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Estimation of Uranium Requirements Based on Future Reactor Strategies

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ABSTRACT

The U_3O_8 requirements are estimated for the high, intermediate, and low growth projections of nuclear power in Korea. To each projection, four illustrative reactor-mix strategies and four fuel cycle options are applied for estimating the requirements. The reactor types considered are PWR, PHWR, and FBR. The fuel cycles considered are once-through cycle, U/Pu recycle, and improved once-through cycle. Also the amount of Pu-fissile recovered from U recycle is estimated. The maximum cumulative (to the year 2000) requirements of U_3O_8 occupy about 4 to 5 percent of the WOCA requirements and are about 23 times larger than the U_3O_8 resources in Korea. For the high nuclear power growth projection, the cumulative amount of Pu-fissile recovered from U recycle is sufficient for the startup of 2 units of 1200 MWe fast reactors by the year 2000.

요 약

우리나라의 장기 우라늄 원광누적 소요량을 원자력 발전 계획모형, 원자로형 투입 방안 및 가능 핵주기에 따라 추정하였다. 투입 가능 노형은 가압경수로, 중수로 및 고속증식로로 선정하였으며, 가능 대체 핵주기로서는 가압경수로의 경우에, U자체 재순환 주기, U 및 Pu 자체 재순환 주기, 연소도 증가에 의한 개량 핵주기를 고려하였다. 또 U 자체 재순환이 가능한 경우에 대해서, 재처리 후 저장된 핵분열성 Pu 누적량을 계산하였으며, 이에 따라 고속증식로의 도입가능시기를 추정하였다. 우라늄 원광 누적 소요량의 최대치는 전세계 우라늄 원광 소요량의 약 4~5%를 차지할 것으로 추정되었으며, 원자력 발전 계획 모형중 상한의 경우에는 U 자체 재순환이 1990년부터 이루어질때, 2000년까지 1200MWe 급 고속증식로 2기가 도입가능할 것으로 추정되었다.

1. Introduction

From a nuclear power program perspective, the choice of reactor types and fuel cycles would be affected by the overall demand for U_3O_8 and other fuel cycle services, as well as the economics, technical feasibility and other factors. If the once-through fuel cycle were extensively deployed, for example, a substantially large capacity of spent fuel storage and waste disposal facilities would be necessary.

Three reactor types, i.e., the PWR, PHWR and FBR, are considered in this thesis. The PHWR has advantage in that it uses natural uranium, providing a simple, low-cost fuel cycle independent from foreign U-235 enrichment requirements. Also this reactor type has better neutron economy, thus better uranium utilization than the PWR. However, these advantages are somewhat offset by the availability of heavy water, operating and maintenance complexities, and high capital cost. The PWR, on the other hand, has been operating commercially much longer and in greater numbers than the PHWR. This reactor type has demonstrated its operability. Although it requires enriched uranium, the PWR has greater potential for future development than the PHWR. It's near-future development potential lies in the U and/or Pu recycle area, which not only minimizes enrichment requirements but also utilizes the available Pu-resources from operating PWRs. Moreover these fuel cycle alternatives have better resource utilization than the once-through cycle, and so these alternatives have the effect of uranium saving. However, U and/or Pu recycle requires reprocessing of discharged fuel.

The nuclear fuel cycle represents about 15% of the bus-bar cost of electricity. Of this 15% the cost of uranium ore concentrate and the U-235 isotopic enrichment represent the major cost components of the PWR once-through cycle. The PHWR, since it does not require separative work, has a somewhat different distribution of costs. However, for both the PWR and PHWR, the yellowcake cost represents more than one-half of the nuclear fuel cycle cost. The long-range projections for yellowcake supply indicate that shortages of high-grade ore will continue to drive the price upward and that the avilability of the yellowake is concerned.

In this regard, only U_3O_8 requirements are considered in this study. The U_3O_8 requirements depend on many factors, in particular, reactor types, fuel cycle options, plant capacity factor, tails assay in the enrichment plant, etc. The growth projections of nuclear power, of course, influence the requirements, too. Thus, high, intermediate and low growth projections are first established, and then four reactormix strategies and four fuel cycle options are considered to estimate the requirements. As a parametric sensitivity study, changes in the plant capacity factor and the time delay of fuel cycle alternatives are made to find how much variations in the requirements occur.

The most distinctive characteristic of the fast reactor is its potential impact on strategic aspects of nuclear energy, such as availability, accessibility and sufficiency of resources and independence of energy supply. Thus, finally the cumulative amount of Pu-fissile is carefully looked into in order to investigate when the introduction of fast reactors is feasible in view of the startup Pu-fissile.

2. Selection of Reactor Types and Fuel Cycles

2.1 Nuclear Power Development Plans in Korea

There have been several reports[1-7] on growth projections of nuclear power covering the period up to the year 2000, and these are summarized in Table 1.

There is a wide range in predicting the number of nuclear power plant units to be

Table 1. Proposed Number of Nuclear Power Plant Units to Be Introduced by the Year 2000

REPORT	No. of Units		
	L[a]	I[b]	H[c]
"Long-range Nuclear Power Program Study", Kaiser Engineers and Constructors, Inc. (1974)	21	25	25
"A Study on Nucelar Power Plant System and Siting", KAERI(1974)		22	
"Review of Electric Power Development Plan", KDI & KECO(1977)		39	
"An Improved Scheme of the Longterm Integrated Management for KECO", KDI(1978)		46	
"Long-term Energy Systems Optimization study", KAERI(1978)		44	
"Long-term Nuclear Power Optimization study", KAERI(1980)	31		44

a. low case b. intermediate case c. high case

introduced by the year 2000.

These projections, however, have a common point of view that nuclear power generation will play a leading role during the next 20 years, and that approximately 45 to 65 percent of the electric power in Korea will be generated by nuclear power plants in the year 2000.

Due to the uncertainties in projecting nuclear growth over a span of 20 years, a wide range of nuclear projections, rather than a single most probable level, is used to estimate the requirements for nuclear fuel. Three different projections are adopted for nuclear reactor-mix strategies and fuel cycle analyis.

That is, the high and low cases of KAERI REPORT[6-7] (1980) and the low case of KAISER REPORT[1] (1974) are chosen for the high, intermediate and low power growth projections, respectively. Modifications of these projections are made by incorporating the nuclear power plant program already committed for the period of 1978 through 1989 (Table 2), and the new nuclear power plant program models A, B, and C are shown in Table 3.

Table 2. Committed Nuclear Power Plant Program

Startup Date	Unit	Type	Capacity, MWe
1978	Kori-1	PWR	587
1982	Wolsung-1	PHWR	679
1983	Kori-2	PWR	650
1984	Unit #5	PWR	900
1985	#6	PWR	900
1986	#7	PWR	900
1987	#8	PWR	900
1988	#9	PWR	900
1989	#10	PWR	900
Total	No. of units: 9 Generating Capacity : 7,316 MWe		

Table 3. New Models of Nuclear Power Plant Program for Period 1978 to 2000

(MWe)

Startup Date	Model A	Model B	Model C
1978~1988	same as the committed program		
1989	1200, 900	900×2	1200, 900
1990	1200, 900	900	1200
1991	1200×2, 900	900	1200
1992	1200×2, 900	900×2	1200
1993	1200×2	900×2	1200
1994	1200×3	900×2	1200
1995	1200×2	900×2	1200
1996	1200×2	900×2	1200
1997	1200×3	1200×2	1200
1998	1200×4	1200×2	1200
1999	1200×3	1200×2	1200
2000	1200×4	1200×2	1200
Total	41units 44,816MWe	30units 28,616MWe	21units 21,716MWe

2.2 Reactor-Mix Strategies

The projections A, B, and C do not

specify reactor types except for the committed ones. The requirements of nuclear fuel depend, however, not only on the nuclear growth projections but also on the types of reactors to be constructed.

Therefore, a series of reactor-mix strategies are considered to give a broad range of requirements.

For the period of 1978 through 1989, the reactor-mix is already fixed with eight PWRs and one PHWR. For the period of 1989 through 2000, four illustrative strategies are postulated and applied to the nuclear power growth projections A,B, and C.

In establishing reactor-mix strategies, only three reactor types, namely, PWR, PHWR and FBR are considered.

The four illustrative reactor-mix strategies for the period of 1989 through 2000 are as follows:

Strategy 1 PWR 100%
Strategy 2 PWR 75%, PHWR 25%
Strategy 3 PWR 50%, PHWR 50%
Strategy 4 PWR 75%, PHWR 20%
FBR 5%

The above figures for each reactor type represent the portion of the installed generating capacity occupied by that reactor

Table 4. Reactor Strategy 1* for High, Intermediate and Low Power Growth Projections (MWe)

Startup Date	Model A	Model B	Model C
	PWR	PWR	PWR
1989	1200, 900	900×2	1200, 900
1990	1200, 900	900	1200
1991	1200×2, 900	900	1200
1992	1200×2, 900	900×2	1200
1993	1200×2	900×2	1200
1994	1200×3	900×2	1200
1995	1200×2	900×2	1200
1996	1200×2	900×2	1200
1997	1200×3	1200×2	1200
1998	1200×4	1200×2	1200
1999	1200×3	1200×2	1200
2000	1200×4	1200×2	1200
Total	900×4 1200×29	900×14 1200×8	900×1 1200×12

*all PWR

Table 5. Reactor Strategy 2* for High, Intermediate and Low Power Growth Projections(MWe)

Startup Date	Model A		Model B		Model C	
	PWR	PHWR	PWR	PHWR	PWR	PHWR
1989	900, 1200		900	900	900, 1200	
1990	1200	900		900	1200	
1991	1200×2	900		900	1200	
1992	1200×2	900	900	900	1200	
1993	1200×2		900	900	1200	
1994	1200×3		900	900	1200	
1995	1200×2		900×2			1200
1996	1200	1200	900×2		1200	
1997	1200×2	1200	1200×2			1200
1998	1200×3	1200	1200×2		1200	
1999	1200×2	1200	1200×2			1200
2000	1200×3	1200	1200×2		1200	
Total	900×1 1200×24	900×3 1200×5	900×8 1200×8	900×6 1200×9	900×1 1200×9	1200×3

* PWR 75% PHWR 25%

Table 6. Recator Strategy 3* for High, Intermediate and Low Power Growth Projections

Startup Date	Model A		Model B		Model C	
	PWR	PHWR	PWR	PHWR	PWR	PHWR
1989	900, 1200		900×2		900, 1200	
1990	1200	900		900	1200	
1991	1200×2	900	900			1200
1992	1200×2	900	900	900	1200	
1993	1200	1200	900	900		1200
1994	1200	1200×2	900	900	1200	
1995	1200	1200	900	900		1200
1996	1200	1200	900	900	1200	
1997	1200	1200×2	1200	1200		1200
1998	1200×2	1200×2	1200	1200	1200	
1999	1200	1200×2	1200	1200		1200
2000	1200×2	1200×2	1200	1200		1200
Total	900×1 1200×16	900×3 1200×13	900×8 1200×4	900×6 1200×4	900×1 1200×6	1200×6

* PWR 50% PHWR 50%

Table 7. Reactor Strategy 4* for High, Intermediate and Low Power Growth Projections

Startup Date	Model A			Model B			Model C		
	PWR	PHWR	FBR	PWR	PHWR	FBR	PWR	PHWR	FBR
1989	900, 1200			900	900		900, 1200		
1990	1200	900			900		1200		
1991	1200×2	900			900		1200		
1992	1200×2	900		900	900		1200		
1993	1200×2			900	900		1200		
1994	1200×3			900×2			1200		
1995	1200×2			900×2				1200	
1996	1200×2			900×2			1200		
1997	1200×2	1200		1200×2				1200	
1998	1200×3	1200		1200×2			1200		
1999	1200	1200	1200	1200×2			1200		
2000	1200×2	1200	1200	1200		1200			1200
Total	900×1 1200×23	900×3 1200×4	1200×2	900×9 1200×7	900×5	1200×1	900×1 1200×9	1200×2	1200×1

* PWR 75% PHWR 20% FBR 5%

type relative to the total installed nuclear capacity.

The reactor-mix strategies established above apply to each of the nuclear power growth projections A,B, and C for the period of 1989 through 2000. Projections A, B, and C for each reactor-mix strategy are given in Tables 4 through 7.

2.3 Fuel Cycles

The fuel requirements also depend on the fuel cycle options available for the selected reactor types.

At prsent, a PWR operating in once-through mode with slightly enriched uranium has a 30 year gross requirement of between 4347 and 4610t/GWe of natural uranium[8] (assuming 70% capacity factor and enrichment tails assay of 0.2w/o).

The PHWRs based on natural uranium, of the type now commercially available, have a better neutron economy and therefore better resource utilization than PWRs when used in once-through mode.

A PHWR operating on a 70% capacity factor would have a 30 years gross requirement of between 3608 and 3716 tons of natural uranium per GWe[9].

There have been a number of fuel cycle alternatives proposed to improve the resource utilization: the improved once-through cycle, the U/Pu recycle, the introduction of fast reactors, the improved U/Pu recycle, and the utilization of thorium in either the once-through or the recycle mode.

The estimates of INFCE/WG.8[8] indicate that, the reactor system itself with thorium-bearing fuels could be available earlier, but the commercial deployment of thorium cycles probably could not be available until the year 2000.

Thus, the introduction of thorium cycles is not considered in this study. The PHWRs with slightly enriched uranium fuel and the PWRs with improved U/Pu recycle are not considered, either, since considerable development work and consequently a heavy investment of time and effort would be required before they could be introduced on a industrial scale.

Therefore, four fuel cycle options; namely the once-through cycle, the improved once-through cycle, the U recycle, and the U-Pu recycle are considered for PWRs.

There are, however, various approaches[8], [10]-[12] to improve uranium utilization in the improved once-through mode.

One of these approaches is the improvement by increasing the burnup, which is considered to be one of the most attractive means.

If the batch-average burnup of fuel could be increased by 50 percent up to the range between 40,000 and 50,000 MWD/MTU, and the refuelling intervals were kept at one year, an uranium saving of between 8 and 12 percent would be obtained.

The recent report[8] of the U.S.A. submitted to INFCE says that the increased burnup of 50,600 MWD/MTU for PWRs could be demonstrated by 1988. In Table 8 is summarized the information available from the report about the PWR fuel cycle with the increased burnup.

No improvement in the once-through cycle, on the other hand, is considered for PHWRs.

Table 8. Fuel Cycle Information·PWRs with Increased Burnup

Fraction of core replaced/refuelling	0.20
Refuelling (years)	1.07
Equilibrium reload enrichment(%)	4.3
Average discharge exposure(MWD/MTU)	50,650
Natural uranium requirements (t/GWe)	
initial core	314
annual equilibrium reload	123
30-year cumulative	
gross	3,823
net	3,691
Natural uranium savings due to increased burnup (30-year cumulative)(%)	
gross	12.1
net	12.0

3. Estimation of U_3O_8 Requirements

The reactor-mixes and fuel cycle strategies are applied to the nuclear power growth projections to identify a wide range of the demand for U_3O_8 requirements.

3.1 Fuel Cycle Parameters

In order to determine the U_3O_8 requirements, the base values must be assumed for the fuel cycle parameters, e.g., enrichment tails assay, fuel cycle lead and lag times, reactor capacity factor, etc.

The tails assay of the enrichment plant is assumed 0.2w/o and the plant capacity factors are assumed 70 percent for PWRs (unless specified otherwise) and 80 percent for PHWRs. The assumed lead and lag times and fractional recoveries of each fuel

Table 9. Lead/Lag Times and Fractional Recoveries of LWR Fuel Cycle Steps

Fuel Cycle Component	Lead/Lag Time (month)	Fractional Recoveries (%)
U_3O_8 concentrates	−19(−16)	
conversion	−15	99.5
enrichment	−11	
fabrication	−7	99.0
spent fuel storage	24	
reprocessing	31	99.0

( ) : lead time for PHWR fuel cycle steps

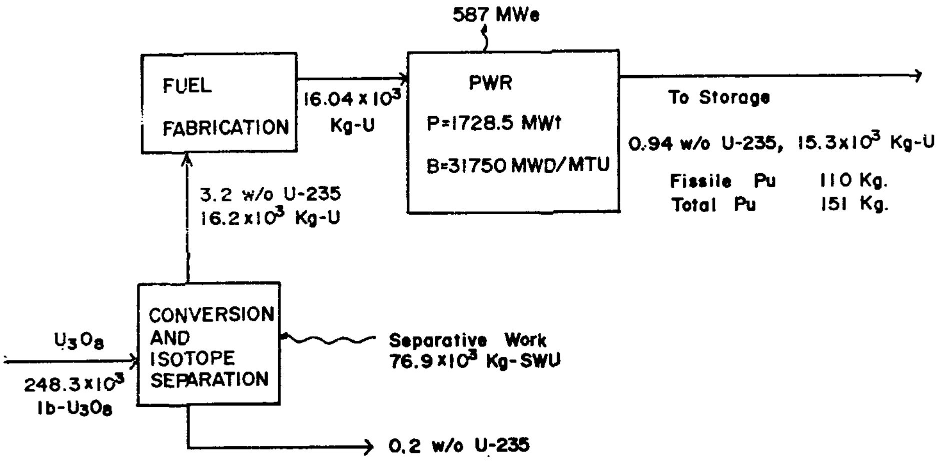

Fig. 1. Material Flowsheet for PWR (No Recycle)

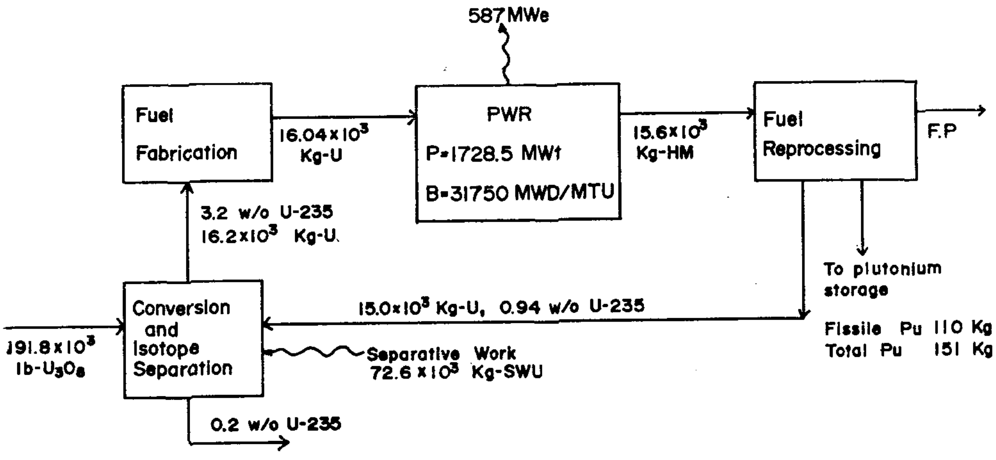

Fig. 2. Material Flowsheet for PWR Self-Generated U Recycle

cycle step are summarized in Table 9.

3.2 Material Flowsheet

Based on the assumed fuel cycle parameters and data available, the fuel mass flow diagrams of the once-through and the selfgenerated uranium recycle are made by using the NUMICE-2 code[13] and hand calculations. In Figs. 1 and 2 are shown the fuel material flowsheets for a 587 MWe PWR in the once-through and the self-generated uranium recycle mode.

The material flowsheet for a 1000 MWe PWR with the selfgenerated U-Pu recycle is made by modifying the data given by Pigford[14], and is shown in Fig. 3. In Fig. 4 is shown the annual mass flow for a 679 MWe CANDU-PHWR. For PWRs with increased burnup, the mass data given in Table 8 are used to estimate the U_3O_8 requirements.

3.3 Classification of Cases

With the assumed fuel cycle parameter values and the mass flow data for each fuel cycle option, the cumulative U_3O_8 requirements are calculated in broadly-grouped four cases. In other words, the parameteric sensitivity study is performed in estimating the requirements.

The four cases are summarized as follows:

CASE 1. (Emphasis on the plant capacity factor)

Reactor Strategy: 1 (PWR 100%)

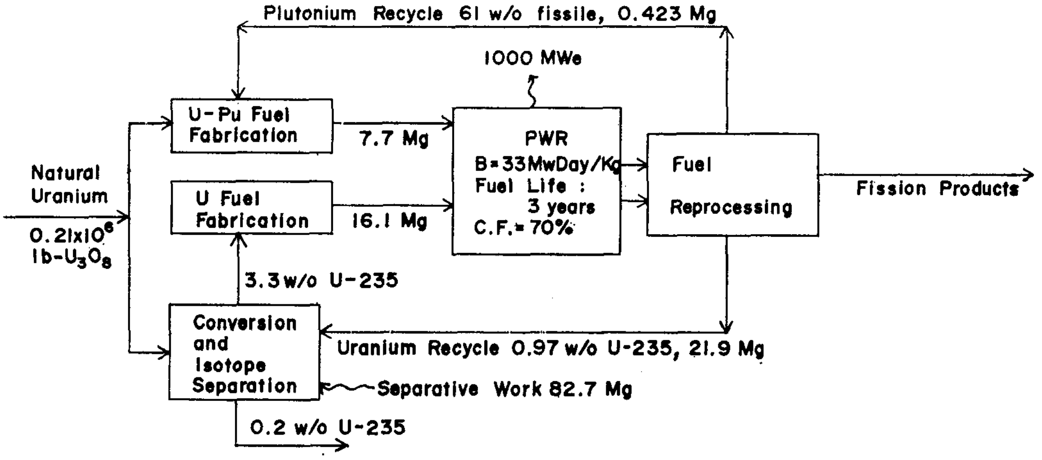

Fig. 3. Material Flowsheet for PWR with Self-Generated U-Pu Recycle

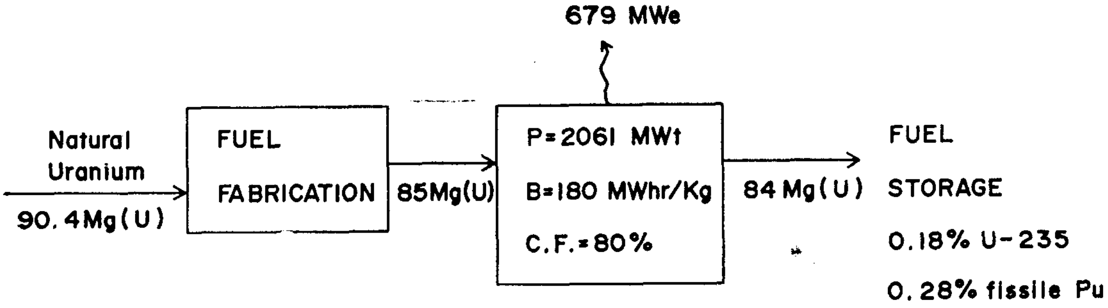

Fig. 4. Annual Quantities for 679 MWe Candu-PHWR (No Recycle)

Fuel Cycle: once-through cycle
Capacity Factor: 80% for PHWRs
80% for PWRs
70% for PWRs
60% for PWRs

CASE 2. (Emphasis on the reactor strategy)
Reactor Strategy:
1 (PWR 100%)
2 (PWR 75%, PHWR 25%)
3 (PWR 50%, PHWR 50%)
4 (PWR 75%, PHWR 20%, FBR 5%)
Fuel cycle: once-through cycle
Capacity Factor: 70% for PWRs
80% for PHWRs

CASE 3. (Emphasis on the fuel cycle)
Reactor Strategy: 4 (PWR 75%, PHWR 20%, FBR 5%)
Fuel Cycle:
once-through cycle for PWRs
U recycle from 1990 〃
U-Pu recycle from 1990 〃
improved once-through cycle from 1990 〃
once-through cycle for PHWRs
Capacity Factor: 70% for PWRs
80% for PHWRs

CASE 4. (Emphasis on the timing of recycle)
Reactor Strategy: 4 (PWR 75%, PHWR 20%, FBR 5%)
Fuel Cycle:
once-through cycle for PWRs
U recycle from 1995 〃
U-Pu recycle from 1995 〃
improved once-through cycle from 1995 〃
once-through cycle for PHWRs
Capacity Factor: 70% for PWRs
80% for PHWRs

4. Introduction of Fast Reactors

The future growth in energy consumption cannot be provided completely from traditional energy resources-the fossile organic fuels-because of their scarcity. Of the proposals for alternative energy sources which could appreciably extend the presently available fuel resources, nuclear power based on the fission of heavy nuclei is by far the most important and is already a practical reality. However, the supply of uranium at economic prices is limited and the fullest utilization of the potential of this energy source can be achieved only by the use of breeder reactors. At present, the U-Pu fuelled, sodium cooled FBR (LMFBR) is the most developed type of fast power reactors.

Now there are several demonstration and experimental fast reactors in operation. The first commercial power reactor, Super Phenix 1 (LMFBR), is under construction and it will generate electricity from 1983. Thus there will be a gradual penetration of the LMFBR as a system for nuclear energy production over the next 20 years.

A unique characteristic of fast reactors is their ability of providing energy whilst, at the same time, producing more fuel than the amount consumed. However, for the startup of fast reactors, some fissile material15)-20) must be supplied. The startup of an 1200 MWe LMFBR requires 3876kg fissile Pu for the initial core plus 7764kg fissile Pu for four replacement loadings before the discharged fuels are recycled16) (with the capacity factor of 70% and the external cycle length of 2 years). This startup plutonium must be obtained from the PWRs operating in the U recycle mode, since the present day cost of uranium and of fuel cycle operations do not justify the reprocessing to recover the plutonium from the fuel discharged from PHWRs, and the open Pu-market is not expected. Thus, the cumulative amount of the Pu-fissile recovered from PWRs in the U recycle mode is estimated in order to find when the startup Pu-fissile is prepared.

5. Results

The estimated U_3O_8 requirementsare summarized in Tables 10 through 12 and Figs. 5 through 7 for projections A,B, and C.

The results of CASE 1 (Section 3.3) indicate that a change of 10% from the 70% base value of the capacity factor results in 11% (in the opposite direction) change in the cumulative (to 2000) U_3O_8 requirements (See Fig. 5).

The case of high nuclear growth projection A, all PWR strategy, the once-through cycle, and the capacity factor of 80%, requires the cumulative (to 2000) requirements of 172.24x 10^6 lb-U_3O_8, and this amount occupies about 4 to 5 percent of the WOCA cumulative requirements.[21] This maximum requirements are about 23 times larger than the Korean uranium resources[22] of which the grade is 0.045%.

The types of reactors employed in future projects change the projection of U_3O_8 requirements considerably in the once-through cycle. The U_3O_8 requirements for the six different reactor-mix strategies are calculated for CASE 2.

The variations of the portion of the portion of the installed capacity occupied by PWRs and PHWRs to the total installed nuclear capacity, namely, the changes from the reactor strategy 1 (PWR 100%) to the reactor strategy 3 (PWR 50%, PHWR 50%), result in the maximum U_3O_8 saving of

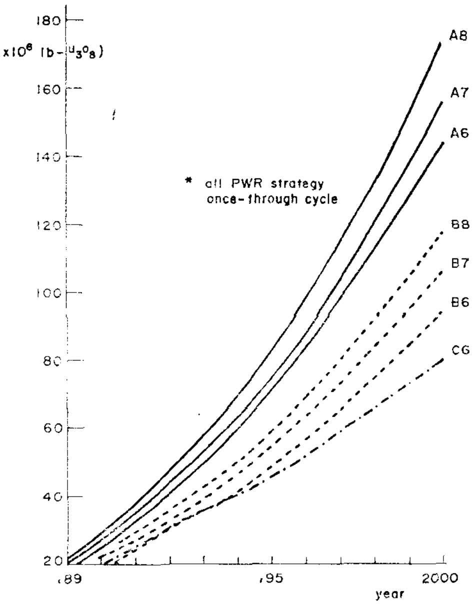

Fig. 5. CUMULATIVE URANIUM REQUIREMENIS Key to the Figure: A8 model A.C.F=80% A7 model A.C.F=70% A6 model A.C.F=60% B8 model B.C.F=80% B7 model B.C.F=70% B6 model B.C.F=60% C6 model C.E.F=60%

Table 10. Cumulative Uranium Requirements*

($\times 10^6$lb-U_3O_8)

Year	RS1**	RS2	RS3	RS4
1990	27.59[a]	26.31	26.31	26.31
	23.23[b]	21.15	22.51	21.15
	24.44[c]	24.44	23.80	24.44
1995	74.96	72.24	67.96	72.88
	54.91	50.26	50.54	51.06
	52.59	51.63	49.50	51.63
2000	155.90	147.54	138.77	144.74
	105.40	99.25	94.80	98.51
	90.57	87.63	83.81	87.08

* capacity factor : 70% for PWRs
80% for PHWRs
fuel cycle : once-through
** RS (Reactor Strategy) :
1 : PWR 100%
2 : PWR 75%, PHWR 25%
3 : PWR 50%, PHWR 50%
4 : PWR 75%, PHWR 20%, FBR 5%
a for nuclear power growth model A
b for nuclear power growth model B
c for nuclear power growth model C

about 10% (See Table 10).

In CASE 3, the emphasis is on fuel options.

The fuel cycle alternatives to increase the utilization of uranium resources are to be introduced sooner or later.

It is assumed that the PWRs would begin recycling U and/or Pu from 1990. However, considering the lead and lag times of each fuel cycle component, no uranium saving effects are assumed until the U and/or Pu of the fuel discharged, that is, the self-generated U/Pu recycle is considered.

About 5%, 9% and 17% reduction in the cumulative (to 2000) U_3O_8 requirements occurs for the improved once-through cycle, the U recycle, and the U-Pu recycle strategies, respectively, in the intermediate nuclear power growth projection B (See Table 11 and)

Table 11. Cumulative Uranium Requirements for Reactor Strategy*

($\times 10^6$lb-U_3O_8)

Year	Model		
	A	B	C
O**	26.31	21.15	24.44
1990 U	25.75	20.69	23.98
T	25.33	20.17	23.46
I	25.80	21.15	23.68
O	72.88	51.06	51.63
1995 U	67.64	47.94	47.79
T	64.41	44.52	43.68
I	69.10	49.47	49.38
O	144.74	98.51	87.08
2000 U	130.02	89.28	78.17
T	117.90	81.47	67.37
I	135.12	93.78	81.65

*PWR 75%, PHWR 20%, FBR 5%

**O once'-through cycle for PWRs and PHWRs

U Urecycle from 1990
T U-Pu recycle from 1990
I improved once-through cycle from 1990
} for PWRs

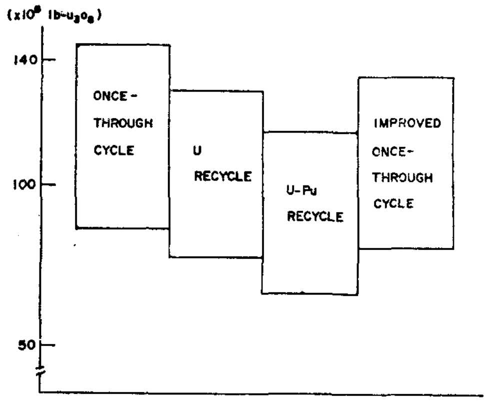

Fig. 6. Cumulative (to 2000) Uranium Requirements

※High Limit of Each Cycle: Model A
Low Limit of Each Cycle: Model C
U Recycle, U-Pu recycle } from 1980
Improved Once-through Cycle
Capacity Factor of 70% for PWRs
Reactor Strategy: PWR 75%, PHWR 20%, FBR 5%

It is assumed that the PWRs would begin recycling from 1990 in CASE 3. In order to investigate the sensitivity of U_3O_8 requirements due to the time delay, another case (CASE 4) is considered in which the recycle would initiate from 1995.

This 5-year delay in initiating the recycle increases about 6-10% of the cumulative (to 2000) requirements for the U recycle and about 3-6% for the U-Pu recycle mode

Table 12. Cumulative Urantum Requirements for Reactor Strategy*

($\times 10^6$lb-U_3O_8)

Year	Model		
	A	B	C
1995 U**	71.46	50.36	50.54
T	69.45	49.37	48.97
2000 U	138.08	97.01	85.82
T	120.94	85.39	71.53

* PWR 75%, PHWR 20%, FBR 5%

** U Urecycle from 1995 for PWRs
T U-Pu recycle from 1995 for PWRs
once-through cycle for PHWRs **Table**

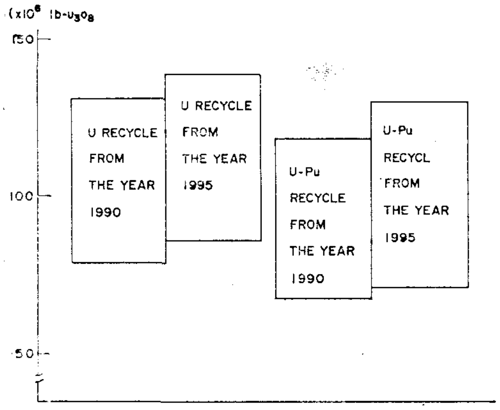

Fig. 7. Cumulative (to 2000) Uranium Requirements
High Limit of Each Case: Model A
Low Limit of Each Case: Model C
Capacty Factor of 70% for PWRs
Reactor Strategy: PWR75%, PHWR 20%, FBR 5%

The 5-year delay in the introduction of the improved once-through cycle also increases about 5-8% of the requirements (See Table 12 and Fig. 7).

Considering only the startup Pu-fissile, as shown in Table 13 and Fig. 8, a fast reactor of 1,200 MWe capacity can be introduced starting the years 1966, 1997 and 1998 for the nuclear power growth projections A,C, and B, respectively, with the U recycle from 1990 assumed. However, if the Pu-fissile of the fuel discharged from PWRs in the 1980's (estimated to be 2481 kg Pu-fissile) is taken into consideration, the first fast reactor can be introduced from 1995 for the high nuclear power growth projection A. An additional fast reactor of 1200 MWe can be introduced in the year 1999 for the projection A.

If the U recycle starts for 1995, the cumulative (to 2000) amount of the recovered Pu-fissile decreases by 25-30%, and the introduction of the fast reactor is delayed by 2 to 3 years (Table 14),

Table 13. Cumulative Pu-Fissile Rcovered*

unit : Kg-Pu fissile

Year	Model		
	A	B	C
1990	1133	1133	1133
1991	2517	2304	2517
1992	3956	3316	3743
1993	5653	4373	5226
1994	7677	5704	7037
1995	1787	7267	9294
1996	13681**	8721	11334
1997	16677	10224	13264**
1998	20854	12587**	16160
1999	25065***	14988	18238
2000	29703	17710	20957

* For U-Recycle from 1990.
Reactor strategy :
PWR 75%, PHWR 20%, FBR 5%

** Startup of a fast reactor (1200MWe) is possible.

*** Startup of additional one unit is possible

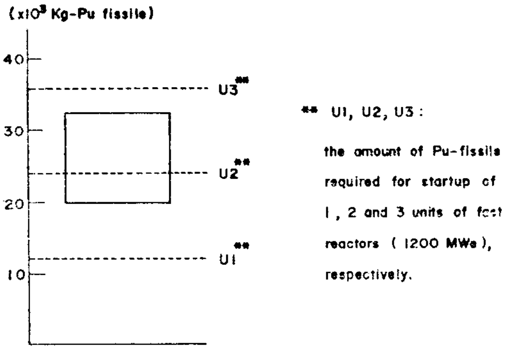

Fig. 8. Cumulative (to 2000) Amount of Pu-Fissile in Discharge Fuel
*** From PWRs**
Capacity Factor of 70% for PWRs
Reactor Strategy: PWR 75%, PHWR 20%, FBR 5%

6. Conclusion

Noting that a major portion of the nuclear fuel cycle cost is represented by the cost

Table 14. Cumulative Pu Fissile Recovered*

unit : Kg-Pu fissile

Year	Model		
	A	B	C
1995	2949	1403	2309
1996	6040	3214	4547
1997	9186	4866	6626
1998	13016**	6883	9176
1999	17387	9229	11627
2000	22417	122557**	14523**

* For U Recycle from 1995
Reactor strategy :
PWR 75%, PHWR 20%, FBR 5%

** Startup of a fast reactor (1200MWe) is possible.

NOTE : Fissile Pu required for fast breeder (1200MWe) startup

initial core	3876Kg-Pu fissile
replacement loadings before discharged fuel is recycled	7764Kg-Pu fissile
Total	11640Kg-Pu fissile

of uranium ore, only the U_3O_8 requirements are considered in this work.

If only the thermal reactor recycle is considered, the U-Pu recycle has a strong incentive in U_3O_8 saving. However, if the introduction of fast reactors is consible by the late nineties, this incentive of the U-Pu recycle decreases, and only the U recycle is recommended for the accumulation of the fissile Pu for the fast reactor startup. If any form of recycles or introduction of fast reactors is not considered feasible in the near future, the PHWRs and PWRS in the improved once-through cycle mode have advantages in reducing the U_3O_8 requirements.

Meanwhile, the option of fast reactors must be kept open or established, since it is anticipated that

i) the price of uranium will not remain low and the availability will be uncertain, and

ii) the present high capital and fuel cycle costs of fast reactors could be made to decrease due to future technical developments.

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References

1. "Long-Range Nuclear Power Program Study", Report 74-101-R, Vol. III, Kaiser Engineers and Constructors, Inc., 1974.
2. "A Study on Nuclear Power Plant System and Siting", KAERI, 1974.
3. "Review of Electric Power Development Plan", KDI & KECO, 1977.
4. "An Improved Scheme of the Long-term Integrated Management for KECO", KDI, 1978.
5. KAERI/85/RR-10/78, "Long-term Energy Systems Optimization Study", KAERI, 1978.
6. KAERI/433/RR-166/80, "Long-term Nuclear Power Optimization study", KAERI, 1980.
7. KAERI/434/RR-167/80, "A Study on the Long-term Nuclear Power Development Strategy", KAERI, 1980.
8. INFCE/WG. 8/USA/DOC. 12, "An Improved Once-Through Fuel Cycle for Light Water Reactors", INFCE, 1978.
9. INFCE/WG. 8/CAN/DOC. 2, "Data Base for a CANDU-PHWR Operating on a Once-Through Natural Uranium Cycle", INFCE, 1978.
10. INFCE/WG. 8/49, "Advanced Fuel Cycles and Reactor Concepts", Final Report, INFCE, 1980.
11. P.M. Lang, "Future Trends in LWR Fuel to Improve Uranium Utilization", *ANS Trans.*, **30**, 1978.
12. N.L. Shapiro and Y. Lieu, "Improvement of Fuel Utilization for Once-Through PWR cycles", *ANS Trans.*, **30**, 1978.
13. Y.S. Kim, "NUMICE-2, A Spectrum Depen-

dent Non-Spatial Cell Depletion Code for CDC-6600", NUS-894, Rev. 1, NUS Corp., 1975.

14. Thomas H. Pigford, "Fuel Cycle Alternatives for Nuclear Power Reactors", Ind. Eng. Chem., Fundam., Vol. 16, No. 1, 1977.
15. "The role of Fast Breeder Reactors in Future Energy Economy", Final Draft, WG/5, Subgroup A, INFCE, 1978.
16. INFCE/PC/2/5, "Fast Breeders", Report of Working Group 5, INFCE, 1980.
17. T.H. Pigford and K.P. Ang, "The Plutonium Fuel Cycles", *Health Physics*, **29**, 1975.
18. INFCE/PC/2/4, "Reprocessing, Plutonium Handling, Recycle", Report of Working Group 4, INFCE, 1980.
19. T. H. Pigford, "Startup of First Generation Fast Breeders with Plutonium or Enriched Uranium", UCB-NE, 3240, 1977.
20. "Advanced Fuel Cycle Alternatives", Rev. Mod. Phys., Vol. 50, No. 1. Part II, Ch. VII, 1978.
21. INFCE/PC/2/1, "Fuel and Heavy Water Availability", Report of Working Group 1, INFCE, 1980.
22. "A Comprehensive Bibliography of Energy" KAERI, 1976.