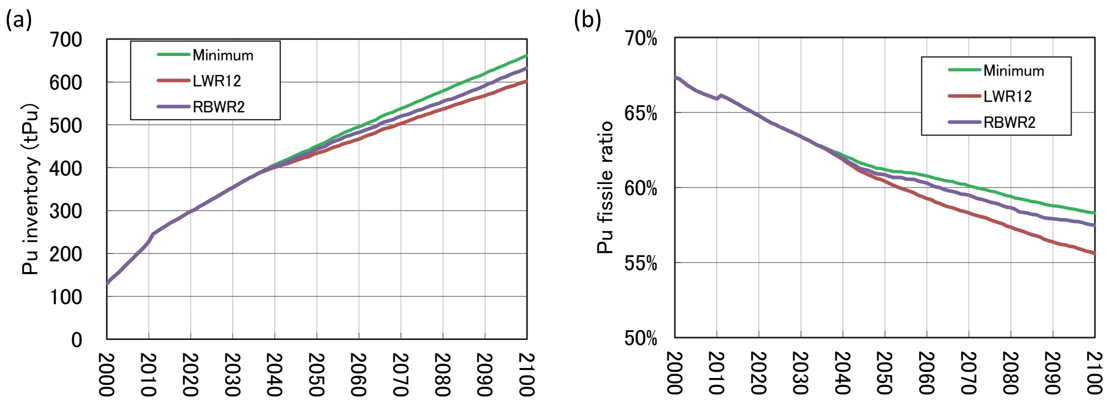

Figure 6. (a) Pu inventory, (b) Pu fissile ratio (Pu239+Pu241).

Table 3. Snapshot in A.D. 2100

Scenario	Minimum	LWR12	RBWR2
Capacity provided by MOX or BF fuel (GWe)	2.6	3.9	2.6
Capacity of NPP with MOX or BF fuel (GWe)	5.0	10.3	2.9
UO_2 SF storage (tHM)	42,000	17,000	18,000
MOX and BF SF storage (tHM)	4,400	6,900	5,200
Unirradiated separated plutonium (tPu)	15	6.3	8.8
Pu inventory (tPu)[*1]	660	600	630
Pu fissile ratio (Pu239+Pu241) (%)	58.3	55.6	57.5

[*1] Whole Pu in Japan including separated Pu and Pu contained in SF

in 2020s.

- By utilizing MOX or BF fuel in 12 LWRs or 2 ABWRs (LWR12 or RBWR2 scenario), even at the maximum reprocessing amount, plutonium will be consumed and the amount of separated and unirradiated Pu will be sufficiently suppressed to less than 40 t.
- If plutonium is assumed to be consumed only by MOX fuel (LWR12 scenario), MOX fuel would be used in reactors that account for 10-12 GWe (about 30% of the domestic power generation capacity). On the other hand, if BF fuel is used in 2 full-MOX ABWRs (RBWR2 scenario), the capacity is minimized to 2.9 GWe, which will contribute to economics of LWRs.
- The total domestic Pu inventory in 2100, until when plutonium-utilizing reactors such as FBRs are assumed to be introduced on a large scale, is more than 600 t. The fissile Pu ratio of the RBWR2 scenario is 57.5% in 2100 that is larger by 2% points than 55.6% in the LWR12 scenario. This larger ratio can be advantageous for the introduction of the FBRs, although estimation of its degree is the future work.

Acknowledgements

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