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Fuel Cycle Analysis of Heavy Water-Moderated Reactor System

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Abstract

New conception of batch and period is defined appropriate for the on-power refuelling scheme of a heavy water-moderated reactor. A computer code ("HWRCOST") is developed using nuclear fuel cycle economic equations based on the continuous energy calculation method. The fuel cycle cost of the CANDU-PHW reactor is calculated and sensitivity analyses are performed with variation of uranium ore price, fabrication cost, spent fuel permanent disposal expenses, and capacity fctor.

요 약

중수형 원자력발전소의 가동중에 연료를 재장전하는 특성을 고려하여 새로운 핵연료 batch와 주기의 개념을 설정하고, 연속적인 에너지 계산방법으로 개발하여 핵주기비 계산관계식을 유도하였으며, 이러한 관계식들로서 중수형 원자로에 사용될 수 있는 전자계산기 코드 HWRCOST를 개발하였다. 이 코드로서 현재 우리나라에 건설중인 CANDU-PHWR의 전수명에 걸친 핵연료 주기비를 계산하였고 아울러 우라늄 원광비, 성형 가공비, 사용핵연료 보관처리비 및 발전소 가동율의 변화에 대한 핵연료 주기비의 감응도를 분석하였다.

I. Introduction

This work deals with the development and formation of a nuclear fuel cycle economics computer code entitled "HWRCOST" apt for a heavy water reactor (HWR).

There are several computer codes available at present which are used for computing the nuclear fuel cycle costs of pressurized water reactor(PWR), boiling water reactor (BWR), high temperature gas-cooled reactor (HTGR), and fast breeder reactor(FBR) other than HWR. Typical of thes aree CINCAS[1], FUELCOST[2], REFCO[3], MIT COST-II[4].

The fuel assemblies in the reactor core are firstly divided into several groups called batches or segments. 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 fuel cycle cost per batch. Taking similar steps for a certain irradiation period, the code can also generate the levelized unit nuclear fuel cycle cost per period.

Formerly, the price of uranium concentrates was so cheap before the oil shock that the fuel cost occupied a small portion in power generating cost. In addition, the fuel cost effect on power generating cost in HWR plant was much less than that of other reactor types in general because of the unnecessity of uranium enrichment process. Since HWR system uses natural uranium for its fuel, the value of spent fuel is not economically attractive. Therefore HWR system has to rely on "throw-away" fuel cycle scheme. For the above reasons, an accurate fuel cost calculation was not needed and it was possible to calculate the fuel cycle cost of HWR by using simple equations with rule-of-thumb method.[5] [6]

At present time, however, the nuclear fuel cycle cost of HWR power plant occupies a considerable portion of power generating cost because the prices of uranium ore and other fuel cycle components have increased rapidly.

In order to calculate the fuel cycle cost of HWR more accurately or to perform sensitivity analysis, an attempt should be made to obtain the effect of the variation of input data, i.e., unit cost of each fuel cycle transaction, taxes, interest rate and reactor operation characteristics. Unlike light water reactor(LWR) types, HWR does not have to be shutdown for refuelling operation, and daily refuelling takes place at full power, which is the unique characteristics of HWR type. In using computer codes developed primarily not for HWR, it must be assumed that each batch is subdivided into many groups so that it is made analogous to daily refuelling fuel mass unit to approximate the continuous refuelling method of HWR. But in application of the above method, one has to take it for granted that it requires a lot of computing time and cost for the accurate calculation.

The purpose of this paper is to derive nuclear fuel cycle economic equations related to the characteristics of refuelling method of HWR power plant as well as to computerize it. Those steps involved are as follows:

1) Following the refuelling scheme in HWR, a new conception of batch and period is defined.

2) Continuous energy calculation method is developed.

3) With this new definition on batch and period, economic equations are derived.

4) With the application of these economic equations new computer code "HWRCO ST" is developed.

5) With the "HWRCOST" the fuel cycle costs of a reference CANDU-PHW reactor are calculated and then sensitivity analyses are performed with the variation of uranium ore price, fabrication cost, spent fuel disposal expenses and capacity factor.

Ⅱ. Derivation of Economic Equations.

1. Definition of Batch and Period

A batch typically defined in LWR is a group of fuel assemblies being removed from the reactor during a refuelling period after having charged to the reactor core in the course of the previous refuelling period or as part of the initial fuel load. In this occasion, the group of fuel assemblies normally has the same fuel composition. On the contrary, however, daily on-power refuelling takes place in HWR type so that refuelling is essentially continuous. Therefore, apart from the definition of the conventional batch the concept that a batch is a group of fuel which is loaded to or discharged from the reactor in the course of refuelling period at the same time must be discarded.

If the fuels were irradiated to a uniform average burnup throughout the core, the HWR channel power would be much higher in the inner channels than the outer ones. In order to maintain a constant and steady-state power distribution, the core has to be divided into several radial regions. Typically the HWR core is divided into the inner and outer region. Since the inner region has higher burnup than the outer, refuelling rate of the inner region is faster than that of the outer region. In other words each region has its refuelling rate different from the others.

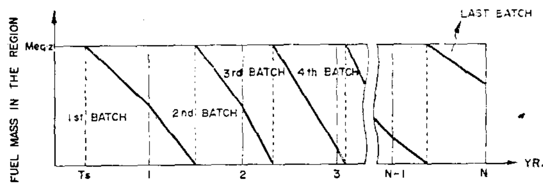
Therefore, as shown in Fig. 1, a batch in each region is defined as below;

1) Initially loaded fuel bundles are defined as the first batch.

2) When the refuelling operation takes place, fresh fuel bundles which are loaded replacing the first batch are defined as the second batch, and the fresh fuel bundles which are loaded from the time when the first batch was all discharged are defined as the third batch, and so on.

3) And the last batch is defined as the fuel which is to be lcaded immediately before the reactor dismantle. Theoretically it would be an ideal case that the fuel bunldes which are loaded earlier will be discharged earlier from the the core.

In practice, however, refuelling begins from the inner region because of its high burnup, and the fuels of some channels in



T_s: First Refuelling Startup Time

N: Reactor Life

Meq. z: Equilvalent Region Fuel Mass

Fig. 1. Definition of Batch

this region are not refuelled until the power rises above the equilibrium value. In order to maintain the uniform reactivity throughout the core, refuelling of some of outer region channels must also take place at the same period of refuelling for inner channels. Due to the decrease in burnup with increasing in radius of outer region channels, the refuelling would tend to proceed generally from inside toward outside.

In addition, all the channels at a given radius are not refuelled at once. Due to the following reasons, some channels in each ring are left for the subsequent cycles; firstly, it is desirable to refuel a channel while the adjacent channels are left for the subequent cycle, because otherwise there is danger of local power peaking; and secondly, it is desirable to have a mixture of different burnups in each ring when equilibrium is reached. The channel missed on the first cycle will be refuelled on the subsequent cycles until the last channls are visited, in such a way that, the degree of burnup among fresh and discharging fuels will be uniformly maintained in each ring. This means that the most burned-up channel is not always subject to undergoing refuelling.

Considering the characteristics of refuelling operation of HWR, the assumption that the fuel bundle loaded earlier will be discharged earlier from the core is reasonable.

In PWR or BWR, the reactor must be shut down during refuelling operations for about one month, but in HWR refuelling operations are carried out continuously with the reactor at power. Therefore, it doesn't need shutdown period for refuelling operation of HWR. In additon, each fuel bundle has different residence time, i. e., different irradiation time, and consequently fuel costs per irradiation period tend to be rather meaningless in HWR. Therefore, accounting period which is typically one year will be chosen, instead of irradiation period, for "per-period" calculations of fuel cycle cost in HWR.

2. Energy Calculation Method

To calculate power generated by a batch, the following assumptions are made for an arbitrary region z:

1) The power generated by a specific batch at time t is the total power being generated at time t multiplied by the fraction of the fuel mass of the specific batch to the total fuel mass of batches which occupy the region z at time t. In other words, this implies that the power generated in an arbitrary region remains constant.

The algebraic expression of the above is

$$P_{z,k}(t)=P_z\frac{M_{z,k}(t)}{\sum\limits_{k=1}^{k} M_{z,k}(t)} \tag{1}$$

where

$P_{z,k}(t)$ = Power being generated by batch k in region z at time t,

$M_{z,k}(t)$ = Fuel mass of batch k in region z at time t,

P_z = Total power being generated by region z (only dependent on capacity factor),

$\sum\limits_{k=1}^{k} M_{z,k}(t)$ = Sum of total fuel mass of batches in the region z at time t,

2) Fuel mass of batch k in region z at time t is a function of refuelling rate and burnup.

Actually the difference between fresh and discharged fuel mass is less than 2% and in equilibrium state the degree of burnup in a region will be uniformly maintaind among the fresh and discharging fuels. Eventually the error bound in the mass of a batch will be reduced to be less than 1%, which means that the mass variation caused by the fuel burnup becomes negligible. Therefore, it is assumed that $M_{z,k}(t)$ is a function of refuelling rate. only Since several refuelling operations are normally carried out daily, refuelling is essentially continuousThe refore, $M_{z,k}(t)$ is approximately expressed by the linear equation,

$$M_{z,k}(t)=at+b,$$

where

a, b=constants determined by the refuelling rate.

3) Total fuel mass of batches which occupies the region at time t is the sum of fuel-mass of batches in the region at time t.

By the assumption that the effect of mass variation caused by the burnup is negligible, the total fuel mass or the number of fuel bundles can be taken as a constant determined by the design.

Then the Equivalent Region Fuel Mass is defined by

$$\sum_{k=1}^{k} M_{z,k}(t)=M_{eq,z} \text{ (constant)}, \qquad (2)$$

where

$M_{eq,z}$=Equivalent region fuel mass of region z.

By the above assumption, the direct energy, $DE_{z,k}$, generated by batch k in region z from time t_s to t_l is defined by

$$DE_{z,k}=\int_{t_s}^{t_l}P_{z,k}(t)\,dt$$
$$=\frac{P_z}{M_{eq,z}}\int_{t_s}^{t_l} M_{z,k}(t)\ dt \qquad (3)$$

It is necessary to obtain the present-worth of the energy before one can calculate the unit cost of fuel. It is convenient in calculating present-worthed energy to use the continuous present-worth factor rather than the discrete present-worth factor or instantaneous present-worth factor, because in Eq. (3) the direct energy is of the integral form.

To obtain the continuous present-worth factor, it is convenient to take a limit in periods used in the discrete present-worth factor in such a way that these periods become shorter. It may be assumed, for example, that a period can be divided by the number of recipt of electrical revenue.

If a period was originally one year, a new period will be 1/M years, where M is the number of the receipt of electrical revenues which can occur daily and there will be Mt periods in the course of t years. Denoting the new rate of interest δ, one obtains the relation between the discrete and the continuous present-worth factor, where x is the interest rate in the discrete present-worth factor and t_R is the reference time.

$$^{-}(1+x)^{(t-t_R)}=\left(1+\frac{\delta}{M}\right)^{-M(t-t_R)} \qquad (4)$$

If M increses indefinitely (*i.e.*, *if* M→∞), then

$$(1+x)^{-(t-t_R)}=\lim_{M\to\infty}\left(1+\frac{\delta}{M}\right)^{-M(t-t_R)} \qquad (5)$$
$$=e^{-\delta(t-t_R)}, \qquad (6)$$

or

$$\delta=\ln(1+x). \qquad (7)$$

Using Eq. (6), the present-worthed energy, $PE_{z,k}$, generated by batch k in region z from time t_s to t_l which is present-worthed to the reference time t_R, has the algebraic form,

$$PE_{z,k}=\frac{P_z}{M_{eq,z}}\int_{s}^{t_l}M_{z,k}(t).\,e^{(t-t_R)}\,dt \qquad (8)$$

3. Derivation of Equations for Fuel Cycle Cost Indices.

One of the most commonly used indices for nuclear fuel is the levelized unit fuel cost per batch, B_{e_k}. The levelized unit nuclear fuel cost per batch is defined[4,9] as that cost which, if charged uniformly for each kilowatt-hour of electricity generated by batch k, could just enable the utility to

1) Pay the required return to those who invested on the batch k based on the outstanding principal of batch k,

2) Pay all the taxes imposed on the batch k, and

3) Reduce the net investment in the 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, B_{e_k} can be shown to be in the form;

$$B_{e_k}=\left[\sum_{q=0}^{Q}\frac{I_{k,q}}{(1+x)^{t_{k,q}-t_R}}+\sum_{l=1}^{L}\frac{\tau_{FR}(PIR_{k,l})-\tau_F(C_{k,l}+D_{k,l})}{(1+x)^{t_{k,l}-t_R}}\right] \Big/ \left[\sum_{i=1}^{I}\frac{0.001(E_{k,i})}{(1+x)^{t_{k,i}-t_R}}-\sum_{l=1}^{L}\frac{0.001(\tau_{FR})(E_{k,l})}{(1+x)^{t_{k,l}-t_R}}\right] \tag{9}$$

where

$I_{k,q}$ = Non-tax investment, expense or credit for batch k,

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

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

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

$PIR_{k,n}$ = Post-irradiation fuel credits for batch k not taken as part of the depreciation reserve in period n,

x = Effective cost of money which depends on the financial structure of utility, rate of return on investment, 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,

$t_{k,q}$ = Time when the fuel cycle component costs are paid,

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

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

The running index q is over all fuel cycle payments and credits other than taxes and return to investors. The running index l is over tax periods and a tax period is defined as the period between two successive tax payments. The running index i is over irradiaion periods, where an irradiation periodis defined as the time span between two successive refuelling of each batch.

Because the refuelling operations carried out continuously in HWR, and each fuel bundle has an individual irradiation period, and also because from the utility's point of view it can be assumed that the receipt of electrical revenue occurs daily, the first term of denominator in Eq. (9) cannot be applied to HWR. Therefore, it is reasonable to replace the first term of denominator in Eq. (9) by the Eq. (8) which uses continuous cash flow concept and continuous present-worth factor.

The algebraic expression of the above is

$$\sum_{i=1}^{I} \frac{0.001(E_{z,k,i})}{(1+x)^{t_{z,k,i}-t_R}}$$

$$=0.001\cdot\frac{P_z}{M_{eq\cdot z}}\int_{t_s}^{t_l} M_{z,k}(t)e^{-\delta(t-t_R)}\,dt \qquad (10)$$

where

t_s=the start time of receipt of electrical revenues of batch k

t_l=the last time of receipt of electrical revenues of batch k

Incorporating the above modification, substitution of Eq. (10) into Eq. (9) yields the levelized unit nuclear fuel cycle cost per batch k in the region z, $B_{e_{z,k}}$

$$B_{e_{z,k}}=\Big[\sum_{q=0}^{Q}\frac{I_{z,q,k}}{(1+x)^{t_{z,k,q}-t_R}}$$

$$+\sum_{l=l}^{L}\frac{\tau_{FR}\cdot PIR_{z,k,l}-(C_{z,k,l}-D_{z,k,l})\tau_F}{(1+x)^{t_{z,k,l}-t_R}}\Big]$$

$$/\Big[0.001\cdot\frac{P_z}{M_{eq\cdot z}}\int_{ts}^{tl}M_{z,k}(t)e^{-\delta(t-t_R)}\,dt$$

$$-\sum_{l=1}^{L}\frac{0.001\cdot\tau_{FR}\cdot E_{z,k,l}}{(1+x)^{t_{z,k,l}-t_R}}\Big] \qquad (11)$$

The revenue requirement per batch in region z, $B_{RR_{z,k}}$ is defined as the sum of money which, if received at the reference time, would just enable the utility to pay out all the money spent on the batch k in the region z and reduce the net investment in the batch k in the region z by an appropriate amount so as to allow the net investment in the batch k in the region z to go to zero when the last cash flow pertaining to the batch k in the region z has occured. This quantity is given by

$$B_{RR_{z,k}}=B_{e_{z,k}}\cdot 0.001\cdot\frac{P_z}{M_{eq\cdot z}}\int_{t_s}^{t_l}M_{z,k}(t)e^{-\delta(t-t_R)}\,dt \qquad (12)$$

The definition of levelized unit nuclear fuel cost per period and the revenue requirement per period are analogous to their "per-batch" counterparts. In Section (II. 1) accounting period was chosen instead of irradiation period. We may write the revenue requirement of the entire region per period, P_{RR_i}, as

$$P_{RR_i}=\sum_{z=1}^{Z}\sum_{k=1}^{K}0.001\cdot B_{e_{z,k}}$$

$$\times\frac{P_z}{M_{eq\cdot z}}\int_i M_{z,k}(t)e^{-\delta(t-t_R)}\,dt \qquad (13)$$

The running index k is over all batches which reside in the region during period i, and the running index z is over all regions which reside in the reactor core.

Also P_{RR_i} can be expressed as below;

$$P_{RR_i}=P_{ei}\sum_{z=1}^{Z}\sum_{k=1}^{K}0.001$$

$$\times\frac{P_z}{M_{eq\cdot z}}\int_i M_{z,k}(t)e^{-\delta(t-t_R)}\,dt \qquad (14)$$

The levelized unit nuclear fuel cost of entire core per period, P_{e_i}, is given by combining Eq. (13) and (14):

$$P_{e_i}=\Big[\sum_{z=1}^{Z}\sum_{k=1}^{K}0.001\cdot B_{e_{z,k}}\cdot\frac{P_z}{M_{eq\cdot z}}$$

$$\times\int_i M_{z,k}(t)e^{-\delta(t-t_R)}\,dt\Big] \qquad (15)$$

$$/\Big[\sum_{z=1}^{Z}\sum_{k=1}^{K}0.001\cdot\frac{P_z}{M_{eq\cdot z}}\int_i M_{z,k}(t)e^{-\delta(t-t_R)}\,dt\Big]$$

III. CANDU-PHW Reactor Cost Analysis

Using the computer code "HWRCOST"

Table 1. Unit cost data (based on 1982.0)

Component	Unit Cost	Escalation Rate (%/Yr.)
U_3O_8 (Yellowcake)	58.59$/lb	4.62
Conversion ($U_3O_8 \rightarrow UO_2$)	4.58$/kg	2.23
Fabrication	50.50$/kg	1.56
Fresh Fuel Shipping	7.94$/kg	3.00
Spent Fuel Disposal	80.99$/kg	3.00

Table 2. Input data for sensitivity analysis

Item	Input Data	
	10% Confidence	90% Confidence
U_3O_8 ($/lb)	47.36	70.24
Fabrication ($/kg)	46.05	55.32
Spent Fuel Disposal ($/kg)	45.60	139.50
Capacity Factor	0.05 Increased 0.05 Decreased	

Table 3. Lead and lag time

Component	Lead Time (Yr.)	Lag Time (Yr.)
U_3O_8 (Yellowcake)	1.750	—
Conversion ($U_3O_8 \rightarrow UO_2$)	1.625	—
Fabrication	1.125	—
Fresh Fuel Shipping	0.625	—
Spent Fuel Disposal	—	10.000

Table 4. Separative work parameters

Unit Separative Work Cost	104.71$/kg
Escalation Rate	6.00%/Yr.
Tails Assay	0.30%
Lead Time	1.0417 Yr.

developed for this work, cost analysis is carried out for the CANDU-PHW reactor[7] which is now under construction in Korea and scheduled to startup in early 1982.

1. Input

(a) Unit Cost of Fuel Cycle Component

The fuel cycle of HWR takes "throw-away" system. Therefore, the fuel cycle consists of U_3O_8 Purchase, Conversion ($U_3O_8 \rightarrow UO_2$), Fabrication, Fresh Fuel Shipping, and Spent Fuel Disposal.

Table 1 shows the reference unit cost of fuel cycle components from J.S. Kim, et al.[9] entitled "Probabilistic Analysis of Fuel Cycle Strategy in Korea". In that paper they forecast the data set of fuel cycle component using probability concept which is based on the unit cost prediction of many previous papers.

Table 2 shows the data for sensitivity analysis from J.S. Kim, et al. Herein "90% Confidence" and "10% Confidence" means that the probabilities the cost will be less than the data are 90% and 10% respectively.

Since the CANDU-PHW reactor uses depleted fuel for the initial loading, it is necessary to calculate the unit separative work cost. The data which are referenced from the SWUCO[10] for this are shown in Table 4.

(b) Economic Data

Table 5 shows the capital structure related to the nuclear fuel of CANDU-PHW reactor and describes tax rates.

In practical calculation, loan and bond can be treated identically, so the total fraction of loan and bond is 0.925 and its weighted interest rate is 10.88%/Yr.

At present, Corporate Income Tax rate is 27%/Yr., but in case of nuclear power plant this tax is exempt from taxation. Besides Corporate Income Tax, Defense Tax and Residence Tax which are 25% and 5% of Corporate Income Tax respectively are levied on fuel. Since this taxation law is temporary, we assume it to be 35%/Yr. as average tax

Table 5. Economic data

Capital Structure	
Loan Fraction	0.626
Interest Rate	0.101
Bond Fraction	0.299
Interest rate	0.125
Stock Fraction	0.075
Earning Rate	0.150
Tax	**Fraction**
Corporate Income Tax	0.2700
Defence Tax	0.0675
Residence Tax	0.0135
Property Tax	0.0000
Revenue Income Tax	0.0000

rate over the reactor life.

(c) **Fuel and Oper ating Data**

The equilibrium fuel management data of the reference CANDU-PHW reactor are shown in Table 6. The reference fuel cycle schedule with the capacity factor 1.0 is shown in Table 7.

On the basis of Table 7, sample calculations are carried out with the assumption that the capacity factor for the first year is 0.45, the sencond year 0.6, third year 0.7 from fourth to the fifteenth year 0.8 and from the sixteenth to the thirty year, it decreases 0.02 annually from 0.8. This assumption is 0.05 higher than the reference capacity factor of LWR recommended from USERDA[11], because there is no reactor shutdown period for refuelling in HWR.

It can be assumed that the sum of energy generated from an arbitrary batch is constant in spite of the capacity factor being in inverse proportion to the irradiation period. Therefore, the "HWRCOST" is designed to accomodate this variation of the capacity factor with the data in Table 7.

Table 6. Equilibrium fuel management data

Fission power	2180MW
Thermal power	2061MW
Thermal efficiency	0.2844
Number of channels	380
Number of bundles per channel	12
Number of fresh bundles per channel per fuelling cycle	8
Weight of uranium in fuel bundle 37 element fuel	18.5kg
Average core burnup	180MWH/kg+

Fuelling Parameters	Inner Region	Outer Region
Number of channels	124	256
Fraction of power	0.383	0.617
Region averaged burnup (MWH/kg)	203	168
Feed rate (kg/EFPD*)	99	192
Feed rate (bundles/EFPD)	5.3	10.4
Refuelling rate (channels/EFPD)	0.67	1.29
Burnup rate ((MWH/kg) EFPD)	0.71	0.54
Maximum bundle discharge burnup (MWH/kg)	260	190
Average channel dwell time (EFPD)	186	198
Average residence time (EFPD)	279	297
Total feed rate (kg/EFPD)		291
Total feed rate (bundles/EFPD)		15.7
Total refuelling rate (channel/EFPD)		1.96

+ This number and numbers derived from it are accurate to $\pm 10\%$.
* EFPD means equivalent full power day.

Table 7. Reference fuel cycle schedule

* Assumed station capacity factor:	1.0
* Time from station startup to; first refuelling	119 days
* Initial load;	296 depleted bundles (0.54% U_{235}) 4264 natural bundles.

Table 7. Reference fuel cycle schedules (continued)

Year of Operation	Bundles Discharged					
	Number		Initial Weight, kgU		Final Weight, kgU	
	Inner	Outer	Inner	Outer	Inner	Outer
First	1,456	2,824	26,791	51,959	26,355	51,134
Second	2,069	4,011	38,273	74,227	37,849	73,401
Third	1,932	3,748	35,722	69,279	35,296	68,454
Equil.	1,952	3,786	36,147	70,104	35,723	69,279

Table 8. Overall direct and discounted costs in reference CANDU-PHW reactor

Component	Cost ($\times 10^8$\$)		Fraction of total discounted cost for this component
	Direct	Discounted	
U_3O_8 (Yellowcake)	6.41414	2.60506	0.6426
Conversion	0.13927	0.06282	0.0155
Fabrication	1.40836	0.63384	0.1564
Fresh Fuel Shipping	0.27303	0.11059	0.0273
Spent Fuel Disposal	4.02125	0.63686	0.1571
Depleted Uranium	0.00419	0.00489	0.0012
Total	12.26024	4.05406	1.0000

Table 9. Comparision between the overall discounted costs for fuel cycle component of PWR* and CANDU-PHWR

Component	Discounted Costs ($\times 10^6$\$)		Fraction of Total Discounted Costs for this Component	
	PWR	HWR	PWR	HWR
U_3O_8 (Yellowcake)	369.976	260.506	0.6382	0.6426
Conversion	8.889	6.282	0.0153	0.0155
Separative Work	155.308	—	0.2679	—
Fabrication	29.990	63.384	0.0517	0.1564
Fresh Fuel Shipping	2.258	11.059	0.0039	0.0273
Spent Fuel Shipping	30.464	—	0.0526	—
Reprocessing	141.404	—	0.2439	—
Spent Fuel Disposal	—	63.686	—	0.1571
Reconversion	1.700	—	0.0029	—
Uranium Credit	−78.146	—	−0.1348	—
Plutonium Credit	−82.119	—	−0.1417	—
Depleted Uranium	—	0.489	—	0.0012
Total	579.724	405.406	1.0000	1.0000

* PWR; 600MWe, Uranium recycle case, operation starts in 1982.0

* HWR; No reprocessing

Table 10. **Levelized unit nuclear fuel cycle cost per batch and revenue requirement per batch in inner region (reference case)**

Batch No.	$B_{e_{I,k}}$ (mills/KWH)	$B_{RR_{I,k}}$ ($\times 10^6$\$)
1	6.174	7.196
2	5.442	7.952
3	6.155	7.590
4	6.039	7.298
5	6.282	7.053
6	6.523	6.810
7	6.756	6.579
8	6.998	6.357
9	7.250	6.143
10	7.513	5.936
11	7.785	5.738
12	8.068	5.546
13	8.362	5.362
14	8.668	5.184
15	8.986	5.012
16	9.321	4.846
17	9.685	4.686
18	10.073	4.527
19	10.489	4.369
20	10.935	4.212
21	11.417	4.057
22	11.937	3.903
23	12.565	3.769
24	13.184	3.616
25	13.864	3.463
26	14.618	3.312
27	15.523	3.175
28	20.682	3.042
29	91.964	0.996
	8.061 (average)	147.73 (total)

Table 11. **Levelized unit nuclear fuel cycle cost per batch and revenue requirement per batch in outer region (reference case)**

Batch No.	$B_{e_{O,k}}$ (mills/KWH)	$B_{RR_{O,k}}$ ($\times 10^6$\$)
1	8.472	16.626
2	6.700	16.514
3	7.445	15.707
4	7.360	15.076
5	7.694	14.527
6	7.992	13.993
7	8.292	13.483
8	8.608	12.994
9	8.936	12.524
10	9.227	12.073
11	9.633	11.640
12	10.003	11.224
13	10.389	10.824
14	10.791	10.439
15	11.214	10.068
16	11.677	9.711
17	12.172	9.357
18	12.705	9.008
19	13.281	8.662
20	13.906	8.319
21	14.658	8.018
22	15.402	7.678
23	16.226	7.342
24	17.216	7.040
25	18.236	6.704
26	20.439	6.423
27	56.316	4.181
	9.828 (average)	290.15 (total)

2. Results and Discussion

The results for the fuel cost of the reference CANDU-PHW reactor are summarized in Table 8. The overall levelized unit nuclear fuel cycle cost turns out to be 9.151 mills/KWH. The overall revenue requirement for the 29 batches of the inner region and 27 batches of the outer region amounts to 4.3788 $\times 10^8$\$. These are the present-worthed values at the scheduled initial operating date of the reference CANDU-PHW reactor, January

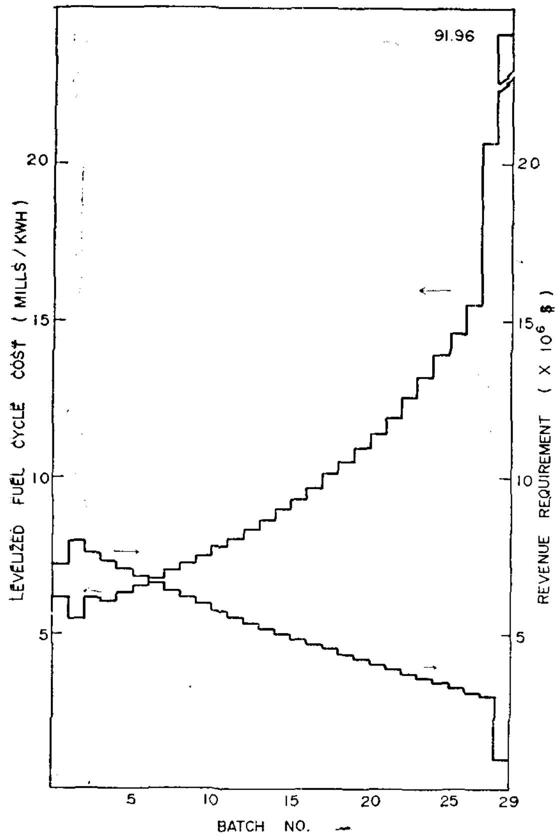


Fig. 2. The Levelized Unit Fuel Cost and Revenue Requirement per Batch in Inner Region (Reference Case)

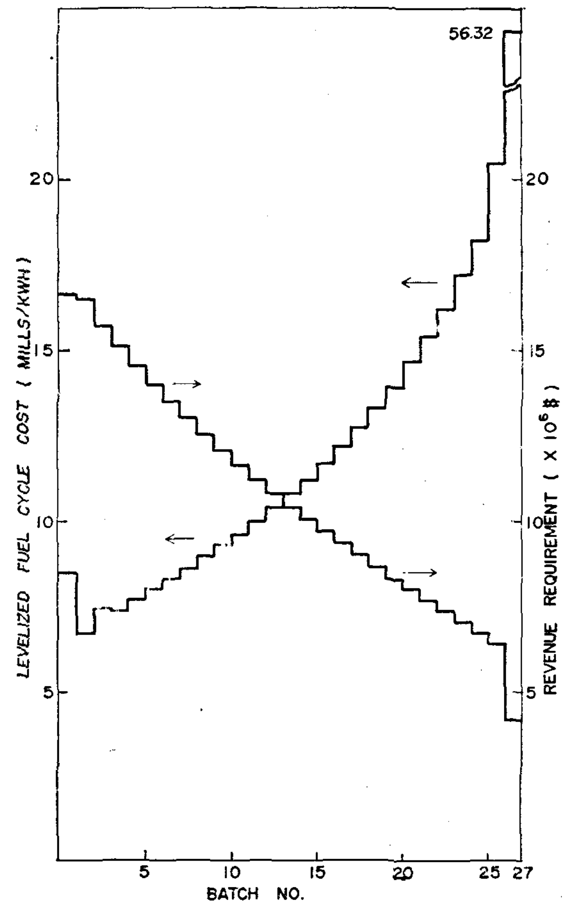


Fig. 3. Levelized Unit Fuel Cost and Revenue Requirement per Batch in Outer Region (Reference Case)

1, 1982.

As shown in Table 8, the uranium ore concentrates represent about 64% of the total fuel cycle cost. Next to this comes the spent fuel disposal cost occupying 16% of the total. The fabrication cost occupies 14% of the total and the rest is allocated to fresh fuel shipping, UO_2 conversion, and depleted uranium inventory for the first batch in order.

Table 9 shows the comparision between the overall discounted costs for the fuel cycle component of PWR (with uranium recycle case) and HWR assumed to be operable in 1982.0. The proportion of yellowcake purchase in the fuel cycle component for PWR is 50% which is calculated from the discounted cost fraction of yellowcake purchase subtract by that of uranium credit. The proportion of U_3O_8 purchase in the fuel cycle components for HWR is 64% which is 14% larger than for PWR. Therefore we may say that the effect on fuel cycle cost in a HWR due to the increase of U_3O_8 price is more serious than in a PWR.

Table 10, Fig. 2 (Inner region) and Table 11, Fig. 3 (Outer region) show the revenue requirement and the levelized unit nuclear fuel cost for the individual batch loaded in

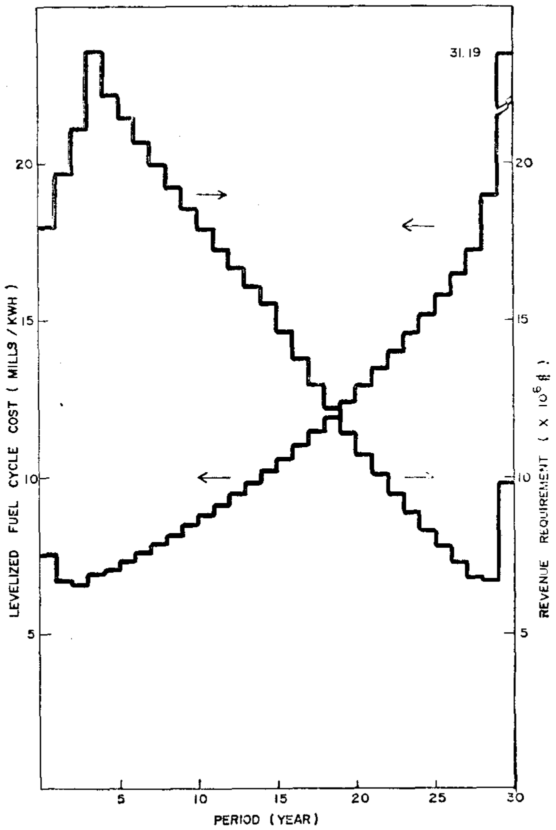


Fig. 4. The Levelized Unit Fuel Cost and Revenue Requirement Per Period (Reference Case)

the CANDU-PHW reactor core throughout its 30 year life time. We consider only the inner region just for convenience's sake, because two regions show identical tendency. Let us divide 29 batches in the inner region into three groups; namely, batches 1 to 5, 6 to 26, and 27 to 29, respectively.

Since the burnup and the residence time of the first batch are smaller than those of others in the first group of batches, its levelized unit nuclear fuel cost becomes higher than that for the second batch. From the second batch, levelized unit nuclear fuel cost increases gradually by the effect of the unit cost escalation of fuel cycle components. But in the fourth batch, the capacity factor increases from 0.6 to 0.7 in the first residence year and in the successive year from 0.7 to 0.8, while this batch is in the core. So the total energy generated by this batch is higher than the third batch.

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 component cost increases with a certain escalation rate as assumed in Table 1. In this group of batches, the increasing rate of the levelized unit nuclear fuel cost is about 4.1%.

We have taken the initial operating date as the reference time for converting the revenue requirements to the present worth and as the beginning of the batch irradiation for the per-batch levelized unit nuclear fuel cost. Also the effective cost of money is taken as 7.626%/Yr. This choice of the reference data is responsible for the trend that the revenue requirements decrease steadily with time, while the per-batch levelized nuclear fuel cost increases as shown in Fig. 2 and Fig. 3. As a matter of course, if the effective cost of money was less than the escalation rate of the fuel cycle component cost, the revenue requirements would turn out to decrease with time.

The third group is those batches which spent the final 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 the reason why the levelized unit nuclear fuel cost for this group of batches increase rapidly.

Table 12. Levelized unit nuclear fuel cycle cost per period and revenue requirement per period (reference case)

Year	P_{e_i} (mills/KWH)	P_{RR_i} ($\times 10^6$\$)
1	7.510	17.953
2	6.638	19.659
3	6.564	21.074
4	6.903	23.533
5	6.992	22.147
6	7.283	21.436
7	7.562	20.679
8	7.846	19.936
9	8.142	19.223
10	8.451	18.537
11	8.773	17.879
12	9.107	17.246
13	9.455	16.637
14	9.818	16.052
15	10.198	15.490
16	10.596	14.582
17	11.016	13.724
18	11.454	12.910
19	11.910	12.135
20	12.384	11.399
21	12.881	10.701
22	13.425	10.058
23	13.996	9.447
24	14.563	8.849
25	15.154	8.279
26	15.798	7.752
27	16.456	7.244
28	17.225	6.794
29	18.964	6.692
30	31.185	9.832
	9.151 (average)	437.88 (total)

In the equilibrium state, the first loading tim e interval between batches is about one year, while the first loading time interval between the first and the second batch is about 0.71 year. As a result the effect of present worth is smaller in the first batch than those in others. Because there is depleted uranium in the first batch, the total sum of fuel component cost is cheaper than the other batches. These two aspects will explain why the revenue requirement of the second batch is larger than the first.

Any average "per-batch" calculation for the entire reactor core is meaningless because of the definition of a batch in this work.

Table 12 and Fig. 4 show the levelized unit nuclear fuel cost and revenue requirement per period. It is noted that the variation of these costs are similar to the case of "per-batch" calculation. The levelized unit nuclear fuel cost of the first and last periods are relatively high because of the fact that the levelized nuclear fuel cost of the first and the last batches exhibit the same trend.

The revenue requirements per period are present-worthed to the time of the initial operating date. The revenue requirements of the first, second and third period are relatively low because the capacity factor is low in these periods. The revenue requirements of the last two periods have relatively high values, because the levelized unit nuclear fuel cost of the last batch is high and affects on the last two periods.

It is fair to say that the model input data being used hitherto are somewhat uncertain, even though they are the best known values so far as we can assume. Therefore, we must consider the effects of uncertain nature of data on the future fuel cost behavior by performing the sensitivity calculation to the small variation of the reference input data.

Table 13. Summary of the variation of levelized unit nuclear fuel costs resulted from changes in individual unit costs and capacity factor

Variables	Input Data		Lev. Cost (mills/KWH)		Changes in P_{ei} per Unit Change in Cost Variable
	10% Conf.	90% Conf.	10% Conf.	90% Conf.	
U_3O_8 ($/lb)	47.36	70.24	8.004	10.342	0.1022 mills/KWH/$/lb
Fabrication ($/kg)	46.05	55.32	9.025	9.289	0.0283 mills/KWH/$/kg
Spent Fuel Disposal ($/kg)	45.60	139.50	8.564	10.123	0.0166 mills/KWH/$/kg
Capacity Factor	0.05 Increased		9.109		0.0497 mills/KWH / 0.05 Inc.
	0.05 Decreased		9.189		0.0329 mills/KWH / 0.05 Dec.

Conf. = Confidence
Inc. = Increased
Dec. = Decreased

It is clear that accurate forecast of the unit cost of fuel cycle components in the future is required if accurate nuclear fuel cycle cost indices are to be obtained.

The result of the effect of varying individual unit cost or capacity factor on levelized unit nuclear fuel cost is shown in Table 13. In changes of levelized unit nuclear fuel cost per unit change in cost variables shown in the last column of Table 13, the effect of U_3O_8 price is the strongest among all other fuel cycle components. This suggests us that an accurate forecast of U_3O_8 price is most essential. The levelized unit nuclear fuel cost of the reference CANDU-PHW reactor will vary between 8.004 mills/KWH and 10.342 mills/KWH.

IV. Conclusion and Recommendations

We have developed a computer code "HW-RCOST", capable of calculating the fuel cycle cost of a Heavy Water Reactor more accurately and reasonably than the conventional method, and have analyzed the fuel cycle of a 600 MWe CANDU-PHW reactor. We have chosen the present-worth cash flow concept as accounting method and defined new batch and period appropriate for a HWR and derived the energy calculation method utilizing the characteristics of on-power refuelling scheme of HWR.

We have estimated both the levelized unit nuclear fuel cost of the plant and the economic sensitivities to the fluctuations in the fuel cycle cost components. It is

Table 14. Comparision between overall discounted cost calculated by HWRCOST and MITCOST-II

Component	HWRCOST	MITCOST-II
U_3O_8 (Yellowcake)	261.129	256.251
Conversion	6.298	6.129
Separative Work	−0.050	−0.049
Fabrication	63.384	61.520
Fresh Fuel Shipping	11.059	10.793
Spent Fuel Disposal	63.686	65.045
Total	405.406	399.689

found that the overall levelized unit nuclear fuel cost without reprocessing is 9.151 mills/KWH, which is 55% of that cost calculated by MITCOST-II for a PWR which is assumed to operate in early 1982.

It is also found that the uranium ore cost occupies some 64% of the revenue requirements. 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 CANDU-PHW reactor, more efforts must be concentrated on the cheap purchase of the uranium ore which could be more expensive for a HWR than for a PWR.

To verify the utility of "HWRCOST", we have calculated the same problem by MITCOST-II. Table 14 shows the comparision between the overall discounted costs calculated by HWRCOST and MITCOST-II and the results are very coincident with each other. The computation was performed by CDC Cyber-72, while the compile time is 13 seconds and the execution time is 8.0 seconds per case, which is about half of those of MITCOST-II.

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References:

1. T.W. Craig, P.J. Fulfor, S.J. McLain and M.C. Edlund, CINCAS, A Nuclear Fuel Cycle Engineering Economy and Accounting Code, Argonne Code Center (1968).

2. N.B. McLeod, FUELCOST, The Calculation of Fuel Costs and Working Capital Requirements in Multi-Batch-Fueled Nuclear Power Reactors, NUS-446 (1968).

3. Royes Salmon, Two Computer Codes (REFCO and POW 76) for Calculating the Fuel Cycle Cost of a Nuclear Power Reactor, ORNL Report ORNL-4675 (1971).

4. Allen G. Croff, MITCOST-II, A Computer Code for Nuclear Fuel Cycle Cost, Thesis, M.I.T. (1974).

5. W.B. Lewis, Appendix I Fueling Cost Evaluation in Outlook for Heavy Water Reactors, AECL-2947 (Sep. 1967).

6. D.S. Craig, Appendix B Calculation of Fuel Cost in Batch Fueling with Organic-Cooled 61-Element Thorium Dioxide, AECL-4271 (Sep. 1972).

7. A.E.C.L. CANDU-PHW Unit 3, PSAR (Feb. 1976).

8. D.R. Vondy, Basis and Certain Features of the Discount Technique in A Comparative Evaluation of Advanced Converters, USAEC Report ORNL-3686 (Jan. 1965).

9. J.S. Kim et al., Probabilistic Analysis of Fuel Cycle Strategy in Korea, Journal of the Korean Nuclear Society, Vol. 8, No. 4 (Dec. 1976).

10. Seprative Work Unit Corporation, SWUCO report, No. 1 (June 1976).

11. USAEC, Nuclear Power Growth 1974-2000 WASH-1139 (74) (1974).