Calculation for Risk Informed Inspection and Cost Effective Maintenance Using Probabilistic Fracture Mechanics

Noriyoshi Maeda, Shinichi Nakagawa, Genki Yagawa and Shinobu Yoshimura

The University of Tokyo, Japan

ABSTRACT

Maintenance activity including inspection, repair and replacement is regarded as the most important key factor for the safety and reliability of a nuclear power plant. The decision making - what kind of and what to extent maintenance should be performed - has to be done based on the evaluation of economical contribution to long life time, taking such issues as aging and life extension into consideration.

Expectation value of cost of countermeasure for accident, expectation value of cost to repair the weld and cost for inspection are calculated as function of inspection frequency. The optimization of inspection frequency can be attained by finding the frequency where sum of the cost of countermeasure for accident multiplied by the empirical number, the cost for repair and cost for inspection takes minimum value.

INTRODUCTION

Nowadays, aging of nuclear power plants becomes more serious problem in Japan as the operational life of several nuclear power plants approaches near 30 years. Considering the lack of location for nuclear power plants, it is not adequate to expect new plants to be constructed smoothly. Therefore, the anticipation for the extension of life of existing plants over their design life has become urgent.

The maintenance of the component of the nuclear power plant has become an important problem as it dominates the plant life, and it is urgent to review the maintenance from the points of view of safety, reliability and economy.

Maintenance activity including inspection, repair and replacement is regarded as the most important key factor for the safety and reliability of a nuclear power plant. So it is the time to review the maintenance from the long time economical point of view.

Recently, it has been generally recognized that nuclear power plants will cease to exist when they become less economical compared to another types of power generation system, as we are in a world-wide economic recession. The economy can be regarded as optimization of the profit defined as a difference between the income obtained by selling the electricity and the cost necessary to generate electricity, which is composed of two main factors: one is the cost needed during commercial operation including the purchase expense of the uranium fuel
and labor cost, and another is the cost for maintenance. The decision making - what kind of and to what extent maintenance should be performed - has to be done based on the evaluation of economical contribution to long life time, taking such issues as aging and life extension into consideration.

Risk informed inspection (RII) has been drawing the attention of utilities as it may give orders among maintenance activities for the components of a nuclear power plant based on a clear probabilistic ground. The risk can be defined as the product of the probability of the accident occurrence and consequence due to the accident. By introducing the economical loss as the consequence and minimizing the resulting risk, maintenance program having high cost performance can be expected to be established. Probabilistic fracture mechanics (PFM) is introduced to calculate the probability of the accident occurrence. Data for the economical loss as the consequence has to be searched world widely.

METHOD OF CALCULATIONS

Cost-benefit analysis using PFM is introduced to optimize the frequency of inspection for welds in a piping line of a nuclear power plant. Figure 1 shows the analyzed piping line having ten welds for which ISI is scheduled every year. The probability of break or leak of a weld by fatigue during normal operation and the crack detection probability through the inspection as ISI are calculated by using PC-PRAISE code(1).

Figure 2 shows the flow chart of calculation:
(1) An inspection frequency during one inspection cycle (ten years) is specified for every welds.
(2) PFM analysis is performed by PC-PRAISE.
(3) The probability of break or leak of a weld by fatigue and the crack detection probability through the inspection are calculated by Monte-Carlo simulation based on the PFM method.
(4) Two expectation values defined by the following formulae are calculated by using the above-mentioned probabilities:

a. Expectation value of cost of countermeasure for accident resulting from the break or leak of the welds

\[
= \text{sum of power generation loss and cost to repair the weld} \\
\times \text{total probability of break or leak of all welds of the piping line} \tag{1}
\]

b. Expectation value of cost to repair the weld which is anticipated to be completed during scheduled shutdown, which does not generate the loss of electricity

\[
= \text{cost to repair a weld} \times \text{crack detection probability by ISI} \tag{2}
\]

Cost for inspection is compared to the two above-mentioned expectation value of cost.

CONDITIONS FOR CALCULATION

(1) Analyzed piping systems and cyclic loading
Type of piping is shown in Table 1 and the material is STS410. Its properties at 300 °C is summarized in Table 2. The cyclic loading which causes fatigue crack growth is shown in Table 3. Many bench-mark PFM calculations have been performed for this weld in the research committee in Japan Welding Engineering Society. Calculated break or leak probabilities in this study are verified by comparing to the results of the bench-mark
calculations. In the following calculations, only leak probabilities are used for evaluation.

(2) Probability of defect existence
Probability of defect existence is anticipated to be 0.01/weld when the weld was judged to be acceptable by the inspection performed for weld at construction.

(3) Leakage
Leakage is defined when more than 3 gallon of fluid from the defect a minute is derived:

\[
\text{Calculated leakage} \geq 3 \text{(gallon per minute)}
\]

(4) Probability of non-detection of defects (\(P_{ND}\))
Probability of non-detection of defects (\(P_{ND}\)) is proposed by some researchers. Two type of \(P_{ND}\) formulae is used in this calculation. A defect (crack) is approximated to have an elliptic shape whose depth is \(a\) and length \(c\). The wall thickness is \(t\).

a. LLNL\(^{(1)}\)
The following equation is given by LLNL (Laurence Livermore National Laboratory) for ferritic steel piping:

\[
P_{ND} (a) = 0.5 (1 - \varepsilon) \text{erfc} 1.33ln(A/A^*) + \varepsilon
\]

\[
A = \begin{cases} \frac{\pi}{2ac} (2c \leq D_b) \\ \frac{\pi}{4aD_b} (2c > D_b) \end{cases}
\]

\[
A^* = \frac{\pi}{4} a^* D_b
\]

In the formula, \(D_b\) means beam diameter of ultrasonic wave (25.4mm), \(a^*\) is the depth of crack when it is undetected with the probability of 50% (63.5mm), and parameter \(\varepsilon\) and \(\nu\) are 0.005, and 1.60, respectively.

b. PNL\(^{(2)}\)
The following equation is given by PNL (Pacific Northwest Laboratory) for ferritic steel:

\[
\text{poor: } P_{ND} = 1 - \text{erf}[0.432 + 0.163ln(a/t)]
\]

(5)

\[
\text{good: } P_{ND} = 1 - \text{erf}[1.75 + 0.583ln(a/t)]
\]

(6)

\[
\text{advanced: } P_{ND} = 1 - \text{erf}[3.03 + 1.106ln(a/t)]
\]

(7)

Poor means the level of defect detection potential of averaged inspectors following the procedures ruled in ASME Sec.XI. Good means the level of the most excellent inspection team among them. Advanced means the level of potential which detects through-wall cracks (intergranular stress corrosion crack) with the probability of 0.999 and also detects cracks having depth of 0.1t (t:thickness) with the probability of 0.9. Figure 3 depicts the calculated \(P_{ND}\) using Eq. (5)-(7).

(5) Distribution of crack depth \(a\) and its aspect ratio \(c/a\)
Crack depth \(a\) and its aspect ratio \(c/a\) are assumed to be probabilistic variables. Its probability density is shown by the following equation.
\begin{align*}
P(a) &= \frac{\lambda \exp(-\lambda a)}{[1-\exp(-\lambda a)]} \\
P(a/c) &= \frac{C}{c/a \cdot S \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \frac{(\ln(a/c)-\ln M)^2}{S} \right]
\end{align*}

Where \( \lambda = 0.16(1/\text{mm}) \), \( M = 1.336 \), \( S = 0.538 \), and \( C = 1.419 \).

(6) Monte Carlo Calculation

Layered Monte Carlo method is introduced to get precise results fast. Number of cells is \( 10 \times 10 = 100 \) and number of samples from 1 cell is 250.

(7) Cost

Three kinds of cost are anticipated (120 yen=1$)

a. sum of power generation loss and cost to repair the weld
   \[ = 100,000,000 \text{ yen/day} \times 60 \text{ days} \]

b. cost to repair a weld
   \[ = 10,000,000 \text{ yen/1 weld} \]

c. cost for inspection
   \[ 1,000,000 \text{ yen/1 weld} : \text{LLNL} \]
   \[ 500,000 \text{ yen/1 weld} : \text{PNL, poor} \]
   \[ 1,000,000 \text{ yen/1 weld} : \text{PNL, good} \]
   \[ 1,500,000 \text{ yen/1 weld} : \text{PNL, advanced} \]

Cost of countermeasure for accident, cost to repair a weld and cost for inspection used above are anticipated value. More real value should be used to get more realistic results.

RESULTS OF CALCULATION

Figure 4-7 shows the calculated results of expectation value of cost of countermeasure for accident, expectation value of cost to repair the weld and cost for inspection as function of inspection frequency.

DISCUSSION

When the three costs are compared in these figures, the inspection cost is relatively high. This may suggest these comparison are too simple to be used in real management. Generally, expectation value has to be multiplied by empirical number to be compared to non-expectation value as inspection cost. The relation between them may resemble to the relation of insurance money and its fee. The empirical number has been searched through cooperative works with atomic energy insurance in Japan.

Figure 5-7 show that the cost of countermeasure for accident decreases by \( 10^3 \) when inspection of better detectability is applied, but the cost for repair during ISI does not change so much. Calculated result using LLNL formula (Figure 4) seems to be equal to the case of "good" of PNL (Figure 6).

The optimization of inspection frequency can be attained by finding the frequency where sum of the cost of countermeasure for accident multiplied by the empirical number and the cost for repair takes minimum value.
In the next step, stress corrosion crack is planned to be introduced as the cause of accident because it generates leakage much more often than fatigue in real boiling water reactor plant.

CONCLUSIONS

Maintenance activity including inspection, repair and replacement is regarded as the most important key factor for the safety and reliability of a nuclear power plant. The decision making - what kind of and what to extent maintenance should be performed - has to be done based on the evaluation of economical contribution to long life time, taking such issues as aging and life extension into consideration.

Expectation value of cost of countermeasure for accident, expectation value of cost to repair the weld and cost for inspection are calculated as function of inspection frequency.

Expectation value has to be multiplied by empirical number to be compared to non-expectation value as inspection cost.

The optimization of inspection frequency can be attained by finding the frequency where sum of the cost of countermeasure for accident multiplied by the empirical number, the cost for repair and cost for inspection takes minimum value.

ACKNOWLEDGEMENT

This study summarizes a part of the research in PFM subcommittee in Japan Welding Engineering Society funded by Japan Atomic Energy Research Institute.

REFERENCES


<table>
<thead>
<tr>
<th>Pipe</th>
<th>Outer Diameter(mm)</th>
<th>Wall Thickness(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16B</td>
<td>406.4</td>
<td>26.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3: Dimension of Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension max. (MPa)</td>
</tr>
<tr>
<td>Tension min. (MPa)</td>
</tr>
<tr>
<td>Number of cycle(cycles/year)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: Mechanical Properties of STS410 Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design stress intensity (MPa)</td>
</tr>
<tr>
<td>Design yield strength (MPa)</td>
</tr>
<tr>
<td>Design ultimate strength (MPa)</td>
</tr>
<tr>
<td>Flow stress (MPa)</td>
</tr>
<tr>
<td>Young's modulus E(GPa)</td>
</tr>
<tr>
<td>Poisson's ratio</td>
</tr>
</tbody>
</table>

X-541
Fig. 1 Analyzed Piping System

Fig. 2 Flow Chart of Calculation
Fig. 3 $P_D$ by PNL

Fig. 4 Cost-Benefit Analysis using $P_{ND}$ of LLNL

Fig. 5 Cost-Benefit Analysis using "poor" $P_{ND}$ of PNL
Fig. 6 Cost-Benefit Analysis using "good" $P_{ND}$ of PNL

Fig. 7 Cost-Benefit Analysis using "advanced" $P_{ND}$ of PNL