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Korean Nuclear Reactor Strategy for the Early 21st Century

–A Techno–Economic and Constraints Comparison–

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21세기 차세대 한국형 원자로 전략

—기술경제 제약요인 비교—

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Abstract

The system analysis for Korean nuclear power reactor option is made on the basis of reliability, cost minimization, finite uranium resource availability and nuclear engineering manpower supply constraints. The reference reactor scenarios are developed considering the future electricity demand, nuclear share, current nuclear power plant standardization program and manufacturing capacity. The levelized power generation cost, uranium requirement and nuclear engineering professionals demand are estimated for each reference reactor scenarios and nuclear fuel cycle options from the year 1990 up to the year 2030.

Based on the outcomes of the analysis, uranium resource utilization, reliability and nuclear engineering manpower requirements are sensitive to the nuclear reactor strategy and associated fuel cycle whereas the system cost is not. APWR, CANDU→FBR strategy is to be the best option for Korea. However, APWR, CANDU→Passive Safe Reactor(PSR)→FBR strategy should be also considered as a contingency for growing national concerns on nuclear safety and public acceptance deterioration in the future.

FBR development and establishment of related fuel cycle should be started as soon as possible considering the uranium shortage anticipated between 2007 and 2032. It should be noted that the increasing use of nuclear energy to minimize the greenhouse effects in the early 21st century would accelerate the uranium resource depletion. The study also concludes that the current level of nuclear engineering professionals employment is not sufficient until 2010 for the establishment of nuclear infrastructure.

요 약

본 연구에서는 2030년까지의 전력수요, 전력생산중 원자력발전의 비중, 기존 원전표준화 계획, 국내제작 능력을 반영하여 개량형 경수로와 중수로(CANDU)에 대한 참조 시나리오를 도출하고 각 참조 시나리오와 핵연료주기 전략별 핵연료주기 비용, 원자력 발전 단가, 우라늄 소요량, 인력 소요량을 계산하였다. 참조 시나리오들에 대한 분석을 한 결과 우라늄 자원활용, 원전안전성, 인력활용 측면이 노형 전략수립의 주요 인자로 작용하며 발전단가는 전략별로 큰 차이가 없는 것으로 나타났다.

1. Introduction

The study on the long-term nuclear power program, Ajou Study [1], proposes that average 1.5 nuclear unit of 1000 MWe capacity is required to be commissioned during the period of 2000–2030 assuming 40 percent nuclear share in 2030. The referenced study chose a top-down approach which suggests the qualitative framework reflecting the future socioeconomic environment rather than dealing with various input data with uncertainty. This study analyzes the future reactor strategy and other aspects such as nuclear engineering professional manpower demand and uranium resources in the early 21st century based on the results of Ajou study.

2. Major Considerations and Assumptions

2.1 Time Horizon

The time horizon of 40 years from 1990 is chosen in this study. In the early 1980s, IIASA study [2] has chosen the time horizon of 50 years based on the following objective assumptions.

(1) The world population will increase drastically for the time being and would reach equilibrium around 2030. In other words, as there will exist a substantial socioeconomic equilibrium around 2030, the long-term plan should consider such environment.

(2) The sustainable energy system should be operated within 50 years to overcome anticipated energy resources depletion.

(3) As the market penetration time of the new energy technology is generally assumed as 50 years, the efficient use of existing energy resources should be promoted up to that time.

The time span of 40 years from 1990 can be justified considering these global assumptions and situation of Korea which requires long lead-time for reactor development and fuel cycle establishment.

2.2 Electricity Demand and Nuclear power

The Ajou study has assumed electricity demand projections referring the cases of the advanced countries and expected socioeconomic developmental path of Korea(Table 2–1).

The required electricity capacity can be determined with electricity demand, capacity factor, power system loss, in-plant loss and reserve capacity margin. If we assume to increase capacity share of nuclear power plants from 36% in 2000 to 40% in 2030 and consider the decommissioning of existing plants, the annual additionally required nuclear capacity can be calculated as shown in table 2–2.

Table 2-1 : Electricity Demand Projection

Unit : GWH

Demand	1987	2001	2011	2021	2030
Reference	64,169	158,808	233,801	335,039	454,158
Low	64,169	132,167	197,432	280,522	380,258
High	64,169	183,914	281,097	399,398	541,399

2.3 Small and Medium Size Power Reactoı (SMPR) and Advanced PWR(APWR)

APWR is an advanced version of currently operating PWR with enhanced safety and economy without drastic changes of design concept. It is assumed that the inherent safe reactors would not be commercialized earlier than the passive safe reactors (PSR). This is because of the fact that PSR design is based on the current LWR design and has lower investment risk than inherent safety reactors. As a representative SMPR, AP600 is selected for comparison purpose, because more data is available than other PSRs. With rather qualitative judgement and applying several reactor selection criteria [3] [4], the comparison of APWR and AP600 indicates that both reactors can be assumed to have same future potential. But it should be noted that the weight of each criterion is subject to change with socioeconomic environment. In other words, PSR such as AP600 will be superior than APWR if the safety or flexibility to electricity demand is emphasized. If the economy or the use of existing technology is emphasized, the APWR will be superior than·PSR.

As a conclusion, this study excludes the PSR for quantitative analysis because it requires more specific and realistic data. Section 4.5 of this study qualitatively deals with the reactor strategies including PSRs.

2.4 Other Constraints

Other constraints applied in this study are as following.

(1) PWRs which will start commercial operation in the 21st century are all APWRs.

(2) Lifetime of existing and new plants is 30 years from commercial operation.

(3) Design improvement of one reactor type is not assumed.

(4) Effects of nuclear power plant life extension is not assumed.

(5) Domestic equipment manufacturing capacity should be considered.

(6) LWR thermal recycle and CANDU tandem cycle will be established as proposed in the Ajou study.

(7) Existing standardization program is effective until 2006. But the construction is subject to adjustment depending on the electricity demand projection.

3. Methodology

3.1 Objectives

(1) Generate the reference reactor scenarios for each electricity demand projection

(2) Estimate the nuclear power plant levelized generation cost for the combinations of reactor scenario and fuel cycle option.

(3) Estimate the required nuclear professionals demand and supply. Suggest the manpower development plan.

(4) Estimate the Uranium requirement and suggest the time schedule for FBR introduction.

(5) Discuss and recommend the reactor strategies.

Table 2–2 : Nuclear Power Demand : Reference Projection

Year	Elec Demand	Nucl Share	Cumul Nucl MW	Decom MW	Nucl Req'd MW	Nucl Req'd Adjusted MW
2000	27616	36	12315	0	112	0
2001	28989	36	12427	0	666	1000
2002	30149	36	13093	0	574	1000
2003	31355	36	13667	0	599	0
2004	32609	37	14266	0	625	1000
2005	33913	37	14891	0	652	1000
2006	35270	37	15543	0	681	0
2007	36680	37	16224	0	710	800
2008	38148	37	16934	587	1328	1300
2009	39673	37	17675	0	773	800
2010	41260	37	18448	0	807	800
2011	43044	37	19255	0	904	900
2012	44594	38	20159	0	800	800
2013	46199	38	20959	1328	2159	2200
2014	47862	38	21790	0	864	900
2015	49585	38	22654	950	1848	1800
2016	51370	38	23553	1900	2833	2800
2017	53220	38	24486	950	1920	1900
2018	55135	38	25456	950	1958	2000
2019	57120	39	26465	950	1998	2000
2020	59177	39	27513	0	1089	1100
2021	61160	39	28602	0	1061	1100
2022	63056	39	29662	0	1025	1000
2023	65011	39	30687	0	1060	1100
2024	67026	39	31746	0	1096	1100
2025	69104	39	32842	1000	2133	2100
2026	71246	39	33975	1000	2172	2200
2027	73455	40	35147	700	1912	1900
2028	75732	40	36359	1000	2253	2300
2029	78079	40	37613	1000	2296	2300
2030	80500	40	38909	112	1453	1500

3.2 Reference Reactor Scenario

Table 3–1 shows the constraints applied to generate the reference reactor scenarios. 25 scenarios for reference, high, and low electricity demand projection are randomly generated using the computer program. Reference scenarios are selected for three cases:

(1) High APWR construction(A>C)

(2) High CANDU construction(C>A)

(3) Same unit number(C=A)

Page 23 of the reference[13] shows scenarios analyzed in this paper.

4. Results and Discussions

4.1 Fuel Cycle System Cost

Table 4–1 is the summary of fuel cycle system cost for each fuel cycle option and reference scenario. Computer program and assumptions of K. Chae is used for this calculation[5].

The table indicates the following order of fuel cycle cost.

(1) (lowest) 'C>A'→'C=A'→'C<A'(highest)

(2) (lowest) TA→OT→TA300→(TA300+RE500)→RE500→RE800(highest)

As we can generally expect, the table indicates that more CANDU operation results in lower fuel cycle cost for any electricity demand projections and fuel cycle options. This is because the front-end and back-end of the CANDU fuel cycle don't need many processings comparing with the PWR fuel cycle. Regarding the fuel cycle, the tandem options have cost advantage over the thermal recycle options.

4.2 Levelized Generation Cost

Table 4–2 is the summary of levelized generating cost calculation. Page 24 of reference [13] describes the methodology and assumptions applied for this calculation. The table indicates the following order of generation cost.

(1) (lowest) 'C>A'→"C=A"→'C<A'(highest)

(2) (lowest) TA→OT→TA300→(TA300+RE500)→RE500→RE800(highest)

It was expected at the beginning of this calculation that there might exist a generation cost variations under the different reactor mix and relevant capacity factor trend. But it appears that the reactor strategies do not have a significant impact to the generation cost. The use of advanced fuel

Table 3–1 : Constraints in Reactor Scenario Generation

Constraints		Value
Time Span		2000–2030
Electricity Demand Projection	Reference	Table 2–1
	Low	Table 2–1
	High	Table 2–1
Nuclear Capacity Demand		Table 2–2
Decommissioning		Table 2–2
Phase 1 Standardization		−2006
Equipment Manufacturing Capacity	Reference and Low Projection	2 units/yr(−2015) 4 units/yr(2016−)
	High Projection	3 units/yr(−2015) 5 units/yr(2016−)
$\frac{\lvert\text{Capacity Demand}-\text{Proposed Capacity}\rvert}{\text{Capacity Demand}}$		<30%(Each Year) <10% (−2030)

Table 4-1 : Fuel Cycle System Cost

Unit : Mills/kwh

Reactor Scenario	Reactor Type	OT	TA	RE500	RE800	TA300	RE500+ TA300
	APWR	6.87	6.73	7.14	7.14	6.80	6.97
A<C	CANDU	4.99	5.29	4.99	4.99	5.74	5.21
	Total	6.63	6.55	6.87	6.86	6.67	6.75
	APWR	6.72	6.53	6.99	7.01	6.65	6.84
C>A	CANDU	5.17	5.43	5.17	5.17	5.54	5.33
	Total	6.43	6.33	6.65	6.67	6.46	6.56
	APWR	6.76	6.55	7.03	7.06	6.70	6.88
A=C	CANDU	5.10	5.39	5.10	5.10	5.53	5.26
	Total	6.47	6.35	6.70	6.72	6.50	6.60

OT : Once-Through
TA : Tandem Cycle Maximum, 2008, Reconfiguration
TA300 : Tandem Cycle 300 tons/year, 2008, Reconfiguration
RE500 : Thermal Recycle 500 tons/year, 2013
RE800 : Thermal Recycle 800 tons/year, 2013
TA300+RE500 : TA300 and RE500 with Tandem Priority

Table 4-2 : Levelized Generation Cost of Each Reactor Scenario

Unit : Mills/kwh

Reactor Scenario	OT	RE500	RE500+ TA300	TA300	TA	RE800
A>C	56.74	56.97	56.86	56.77	56.65	56.97
C>A	56.27	56.49	56.40	56.30	56.17	56.51
A=C	56.49	56.71	56.62	56.52	56.37	56.74

cycle does not significantly improve the overall generation cost. The delay of advanced fuel cycle introduction and lesser scale merit in the early stage of the new fuel cycle system is the main reason.

4.3 Nuclear Professional Manpower Supply and Demand

Figure 4-1 illustrates the total nuclear professionals (B.S. in nuclear engineering) demand and supply. It was assumed that the nuclear professional manpower demand for other fields such as research and development, fuel cycle, radwaste management and Government licensing is 50% of the nuclear power plant construction, operation and maintenance manpower demand. This graph is prepared for the lowest and the highest nuclear professional manpower demand of each year for each reactor scenario. The peaks appears in the graph are the result of the successive decommissionings of existing plants and relevant backup constructions. Manpower supply estimation incorporates university capacity and retirement of existing nuclear professionals in the future. The graph indicates that:

(1) The supply of nuclear professionals is sufficient up to 2010. But,

(2) The period up to 2010 is an important period to establish all nuclear infrastructures. So intensive research and development, radwaste management, fuel cycle establishment and licensing streamlining are required during the period. The current level of active nuclear professionals is insufficient for this reason.

(3) The demand forecast assumed that 100% localization is achieved and did not consider the manpower saving effects of standardization and multi-unit construction. But if we assume the current level of self-reliance and expected standardization merit has zero-sum effect, this demand forecast can be used for policy guidance.

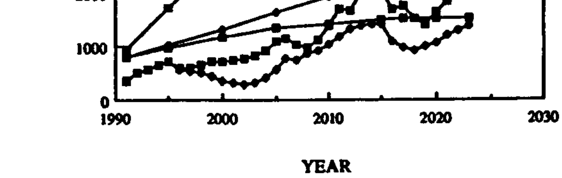

Figure 4–1 : Nuclear Professionals Demand and Supply (Total Nuclear Sector)

4.4 Time Schedule for the Introduction of FBR

(1) Uranium Supply and Demand: Production Base

The annual uranium requirement calculated during the study is used for uranium supply and demand analysis. Figure 4–2 indicates the uranium which would be available and required for Korea. The upper limit of each year's uranium requirement represents the once-through fuel cycle option. There will be an uranium shortage from 2000.

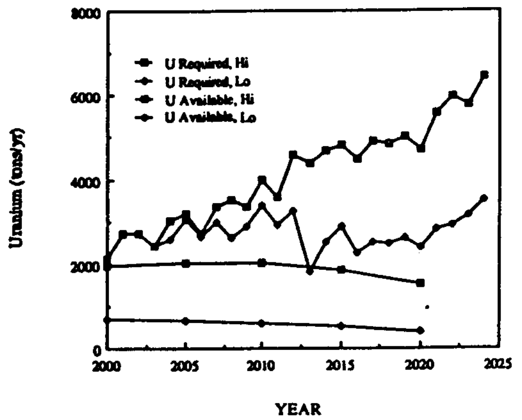

Figure 4–2 : Uranium Availability and Annual Demand (Reference Projection. Production Base)

(2) uranium Supply and Demand: Reserves Base

In the analysis, it is assumed optimistically that all RAR(Reasonably Assured Reserves) and EAR(Estimated Assured Reserves) category I reserves are already developed and produced. The required cumulative uranium calculated during the fuel cost estimation is applied. The expected time of uranium shortage can be identified by comparing the cumulative uranium requirement of each year and uranium reserves available for Korea. Figure 4–3 illustrates the lower and upper values of cumulative uranium requirement for reference electricity demand projection. The figure indicates that if the current world nuclear energy demand growth trend continues, there will be a supply shortage between 2007 and 2032 for the WOCA (World Outside the Centrally Planned Economies Area) reserves and between 2014 and 2050 for the world reserves. It should be noted, however, that increasing use of nuclear energy could be justified in the near future because of the environmental impacts of other energy options. In that case, high nuclear energy demand scenario can be applied. If we assume the high scenario, the uranium shortage will happen between 2007 and 2015 for the WOCA reserves and between 2014 and 2029 for the world reserves. The lower value of the cumulative uranium requirement represents the large size back-end fuel cycle operation. Hence the lower values shown in the Figure 4–3 can be considered as non-realistic for Korea.

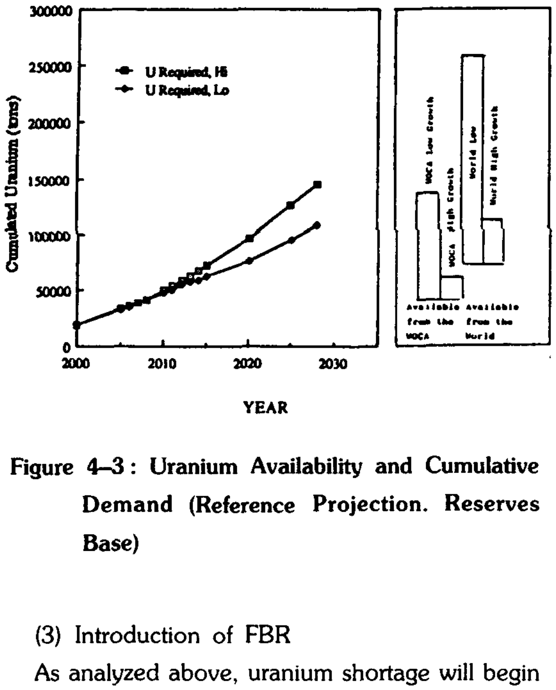

Figure 4–3 : Uranium Availability and Cumulative Demand (Reference Projection. Reserves Base)

(3) Introduction of FBR

As analyzed above, uranium shortage will begin from 2000 with production (realistic) viewpoint and there will be an uranium shortage between 2006 and 2032 with reserves (optimistic) viewpoint. Although the CPE(Centrally Planned Economies Area) countries are now in drastic economic reformation, the current production capacity would remain at the level of self-sufficiency for the time being. The long lead time for the new uranium production also supports the opinion that CPE countries reserves will not be fully utilized until 2030. Hence the improvement of uranium efficiency is the key element for the nuclear program of the next century. According to the plan of KAERI in Ajou Study, the tandem cycle will be established in 2008 and thermal recycle will be established in 2013. The problem lies in the long lead time for R&D and construction of advanced fuel cycle system and international nonproliferation policy. It is questionable for Korea whether the commercial operation of large scale back-end fuel cycle system for APWRs and CANDUs would be possible before the anticipated uranium shortage. The calculation indicates that significant uranium saving in the early 21st century is not expected without large scale fuel cycle system.

In this context, introduction of the FBR plant and establishment of the related fuel cycle can be justified. The timing of the lead FBR plant commercial operation should consider the WOCA uranium reserves and the FBR commercialization trend. This study recommends the commercial operation of the FBR around 2020 and establishment of the related fuel cycle before that time.

4.5 Reactor Strategy for the Early 21st Century

The following general criteria for Korean reactor strategy were derived through this study.

(1) The general tendency of the world reactor strategies are similar to each other. This general tendency is ;

1) Short and intermediate-term : ALWR and PSR(Passive Safe Reactor)

2) Long-term : FBR

3) Supplementary option considering the delay of FBR : HCLWR

(2) The comparison of APWR and PSR indicates that APWR and PSR have similar future potentials.

(3) FBR is an ultimate reactor option considering the uranium shortage in the early 21st century.

(4) Tandem cycle option has a cost saving effect than thermal recycle option.

The following reactor strategy candidates are considered for review in this section incorporating the general criteria discussed above.

(1) APWR→FBR Strategy

This strategy can maximize the effects of current standardization program with improved safety and economy. The manpower and financial resources can be concentrated to the FBR development and related fuel cycle establishment. If the public concerns on nuclear safety increase, this strategy will not be easily accepted.

(2) APWR→PSR→FBR Strategy

PSR can be easily accepted by the public with its passive safety features. The site assurance for PSR plant is questionable because of the smaller unit capacity. There are no additional fuel cycle requirements comparing with APWR→FBR strategy. The strategy requires one small and one large scale development programs. If the scale-up of PSR is possible in the early 21st century, this strategy can be more easily accepted.

(3) APWR→FBR CANDU→FBR Strategy

This strategy can be selected if the commercialization of FBR is delayed. As it requires one small, one medium and one large scale reactor development programs, there could exist a resource problems. The technical and commercial viability of High Conversion PWR(HCPWR) is not well identified yet.

The comparison indicates that the APWR→FBR strategy has advantage over other strategies and the limited technological capability and manpower resources are the major constraints in establishing the future reactor strategy.

It should be noted, however, that if the importance of nuclear safety increases, the importance of generation cost would decrease. With the slight increase of weighting factor for nuclear safety, the APWR→PSR→FBR strategy will be selected.

CANDU reactors should be considered simultaneously with APWR→FBR strategy considering its high potential in uranium savings through the tandem cycle.

5. Conclusions and Recommendations

It is appeared that the uranium resource utilization, reliability and nuclear engineering manpower requirements are sensitive to the nuclear reactor strategy and associated fuel cycle whereas the system economy is not.

Based on the outcomes of this analysis, it is recommended that APWR, CANDU→FBR strategy is an appropriate option for Korea with the following reasons.

(1) Because of the anticipated uranium shortage in the early 21st century, early FBR deployment program is required.

(2) Other reactor type will have technological life time of 10 to 15 years in Korea if we assume the completion of the phase 1 standardization program in 2006 and the commercialization of FBR around 2020. In this case, the benefit of new reactor development would not be greater than the investment requirements.

(3) The limited financial and manpower resources should be concentrated to the development and commercialization of FBR.

(4) CANDU reactors should be used as much as possible for the uranium efficiency improvement. The generation cost of CANDU and APWR is almost equal.

However, the study also recommends to consider the APWR, CANDU→PSR→FBR strategy as a contingency for the growing national concerns on the nuclear safety in the future considering the following aspects.

(1) The nuclear safety is not only a national concerns but also an international concerns. The viability of nuclear power is depend on the public and international acceptance on nuclear power. Any cost additionally required for the public and international acceptance could be justified in the

near future.

(2) Hence the use of passive/inherent safety features would be unavoidable in the early 21st century, if the public acceptance is to be deteriorated rapidly.

The uranium shortage will happen between 2007 and 2032 with the world low demand scenario and based on the WOCA reserves. But this is an optimistic prospect. If we consider the increasing use of nuclear energy in the near future to reduce the greenhouse effects, uranium shortage will happen between 2007 and 2015. But it should be noted that as the actual production capacity is far less than the reserves, the uranium shortage will happen at the beginning of the next century. In this context, the commercialization of FBR and the operation of related fuel cycle should be done as soon as possible. More importantly, such program should be supported by the international nuclear non-proliferation regime. The fuel cycle strategies should be focused to the FBR fuel cycle. The introduction of thermal recycle in 2013 and its lower scale merit at the initial period do not have significant uranium saving effect to the APWR. Hence, the fuel cycle development programs should be focused to the FBR applications.

The current nuclear professionals supplying trend is not sufficient for the future. The research and development, Government licensing, radwaste management and fuel cycle operation require many nuclear professionals in addition to nuclear power plant construction, operation and maintenance. The nuclear sector should be more positive in securing the nuclear manpower. The university education should be able to supply the qualified manpower to the nuclear sector.

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