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Fuel Cost Analysis of CANDU-PHWR Wolsung Nuclear Power Plant Unit 1

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Abstract

Being based on the Segal method, calculation was carried out for the natural uranium nuclear fuel cost with Zircaloy-4 cladding having design parameters of Wolsung Nuclear Power Plant, CANDU-PHWR (Unit 1), currently under construction in Korea aiming at its completion in 1982.

An attempt was also made for the sensitivity analysis of each fuel component; i.e., depreciation of fuel manufacturing plant caused by its life time, its load factor, production scale expansion of plant facilities, variations of construction and operating costs of fuel manufacturing plant, fluctuation of interest rates, extent of uranium ore price increases and effect of learning factor.

요 지

CANDU-PHWR형 원자로인 월성 1호기의 Zircaloy-4 피복 핵연료 설계치를 중심으로 Segel method에 의하며 FACOM 230 OS2/VS 콤퓨터 시스템을 사용하여 핵연료비를 계산하였다.

아울러 핵연료 제조공장의 수명, 가동율, 공장시설 생산규모 증대, 건설비 및 운전비의 변동, 이자율의 변화, 원광가격의 물가상승율, 기술개발인자 등이 핵연료비 계산에 미치는 효과에 대한 민감도를 분석하였다.

I. Introduction

The nuclear fuel design parameters used in this study are quoted from Wolsung Nuclear Power Plant Unit 1[1] (680 MWe of CANDU-PHWR type) now under construction, scheduled for commissioning by 1982. As it was contracted that the fuel for the initial core loading of this Plant was to be supplied by the Canadian vendor, locally produced fuel was assumed to be used herein in early 1984.

There is not many a reference in respect of the fuel cost calculation on CANDU type.

Three factors are largely attributable to this; 1) uranium price of $8/1b range that prevailed prior to the energy crisis in 1973 had relatively negligible impacts on the total generation cost (mills/kWh) of CANDU type using natural uranium as fuel, 2) technical know-how for fuel manufacturing plants and their processing cost were not readily available, and 3) Canada herself abounds in nuclear fuel resources.

But strategization by uranium producing countries of nuclear fuel resources like that of oil led to a drastic increase of the current U_3O_8 cost up to $40/1b[2]. More to the point, in light of the prospect that LWR type is expected to face with undersupply of uranium enrichment capacity in early 1980's[3], more attention is being mounted on the availability of HWR type. Considering the international trends toward limiting uranium exports so as to block the probable intention of using plutonium reprocessed from CANDU reactors for weaponry development by several countries like India, this study must have a considerable significance in working out a way to achieve a self-reliance on nuclear fuel requirement.

Nuclear fuel cost means the total cost ($/kg-U) that the reactor owner has to pay when he buys fuel assemblies from the fabricators for use as a fuel for power reactors. In this study, fuel manufacturing process deals only with the conversion process in which U_3O_8 is procured and processed to UO_2 assemblies. And it omitted reprocess and Pu credit, because spent natural uranium fuel is economically worthy of scarce reuse and is of "once through" only[4].

II. Background

1. Nuclear Fuel Design

The fuel bundle for use in Wolsung-1, as illustrated in Table 1[1], consists of 37 fuel elements around which there are 6, 12 and 18 fuel pieces formed in concentric circle, and is clad with zircaloy-4. It is about 0.5 m long and its uranium weighs 18.5 kg. The amount of fuel replacements required annually is 84 tons of uranium. One advantage of CANDU reactor is that it is possible for fuels to be replaced while reactors are in operation.

NPD Nuclear Power Plant of early CANDU type used a fuel bundle containing only seven fuel elements. Since then, in an effort to upgrade power density and thermal efficiency, a study has been concentrated on the advancement of a fuel design to effect the increase in fuel element numbers and the size of fuel bundles. Power output of the fuel used in NPD was 210 kW/bundle, but Wolsung-1 was designed to have its power output up to 830 kW/bundle, roughly four times that of NPD[5].

Canada's Gentilly-2 which is referred to as Wolsung's reference plant made use of the most advanced design data of CANDU type reactor with a fuel bundle of 37 elements.

The fuel cost assumed in this study is based on the price of early 1984 with the operation of a fuel fabrication plant assumed in the same year. In the calculation of fuel cost was cited a method proposed by W.C. Durunt on fuel fabrication process as reference [6]. The method made available for fabricating fuels for CANDU type is:

1) Reactor owner purchases uranium ores.

2) Uranium ores are reduced to UO_2 powder.

3) UO_2 pellet is loaded into zircaloy sheath tube and bundled up with fuel elements.

4) Fuel bundles are transported from the

Table 1. Design Parameters of CANDU Fuel

Parameters	Wolsung Unit 1[a]	Pickering[b]
Bundle Diameter (mm)	102.4	100
Bundle Length (m)	0.475	0.500
Weight of Uranium (kg-U/Bundle)	18.5	19.7
Number of Elements per Bundle	37	28
Element Sheath OD (mm)	13.08	15.20
Element Sheath Wall (mm)	0.42	0.42
Fuel Pellet OD (mm)	12.2	14.3
Fuel Pellet Length (mm)	16.4	20.9
Fuel Density (g/cm)	10.5	10.6

a. is taken from reference[1)]
b. is taken from reference[7)]

fabrication plant to the site of a nuclear power plant and stored there.

Design parameters of the fuel for Wolsung-1 which is fabricated by means of the process as we have seen above are described in Table 1[1), 7)].

2. Components of Fuel Costs

A fuel cost breaks down into capital cost, operating cost, material cost (including an interest incurred for a period of fabricating fuels attributing to the expenditure for the procurement of U_3O_8 and Zircaloy) and freight on the part of conversion and fabrication plants. Capital cost and operating cost are divided into the two categories of fixed cost and variable cost. Fixed cost corresponds to the item in which the major cost is on the linear cost increase according to the scale of fuel fabrication plant. However, it includes labor cost for plant operators. Variable cost involves the costs on buildings upkeep and equipment, materials, adminstrative staff cost, maintenance cost, and costs on water supply, electricity, steams and other administrative supplies, all of which have negligible effects on the scale of fuel fabrication plant.

2.1. Capital and Operating Cost for Conversion and Fabrication Plant

Capital cost of a plant is the total of buildings and equipment costs. It is subject to be depreciated through plant lifetime. The linear method is applied to the depreciation[8)] based on the normal lifetime of 15 years in respect to buildings and 8 years in case of equipment.

Operating cost consists of the cost relating to labor, O & M, and working capital and other overhead charge. Working capital means the floating capital associated with the purchase of Zircaloy. Uranium ores of nuclear fuel are not the item that fuel fabricators account for.

2.2. Material Cost (including the material purchase-related interest)

Fuel materials needed for CANDU type are essentially uranium ores and Zircaloy. It is a generally accepted practice for reactor owners to buy U_3O_8 and for fuel fabricators to secure Zircaloy. Calculation of material cost has to put into consideration of the irrecoverable material loss allowances that could occur in the process of fuel fabrication. On the other hand, the interest incurred in relation to the procurement of materials is applied in respect to the period in which fuel is fabricated.

2.3. Shipping Cost

Shipping cost means the cost required for the transportation of fuels from the fabricating plant to the site of a nuclear power plant. There is, of course, a difference in the calculation of shipping cost depending on distance and delivery means; however, because of inland transportation, no significant difference cost is expected.

3. Calculation of Fuel Cost

3.1. Capital Cost and Operating Cost

Cost is calculated based on an individual case of conversion and fabrication process, and consists of the two categories, namely, fixed cost and variable cost. Capital cost is a variable cost in which there is no linear cost increase versus the scale of plant capacity. It is made up of construction cost and equipment cost. Given the factor of variable cost as V_n and fixed cost as F_n in respect of an individual conversion and fabricating plant, it is expressed in the formulae (1) and (2)[7].

$$V_n(\$/\text{kg-U})=\frac{1}{M}\times [Bb+Ee+vA(1+\text{U})(1+\text{wt})](1+\text{o}) \quad (1)$$

$$F_n(\$/\text{kg-U})=\frac{1}{M}\times (1-\text{v})A(1+\text{U})(1+\text{wt})(1+\text{o}) \quad (2)$$

where

M: annual plant capacity (kg-U/yr)
B: cost of buildings
b: fractional annual charge rate
Bb: annual capital charge on buildings
E: cost of equipment
e: fractional annual charge rate
Ee: annual capital charge on equipment
v: fraction of variable cost
$1-v$: fraction of fixed cost
A: annual labor cost
U: annual cost of supplies as a fraction of A
w: fractional annual charge rate on working capital
t: processing time as fraction of a year (wks/52wks)
o: overhead fractional charge rate
n: $n=1$, case of conversion plant
$n=2$, case of fabrication plant

As its result, total of the capital and operating cost of each fabrication plant is the total derived from the formula above. As it doesn't put the operating availability of 100% and the annual increase of production capacity into consideration, total C_n of the capital and operating cost in consideration of the two factors is expressed in the formula (3).

$$C_n(\$/\text{kg-U})=\frac{V_n(m)^{-a}}{L}+F_n \cdots\cdots\cdots (3)$$

where,

L: load factor expressed as a fraction
m: ratio of the annual capacity of the new plant to the reference plant
$a \fallingdotseq 0.32$, fuel design constant[9]

3.2. Material Cost

Material cost consists of uranium ore cost, fabrication cost including Zircaloy procurement and the procurement-related interests. In other words, uranium ore cost is expressed as Hore of Formula (4), fabrication cost including zircaloy procurement as Hzr of formula (5) and the procurement-related interest as I of formula (6).

$$\text{Hore}(\$/\text{kg-U})=h_0(1+\text{d})\cdots\cdots\cdots\cdots\cdots (4)$$

$$\text{Hzr}(\$/\text{kg-U})=[h(1+\text{wt})\leftarrow(1+\text{o})\times (1+\text{d})](\text{m})^{-c} \quad (5)$$

$$\text{I}(\$/\text{kg-U})=i[(\text{Hore})t_1+(\text{Hzr})t_2]\cdots (6)$$

where,

h_0: uranium ore cost (\$/kg-U)
h: zircaloy cost (\$/kg-U)
d: fractional irrecoverable loss allowance
$c=0.05$, fuel design constant[9]
i: interest rate
t_1: total processing time (18 wks/52 wks)
t_2: fabrication time (12 wks/52 wks)

Therefore, the total material cost of H which totals formulas (4), (5) and (6), and

Table 2. Financial Assumption in Korea

1. Capital Charges (% per annum)

	Building (b)	Equipment (e)
Return on Investment	10.9	7.9
Depreciation[a]	6.7	12.5
Residence Tax	1.4	1.4
Revenue Tax	0.5	0.5
Property Tax	0.2	0.2
Insurance	0.5	0.5
	20.2	23.0

2. Working Capital Charges[b] (W)

Conversion Process: 14% per annum

Fabrication Process: 13.7% per annum

3. Overhead Charges (O)

Research & Development:	5%
Warranty:	1%
Administation & Marketing:	6%
	12%

4. Interest on Material (U_3O_8 & Zr-4) Purchase (i): 12.6% per annum

a. % Depreciatian per annum $= \dfrac{100\%}{\text{Expected lifetime in years}}$

b. Average value of return on investment + Tax rate + Insurance

is expressed as:

$$H(\$/\text{kg-U}) = \text{Hore} + \text{Hzr} + \text{I}. \quad \cdots\cdots\cdots(7)$$

3.3. Shipping Cost

Shipping cost means the cost required for the transportation of finished products of nuclear fuel (in the form of bundles) from fabrication plant to the site of a nuclear power plant.

$$T(\$/\text{kg-U}). \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(8)$$

Therefore, the total nuclear fuel cost of N which totals formulas (3), (7) and (8) is expressed as:

$$N(\$/\text{kg-U}) = C_n + H + T. \quad \cdots\cdots\cdots\cdots\cdots(9)$$

4. Input Data for Computer Calculation

4.1. Financial Structure and Cost Escalation Rate

4.1.1. Financial Structure

The method used in the calculation of capital cost of fuel fabrication plant was based on the 1972 data of Segel[7], which was subsequently modified to the situation of Korea. In other words, it was assumed that buildings achieve 100% localization, and the cost escalation rate applied used the statistical figures[10] prevailing in Korea. As for equipment and materials, it was premised that its 90% is imported from abroad and the localization is 10%. The cost escalation rate applied was cited from the UN Statistics[11]. As for the financial structure, the financial type[12, 13] of Korea Electric Co. was used as reference.

4.1.2. Cost Escalation Rate

The cost escalation rate by the related field of activity to calculate building cost and operating cost of the fuel fabrication plant is shown in Fig. 1. The actual results previous to 1976 were based on the data of Bank of Korea and UN Statistics[10, 11], respectively, and the future forecasts are the assumed value as against the actual results.

4.2. Capital and Operating Cost of Fuel Fabrication Plant

Each capital cost for the fabrication pro-

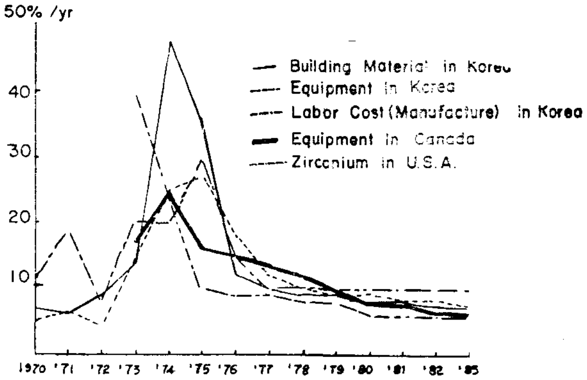

Fig. 1. Trend of Escalation

Table 3. *Cost Estimation for 100 ton-U/Yr Manufacturing Plants in Korea*
Unit: 10^3\$ (Early 1984 dollars)

		Conversion Plant	Fabrication Plant
Capital Cost	Building (B)	978	1.119
	Equipment (E)	2,229	4,604
Annual Labor Cost (A)		247	834

cess was calculated being based on the related escalation rate of Fig. 1, and the financial assumption and the data of manpower requirements in Korea[13, 14], using the value[7] assumed by Segel. The results are shown in Table 3.

On the other hand, most of the operating cost is made up of labor cost, but it includes the cost required for electricity, water and steam supply and office supplies. This cost is called "utility cost" and is expressed as a rate in terms of the personnel cost. And the result is applied to the caculating formula of nuclear fuel cost. The rate of the utility cost represented in the labor cost varies according to the process and is shown in Table 4.

Table 4. Annual Utility Cost as a Fraction of Labor Cost

Process	Fraction of Utility Cost vs. Labor Cost (u)
Conversion	0.20
Fabrication	0.15

4.3. Material Cost

4.3.1. Uranium Ore Cost

Fig. 2 estimates the escalation rate between the past uranium ore cost and the future uranium cost prediction, based on the 1976 price. That is, the cost per pound of U_3O_8 was risen from \$7[16, 17, 18] prior to 1973 to \$40[3, 19] in 1976. On the other hand, the recently published data indicates that the escalation rate of uranium ore is being assumed to be between 4 to 7% annually. The escalation rate after 1976 was quoted from the data prepared by NUEXCO, Union Carbide and KNS, but the base nuclear fuel cost was calculated using NUEXCO data indicating the uranium cost escalation of 6.5% annually.

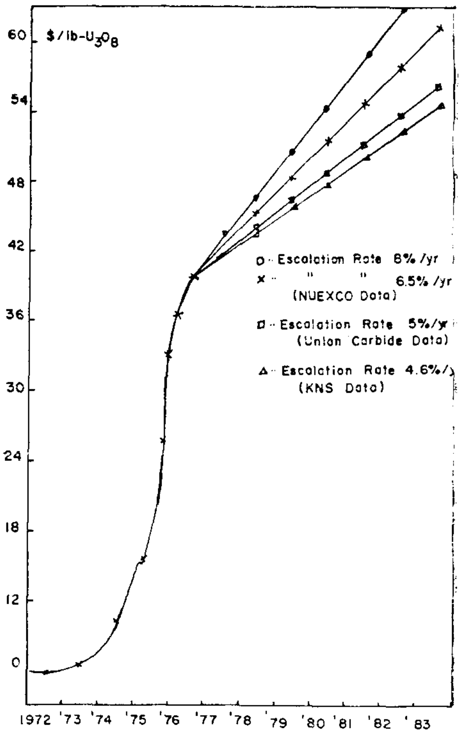

Fig. 2. Trend of Uranium Ore Cost (U_3O_8)

4.3.2. Zircaloy Cost

Zircaloy cost was divided per fabrication processes and calculated using formulas 10, 11 and 12. The fabrication process breakdown consists of tubing end cap and other Zircaloy sheet (end plate, element spacer, bearing pad).

4.3.2.1. Tubing

$$\text{Tubing }(\$/\text{kg-U}) = a'\frac{LN}{W}[(1.12(d_0-t_0)t_0+d_0)]\ (\text{er}). \cdots\cdots (10)$$

where, Tubing: tubing cost ($/kg-U)

$a'=0.229$, constant value of tubing design parameter (value of 1972)

er: escaalation rate

L: length of a element (m)

N: number of elements per bundle

W: weight of uranium per bundle (kg-U/bundle)

d_0: outside diameter of tube (mm)

t_0: wall thickness of the tube (mm)

4.3.2.2. End Caps

$$\text{End Caps }(\$/\text{kg-U}) = \frac{2b'N}{W}d_0(\text{er}). \cdots (11)$$

where, End cap: cost of end caps ($/kg-U)

$b'=0.033$, constant value of end caps design parameter (value of 1972).

4.3.2.3. Other Zircaloy Sheet

$$\text{Other Zircaloy Sheet }(\$/\text{kg-U}) = c'\frac{D^2/L}{W}(\text{er}). \cdots\cdots (12)$$

where, D: bundle diameter (mm)

L: bundle length (m)

c': 4.255×10^{-3}, constant value of design parameter of other zircaloy sheet

The nuclear fuel design cost of Wolsung Unit 1 in Table 1 was calculeted according to the above formulas of (5), (6) and (7) and the results appear in Table 5.

4.4. Other Input Data

In addition to the input data as described above, it must consider the processing time required for the products and the irrecoverable loss allowance of materials that takes place during the fabrication. The resultant estimates were made in Tables 6 and 7.

Table 5. Cost of Zr-4 Material for Wolsung Nuclear Power Plant (h)
(Capacity: 100 ton-U/Yr, Early 1984 dollars)

	Cost ($/kg-U)
Tubing	13.83
End Cap	5.56
Other Zircaloy Sheet	3.84
Total	23.23

Table 6. Processing Time

Process	Elapsed Time (wks)
U_3O_8 to Natural UO_2 (t_1)	6
Fuel Fabrication (from UO_2 Powder to Finished Assembly) and Delivery to Customer's Inventory (t_2)	12

Table 7. Allowance for Irrecoverable Material Loss

Process	% (d)
Zircaloy during Fabrication	5
U_3O_8 during Conversion to UO_2	0.5
UO_2 during Fabrication	0.2

III. Results and Sensitivity Analysis

1. Results

The input data as we have seen above mainly dealing with (1) fuel design parameter, (2) plant financial assumption, (3) cost escalation rate, (4) capital cost, (5) operating cost, (6) material cost, (7) products fabrication period, and (8) loss allowance of materials during their processes was applied to the formula (9) in the preceeding Chapter II and was calculated using FACOM 230 computer system.

The computation of nuclear fuel costs calculated based on the early 1984 price under the assumption of an annual capacity

Table 8. CANDU-PHWR Fuel Costs in Korea (Early 1984 dollars)

Component	Summary (100 ton-U/Yr)	Fuel Cost ($/kg-U)
Conversion	Building Charge is 20.2% of $978,000 (in Tables 2 & 3) Equipment Charge is 23.0% of $2,229,000 (in Tables 2 & 3) Labor Cost is $247,000 (in Table 3)	14.07
Fabrication	Building Charge is 20.2% of $1,119,000 (in Tables 2 & 3) Equipment Charge is 23.0% of $4,604,000 (in Tables 2 & 3) Labor Cost is $834,000 (in Table 3)	28.52
Material (Excluding U_3O_8)	Zircaloy-4 Cost in Table 5. Interest Charge on Value of U_3O_8 and Zircaloy during Manufacturing Process	24.39
Shipping[a]		1.00
Fuel Cost excluding U_3O_8 Purchase Cost (A)		67.98
U_3O_8 Purchase Cost (B)		161.96
Total Fuel Cost (A+B)		229.94

[a] is taken from reference 20) Page 115

of 100 tons of uranium and load factor of 80% is listed in Table 8.

It is indicated in Table 8 that, under the same assumption, an estimate using the same year price puts nuclear fuel costs (without U_3O_8 purchasing cost) at $67.98 per kilogram of uranium, and it amounts to $33.05 if calculated converted into the current price of 1976. It is revealed, however, that the purchasing price of foreign manufactured nuclear fuel on the basis of the 1976 price remains in the range of $35-37 per kilogram of uranium. A comparison between the above two price comparisons is as shown in Fig. 3.

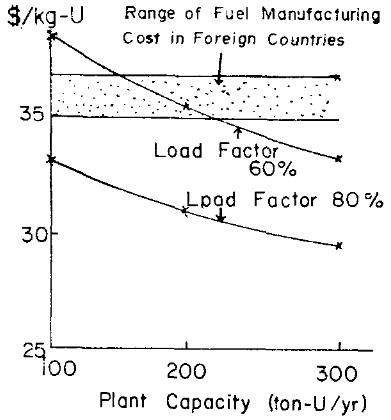

Fig. 3. Sensitivity of Fuel Manufacturing Costs on Plant Capacity at Different Load Factor (1976 dollors)

Fig. 3 also compares the economics between a variational load factor of plant production capacity and the imports of foreign manufactured nuclear fuel. This shows the locally manufactured nuclear fuel (annual capacity: 100 ton-U, load factor: 80%) based on the 1976 price to be cheaper than foreign manufactured by 8~9%.

Twofold or threefold expansion of local facilities is indicative of making it to be cheaper further by 16~20%.

The total nuclear fuel cost of $229.94 per kilogram of uranium as shown in Table 8 breaks down to $161.96 of uranium cost that is equivalent to 70% of the total. Of the fuel costs of $67.98 with uranium cost not including, conversion and fabrication process each accounts for 20.7% and 42.0%, respectively, and the remaining 35.9% is for material cost.

2. Sensitivity Analysis

2.1. Plant Lifetime of Equipment and Building

As shown in Table 8, the base plant lifetime of equipment and building was 15 years and 8 years each. An analysis was made assuming that 5 years of equipment lifetime would be extented to 15 years and 5 years of building lifetime would be also extented to 13 years. The results appears in Table 9.

Table 9. Sensitivity of Fuel manufacturing Costs a to Lifetime of Plant

Lifetime of Plant	Fuel Cost ($/kg-U)	Cummulative Variational Rate (%)
B: 10 yrs, E: 5 yrs	75.26	6.8
B: 15 yrs, E: 8 yrs	67.98	0
B: 20 yrs, E: 10 yrs	65.41	−3.9
B: 20 yrs, E: 13 yrs	63.44	−7.2

a. Without U_3O_8 purchase cost
B: Lifetime of buliding
E: Lifetime of equipment

2.2. Variations of Load Factor

The base fuel cost as shown in Table 8 is the result of calculation of input with the load factor of 80%. But the result of a sensitivity analysis on the variations of fuel manufacturing costs under the assumption of a load factor drop from 100% to 60% is shown in Fig. 4.

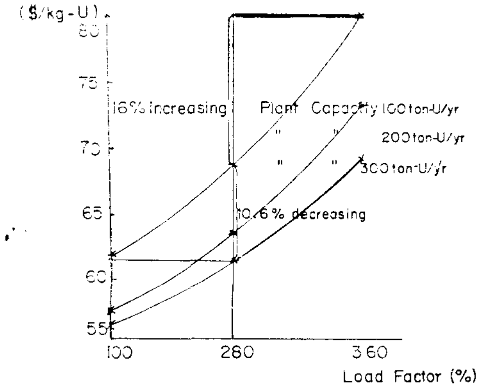

Fig. 4. Sensitivity of Fuel Manufacturing Costs to Load Factor

As pointed out in Fig. 4, variational fuel manufacturing costs of the base load factor within the drop range of 80% to 60% and adversely 80% to 100% resulted in such that the former is greater than the latter. In other words, ideally, increment of the load factor to 100% brings forth the fuel cost reduction against the base fuel manufacturing cost up to only by 10.6%, whereas drop of the same range to 60% yields an increase of cost reduction up to 16%.

2.3. Expansion of Plant Facilities

As shown in Table 8, an annual capacity of fuel fabrication plant that is used in the calculation of the base fuel cost was 100 tons of uranium. But consideration was taken of the facilities expansion of fuel fabrication plant, assuming that the current power plant of CANDU reactor will be enlarged twofold or threefold. That is, fuel manufacturing costs were calculated in each case of an annual production of 200 tons and 300 tons of uranium, and the result is summarized in Fig. 5.

An analysis of the result indicates that upward production scale from 100 tons to 200 tons of uranium per year reduces fuel cost

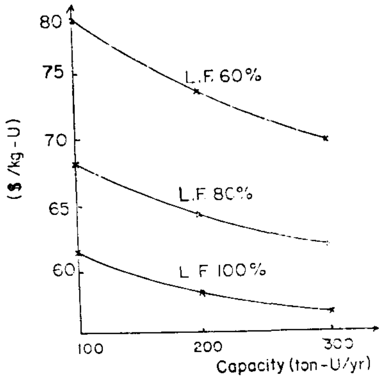

Fig. 5. Sensitivity of Fuel Manufacturing Costs to Plant Capacity

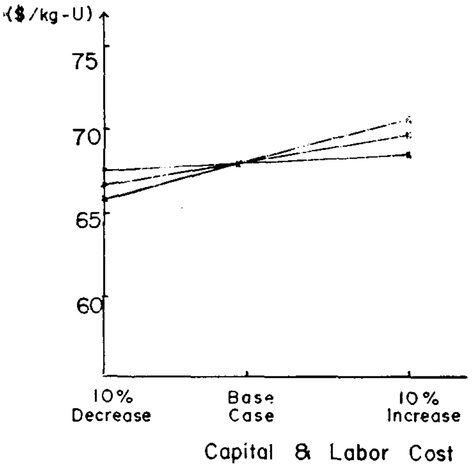

Fig. 6. Sensitivity of Fuel Manufacturing Cost to Capital Cost & Labor Cost

in a relatively wide range. However, such a cost reduction is applicable on the production scale increase from 200 tons to 300 tons. In case of the load factor of 80%, for example, a variational rate from 100 tons to 200 tons reveals 7.2%, but it is only 3.7 % if uranium production scale is upgraded from 200 tons to 300 tons. Thus, it is concluded that the optimum annual production scale is 200 tons of uranium per year.

2.4. Plant Construction and Operating Cost

The input data of construction and operating cost of a fuel fabrication plant against the base fuel costs as shown in Table 8 is based on Table 3. An analysis was made of the input data of costs each upward and downward within the limit of 10%, and the result appears in Fig. 6. In Fig. 6, it is pointed out that some variations of capital and personnel cost don't affect seriously on fuel costs. Rather the importance is that variations of equipment cost in the category of capital cost emphasize a sizeable sensitivity.

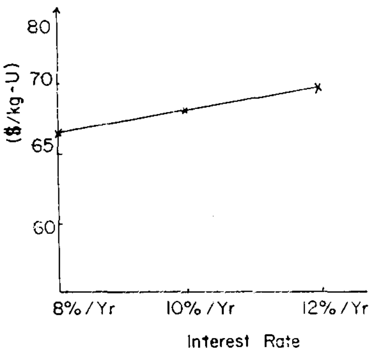

Fig. 7. Sensitivity of Fuel Manufacturing Costs to Interest Rates of Equipment Capital Cost

2.5. Variations of Interest Rates

The interest on a debt (loan) differs between local currency and foreign exchange. The input data in Table 9 apply an interest rate of 12.6% to the local currency and 10% to foreign exchange. In the work of sensitivity analysis herein, fixed rate was applied to the interest rate on local loan and dividend rate on the stocks, whereas a variation was made of an interest on foreign loan. According to the monetary fluctuations of an international balance of payments, an annual interest rate became varied within the limit of 8% to 12%, and the result is given in Fig. 7.

Fig. 7 makes an analysis of the effects, to which extent foreign currency has its sensitivity on fuel costs, because the input in this study assumes that it accounts for 90% of the equipment capital cost. It shows that the actual interest rates available on the introduction of a foreign loan are estimated to be lower than those on the base fuel costs, and this is because that almost all of its current interest rate is less than 10% annually. It is also indicated that, if an annual interest rate is up to 12% that is foreseeable largely due to the adverse inter-

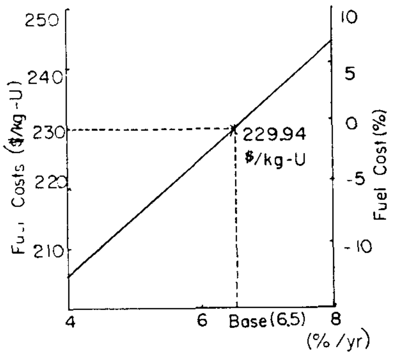

Fig. 8. Sensitivity of Fuel Costs to Escalation Rates of U_3O_8

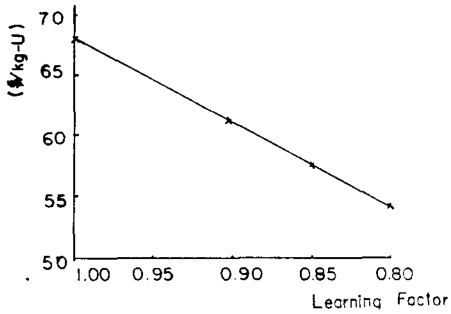

Fig. 9. Sensitivity of Fuel Manufacturing Costs to Learning Factor

national balance of payments, its difference in the range of up to 2% will not affect seriously on the total fuel cost (without purchasing cost of U_3O_8).

2.6. Uranium (U_3O_8) Cost Escalation Rate

There are a few papaers assuming the range of an annual uranium cost escalation rate in the future with the current price of $40/lb as its basis. Two U.S. corporations, namely, Union Carbide and NUEXCO, put this at 5%[19] and 6.5%[20] per annum, respectively, and Korea Nuclear Society estimates it at 4.6%[21]. With the above estimation into consideration an analysis of sensitivity was made between the range of 4~8% per year, and the result of which is illustrated in Fig. 8.

The variations of uranium cost to escalation rate as shown in Fig. 8 have too much effects on the total fuel cost. Each application of an annual escalation rate of 6.5% and 4% produces a variational rate of up to 12.1% difference in fuel costs, but the absolute value amounts to approximately $25 per kilogram of uranium. It corresponds to about 36% of fuel costs amounting to $67.98 per kilogram of uranium not including uranium ore cost. We have already seen that securing of uranium ore is of the uttermost importance as it accounts for 70 % of the total fuel costs indicated in Table 8. Therefore, the importance is once again emphasized that an escalational adjustment of uranium cost affects too heavily on the cost sensitivity.

2.7. Learning Factor

Generally speaking, this is the technical accumulation of production experience, mass production capability through code standardization and the development of technology that is most sensitive in effecting cost reduction. These elements are called "learning factor ($\leqq 1$)", and fuel cost reductions can be calculated by multiplying it by the fuel costs. For example, Canada set tne 1970 (starting date for fuel fabrication) as the learning factor 1.0, 1975 as 0.78, 1930 as 0.71, 1985 as 0.67 and 1990 as 0.66[7].

The base fuel cost as calculated in Table 8 is the value with the learning factor as 1.0. It is presumed that, considering the current trends of technological capability, development and the operation of a research fuel fabrication facility scheduled for operation in 1979 in Korea, the accumulation of related technology will be achieved starting in early 1984. Therefore, an analysis was made of the sensitivity to the fuel costs applying the learning factor in the range of 1.0 to 0.8, and the result of which is given in Fig. 9.

Fig. 9. stresses the fact as to how it is important to accumulate the technology to achieve through R & D of local fuel fabrication technology and the operation of fuel fabrication facilities for research purposes. The learning factor of 0.9 for 1984 will ensure the reduction of fuel costs (uranium purchasing cost not included) by approximately 13%, and it will be more so if we consider the necessity of fuel fabrication in a large quantity that is expected at the time when another unit of CANDU power reactor is constructed in Korea. Canada having used 0.78 as its learning factor is an appropriate case illustrating the importance of technology development. We will have to make our best to develop the technology so that we can attain the application of a learning factor of up to 0.8 by, at least, 1984.

IV. Conclusions

Calculation was made in this study for the sensitivity of the fuel costs based on the fuel design parameters that are readily available from the heavy water reactor of Wolsung-1 CANDU-PHWR type currently under construction in Korea and, as a result of its sensitivity analysis, the following characteristics have been drawn therefrom:

1. Sound economics is assured when a comparison is made between the base fuel manufacturing cost of $33.05 per kilogram of uranium (the 1976 price without uranium ore) produced by a local fuel fabrication plant (capacity: 100 ton-U/yr and load factor: 80%) and the fuel manufacturing cost of $36 imported from Canada.

2. The factors giving the most sensitive effects to fuel manufacturing costs (without uranium ore cost) emerge through variations of the load factors and increase of production scale. Upgrading of load factors through the acquisition of operating techniques and work input effects will come to much in reducing fuel costs.

3. As an identical reactor type with Wolsung-1 is expected to be further installed, it will have to be that the base capacity of fuel fabrication plant (100 ton-U/yr) be expanded two- or three-folds. It was ascertained that this will enable to make the base fuel manufacturing costs lower by 7% to 10%.

4. Considering the uranium cost which accounts for 70% of the total fuel cost, securing of uranium ore is surfaced as the foremost importance and a variational range of fuel costs extremely depends on an annual escalation rate of uranium costs. Therefore, it is judged that the overriding problem of great importance facing nuclear power projects is "what measures should be taken" and "how to implement them" to ensure the supply of uranium ore.

5. Accumulation of operating experience for fuel fabrication plant, mass fabrication of fuel through code standardization and technology development will lead us to cost reductions progressively lower than the initial fuel costs. An analysis was also made that the application of such a learning factor after the operation of a fuel fabrication plant in Korea is expected to help much in reduce the of fuel costs components. At the same time, the importance of developing related technology must be stressed to the utmost extent.

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