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The Economic Evaluation for Kori-1 Steam Generator Replacement

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ABSTRACT

The economic evaluation was performed for Kori-1 steam generator(SG) replacement, in which the six senarios were evaluated for a 30, 40 and 50 year plant operating period : Scenario 1-Current Maintenance Approach ; Scenario 2-SG Replacement as Early as Possible(1998) ; Scenario 3-Scenario 2+4.8% Rerate ; Scenario 4-18% Plugging Limit ; Scenario 5-SG Replacement when Plugging Rate exceeds 15% ; Scenario 6-Scenario 5+4.8% Rerate. The results of the evaluation indicate that immediate replacement of existing SGs was the most profitable alternative, especially in combination with a 4.8% rerate.

1. Introduction

In recent years the replacement of PWR(Pressurized Water Reactor) SGs(Steam Generators) has become a more important consideration for PWR owners[1-5]. The damage being experienced by SGs, together with the high costs associated with steam gnenerator repairs, provides a strong incentive to consider SG replacement. A number of factors are expected to affect the utility's replacement decision including : government policies, technical issues, public acceptance, and plant economics. This paper describes the economic evaluation information to serve as a basis for a decision to replace the Kori-1 SGs.

Kori-1 is a two-loop plant having a Westinghouse Nuclear Steam Supply System with 51 Series SGs. The SG tubes in the current SGs were made of mill annealed Alloy 600. A number of tube degradation mechanisms have been observed in the Kori-1 SGs since its commercial operation in April 1978. The status of Kori-1 SG tube degradation has been described in elsewhere.[6-8]

The economic evaluation methodology utilized in this study was "PWR Steam Generator Cost-Benefit Methodology", which has been developed for denting damage by Electic Power Reasearch Institute[9]. This methodology is modified to address SGR(Steam Generator Replacement). Furthermore sensitivity analyses were carried out in order to evaluate the effect of uncertainties in the input values on the decision outcome.

2. Economic Evaluation Methodology

EPRI's SG cost-benefit model[9)] consists of three major components such as damage element, performance element, and consequence element. The concept of the damage element is to determine the damage rate as a function of hardware configurations and operating procedures. The performance element describes the relationship between the average rate of degradation for the SG and the damage occuring to individual tubes. The form of this relationship could be determined from historical tube-plugging data. The development of the consequence element involves specifying three types of costs, which are associated with SG problems and corrective options: the direct installation, operating, and maintenance costs of the fixes ; short-term replacement power costs required for forced outages; and long-term replacement costs for derates and SGR due to plugged tubes.

Damage Element

The tube degradation projection is an important part of the economic evaluation of SGR. Various tube degradation mechanisms such as, but not limited to, pitting, primary water stress corrosion cracking, and sleeve bulge were considered and a degradation projection was made for each mechanism. The results of the Kori-1 SG tube degradation projection have been presented in refs[6-8].

Performance Element

The SG maintenance activities such as plugging rate and forced outage frequency, were calculated based on the tube degradation projection together with Kori-1 maintenance criteria. Tube plugging projection has been presented elsewhere[6-8)]. Forced outage frequency is defined as the number of forced outages per SG year. Both outage frequency and duration were selected from recent Kori-1 operation history[10)].

Consequence Element

The total cost calculation is illustrated by bar chart in Figure 1. The costs can be divided into two groups : costs introduced to improve the SG's performance (the fix cost) and costs resulting from degradaded performance (the damage cost). Fix costs include the initial hardware, ongoing maintenance, and long-term replacement power costs during scheduled outages to implement corrective options. Damage costs include direct costs for replacement and shutdown, the costs of derates and anticipated outages to make repairs, and the cost of forced outages.

For the Kori-1 SGR evaluation, the "Present Value of Revenue Requirements"(PVRR) is utilized as the decision criterion. The PVRR is the present value of all revenues that the utility must collect from its customers as a result of imple-

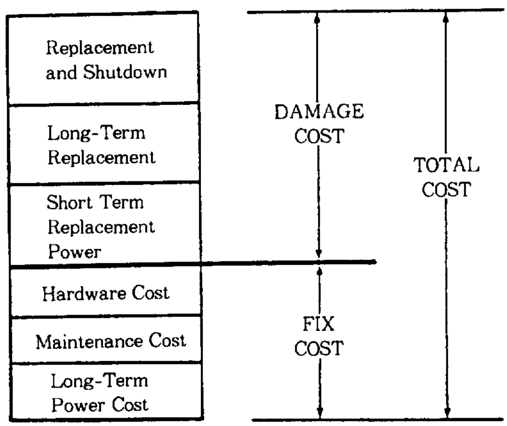

Fig. 1. Definition of Cost Categories[9]

menting a given plan. The revenues that must be collected equate to the costs incurred in carrying out the plan plus the returns paid to investors supplying the capital required by the plan. Future costs are escalated at the appropriate escalation rates. The present value of all the costs are computed using the specified discount rate.

$$(\text{Present Value}) = C_0 \times (1+s/100)^r/(1+d/100)^r$$

where C_0 = Cost for any future year

s = Escalation rate (%/year)

d = Discount rate (%/year)

r = Period (year)

3. Input Parameters for Kori-1

The input values for the economic evaluation of Kori-1 SGR are summrized in Table 1.

The results of the tube degradation projection are used for defining the number of tubes to be plugged or repaired in some manner. This allows determination of the duration required for those activities. For most activities such as tube plugging, sleeving, and inspection, costing rates are specified in the input as a fixed setup (mobilization) cost for the plant plus a unit cost per tube. For other activities such as chemical cleaning and sludge lancing, which may occur for the entire SG rather than a given number of tubes, the unit cost is defined as cost per SG.

Plugging, sleeving and sludge lancing are performed at each outage, and chemical cleaning is performed every 5th outage. The planned outage duration is 58 days.

The summed product of the Kori-1 Mean Outage Frequencies and the Kori-1 Mean Forced Outage Downtimes is the number of forced outage

Table 1. Input Data for Kori-1 SG Replacement Evaluation

INPUT PARAMETER		INPUT DATA
Fuel Cycle		15 months
Inspection Type	ECT	Bobbin/RPC : 30KWon/tube +0.1BWon/cycle MRPC(TS) : 43KWon/tube MRPC(UB) : 160KWon/tube
	UT	550KWon/tube Fixed Setup = 50MWon
Maintenance Activity	Plugging	2.5MWon/tube(2plugs/tube)
	Sleeving	5MWon/sleeve Fixed Setup = 0.5BWon
	Lancing	50MWon/SG
	Chemical Cleaning	1.0BWon/SG
Planned Outage		58days(SG Window = 36days)
SG Replacement Duration		78(days) (Ex. Out. Period = 42days)
Maintenance Rate	ECT	Bobbin(1/4) = 1000tubes/day Bobbin(F-L) = 300tubes/day MRPC(TS) = 300tubes/day MRPC(UB) = 80tubes/day Setup = 1day/SG
	Plugging	50tubes/day Setup = 1day/SG
	Sleeving	20tubes/day Setup = 1day/SG
	UT	50tubes/day Setup = 1day/SG
	Lancing	3days/SG
	Chemical Cleaning	8days/SG
Forced Outage Frequency		0.5times/cycle Mean Downtime = 14 days
SG Uprating		4.8BWon
Repl. Power	Ex. Outage/ Power Reduction	33.66 Won/KwH
	Uprating	17.93 Won/KwH
Discount Rate		8%/year
Inflation Rate		5%/year

days per SG-year for Kori-1. These values, as well as the forced outage frequency and duration values are seen in Table 1.

The replacement power cost during the excess outage is considered as the same as that during plant operation (power reduction).

4. Description of Scenarios

The specific maintenance, repair or replacement strategy must be defined to permit a precise definition of the costs of executing such strategy. Specific strategies are designated as "scenarios", since they are defined both in terms of the maintenance activities performed and the point in time in which they are performed.

This section provides a six "scenarios" related to SG maintenance and replacement which were evaluated. These scenarios included combinations of the following :

- Steam generator replacement with generators having the same overall heat transfer capabilitiy as the current SGs, operating at a 1728.5 MWt power level
- Steam generator replacement with generators having increased overall heat transfer capabilitiy, operating at an 1811 MWt power level(4.8% rerate)
- Alternate plugging limit of 18% instead of the current 15%

Following are descriptions of the specific scenarios evaluated.

Scenario 1-Current Maintenance Approach

Employ the current maintenance approach (sleeving and plugging) followed by power reduction after 15% effective tube plugging. No SGR is assumed.

Scenario 2-SGR as Early as Possible(1998)

Replace SGs as early as possible. The current maintenance approach will be utilized until SGR with a SG having similar overall heat transfer capability as the original SGs.

Scenario 3-Senario 2+4.8% Rerate

This is identical to Scenario 2, except that rerating of 4.8% is performed at the time of SGR.

Scenario 4-18% Plugging Limit

This is identical to Scenario 1, except that reduced power operation occurs when the effective plugging rate reaches 18%.

Scenario 5-SGR when Plugging Rate exceeds 15%

The current maintenance approach will be utilized up to a 15% effective tube plugging level. Steam generator replacement is performed upon reaching a 15% effective plugging limit. No uprate is assumed.

Scenario 6-Scenario 5+4.8% Rerate

Same as Scenario 5, except that rerating of 4.8 % is performed at the time of SGR.

Replacement Timing

The earliest SGR timing was selected as 1998, taking into account the manufacturing period and Kori-1's planned outage schedule. The manufacturing duration is assumed to be about 3 years, say, from Jan. 1995 to Feb. 1998. The actual replacement would start around Mar. 1998. And plugging limit of 15% is expected to be arrived in around 2004[6-8].

18% Plugging Limit

The previous study[11] on 'Kori-1 Steam Generator Tube Plugging Analysis' indicated that the plugging limit could be increased up to 18% without affecting the SG safety. Therfore 18% plugging limit was included in scenarios.

Rerating

The steam pressure (at the turbine inlet) corresponding to the maximum thermal output of 1728.5 MWt is 729 psia. The Valves-Wide-Open SG outlet pressure at 1728.5 MWt is 765 psia. Using this steam line loss of 36 psia, the turbine curves could be modified for an assumed rerating of 4.8 %. No significant turbine modifications were assumed to achieve the 1811 MWt power rating.

Plant Life Extension

Much attention has been directed in recent years to means of extending nuclear power plant life. The feasibility study on the Kori-1 plant life extension has been underway. Therefore, the evaluation was performed for three planning period: 30 years(the original design period for the Kori-1 plant), 40 years, and 50 years(life extension).

5. Evaluation Results

The six scenarios were evaluated for a 30, 40 and 50 year operating period.

5.1 30 Years(Design life) Operation

Table 2 presents the deterministic evaluation results for the thirty year plant operation period. The positive values reflect cost increases whereas negative values reflect cost savings. Of the six scenarios, Scenario 3, Immediate Replacement with Rerate, has the lowest present value of revenues requirements, 112.2 BWon. This is followed by Scenario 2, Immediate Replacement without Rerate, with a PVRR of 133.1 BWon, and Scenario 1, Current Maintenance Approach, with a PVRR of 153.2 BWon. The first two scenarios (2 and 3) do incorporate immediate SGR.

In comparing the cost elements for each of the six scenarios in Table 2, it can be seen that

Table 2. Evaluation Results for 30 Year Plant Operation Period

Unit : BWon

Scenario No.	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Bobbin+RPC Inspection	4.6	3.0	3.0	4.6	4.0	4.1
UT Inspection	1.9	0.4	0.4	1.9	1.1	1.1
Tube Plugging	1.6	0.3	0.3	1.6	0.9	0.9
Tube Sleeving	16.5	3.0	3.0	16.5	9.7	9.7
Sludge Lancing	1.0	1.0	1.0	1.0	1.0	1.0
Chemical Cleaning	3.3	-	-	3.3	1.8	1.8
Replace Power-Excess Outage	86.0	9.7	9.7	86.1	46.9	46.9
SG Replacement	-	86.9	86.9	-	72.8	72.8
Plant Rerating	-	-	4.2	-	-	3.5
Power Generation Loss	8.5	-	-25.1	1.5	0.2	-8.6
Replace Power-SG Replacement	-	17.5	17.5	-	14.7	14.7
Replace Power-Forced Outage	29.8	11.3	11.3	29.8	23.5	23.5
Total Revenue Requirements	153.2	133.1	112.2	146.3	176.6	171.4

Scenarios 1 and 4 have the higher inspection costs. This is because SGR does not occur for these scenarios. Examining the UT costs, it can be seen that UT costs are indicative of sleeves installed, since all new sleeves are UT inspected. Scenarios 1 and 4, which involve extended operation with the current SGs, have the higher UT costs. The smallest UT costs are incurred for Scenarios 2 and 3, since sleeving (and UT) is conducted only up until 1998 SGR.

The PVRRs for plugging are higher for Scenario 1 than for most other scenarios, since all of the plugging in this scenario is near term, and plugging is performed to a level approaching the plugging limit. The Scenario 4 PVRR is the same as the Scenario 1. The minimum plugging costs are seen for Scenario 2 and 3, since sleeving and minimal plugging are performed prior to a 1998 replacement.

Sleeving costs are more significant than the other costs reviewed so far. The highest sleeving PVRRs are in Scenario 1 and 4, since plugging and sleeving are continuously performed for these scenarios.

The replacement SGs for Senarios 3 and 6 are modelled to have the same overall heat transfer characteristics as the original 51 Series SGs.

Replacement power costs from SGR are incurred from extension in the Kori-1 planned SG outage window of 39 days to 72 days for the SGR window. These costs are higher for the scenarios with replacement occurring at earlier dates, since the costs are discounted over a fewer number of years. Since there is no SGR for Scenarios 1 and 4, there are no excess outage costs for these scenarios.

Power generation loss occurs when the steam pressure decreases below its current value of 800 psi, causing a reduction in the electrical output. A greater power loss occurs for Scenario 1 than Scenario 4 (8.5 BWon vs. 1.5 BWon), since power reduction begins at different plugging limit (15% vs. 18%).

Forced outage costs reflect the reduced potential for forced outages after SGR. Since in scenarios without SGR the current SGs are in operation approximately 11 years longer than for other scenarios, forced outage costs for these scenarios are higher. Forced outage costs are "soft" costs, in that they are only incurred if a forced outage occurs.

5.2 40 Years and 50 Years Operation(Life Extension)

Table 3 presents the variations of costs for each scenarios with plant operation period. All of the same aspects related to comparisons of costs between different scenarios for 30 year operation remain applicable to the 40 year and 50 year plant operation cases. For the 40 year case, the difference between Scenarios 1 and 3 are significant; the PVRRs for these cases are 324.5 and 94.5 BWon, respectively. Much of the difference is due to the increase in forced outage and excess outage costs for Scenario 1, and the additional revenue from higher electric power output due to rerating for Scenario 2. The continuous sleeving/plugging strategy, Scenario 1, becomes less attractive for a

Table 3. Evaluation Results Comparison for Plant Operation Period

Unit : BWon

Operating Life	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
30year	153.4	133.0	112.1	146.3	176.6	171.4
40year	324.5	134.3	94.5	294.4	177.9	153.9
50year	455.7	135.3	81.2	408.0	178.9	140.6

40 year plant operation period.

For the 50 year planning period, Scenarios 2 and 3 clearly provide the more attractive economic option. Even with the modest rerate level utilized, the value of additional power generated by rerate seems to approach that of the SGR. Forced outage costs for the early replacement cases (Scenarios 2 and 3) will be lower than for any of the other scenarios.

5.3 Sensitivity Analysis

Sensitivity analysis provides a means of evaluating the effect of uncertainties in the input values on the decision outcome. It is a method of identifying decision variables which may require closer study for which additional information may be beneficial to the decision process. Sensitivity analyses were performed for a 30-year plant operation period for Scenarios 1 and 2. Since only a few of the variables in the analysis have an appreciable effect on the outcome, these variables merit greater attention, such as discount rate, SGR costs, rerating, forced outage rate, etc.. For convenience, Table 4 provides shortened description of the sensitivity analysis input variables. The range of the main variables developed for use in the sensitivity analysis are as follows :

- Discount Rate : 6%～12%
- S/G Replacemetn Costs : 80～120 BWon
- Forced Outage Rate : 0.5/EFPY～1.0/EFPY
- Rerating : 0～4.8%

Figure 2 shows the sensitivity analysis result for Scenario 1. Three variables are more significant in terms of their effect on the present value of reve-

Table 4. Sensitivity Analysis Variables

Input Variable	Description
SGR	Fixed cost for SG replacement
EOC	Excess outage cost
FOF	Forced outage frequency
CFR	Cost for rerating
FCS	Fixed cost for sleeving
UCS	Unit cost for sleeving
UCU	Unit cost for UT inspection
UCE	Unut cost for ECT inspection
CDR	Constant discount rate for present value calculation

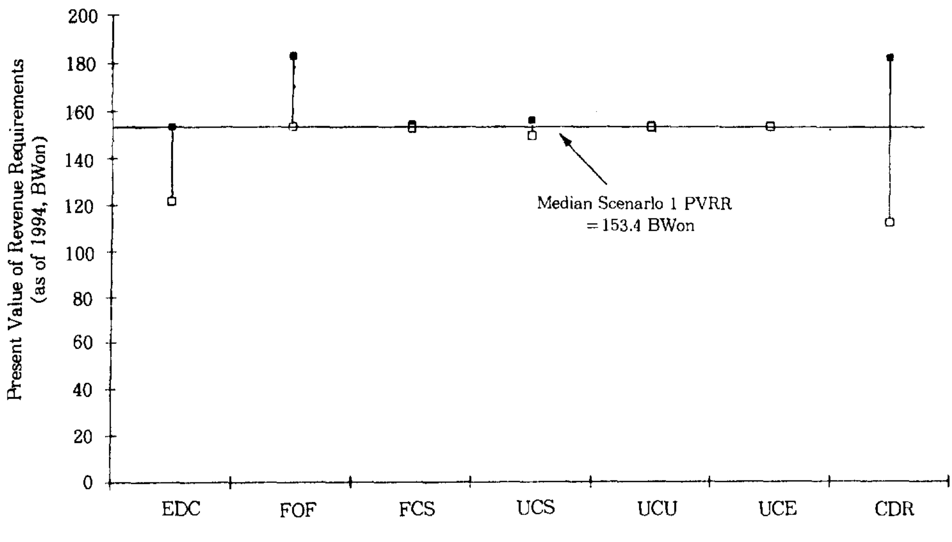

Fig. 2. Sensitivity analysis result for Scenario 1

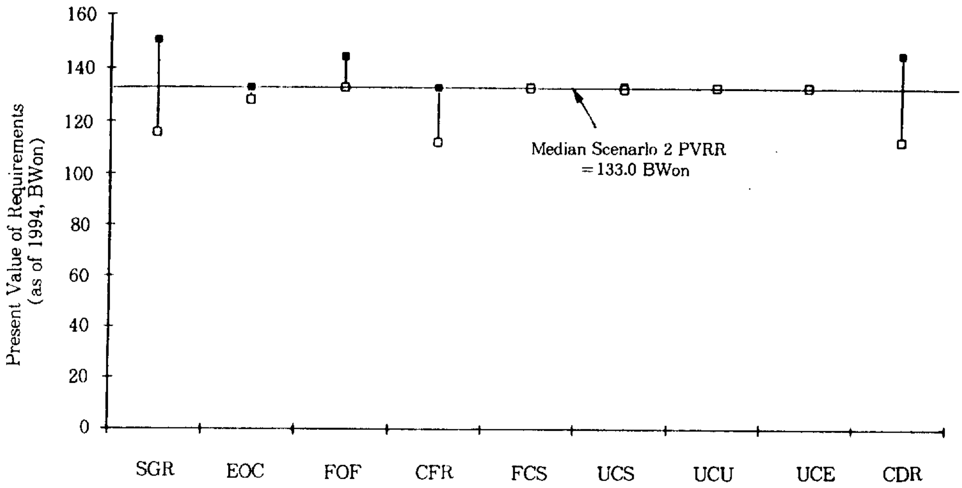

Fig. 3. Sensitivity analysis result for Scenario 2

nue requirements : these are excess outage, forced outage rate, and discount rate. The financial variable(e.g. discount rate) has a more pronounced effect on PVRR than other variables, since the time frames for the maintenance activities are spread over a longer period of time.

Figure 3 illustrate the sensitivity analysis result for Scenario 2. The most signifiant factor in determining the PVRR is the cost for SGR. The value of 100 BWon for SGR costs is rather conservative. The economic feasibility of Scenario 2(Immediate SGR) would significantly be increased, if SGR costs were lowered down to 80 BWon(this assumption is practically reasonable at present).

6. Conclusion

The economic evaluation results for Kori-1 SGR indicates that the SGR as early as possible with a 4.8% power rerating is the most profitable alternative. In the assumed plant life extension beyond 30 years, immediate replacement of existing SGs appears to be more cost effective strategy.

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