〈Technical Note〉

SFR DEPLOYMENT STRATEGY FOR THE RE-USE OF SPENT FUEL IN KOREA

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The widespread concern regarding the management of spent fuel that mainly contributes to nuclear waste has led to the development of the sodium-cooled fast reactor (SFR) as one of the most promising future types of reactors at both national and international levels. Various reactor deployment scenarios with SFR introductions with different conversion ratios in the existing PWR-dominant nuclear fleet have been assessed to optimize the SFR deployment strategy to replace PWRs with the view toward a reduction in the level of spent fuel as well as efficient uranium utilization through its reuse in a closed fuel cycle. An efficient reactor deployment strategy with the SFR introduction starting in 2040 has been drawn based on an SFR deployment strategy in which burners are deployed prior to breakeven reactors to reduce the amount of PWR spent fuel substantially at the early deployment stage. The PWR spent fuel disposal is reduced in this way by 98% and the cumulative uranium demand for PWRs to 2100 is projected to be 445 ktU, implying a uranium savings of 115 ktU. The SFR mix ratio in the nuclear fleet near the year 2100 is estimated to be approximately 35-40%. PWRs will remain as a main power reactor type until 2100 and SFRs will support waste minimization and fuel utilization.

KEYWORDS : Sodium cooled Fast Reactor, Burner, Breakeven Reactor, Spent Fuel

1. INTRODUCTION

It is generally recognized that the spent fuel discharged from nuclear power plants constitutes the main contribution to nuclear waste. The management of spent fuel from nuclear power plants differs depending on the perspectives and scenarios posed by the countries directly concerned. However, there is a general consensus on the need for a deep geological repository and a reduction in the burden of the disposal of highly radioactive waste as these issues pertain to non-proliferation. This has led to the definition and implementation of joint research programs worldwide. Many studies have been performed regarding advanced fuel cycle options to manage spent fuel and/or reduce hazardous materials [1,2].

More than 700 tons of spent fuel is discharged annually from the present nuclear fleet composing of 16 PWRs and 4 PHWRs in Korea [3,4]. The spent fuel arising is temporarily stored at each nuclear power plant site and is held there until its final waste disposal process begins. With a continuous expansion of the nuclear power capacity, the overall PWR spent fuel storage capacity is foreseen to be saturated by 2016, even if consideration of the expansion of the spent fuel storage pools at each nuclear power site becomes a reality. In addition, it is difficult to decide on a waste disposal site that can meet widespread public acceptance. Realization of a radioactive waste disposal is an impending challenge in Korea.

Korea's share in the world reactor-related uranium requirement was 5.1% in 2005 [5]. The share by 2015 is projected to be 5-7%. The role of nuclear power in electricity generation is expected to become more important in Korea due to its increasing electricity demand coupled with its relatively scant level of natural resources. Concerning the security of a uranium supply, however, difficulty is expected in securing uranium of a level greater than 5% of the world uranium market considering the projection that the overall nuclear capacity for the world's population will more than double in the coming nuclear renaissance era. This is especially true for several Asian countries.

Sodium-cooled fast reactors (SFRs) can recycle transuranics (TRU) through the reuse of PWR spent fuel, which is also synergistic with the efficient use of natural uranium, thus contributing to sustainable development. The SFR designed for the integral recycling of all actinides (uranium and TRU) is known as the Generation-IV (Gen-IV) concept, which has the shortest time horizon possible. In this context, according to the Nuclear Technology Roadmap established in Korea in 2005, this type of SFR was chosen as one of the most promising future types of reactors that is likely deployable by 2030. The SFR Basic Key Technologies Development Project for the development of the conceptual design of a Gen-IV SFR is being conducted by KAERI under the third national mid- and long-term nuclear R&D program, newly launched as a 10-year program in 2007.

The neutron balance feature of a fast reactor allows flexibility in its design to achieve a conversion ratio, which can be lower than, equal to or higher than one, according to specific objectives. This favorable neutron balance feature makes flexible waste management strategies possible by introducing fast reactors having the appropriate conversion ratio. This approach is considered most appealing as far as future nuclear systems are concerned.

This paper presents the results of fast reactor deployment strategy studies pertaining to the Korean context.

2. SCENARIO STUDIES

The current global nuclear energy system is almost entirely based on thermal reactors. This mature technology will continue to dominate the nuclear fuel cycle for many decades. A revival of nuclear energy would renew the interest in fast reactors that enhance the capability of alleviating the potential limits on nuclear energy growth associated with the availability of uranium and waste disposal sites. From this perspective, comprehensive analyses of the transition scenario from thermal to fast neutron systems have been and are being performed at national and international levels [6-12]. These scenario studies mainly focus on a transition from thermal to fast reactors with a single mission, i.e., transmutation and breeding.

A PWR-SFR coupled scenario study has shown that SFRs can substantiate domestic waste management claims in Korea through transmutation [13]. As an extension of this study, efficient reactor deployment scenarios with the introduction of SFRs having different conversion ratios are sought here to optimize the SFR deployment strategy to replace the existing nuclear fleet that is mainly composing of PWRs, only in terms of spent fuel reduction and efficient uranium utilization through its reuse in a closed fuel cycle. An Accelerator-Driven subcritical System (ADS), a Hybrid Power Extraction Reactor (HYPER) being developed as one nuclear option, is not included in the future nuclear fleet, as it is only at the stage of fundamental research.

This scenario study aims to find an efficient reactor deployment scenario that can meet the following requirements:

(1) The amount of cumulative PWR spent fuel arising shall be kept below 20 ktHM, which is the estimated capacity requirement for a repository at present, and
(2) The amount of cumulative uranium demand shall be less than 5.0% of the identified uranium resources in the world.

2.1 Description of Scenarios

2.1.1 Description of Reactor Deployment Scenarios

Deployment scenarios were simulated for the period of 2005-2100. Seven deployment scenarios for a reactor strategy are considered to evaluate the total amount of cumulative spent fuel and uranium demand with different SFR missions and mix ratios in the future nuclear fleet:

Case 1: PWR once-through cycle (OTC), direct disposal of spent fuel without treatment
Case 2: Breeder (BR) only with all of the decommissioned PWRs being replaced with Breeders (BRs)
Case 3: Burner (BN) only with a mix ratio of SFRs in 2100 of 30 ~ 40%
Case 4: Breakeven (BK) reactor only with a mix ratio of SFRs in 2100 of 30 ~ 40%
Case 5: (BK + BN) with a mix ratio of SFRs in 2100 of 30 ~ 40%
Case 6: (BN + BK) with a mix ratio of SFRs in 2100 of 30 ~ 40%
Case 7: (BN + BK) with a mix ratio of SFRs in 2100 of ~50%

In all of the cases of SFR deployment (Cases 2-7), a demonstration SFR is introduced in 2030 and commercial SFRs are then deployed from 2040 in accordance with the corresponding SFR-type deployment scheme.

2.2.2 Long-Term Nuclear Power Generation Scenarios

In 2007, 16 PWRs (including 6 OPRs) and 4 PHWRs were in operation. The installed nuclear electricity generation capacity in 2006 was 17.7 GWe, supplying 39.0% of the total electricity. According to the “Third Basic Plan for Long-term Electricity Supply and Demand,” the installed nuclear capacity will become 27.3 GWe in 2020 and the nuclear share will be 43.4% of the total electricity generation [4].

With the basic assumption that nuclear power is maintained as a major electric power source, three scenarios (high, reference, and low cases) for the total and nuclear power electricity generation differentiated by either annual growth rates or nuclear shares are considered in this study. The total generation and nuclear electricity generation for three scenarios by 2020 are given using the same data from the “Third Basic Plan for Long-term Electricity Supply and Demand”. After 2020, the total electricity generation for the reference scenario

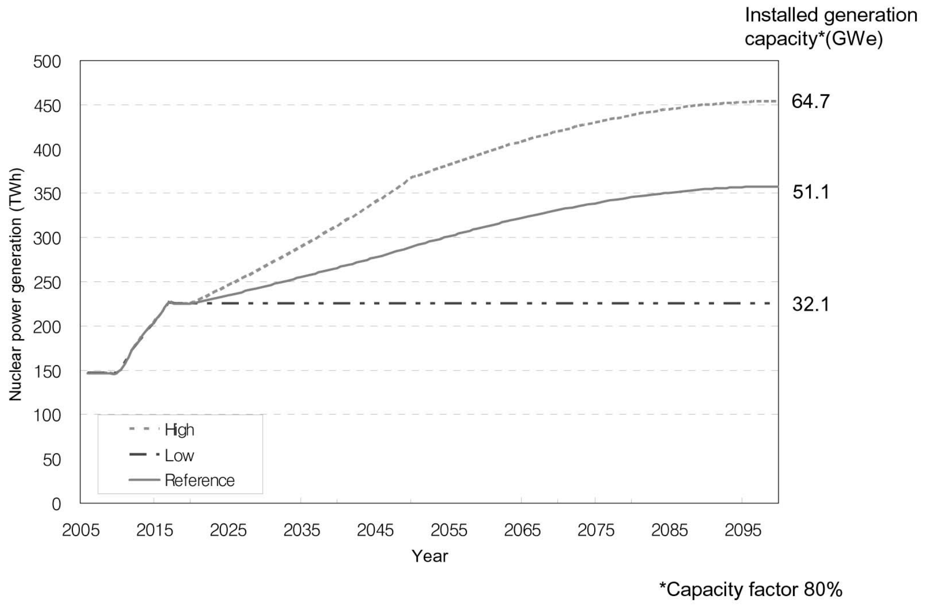

Fig. 1. Long-Term Nuclear Power Projection

is projected to grow annually by 1.0% for the next 30 years (2021-2050); adjusted after 2050 to decrease gradually to 0% by 2100. In the reference scenario, the nuclear share of 43.4% planned as of 2020 is maintained until 2100. In the high scenario, the nuclear share gradually increases to 55.0% by 2050; past this date, it is held constant until 2100. On the other hand, the low scenario assumes nuclear power generation at 225 TWh as of 2020, and this rate is held until 2100.

Figure 1 shows the long-term nuclear power generation projections estimated for the high, reference, and low nuclear power generation scenarios. The reference scenario was used to begin the SFR introduction scenario study. In the reference scenario, the total installed nuclear capacity is projected to increase to 51.1 GWe in 2100, which corresponds to a nuclear electricity generation rate of 350 TWh/yr as estimated by an average capacity factor of 80%. With the same average capacity factor, the installed generation capacities for the high and low scenarios are estimated to be 64.7 GWe and 32.1 GWe, respectively.

2.2 Assumptions

The lifetime of existing nuclear power plants has been extended up to 60 years, which is identical to that of SFRs. Commercial SFRs are introduced into the power grid from 2040 following the introduction of a demonstration SFR in 2030. CANDU (PHWR) reactors will no longer be constructed and those in operation will be retired around the year 2050. Three types of U-TRU-Zr metallic-fuelled SFRs, breeder (BR) (breeding ratio 1.22), breakeven (BK) reactors (breeding ratio 1.0) and burner (BN) (conversion ratio 0.61), are considered for SFR deployment. The power capacities of the PWRs and SFRs are 1,000 MWe and 600 MWe, respectively.

Existing SFR fuel is supplied via the pyroprocessing of spent fuels. All TRUs (Pu and MA) produced from PWRs and SFRs are recycled and transmuted in SFRs. Recycling of CANDU (PHWR) spent fuel is not considered in this study. It is assumed that a reasonable amount of PWR spent fuel should be maintained to supply SFR fuel without interruption, even after 2100.

No limit to the fuel cycle facility capacities for fuel fabrication, pyroprocessing, and interim storage is considered. Out-of-core cycle parameters such as cooling times and fabrication delays are not considered. It is expected that the impact in the variations of such parameters would be not be significant to explore the reactor strategy from the viewpoint of the total fuel mass balance, especially in a closed fuel recycle.

Uranium demand for and spent fuel arising from PWRs were estimated using the following specifications: 0.25 wt% and 4.30 wt% uranium enrichments for the tail assay and fresh fuel respectively; three batches refueling for a cycle length of 1.5 years; 50 GWd/t of discharge burn-up; 34.0% thermal efficiency; and an 80% plant operation load factor.

For the fuel mass balance data for a breeder (BR), another scenario study [14] was referenced. Input data for a burner (BN) and a breakeven (BK) reactor were prepared based on the Korea Advanced Liquid Metal Reactor (KALIMER)-600 design specifications [15,16].

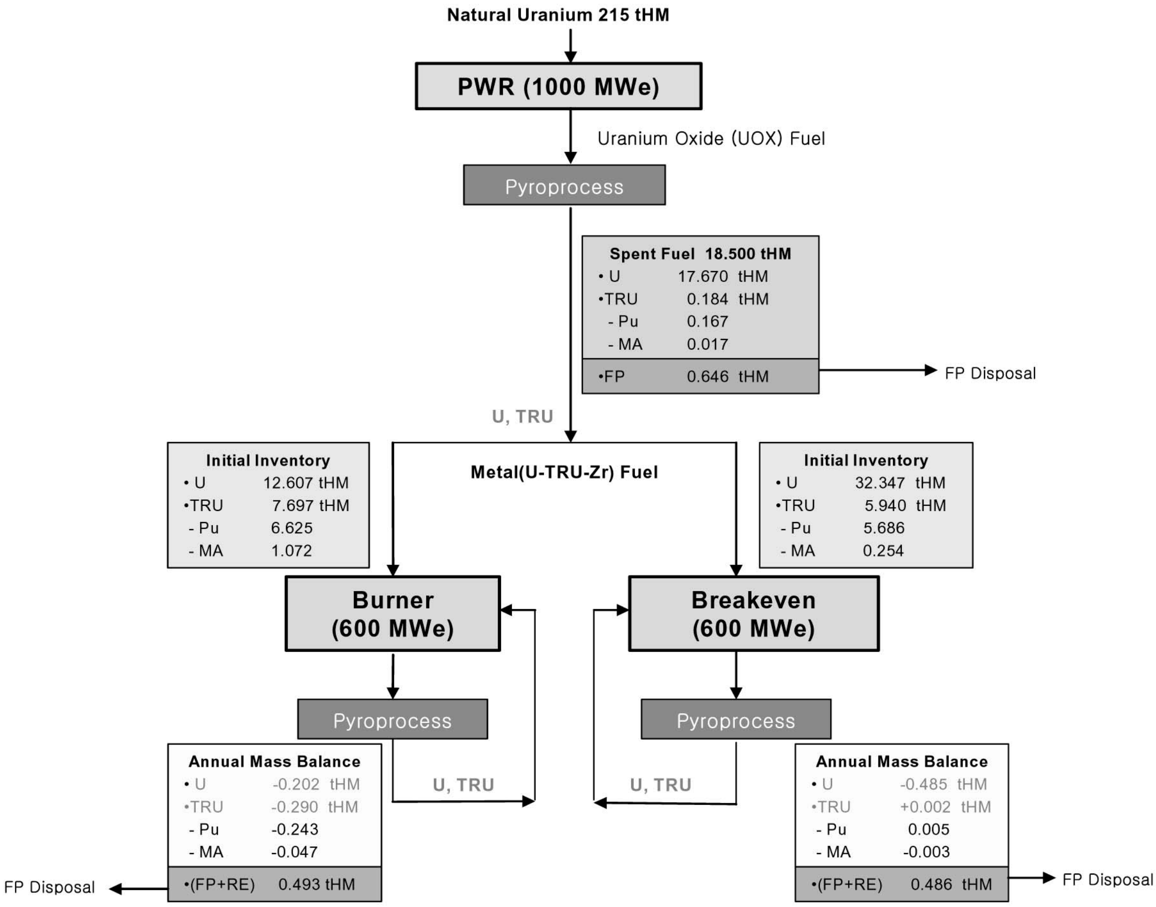

Fig. 2. Annual Fuel Mass Balance

With full plutonium production in the core, the breakeven (BK) reactor core with a breeding ratio of ~1.0 does not need to use blankets, which precludes the production of excess plutonium. The breakeven reactor can operate at equilibrium with a depleted uranium feed only.

Details of the annual fuel mass balance for the PWR-SFR coupled equilibrium fuel cycles considered in this study are schematically shown in Figure 2. The start-up fuel for the SFRs is composed of recovered PWR discharged TRU and depleted uranium. The isotopic compositions of the PWR TRU are given based on a typical five-year cooled 50 GWd/t burnt PWR spent fuel discharged from domestic nuclear power plants. The amount of PWR spent fuel required for providing the initial start-up fuel inventory for the SFRs depends on the initial SFR fuel composition. The fractions of Pu and MA for a breakeven reactor are 14.85% and 0.6%, respectively; for a burner these values are 32.63% and 5.28%, respectively. The initial uranium inventory for a breakeven reactor (32.3 t) is higher than that for a burner (12.6 t), which indicates that a breakeven reactor can utilize the PWR spent fuel stock already kept at nuclear power plants more efficiently with its deployment.

By forming a closed fuel cycle, the remaining and newly bred fissile material is recovered and recycled together with long-lived radiotoxic nuclides. For a breakeven reactor, the build-up of Pu (5 kg/yr) and the consumption of minor actinides (3 kg/yr) occur at quite low levels. For the equilibrium fuel composition of the breakeven reactor, the fact that its spent fuel composition is very close to that of fresh fuel implies that plutonium is neither extracted nor added to the fuel. The fuel composition is adjusted by simply adding another portion of depleted uranium to the main fuel to compensate the burnt-up of a component in the core.

In the case of a burner, a significant Pu burning (243 kg/yr) is obtained together with a significant consumption of minor actinides (47 kg/yr), which induces significant burning of TRU (290 kg/yr). The comparison of the TRU mass balances implies that the burner could be used more efficiently to reduce the PWR spent fuel arising from existing nuclear power plants.

Table 1. Main Results of the Scenario Studies (as of the End of the Year 2100)

Scenarios		Reference (First Investigation)							High	Reference	Low
		1	2	3	4	5	6	7	8	9	10
		PWR-OTC	BR only	BN only	BK only	BK+BN	BN+BK	BN+BK	BN+BK	BN+BK	BN+BK
Uranium resource	Cumulative demand (ktU)	885	509	717	727	728	723	685	537	445	335
	Savings (ktU)	0	375	158	159	157	162	200	143	115	86
	Cumulative. domestic demand/ Identified resources*(%)	6.0	3.4	4.9	4.9	4.9	4.9	4.9	3.6	3.0	2.3
Spent fuel	Cumulative amount (ktHM)	83.2	41.0	1.0	50.2	22.0	15.1	1.2	1.0	2.0	6.7
	Savings (ktHM)	0.0	40.1	74.4	33.2	57.6	66.1	82.0	82.0	64.6	46.8
MA	Cumulative amount (t)	77.9	38.4	0.9	44.9	23.5	14.1	1.1	1.0	2.8	6.3
	Savings (t)	0.0	37.5	69.6	31.1	75.7	61.9	78.8	75.5	60.5	43.8
SFR mix ratio	Total (%)	-	100.0	41.6	35.0	37.2	35.0	50.4	37.1	37.6	44.8
	BN								22.3	23.5	22.4
	BK								14.8	14.1	22.4
	Remark		does not satisfy Req. (1) in Sec. 2.1	Insufficient fuel supply is expected after 2100	does not satisfy Req. (1) in Sec. 2.1	does not satisfy Req. (1) in Sec. 2.1	Satisfies Reqs. (1) and (2) in Sec. 2.1	Insufficient fuel supply is expected after 2100	Satisfies Reqs. (1) and (2) in Sec. 2.1		

(Notes) BR: Breeder, BN: Burner, BK: Breakeven
*14.80 million tU [OECD/NEA-IAEA, Uranium 2005: Resources, Production and Demand (2006)].

Based on the annual fuel mass balance given above, the front and back end mass flow of fuel materials, amount of spent fuel and minor actinides vs. time are estimated with basic formulae that can simulate scenarios and quantify the scale of deployment of reactors.

3. RESULTS AND DISCUSSIONS

3.1 Results of the Reference Scenario

The main results obtained in the scenario analyses are given in Table 1. For each deployment scenario, potential scenarios were determined in a heuristic manner subject to the two requirements given in Sec. 2.1. In this table, the results for the first seven cases (Cases 1-7) were obtained up to 2100 based on the reference scenario, assuming that the total spent fuel arising includes that from CANDUs. From a synthetic comparison of the results obtained for the reference scenario (Cases 1-7), Case 6 (BN+BK), in which burners (BNs) are deployed prior to breakeven reactors (BKs), was selected as the most appropriate SFR deployment scenario. The results of the last three cases (Cases 8-10) will be discussed later.

Figure 3 shows the accumulation of the annual PWR spent fuel arising for several SFR deployment cases compared with the PWR once-through (PWR-OTC) strategy with no reprocessing (Case 1). The accumulation of PWR spent fuel is greatly reduced upon the introduction

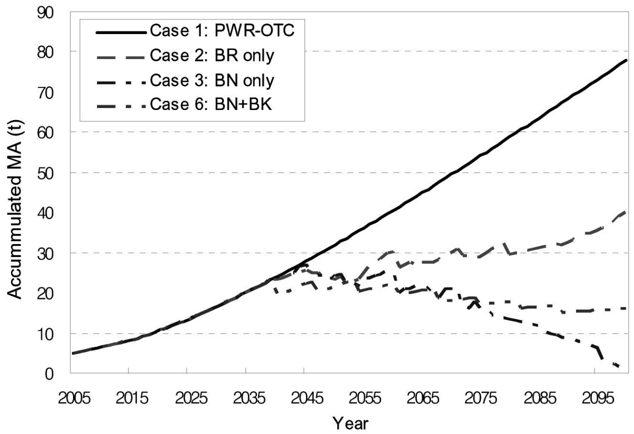

Fig. 3. Cumulative Spent Fuel (Reference Scenario)

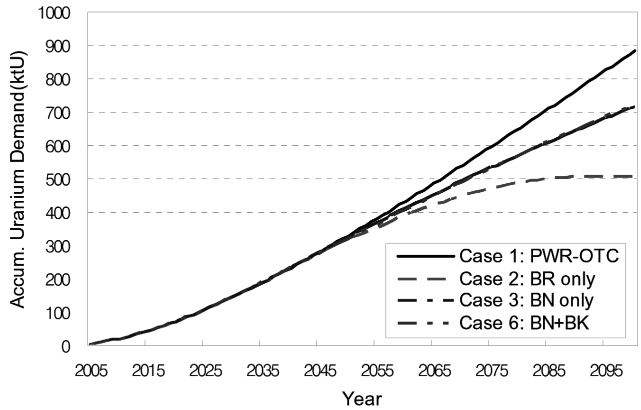

Fig. 4. Cumulative Uranium Demand (Reference Scenario)

of the SFR due to the fact that a substantial amount of spent fuel is used to fuel the start-up cores of the SFRs. SFRs are to be deployed in support of a substantial reduction of the level of PWR spent fuel at the first stage of deployment. The continuous deployment of burners effectively reduces the ongoing accumulation of PWR spent fuel to below 20 ktHM 30 years after the introduction of commercial SFRs, thus lightening the burden of PWR spent fuel management.

Figure 4 illustrates the cumulative uranium demands for various SFR deployment strategies in comparison with the PWR once-through (PWR-OTC) strategy with no reprocessing. It is clearly shown in the figure that the introduction of SFRs, in which TRUs are recycled through the reuse of PWR spent fuel, substantially reduces uranium demand. The introduction of breeders (BRs) effectively reduces the uranium demand through producing excess TRU during the operation. This leads to the efficient use of natural uranium, thus contributing to sustainable nuclear power development. The cumulative uranium demand is estimated to be less than 740 ktU, 5% of the amount of identified uranium resources of 14.8 million tU [5], for all cases with SFR deployment. The uranium saving is estimated to exceed 158 ktU upon the deployment of the SFRs.

The amount of installed capacity and the deployment rates for burners are limited by the amount of TRU or plutonium available to supply as start-up fuel upon the introduction of the burner. The level of TRU availability strongly depends on the amount of PWR spent fuel accumulated from the achievement of nuclear power plant operations as well as the spent fuel arising from existing nuclear power plants. It is noted that the continuous deployment of burners only (Case 3) could effectively exhaust all of the PWR spent fuel accumulation in a shorter period of time before 2100. In this case, scenario solutions are sought subject to the requirement that a reasonable amount of PWR spent fuel accumulation should be maintained.

3.2 Applicability to Different Nuclear Power Development Environments

The SFR deployment scenario (Case 6) selected as the most appropriate scenario, is applied to the other two cases of the high and low cases (corresponding to Case 8 and 9 for an analysis, respectively) in an effort to investigate its applicability to various nuclear power development environments. In this investigation, spent fuel is only assumed to be produced from PWRs.

The results obtained from the analyses of the last three cases (Cases 8-10) show that the SFR deployment strategy (Case 6) is applicable to a range of nuclear power development environments, even with no added nuclear capacity to the existing nuclear fleet after 2020 (Case 10). From a comparison of the results for these three cases (Cases 8-10), Case 9 (BN+BK) was selected as the most appropriate SFR deployment scenario.

With the most appropriate deployment scenario (Case 9), where breakeven reactors (BKs) are deployed from 2068 after the deployment of burners (BNs) starting in 2040, the PWR spent fuel accumulation is reduced to an amount below 20 ktHM. This projection is shown in Figure 5. In Figure 6, the cumulative uranium demand for PWRs up to 2100 is estimated to be 445 ktU, which indicates uranium savings of 115 ktU with the introduction of the SFR. The cumulative uranium demand represents 3.0% of the identified uranium resources of 14.8 million tU, which implies a secure purchase in the world uranium market. The PWR spent fuel disposal is reduced by 64.6 ktHM and the SFR mix ratio in the nuclear fleet is estimated to be 37.6% by the year 2100. From these results, it is conjectured that an appropriate SFR mix ratio in the nuclear fleet around the

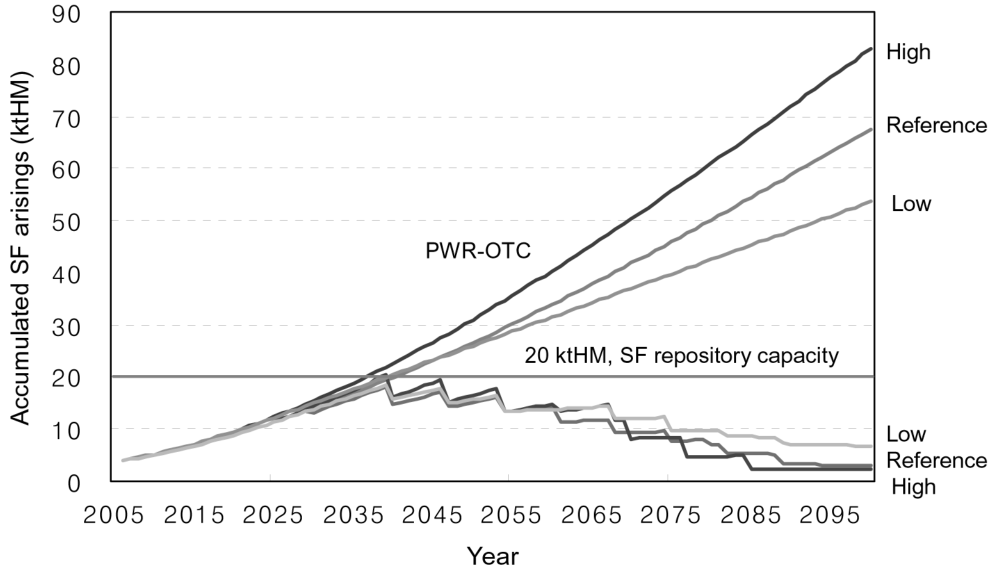

Fig. 5. Cumulative PWR Spent Fuel

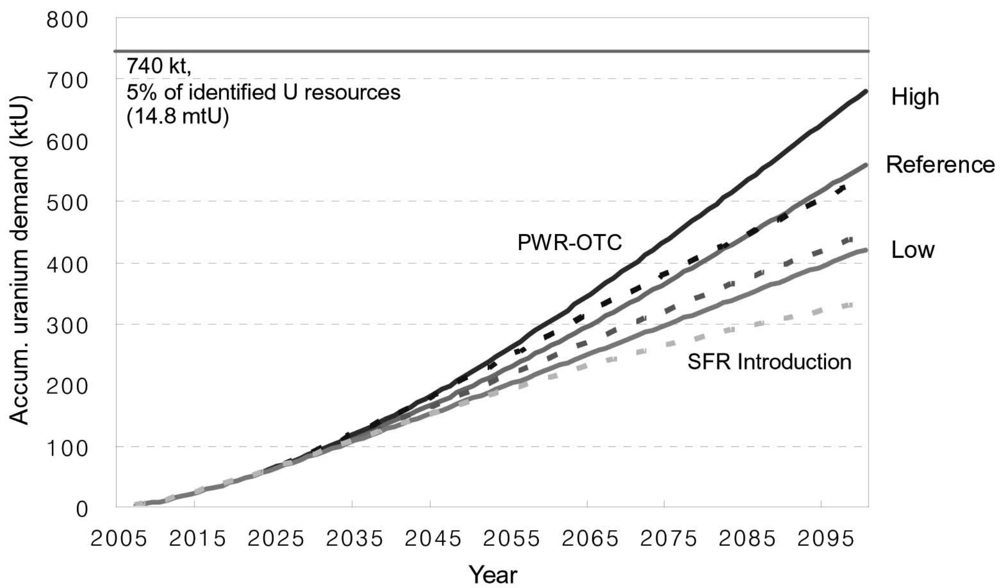

Fig. 6. Cumulative Uranium Demand for PWRs

year 2100 will be 35.0-40.0% for the long-term nuclear power projection that corresponds to the reference and high scenarios.

Figure 7 illustrates the reactorwise generation capacities within the total nuclear power demand for Case 9, where the SFR mix ratio in the nuclear fleet in 2100 is 37.6%. 24 burners (22.3%) and 16 breakeven reactors (14.8%) constitute the SFR mix. Figures 8 and 9 show the reactorwise generation capacities for Cases 8 and 10, respectively. As shown in Figure 9, where the reactor mixing strategy is sought for Case 10 based on the low scenario, the relative importance of burners (BNs) in the SFR mix is smallest compared to that for the other two scenarios (see SFR mix ratio in Table 1). In other words, the relative importance of burners in the SFR deployment would be increased with greater

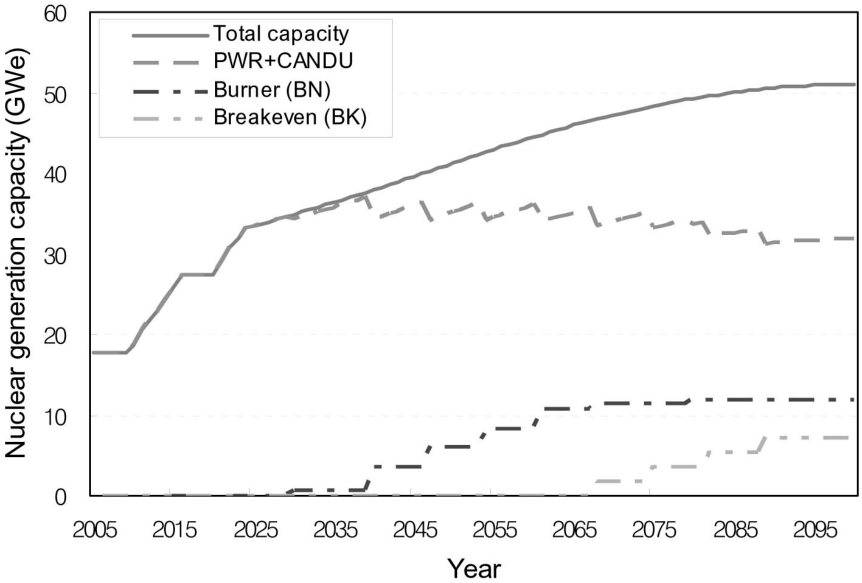

Fig. 7. Reactorwise Nuclear Capacities (Case 9: Reference Scenario)

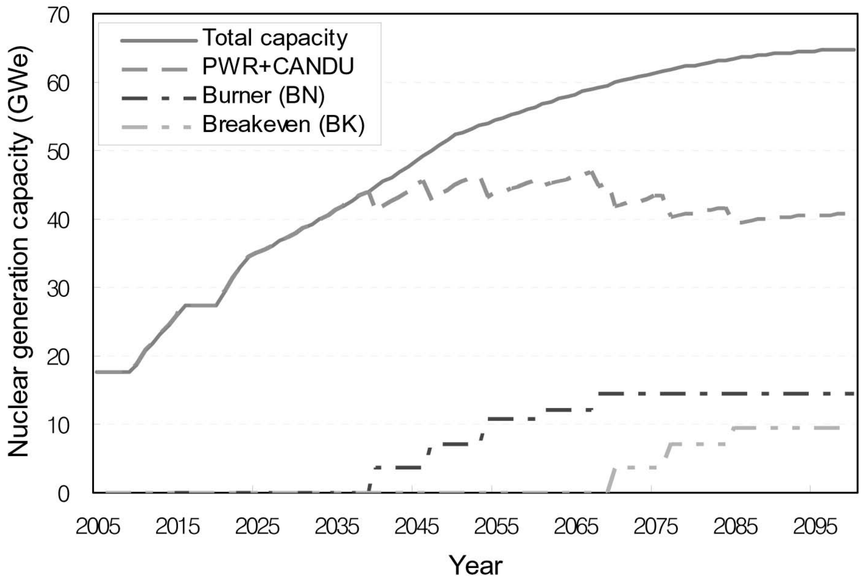

Fig. 8. Reactorwise Nuclear Capacities (Case 8: High Scenario)

emphasis on nuclear power expansion by employing PWRs as a main nuclear power system. The role of burners for waste management would become more important at an early stage of SFR deployment.

In terms of the evolution of nuclear reactors up to 2100 drawn based on the most appropriate SFR deployment scenario (Case 9), the appropriate SFR mix ratio by the year 2100 is estimated at 35.0-40.0% for the long-term nuclear power projection. SFRs are to be deployed in support of a substantial reduction of PWR spent fuel at the first stage of deployment. For efficient spent fuel management, it would be desirable to deploy SFRs continuously in the nuclear fleet, even after 2100, so as to build a symbiotic nuclear power system consisting

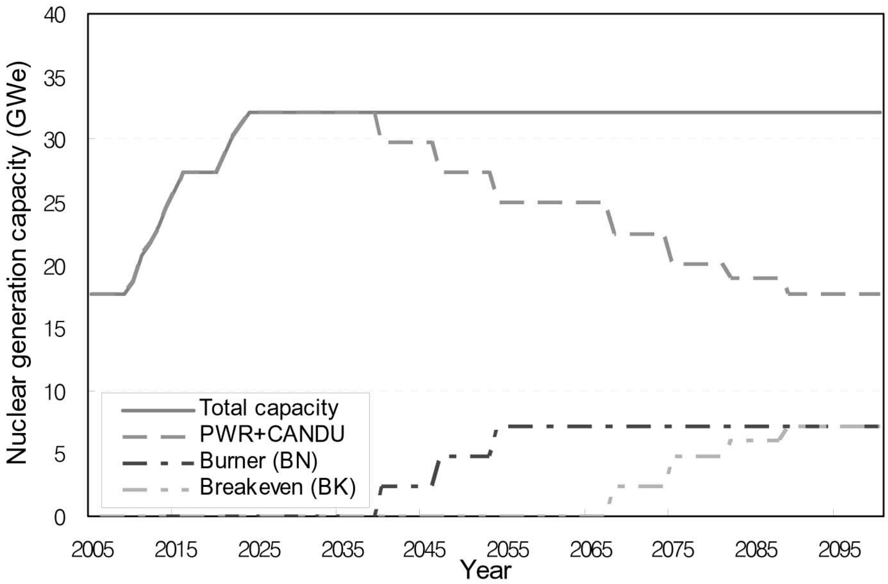

Fig. 9. Reactorwise Nuclear Capacities (Case 10: Low Scenario)

of PWRs and SFRs in which the PWRs fuel the SFRs.

4 .CONCLUSIONS

An efficient reactor deployment strategy with SFR introduction starting in 2040 is formulated based on an SFR deployment strategy in which burners are deployed prior to breakeven reactors in order to reduce the level of PWR spent fuel substantially at an early deployment stage. In the case of the most appropriate deployment scenario, where breakeven reactors (BKs) are deployed from 2068 after the deployment of burners (BNs) starting in 2040, PWR spent fuel accumulation is reduced to an amount below 20 ktHM 30 years after the introduction of commercial SFRs. The PWR spent fuel disposal level is reduced by 64.6 ktHM (98%). The cumulative uranium demand for PWRs up to 2100 is 445 ktU, representing uranium savings of 115 ktU and requiring only 3.0% of the world uranium market demand. The SFR mix ratio in the nuclear fleet by the year 2100 is estimated to be approximately 35-40%. PWRs will remain as a main power reactor type until 2100, and SFRs will support waste minimization and fuel utilization efforts.

A timely deployment of SFRs with different conversion ratios and the recycling of TRUs through the reuse of PWR spent fuel in SFRs can lead to a substantial reduction of the amount of PWR spent fuel and lessen the environmental burden by decreasing the radiotoxicity of high-level waste. Moreover, significant improvement in the utilization of natural uranium resources will ensue.

In this study, the decay heat load for the disposal of waste was not considered. This will require a more detailed isotopic composition variation analysis. A reactor deployment scenario study with SFR (burners and breakeven reactors) combined deployment will also be performed involving SFR conceptual designs under development along with a detailed fuel cycle facility capacity plan. This will also include other nuclear energy systems, if necessary.

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