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Power Cost Analysis of Go-ri Nuclear Power Plant Units 1 and 2

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Abstract

An attempt is made to analyze the unit nuclear power cost of the Go-ri units 1 and 2 in terms of a set of model data. For the calculational purpose, the power cost is first decomposed into the cost components related to the plant capital, operation and maintenance, working capital requirements, and fuel cycle operation. Then, POWERCO-50 computer code is applied to enumerate the first three components and MITCOST-II is used to evaluate the fuel cycle cost component. The specific numerical results are the fuel cycle cost of Go-ri unit 2 for three alternative fuel cycles presumed, levelized unit power cost of units 1 and 2, and the sensitivity of the power cost to the fluctuation of the model data. Upon comparision of the results with the power cost of the fossil power plants in Korea, it is found that the nuclear power is economically preferred to the fossil power. Nevertheless, the turnkey contract value of Go-ri unit 2 appears to be rather expensive compared with the available data on the construction cost of the PWR plants. Therefore, it is suggested that, in order to make the nuclear power plants more attractive in Korea, the unfavorable contract of such kind must be avoided in the future introduction of the nuclear power plant. Capacity factor is of prime importance to achieving the economic generation of the nuclear electricity from the Go-ri plant. Therefore, it is concluded that more efforts should be directed to make the maximum use of the Go-ri plant.

요 약

고리 1호기 및 2호기 원자로의 발전단가에 대한 해석을 시도했다. 해석의 편의상 발전단가를 우선 건설, 운전 및 관리, 운전자금 및 핵연료 등에 관련된 비용성분으로 나누고, 이 중 첫 세성분에 대한 cost는 POWERCO-50 계산코오드를, 그리고 핵연료비는 MITCOST-II를 써서 계산했다. 중요한 계산결과로서는 다른 세가지 핵연료 주기에 대한 고리 2호기의 핵연료 주기비, 고리 1호 및 2호기의 발전단가 및 발전단가계산에 사용된 코스트 자료의 변화에 따른 발전단가의 민감도 등이다.

제래식 화력발전단가와 비교함으로써 원자력발전이 보다 경제적으로 유리하다는 사실을 알아내었지만 고리 2호기의 건설비가 다른 PWR 발전에 비해 다소 고가임을 지적했다. 때문에 원자력발전을 유리하게 하기 위해서는 장차 도입될 원자력발전로의

경우 고리 2호기와 같은 turnkey 계약이 지양되어야 함을 지적했다. 또한 발전단가가 발전소 가동율의 변화에 따라 민감하게 변동한다는 사실로부터 발전소를 최대한 가동시킬 수 있도록 노력이 경주되어야 한다고 결론을 내렸다.

1. Introduction

It has been known to us that the Go-ri nuclear power plant is economically competitive with the existing fossil power plants in Korea. However, recent years have seen the price upswing in fuel cycle elements such as uranium ore, enrichment service, and fuel fabrication, etc., as well as the high contract value of the plant construction cost, as met in the case of the Go-ri unit 2. On the other hand, rapid escalation in the oil price is considered to affect strongly the power cost of oil-fired plants. Therefore, it is the time to reassess the nuclear power economics of the Go-ri plant.

As an effort to do so, we analyzed the nuclear fuel cycle cost of the Go-ri unit 1 in our previous paper (hereafter referred to as paper 1)[1]. Even though the fuel cycle cost is an important economic index for the nuclear electricity, it is the power cost that ultimately provides a firm basis for justifying the nuclear plants in competition with the other fossil plants. Therefore, we consider it valuable to analyze the power cost of Go-ri units 1 and 2 under the current economic circumstances. Motivated by this, we herein attempt to evaluate the levelized unit power cost of nuclear electricity from the Go-ri plant.

In general, the power cost can be subdivided into four major cost components which are related to plant construction, non-fuel working capital, operation and maintenance, and fuel cycle operation. The computer codes such as POWERCO-50[2] and PACTOLUS[3] can enumerate these four cost components all together. However, we separated the fuel cycle cost component from the other cost components and evaluated it using MITCOST-II[4] discussed in paper 1. The rest of the power cost components are then computed by POWERCO-50. The reason for treating this way is that, in connection with the fuel cycle management scheme, MITCOST-II can give us more versatile information than POWERCO-50. In addition, in order for POWERCO-50 to be operable, the input data concerning expenditures on each batch of fuel assemblies must be prepared either by hand calculation or by computer codes like MITCOST-II.

So far as the calculational methods are concerned, both POWERCO-50 and MITCOST-II are based on the present-worthed cash flow precedure. The power cost is determined by requiring that the total income from the sale of electricity must provide for the total expenses on generating the electricity. When expenses spent on the fuel cycle operation are extracted from the total expenses, the fuel cycle cost component is obtained. Just for the purpose of clarifying the calculational procedure, the basic formulas upon which PWERCO-50 is based are rederived here in the same spirit as the original derivation, but following a slightly different procedure. Those for the fuel cycle cost are omitted here, since they are given already in paper 1.

The specific numerical results are the levelized unit fuel cycle cost of Go-ri unit 2 and the levelized unit power costs of units 1 and 2. In computing the above costs, some essential data in relevant with the plant design and operation parameters must be known in advance. Due to the lack of information on some of parameters, however, the uncertainties are inevitably associated with the power cost evaluations of two units. Therefore, to remedy this situation, the effects of the uncertaintes in plant operation and various cost data on the power costs are also investigated by performing the sensitivity analysis.

2. Method of Power Cost Evaluation: POWERCO-50

The power cost of a given nuclear power plant is usually divided into four components, representing the cost contributions due to plant capital, non-fuel working capital, fuel cycle cost, and plant operation and maintenance cost. POWERCO-50 determines these cost components all together based on the present-worthed cash flow procedure. As discussed in detail in Reference 2, the original approach to the theoretical formulation for the power cost is very simple. However, since we find that the effective cost of money to be used in present-worthing all the cash incomes and expenditures does not come out naturally from the original approach, we present herein an alternative derivation, treating the contribution of the fuel cycle cost separately from the other three cost components of the power cost.

Suppose that, for a given power plant having N years of plant life, a company makes an initial capital investment of V_p. In order to establish the cash flow balance equation with regard to the i^{th} year of the plant operation, let us define the followings:

V_i=the outstanding principal at the beginning of the i^{th} year,

E_i=the total kilowatt-hours of electricity produced in year i,

G_i=all the cash expenses accruing from the operation and maintenance of the plant in year i,

D_i=the depreciation charges allocated in year i,

W_i=the working capital tied up for the plant operation in year i,

T_{ci}=the corporate income tax obligation in year i,

T_i'=the sum of the local property tax, revenue income tax, interim replacement cost, and property insurance in year i,

One notes that the cash income in year i is the revenue received from the sale of electricity, if unit price (mills/kwhe) is uniformly charged over the life of the plant

$$=10^{-3}e\ E_i.$$

Also, one notes that the cash expenditures in year i are

the bondholders' and stockholders' return= $V_i(b+s)$

the interest the company pays for the working capital=xW_i,

the corporate income tax, T_{ci},

$$T_{ci}=k_t(10^{-3}eE_i-G_i-bV_i-D_i-T_i') \quad (1)$$

the charges for the local property tax, revenue income tax, property insurance and interim replacement cost,

$$T_i'=10^{-3}k_reE_i+k_vf_iV_p+k_pW_i+k_aV_p+k_b\ (V_p+W_i), \quad (2)$$

where

b=annual rate of return to bondholders $=f_bi_b$,

s=annual rate of return to stockholders $=f_ei_e$,

f_b=fraction of investment in the form of bond,

f_e=fraction of investment in the form of stock,

i_b=bond interest rate per year,

x=annual interest rate applied to the working capital,

i_e=rate of return to stockholders per year,
k_t=the corporate income tax rate,
k_r=revenue income tax rate,
k_v=property tax rate for the plant capital investment,
f_i=the fraction of the plant capital remaining at the start of year $i\left(=\frac{N+1-i}{N}\right)$,
k_p=tax rate for the working capital,
k_a=the equivalent annual rate for interim replacement,
k_b=property insurance rate.

Thus the total expenditure in year i becomes $G_i+V_i(b+s)+xW_i+T_{ci}+T_i'$. Therefore, the funds available to write off the outstanding principal at the end of the i^{th} year is $10^{-3}eE_i-\{G_i+V_i(b+s)+xW_i+T_{ci}+T_i'\}$. This then leads to the outstanding principal at the beginning of $(i+1)^{th}$ year.

$$V_{i+1}=V_i-[10^{-3}eE_i-\{G_i+V_i(b+s)+xW_i+T_{ci}+T_i'\}].$$

Replacing Eqs. (1) and (2) for T_{ci} and T_i', one gets the recursion relation,

$$V_{i+1}=V_i(1+i_{vs})+G_i(1-k_t)-k_tD_i+(1-k_t)(k_vf_i+k_a+k_b)V_p+W_i[(1-k_t)(k_p+k_b)+x]-10^{-3}eE_i(1-k_e), \quad (3)$$

where

$$i_{vs}=(1-k_t)b+s, \quad (4)$$

$$k_e=k_t+(1-k_t)k_r. \quad (5)$$

Requiring that the outstanding principal at the end of plant life, V_{N+1}, must vanish, one finds that the levelized unit cost of electricity is given by

$$e=\frac{k_yV_p+k_w\sum_{l=1}^{N}P_{l,vs}W_l+\sum_{l=1}^{N}P_{l,vs}[G_l(1-k_t)-k_tD_l]}{10^{-3}(1-k_e)\sum_{l=1}^{N}P_{l,vs}E_l} \quad (6)$$

where

$$k_y=1+(1-k_t)\sum_{l=1}^{N}P_{l,vs}(k_vf_l+k_a+k_b), \quad (7)$$

$$k_w=(1-k_t)(k_p+k_b)+x, \quad (8)$$

$$P_{l,vs}=(1+i_{vs})^{-l}. \quad (9)$$

Eq. (6) can be rewritten as a sum of three cost components; plant capital, working capital, and operation and maintenance costs. Denoting these by u_p, u_w, and u_o, respectively, one finds

$$u_p=\frac{k_yV_p-k_t\sum_{l=1}^{N}P_{l,vs}D_l}{10^{-3}(1-k_e)\sum_{l=1}^{N}P_{l,vs}E_l}, \quad (10)$$

$$u_w=\frac{k_w\sum_{l=1}^{N}P_{l,vs}w_e}{10^{-3}(1-k_e)\sum_{l=1}^{N}P_{l,vs}E_l}, \quad (11)$$

$$u_o=\frac{(1-k_t)\sum_{l=1}^{N}P_{l,vs}G_e}{10^{-3}(1-k_e)\sum_{l=1}^{N}P_{l,vs}E_l}, \quad (12)$$

Assuming that annual working capital requirements are the same throughout the life of the plant, i.e., $W_1=W_2=W_3=\cdots\cdots W_n=W_p$, and that the interest rate tied up for the working capital, x, is the same as the effective cost of money, i_{vs}, Eq. (11) becomes

$$u_w=\frac{k_hW_p}{10^{-3}(1-k_e)\sum_{l=1}^{N}P_{l,vs}E_l} \quad (13)$$

where

$$k_h=1-P_{N,vs}+(1-k_t)(k_p+k_h)\sum_{l=1}^{N}P_{e,vs} \quad (14)$$

Eqs. (10), (12) and (13) are the basic formulas by which POWERCO-50 enumerates the power cost components. The levelized unit power cost is the sum of these components and the fuel cycle cost can be evaluated in terms of MITCOST-Ⅱ following the procedure discussed in paper 1. There are a couple of things to be noted. Firstly, in deriving Eq. (6) we tacitly assume that all capital is maintained at a constant bond to equity ratio. Secondly, the effective cost of money

Table 1. The Unit Costs of Fuel Cycle Elements

Fuel Cycle Elements	Unit Costs	Annual Escalation rate (%/yr)	Lead(−)/Lag(+) time (yr)
U_3O_8 Purchase	42.24[a] \$/lb U_3O_8	4.6[a]	−1.417, −2.167[b]
UF_6 Conversion	3.84[a] $/kg U	2.23[a]	−1.292, −2.042[b]
Enrichment	58.79 $/kg-SWU	6[a]	−1.042, −1.75[b]
UO_2 Fabrication	101.74, 186.03[b] $/kg U 305.21[c] $/kg HM	1.56[a]	−0.625, −1.167[b]
Fresh fuel shipping	6.02[a], 18.03[c] $/kg HM	3[a]	−0.208, −0.625[b]
Spent fuel shipping	76.48$/kg HM	3	+0.458
Reprocessing	249.18 $/kg HM	3.568	+0.792
Reconversion	6.46 $/kg U	2.23	+1.125
U Credit	—	—	+2.292
Pu Credit	14.047 $/kg-fissile Pu	3.2	+1.167

a. is taken from paper 1.
b. refers to the initial core, i.e., batches 1, 2, and 3
c. refers to the mixed oxide fuel (PuO_2-UO_2)

used in MITCOST-II is different from that in POWERCO-50 by an amount of k_v $(1-k_t)$. This stems from the fact that in MITCOST-II the local property tax is imposed on the outstanding principal which pertains to fuel investment, while, in POWERCO-50 it is imposed on some fraction of fuel investment for initial core. Noting that the property tax rate is a few percent, as it stands now, and that the present worth factor appears both in numerator and in denomenator, it is not likely that this makes any significant difference in the final result of the levelized unit power cost. In view of this fact as well as many versatile information that MITCOST-II can give us in relation with fuel management scheme, we hence use MITCOST-II to evaluate the fuel cycle cost contribution to the power cost.

3. Numerical Analysis and Discussion

3.1. Levelized Unit Nuclear Fuel Cycle Cost of Go-ri Unit 2

In connection with the fuel cycle cost analysis of Go-ri unit 1, we have discussed an input data model to MITCOST-II in paper 1. Since most of the model data are also applicable to Go-ri unit 2, let us concentrate on what we have not considered in paper 1. The Go-ri unit 2 is scheduled to start its initial commerical operation in Jan. 1981 with the design power level of 605 MWe.

We consider three alternative fuel cycles for this unit; (a) a typical light water fuel cycle without plutonium recycle, (b) the same as (a) but with plutonium recycle, and (c) the simple throuh-away fucl cycle without spent fuel reprocessing. Note that only the case (c) fuel cycle is assumed for the unit 1.

Table 1 lists the model prices for the fuel cycle elements of Go-ri unit 2. For the unit prices on uranium ore, UF_6 conversion, and fuel fabrication, the model data in paper 1 are used without modification. The enrichment service charge is obtained from KECO[5]. The escalation rate of 6% is higher by 2% than the rate set by the current policy of ERDA, but is presumed on the basis of the actual price history of U.S. AEC (now ERDA) in the past. Reprocessing and shipping

Table 2. Fuel Mass Balances for Individual Batches, Fuel Cycles of Case (a) and (c)

Batch	Subbatch	Uranium Enrichment (w/o U-235)		Uranium Weight (kg U)		Fissile Plutonium Weight (kg Pu)		Total Plutonium Weight (kg Pu)		Average Discharge Burnup (MWD/MTMi)
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	
1	—	1.80	0.90	17,251	16,938	—	75	—	95	12,100
2	—	2.40	0.80	17,251	16,700	—	100	—	136	23,050
3	—	3.00	0.86	15,197	14,573	—	99	—	138	30,550
4	A	3.29	1.49	2,054	1,992	—	12	—	15	21,700
	B	3.29	0.96	15,197	14,536	—	102	—	141	32,600
5	A	3.29	1.45	2,054	1,990	—	12	—	16	22,450
	B	3.29	0.93	15,197	14,527	—	102	—	142	33,150
6	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	15,197	14,527	—	102	—	142	33,150
7	A	3.29	1.46	2,054	1,990	—	12	—	16	22,250
	B	3.29	0.94	15,197	14,528	—	102	—	142	33,050
8	A, etc	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B, etc	3.29	0.93	15,197	14,527	—	102	—	142	33,150

Batches subsequent to batch 8 have the same data as batch 8.

cost are from Roger[6]. According to Roger's data, the reprocessing cost in June, 1975 was about 170 per kilogram of heavy metal. However, the future behavior of the reprocessing cost is quite uncertain mainly because of the probable capacity shortage of the reprocessing plants[7]. We tentatively presumed that the reprocessing cost would be 250 per kilogram of heavy metal at the operating date of Go-ri 2. Note that this is the reprocessing price suggested by Numphries[8]. The annual escalation rate of 3.568% is obtained from Roger[6]. On the other hand, the Roger's procedure applied to our case resulted in 65 per kilogram of heavy metal for the fuel shipping, provided that the spent fuel is transported to the reprocessing plant located in the central region of U.S.A. It is not easy to fix the plutonium price, since the plutonium market is not formed. For the fuel cost evaluation of the unit 2, NEC[9] price of 12 \$/gm for fissile plutonium is used, on 1976 U.S. dollars. The escalation rate is taken as 3.2% annually. Lead and lag times in Table 1 are typical of the PWR plant[10].

Table 2 shows the amount of uranium material required to load the reactor core of Go-ri unit 2 and plutonium production for the case that uranium is only fueled. The fuel requirement in the case of plutonium recycle is given in Table 3. The reactor core of Go-ri unit 2 is divided into three annular zones. The initial core consists of batches 1, 2, and 3, in which batch 1 occupies the central zone, batch 2 the intermediate and batch 3 the outer zone. At the end of the first fueling cycle, fuel of batch 1, most heavily burned, is removed from the reactor: fuel of batch 2 is moved to the position of batch 1; fuel of batch 3 to the position of batch 2. Now the fresh fuel of batch 4 loads partly the outer zone of the core (or the zone initially occupied by batch 3) and partly the intermediate zone of the core (or zone initially occupied by batch 2). The part of batch 4 fresh fuel which goes to the outer zone of

Table 3. Fuel Mass Balances for Individual Batches, Fuel Cycle of Case (b)

Batch	Subbatch	Uranium Enrichment (w/o U-235)		Uranium Weight (kg U)		Fissile Plutonium Weight (kg Pu)		Total Plutonium Weight (kg Pu)		Fuel Weight (kg HM)		Average Discharge Burnup (MWD/MTMi)
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	
Batch 1 through 5-Same data as in Table 2												
6	A	3.29	1.46	2,054	1,990	6	12	—	16	2,054	2,006	22,350
	B	3.29	0.93	12,998	12,425	—	87	—	121	12,998	12,546	33,150
	P	0.711	0.37	2,111	2,058	68	42	88	67	2,199	2,125	33,150
7	A	3.29	1.46	2,054	1,990	—	12	—	16	2,054	2,006	22,250
	B	3.29	0.94	12,363	11,819	—	83	—	116	12,363	11,935	33,050
	P	0.711	0.38	2,705	2,638	94	61	129	98	2,834	2,736	33,050
8	A	3.29	1.46	2,054	1,990	—	12	—	16	2,054	2,006	22,350
	B	3.29	0.93	12,003	11,474	—	81	—	112	12,003	11,586	33,150
	P	0.711	0.39	3,046	2,971	107	69	148	113	3,194	3,084	33,150
9	A	3.29	1.46	2,054	1,990	—	12	—	16	2,054	2,006	22,350
	B	3.29	0.93	11,897	11,372	—	80	—	111	11,897	11,483	33,150
	P	0.711	0.39	3,148	3,070	110	71	152	116	3,300	3,186	33,150
10	A	3.29	1.46	2,054	1,990	—	12	—	16	2,054	2,006	22,350
	B	3.29	0.93	11,905	11,380	—	80	—	111	11,905	11,491	33,150
	P	0.711	0.39	3,139	3,061	110	71	153	116	3,292	3,177	33,150
11	A	3.29	1.46	2,054	1,990	—	12	—	16	2,054	2,006	22,350
	B	3.29	0.93	11,393	10,891	—	76	—	106	11,393	11,087	33,150
	P	0.711	0.40	3,611	3,523	133	90	193	148	3,804	3,671	33,150
12	A	3.29	1.46	2,054	1,990	—	12	—	16	2,054	2,006	22,350
	B	3.29	0.93	11,065	10,577	—	74	—	103	11,065	10,680	33,150
	P	0.711	0.41	3,910	3,815	150	102	222	171	4,132	3,986	33,150

the core is referred to as the subbatch 4B. At the end of each subsequent fueling cycle, the similar sequence of fuel movements is respeated. Subbatches A and B are similarly defined. The only difference between subbatch A and B is that subbatch A remains in the reactor core for two irradiation period, while subbatch B remains for three consecutive irradiation period. Table 3 shows that the recycle of plutonium starts at the beginning of the third refueling cycle, which corresponds to the fuel of batch 6. It is noted that the subbatch A consists of uranium fuel only, whereas the subbatch B now contains the mixed oxide of uranium and plutonium. The batch P in Table 3 denotes the fuel or mixed oxide and must be recognized as a part of the subbatch B. Table 4 shows the average burnup attainable by the individual batches. It is noted that the butnup level of subbatch B fuel elements is also applicable to the batch P fuel elements in Table 3.

Based on these data, we estimated the fuel cycle cost of Go-ri unit 2 for three alternative fuel cycles. The numerical results for

Table 4. Estimated Batch Burnup Increment (MWD/MTU)

Region	Batch	Cycle						Average Discharge Burnup
		1	2	3	4	5	6, etc.	
1	1	12,100						12,100
2	2	12,900	10,150					23,050
3	3	8,600	11,150	10,800				30,550
4	4A		9,550	12,150				21,700
	4B		9,550	12,150	10,900			32,600
5	5A			10,350	12,100			22,450
	5B			10,350	12,100	10,700		33,150
6	6A				10,400	11,950		22,350
	6B				10,400	11,950	10,800	33,150
7	7A					10,200	12,050	22,250
	7B					10,200	12,050	33,050
8	8A, etc.						10,300	22,350
	8B, etc.						10,300	33,150
Cycle Average Burnup		11,300	10,250	11,100	11,150	10,950	11,050	

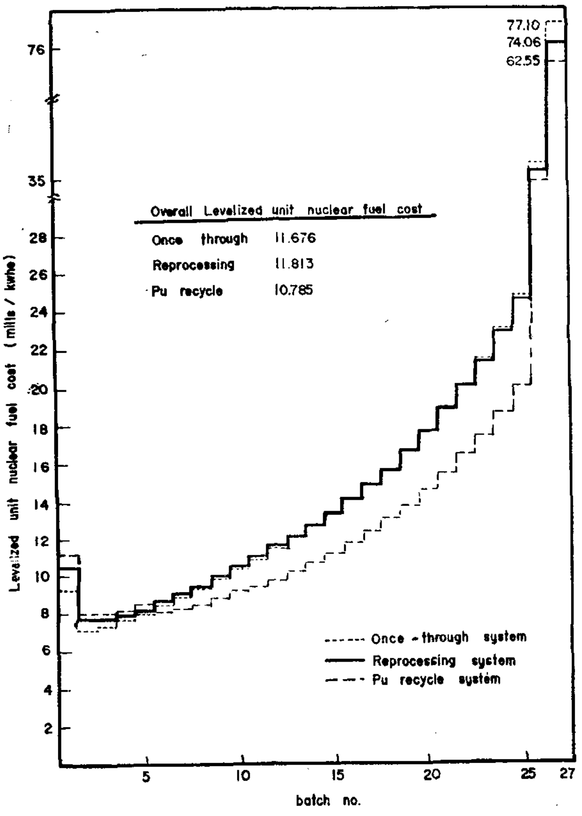

Fig. 1. The Levelized Unit Fuel Cost per Batch.

the overall unit fuel cycle cost are summarized in Table 5 for the case (a), in Table 6 in case (b), and in Table 7 for the case (c) of the fuel cycle. Upon comparing these tables, it is readily noticeable that the lowest fuel cycle cost is achieved by recycling plutonium. In addition, the overall fuel cycle cost is lower in the fuel cycle of no-reprocessing than in that of reprocessing without plutonium recycle. At first sight this result may give the impression that the reprocessing, if plutonium is not recycled, will not be economically advantageous. However, it must be noted that the result is based on the overall reprocessing cost of 250$/kg of heavy metal, and that we did not consider the expenses required for the permanent disposal of the spent fuel in the fuel cycle of no-reprocessing. Therefore, it is premature to say anything about the relative disadvantages of the reprocessing from this result only. An investigation is currently underway how the reprocessing service charge as well

Table 5. Breakdown of the Overall Discounted Costs for Fuel Cycle Operation of Go-ri Unit 2; Case (a) Fuel Cycle

Item	Direct cost ($\times 10^6\$$)	Discounted cost ($\times 10^6\$$)	Fraction (%)
1. U_3O_8 purchase	667.4928	276.0459	51.5
2. UF_6 conversion	16.6889	7.6481	1.4
3. Enrichment	411.7763	157.1554	29.3
4. Fabrication	61.7474	31.4633	5.9
5. Fresh fuel shipping	4.1954	1.7904	0.3
6. Spent fuel shipping	57.7582	19.0943	3.6
7. Reprocessing	211.3336	66.3402	12.4
8. Reconversion	4.2297	1.3892	0.3
9. U Credit	−240.9646	63.3172	−11.8
9—1 U_3O_8	(−198.7938)	(−52.7673)	(−9.9)
9—2 Conversion	(−4.2567)	(−1.2711)	(−0.2)
9—3 Enrichment	(−37.9141)	(−9.2788)	(−1.7)
10. Pu credit	−75.2976	−23.0051	−4.3
11. Other expenses		61.0617	11.4
Total		535.6662	100.0

The levelized unit nuclear fuel cost: 11.813206 mills/kwhe

as the permanent disposal expenses affect the fuel cycle cost. What we found so far is that, even when 50$/kg heavy metal is assumed for the permanent disposal of spent fuel, no-reprocessing is preferred to reprocessing in case that the reprocessing charge is 250$/kg.

Fig 1 shows the levelized unit fuel cycle costs as a function of batch number for fuel cycles of Go-ri unit 2. Two common features are noted in the cost trend; relatively higher fuel cycle costs of batches 1, 25, and 26 than those of batches in their vicinity, and the steady increase in the fuel cycle costs of batches from 2 to 24. The former is due to their shorter irradiation period, while the latter results from the price escalations in the fuel cycle elements. Plutonium recycling lowers considerably unit fuel cycle costs for most of batches. On the other hand, the fuel cycle costs of batches 1 to 5 in the case of plutonium recycle are higher than those in the other two fuel cycles. This is reponsible for the fact that the credits for the plutonium recovered from these batches are not claimed at the moment they are recovered, since they will be eventually taken into account in the recycling batches starting from batch 6.

It is worthy to note that, even though the fuel cycle of no-reprocessing results in the lower overall unit fuel cycle cost than that of reprocessing without Pu recycle, the fuel cycle costs for batches 19 to the rest are higher in the former than in the latter. This simply implies that the reprocessing for these batches has economic advantages over no-reprocessing. Considering that factors such as the reprocessing charge and Pu price are involved in obtaining this result and that numerical values used for these factors are rather uncertain, the result may not be accepted as conclusive. However, it is clear that if our assumptions for the above factors

Table 6. Breakdown of the Overall Direct and Discounted Costs for Fuel Cycle Operation of Go-ri Unit 2; Case (b) Fuel Cycle

Item	Direct cost ($\times 10^6$\$)	Discounted cost ($\times 10^6$\$)	Fraction (%)
1. U_3O_8 purchase	544.6300	233.1635	47.7
2. Conversion	13.7622	6.5551	1.3
3. Enrichment	323.4684	128.6165	26.3
4. Fabrication	83.8518	38.9062	0.8
4-1 UO_2 fabrication	(50.6951)	(27.4607)	(5.6)
4-2 Mixed oxide fabrication	(33.1567)	(11.4455)	(2.4)
5. Fresh fuel shipping	5.8694	2.3530	0.5
6. Speet fuel shipping	57.7450	19.0884	3.9
7. Reprocessing	211.2862	66.3202	13.6
8. Reconversion	4.2019	1.3823	0.3
9. U credit	−200.1268	−54.5785	−11.8
9-1 U_3O_8 purchase	(−166.9330)	(−45.8852)	(−9.4)
9-2 conversion	(−3.6086)	(−1.1201)	(−0.2)
9-3 enrichment	(−29.5852)	(−7.5732)	(−1.6)
10. Other expenses		47.1484	9.6
Total		488.9551	100.0

The levelized unit nuclear fuel cost: 10.783072 mills/kwhe

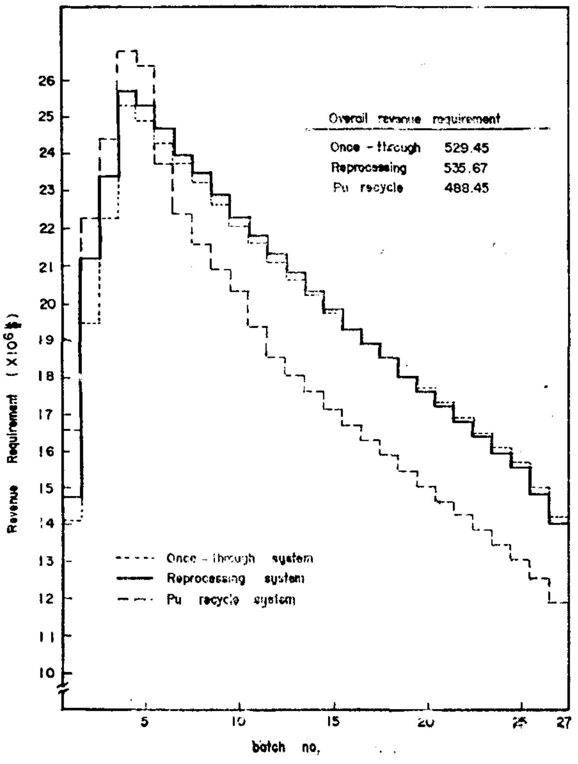

Fig. 2. The Revenue Requirement per Batch.

will be the case, the proper combination of two fuel cycle management schemes, (a) and (b), can generate the unclear electricity more cheaply than otherwise.

Fig. 2 shows the revenue requirements for the individual batches loaded in the Go-ri unit 2 throughout its 30 year plant life. The forementioned features in cost trends are also observed in this figure. Fig. 3 represents the levelized unit fuel cycle cost per irradiation period. The cost behaviour is very similar to the case of the unit cost per batch.

3-2. Levelized Unit Power Cost of Go-ri Units 1 and 2

Table 8 lists the major economic parameters needed for computing the power cost of the Go-ri plant. In general, plant capital or the construction cost of a given power plant can be evaluated using the computer codes, CONCEPT[11] or ORCOST[12]. However, we need not rely upon the codes, since units 1

Table 7. Breakdown of the Overall Direct and Discounted Costs for Fuel Cycle Operation of Go-ri Unit 2; Case (c) Fuel Cycle

Item	Direct cost ($\times 10^6$\$)	Discounted cost ($\times 10^6$\$)	Fraction (%)
1. U_3O_8 purchase	667.4928	276.0459	52.1
2. Conversion	16.6889	7.6481	1.4
3. Enrichment	411.6626	157.0982	29.7
4. Fabrication	61.7474	31.4633	5.9
5. Shipping (fresh fuel)	4.1954	1.7904	0.3
6. Other expenses		55.3991	10.5
Total		529.4450	99.9

The levelized unit nuclear fuel cost: 11.677008 mills/kwhe

Table 8. Economic Parameters

Item	Go-ri unit 1	Go-ri unit 2
Plant capital, V_p($\times 10^6$\$)	295	648
Project life (yr)	30	30
Capital structure		
Weighted average fraction, (%)		
bond, f_b	89.85	87.47
stock, f_s	10.15	12.53
weighted average interest rate (%/yr)		
bond, r_b	8.447	10.11
stock, r_s	14.84	13.99
Tax rates (%/yr)		
Effective corporate tax rate	36.05	39.25
Revenue income tax rate	0.607	0.662
Property tax rate	0.0808	0.0881
Property insurance rate (%/yr)	0.405	0.405

and 2 of the Go-ri plant are already contracted and, thereby, the contract values for two units are available. The unit 1 was originally contracted with the construction cost of \$1.99×10^8. \$2.95×10^8 in Table 8 is the current value for the unit 1. The increase is primarily due to the delay in the plant construction and the price escalation of equipments and materials. On the other hand, the figure for the plant capital of the unit 2 corresponds to the contract value. The plant life of both units is taken as 30 years.

The capital funds required for plant construction, operation and maintenance expenses, and fuel loading are obtained in the forms of stocks, bonds, and loans. The returns on these capital sources are different from one form of investment to another. Table 8 also shows the financial structure and rates of returns on investments for the Go-ri plant. In POWERCO-50, the bonds and loans are treated as a single bond item, because the interest paid to them are both tax deductible. We noted that the bond to equity ratio in the plant capital is different from that in the operation and maintenance cost, whereas a single numerical value for the bond fraction or the stock fraction in the total investment is needed in POWERCO-50 To

Table 9. Operation and Maintenance Expenses for the First Year Operation of Go-ri Plant (×10^3 \$)

Item	Go-ri unit 1	Go-ri unit 2
1. Staff payroll	462.7	567.8
2. Consumable supplies and equipment	637.0	826.9
3. Outside support services	224.8	291.8
4. Miscellaneous	131.1	170.3
5. General and administrative (15% total of four items above)	218.3	278.5
6. Liability insurance	30	30
Total	1,703.9	2,165.3

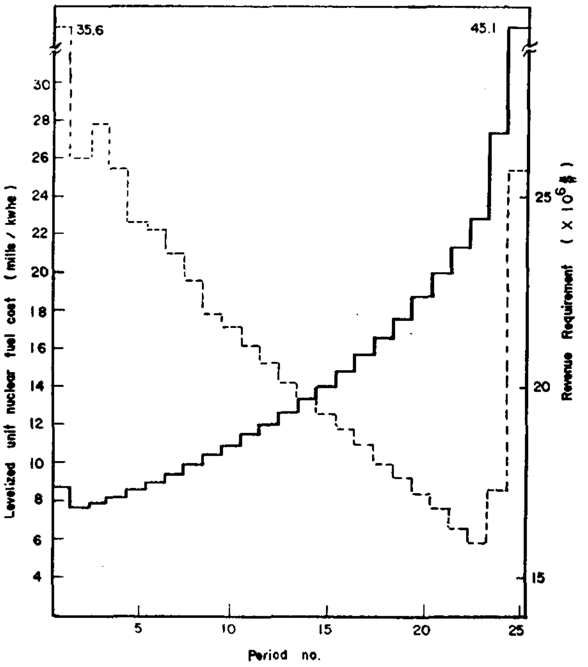

Fig. 3. The Levelized Unit Fuel Cost and Revenue Requirement per Period.

Table 10. Non-fuel Working Capital Requirements ($\times 10^3$\$)

Item	Go-ri unit 1	Go-ri unit 2
Average net cash required	45.2	57.7
2.7% of annual direct O & M cost excluding liability insurence		
50% of insurance annual cost	15.8	1,463.8
Materials and supplies in inventory		
25% of annual cost of materials and supplies	159.2	206.7
Total	820.2	1,728.2

determine this parameter with a due regard to the actual capital structure we first computed the total present worth of the plant capital and operation and maintenance cost. Using the ratio of the present worth values of the two, we adjusted the weighted average value for bond or stock fraction of the total investment. Taking the similar steps for the return rates on investments, the average bond interest rate and average rate of return on stock investments are adjusted. The results are given in Table 8.

Taxes to be included in the annual capital expenditures are five kinds; residence tax, defense tax, corporate income tax, revenue income tax, and property tax. For simplicity, We absorbed the residence and defense taxes into the corporate income tax with the resulting corporate income tax rate of 29.7%. Since this income tax rate is expected to rise with time, the escalation in the tax rate over the life of the plant must be accounted for. The effective corporative income tax rate in Table 8 denotes the tax rate adjusted so that the corporate income tax rate 30 years later in Korea will reach 50%, the current tax rate in U.S. The revenue income and property tax rates are then obtained from multiplying the current ratios of the two to the corporate income tax rate.

Property insurance expenditures for the nuclear power plant depends on the risk involvement. In conjunction with this, the Go-ri plant is divided into three zones; hot, warm, and cold zones. Hot zone represents 50% of the plant capital with the insurance rate of 0.5 to 0.7%. Warm zone occupies 15 % of the plant with the insurance rate of 0.3% to 0.4%. The rest of 35% belongs to the cold zone with the insurance rate of 0.1 to 0.2%. The property insurance rate given in Table 8 is the weighted average value over the three zones.

Table 9 shows the operation and maintenance expenses required for the first year operation of Go-ri plant. Expenses for the staff payroll depend on the manpower requirements for the plant as well as the wages or salary level paid to the plant workers in the Korea Electric Company (KECO). According to the recent report of Kaiser

Engineers[10], the nuclear power plant like the Go-ri units 1 and 2 may require 25 operators, 40 engineers, and 35 maintenance workers for the plant operation. Considering that KECO does not have the previous experience of operating the nuclear plants, the manpower requirements for the Go-ri unit 1 and 2 may exceed this number. We presumed that about 40% more than Kaiser estimation will be employed for the unit 1, while roughly 10% more is needed for the operation of the unit 2. On the other hand, the wages or salaries are estimated on the basis of IAEA data[13] with a proper account for the wage escalation observed in recent years[14]. For the staff payroll, the current payments to operators, engineers, and maintenance workers are estimated at 123,000 won, 145,000 won, and 108,000 won, respectively. Figures for staff payroll in Table 9 are then obtained under the assumption that salaries will rise by 10% annually from now on.

We found it very difficult to determine expenses for such items as consumable supplies and equipment, outside support services, and miscellanecus item related to public relations, new staff training, rents, and travel, etc. The figures in Table 9 are the rough estimation based on the IAEA data[15] and the data for the light water reactor plants in U.S.[16].

Table 11. The Levelized Unit Cost of Nuclear Electricity (mills/kwhe)

Item	Go-ri unit 1	Go-ri unit 2
Plant Investment	9.3388	21.6694
Working Capital	0.0350	0.0718
Operating and Maintenance cost	1.2464	1.4225
Subtotal	10.6202	23.1637
Fuel Cycle Cost	7.3313	11.8132[a]
Total	17.9520	34.9769

(a) This correspods to case (a) fuel cycle

Table 12. Breakdowns of Fixed Charge Rates

Item	Go-ri unit 1	Go-ri unit 2
Fixed Charge Rate Depreciable Capital		
Average Interest Rate	0.09096	0.10596
Sink and Depreciation	0.00721	0.00543
Income Tax	0.00110	0.00115
Revenue Tax	0.00063	0.00078
Property Tax	0.00058	0.00065
Property Insurance	0.00405	0.00405
(Total)	(0.10453)	(0.11802)
Fixed Charge Rate Nondepreciable Capital		
Average Interest Rate	0.09096	0.10596
Sink and Depreciation	0	0
Income Tax	0.00857	0.01115
Revenue Tax	0.00063	0.00081
Property Tax	0	0
Property Insurance	0.00405	0.00405
(Total)	(0.10421)	(0.12197)
Levelized Annual Income Required $(\times 10^6\$)$	35.0643	81.7505
Levelized Power Production $(\times 10^9$ kwhe/yr)	5.8436	5.8335

For the general and administrative expense, 15% of the total of the above-mentioned items is taken, since this is usally observed in the U.S. LWR plants[15]. Finally, the liability insurance is taken as $30,000 per year.

Table 10 shows the non-fuel working capital requirements for the Go-ri plant. As indicated in Table 10, the figures are all based on the procedure suggested in the NUS Guide[16].

The numerical values thus listed for various parameters are then used to determine the levelized unit cost of nuclear electricity of the Go-ri units 1 and 2. Table 11 is the summary of the results in which the fuel cycle cost of the unit 1 is taken from the result of paper 1. As can be read in the table, the plant capital and fuel cycle cost contribute mostly to the power cost of two units. The fuel cycle cost is known to be only 20 or 30% of the plant capital in the early 1970's[17], when the uranium ore and enrichment service charge was 8$/1b U_3O_8 and 26$/kg SWU, respectively, and the construction cost was in the range of 200 to 300$/KWe. In contrast with this, the fuel cycle cost of unit 1 is almost comparable to the plant capital contribution. This is primarily due to the fact that the price escalation in the uranium ore and enrichment since the petroleum crisis affects the fuel cost strongly. On the other hand, in the case of Go-ri unit 2, the plant capital contribution is nearly twice the fuel cycle cost. A high turn-key contract value of 1000$/KWe for unit 2 is supposedly responsible for this proportion.

Recently, Humphries[8] reported that the unit power cost in U.S. would range from 21.5 mills/kwhe to 32.3 mills/kwhe in 1985. He obtained this result on the basis of the fuel cycle element costs similar to ours and the construction cost of roughly 600$/KWe. Taking into account the difference of the construction cost we have used for the Go-ri plant and the escalation effects till that time, our estimation for the power cost is found to well within the Humphries' estimation. On the other hand, the power cost of oil-fired plant in U.S.[18] is currently 60 mills/kwhe. Also, the power cost of the typical oil-fired plants in Korea is reportedly known to range from 64.2 to 71.0 mills/kwhe[19]. In comparison with these, the nuclear power cost of the Go-ri plant appears to be considerably cheap, which in turn justifies the economic competition of the nuclear power in Korea.

In Table 12 we present the power cost of the Go-ri plant in terms of fixed charge rate. Annual fixed charge rate is decomposed into components in the table.

Table 13. Results of Sensitivity Calculation.

(Δ mills/kwhe)

Variables	unit	Go-ri unit 1	Go-ri unit 2
1. Plant investment	10^{6}\$	0.0305	0.0332
2. Bond interest rate	%/yr	0.5833	1.3930
3. Corporate taxrate	%/yr	0.0211	0.0370
4. Operating and maintenance cost	10^{6}\$/yr	0.3670	0.3216
5. Capacity factor	0.05/yr	3.2046	7.6348

It is fair to say that the input data used in the power cost evaluation involve some uncertainties, even though they are the best that we can presume. Therefore, we must take into account the effects of the uncertain nature of the data on the estimation of the power cost. This is done by performing the sensitivity calculation to the small variations of the input data. The input data we considered important in this regard are the plant capital, operation and maintenance cost including the working capital, bond interest rate, the corporate income tax rate, and the plant capacity factor. Table 13 gives the major results we obtained. As seen clearly, the capacity factor affects the power cost most strongly. This means that the forced shutdown due to the accidental circumstances hurts mostly the economics of the Go-ri plant. Therefore, the efforts must be made to avoid the accidental shutdown and thereby to make full use of the Go-ri plant.

4. Conclusion

We have computed the levelized unit power cost of the Go-ri plant. For the computational purpose, the power cost is first divided into four cost componetns related to plant construction, operation and maintenance, non-fuel working capital requirements, and fuel cycle. Then POWERCO-50 is applied to estimate the first three components, while MITCOST-II is used to evaluate the fuel cycle cost. We found that the levelized unit power cost of the Go-ri unit 1 is 17.9520 mills/kwhe, and that for the unit 2 the three alternative fuel cycles, (a), (b), and (c), resulted in the unit power cost of 34.9769, 33.7468, and 34.8407 mills/kwhe, respectively. Also, we found that plant capital and fuel cycle contribute mostly to the power costs of two units.

When compared with the power cost of the oil-fired plants in Korea, the nuclear power from the Go-ri plant appears to be substantially cheaper. However, it must also be stated that the plant capital contribution in unit 2 is higher than the projections for the nuclear plants in U.S. in WASH-1345[20]. As mentioned already, the high turnkey contract value for the construction of unit 2 is responsible for this. Therefore, to make the nuclear power more attractive in Korea, the unfavorable contract of this kind should be avoided in the future introduction of nuclear power plants. Currently, the plutonium utilization in light water reactors is confronted with the licensing problem in U.S.[21]. So far as our stuty is concerned, the fuel cycle of the plutonium recycle seems to be the most favorable one for the Go-ri unit 2. For it renders the cheapest nuclear fuel cycle cost among fuel cycles considered in this paper. Therefore, if the Pu recycle is permitted in the light water reactors it is worth while to consider the feasibility of the Pu recycle also in the Go-ri unit 1. On the other hand, when the reprocessing service charge is assumed to be 250$/kg of heavy metal, the reprocessing without Pu recycle is observed to be less economical than the case of no-reprocessing. However, on the basis of per-batch fuel cycle cost, the fuel cycle of reprocessing appears to be more economical than that of no-reprocessing for fuel batches loaded later in the reactor core of the unit 2. As a matter of fact, in order for this to be the case, our assumptions and model data used in this paper must be the right ones. Even so, it is at least inferred that, depending on the economic circumstances, the timely reprocessing will certainly contribute to the cheap generation of the nuclear electricity from the Go-ri plant. Therefore, further study is for the evaluation of advantages or disadvantages of the reprocessing to establish the economic fuel cycle methodology of the Go-ri plant.

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