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Fuel Cycle Strategy of Go-ri Nuclear Power Plant

—A Statistical Analysis—

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Abstract

An attempt is made to establish an optimum fuel cycle strategy for the Go-ri nuclear power plant units 1 and 2. The total capital required for the fuel cycle operation is selected as a figure of merit for economic comparison of several alternative fuel cycle schemes available for the plant, and evaluated using a probabilistic method coupled with a sampling procedure of the fluctuating fuel cost data. The results are presented in the form of probability histograms. On the basis of the most likely values of the capital requirement obtained from the histograms, a conclusion is drawn that reprocessing cycle with either uranium only or both uranium and plutonium recycled is the most economic choice for the Go-ri plant.

요 약

고리원자력발전소 1호 및 2호기에 대한 최적 핵연료주기를 확립하고자 했다. 고리발전소가 채택할 수 있는 몇가지 핵연료주기의 경제성을 비교하기 위한 기준으로서 개개핵연료주기의 운용에 소요되는 총 요구 비용을 잡았고, 그 요구비용은 핵연료 가격자료의 시세변동을 고려하여 표본추출에 의한 확율적 방법으로 계산하였다. 결과는 핵연료주기 요구비용에 대한 확율분포 히스토그램으로 제시했으며 이 히스토그램에서 얻은 요구비용의 기대치를 근거로 우라늄이나 우라늄과 플루토니움이 모두 재사용되는 재처리주기가 고리발전소의 경우 가장 경제적인 핵주기라는 결론을 얻었다.

Ⅰ. Introduction

The cost parameters of individual fuel cycle components are the basic economic data for the evaluation of nuclear fuel economics. The recent fuel market condition, however, makes it very difficult to prepare a set of widely acceptable cost parameters for fuel economics study not only because market prices of important fuel cycle components such as yellow cake, reprocessing, spent fuel disposal, etc. fluctuate in current values, but also because all prices tend to escalate rapidly, yet long-term projection on their behaviour is not possible with any certainty[1,2] This then led to much controversy and serious skepticism over credibility of fuel cost computations which are based on any single set of cost parameters for fuel cycle components.[2]

In order to get around this shortcoming, we have proposed an alternative approach[4] to fuel cost computations in which all the cost parameters, direct or indirect, are treated as statistical variables associated with a certain probability distribution function and then either the levelized unit fuel cycle cost or the total capital requirement is computed by a random sampling of the cost parameters. The method allows banded numerical values for the unit price of a specific fuel cycle component as raw data. Therefore, it can take into account very naturally fluctuations or uncertainties involved in each of fuel cycle component cost.

This paper is intended for applying this sampling technique to reevaluating several fuel cycle options available for Go-ri nuclear power plant units 1 and 2. What concerns us most is to establish the cheapest fuel cycle scheme for the plant. As is well known, some of contemporary issues left unresolved yet for the plant are the reprocessing and recycling economics of spent fuels. In an endeavor to resolve these issues we here attempt to quantify relative advantages and/or disadantages of the reprocessing cycles over those of a throw-away cycle on a more realistic basis and thus to provide a solid foundation for establishing a suitable fuel cycle strategy for the Go-ri plant.

Table 1. Basic Equations for Cost of Individual Fuel Cycle Component

Fuel Cycle Components	Basic Equation
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	$C_n=C_3\prod_{i=1}^{n}(1+x_3)$
4. Fabrication	$C_n=C_4\prod_{i=1}^{n}(1+x_4)$
5. Fresh fuel shipping	$C_n=C_5\prod_{i=1}^{n}(1+x_1)$
6. Spent fuel shipping	$C_n=C_6\prod_{i=1}^{n}(1+x_1)$
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	$C_n=pC_4\prod_{i=1}^{n}(1+x_3)$

Ⅱ. Description of Computational Procedure

In our previous paper[4] we mentioned that the total capital required for the fuel cycle operation in the entire lifetime of the plant can serve better as a figure of merit for economic comparison of several alternative fuel cycle schemes. For a multi-batch PWR fuel the total capital requirement R is given by

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

$M_{k,q}$ stands for the quantity of fuel or process material associated with the fuel cycle component q in batch k. $C_{k,q}$ denotes the unit price of fuel cycle component q in batch k. $t_{k,q}$ refers to the typical lead and lag times, while t_r a reference time. x is the effective cost of money. These notations

Table 2. Cost Parameters And their Numerical Values

Variable					Fixed Constants		
item	unit	lower bound	middle value	upper bound	item	unit	cost
General Escalation Rate, x_1	%/yr	0	5	10	U_3O_8 Oil Shock Effect, S	\$/lb-U_3O_8	19.9
Esalation Rate for Conversion, x_2	%/yr	0	4	8	Conversion Bast Cost, C_2	\$/kg-U	4
Escalation Rate for Enrichment, x_3	%/yr	2.5	6.5	10.5	Enrichment Base Cost, C_3	\$/kg-SWU	61.3
Escalation Rate for Fabrication, x_4	%/yr	0	3	6	Fresh Fuel Shipping Base Cost C_5	\$/kg-HM	6.24
U_3O_8 Base Cost, B	\$/lb-U_3O_8	15.8	23.1	30.5	Reconversion Base Cost, C_8	\$/kg-U	6.75
Fabrication Base Cost, C_4	\$/kg-U	100	125	150			
Spent Fuel Shipping Base Cost, C_6	\$/kg-HM	77.3	105.5	133.7			
Reprocessing Base Cost, C_7	\$/kg-HM	197	322.5	448			
Spent Fuel Disposal Base Cost, C_9	\$/kg-HM	148	244.5	341			
Plutonium Base Value, C_{10}	\$/gm-Pu	−2	13.5	29			
Fabrication Penalty for Mixed Fuel, P	%	100	200	300			

are the same as defined in ref. 4.

Computation of R basically involves two sampling procequres: one in projecting the future behaviour of the unit cost of individual fuel cycle component $C_{k,q}$ and the other in determining the probability historgam of the total capital requirement R.

Listed in Table 1 are equations to be used for projecting the price trends of individual fuel cycle components. C_n stands for the nth year price of the designated components and is given in terms of its base cost (1977 price) and annual escalation rate. Shown in Table 2 are the numerical values of the latter parameters which in turn are categorized into two groups; fixed constants and variables.

The first group includes 1977 base prices of conversion, enrichment, fresh fuel shipping, and reconversion. These are the parameters for which relatively reliable cost data are available and are treated as known constants throughout this study. The second group of parameters are the ones to which a fixed numerical value can hardly be assigned with any certainty. All we know about them is that they lie somewhere in a band of numerical values. In Table 2 are listed the upper and the lower bounds of these parameters.

Parameters of fixed constants are simply plug numbers in computation of C_n. Variable parameters, however, presents a bit of complication and requires a due treatment in computation procedure. One usual procedure to handle such parameters is a statistical approach. We previously postulated a normal probability distribution function according to which variable parameter can take on a specific numerical value. We then generated the probability histogram for C_n by sampling repeatedly all possible values of the variable parameters.

There has raised an objection as to the choice of the normal distribution function for a realistic probability number. Obviously, the normal distribution function puts more weight on figures in the vicinity of Gaussian center than those lying near two ends, whereas it is priori unknown which figures are more reliable. In view of this objection we postulated an additional probability distribution function, e.g., random distribution for the interval from the lower to the upper bound of variable parameters.

Computations on C_n and R are proceeded through a random sampling procedure via computer codes, NRAND5) and RANF6). For a given batch of fuel, all the fuel cycle component costs are subjeced to a simultaneous random sampling. The set of sampled price data is then used to compute the total capital requirement. The procedure continued to 400 cases in number, thus generating the probability histograms on both the unit price of individual fuel cycle component and the total capital requirement.

Ⅲ. Results and Discussions.

Fuel cycle schemes in interest for the Go-ri plant are (Ⅰ) a throw-away cycle of the spent fuel, (Ⅱ) a typical reprocessing cycle of LWR with uranium only recycled, and (Ⅲ) the reprocessing cycle with both uranium and plutonium recycled. Pu-recycled cycle (Ⅲ) has long been regarded as a very interesting fuel cycle option for LWR plants due to its potential economic benefits. According to the recent US government policy, however, the utilization of recovered plutonium as water-reactor recycling fuel must be waiting for more years to come. As a result, we considered only first two options (Ⅰ) and (Ⅱ) for the Go-ri unit 1, which will go into full power operation at the end of this year. For the unit 2 which is scheduled to start its commercial operation in January 1981, all three options were considered.

Initial core of the Go-ri reactor contains 121 fuel assemblies which are allocated into three batches. Recycled fuels consisting of 40 assemblies are loaded following a typical out-in refueling procedure. Table 3 and 4 summarize the fuel mass balances as well as

Table 3. Fuel Mass Balance and Average Burnup of Go-Ri Unit 1.

Batch	Sub-batch	Uranium Enrichment (w/o U-235)		Uranium Weight (kg U)		Fissile Plutonium Weight (kg Pu)		Total Plutonium Weight (kg Pu)		Average Discharge Burnup (MWD/MTM$_i$)
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	
1	A	2.1	0.9	16,186	15,804	—	81.1	—	103.4	16,244
	B	2.1	0.6	404	395	—	2.0	—	2.6	26,644
2	A	2.83	0.9	15,707	15,123	—	98.4	—	129.0	27,382
	B	2.83	0.6	403	389	—	2.5	—	3.2	39,182
3	A	3.2	0.9	15,580	14,911	—	102.5	—	136.9	32,390
	B	3.2	0.7	400	383	—	2.6	—	3.4	42,160
4	A	3.2	1.0	15,707	15,115	—	102.2	—	134.4	31,170
	B	3.2	0.7	403	387	—	2.6	—	3.4	41,880
5	A	3.2	1.0	15,707	15,050	—	102.2	—	134.4	31,500
	B	3.2	0.7	403	386	—	2.6	—	3.4	42,000

Batches subsequent to batch 5 have the same data as batch 5

Table 4. Fuel Mass Balance and Average Burnup of Go-Ri Unit 2

Batch	Sub-batch	Uranium Enrichment (w/o U-235)		Uranium Weight (kg U)		Fissile Plutonium Weight (kg Pu)		Total Plutonium Weight (kg Pu)		Average Discharge Burnup (MWD/MTM$_i$)
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	
For fuel cycles (Ⅰ) and (Ⅱ)										
1	—	1.80	0.90	17,251	16,938	—	75	—	95	12,100
2	—	2.40	0.80	17,251	16,700	—	100	—	136	23,050
3	—	3.00	0.86	15,197	14,573	—	99	—	138	30,550
4	A	3.29	1.49	2,054	1,992	—	12	—	15	21,700
	B	3.29	0.96	15,197	14,536	—	102	—	141	32,600
5	A	3.29	1.45	2,054	1,990	—	12	—	16	22,450
	B	3.29	0.93	15,197	14,527	—	102	—	142	33,150
6	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	15,197	14,527	—	102	—	142	33,150
7	A	3.29	1.46	2,054	1,990	—	12	—	16	22,250
	B	3.29	0.94	15,197	14,528	—	102	—	142	33,050
8	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	15,197	14,527	—	102	—	142	33,150
Batches subsequent to batch 8 have the same data as batch 8										
For fuel cycle (Ⅲ) ; Batch 1 through 5-same data as in the above										
6	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	12,998	12,425	—	87	—	121	33,150
	P	0.711	0.37	2,111	2,058	68	42	88	67	33,150
7	A	3.29	1.46	2,054	1,990	—	12	—	16	22,250
	B	3.29	0.94	12,363	11,819	—	83	—	116	33,050
	P	0.711	0.38	2,705	2,638	94	61	129	98	33,050
8	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	12,003	11,474	—	81	—	112	33,150
	P	0.711	0.39	3,046	2,971	107	69	148	113	33,150
9	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	11,897	11,372	—	80	—	111	33,150
	P	0.711	0.39	3,148	3,070	110	71	152	116	33,150
10	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	11,905	11,380	—	80	—	111	33,150
	P	0.711	0.39	3,139	3,061	110	71	153	116	33,150
11	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	11,393	10.891	—	76	—	106	33,150
	P	0.711	0.40	3,611	3,523	133	90	193	148	33,150
12	A	3.29	1.46	2,054	1,990	—	12	—	16	22,350
	B	3.29	0.93	11,065	10,577	—	74	—	103	33,150
	P	0.711	0.41	3,910	3,815	150	102	222	171	33,150

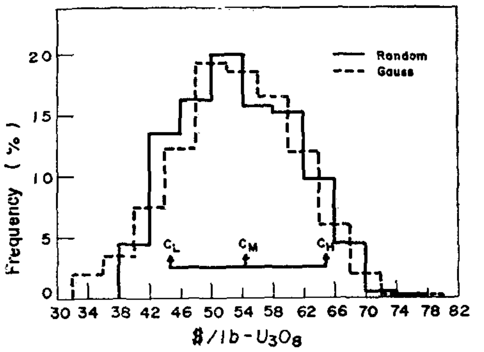

Fig. 1. Probability Histogram on 1981 U_3O_8 Price

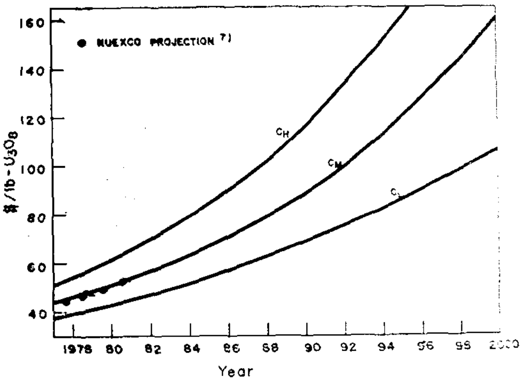

Fig. 2. Projected U_3O_8 Prices

the average burnup of individual fuel batches of the Go-ri units 1 and 2. Based on these data and price projections to be presented shortly we computed the total capital requirement for the above-mentional fuel cycles.

Fig. 1 represents a probability histogram for the 1981 price of pound U_3O_8. C_M denotes the most likely value in the sense that the probability U_3O_8 price will be either higher or lower than C_M is 50%. C_L and C_H are the 10% confidence values in that either the probability U_3O_8 price will be lower than C_L or the probability it will be higher than C_H is 10%. A glance at Fig. 1 indicates that the random distribution function results in a rather wider range of the output U_3O_8 price than the normal distribution does, but that two distribution functions bring about almost the same values on C_M. Fig. 2 depicts

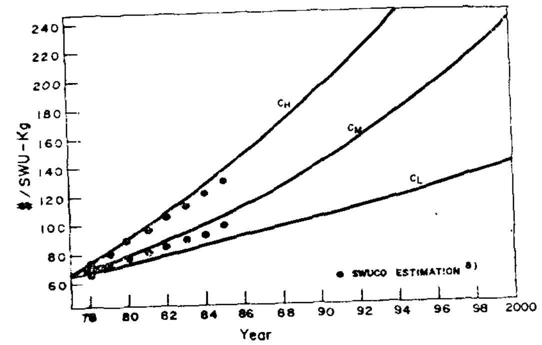

Fig. 3. Projected Enrichment Service Cost

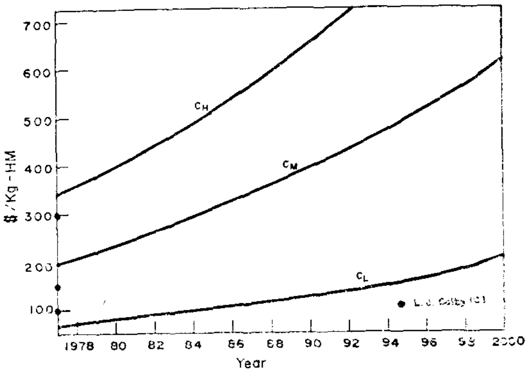

Fig. 4. Projected Reprocessing Prices Service Cost

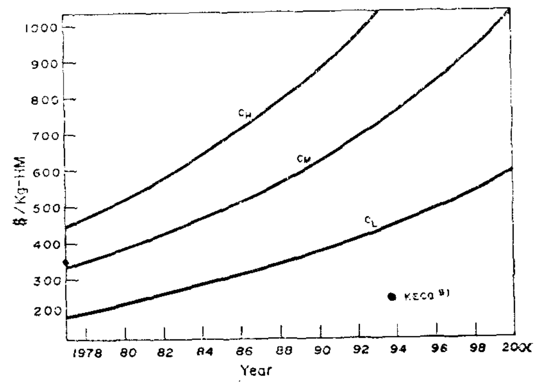

Fig. 5. Projected Spent Fuel Disposal Cost

Table 5. Cost Projections on Conversion, Fabrication, Fresh Fuel Shipping, Spent Fuel Shipping, Reconversion, Pu value and Fabrication Penalty for Mixed Fuel*

Year	Conversion ($/kg-U)			Fabrication ($/kg-U)			Fresh Fuel Ship. ($/kg-HM)			Spent Fuel Ship. ($/kg-HM)			Reconversion ($/kg-U)			Pu value ($/gm-Pu)			Fabrication Penalty ($/kg-HM)		
	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H	C_L	C_M	C_H
1977	—	4.0	—	100.0	125.0	150.0	—	6.3	—	77.3	105.5	133.7	—	6.8	—	−2	13.5	29	—	—	—
1978	4.0	4.2	4.3	105.6	129.1	154.9	6.3	6.6	6.9	82.3	113.5	141.8	6.8	7.0	7.3	−0.4	17.9	30.6	132.3	259.1	385.8
1979	4.1	4.3	4.6	108.4	132.4	161.7	6.5	6.9	7.4	88.1	119.6	151.1	6.9	7.3	7.7	−0.5	18.1	32.1	133.7	262.6	405.8
1981	4.4	4.7	5.0	114.4	147.3	171.0	7.0	7.6	8.4	96.6	133.0	165.5	7.4	7.9	8.5	−0.6	20.9	35.3	138.9	279.6	420.3
1983	4.7	5.1	5.5	124.2	152.0	179.8	7.6	8.4	9.4	103.2	145.3	187.3	7.9	8.6	9.3	0.5	22.1	39.7	152.5	303.5	454.5
1986	5.2	5.7	6.4	135.1	163.1	199.2	8.6	9.9	11.1	118.3	165.5	218.5	8.8	9.7	10.9	0.5	25.9	46.8	159.6	325.5	491.3
1989	5.6	6.4	7.2	143.7	178.0	220.8	9.9	11.4	12.9	137.1	198.2	251.7	9.5	10.8	12.2	1.2	29.7	52.4	179.8	346.3	533.7
1993	6.5	7.6	8.5	161.3	202.5	243.7	11.6	13.8	16.3	163.2	233.8	314.4	10.9	12.8	14.4	1.9	34.8	64.2	207.3	400.1	592.9
1997	7.5	8.9	10.2	181.3	229.1	277.0	13.6	16.6	20.2	207.4	289.2	384.6	12.7	15.1	17.2	1.0	42.9	80.6	233.2	454.2	675.2
2002	9.1	10.6	12.8	209.11	263.7	326.1	17.3	21.1	25.6	249.4	365.2	481.0	15.4	17.9	21.5	2.9	53.4	98.2	234.5	523.4	812.2

*Figures are based on the random distribution function for the variable parameters

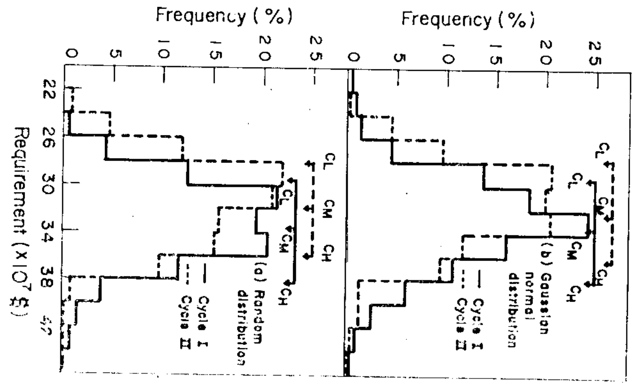

Fig. 6. The Probability Histogram of the Total Capital Requirement of Go-ri unit 1; (a) Random Distribution (b) Gaussian Normal Distribution.

the projected cost trends of U_3O_8 in terms of the most likely values and 10% confidence values. For the purpose of comparison Nuexco data are also plotted in it with black circles. Figs. 3-5 show the cost projections on enrichment, reprocessing, and spent fuel disposal, respectively. Cost data available for these components are also shown in them. For the rest of fuel cycle components the cost projections are given in Table 5.

Figs. 6 and 7 depict the probability histogram of the total capital requirement for fuel cycle schemes presumed for the units 1 and 2. Both random and normal distribution functions were tested in computing the capital requirement histogram of the unit 1 fuel cycles, while only the random distrib-

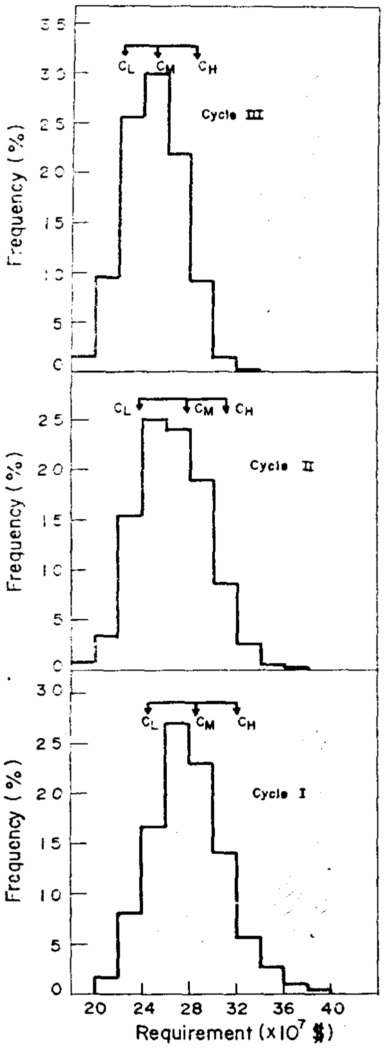

Fig. 7. The Probalility Histogram of the Total Capital Requirement of Go-ri unit 2 (Random Distribution)

ution function was adopted for the unit 2 fuel cycles. As shown in Figs. 6a and 6b, the choice of distribution function has some effects on the detailed shapes of histograms but little on the most-likely and 10% confidence values.

It is worthy to note that the capital requirement histogram of a fuel cycle overlaps considerably with that of another cycle.

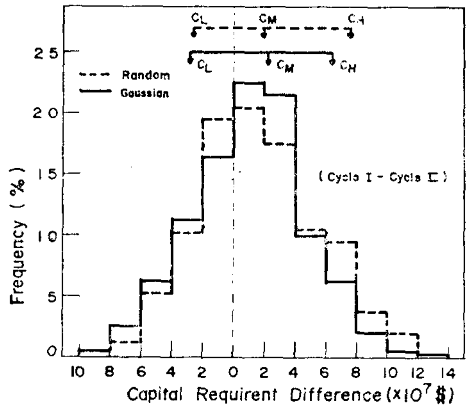

Fig. 8. The Probability Histogram on the Difference of the Total Capital Requirement for Go-ri unit 1

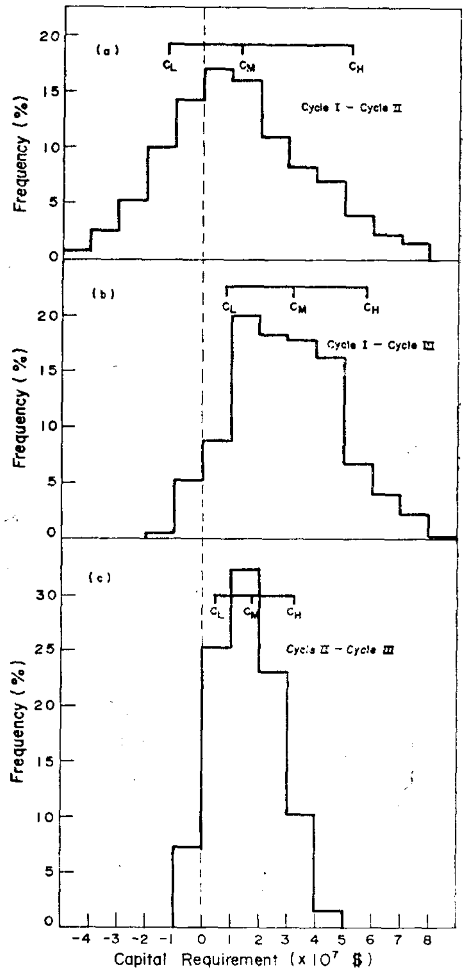

Fig. 9. The Probability Histogram of the Difference of the Total Capital Requirement for Go-ri unit 2.

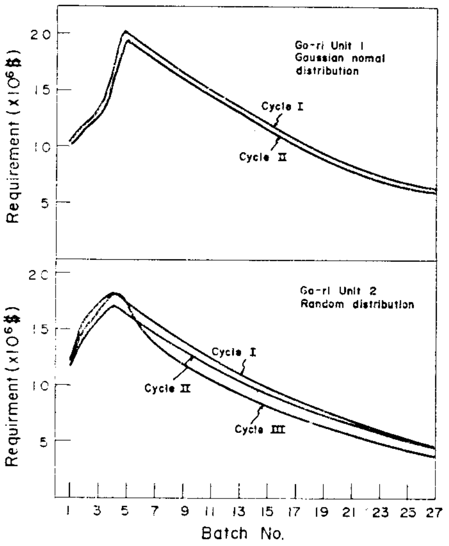

Fig. 10. Per-Batch Capital Requirements.

This implies that one cannot jump to a hasty conclusion that one specific fuel cycle is more economic than the other one. Judging from the most likely values, however, one can say that cycle (II) is the economic choice for the unit 1, whereas cycle (III) is the most advantageous for the unit 2. This trend is more easily observed in Figs. 8 and 9 which show the probability histograms on the capital requirement difference between two cycles. Take, for instance, Fig. 9b. The larger area on the positive side of the capital requirement difference between cycles (I) and (III) means that cycle (III) is more likely to be cheaper than cycle (I).

Plotted in Fig. 10 is the most likely value of the per-batch capital requirement versus batch number. The cost advantage of the reprocessing cycle (II) over the throw-away cycle (I) is observed in all the fuel batches in the unit 1. In the unit 2 fuel batches, however, plutonium recycling cycle (III) requires the highest per-batch capital investment for initial six batches than the other two cycles. This is attributed to the fact that the plutonium credits incurred from these batches are not claimed till the moment they will be actually recycled in later batches.

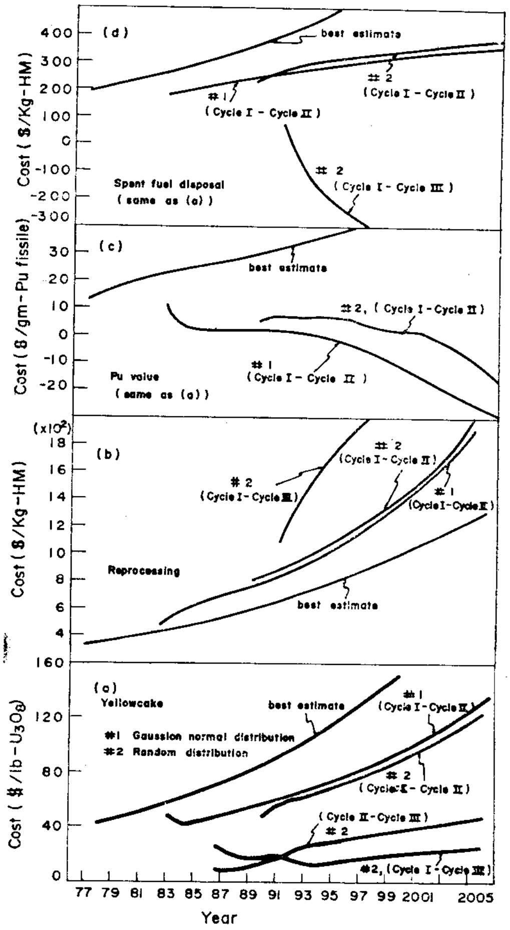

Fig. 11. The Break-even Costs of (a) Yellow Cake, (b) Reprocessing, (c) Pu-value and (d) Spent Fuel Disposal.

Fig. 11a compares the break-even cost of pound U_3O_8 with its projected most likely value. Similar comparisons are made for reprocessing, plutonium and spent fuel disposal costs in Figs. 11b, 11c, and 11d, respectively. The break-even cost referred here is such cost that gives rise to the same total capital requirements in two competing fuel cycle schemes. It can serve a useful index to determine the relative advantage of one cycle over another.

Considering the throw-away cycle (I) and the reprocessing cycle (II) the U_3U_8 break-even cost falls far below the projected most likely values or lies in the vicinity of the 10 % confidence values. This price of U_3O_8 is hardly anticipated under the present situation that the U_3O_8 price keeps snowballing. Therefore, there seems to be a high incentive for the reprocessing of the spent fuel in both units of the Go-ri plant. The similar statements can be drawn from the behaviour of the break-even costs of the other fuel cycle components.

IV. Conclusion

The Go-ri nuclear power plant unit 1 is currently undergoing a series of start-up tests toward its full power operation at the end of this year. Fuel cycle cost is considered most important for achieving the potential economic benefits of the nuclear power from the plant. As a means to investigate the economic performance of the unit 1 and the unit 2 of the plant, we evaluated the total capital requirements for some selected fuel cycle operations in terms of a probabilistic approach.

As for the fuel cycle options, the reprocessing and subsequent recycling of either uranium or plutonium, or both are found to be the most economic choices for the plant. Despite the increasing tendency of the reprocessing service charge and fabrication penalty price of the mixed oxide (UO_2/PuO_2), indications are that these fuel cycle options can give rise to several-ten million dollars worth of savings during the 30-year plant operation in comparison with the throw-away cycle. The main reason for this is less U_3O_8 requirements in the reprocessing cycle than in the throw-away cycle, coupled with the substantially high price of U_3O_8.

The computational method we adopted here is based on a sampling procedure of fluctuating fuel cost parameters termed variable parameters. To facilitate the sampling we presumed a Gaussian and a random probability distribution function for variable parameters. Two distribution functions did not result in any appreciable differences of computed results, particularly in the most likely values of individual fuel cycle component costs and total capital requirement. The proposed method can bring us more reliable results of the fuel economics computation when the data set required for it fluctuates widely, as seen in the today's international fuel market. The method, therefore, has a potential applicabilities to other studies, say, economic comparisons of different nuclear power stations.

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