Journal of the Korean Nuclear Society
Volume 8, Number 4, December, 1976

Probabilistic Analysis of Fuel Cycle Strategy in Korea

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(Received September 20, 1976)

Abstract

A statistical approach is employed to investigate the relative advantages of several alternative fuel cycles suitable for a hypothetical 1125 MWe plant in Korea. All the fuel cost parameters are treated as statistical variables, each being associated with an appropriate probability distribution function. Through a random sampling procedure, the probability histograms on both capital requirements and break-even costs of various fuel cycle components are obtained. The histograms are then utilized to quantify the cost-benefit of the fuel cycle with reprocessing or the plutonium recycle over the throw-away cycle.

요　　약

우리나라에서 건설될 가상적인 1125MWe PWR 발전소에 대해 통계적인 방법으로 몇가지 서로 다른 핵주기간의 상호 경제성을 살펴 보았다. 모든 핵연료 파라메타들은 각기 적절한 확률분포함수를 갖고 있는 통계적인 변수로 취급하였고, 무작위 표본 추출 방법으로 요구비용 및 여러가지 핵주기성분에 대한 break-even 코스트들의 히스토그램을 얻었다. 이 히스토그램으로 throw-away 주기에 대한 재처리 및 플루토늄 재장전주기의 cost-benefit를 조사하였다.

1. Introduction

It has long been recognized that the reprocessing of spent fuel and the subsequent recycle of the fissile materials recovered from it would be economically more advantageous than simply throwing it away. Recent economic studies, however, raise some doubts on this due to the price upswing in the reprocessing and related service charges[1,2]. This paper is designed to examine the economics of reprocessing, especially the cost-benefit of reprocessing and plutonium recycle over the throw-away fuel cycle for a typial PWR plant in Korea, For a given nuclear plant, several alternative fuel cycles are optional for the utility. Among many options, a throw-away cycle, a reprocessing cycle, and a reprocessing cycle with plutonium recycle are of current interest to us. The total capital required for each of these cycles differs from one cycle to another, and is used here as a figure of merit for economic comparison. In general, it depends on both the unit price of fuel cycle components and the taxation. The latter contributes indirectly to the total capital requirement and can be determined if the investment structure, rates of returns on investment, tax rates, and depreciation methods of the utility are known[2]. As the case may be, it affects the cost-benefit of one fuel cycle over another. To eliminate such possibility and to make comparison on the basis of the capital spending itself on the fuel, the tax effect is neglected by assuming a zero tax rate.

The computation of capital requirement on a specific fuel cycle requires a set of cost parameters. The market condition of nuclear fuel today, however, makes it very dfficult to prepare a unique set of the reliable cost parameters[4]. Quoted prices for some of fuel cycle components such as yellowcake, reprocessing, shipping, disposal of spent fuel, etc., fluctuate widely in current values. Also, all prices tend to escalate rapidly, yet the long-term projection on the general escalation rates cannot be made with certainty. In addition, The market price of plutonium, which is prerequisite to quantify the cost-benefit of the plutonium recycle, is presently unknown because the plutonium market has not yet been established[3].

As a result, any cost parameter is bound to have uncertainties to a certain extent. This, in turn, leads to a skepticism over the credibility of the computed results, as we see in the cost-benefit study of the nuclear versus the throw-away fuel cycles[6,7]. To circumvent this situation, we adopt here an approach in which all the cost parameters are treated as statistical variables governed by a certain probability distribution function[8]. This approach takes into account the uncertainties of data. Thus the capital requirement as well as the unit price of cycle components is not given by a numerical value with 100% accuracy but by a band of numerical values with probability, thus being given in probability distribution, associated with each of them.

II. Statistic Estimate of the Total Capital Requirement

The total capital requirement for a multi-batch PWR fuel cycle is given by[3],

$$R=\sum_{k,q} M_{k,q}C_{k,q}(1+x)^{t_R-t_{k,q}} \qquad (1)$$

x=effective cost of money,

t_R=reference time,

$t_{k,q}$=time when the payment of each of fuel cycle components occurs,

$M_{k,q}$=fuel mass associated with the fuel cycle component q in batch k,

$C_{k,q}$=unit price of the fuel cycle component q in batch k.

The running index k is over all batches, while the index q is over all the individual cycle components. Thus, for a typical PWR fuel cycle with reprocessing, the sum over q will include the investments on yellowcake conversion, enrichment, fabrication, and fresh fuel shipping in the pre-irradiation period, those on spent fuel shipping, reproceseing, reconversion in the post-irradiation period, along with the credit produced from the recovered fissiles.

The computation of R is made by treating parameters, $M_{k,q}$, $t_{k,q}$, and x as known constant and $C_{k,q}$ as a statistical variable of a certain probability distribution function. In order to determine the distribution function, we took following steps. Suppose that C is the mid-1976 price of a fuel cycle component and that x_i is its projected escalation rate of the ith year, then the price of the nth year, C_n, will become

$$C_n = C\prod_i (1+x_i). \tag{2}$$

In so far as we can assemble the data for C and x_i, they are found to fall on a band of numerical values. Based on this information, we have assumed a normal distribution function for C and x_i centered on the midpoints of the respective band. The exact shape of the distribution function is fitted in such a way that the probability that C or x_i will be less than the lower end value of the respective band or the probability that C or x_i will exceed the upper end value is 10%. Then the computer code NRAND[9], normal distributed random numbers generating subroutine, is employed to determine the probability histograms of C_n and x_i through a random sampling procedure.

For a given batch of fuel, all of the related fuel cycle components are subjected to the random sampling at one time. The set of the sampled price data is then used to compute the total capital spending on the batch. This procedure continued to 500 cases in number, thus generating the probability histograms on both the unit cost of fuel cycle components and the capital requirements.

Table 1. Projected Form of Cost Bexhavior.

Fuel Cycle Components	Basic Equation for Unit Cost
1. U_3O_8 Purchase	$C_n=\{B+(I-D)_n\}\prod_{i=1}^{n}(1+x_1)+S$
2. Conversion	$C_n=C_2\prod_{i=1}^{n}(1+x_2)$
3. Enrichment	$C_n=C_3\prod_{i=1}^{n}(1+x_{4,5})$
4. Fabrication	$C_n=C_4\prod_{i=1}^{n}(1+x_3)$
5. Fresh fuel shipping	$C_n=C_5\prod_{i=1}^{n}(1+x_1)$
6. Spent fuel shipping	$C_n=C_4\prod_{i=1}^{n}(1+x_1)$
7. Reprocessing	$C_n=C_7\prod_{i=1}^{n}(1+x_1)$
8. Reconversion	$C_n=C_8\prod_{i=1}^{n}(1+x_2)$
9. Spent fuel permanent disposal	$C_n=C_9\prod_{i=1}^{n}(1+x_1)$
10. Pu cost	$C_n=C_{10}\prod_{i=1}^{n}(1+x_1)$
11. Fabrication penalty cost	$C_n=pC_4\prod_{i=1}^{n}(1+x_3)$

III. Numerical Results and Discussion

III-1. Unit Cost of Fuel Cycle Components

Table 1 lists the form of equations which are actually used to determine the probability histograms of each fuel cycle component, C_n. As for the price of yellowcake, the equation for C_n differs from Eq. 2. Except for S_n, the form would be the same as that suggested by the GA guide[10]. B represents the 1976 price of the yellowcake and can be estimated by the current cost for milling and mining, exploration, returns on investment, and related taxes. I_n and D_n are called the inflator and deflator, respec-

Table 2. Designation of Cost Parameters and Numerical Values

Random variables	Statisticale variables			Contants	
Item	C_L	C_M	C_H	Item	
x_1: General escalation rate (%/yr)	0	5	10	C_2: Conversion cost ($/kg U)	3.57
x_2: Escalation rate for conversion (%/yr)	0	4	8		
x_3: Escalation rate for fabrication (%/yr)	0	3	6	C_3: Enrichment cost ($/kg SWU)	73
x_4: Escalation rate for enrichment (before 1980) (%/yr)	4	6.74	7.48	C_4: Fabrication cost for initial core ($/kg)	121.79
x_5: Escalation rate for enrichment (after 1980) (%/yr)	2	5	8		
B: U_3O_8 Base Cost ($/lb U_3O_8)	18.23	18.98	19.72	Fabrication cost for reload core ($/kg)	93.37
C_6: Spent fuel shipping base cost ($/kg HM)	71.61	97.69	123.77		
C_7: Reprocessing base cost ($/kg HM)	189.87	300	410.13	C_5: Fresh fuel shipping cost ($/kg)	5.8
C_9: Spent fuel disposal base cost ($/kg HM)	35	52.5	70		
C_{10}: Plutonium base cost ($/gm fissile Pu) (before 1980)	−1	12	25	C_8: Reconversion cost ($/kg U)	6.49
Plutonium base cost ($/gm fissile Pu) (after 1980)	20	30	40		
P: Mixed fuel fabrication penalty (%)	100	200	300		
S: Oil shock effect	24.26	31.98	39.69		

tively. They account for the cost increase or decrease resulting from changes in the ore grade and productivity in uranium mining. The addition of S_n is artificial, but is introduced herein to take into account the abrupt change of uranium cost due to causes other than the above-mentioned, like the previous oil embargo effect[5].

Table 2 shows the numerical values of various parameters which appear in Table 1. The mid-1976 prices for conversion, enrichment, fabrication, and fresh fuel shipping are treated as known constants, since a single numerical value can be assigned to each of them with a relatively high accuracy. The rest of parameters is assumed to be statistical variables, each having an appropriate normal distribution function. For the quoted data of them show the fluctuation within a band of numerical values. In Table 2 are listed the mid-point and two end point values of the band.

For the conversion and fabrication, their escalation rates appear to be lower. This is due to the anticipation in the cost reduction by the improvement of the related technology[11]. The plutonium base cost changes abruptly, turning the of 1980. As mentioned early, its market price is currently unknown. Twelve dollars per gram plutonium is so-called plutonium exchange value[12]. The price is expected to increase in time, being affected by the price increase of the uranium price and realization of Pu recycle in 1980's. This view forms a basis of the proposed plutonium base cost in Table 2.

The histograms in Fig. 1 are representative of probability distributions that the yellowcake will be priced at a specific value in years of 1978, 1983, and 1988. The arrows indicate the best estimate, C_M, the 10% confidence value, C_L, and the 90% confidence value, C_H. They are defined as such values that satisfy.

Table 3. The Unit Price Behaviour of Conversion, Fabrication, Reconversion and Fresh fuel shipping Cost.

	Conversion			Fabrication			Reconversion			Fresh fuel shipping		
	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H
1976	—	3.57	—	—	93.37	—	—	6.49	—	—	5.80	—
1978	3.65	3.86	4.10	97.12	99.26	101.30	6.63	7.02	7.46	5.96	6.41	6.86
1980	3.88	4.19	4.50	102.27	105.23	108.04	7.06	7.62	8.18	6.41	7.07	7.71
1982	4.14	4.51	4.94	107.98	111.54	115.18	7.53	8.20	8.98	6.97	7.77	8.67
1984	4.34	4.90	5.44	113.63	118.28	123.10	7.89	8.90	9.89	7.48	8.50	9.69
1986	4.59	5.21	5.94	119.48	124.91	130.74	8.34	9.47	10.80	7.92	9.31	10.84
1988	4.92	5.64	6.52	126.28	132.99	139.66	8.95	10.26	11.85	8.65	10.17	12.15
1990	5.26	6.13	7.10	133.19	140.74	148.97	9.55	11.14	12.90	9.47	11.33	13.75
1992	5.72	6.62	7.71	141.40	149.65	158.40	10.40	12.03	14.01	10.29	12.50	15.07
1994	6.00	7.17	8.52	148.71	158.86	169.10	10.92	13.04	15.48	11.22	13.87	16.82
1996	6.35	7.75	9.19	156.72	168.76	179.93	11.55	14.09	16.70	12.13	15.02	18.87
1998	6.92	8.31	10.04	166.31	178.39	190.07	12.58	15.10	18.24	13.16	16.69	20.65
2000	7.40	9.00	10.80	175.27	189.93	202.59	13.45	16.36	19.64	14.31	18.51	22.77

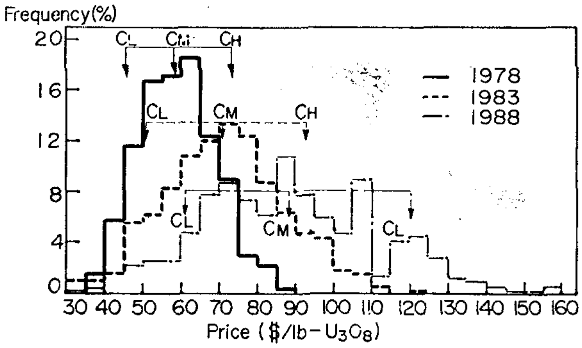

Fig. 1. The Probabilitic Distribution of the Yellowcake Price in the Years of 1978, 1983 and 1988

$$\int_{-\infty}^{C_M} f(x)dx \Big/ \int_{-\infty}^{\infty} f(x)\,dx = 50\%,$$
$$\int_{-\infty}^{C_L} f(x)dx \Big/ \int_{-\infty}^{\infty} f(x)\,dx = 10\%, \qquad (3)$$
$$\int_{-\infty}^{C_H} f(x)dx \Big/ \int_{-\infty}^{\infty} f(x)\,dx = 90\%,$$

Similar histograms are obtained for other fuel cycle components and C_M, C_L and C_H are defined likewise. Figs. 2 to 8, and Table 3 show the projected price behaviour of various fuel cycle components in terms of C_M, C_L, and C_H.

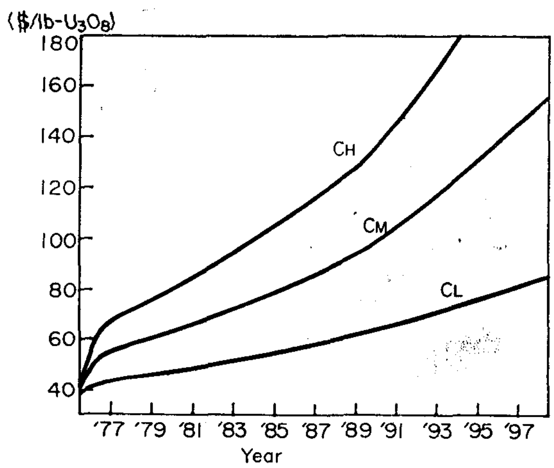

Fig. 2. U_3O_8 Concentrates Cost Estimation

III-2. Cost-Benefit of Reprocessing and Plutonium Recycle

The nuclear power plant considered herein is a 1125 MWe pressurized water reactor. The plant is assumed to start its initial operation on July 1, 1984. Tables 4 and 5

Table 4. Fuel Mass Balance and Average Burnup for Individual Batches

Batch No.	Uranium enrichment (w/o U-235)		Uranium weight (Kg-U)		Fissile plutonium weight (Kg-Pu)		Total plutonium weight (Kg-Pu)		Average burnup (MWD/MTMi)
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	
1	1.7	0.73	30455	29830	—	141	—	201.4	13850
2	2.4	0.70	30455	29401	—	181	—	258.6	25250
3	3.1	0.84	28147	26921	—	187	—	267.1	32700
4	3.3	0.9677	30454	29222	—	204	—	291.4	32570
5	3.2	0.8883	30454	29112	—	203	—	290.0	33120
Batches subsequent to batch 5 have the same data as batch 5 in the case of fuel cycles (I) and (II).									
6	3.2	0.9058	25957	24829	—	173	—	247	32630
	0.711	0.35	4327	4215	129	79	184	113	33600
7	3.2	0.9081	24821	23743	—	165	—	236	32580
	0.711	0.36	5394	5256	171	109	244	155	33600
8	3.2	0.9100	23823	22790	—	158	—	226	32540
	0.711	0.35	6360	6195	193	122	276	174	33600
9	3.2	0.9104	23676	22649	—	157	—	224	32530
	0.711	0.35	6505	6336	196	123	280	176	33600
10	3.2	0.9102	23785	22754	—	158	—	226	32540
	0.711	0.36	6349	6299	195	124	279	177	33600
11	3.2	0.9114	23077	22077	—	153	—	218	32510
	0.71	0.38	7028	6851	237	156	339	223	33600
12	3.2	0.9129	22567	21590	—	150	—	215	32480
	0.711	0.39	7492	7304	262	176	374	251	33600
13	3.2	0.9127	22550	21574	—	150	—	218	32480
	0.711	0.39	7495	7308	268	181	383	255	33600
Batches subsequent to batch 13 have the same data as batch 13 is the case of fuel cycle (III).									

are the mass and energy data, respectively, being provided by the GA Guide[10]. As for the fuel cycle of the plant, three alternative cycles as shown in Fig. 9 are assumed to be optional for the utility. They are (I) a throw-away cycle in which the spent fuel is permanently disposed unreprocessed, (II) a typical PWR fuel with reprocessing, and (III) a reprocessing cycle with plutonium recycle. The latter two cycles, namely (II) and (III) differ from each other in that the recovered fissile materials are only credited in (II), whereas the recovered plutonium is actually self-recycles in cycle (III).

Fig. 10 depicts the probability histograms of the total capital requirements for the above three fuel cycles. The arrows stand for C_M, C_L, and C_H which are defined in Eq. 3. It is noted that considerable portions of histograms overlap with one another. Therefore, the histogram alone does not give us a definite conclusion that one specific fuel cycle is more advantageous than the other ones. In terms of the best estimate, however, the fuel cycle (III) is likely to be the least expensive among three cycles.

Next to this comes reprocessing cycle. Another way to observe this trend is to

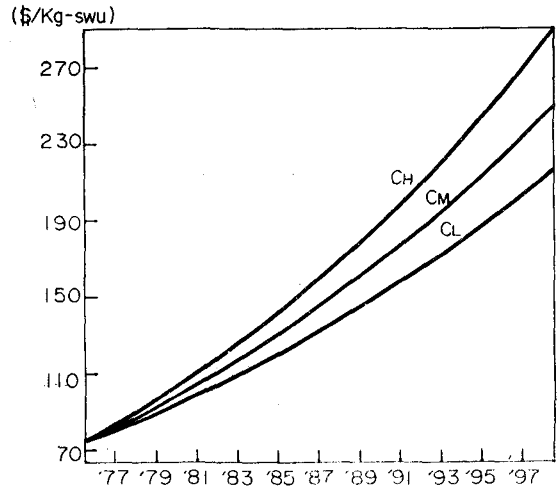

Fig. 3. Enrichment Cost Estimation

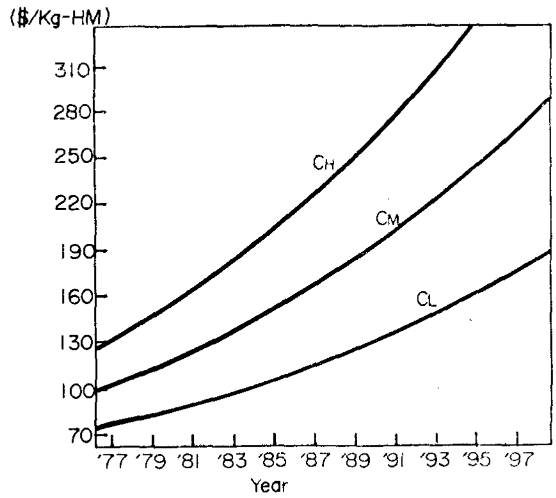

Fig. 4. Spent Fuel Shipping Cost Estimation

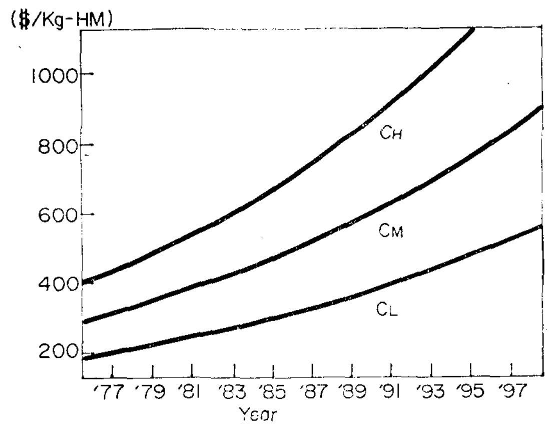

Fig. 5. Reprocessing Cost Estimation

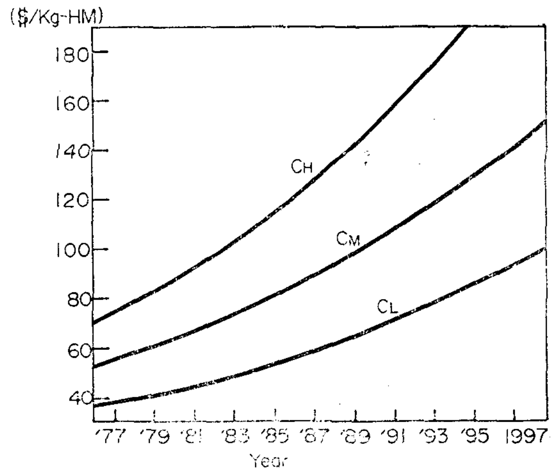

Fig. 6. Permanent Disposal Cost Estimation

draw the probability histogram of the difference of the capital requirements between cycles. For example, Fig. 11 stands for the difference histogram between cycles (I) and (II). The larger area occupied by the positive value of the capital requirement difference implies that cycle (I) is more likely to be costly than cycle (II). Similar comparision between (I) and (III) and that between (II) and (III) are also shown in Fig 11. Thus it is quite probable that Pu-recycle and reprocessing will become more advantageous than the throw-away cycle.

Fig. 12 shows per-batch capital requirement, Br, as a function of the batch number. The upper set of three curves represents the upper limit with a probability of 10% or less that Br will exceed these values whereas the lower set of three curves the lower limit with a probability that Br will be less than values. The middle set of three curves defines the best estimates for Br.

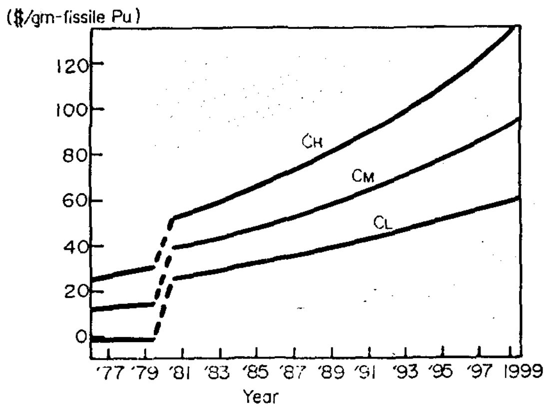

Fig. 7. Plutonium Cost Estimation

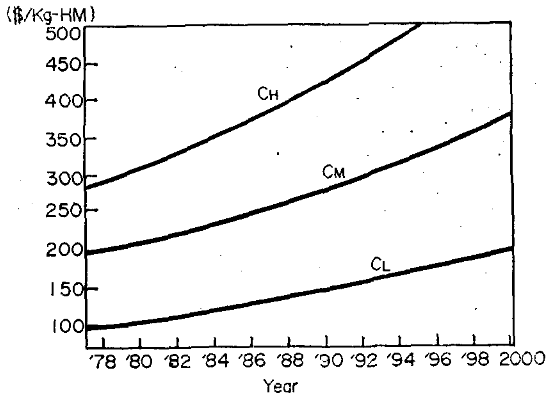

Fig. 8. Fabrication Penalty Cost Estimation

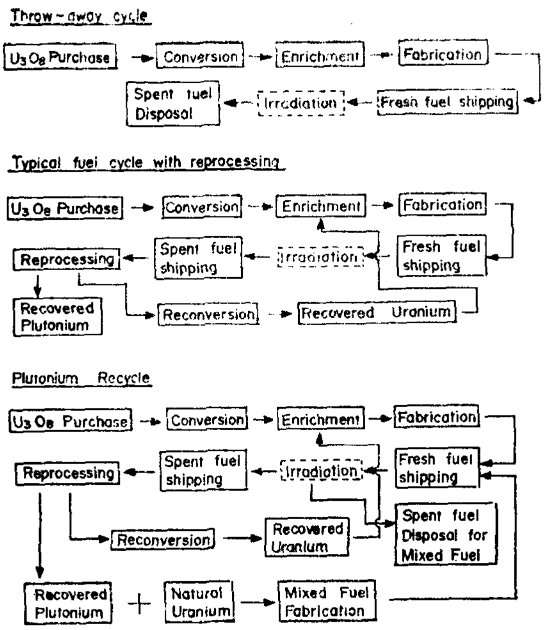

Fig. 9. Alternative Fuel Cycles

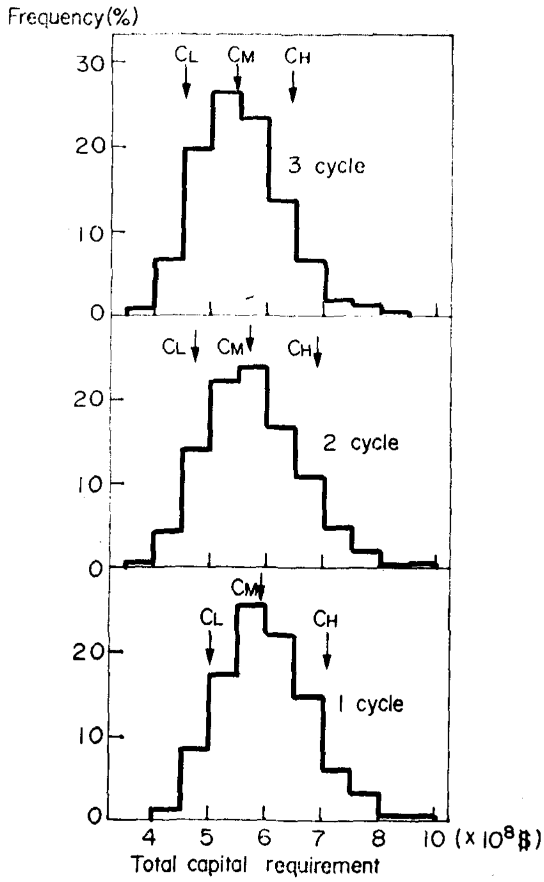

Fig. 10. The Probability Histograms of The Total Capital Requirements

Despite that plutonium recycle appears to be most economical, the per-batch capital requirement for some initial batches 1 to 6 is higher than those in any other cycles. This attributed to the fact that the credits for the plutonium recovered from these batches are not claimed at the moment that they are recovered, since they will be eventually taken into account as the recycling batches. The comparison is also made

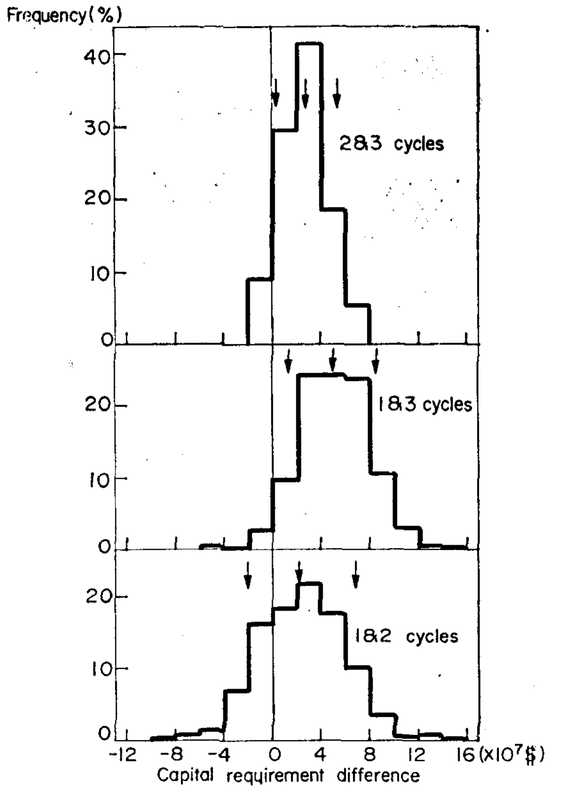

Fig. 11. **The Probabitity Histograms of the Difference of the Tatal Capital Requirement**

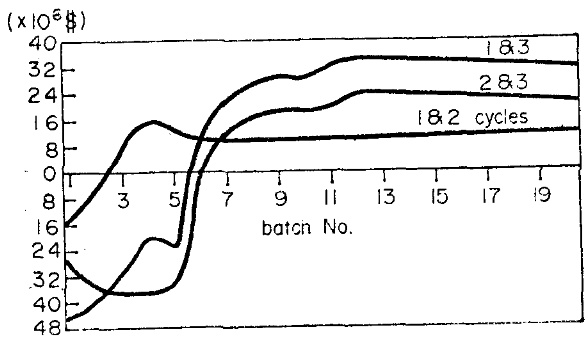

Fig. 13. **The Differences of Per Batch Capital Requirement**

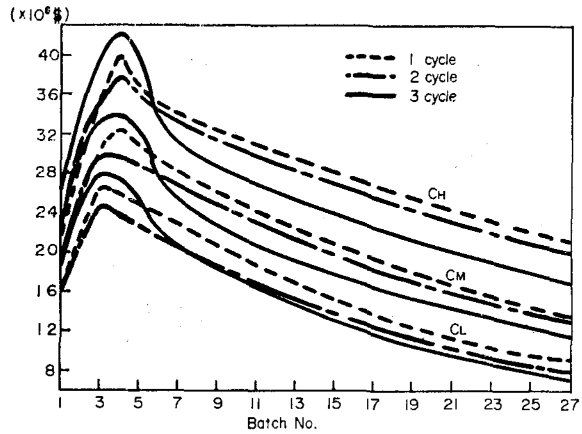

Fig. 12. **Per Batch Capital Requirement**

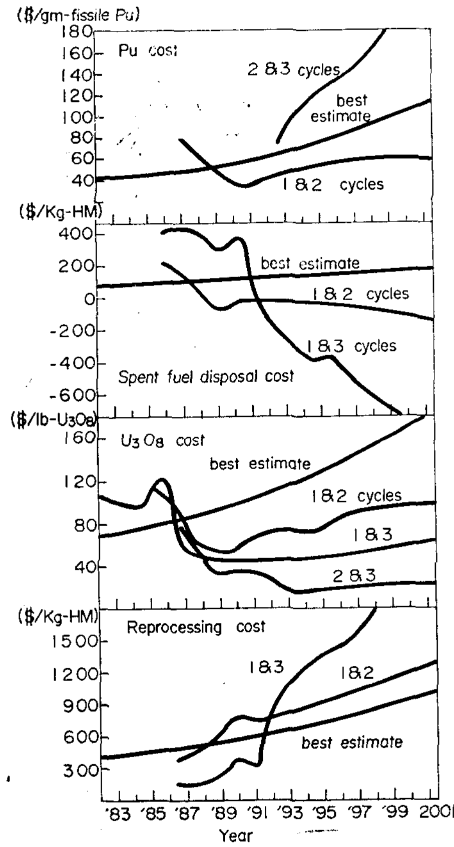

Fig. 14. **The Break-even Costs of Reprocessing, Yellowcake, Spent Fuel Disposal and Plutonium Components**

in Fig. 13 in terms of difference of the per-batch capital requirement between cycles. The cost advantage of reprocessing and plutonium recycle, partcularly starting from batch 7; is again clearly depicted.

In Fig. 14 break-even costs of yellow-

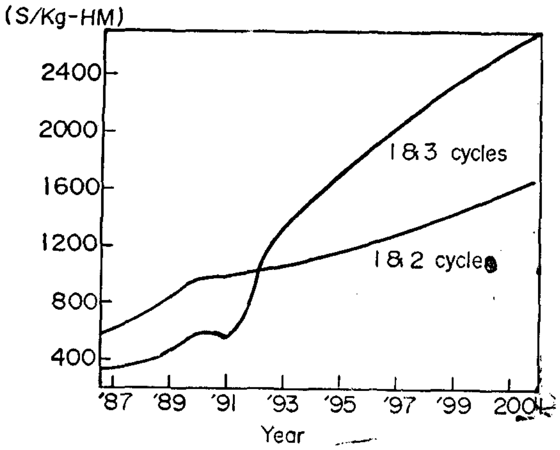

Fig. 15. The Break-even Costs of Grand Reprocessing Component

cake, reprocessing, permanent disposal, and plutonium are compared with their respective best estimates. The break-even costs here refer to as such costs that make the total capital requirements of any two particular cycles being equal to each other. Fig. 14 shows that, in order for the throw-away cycle to be economically comparable with fuel cycles of reprocessing or plutonium recycle, the unit prices of yellowcake, plutonium and permanent disposal must be much lower than that projected by our best estimates. As for the yellowcake, the break-even cost is seen to lie below the 10% confidence value in Fig. 2. Considering the uranium market condition today, the price of yellow-cake below the 10% confidence value is hardly anticipated. It is, therefore, very probable that the utility will gain much from the reprocessing or plutonium recycle, especially in the 1980's.

The break-even cost for the permanent disposal appears to be negative, which implies that, even without the expenses for the permanent disposal of spent fuel, the reprocessing or plutonium recycle can bring forth benefit. The reprocessing break-even cost lies very close to the best estimates. Therefore, it is not derivable with any accuaracy the cost advantage of the reprocessing cycle from the reprocessing service charge alone. To facilitate the utility decision-making on reprocessing versus throw-away, the break-even cost of grand reprocessing including the reprocessing, spent fuel shipping and reconversion penalty is shown in Fig. 15.

4. Conclusion

There has been much talk over the economics of reprocessing or plutonium recycle in the LWR power plant. Some say that reprocessing or plutonium recycle will be economically more advantageous than a throw-away cycle, while others say to the contrary. At first sight the matter appears to be very confusing, yet we found a deficiency in the present method of fuel economics studies. An economics study requires a set of numerical values for various cost parameters. But fluctuations in the current cost and uncertainties in the general escalation rates make it very difficult to assign a single numerical value to each of fuel cost components. Therefore, it is quite conceivable that discrepancies can exist between economic studies, if the studies are based on any single set of cost paramaters.

To avoid such possibility, we proposed here a probabilitic approach. In this approach each cost parameter is presented in terms of the probability distribution function or probability histogram. To be more specific, we computed the probability histograms on unit cost of fuel cycle components and the total capital requirement for three fuel cycles depicted in Fig. 8. It is observed that histograms of the latter overlap with one another. Therefore, a definite conclusion on the cost advantage of reprocessing or plutonium cannot be made from histogram alone. But comparison of expectation value shows that a substantial saving is likely to be achieved by the reprocessing or plutonium recycle. As compared with the throw-away cycle, the reprocessing cycle can save as much as $\$2.33\times10^7$, and the plutonium recycle $\$5.02\times10^7$ over the 30 year project life span of the 1125 MWe PWR plant.

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