Degradation Analysis and Risk-Informed Management of Feedwater System in Nuclear Power Plants

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Abstract: The flow accelerated corrosion (FAC) occurred on the shell side near the inlet nozzle of the feedwater heater is considered the major failure mechanism of the feedwater system in a nuclear power plant. Therefore, a semi-empirical formula proposed by Siemens/KWU is used in the present study to predict the extent of corrosion of the heater-wall caused by FAC. The formula is proved to be able to predict the amount of corrosion very accurately, and sensitivity analysis indicates that, aside from other factors, fluid velocity, steam quality and oxygen content have significant influences on the corrosion rate. A Monte Carlo method that considers randomness of several parameters is employed to simulate amounts of wall-corrosion of individual feedwater heaters and evaluate their relative risks. Under the assumption that risks for other components of the feedwater system are also known, probabilistic-risk-assessment (PRA) is applied to the entire feedwater system. Several importance measures including Fussell-Vesely (FV), risk achievement worth (RAW), and difference importance measure (DIM) are adopted for risk ranking of individual heaters and other components. It is found that although RAW is simpler to use but its result is not so distinctive among individual components as compared to the other two measures. Since the risk-significance of each component obtained or assumed evolves with time, a proper and economical inspection program that emphasizes certain components at certain times can therefore be made.

Key Words: Nuclear power plant, feedwater system, heater, degradation, risk-informed management.

1. Introduction

In recent years, leakages have been found in feedwater heaters at some nuclear power plants [1]. It is, therefore, suggested that more extensive examination of the feedwater system of nuclear power plants should be made [2]. In cases where the wall of a heater is found to be corroded, they are usually evaluated according to ASME Boiler & Pressure Vessel Code to decide whether a repair or replacement action is needed [3]. The evaluation procedure is rather straightforward but too conservative. It is not consistent with the current trend of risk-based inspection or risk-informed management as well [4]. Therefore, in the present paper, a probabilistic method is proposed to evaluate quantitative risks of individual heaters of a feedwater system. Comparison is made among risks of all...
components of the system. An appropriate risk-based inspection or risk-informed management program can then be implemented accordingly.

2. Formulation

2.1. Degradation Model

In order to determine relative importance measures of components in a system, an appropriate aging physics model of each component has to be considered in advance. Based on the model, together with an associate failure criterion, the failure probability of the component can be evaluated and then incorporated into the probabilistic risk analysis (PRA) of a particular power plant [5]. After repeating the process for all components, the risk metric of the system can be established and risk ranking action can be achieved [6].

For feedwater heaters, it has been pointed out that flow accelerated corrosion (FAC) occurred on the shell side of the tube (as shown in Fig. 1) is the major cause of its degradation [2]. In fact, FAC occurs frequently in nuclear pipes and is by no means a new aging mechanism. Several models have been proposed to predict FAC in nuclear pipes. Although none has been addressed in particular to feedwater heaters, the failure mechanism is basically the same for both pipes and heaters. Therefore, in the present study, the following formula proposed by Siemens and sometimes called KWU formula is adopted for the prediction of thinning rate of the heater-wall [7]:

\[
\Delta \phi_k = 6.35K_C \left\{1.8Be^{0.118p} \left[1 - 0.75(pH - 7)^2\right] + 1\right\} f(t)
\]

(1)

in which \( \Delta \phi_k \) is the thinning rate in \( \mu g/cm^2 \cdot hr \), \( K_C \) is a non-dimensional geometry factor, \( V \) is the flow velocity in m/s, \( g \) is the amount of dissolved oxygen content in ppb, \( pH \) is the scale of concentration of hydrogen ion (water chemistry), and

\[
B = -10.5\sqrt{h} - (9.375 \times 10^{-4} T^2) + 0.79T - 132.5
\]

(2)

\[
N = -0.0875h - (1.275 \times 10^{-3} T^2) + (1.078 \times 10^{-2} T) - 2.15
\]

(3)

\[
f(t) = 0.9999934 - 3.356901 \times 10^{-7} t - 5.624812 \times 10^{-11} t^2 + 3.849972 \times 10^{-16} t^3
\]

(4)

where \( h \) is the content of chromium and molybdenum in %, \( T \) is the temperature in \( ^0K \),

![Fig. 1: FAC in Feedwater Heater.](image)
and \( t \) is the operation hour. Since the droplet-impact wear [8] is observed for feedwater heaters, the following flow velocity that takes into account the two-phase flow has to be considered [7]:

\[
V = \frac{\dot{m}}{\rho_w} \left( \frac{1-x_w}{1-\alpha} \right)
\]  

(5)

in which \( \dot{m} \) is the mass flow rate in kg/m\(^2\)s, \( \rho_w \) is the density of saturated liquid water in kg/m\(^3\), \( x_w \) is the steam quality, and \( \alpha \) is the vapor ratio of the steam mixture.

### 2.2. Failure Criterion and Probabilistic Analysis

For nuclear power plant components such as pressure vessels and pipes, ‘failure’ is frequently defined as component rupture or leakage. However, in the present study, it is defined as ‘the thickness of the heater-wall is reduced to or below the following ASME Code required thickness’ [3]:

\[
t_{m} = \frac{0.9 P r_{i}}{S E - 0.6 P}
\]  

(6)

in which \( t_{m} \) is the allowable thickness, \( P \) is the pressure, \( r_{i} \) is the inner radius, \( S \) is the stress and \( E \) is the fusion efficiency. It should be mentioned that a code-required safety factor 0.9 is considered in Eq. (6) based on the viewpoint of replacing the currently employed deterministic inspection program with a risk-based one.

From the calculation result of Eqs. (1) and (6), one can predict whether a heater has to be repaired or replaced. However, it is a deterministic approach and cannot be used in the further risk analysis. Therefore, some parameters in Eq. (1) are considered random based on real observations and/or reasonable assumptions. A simple Monte Carlo method can then be employed to simulate the randomly occurred wall-thickness reduction and find its probability of exceeding the code-required standard based on simple statistics.

### 2.3. Feedwater System and Importance Measures of Components

The above procedure determines the risk of a feedwater heater. For a feedwater system, there are usually several heaters as well as other components. To be able to implement a risk-based inspection or risk-informed management program, the relative importance measure of each component has to be found. It indicates that each component’s risk has to be evaluated based on the above algorithm, its equivalencies and/or expert judgments. After obtaining all the information and understanding the hierarchy of the system, one can determine each component’s importance through one of the following measures [9, 10].

(i) Fussell-Vesely Importance

\[
FV(X_{j}) = \frac{\left( \bigcup_{i=1}^{n} \text{MCS}^{i}_{j} \right)}{\left( \bigcup_{i=1}^{n} \text{MCS}_{i} \right)} \approx \frac{\left( \bigcup_{i=1}^{n} \text{MCS}^{i}_{j} \right)}{R_{0}}
\]  

(7)
where $p(\bigcup_{i}^{n} \text{MCS}_i)$ is the probability of the union of all the minimum cutsets $i$ containing basic event $X_j$, and $p(\bigcup_{i}^{n} \text{MCS}_k)$ is the nominal risk ($R_o$) computed as probability of all the minimum cutsets.

(ii) Risk Achievement Worth

$$\text{RAW}(X_j) = \frac{R_j^*}{R_o}$$

where $R_o$ is the nominal value of the risk metric (reference overall model risk) and $R_j^*$ is the risk when $X_j$ definitely occurs, i.e. overall model risk with probability of basic event $X_j$ set to 1.

(iii) Differential Importance Measure

$$\text{DIM}(X_j) = \frac{dR_{X_j}}{dR} = \sum_{i} \frac{\partial R}{\partial q_i} dq_i$$

where $dR_{X_j}$ is the change in the risk metric caused by a change in $X_j$, $dR$ is the total change in risk $R$ due to a change in all basic events, and $q_i$ denotes the corresponding probability. Under the assumption of uniform percentage change of $dq_i$ for all $i$, the measure becomes [9]

$$\text{H1}: \text{DIM}(X_j) = \sum_{i} \frac{\partial R}{\partial q_i} dq_i$$

and under the other assumption of uniform percentage change of $dq_i/q_i$ for all $i$, it becomes [9]

$$\text{H2}: \text{DIM}(X_j) = \sum_{i} \frac{\partial R}{\partial q_i} dq_i$$

The above important measures will be used for risk ranking of components of a feedwater system stated below.

3. Numerical Calculation

The tube side of the feedwater system in a BWR nuclear power plant is illustrated as an example. Its system diagram is shown in Fig. 2. Since heaters are emphasized in the present study, the two high pressure side heaters and ten low-pressure side heaters are labeled separately as HPxx and LPxx. Other components are simplified to consist of...
feedwater pump (FP), condenser & de-mineral device (CD) and condenser & condenser heat well (CC). The system’s fault tree is shown in Fig. 3.

Fig. 2: System Diagram.

Fig. 3: Fault Tree of the System
For each heater in the system, its environmental parameters needed in Eq. (1) can either be found or deduced from individual power plant reports. Based on sensitivity analysis and physical judgments, temperature, oxygen content, pH value and fluid velocity are all considered random in our study. They are further assumed to have normal distributions with mean values obtained from power plant reports and 10% of coefficients of variation. Other parameters are considered deterministic. Monte Carlo simulation can then be applied to find the thinning rate of each heater-wall. Given an initial value, random samples of wall-thickness of the heater can be drawn. Statistical methods can subsequently be applied to test the result, and the probability for the heater-wall to exceed its code-required value is then evaluated. As an example, based on conditions shown in Table 1, Fig. 4 indicates sample outcomes of the thinning rate of LP2A. Through Chi-square test, the rate is found to follow a lognormal distribution at the significance level of 5%. The probability for the heater-wall to exceed its code-required value is calculated and shown in Fig. 5, in which EOC indicates the end-of-cycle maintainability time defined as one and a half year.

For the entire system shown in Figs. 2 and 3, the basic events of heaters are defined as their exceeding of code-required values as before. For other components including feedwater pump (FP), condenser & de-mineral device (CD) and condenser & condenser heat well (CC), their basic events are considered as malfunctions caused by fire accident according to power plant reports. Under the operational conditions shown in Table 2, the

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>T</td>
<td>405</td>
<td>40.5</td>
<td>Normal</td>
</tr>
<tr>
<td>Exposure time (hr)</td>
<td>t</td>
<td>13140</td>
<td>0</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Oxygen content (ppb)</td>
<td>g</td>
<td>30</td>
<td>3</td>
<td>Normal</td>
</tr>
<tr>
<td>Water chemistry (pH)</td>
<td>pH</td>
<td>7</td>
<td>0.7</td>
<td>Normal</td>
</tr>
<tr>
<td>Steam quality</td>
<td>x_{st}</td>
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<td>0</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Geometry factor</td>
<td>K_{C}</td>
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<td>0</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Cr + Mo (%)</td>
<td>h</td>
<td>0</td>
<td>0</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Fluid velocity (m/s)</td>
<td>V</td>
<td>4.02</td>
<td>0.40</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Fig. 4: Sample Thinning Rates of LP2A.
Table 2: Operational Conditions for Individual Heaters.

<table>
<thead>
<tr>
<th>FWH</th>
<th>Pressure (MPa)</th>
<th>Temperature (°F)</th>
<th>Fluid velocity (m/s)</th>
<th>Oxygen content (ppb)</th>
<th>Water chemistry (pH)</th>
<th>Steam quality (%)</th>
<th>Allowable wall-thickness (mm)</th>
<th>Thickness detected at EOC17 (mm)</th>
</tr>
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<tbody>
<tr>
<td>HP1A</td>
<td>2.76</td>
<td>475</td>
<td>7.47</td>
<td>35</td>
<td>7</td>
<td>94</td>
<td>16.41</td>
<td>22.17</td>
</tr>
<tr>
<td>HP1B</td>
<td>2.76</td>
<td>475</td>
<td>7.47</td>
<td>35</td>
<td>7</td>
<td>94</td>
<td>16.41</td>
<td>21.84</td>
</tr>
<tr>
<td>LP2A</td>
<td>1.72</td>
<td>405</td>
<td>4.02</td>
<td>30</td>
<td>7</td>
<td>88</td>
<td>10.21</td>
<td>12.60</td>
</tr>
<tr>
<td>LP2B</td>
<td>1.72</td>
<td>405</td>
<td>4.02</td>
<td>30</td>
<td>7</td>
<td>88</td>
<td>10.21</td>
<td>14.15</td>
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<tr>
<td>LP3A</td>
<td>0.69</td>
<td>350</td>
<td>4.33</td>
<td>25</td>
<td>7</td>
<td>99.9</td>
<td>4.11</td>
<td>9.07</td>
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<td>0.69</td>
<td>350</td>
<td>4.33</td>
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<tr>
<td>LP4A</td>
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<td>4.57</td>
<td>22</td>
<td>7</td>
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<td>2.08</td>
<td>9.60</td>
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<td>22</td>
<td>7</td>
<td>98</td>
<td>2.08</td>
<td>8.66</td>
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<tr>
<td>LP5A</td>
<td>0.34</td>
<td>300</td>
<td>5.73</td>
<td>22</td>
<td>7</td>
<td>85.5</td>
<td>2.21</td>
<td>9.63</td>
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<td>7</td>
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<td>8.71</td>
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<tr>
<td>LP6A</td>
<td>0.34</td>
<td>280</td>
<td>5.49</td>
<td>20</td>
<td>7</td>
<td>90</td>
<td>2.29</td>
<td>10.01</td>
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<td>280</td>
<td>5.49</td>
<td>20</td>
<td>7</td>
<td>90</td>
<td>2.29</td>
<td>10.54</td>
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</tbody>
</table>

Fig. 5: Probability of exceeding Code-required Value.

occurrence probabilities of the basic events for heaters at each EOC are obtained following procedures stated above. The results are summarized in Table 3. In the same table, the occurrence probabilities of basic events for CC, FP and CD are deduced from plant reports. Having all these information and in consideration of the system structure, the importance measures of the components at any time (EOC) can be found. For example, Fig. 6 indicates the Fussell-Vesely important measure of each component for the studied system at the 26th EOC, in which notations HP and LP have been put aside for simplicity. To examine how the risk ranking of each component varies with time, Fig. 7 is constructed, which includes FV, RAW, DIM H1 and DIM H2 measures. For some measures, curves do not appear in the diagram since their values are too small.
Table 3: Occurrence Probabilities of Basic Events.

<table>
<thead>
<tr>
<th>Component</th>
<th>EOC18</th>
<th>EOC19</th>
<th>EOC20</th>
<th>EOC21</th>
<th>EOC22</th>
<th>EOC23</th>
<th>EOC24</th>
<th>EOC25</th>
<th>EOC26</th>
<th>EOC27</th>
<th>EOC28</th>
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<tbody>
<tr>
<td>FP</td>
<td>0.00164</td>
<td>0.00329</td>
<td>0.00493</td>
<td>0.00657</td>
<td>0.00821</td>
<td>0.00985</td>
<td>0.01148</td>
<td>0.01311</td>
<td>0.01474</td>
<td>0.01636</td>
<td>0.01798</td>
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<tr>
<td>CD</td>
<td>0.00284</td>
<td>0.00568</td>
<td>0.00851</td>
<td>0.01133</td>
<td>0.01414</td>
<td>0.01695</td>
<td>0.01975</td>
<td>0.02254</td>
<td>0.02532</td>
<td>0.02809</td>
<td>0.03086</td>
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<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
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<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
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</tr>
<tr>
<td>HP1B</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
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<tr>
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<td>0.00017</td>
<td>0.0013</td>
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<td>0.00004</td>
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<td>0.00038</td>
<td>0.00085</td>
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<td>0.00001</td>
<td>0.00003</td>
<td>0.00024</td>
<td>0.00374</td>
<td>0.01595</td>
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Fig. 6: Fussell-Vesely Importance Measures of Components at the 26th EOC.

Fig. 7: Risk ranking of components based on (a) FV, (b) RAW, (c) DIM H1, and (d) DIM H2 measures.

4. Conclusion

The present study illustrates how a deterministic physics failure model can be incorporated into FTA and PRA analyses, and how the risk metric of a system can be constructed for use in the risk-based inspection or risk-informed management. With regard to the studied feedwater system, under the assumptions made, it is concluded that
heaters at the second half of the low-pressure section such as LP6A, LP6B, LP5A, LP5B and LP4B need to be inspected more frequently. Other heaters that need attention are LP2A and LP3A. From the experience gained, it is found that RAW importance measure is easier to apply and would give us more conservative result. Although the FV and DIM measures are more difficult to apply, they usually give us more distinctive risk indices among different components.

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References


W. F. Wu received the B.S. degree in Civil Engineering from National Taiwan University in 1977, the M.S. and Ph.D. degrees in Aeronautical and Astronautical Engineering from University of Illinois at Urbana-Champaign, IL in 1983 and 1985, respectively. He had worked at Florida Atlantic University, Boca Raton, FL and Columbia University, New York, NY before joining National Taiwan University as an associate professor in 1988. He is now a professor at the Department of Mechanical Engineering with a joint appointment at the Graduate Institute of Industrial Engineering. He has served as the chairman of the Department of Mechanical Engineering from 2001 to 2004. His research interests include random vibration, reliability engineering and probabilistic risk assessment.