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Fuel Cycle Cost Analysis of Go-ri Nuclear Power Plant Unit 1

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Abstract

A system of model price data for the fuel cost estimation of the Go-ri plant is developed. With the application of MITCOST-II computer code the levelized unit fuel costs over the entire lifetime of the plant are evaluated. It is found that the overall levelized unit fuel cost is 7.332 mills/Kwhe and that the uranium ore and enrichment service represent more than 85% of the unit cost, assuming a simple once-through fuel cycle process with no reprocessing of the spent fuel. The effects of the cost fluctuations in these fuel cycle elements and the capacity factor changes are also evaluated. The results indicate that the fuel costs are most sensitive to the variation of uranium ore price. Efforts must, therofere, be employed for the arrangement of cheap and timely supply of uranium ore in order to achieve the economic generation of nuclear power.

요 약

고리원자로의 핵연료비 추정을 위한 가격 모델을 수립하고 이를 기초로 MITCOST-Ⅱ 전자계산 code를 써서 고리 발전소의 전수명에 걸친 핵연료주기비를 계산하였다. 사용후 연료를 재처리 하지 않는다는 간단한 핵주기를 가정하였는데 평균 단위 핵연료비는 7.332 mills/Kwhe으로 추정되었으며 이중 우라늄 원광비와 농축비가 85% 이상을 차지하고 있음을 알아내었다. 또한 원광가격과 농축가격의 변동 및 발전소 가동율의 변화에 따른 영향을 계산했으며 그 결과 핵연료비가 원광가격 변동에 매우 민감하게 변화한다는 사실도 알아내었다. 따라서 경제적으로 전력을 생산하기 위해서는 적기에 염가로 우라늄을 확보할 수 있도록 노력을 기울여야 한다고 제안하였다.

1. Introduction

The first nuclear power plant in Korea, Go-ri power plant unit 1, is currently under construction. It has been known to us that the power cost of this plant will be cheaper than that of the existing conventional plants. However, to our best knowledge so far, no quantitative analysis has been made on the economic aspects of Go-ri plant. Therefore, it is not clarified precisely how cheap the cost of nuclear electricity of this plant will be. In view of this fact as well as the fact that more nuclear plants are to be introduced into Korea in the near future, we consider it valuable to make a systematic study on the economics of nuclear power plants in Korea. As an effort to do so, we attempt in this paper to estimate the nuclear fuel cycle cost of the Go-ri plant by developing a reference price model for the fuel cycle elements, and thereby to provide a firm basis for conforming the economic justification of the nuclear power plants.

There are several computer codes which have been used for computing the nuclear fuel cycle costs. Typical of these are CINCAS1), FUELCOST2), REFCO3) and MITCOST4, 5). In this paper we dealt with the MITCOST-II5) developed recently at MIT. In using this code, the fuel assemblies in the reactor core are firstly divided into several groups called batches. Then both the total money spent on a given batch and the total electricity generated by the batch are calculated. By dividing the former by the latter, the code gives rise to the levelized unit nuclear fuel cost per batch. Taking similar steps for a certain irradiation period, the code can also generate the levelized unit fuel cost per irradiation period. These are representative of the fuel costs producing the nuclear electricity, and are used in MITCOST-II as price indices for the nuclear fuel.

In computing these price indices the numerical values for some of the plant design and operation parameters must be given in advance. These include the burnup level, thermal efficiency, capacity factor, fuel requirements, and the economic data such as the unit price of the fuel cycle elements, tax rates, return on investments, depreciation method, etc. Among these factors, it is very difficult to know precisely the unit price of fuel cycle elements and the capacity factor throughout the expected 30 years' lifetime of the Go-ri plant. Nevertheless, the knowledge on these parameters is necessary for preparing the input data system to MITCOST-II. Therefore, we have made relevant assumptions on the cost data available, and developed a model price system for the fuel cycle elements. For the capacity factor, we made use of the statistical data obtained from the past experience of the plant operation in USA6).

The fuel cost determined in this way is somewhat uncertain because of the imprecise nature of the model input data. In order to account for this uncertainty we evaluated the economic sensitivity of the fuel cost to the changes in the fuel cost components. In particular, we investigated the effects of fluctuation of the uranium ore and enrichment costs. Without any previous experience of operating the nuclear power plant, we do not know at the present time to what extent we will be able to utilize the availability of the Go-ri plant. Therefore, we also treated the capacity factor as a variable in the sensitivity analysis.

Finally, the Go-ri nuclear fuel cycle we have considered herein consists of uranium ore purchasement, UF_6 conversion, enrichment, fuel fabrication, and burnup in the reactor core. Accordingly, the fuel cycle of the Go-ri plant is a simple once-through process with no reprocessing of the spent fuel. In assumming the once-through process the following factors are borne in mind: Namely, 1) It will be difficult to get reprocessing service at least till 1990, judging from the current world reprocessing capacity7); 2) The market prices connected with the transportation of the spent fuel, reprocessing, reconversion and the waste disposal problem are very unstable; 3) The market price of recovered plutonium is not formed; 4) There are indications that the economics of the reprocessing is doubtful[8].

2. Fuel Cycle Cost Evaluation Code: MITCOST-II

The fuel cost comprises the second major component of the power generating cost, and is second only to the construction cost. MITCOST-II is one of the computer codes capable of computing the nuclear fuel cycle cost over the entire lifetime of a given power plant. The code computes both the levelized unit nuclear fuel cost per batch and that per irradiation period. These are important economic indices that are useful for selecting the reactor types and for establishing the reactor core management scheme.

As noted in the introduction, this paper is intended not to develop new methods for the fuel cycle cost evaluation but for applying the known method to the Go-ri fuel cycle cost analysis with the development of model input system appropriate to nuclear plants in Korea. Therefore, we omit the mathematical details in formulating MITCOST-II. Instead, a brief summary is given on the key formulas upon which our fuel cycle analysis is based.

(A) The levelized unit nuclear fuel cost per batch

The nuclear fuel differs from the conventional fuel such as coal and oil which are normally considered as consumable item. In nuclear fuel, however, each batch of fuel produces energy for several years and, therefore, is treated as a capital asset and is consequently subject to depreciation. Before a given batch of fuel assemblies produces the nuclear electricity, the electric utility pays for the U_3O_8 procurement, conversion and enrichment service charges, fabrication costs and expenses occurring from the contract of these fuel cycle elements. While the batch is producing the electricity, the utility also pays the taxes, returns on investments to bond and stock-holders. In connection with these practices, the levelized unit nuclear fuel cost per batch, Be_k, is defined as the unit cost which, if charged uniformly for each killowatt-hour of electricity produced by batch k, would enable the electric utility to 1) pay the required return to those who invested on the batch k fuel assemblies, 2) pay all the taxes imposed on batch k, and 3) reduce the net investment in batch k by an appropriate amount so as to make the capital investment at the end of the investment period go to zero.

Assuming that the taxes and returns on investments are paid at the same time, Be_k can be shown to be in the form;

$$Be_k=\frac{\displaystyle\sum_{q=0}^{Q}\frac{I_{k,q}}{(1+x)^{t_{k,q}-t_R}}-\sum_{l=1}^{L}\frac{\tau_F(C_{k,l}+D_{k,l})}{(1+x)^{t_{k,l}-t_R}}}{\displaystyle\sum_{i=1}^{I}\frac{0.001(E_{k,i})}{(1+x)^{t_{k,i}-t_R}}-\sum_{l=1}^{L}\frac{0.001\tau_{FR}(E_{k,l})}{(1+x)^{t_{R,l}-t_R}}} \qquad (1)$$

where

$I_{k,q}$=the captial invested on batch k of nuclear fuel, which includes U_3O_8, conversion, enrichment, and fabrication costs,

$E_{k,i}$=the total killowatt-hours of electricity produced by batch k during the i^{th} irradiation period,

$C_{k,n}$=expenses other than fuel cycle element costs for batch k in the period n,

$D_{k,n}$=depreciation cost allowed for batch k in the period n

x=the effective cost of money which

depends on the financial structure of utility, rate of return on investments, and tax rates,

$$=s+(1-\tau_F)b+\tau_p(1-\tau_F)$$

$$\tau_{FR}=\tau_F+\tau_R(1-\tau_F)$$

where,

s=per period rate of return to stockholders $=f_s r_s$

b=per period rate of return to bondholders $=f_b r_b$

f_s=fraction of investment in the form of stock

f_b=fraction of investment in the form of bond

r_s=rate of return to stockholders per period

r_b=bond interest rate per period

τ_F=corporate income tax rate

τ_p=property tax rate

τ_R=revenue income tax rate

$t_{k,q}$=the time when the fuel cycle element costs are paid

$t_{k,l}$=the time when taxes and returns on investments are paid

$t_{k,i}$=the equivalent time for the receipt of power revenues for batch k in the irradiation period i.

In Eq. 1 the running index q is over all fuel cycle payments, and l over tax periods. It is noted that the first term in the denominator denotes the present-worth value of the total electricity by batch k in the i^{th} irradiation period. Therefore, the quantiy

$$B_{RRk}=Be_k\cdot\frac{0.001(E_{k,i})}{(1+x)^{t_{k,i}-t_R}} \qquad (2)$$

represents the revenue requirement for batch k fuel assemblies. In other words, B_{RRk} is the sum of money which, if charged uniformly at time t_R for each killowatt-hour of electricity produced by batch k, would just enable the utility to pay out all the money spent on the batch k.

(B) The levelized unit fuel cost per irradiation period

There are two principal effects of extended neutron irradiation on fuel; the loss of reactivity and the change in the physical properties. Due to either of these two effects, there comes the time when some parts of fuel assemblies loaded in the reactor core must be replaced by the fresh fuels. The time span between two successive refueling is called the irradiation period. From the above discussion one notes that the present-worth value of the total electricity generated in the period i is $\sum_{k=1}^{K}\frac{0.001E_{k,i}}{(1+x)^{t_{k,i}-t_R}}$ and that the revenue requirement in this period, P_{RRi}, may be written as

$$P_{RRi}=\sum_{k=1}^{K}Be_k(0.001)(E_{k,i})\frac{1}{(1+x)^{t_{k,i}-t_R}}$$

$$=Pe_i\sum_{k=1}^{K}\frac{0.001(E_{k,i})}{(1+x)^{t_{k,i}-t_R}} \qquad (3)$$

Therefore, levelized unit fuel cost in this period, Pe_i, is given by

$$Pe_i=\frac{\sum_{k=1}^{K}\frac{Be_k\cdot E_{k,i}}{(1+x)^{t_{k,i}-t_R}}}{\sum_{k=1}^{K}\frac{E_{k,i}}{(1+x)^{t_{k,i}-t_R}}} \qquad (4)$$

3. Input Data Model for Fuel Cost

(A) Unit Costs of Fuel Cycle Elements

(1) Uranium Ore Concentrates

The uranium price, like any other commodities, depends on the resource availability, the requirements, and the psychological attitude toward the uranium resources. For a long time before the petroleum crisis the uranium price had been kept levelling off a \$6/lb U_3O_8, primarily due to the surplus of uranium supply that the industry held[9].

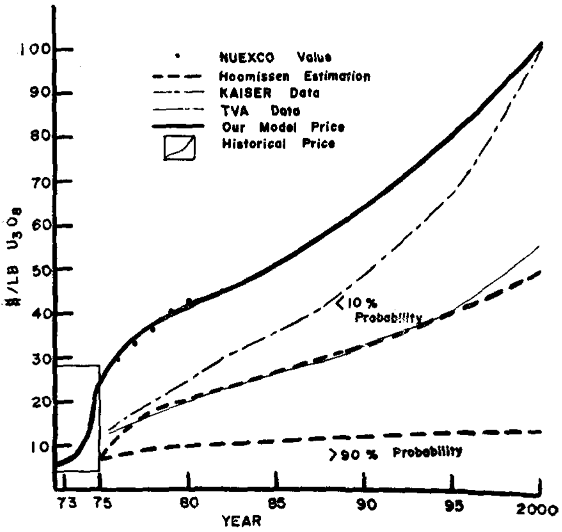

Fig. 1. Unit cost of uranium ore concentrates

Since the crisis, the demand for nuclear power plants has increased in the number and the capacity. Thus the surplus of uranium stockpile decreases rapidly and thereby a supply shortfall is expected in the late 1970's. This then makes the rapid price increase for the uranium ore as observed these days. Currently, the uranium price reaches $26/lb U_3O_8, a record high price.

Fig. 1 is a collection of available data on the U_3O_8 price. Black circles are monthly report of Nuclear Exchange Corporation[10] (NEC hereafter) on the actual market price for pound U_3O_8, while curves denoted by H, K, and T are the price forecasts of Hoomissen[9], Kaiser Engineers[11] and TVA[12] respectively. Hoomissen's forecast is based only upon the balance between the uranium supply and demand, and consists of two curves. The upper curve represents the upper limit with a probability of only 10% or less that the uranium prices will exceed these values, whereas the lower curve denotes a set of prices with a 90% probability that the actual price will be greater than those prices. It is noted that Hoomissen predicts rather lower escalation rate than Kaiser and TVA. This is supposedly ascribed to the fact that Hoomissen did not take into account the inflationary effects of money, which the other two considered. In fact, Kaiser Engineers' and TVA's predictions have assumed 2% of annual inflation rate.

One noteworthy feature of Fig. 1 is that the reported uranium market prices and escalation rates of NEC are substantially higher than the rest of predictions. Considering that the current world uranium reserves can supply the present capacity of the nuclear power plants, it is likely that the psychological impacts of the petroleum crisis are responsible for the high uranium prices. As mentioned above, the petroleum crisis has stimulated the rapid expansion of the nuclear power plants. This then resulted in stimulating the demand for uranium and its stockpile. Also, the crisis has changed the national attitude toward the conservation and diversification of the energy resources, as manifested in the fact that the world uranium market has changed from the buyer's to the seller's market. As a result, the uranium market sees the provisional supply shortage, and the uranium price will eventually continue to go upward.

It is extremely difficult to predict at what level the uranium price will be stabilized, and when and how the future price behaviour will become. Neverthless, it is prerequisite to establish the uranium price for the fuel cost estimation. To do so, we have made the following assumptions: 1) The uranium price will continue to rise as NEC reports, and reach $28/lb U_3O_8 at the end of this year; 2) After then on, the uranium price will be determined by the balance be-

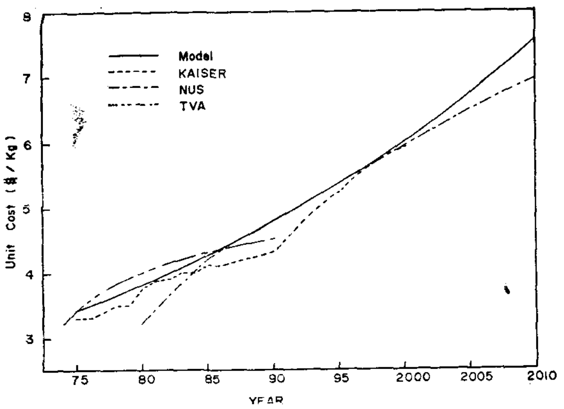

Fig. 2. U_3O_8/UF_6 **Conversion cost**

tween the supply and demand. In other words, it will behave like Hoomissen's upper curve; 3) The annual inflation rate will be 2%. Under these assumptions we obtained the solid curve in Fig. 1 as the reference price model for pound U_3O_8. It is noted that the market prices of NEC fall on the model curve.

(2) U_3O_8/UF_6 conversion

The next process step in the fuel cycle is the conversion of the uranium ore concentrates to uranium hexafluoride, the feed material suitable for the gaseous diffusion enrichment plants. At present the world capacity for the conversion of U_3O_8 to UF_6 amounts to a total of 32,700 Mt/yr7) including the U.S. capacity. This is considered to meet the world conversion requirements for the nuclear power plants currently in operation and planned to operate before 1980.

Fig. 2 shows the projected cost of the UF_6 conversion per Kg U, made by Kaiser, TVA, and NUS13). It is noted that three projections are in the similar cost trend and that the conversion cost is relatively stabilized compared with the other cost components of the fuel cycle. Assuming that the actual conversion cost may lie somewhere in the middle of these projections, we obtained the solid curve of Fig. 2 as the conversion cost model. For this model curve we take the current conversion cost as $3.4/kg U and the annual escalation rate as 2.23%. Our conversion model cost after 1985 appears to be higher than the Kaiser estimations. But our prediction is quite conceivable if the conversion requirments will have absorbed the current production capacity and the new plants are necessarily built.

(3) Enrichment

Currently, the world enrichment services are in the hands of a few countries such as USA, France, USSR and Communist China. The total capacity of the free world is in the order of 18,000 metric tons of SWU per year7). France and Great Britain occupy a small portion of the total capacity. Therefore, it is highly probable that our demand for enrichment services will be heavily dependent upon the enrichment facilities of US Energy Research and Development Administration (ERDA). Accordingly, the enrichment service charges are expected to change in time, following the price policy of ERDA.

According to the recent announcement of US ERDA, the enrichment charges will be 53.35$/kg SWU with 2% escalation rate every six months as of August 20, 1975.

The US ERDA currently operates its three facilities under the split tails policy. Under this policy, the plants are operating with a 0.3% tail assay, while the paper transaction with the customer is based on a 0.2% tail assay. Also, the enrichment of the tail assay will increase to 0.275% as of October 1, 1977, and to 0.3% as of July 1, 1981. In Fig. 3 the ERDA pricing is shown along with the projected enrichment costs of TVA, Kaiser, and NUS. It was observed that the actual

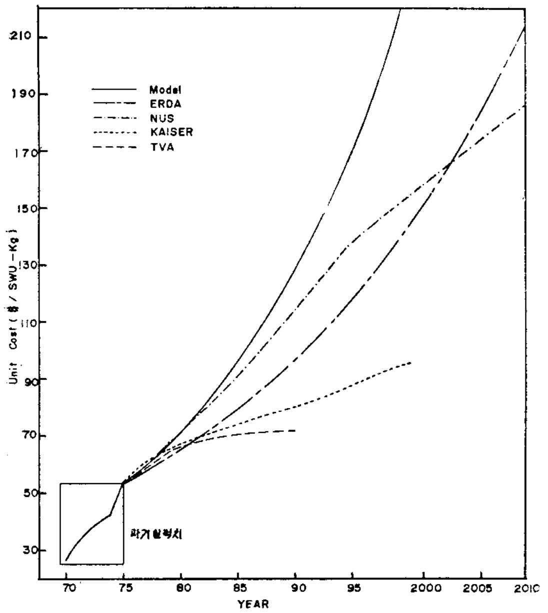

Fig. 3. **Uranium enrichment service charge**

enrichment cost is roughly $8 lower than the ERDA price. For the purpose of comparison we scaled up the projected costs by $8 so that they fall on the current ERDA price. Fig. 3 indicates that the escalation rates in all the projections are similar to each other until 1980, while they differ considerably after 1980. In particular, Kaiser and TVA predict a slow increase in the enrichment cost. On the other hand, the NUS data show that the current escalation rate is annually 6%, 2% higher than the value of ERDA, and that it is diminished to 4% after 1980.

There are many reasons to believe that the enrichment cost will be ever increasing from now on with the higher escalation rate than ERDA policy. Firstly, there is an indication that the annual demand for the uranium enrichment in the free world will range from 30,000 to 40,000 metric tons of SWU by the early 1980's and thereby the existing and currently planned separative work capacity will be nearly absorbed within next ten years. Secondly, in the face of the expected shortage of enrichment capacity, the US private industry shows their interest in constructing the new enrichment facilities. Even though this will alleviate the uncertain situation of the enrichment supply, the privately-owned plant will cost more than the ERDA. Thirdly, in the retrospect of the past USAEC price policy, the annual escalation rates of the enrichment service changes by 2 or 3% higher than announced.

Based on these observations, we assumed that the initial escalation rate, 6%, projected by NUS will prevail throughout the lifetime of the Go-ri plant. The solid curve in Fig. 3 is our model price for enrichment to be used in the fuel cost estimation.

(4) Fabrication

The fuel fabrication plant performs two basic operations; the chemical conversion of UF_6 to UO_2 and fuel pellet production or fuel element fabrication. Currently, most of Nuclear Steam Supply System vendors possess the fabrication plant. Thus the capacity

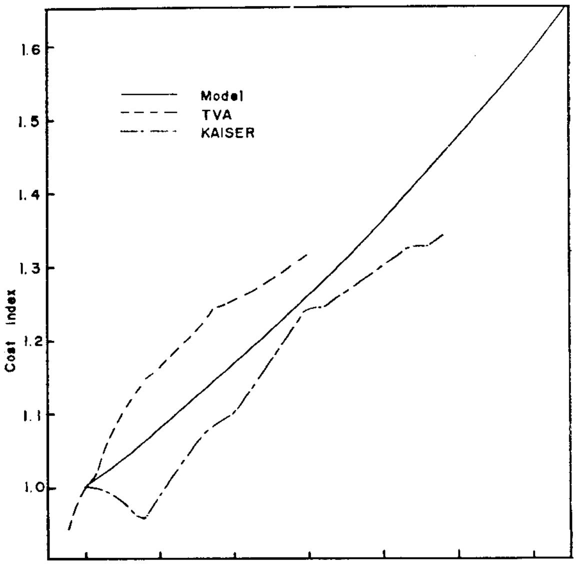

Fig. 4. **Unit cost of fuel fabrication**

problem of the fabrication is less serious, compared with the problems involved in the uranium ore and enrichment services capacity. In addition, since the fabrication technology has ever been improving, the cost reduction in fabrication is expected. Fig. 4 is the fabrication cost data for reload core, which TVA and Kaiser forecast. It is shown that the TVA forecast is higher than the Kaiser's and that kaiser data fluctuate in time. The solid line in Fig. 4 is our model price which is obtained with the assumption that the future fabrication cost may lie in the middle of two forecasts. For the model curve the current fabrication cost is taken as $92/kg U and the annual escalation rate as 1.56%.

(5) Fresh Fuel Shipment

The transportation cost of fresh fuels depends on the transportation area where fuel is supplied. We could not find proper references for the cost of the transportation. The fuel division of KECO[15] considered it to be $4/kg U as of the middle of July, 1974 and to increase with the annual escalation rate, 3.59%. On the other hand, Selak[14] says that the current transportation fee is $5/kg U with the annual escalation rate, 3%. We take Selak prediction in the fuel cost computation. The reason is that the transportation cost represents such a small portion of the total fuel cost that it will not make any differences to which data we use, and these two predictions are very similar to each other.

(B) Economic Data

The capital spent on the preparation of the nuclear fuel is raised by the electric utility in the form of stocks, bonds, and loans. The returns on these investments differ from one form of investment to the other. Therefore, the nuclear fuel costs depend on the financial structure of the capital investments. Table 1 summarize the capital investment structure and rates of returns on investments for the fuels of the Go-ri reactor. Table 1 also lists the types and rates of taxes to be imposed on the Go-ri nuclear fuel. In the fuel cost calculation

Table 1. Economic data

Capital structures		Fraction	Return rate
Initial core	loan	0.9	8%
	bond	0.023	12.5%
	stock	0.077	15%
Reload core	loan	0.7	9%
	bond	0.069	12.5%
	stock	0.231	15%
Tax	Tax rate		
Corporate income tax	27%		
Residence tax	5% of Corporate income tax		
Revenue income tax	5%		
Property tax	2%		
Depreciation method	Unit of energy production		

Table 2. Burnup data

Batch	Sublot	Burnup(MWD/MTU)			
		Period 1	Period 2	Period 3	Period 4
1	1	16244	×	×	×
	2	16244	10400	×	×
2	1	16620	10762	×	×
	2	16620	10762	11800	×
3	1	13720	8900	9770	×
	2	13720	8900	9770	9770
4	1	9750	10710	10710	×
	2	9750	10710	10710	10710
5—23	1	10500	10500	10500	×
	2	10500	10500	10500	10500
24	1	10500	10500	10500	×
25	1	10500	10500	×	×
26	1	10500	×	×	×

we combined the residence tax with the corporate income tax. Thus the effective corporate income tax becomes 28.35% annually.

(C) Plant Operation Data

The Go-ri nuclear power plant unit 1 is based on a 565 MWe Pressurized Water Reactor manufactured by Westinghouse. The overall thermal efficiency of the plant is 32.7%. The reactor core contains a total of 121 fuel assemblies which are allocated to three batches. For the initial core the batch 1 contains 41 fuel assemblies and batches 2 and 3 share equally the rest of 80 assemblies. Each batch is divided into sublots 1 and 2. The number ratio of the sublot 1 fuel assemblies to the sublot 2 fuel assemblies is 40 : 1 for the 1st batch, while it is 39 : 1 for the remaining batches. The fuel management of the Go-ri core follows the out-in refueling scheme in which 40 assemblies are replaced by the fresh fuel at the end of each irradiation period. In this scheme the sublot 2 fuel assemblies remain in the reactor core approximately one year longer than the sublot 1 fuel assemblies.

Table 2 gives the energy data to be produced from the individual fuel batches of the Go-ri reactor core during each irradiation period. The data are provided by the KECO and are obtained under the assumption that the refueling interval is a little longer than one year with 0.125 years' refueling downtime, and the capacity factor is constantly 0.8 throught the plant lifetime. According to US ERDA recommendation, the capacity factor of typical PWR plant is 0.4 for the first year of plant operation, 0.55 for the second year, 0.65 for the third year, 0.75 for periods between the 4th and the 15th years, and 0.02 annual decrease from 0.75 since then.

Table 3. Amount of uranium loaded

Batch	Sublot	Total U(Kg)	Enrichment(w/o)
1	1	16186	2.1
	2	404	2.1
2	1	15707	2.83
	2	403	2.83
3	1	15580	3.2
	2	400	3.2
4—23	1	15707	3.2
	2	403	3.2
24—26	1	16110	3.2

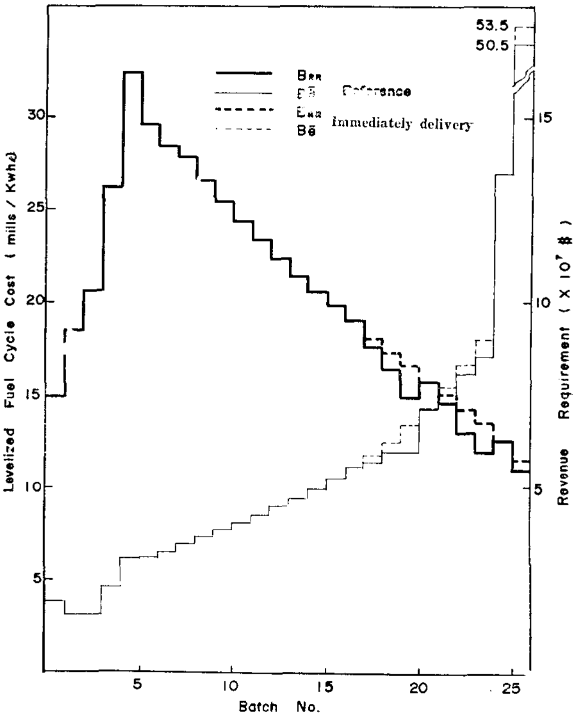

Fig. 5. The levelized unit fuel cost and revenue requirement per batch (reference case and immediate delivery case)

Table 3 shows the amount of uranium material required to load the Go-ri reactor core. The loss factor is assumed to be 0.5%

for the UF_6 conversion from U_3O_8 and 1% for the fabrication process. And the payment lead times are also assumed to be 17 months for U_3O_8 purchase, 15.5 months for conversion, 12.5 months for enrichment, 7.5 months for fabrication, and 2.5 months for fresh fuel shipping. Since we do not consider the reprocessing process of the spent fuel, the uranium recovered from the reprocessing process is not accounted for in this table.

Table 4. The overall fuel cycle costs

Fuel Cycle Elements	Direct Cost (10^4\$)	Present-worth Cost (10^4\$)	%
1. U_3O_8 Purchase	435.7325	143.3808	59.1
2. Conversion(U_3O_8/UF_6)	12.9707	5.0825	2.1
3. Enrichment	202.5120	65.7048	27.1
4. Fabrication	55.4028	27.2309	11.2
5. Shipping(Fresh fuel)	3.2959	1.2163	0.5
Total	709.9139	242.6153	100

* Total Revenue Requirement 2.64602×10^8\$
* The Levelized Unit Fuel Cycle Cost
7.3318 mills/Kwhe
* Electricity Produced
9.794997×10^{10}Kwhe(Direct)
3.608963×10^{10}Kwhe(Present-worthed)

4. Results and Discussions

The numerical results for the fuel cost of Go-ri unit 1 are summarized in Table 4. The overall levelized unit nuclear fuel cost is 7.332 mills/Kwhe. The overall revenue requirement for the twenty-six batches amounts to $\$2.646\times10^8$. These are the present worth value at the scheduled initial operating date of the Go-ri plant, July 1, 1976.

As shown in Table 4, the uranium ore concentrates represent about 59% of the total fuel cycle cost. Next to this comes the enrichment cost occupying 27% of the total. The rest is allocated to the fabrication, the UF_6 conversion, and the fresh fuel shipment in order. This proportion of the fuel cycle element costs is markedly different from the previously known values; 30% in the uranium ore, 25% in the enrichment, and 25% in the fabrication and the like. It is primarily due to the price upswing for the yellowcake and enrichment services since the petroleum crisis. The relatively stable fabrication cost due to the continued development of the fabrication technology is also responsible for this fuel cost allocation.

Table 5 and Fig. 5 show the revenue requirement and the levelized unit fuel cycle cost for the individual batch loaded in the Go-ri reactor core throughout its 30 years' lifetime. Just for convenience' sake, let us divide the 26 batches into three groups; batches 1 to 4, 5 to 24, and 25 to 26. The first group of batches corresponds to the fuel assemblies of the initial core and those of the first refueling. For these batches some of the fuel cycle element cost data are available, since the uranium ore, enrichment and fabrication are already contracted. It is known that the contract prices for the initial core are \$7.94/1b U_3O_8 for the uranium ore, \$36.83/Kg SWU for the enrichment services, and \$178.53/Kg U for the fabrication. For fuels of batch 4 only the uranium ore price is available with the contract price, \$17.55/1b U_3O_8. We used these contract values instead of the model input data discussed in Section 3, and obtained the results given in Tables 4 and 7. It is noted that the levelized unit fuel cost for this group of batches ranges from 3.1 to 3.9 mills/Kwhe for the initial core, and 4.66 mills/Kwhe for the batch 4, which is substantially lower value than the levelized unit fuel cost for the other group of batches. It is also noted that the contribution of the fuel cycle elem-

Table 5. Summary of levelized unit nuclear fuel cost per batch and revenue requirement per batch

Batch No.	Sublot 1		Sublot 2		Batch Aggregates	
	Lev. Cost mills/Kwhe	Rev. Req. $	Lev. Cost mills/Kwhe	Rev. Req. $	Lev. Cost mills/Kwhe	Rev. Req. $
1	3.8713	.727429 E +07	2.5318	.184312 E +06	3.8214	.745860 E +07
2	3.1057	.902710 E +07	2.3194	.234729 E +06	3.0792	.926183 E +07
3	3.1061	.100447 E +08	2.5328	.260842 E +06	3.0884	.103055 E +08
4	4.6565	.127779 E +08	3.6541	.331591 E +06	4.6248	.131095 E +08
5	6.2267	.157747 E +08	4.9375	.409603 E +06	6.1858	161843 E +08
6	6.2518	.144410 E +08	4.6598	.374919 E +06	6.2107	.148160 E +08
7	6.5707	.138360 E +08	5.2100	.359246 E +06	6.5276	.141953 E +08
8	7.0534	.135408 E +08	5.5924	.351558 E +06	7.0071	.138923 E +08
9	7.4081	.129658 E +08	5.8735	.336624 E +06	7.3595	.133025 E +08
10	7.7821	.124175 E +08	6.1701	.322396 E +06	7.7309	.127399 E +08
11	8.1753	.118930 E +08	6.4818	.308773 E +06	8.1216	.122018 E +08
12	8.5900	.113927 E +08	6.8103	.295772 E +06	8.5335	.116884 E +08
13	9.0267	.109147 E +08	7.1597	.283399 E +06	8.9676	.111981 E +08
14	9.4921	.104595 E +08	7.5371	.271643 E +06	9.4302	.107311 E +08
15	10.0015	.100295 E +08	7.9530	.260526 E +06	9.9367	.102900 E +08
16	10.5717	.962384 E +07	8.4211	.250061 E +06	10.5038	.987389 E +07
17	11.1952	.922208 E +07	8.9352	.239724 E +06	11.1239	.946180 E +07
18	11.5404	.857303 E +07	9.2283	.222910 E +06	11.4675	.879594 E +07
19	11.9280	.796193 E +07	9.5594	.207116 E +06	11.8535	.816905 E +07
20	12.0293	.718663 E +07	9.6633	.187036 E +06	11.9551	.737367 E +07
21	14.4319	.768448 E +07	11.6195	.200042 E +06	14.3438	.788453 E +07
22	15.0434	.710676 E +07	12.1433	.185079 E +06	14.9528	.729184 E +07
23	15.3000	.638147 E +07	12.3834	.166246 E +06	15.2090	.654772 E +07
24	16.0781	.604042 E +07			16.0781	.604042 E +07
25	26.9337	.929196 E +07			26.9337	.629196 E +07
26	50.4961	.549764 E +07			50.4961	.549764 E +07
	7.3911	.258358 E +09	5.5039	.624413 E +07	7.3318	.264603 E +09

ent costs to the levelized unit cost is in the different order from that shown in Table 4. The fabrication cost for batches of the initial core is usually found to be higher than that for the refueled batches. In the case of the Go-ri plant, however, the contract price for the fabrication is too much higher. This is why the fabrication cost occupies a rather high proportion of the levelized unit fuel cost, as appeared in Table 7.

The second group of batches corresponds to the equilibrium batches in which the burnup per metric ton of uranium reaches the steady state. In other words, every batch belonging to this group generates the same amount of energy. As a result, the input data become the same except that the fuel cycle element cost increases with a certain escalation rate as assumed in Section 3. Fig. 5 shows the variation of the levelized unit fuel cost and the revenue requirements as a function of batch number. For this

Table 6. Summary of levelized unit nuclear euel cost per period and revenue requirement per period

Period No.	Sublot 1		Sublot 2		Period Aggregates	
	Lev. Cost mills/Kwhe	Rev. Req. $	Lev. Cost mills/Kwhe	Rev. Req. $	Lev. Cost mills/Kwhe	Rev. Req. $
1	3.3787	.178133E+08	2.4562	.329102E+06	3.3558	.181424E+08
2	3.6212	.102771E+08	2.7521	.271716E+06	3.5920	.105488E+08
3	4.7038	.127827E+08	3.3488	.322698E+06	4.6574	.131054E+08
4	5.7047	.145110E+08	4.0499	.345142E+06	5.6510	.148561E+06
5	6.3497	.146243E+08	4.6870	.371130E+06	6.2945	.149954E+08
6	6.6253	.139113E+08	5.1741	.371665E+06	6.5773	.142830E+08
7	7.0107	.134206E+08	5.4082	.354168E+06	6.9577	.137748E+08
8	7.4145	.129401E+08	5.7115	.341002E+06	7.3582	.132812E+08
9	7.7885	.123924E+08	6.0295	.328195E+06	7.7303	.127206E+08
10	8.1824	.118695E+08	6.3340	.314323E+06	8.1213	.121839E+08
11	8.5973	.113700E+08	6.6555	.301112E+06	8.5331	.116711E+08
12	9.0363	.108952E+08	6.9972	.288616E+06	8.9688	.111838E+08
13	9.5068	.104502E+08	7.3650	.276959E+06	9.4360	.107272E+08
14	10.0218	.100296E+08	7.7677	.265940E+06	9.9472	.102956E+08
15	10.5895	.961919E+07	8.2116	.255178E+06	10.5108	.987436E+07
16	11.1024	.912459E+07	8.6344	.242761E+06	11.0208	.936735E+07
17	11.5545	.856236E+07	9.0360	.229071E+06	11.4712	.879143E+07
18	11.8325	.787720E+07	9.3466	.212861E+06	11.7503	.809006E+07
19	12.7964	.762326E+07	10.0176	.204160E+06	12.7044	.782741E+07
20	13.8348	.734391E+07	10.7464	.195149E+06	13.7327	.753906E+07
21	14.9251	.702726E+07	11.4524	.184466E+06	14.8102	.721173E+07
22	15.4789	.648788E+07	12.0487	.128474E+06	15.3938	.661136E+07
23	19.4720	.722586E+07	10.2633	.765317E+06	19.3528	.730239E+07
24	31.1693	.101805E+08	12.3834	.337263E+05	51.0139	.102142E+08
	7.3912	.258359E+09	5.5039	.624415E+07	7.3318	.264604E+09

graph we took the initial operating date the reference time for converting the revenue requirements to the present worth and the beginning of the batch irradiation that for the per-batch levelized unit fuel cost. Also, the effective cost of money is taken 8.941% /yr. This choice of the reference data is responsible for the trend that the revenue requirements decrease steadily in time, while the per-batch levelized unit cost increases in Fig. 5. As a matter of course, if the effective cost of money were less than the escalation rate of the fuel cycle element cost, the revenue requirements would turn out to decrease in time.

The third group of batches are those fuel assemblies which spent the last two years of the plant life in the reactor core. The period during which the batches produce useful energy is shorter than the first two groups of batches. This is why the levelized unit fuel cost for this group of batches becomes higher.

Table 6 and Fig. 6 show the levelized unit

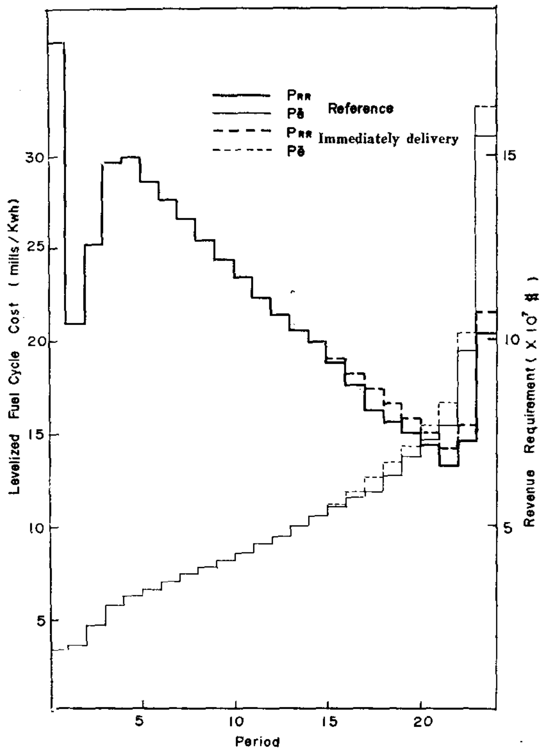

Fig. 6. The levelized unit fuel cost and revenue requirement per period (reference case and immediate delivery case)

Table 7. Fuel cycle costs for initical core (Batch 1, 2 & 3)

Fuel Cycle Elements	Direct Cost (10^6\$)	Present-worthed (10^6\$)	%
1. U_3O_8 Purchase	499. 8184	622. 5462	25. 4
2. Conversion (U_3O_8/UF_6)	60. 3915	75. 2203	3. 1
3. Enrichment	666. 0569	759. 3507	31. 0
4. Fabrication	869. 0991	969. 4308	39. 5
5. Shipping (Fresh fuel)	24. 8404	26. 2344	1. 1
Total	2120. 2063	2452. 7824	100. 1

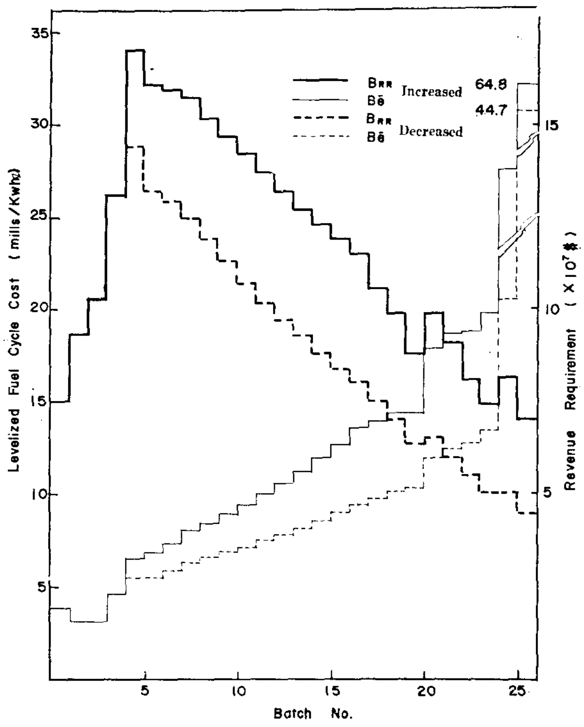

Fig. 7. The levelized unit fuel cost and revenue requirement per batch (±1% change in the escalation rate of the uranium ore cost from the model escalation rate of Fig. 1)

fuel cost per irradiation period. It is noted that the variation of this cost is very similar to the case of the unit cost per batch.

It is fair to say that the model input data we have used hitherto are somewhat uncertain, even though they are the best known values that we can assume. Therefore, we must consider the effect of the uncertain nature of the data on the future fuel cost behaviour by performing the sensitivity calculation to the small variation of the reference input data. In connection with which the important cost components of the fuel price are found to be the uranium ore concentrates and the enrichment services. The capacity factor is also considered to be important, since the fuel prices are strongly affected by this factor. Table 8 is the summary of our sensitivity analysis on the levelized unit fuel cycle cost. In the reference case, we assumed that the unit cost of yellowcake which is required for every 5 years will be fixed under the every 5 years fixed-price contract, after 1990. But, before that time, it is not possible in practice to

Table 8. The levelized fuel cycle costs and revenue requirements for several cases

cases	levelized unit cost (mills/kwhe)	revenue requirement (10^8 $)
Reference	7.3318	2.64602
Uranium immediate delivery case	7.4288	2.68103
Uranium unit cost escalation rate		
1% increase	8.4033	3.03272
1% decrease	6.5101	2.34946
Separative work unit cost escalation rate		
2% increase	7.8178	2.82140
2% decrease	6.9733	2.51664
Capacity factor		
0.05 increase	7.2342	2.77107
0.05 decrease	7.3503	2.45065

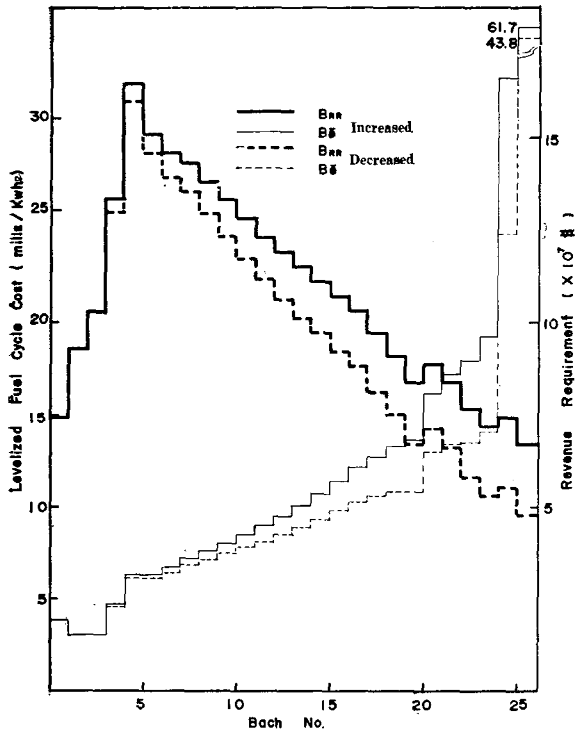

Fig. 8. The levelized unit fuel cost and revenue requirement per batch(±2% change in the escalation rate of separative work charge from the model 6% escalation rate)

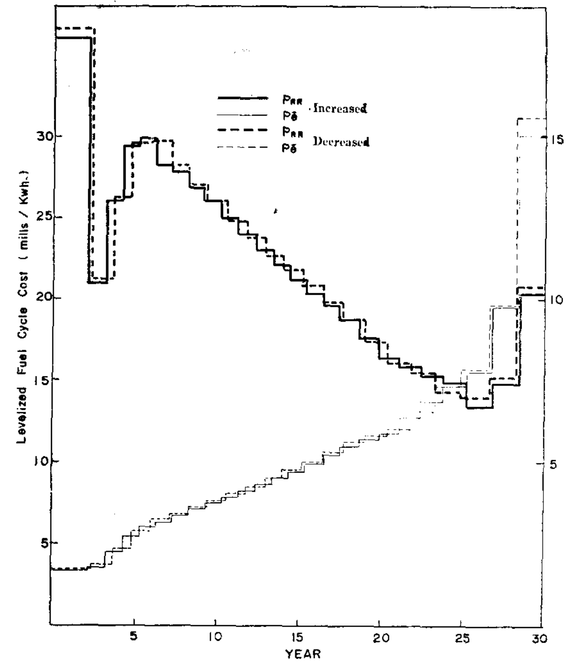

Fig. 9. The levelized unit fuel cost and revenue requirement per year(capacity factor: 0.05 increased and decreased anually over the reference case)

contract with a fixed-price because the uranium market is not stable and is the seller's market.

In Fig. 5 is shown the results of the immediate delivery case, that is, the yellowcake is immediately delivered after contract with the market uranium price at that time. As a matter of course, both the levelized unit fuel cost and revenue requirement are a little higher than those in reference case.

As shown in Fig. 7, ±1% change of the uranium ore price from the model escalation rate gives rise to the changes in levelized unit fuel cycle cost by the amount ranging from 11 to 15%. This simply implies that the uranium ore comprises the main portion of the unit fuel cost. Therefore, in order to produce cheap nuclear electricity, efforts must be made on the economic acquisition of uranium ore. Fig. 8 also indicates that ±2%

fluctuation of the enrichment service charge from 6%, the model escalation rate, resulted in the maximum 8% change in the levelized unit fuel cost. Even though the effect of the enrichment cost changes appears to be less than that of the uranium ore concentrates, the favorable contract of the enrichment service is still important for the economics of the nuclear energy.

Finally, we have investigated the effect of changes of the plant capacity factor. Fig. 9 gives the efffects of the capacity factor change by ±0.05 from the model values. Since we fix the plant lifetime to 30 years, the batches required in the case of the increased capacity are 27, while 24 batches are needed in the case of the decreased capacity. The effect in terms of mills/Kwhe is not large. When the capacity factor is increased by 0.05, the levelized unit fuel cost becomes 7.2342 mills/Kwhe, being 0.0976 mills decreases from the reference 7.3318 mills/Kwhe. On the other hand, the 0.05 decrease in the capacity factor increases the levelized unit fuel cost by 0.0185 mills/Kwhe. When this effect is evaluated throughout the plant life time, this then turn out to be very significant amount of money. Therefore, the continuous and full capacity operation of the Go-ri plant is paramount to produce the cheap nuclear electricity from this plant.

5. Conclusion

We have developed a system of price models for the unit cost of the fuel cycle elements of the Go-ri nuclear power plant. On the basis of this model we have estimated both the levelized unit fuel cost of the plant and the economic sensitivities to the fluctuations in the fuel cost components. It is found that the overall levelized unit fuel cost is 7.332 mills/Kwhe, which is roughly three times that cost prior to the petroleum crisis. It is also found that the uranium ore cost occupies some 60% of the levelized unit cost, while the enrichment service charges account for 27%. This indicates that the uranium ore cost is the most important fuel cost component. The sensitivity calculation also reflects this fact by revealing that the unit fuel cost is strongly affected by the change in the uranium ore price. Therefore, in order to achieve the economic production of the nuclear electricity from the Go-ri plant, efforts must be concentrated on the cheap purchase of this expensive material. To this end we should (1)continue to survey the foreign as well as U.S. uranium markets, and (2) collect information on the transaction prices of the uranium ore. In addition, it is advisable (1) to purchase or contract the uranium ore in quantities sufficient to feed several batches at a fixed price at one time and (2) to participate in the development of the foreign uranium mines.

Unlike the uranium market situation, the enrichment facilities available to us are very limited. Currently, there are some activities to build new enrichment facilities in Europe. However, since the cost projections on these facilities are no more favorable than the US ERDA pricing, our demand for enrichment will be dependent upon the ERDA facilities. Therefore, the fuel cost reduction by a proper choice of enrichment contract dose not look feasible under the present situation.

We have assumed that the fuel cycle of the Go-ri plant is a simple once-through process with no reprocessing. This is based on an assumption that the reprocessing of the spent fuel would not give us any economic benefit for the time being. To investigate the validity of this assumption we are considering a study on the cost-benefit analysis of the spent fuel reprocessing in Korea.

Finally, the capacity factor affects the fuel cost indirectly. Therefore, it is also critical to get rid of accidental shutdowns of the plant and to repair it at an earliest period in the case of unscheduled shutdowns so as to achieve the economic power generation.

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