〈Technical Notes〉

DYNAMIC MODELING AND ANALYSIS OF ALTERNATIVE FUEL CYCLE SCENARIOS IN KOREA

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The Korean nuclear fuel cycle was modeled by the dynamic analysis method, which was applied to the once-through and alternative fuel cycles. First, the once-through fuel cycle was analyzed based on the Korean nuclear power plant construction plan up to 2015 and a postulated nuclear demand growth rate of zero after 2015. Second, alternative fuel cycles including the direct use of spent pressurized water reactor fuel in Canada deuterium uranium reactors (DUPIC), a sodium-cooled fast reactor and an accelerator driven system were assessed and the results were compared with those of the once-through fuel cycle. The once-through fuel cycle calculation showed that the nuclear power demand would be 25 GWe and the amount of the spent fuel will be ~65000 tons by 2100. The alternative fuel cycle analyses showed that the spent fuel inventory could be reduced by more than 30% and 90% through the DUPIC and fast reactor fuel cycles, respectively, when compared with the once-through fuel cycle. The results of this study indicate that both spent fuel and uranium resources can be effectively managed if alternative reactor systems are timely implemented along with the existing reactors.

KEYWORDS : Dynamic Analysis, Fuel Cycle, DUPIC, Sodium-cooled Fast Reactor, Accelerator Driven System

1. INTRODUCTION

Many studies have been performed for advanced fuel cycle options with the aim of managing spent nuclear fuel and/or reducing environmentally hazardous materials [1]. Generation-IV(Gen-IV) reactor systems are being developed with fuels and coolant materials different from those of conventional nuclear reactors in order to extensively increase their safety and economic efficiency and to drastically minimize radioactive wastes [2]. In the Gen-IV concept, various mixes of new reactors and fuel cycle technologies are considered as future nuclear energy systems. The mixed fuel cycle system will also evolve over time because new reactor technologies are being developed and more efforts are being invested to improve the sustainability, safety, economics and proliferation resistance of future nuclear energy systems. However, the time-scale involved in such an evolution is long, from decades to even a century. Considering the time-evolving feature of the nuclear fuel cycle, a dynamic analysis method can be used to assess current and future nuclear energy system scenarios.

There are 16 pressurized water reactors (PWR) and 4 Canada deuterium uranium (CANDU) reactors currently operating in Korea. Meanwhile, advanced reactors and associated fuel cycle options are being studied as alternatives to the once-through fuel cycle. For example, the direct use of PWR spent fuel in CANDU reactors (DUPIC) is considered as a mono recycling scenario, in which both the uranium and transuranics (TRU) are homogeneously recycled [3,4]. Sodium-cooled fast reactors (SFR), such as the Korea advanced liquid metal reactor (KALIMER), have also been under development since 1992 [5,6]. In addition, accelerator driven systems (ADS), such as the hybrid power extraction reactor (HYPER), have been studied since 1997, aiming at transmuting the TRU and long-lived fission products (FP) such as ^{129}I and ^{99}Tc that are incinerated in the target assemblies [7,8]. If these advanced reactors are successfully implemented into the Korean nuclear fuel cycle, the spent fuel as well as the natural resource will be optimally managed.

In this study, symbiotic fuel cycles between the existing nuclear power plants and the DUPIC, SFR and ADS are modeled and analyzed. The purpose of this study is to estimate the key fuel cycle parameters represented by the numbers of nuclear power plants and the amount of spent fuel, which are used for a comparative analysis of the fuel cycle options from the viewpoint of spent fuel management. In the future, these parameters can also be used to determine optimum fuel cycle scenarios by considering the cost and proliferation characteristics of each fuel cycle. The fuel cycle calculations were performed by the dynamic fuel cycle analysis code DYMOND [9,10].

2. DYNAMIC FUEL CYCLE MODEL

The DYMOND code was originally developed for nuclear deployment scenario studies of the Gen-IV fuel cycles. This code uses a commercial system dynamics tool ITHINK [11] to model long-term nuclear reactor deployment scenarios and nuclear fuel cycle structures. It is capable of dynamically determining the number of new reactors to be deployed and the number of existing reactors to be replaced for a given nuclear energy demand. It has three main models that should be prepared by the user: the nuclear energy demand, the reactor history, and the fuel cycle models. In this study, these models of the DYMOND code are modified and refined to analyze the proposed Korean nuclear fuel cycle scenarios.

2.1 Nuclear Energy Demand Model

The DYMOND code predicts the amount of energy demand in the future and determines the number of reactors needed to meet that demand. The nuclear energy demand is pre-determined in the code as a time-dependent equation or a pre-set exponential growth function as follows:

$$E(t) = E(t_0)(1+r)^{(t-t_0)} \tag{1}$$

where E(t) is the energy demand in the year t, t_0 is the reference year, and r is the demand growth rate, which is determined by the user.

2.2 Reactor History Model

The reactor history model is used for modeling the whole reactor life-time from its licensing to its shutdown, which is schematically shown in Fig. 1. In this model, each rectangle represents a conveyor or a stock value with a certain number of reactors at a particular stage and a stock regulator (valve in Fig. 1) represents a transfer from one stage to another. Every conveyor/stock value is specified by a time characteristic. For example, the time characteristic of "reactors under licensing" is "licensing time (T_{LS})". A reactor that has started its licensing process through the valve "order reactors" will be on the "reactors under licensing" conveyor during T_{LS}. Sequentially, a "reactor under licensing" moves to the conveyor "reactors under construction" through the valve "begin construction" during the "construction time (T_C)". In the model, there is a conveyor of "under construction needs fuel" to consider the "fuel preparation time (T_F)" since the fuel is ordered after construction. After that, each built reactor is accumulated in stock "ready reactors" and they become operational only if there is sufficient fuel for them. If the time is not specified in the model, the time characteristic is a differential time, which is typically 1 yr in this study. Although the overall simulation period is 100 yrs, a time step of 1 yr is not problematic in this dynamic analysis because the reactor calculation is performed separately and the results are fed into the DYMOND code.

As shown in Fig. 1, the operating reactors are divided into three groups: "fresh reactors", "reactors near retirement" and "reactors near shutdown". The "reactors near retirement" still need "fuel preparation time" while the "reactors near shutdown" do not. This categorization is used to determine the ordering of new reactors, as explained below. In order to determine the number of new reactors to order or build, the demand should be compared with the number of deployed reactors. Since licensing, construction, and fuel preparation take time ("preoperation time" in the model), some of the current reactors may retire during this period. Therefore, the demand should not be compared with all the reactors but with only those far from retirement. The conveyor time of the "fresh reactors" is T_L-T_P, where T_L is the "reactor life-time" and T_P is the "preoperation time". The conveyor time of "reactor near shutdown" is T_F.

In order to determine the number of new reactors to be built, the demand at the time after the "preoperation time" should be compared with the current potential power. From Eq. (1), the demand prediction at time $t+T_p$ is

$$E(t+T_p) = E(t_0)(1+r)^{(t+T_p-t_0)} \tag{2}$$

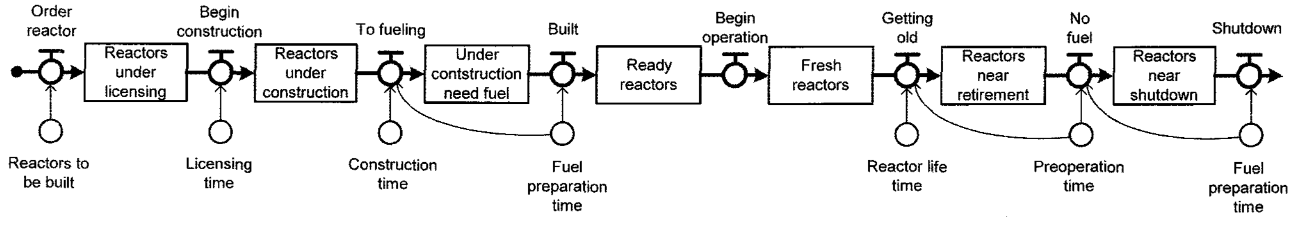

Fig. 1. Schematic Model of the Reactor History

The net demand can then be obtained as the difference between the demand prediction and the total potential power as follows

$$E_{net}(t+T_p) = E(t+T_p) - \sum_i P_{p,i}(t) \tag{3}$$

where $P_{p,i}$ is the potential power of reactor type i, which is a sum of the reactor type i power for the "reactors under licensing", "reactors under construction", "reactors under construction needs fuel", "ready reactors" and "fresh reactors".

The number of reactors to be built, R_i, can then be calculated by

$$R_i(t) = \frac{C_i(t+T_p)\cdot E_{net}(t+T_p)}{P_{e,i}} \tag{4}$$

where $C_i(t+T_p)$ is a capacity fraction of ordering reactor type i at time $t+T_p$, which is defined as a fraction of reactor type i power over the total reactor power and is determined by the user. $P_{e,i}$ is the electric power of reactor type i. When the reactor is ordered from the licensing process, the whole reactor life-time is considered, as shown in Fig. 1. In the reactor history model, a Korean nuclear fuel cycle modeling is incorporated into the capacity fraction by considering PWR, CANDU · DUPIC and fast reactor systems.

2.3 Fuel Cycle Model

As shown in Fig. 2, there are 6 stages in the fuel cycle model: mining, enrichment, fuel fabrication, irradiation in a reactor, spent fuel storage, and geological disposal. As described in the reactor history model, a reactor will not start if there is not sufficient fuel for it. Therefore, it is necessary to know how much fresh fuel is requested or fabricated and what part of it will be loaded into the reactors. The fuel request for the reactor type i and fuel type j is divided into two parts: fuel for startup and refueling.

$$FR_{ij}(t) = N_i(t)\lambda_c\, n_b \frac{P_i\, L_i}{B_{ij}} + [N_O(t) + N_R(t) + N_F(t) - N_S(t)]\frac{P_i\, L_i}{B_{ij}}dt \tag{5}$$

The fuel request for a startup is ordered between "reactors under construction" and "under construction needs fuel" stage in advance of the "ready reactors". In Eq. (5), $N_i(t)$ is the number of reactor type i transfers from "reactor under construction" to "under construction needs fuel", which is represented by the valve "to fueling" shown in Fig. 1. λ_c and n_b are the cycle length and number of batches, respectively. The fuel requests for a startup are then calculated by multiplying these parameters to the fuel consumption rate, which is obtained from the thermal power of the reactor (P_i), the load factor (L_i) and the fuel burnup (B_{ij}). The fuel requests for refueling can be estimated from the number of "operating reactors" (N_O), "reactors under construction, needs fuel" (N_F), "ready reactors" (N_R), and "reactors near shutdown" (N_S), and the fuel consumption rate, multiplied by the differential time (dt).

The mined uranium ore is sent to enrichment plants where it is converted into enriched uranium and the tails are depleted uranium. The amount of mined uranium is calculated as follows:

$$M_{ij}(t - T_F - T_E - T_M) = FR_{ij}(t)\cdot[1 + (\text{Fuel-to-tails conversion factor})_j] \tag{6}$$

where T_F, T_E and T_M are the fuel fabrication time, enrich-

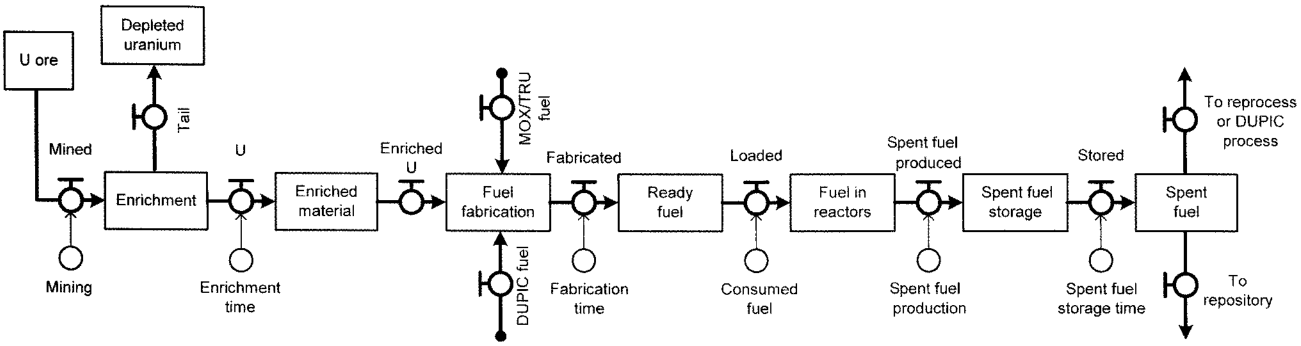

Fig. 2. Schematic Model of the Fuel Cycle

ment time, and the uranium mining time, respectively. The fuel-to-tails conversion factor is as follows:

$$(\text{Fuel-to-tails conversion factor})_j = \frac{e_j - e_N}{e_N - e_T} \quad (7)$$

where e_j, e_N and e_T are the enrichment of fuel type j, natural uranium and tails, respectively.

After fabrication, the fuel is loaded into the reactor and finally discharged as a spent fuel. The amount of the spent fuel is calculated by

$$SF_{ij}(t) = N_{o,i}(t)\frac{P_i L_i}{B_{ij}}dt + N_{s,i}(t)[\lambda_c n_b \frac{P_i L_i}{B_{ij}} - \frac{P_i L_i}{B_{ij}}dt] \quad (8)$$

where the first term on the right-hand side of Eq. (8) is "fuel consumption rate" and the second term is "initial load". $N_{o,i}$ is the number of operating reactors and $N_{s,i}$ is the number of shutdown reactors at time t. The amount of plutonium (Pu), minor actinides (MA) and FP are then calculated by

$$M_{Pu} = \sum_{i,j}[SF_{ij} \cdot (F_{Pu})_{ij}] \quad (9)$$

$$M_{MA} = \sum_{i,j}[SF_{ij} \cdot (F_{MA})_{ij}] \quad (10)$$

$$M_{FP} = \sum_{i,j}[SF_{ij} \cdot (F_{FP})_{ij}] \quad (11)$$

where F_{Pu}, F_{MA} and F_{FP} are the fraction of Pu, MA and FP in the spent fuel, respectively.

As shown in Fig. 2 for the DUPIC and fast reactor scenarios, the fuel cycles start from the "fuel fabrication" stage, which means uranium mining and an enrichment process are not required for these fuel cycles. After being discharged from the reactor, the spent fuel remains in the storage pool for a given cooling period before reprocessing. In Fig. 3, a typical wet reprocessing process such as plutonium uranium extraction (PUREX) or uranium extraction (UREX) is used to separate the spent fuel into Pu, MA and FP streams [12,13]. For the SFR and ADS fuel cycle models in this study, however, the reprocessing process is replaced by a pyro-metallurgical process to recover Pu and MA together as a TRU [14, 15]. This approach is more proliferation-resistant when compared to the wet process.

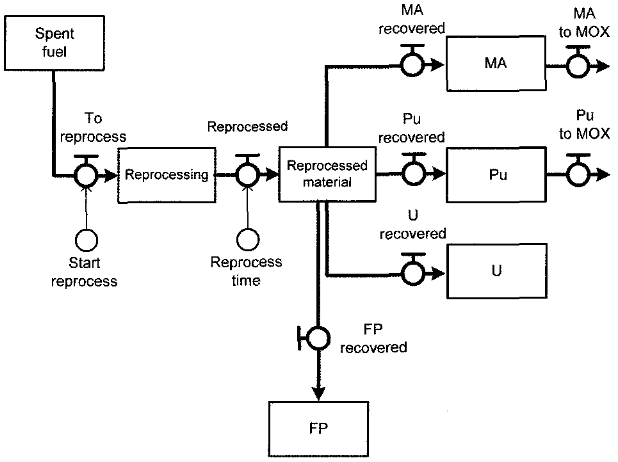

Fig. 3. Schematic Model of the Spent Fuel Reprocessing Process

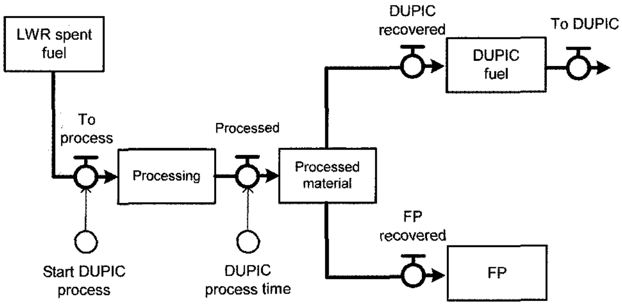

Fig. 4. Schematic Model of the DUPIC Process

The DUPIC process is also incorporated into the fuel cycle, as shown in Fig. 4. The DUPIC process is performed only once for the PWR spent fuel, in which only the volatile and semi-volatile FP are naturally removed from the PWR spent fuel. Because the final disposal plan of the process waste has yet to be decided, the FP from the recycling process was assumed to be stored in the storage.

3. FUEL CYCLE ANALYSIS RESULTS

For a comparative analysis of the fuel cycle options, the once-through fuel cycle was first analyzed based on the current nuclear power plant construction plan and the existing nuclear power plants such as the PWR and CANDU reactors. After setting up the once-through fuel cycle model, the DUPIC, SFR and ADS scenarios were modeled based on the same nuclear energy demand prediction used for the once-through fuel cycle. The important fuel cycle parameters such as the amount of spent fuel and corresponding Pu, MA and FP inventories were then estimated and compared with those of the once-through fuel cycle.

3.1 Once-Through Fuel Cycle

The total electricity capacity of the operating reactors was 14 GWe in 2000. The nuclear capacity is expected to increase to 25 GWe in 2015 based on the Korean nuclear power plant construction plan set by the Ministry of Commerce, Industry and Energy [16]. The growth rate of nuclear power from the year 2016 to 2100 was conservatively assumed to be zero, which can be a lower limit of the nuclear power growth rate considering the current population growth rate. For the reactor information of the once-through fuel cycle, the current operating reactors were considered, which included 12 PWRs and 4 CANDU reactors. The reactor life-time is 40 and 30 yrs for the PWR and CANDU reactors, respectively. In this scenario, all the CANDU reactors are shutdown after their life-time and there will be no more CANDU reactor constructions. The attribute set used for the power plants of this scenario is represented in Table 1, which includes a PWR, CANDU, DUPIC, SFR and an ADS [17,18].

Figure 5 shows the nuclear power demand variation until 2100. The demand power increases as an exponential function and becomes 25 GWe in 2015. The demand power thereafter remains constant until 2100. Figure 6 shows the electricity capacity fraction of each reactor type needed to meet the nuclear power demand curve. If all the CANDU reactors are shutdown, the electricity generation rate is dominated by the PWR after 2040. As shown in Fig. 7, the number of operating PWR increases with time and becomes 25 in 2100 for a reactor power of 1 GWe, while the number of CANDU reactors becomes zero after 2030. The total

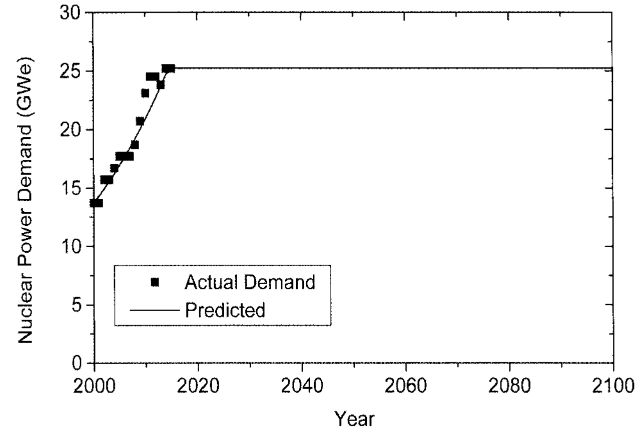

Fig. 5. Nuclear Power Demand Prediction

Table 1. Reactor Specifications

	PWR	CANDU	DUPIC	SFR	ADS
Reactor power, GWe	1.0	0.713	0.713	0.6	0.35
Burnup, GWd/t	40	7	15	113	190
U enrichment, wt%	4	0.71	-	-	-
Life-time, yrs	40	30	40	60	60
Thermal efficiency, %	35	35	35	39	35
Load factor, %	85	85	85	85	85
Cycle length, yrs	1.5	1	1	1.5	0.5
Number of batches	3	1	1	4	7.5
<u>Mass fraction in charge</u>					
U	1.0	1.0	0.9627	0.6674	0.1653
TRU	-	-	0.0081	0.2826	0.8601
FP	-	-	0.0287	0.0481	0.0037
<u>Mass fraction in discharge</u>					
U	0.9471	0.9890	0.9523	0.6501	0.1525
TRU	0.0113	0.0037	0.0083	0.2718	0.6520
FP	0.0416	0.0072	0.0388	0.0781	0.1955

uranium mined for the once-through fuel cycle will be 456000 tons until 2100.

The spent fuel inventory, given in Table 2, continuously increases with time and will be ~65000 tons in the year 2100, while the CANDU spent fuel inventory remains constant at ~9000 tons from 2040. The amount of U and Pu in the spent fuel will be 61840 and 614 tons, respectively. The amount of MA and FP in the spent fuel will be 51 and 2392 tons, respectively. If all the spent fuel is to be directly disposed of, a repository site with a capacity of 65000 tons of spent fuel will be required, which is even greater than the saturation limit of 63000 tons for Yucca Mountain Repository of the United States [19].

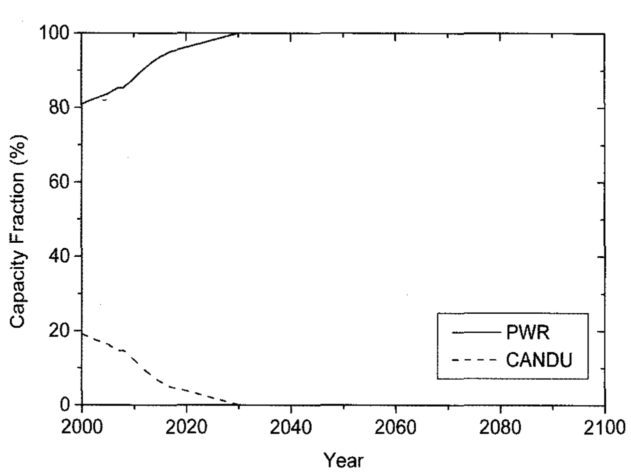

Fig. 6. Deployed Electricity Capacity of Each Reactor Type for the Once-through Fuel Cycle

3.2 Alternative Fuel Cycle Scenarios

3.2.1 DUPIC Fuel Cycle

The DUPIC fuel cycle involves a single recycling of the PWR spent fuel materials in CANDU reactors. The DUPIC recycle is a non-aqueous process that removes only the volatile and semi-volatile FP from the PWR spent fuel. During the DUPIC process, the PWR spent fuel assembly is mechanically separated into the irradiated UO_2 and the structural materials. The irradiated UO_2 material is fabricated again as CANDU fuel bundles. These fuel bundles are burned again in CANDU reactors and then disposed of as spent fuel in a geological repository.

The specifications of the DUPIC fuel CANDU reactor are the same as those of the standard CANDU reactor, which has 380 fuel channels and 4560 fuel bundles. The operation data of the DUPIC reactor are almost the same as those of the standard natural uranium CANDU reactor except for a life-time of 40 yrs and a discharge burnup of 15000 MWd/t. In this fuel cycle model, the capacity fraction of the DUPIC reactor was determined to be 50% and 30% for the periods of 2015-2055 and 2056-2100, respectively, based on the preliminary calculation of the mass flow between the PWR and DUPIC reactors. The natural uranium CANDU reactors are shutdown after their life-time as was the case of the once-through fuel cycle.

Figure 8 shows the number of operating reactors, in which the variation of the number of CANDU reactors is the same as that of the once-through fuel cycle. The number of PWRs increases to 24 in 2015 to meet the demand power. If the DUPIC reactor is deployed, the number of operating PWRs decreases and becomes 13 in 2060, because the demand power is shared by the DUPIC reactors. After 2060, the number of PWRs slightly increases, because the capacity fraction of the PWR increases from 50% to 70%, and becomes 17 in 2100. The number of DUPIC reactors

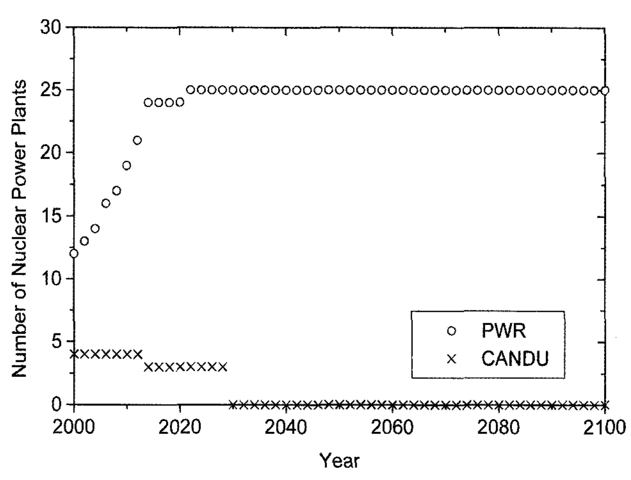

Fig. 7. Number of Operating Reactors for the Once-through Fuel Cycle

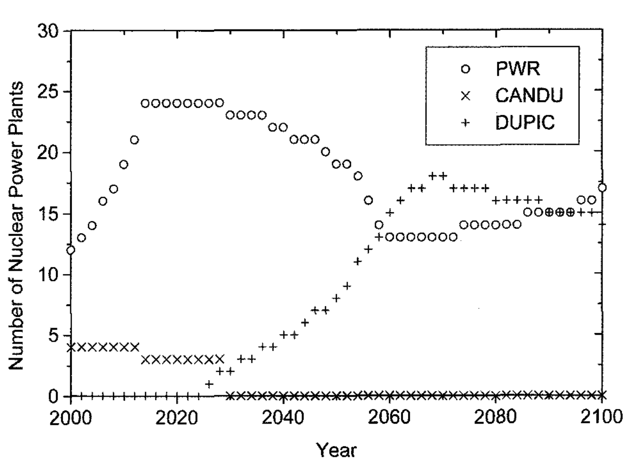

Fig. 8. Number of Operating Reactors for the DUPIC Fuel Cycle

Table 2. Spent fuel Inventory of each Fuel Cycle (ton)

		2000	2020	2040	2060	2080	2100
Once-through	U	4794	14960	27460	39000	50480	61840
	Pu	36	111	236	364	489	614
	MA	3	8	18	30	40	51
	FP	127	391	881	1390	1893	2392
	Sum	4960	15470	28595	40784	52902	64897
DUPIC	U	4794	13280	24220	30520	35890	42890
	Pu	36	105	209	263	282	318
	MA	3	8	16	22	25	30
	FP	127	379	785	1050	1240	1500
	Sum	4960	13772	25230	31855	37437	44738
SFR	U	4794	13540	20270	11650	7658	3020
	Pu	36	106	184	130	85	34
	MA	3	8	16	11	7	3
	FP	127	382	697	520	340	145
	Sum	4960	14036	21167	12311	8090	3202
ADS	U	4794	14770	21570	13030	7717	2076
	Pu	36	110	190	135	84	23
	MA	3	8	15	11	7	2
	FP	127	390	710	520	335	92
	Sum	4960	15278	22485	13696	8143	2193

increases from the year 2025, becomes 18 in 2070, and slowly decreases to 14 in 2100.

In this fuel cycle, the PWR fuel is a major part of the spent fuel inventory until 2070. After 2070, the DUPIC fuel inventory dominates the spent fuel inventory and becomes 34000 tons. The accumulation of PWR spent fuel decreases from 2050, because it is used in the DUPIC reactors. The standard CANDU spent fuel inventory remains at a constant value of 9000 tons after 2030. As indicated in Table 2, the amount of spent fuel in 2100 is 44738 tons, which is a reduction of 31% when compared with the once-through fuel cycle. The amount of Pu and MA in the spent fuel is 318 and 30 tons, respectively, which is 48% and 41% smaller than those of the once-through fuel cycle. Note that the spent fuel inventory in Table 2 does not include the waste produced from the recycling process. The FP inventory in the spent fuel is 1500 tons, while the total FP inventory including the process waste is 2002 tons in 2100. In the DUPIC fuel cycle, the spent fuel accumulation is reduced by using the PWR spent fuel again in the CANDU reactor instead of using newly mined uranium fuel in the CANDU reactor. The amount of mined uranium in the DUPIC fuel cycle is 336000 tons in 2100, which is a reduction of 26% when compared with the once-through fuel cycle. Therefore, mono-recycling of PWR spent fuels in a CANDU reactor can contribute to a reduction of the spent fuel inventory and lower usage of natural uranium resources as well.

3.2.2 SFR Fuel Cycle

The core layout of the SFR (KALIMER-600) burner used in this study consists of 84 inner driver fuel assemblies, 114 middle assemblies, and 132 outer fuel assemblies. The active core height is 113.0 cm and the equivalent core diameter is 343.8 cm. The average TRU content is 29.88% at the beginning of an equilibrium cycle (BOEC) and 29.48% at the end of an equilibrium cycle (EOEC). The SFR fuel cycle adopts an integral fuel cycle strategy in which almost all the TRUs are recycled in a closed fuel cycle. The FP including rare earth is assumed to be separated from the TRU through pyro-processing of the metal fuel. The fuel material mass fractions are given in

Table 1 for the BOEC and EOEC states.

Regarding the recycling options for the SFR, it was assumed that the spent fuel is cooled for 5 yrs, the reprocessing takes 6 months, and the refabrication time is 2 yrs [20]. It was also assumed that the pyro-process treatment returns 99.9% of the TRU to the core and loses 0.1% of the TRU as a waste stream. In addition, 5% of the rare earth FP is recycled and all the other FPs are passed to the waste stream. For the fuel cycle strategy, the capacity fraction of the SFR was determined to be 25, 10 and 20% for the periods of 2030-2040, 2041-2070 and 2071-2100, respectively. In order to feed the SFR, the PWR and CANDU spent fuels are reprocessed from 2025 and SFR spent fuel reprocessing begins in 2035.

Figure 9 shows that the numbers of operating reactors are 20 and 9 for the PWR and SFR, respectively, in 2100. The variation of spent fuel inventory with time is given in Table 2. The spent fuel inventory, excluding the process waste, is 3202 tons, which is much smaller when compared to the once-through fuel cycle, because almost all of the PWR spent fuel is processed and used to feed the SFR. From 2000 to 2100, the SFR transmutes the TRU by 56 tons, ^{129}I by 0.8 tons and ^{99}Tc by 3.2 tons, respectively. The TRU inventory in the spent fuel is 37 tons, while the total TRU inventory including the process waste is 553 tons in 2100, which is 17% lower than that of the once-through fuel cycle. In the SFR, the FP is transmuted in the FP rods loaded in the core. The FP inventory in the spent fuel is 145 tons, while the total FP inventory including the process waste is 2824 tons in 2100. These results show that the SFR burner cycle effectively reduces the spent fuel inventory through the recycling and transmutation processes.

3.2.3 ADS Fuel Cycle

The ADS was originally designed to transmute TRU as a fuel and some of the long-lived FP (^{129}I and ^{99}Tc) as a target assembly. The base ADS design has a thermal power of 1000 MW and the system operates under a subcritical condition with an effective multiplication factor of 0.98. The core consists of 42 inner core fuel assemblies, 54 middle core fuel assemblies and 90 outer fuel assemblies. The number of batches is 7 for the inner core and 8 for the middle and outer cores. The fuel material fractions are given in Table 1 from the BOEC to EOEC state. The TRU inventory is 6510 kg at the BOEC and 282 kg of TRU is transmuted per year. The FP including rare earth is assumed to be separated from the TRU through pyroprocessing. In the case of FP, ^{129}I and ^{99}Tc are transmuted with rates of 7 and 27 kg/yr, respectively.

As was the case for the SFR fuel cycle, the deployment fractions of the ADS were determined to be 25, 10 and 20% for the periods of 2030-2040, 2041-2070 and 2071-2100, respectively. In order to feed the ADS, the PWR and CANDU spent fuels are reprocessed from 2025 and the ADS spent fuel reprocessing begins in 2035. The results are shown in Fig. 10 for the number of operating reactors, which are 20 and 15 for the PWR and ADS, respectively, in 2100. The variation of the spent fuel inventory is also included in Table 2. The total spent fuel inventory, excluding the process waste, is 2193 tons. Until 2100, the ADS transmutes the TRU by 130 tons, ^{129}I by 4 tons and ^{99}Tc by 16 tons, respectively. The TRU inventory in the spent fuel is 25 tons, while the total TRU inventory is 249 tons in 2100. The FP inventory in the spent fuel is 94 tons, while the total FP inventory is expected to be 2362 tons in 2100. These results show that the ADS cycle is more effective in

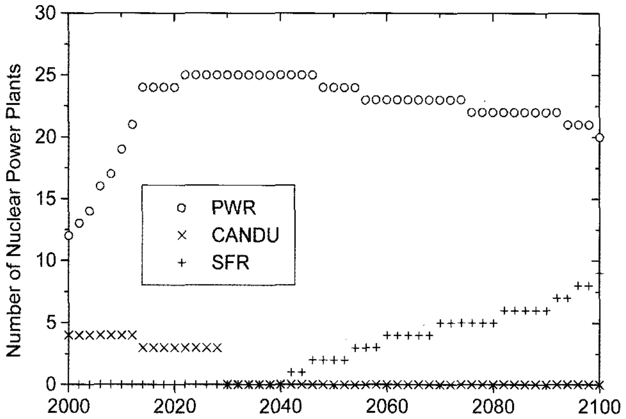

Fig. 9. Number of Operating Reactors for the SFR Fuel Cycle

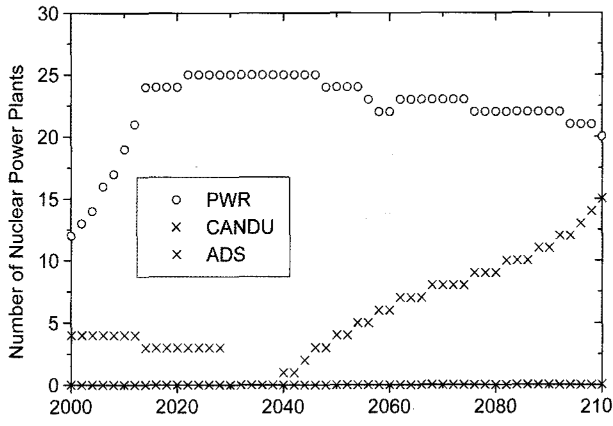

Fig. 10. Number of Operating Reactors for the ADS Fuel Cycle

transmuting TRU and reducing the spent fuel inventory when compared with the SFR cycle with the same deployment scenario.

4. SUMMARY AND CONCLUSIONS

The Korean nuclear fuel cycle scenarios were investigated for a period of 100 yrs from 2000, including the once-through fuel cycle, based on the existing nuclear power plants and advanced fuel cycles based on the DUPIC, SFR and ADS. For the individual fuel cycle option, a dynamic calculation was performed to obtain the mass flow of the spent fuel. The results of the once-through fuel cycle calculation can be summarized as follows:

- The nuclear power demand will grow to 25 GWe in 2100.
- The amount of spent fuel is expected to be 64897 tons in 2100.
- The amount of Pu, MA and FP is estimated to be 614, 51 and 2392 tons, respectively, in 2100.

The results of the alternative fuel cycle studies were compared with those of the once-through fuel cycle. The results of the comparison of the total spent fuel inventory including the process waste are as follows:

- The DUPIC fuel cycle reduces the total spent fuel by 30%, Pu by 48%, MA by 41% and the FP by 16%.
- The SFR fuel cycle reduces the total spent fuel by 90%, Pu by 17% and the MA by 10%, but the FP inventory increases by 18%.
- The ADS fuel cycle reduces the total spent fuel inventory by 93%, Pu by 60%, MA by 94% and the FP by 1%.

The results of this study were obtained under a given nuclear demand curve and a capacity fraction model of each reactor type. Although the results have uncertainties depending on the demand power and capacity fraction models, the results provide general trends of the spent fuel accumulation and transmutation. The DUPIC fuel cycle has medium effectiveness in reducing the spent fuel inventory due to a homogeneous recycling of uranium fuel, but has good effectiveness in transmuting Pu and MA, owing to its high thermal flux reactor system. The spent fuel reduction is most effective for the ADS, owing to the pyro-process that separates uranium material from the spent fuel and the high burning capability of the reactor system.

It is not easy to judge the advantages or disadvantages of a given fuel cycle option based only on the spent fuel inventory. There are many other important parameters that characterize a fuel cycle such as the economics, proliferation-resistance, environmental effects, technical feasibility of the recycling process and reactor system, etc. However, the costs of the spent fuel recycling and the advanced nuclear power plant construction still have large uncertainties. A proliferation-resistance model is currently under development. Technologies are being developed for the SFR and ADS, and the commercialization of these reactors has not yet been decided. As an alternative, it is recommended that the DUPIC fuel cycle be utilized in the Korean nuclear fuel cycle in order to reduce the spent fuel inventory until the SFR or ADS is implemented in the fuel cycle after technological development is completed.

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