Scenario Analysis of Breakeven Molten Salt Fast Reactors for Spent Nuclear Fuel Management in Korea

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***Keywords :** Nuclear power plant, Spent nuclear Fuel, Breakeven molten salt fast reactor (BeMFR), Closed fuel cycle, TRU, HALEU

1. Introduction

Rising environmental concerns and the pursuit of stable energy supply have revived attention to nuclear power as a substitute for fossil fuels [1], yet its sustainable expansion remains challenged by spent fuel management and the limited availability of uranium resources. One promising approach is the reuse of spent fuel as a resource, made feasible through the development of advanced reactor technologies. Previous studies have explored the closed fuel cycle combined with molten salt fast reactors (MSFRs) as a means to overcome critical challenges in nuclear power. Within this context, the breakeven molten salt fast reactor (BeMFR) concept seeks to equalize fissile material production and consumption, thereby supporting sustainable reactor operation.

Figure 1 illustrates the fuel cycle of the BeMFR. Criticality is initially achieved either with TRU derived from spent fuel or with HALEU produced from natural uranium. Sustained operation is enabled through continuous feeding of make-up fuel and removal of fission products. In both the initial startup using TRU and the subsequent operation, spent nuclear fuel is effectively recycled as an energy source. This study evaluates the role of BeMFRs in reducing the accumulation rate of spent fuel while simultaneously responding to future nuclear energy demand.

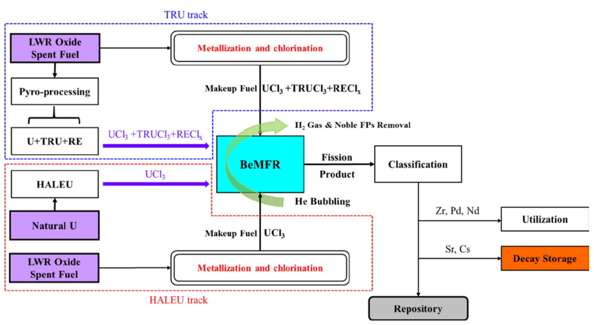

Fig. 1. Fuel cycle using BeMFR starting with TRU or HALEU

2. Current Status of Nuclear Power Plants in Korea

Figure 2 presents the trends in total electricity generation, nuclear power generation, and the nuclear share in the Republic of Korea from 1985 to 2024 [2]. Overall power production has shown a steady increase, with the exceptions of 1997–1998, influenced by the IMF financial crisis, and 2018–2020, affected by nuclear phase-out policies and the COVID-19 pandemic. Since the 2010s, the pace of growth in electricity production has moderated compared to earlier decades. The nuclear share has generally remained close to 30%, though lower than in the late 1980s. Given its strong dependence on national energy policies, future projections of the nuclear fraction are uncertain, but a plausible range can be assumed to lie between 20% and 50%.

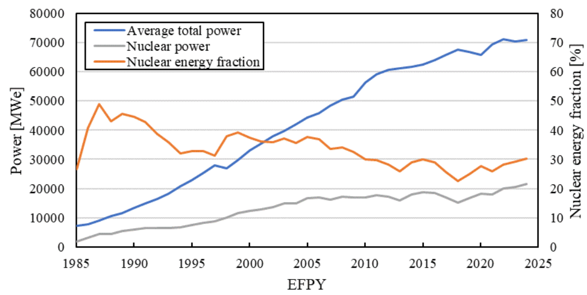

Fig. 2. Total and nuclear power production and nuclear power fraction since 1985

Tables I and II summarize the status of nuclear power plants in Korea as of 2024. Table I provides information on reactor types and their nominal capacities, while Table II details capacity factors, operational periods, and cumulative electricity generation. In total, 28 nuclear power reactors have been constructed, consisting of 24 light water reactors (LWRs) and 4 heavy water reactors (HWRs). Among these, 23 LWRs remain in operation and 1 has been permanently shut down, while 3 HWRs are still operating and 1 has been retired.

Table I: Models and powers of nuclear power plants in Korea

Name	Unit	Model	Power [MWe]
Kori	1	WH 60	562
	2	WH F	621
	3-4	WH F	948
Shin-kori	1-2	OPR-1000	996
Saeul	1-2	APR-1400	1,413
Wolsong	1-4	CANDU 6	645
Shin-wolsong	1-2	OPR-1000	993
Hanbit	1-2	WH F	936

	3-6	OPR-1000	980
Hanul	1-2	France CP1	939
	3-6	OPR-1000	991
Shin-hanul	1-2	APR-1400	1,418

Table II: Detailed information of nuclear power plants in Korea

Name	Capacity factor	Operation start date	Permanent shutdown date	Total energy production [MWe-d]
Kori-1	75.77%	1978-04-29	2017-06-18	6.190E+06
Kori-2	83.62%	1983-07-25	-	7.718E+06
Kori-3	83.52%	1985-09-30	-	1.144E+07
Kori-4	84.74%	1986-04-29	-	1.144E+07
Shin-kori-1	76.96%	2011-02-28	-	3.938E+06
Shin-kori-2	84.17%	2012-07-20	-	3.879E+06
Saeul-1	81.40%	2016-12-20	-	3.479E+06
Saeul-2	83.81%	2019-08-29	-	2.405E+06
Wolsong-1	79.23%	1983-04-22	2019-12-24	5.845E+06
Wolsong-2	89.24%	1997-07-01	-	5.860E+06
Wolsong-3	85.32%	1998-07-01	-	5.500E+06
Wolsong-4	91.12%	1999-10-01	-	5.560E+06
Shin-wolsong-1	82.05%	2012-07-31	-	3.800E+06
Shin-wolsong-2	84.14%	2015-07-24	-	2.945E+06
Hanbit-1	84.46%	1986-08-25	-	1.111E+07
Hanbit-2	84.04%	1987-06-10	-	1.084E+07
Hanbit-3	82.79%	1995-03-31	-	8.558E+06
Hanbit-4	84.89%	1996-01-01	-	7.603E+06
Hanbit-5	80.17%	2002-05-21	-	6.586E+06
Hanbit-6	84.80%	2002-12-24	-	6.798E+06
Hanul-1	85.77%	1988-09-10	-	1.072E+07
Hanul-2	87.04%	1989-09-30	-	1.055E+07
Hanul-3	84.63%	1998-08-11	-	8.213E+06
Hanul-4	84.81%	1999-12-31	-	7.643E+06
Hanul-5	87.21%	2004-07-29	-	6.530E+06
Hanul-6	88.86%	2005-04-22	-	6.406E+06
Shin-hanul-1	80.93%	2022-12-07	-	9.908E+05
Shin-hanul-2	90.60%	2024-04-05	-	4.208E+05

Figure 3 illustrates the number of nuclear power plants (NPPs) and their corresponding electricity generation derived from Table II, and Figure 4 presents the accumulation of spent nuclear fuel (SNF). In generating Figure 3, it is assumed that each plant maintains constant power output throughout its operational period, while for Figure 4 the average discharge burnup is taken to be approximately 45 MWth-d/kgU for LWRs and 7 MWth-d/kgU for HWRs.

At present, the total installed electric capacity of nuclear power in Korea is estimated at about 21,500 MWe. The cumulative SNF inventory is estimated to be approximately 1.04×10^7 kg from LWRs and 1.07×10^7 kg from HWRs. As of 2024, the daily production rate of SNF is projected to be around 1,280 kg from LWRs and 780 kg from HWRs.

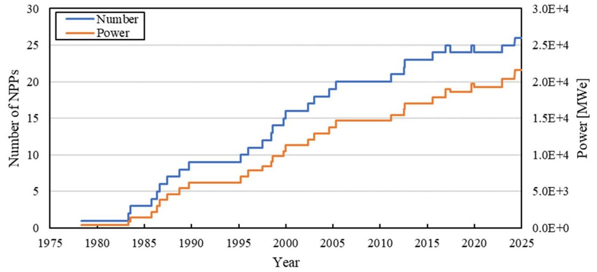

Fig. 3. Number of NPPs and total nuclear power from 1978 to 2024

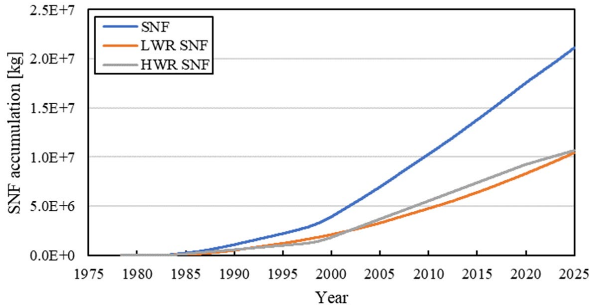

Fig. 4. Spent nuclear fuel accumulation state from 1978 to 2024

3. Possible Effect of BeMFR

3.1 Examples of BeMFRs

The BeMFR is a reactor concept based on the MSFR design that aims to achieve breakeven and mitigate spent fuel accumulation. It sustains long-term operation by balancing fissile material production and consumption, starting with either TRU from spent fuel or HALEU from natural uranium, and maintaining criticality through continuous refueling and fission product removal.

The reactor features a cylindrical core filled with liquid fuel, which is surrounded by a stainless-steel reflector to improve neutron economy. A heat exchanger connected to the core enables circulation of the molten salt fuel between the active region and the secondary system. An example of the reactor shape is shown in Fig. 5, and corresponding design parameters are listed in Table III. These examples are taken from previous studies. [4-5]

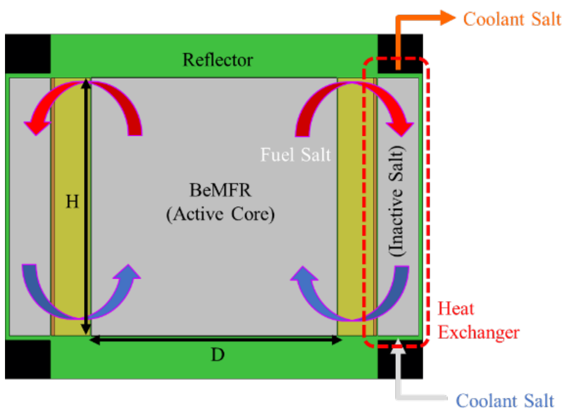

Fig. 5. Side view of BeMFR

Table III: Design parameters of two BeMFR examples [5]

	Reactor A	Reactor B
Power	3,000 MWth	3,000 MWth
KCl-TRUCl$_3$-UCl$_3$-RECl$_3$	46.00-8.48-38.22-7.30	49.00-8.24-34.52-8.24
Cl-37 enrichment	99 at.%	99 at.%
Fuel density at 650°C	3.676 g/cm^3	3.563 g/ cm^3
Active core diameter	330 cm	330 cm
Active core height	330 cm	330 cm
Active core volume	2.822E+7 cm^3	2.822E+7 cm^3
Inactive salt volume of initial core	1.500E+7 cm^3	1.500E+7 cm^3
U mass	66,791 kg	61,039 kg
TRU mass	14,947 kg	14,696 kg
RE mass	7,536 kg	8,607 kg

3.2 Verifying the impact of BeMFR of Reactor A through simulation

When examining the impact of the BeMFR, several assumptions are made:

- The operational lifetime is assumed to be 40 years divided by the capacity factor for existing nuclear power plants, and 60 years divided by the capacity factor for the APR-1400.
- No additional LWRs or HWRs are assumed to be constructed after 2025.
- Beginning in 2030, new BeMFRs are built annually until the accumulated TRU is depleted.
- The BeMFR is assumed to start up solely with spent nuclear fuel, requiring 67 tons of U, 15 tons of TRU, and 8 tons of RE, totaling 89 tons of SNF, based on the specifications of Reactor A in Table III.
- In this study, BeMFRs are constructed only while recovered TRU is available, with one reactor added whenever 15 tons of TRU accumulate from existing nuclear power plants. Once the TRU is depleted, no further BeMFR construction is assumed.
- The BeMFR is modeled with a thermal power of 3,000 MWth, an thermal efficiency of 40 %, and a capacity factor of 0.85. Its operational lifetime is considered unlimited for the purpose of this study.
- The daily SNF consumption for 3,000 MWth BeMFR is estimated to be about 3.121 kg.

The following figures compare scenarios with and without BeMFR deployment until 2100. As shown in Fig. 6, without additional LWRs or HWRs, a large wave of reactor shutdowns occurs around 2030, with the last LWR closing in the 2090s. In contrast, if the BeMFR starts solely with spent nuclear fuel, the maximum number of NPPs reaches 32, and after the final LWR shutdown, a total of 23 BeMFRs can be constructed. From 2030 to 2047, a total of 18 BeMFRs can be constructed in this way. After this period, the intervals between successive constructions become longer, and after an additional 5 BeMFRs, construction ceases due to TRU depletion. This result indicates that, in order to continuously meet nuclear energy demand, further BeMFR deployment must be achieved using HALEU fuel.

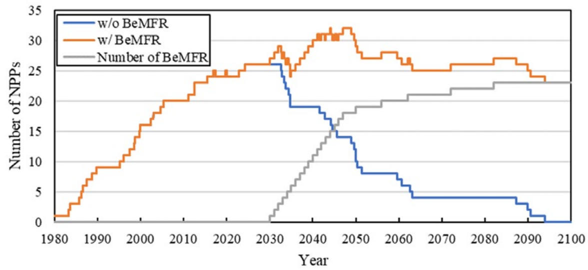

Fig. 6. Comparison of the number of NPPs until 2100 without and with the use of BeMFR

Looking at Fig. 7, total nuclear power generation rises until the late 2040s, peaking at about 29,500 MWe, before declining to around 23,500 MWe at 2100. The power drop in the 2030s can be offset by concentrated construction of TRU-fueled BeMFRs, while the decline after the 2050s can be compensated by deploying HALEU-fueled BeMFRs.

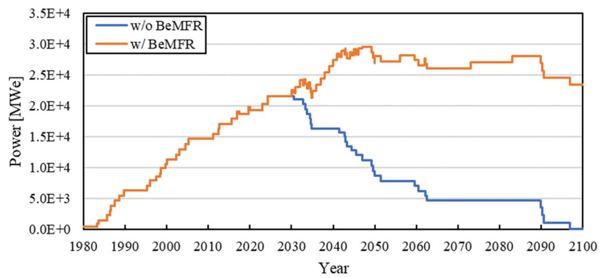

Fig. 7. Comparison of the total nuclear power until 2100 without and with the use of BeMFR

Fig. 8 shows SNF accumulation until 2100 with and without BeMFR. Without new LWRs or HWRs, SNF accumulation slows after the 2040s, but still requires storage for twice the currently accumulated amount. With BeMFR deployment, peak SNF accumulation is reduced by about 8%, and begins to decline after the final LWR shutdown; without further BeMFRs, existing SNF alone could support operation for about 1,400 years.

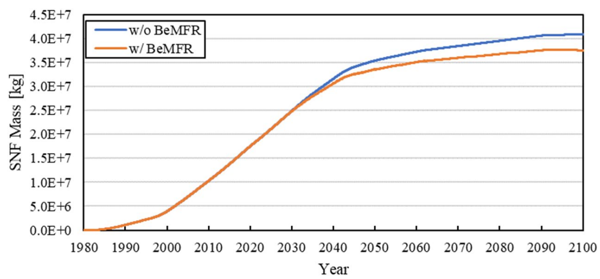

Fig. 8. Comparison of the spent nuclear fuel accumulation until 2100 without and with the use of BeMFR

Figure 9 shows the accumulation of TRU without and with the use of BeMFR. As discussed earlier, 15 tons of TRU is required for the construction of a single BeMFR. The first construction occurs in 2030, and thereafter, one BeMFR is constructed annually until the available TRU is depleted. In the case without BeMFR construction, the accumulated mass of TRU will eventually reach about 360 tons. Each sharp decrease in TRU inventory corresponds to the additional construction of one BeMFR.

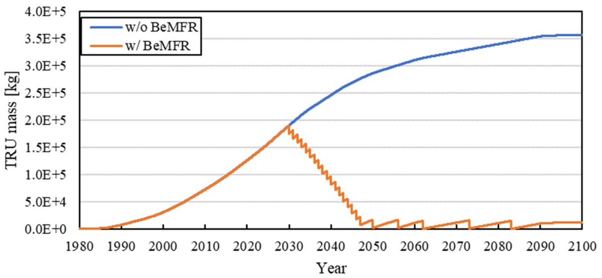

Fig. 9. Comparison of the TRU accumulation until 2100 without and with the use of BeMFR

4. Conclusions

This study examined the potential role of BeMFRs in addressing critical challenges in nuclear power: the sustainable supply of fissile resources and the management of SNF. By utilizing SNF as both startup material and a long-term energy resource, BeMFRs enable a closed fuel cycle that reduces the accumulation of SNF while maintaining a stable supply of nuclear energy. The results indicate that initial deployment with TRU from existing spent fuel can support early BeMFR construction, while subsequent expansion may be complemented by HALEU, thereby ensuring continuity of nuclear energy generation.

Overall, BeMFR deployment not only mitigates the burden of spent fuel storage but also alleviates concerns regarding uranium resource limitations, highlighting its potential contribution to the sustainable development of nuclear power. Nonetheless, further investigation is required to refine fuel cycle strategies, assess long-term safety and economics, and evaluate integration with existing nuclear infrastructures. These efforts will be crucial to realizing the practical deployment of BeMFRs as a viable pathway toward a sustainable nuclear energy future.

Acknowledgments

This research was supported by the KAIST Convergence Research Institute Operation Program and Korea Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Government (MTIE) (RS-2024-00439210), and the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIP) (2021M2D2A207638322).

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