Reliability of PHT Piping System in PHWR against Erosion Corrosion

A. SRIVIDYA¹, H.N. SURESH¹*, A.K. VERMA¹ and GOPIKA VINOD²

¹Reliability Engineering Group, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
²Scientist, RSD, BARC, Mumbai

(Received on December 31, 2006)

Abstract: Erosion corrosion (EC), also referred to as Flow Accelerated Corrosion (FAC), is one of the major degradation mechanisms in Primary Heat Transport (PHT) piping system of Pressurized Heavy Water Reactor (PHWR) and therefore needs to be addressed in assessing reliability of piping system. In this paper, an existing model is used to find the FAC rate in the straight and elbow section of an outlet feeder. The effect of various factors affecting FAC is highlighted. Deterministic method is first used to evaluate the FAC rate and probabilistic method is applied to evaluate the reliability of the system under consideration. The point estimate of reliability of the piping component is illustrated, considering the component to be in series.

Keywords: Degradation, Erosion Corrosion, Flow Accelerated Corrosion, Feeders, Reliability Index, Exposure period.

1. Introduction

Piping system made of carbon steel is used to carry heavy water in a PHWR and forms a part of passive structural components in NPP. This is one of the most critical systems because of its complex layout. Several degradation mechanisms act on the piping system, FAC being one of them which results in metal loss leading to thinning of piping walls. This can result in fatal accidents. Several accidents in the past were due to thinning related to FAC [1-2]. Hence, this needs to be carefully studied and analyzed. Reliability predictions based on degradation models can be useful when data is rare or few in numbers. Degradation models can be applied in nuclear power plant components.

2. Erosion–Corrosion

Erosion corrosion is an accelerated form of corrosion caused by relative motion between corrosive medium and the metal surface, leading to loss of material. Modeling erosion corrosion is complex as it is affected by number of parameters like pH, dissolved oxygen content, fluid velocity, chemical composition of steel pipe (chromium and molybdenum) content and particle impact angle. Attempts have been made by many researchers to develop models for the estimation of EC rate and subsequently to determine the remaining service life. The model developed by Stack et al. [3] is applicable for low particle impact angles, low flow velocity, constant temperature and constant pH of flowing fluid.
Abdulsalam and Stanley [4] developed a steady state model considering steady hydrogen flux through metal and established that erosion corrosion is dependent on kinetic rate of metal oxide film dissolution at low temperatures and on mass transfer limited rate at high temperatures. Ting and Ma [5] developed a model considering the statistical data of pipe wall thickness from Taiwan PWR nuclear power plant for different piping components with different operating conditions. The model can be used for both steady and unsteady conditions. Kastner [1] developed a deterministic model for estimating the erosion corrosion rate as a function of Keller’s Geometry Factor, Flow Velocity, Fluid Temperature, Material Composition, Fluid Chemistry, Exposure Time and Steam Quality in case of two phase flow. Kastner’s model is used in this paper.

2.1 Factors Affecting Erosion Corrosion

Several factors are identified [6] that affect the EC rate and are classified as:

Hydrodynamic – Fluid velocity, Pipe geometry, Roughness of inside surface.
Metallurgical – Chemical composition-Chromium, Molybdenum and Copper in steel.
Environmental – Temperature, Water chemistry including dissolved Oxygen and pH.

Sensitivity analysis is carried out to illustrate the effect of these parameters on FAC rate and is discussed in section 4.

2.2 Erosion Corrosion Rate Calculation

Erosion corrosion rate, also called Flow Assisted Corrosion (FAC) rate, can be determined by using Kastner’s model [1] to find out the thickness of pipe. The model used estimates corrosion rate as a function of Keller’s geometry factor, flow velocity, fluid temperature, material composition, fluid chemistry (pH at 25°C and dissolved oxygen), exposure time and in the case of 2 phase flow, steam quality. The pipe thickness can be calculated as a function of time.

The wall corrosion $t_c(T)$ is the thickness of pipe corroded and is given by

$$ t_c(T) = \frac{RT}{\rho_S} $$

(1)

$R$ = FAC rate ($\mu g/cm^2/hr$)
$T$ = exposure time (hr)
$\rho_S$ = density of steel ($\mu g/cm^3$)

Once FAC rate is found, the thickness can be calculated by

$$ t_p(T) = t_o - t_c(T) $$

(2)

$t_p(T)$ = pipe wall thickness at time T (cm)
$t_o$ = original nominal pipe thickness (cm)
$t_c(T)$ = calculated thickness of pipe corroded at time T (cm)

$$ R = 6.35 \times K \times (B \times e^{N \times \theta}) \times (1 - 0.175 \times (pH - 7)^2) \times 1.8 \times e^{(-0.1187)} \times 1 + 1) \times f(T) $$

(3)

$$ B = -10.5 \times \theta - (9.375 \times 10^{-4} \times \theta^2) + (0.79 \times \theta) - 132.5 $$

(4)

$$ N = -0.0875 \times h - (1.275 \times 10^{-3} \times \theta^2) + (1.078 \times 10^{-2} \times \theta) - 2.15 \quad \text{For } 0 \leq h \leq 0.5\% $$

$$ N = (-1.29 \times 10^4 \times \theta^2 + 0.109 \times \theta - 22.07) \times e^{0.154 h} \quad \text{For } 0.5\% \leq h \leq 5\% $$

(5)
Reliability of PHT Piping System in PHWR against Erosion Corrosion

\[ R = \text{calculated specific rate of material loss (µg/cm}^2\text{ hr)} \]

\[ K_C = \text{geometrical factor} \]

\[ V = \text{flow velocity (m/s)} \]

\[ pH = \text{pH value} \]

\[ g = \text{oxygen content ((µg/kg)} \]

\[ h = \text{content of chromium and molybdenum in steel} \]

\[ \theta = \text{temperature (°K)} \]

\[ f(T) = \text{a time correction factor} \]

The time correction factor \( f(T) \) is a function of exposure period and is given by

\[ f(T) = C_1 + C_2 \times T + C_3 \times T^2 + C_4 \times T^3 \] (7)

where \( T \) is the exposure time (hrs)

\[ C_1 = 0.9999934, C_2 = -0.3356901 \times 10^{-6}, C_3 = -0.5624812 \times 10^{-10}, C_4 = 0.3849972 \times 10^{-15} \]

Keller’s geometrical factor \((K_C)\) for different configurations is given by Kastner et.al. [7]. Kastner’s model being a conservative one, calls for the introduction of a correction factor [1] to take care of the inherent uncertainties. Depending upon the corrosion rate, the error factors are employed as shown in Table 1.

Table 1: Error Factor for Kastner’s Model

<table>
<thead>
<tr>
<th>Erosion Corrosion Rate (µg/cm²/hr)</th>
<th>Error Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>6.83</td>
</tr>
<tr>
<td>10-50</td>
<td>6.62</td>
</tr>
<tr>
<td>50-200</td>
<td>5.46</td>
</tr>
<tr>
<td>200-2000</td>
<td>14.99</td>
</tr>
</tbody>
</table>

The multiplied values are then used in finding the corroded wall thickness \((t_C)\) and the remaining pipe wall thickness \((t_p)\).

3. Reliability Analysis Concepts

Reliability is the probability of a structural component performing satisfactorily during its lifetime. It is quantified by reliability index \((\beta)\) [8] a measure of structural safety, defined as the ratio of mean of safety margin \((Z)\) and the standard deviation \((\sigma)\) of the safety margin.

The reliability index is given by

\[ \beta = \frac{\mu_Z}{\sigma_Z} \] (8)

Safety margin at any time \(T\) is given by

\[ Z = \left( \frac{t_T - t_{min}}{t_{min}} \right) \] (9)

Where \( t_{min} \) is the minimum wall thickness obtained from 0.8 times \( t_o \) [9] or ASME Boiler and Pressure Vessel Code [10].

The thickness of the pipe is assumed deterministic [11-12] as good control is observed from equation .
\[ t_o = t_{\text{min}} + A_t R T' \]  
where \( R \) is the predicted EC rate and \( A_t \) is the modeling error and \( T' \) is the service life and \( t_o \) is the design thickness.

The thickness at any time \( T \) where \( T < T' \) is given by

\[ t_T = t_o - A_t R T \]  

Due to randomness in \( R \) and \( A_t \), \( t_{\text{min}} \) is also a random variable. If \( Z \leq 0 \), it represents a failure state and \( Z > 0 \) represents a safe state.

The relationship between reliability index \( \beta \) and failure probability \( p_f \) [11-12] is given by

\[ \Phi(\beta) = \Phi(\beta + \beta) \]  

where \( \Phi(\cdot) \) is the cumulative distribution of standard normal variable.

The probability of failure represents the probability of wall thickness at any time becoming less than the required wall thickness.

The expected value of safety margin at any time \( T \) [12] is

\[ \mu(Z_T) = \frac{t_T - t_{\text{min}}}{t_{\text{min}}} = \frac{(t_o - t_{\text{min}}) - (A_t R T)}{t_{\text{min}}} \]  

The standard deviation \( \sigma_Z \) of the safety margin at different time during the service life [12] is obtained by finding the variance of \( (Z_T) \) which is given by

\[ \text{Var}(Z_T) = \left( \frac{T^2}{t_{\text{min}}^2} \right) \times \left( \text{Var}(A_t) \times \mu(A_t)^2 + \text{Var}(R) \times \mu(R)^2 \right) \]  

where the variance of \( R \) and \( A_t \) [11] are given by

\[ \text{Var}(A_t) = \left[ \text{COV}(A_t) \times \mu(A_t) \right]^2 \]  

\[ \text{Var}(R) = \left[ \text{COV}(R) \times \mu(R) \right]^2 \]  

where \( \text{COV}(A_t) \) and \( \mu(A_t) \) are the coefficients of variation and the nominal mean value of modeling error \( (A_t) \) respectively and \( \text{COV}(R) \) and \( \mu(R) \) are the coefficients of variation and the nominal mean value of wear rate \( R \), respectively.

The computed failure probability gives the probability of failure of the piping system at any point of time \( T \) against erosion–corrosion.

### 3.1 Reliability of Series Systems

The identification of systems and subsystems is dependant on the level of modeling adopted in reliability analysis. Between the available analytical and simulation methods of reliability analyses, the former one is employed in this paper.

First Order Second Moment method (FOSM) [8] is employed to find the reliability indices at different exposure times. The mean and the standard deviation of the safety margin equation required for computing reliability are determined from the first order approximation. The different sections within a given piping which undergo erosion corrosion are considered separately in this study for all possible locations of the erosion corrosion damage connected in series.
If there are ‘n’ locations within a piping, there are n elements and the system failure occurs when the thickness at any location is less than or equal to $t_{\text{min}}$ at any time. For a series system having equally correlated ‘n’ failure elements with safety margin linearly and normally distributed as per the FOSM, the probability of failure is given by [13]

$$p_f = (1 - \Phi_n(\beta_i, \rho)) = 1 - \int_{-\infty}^{+\infty} \phi(t) \prod_{i=1}^{n} \left[ \Phi \left( \frac{\beta_i + \sqrt{\rho}t}{\sqrt{1 - \rho}} \right) \right] dT$$

(17)

Where $\Phi_n(\beta_i, \rho) = n$-dimensional standard normal distribution, $\phi(\cdot)$ and $\Phi(\cdot)$ are the density and distribution functions of the standard normal variate, $\rho$ is the correlation coefficient and $\beta$ is the reliability index.

Assuming that $\beta_i = \beta_e$ (the element reliability index) for $i = 1, 2 \ldots n$, the system failure probability is given by

$$p_f = 1 - \int_{-\infty}^{+\infty} \left[ \Phi \left( \frac{\beta_e + \sqrt{\rho}t}{\sqrt{1 - \rho}} \right) \right] \phi(t) dT$$

(18)

Once the probability of failure is known, the corresponding system reliability index can be determined using

$$\beta = -\Phi^{-1}(p_f) \text{ or } p_f = \Phi(-\beta)$$

(19)

By numerical integration, the probability of failure for different correlation coefficients is estimated.

4. Case Study

To demonstrate feasibility of the model, a case study has been described in this section. The example case consists of PHWR outlet feeder which has 306 small pipes ranging from 32mm to 70mm in diameter, and 2m to 22m in length, which connects the outlet header to the steam generator. Feeder made of carbon steel A106GrB having the following Chemical composition [14] (%) C, Mn, P, Si, Cr, Ni, Mo as 0.3, 0.29, 0.035, 0.1, 0.4, 0.4 and 0.15 respectively is used. According to Ting and Ma [5], the susceptible piping components in nuclear power plants are 90° elbow, 45° elbow, Reducer, Tee and Straight Pipes. An elbow with an R/D of 0.5 is considered for the study. Other parameters of study for one such feeder [15] are shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2: FAC Parameters for the Example Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Operational time</td>
</tr>
<tr>
<td>Piping Material (Cr )</td>
</tr>
<tr>
<td>Piping geometry (elbow with R/D of 0.5&quot;)</td>
</tr>
<tr>
<td>Piping geometry (Straight )</td>
</tr>
<tr>
<td>Fluid velocity</td>
</tr>
<tr>
<td>Dissolved oxygen concentration</td>
</tr>
<tr>
<td>Water chemistry</td>
</tr>
<tr>
<td>Water temperature</td>
</tr>
<tr>
<td>Initial thickness of pipe</td>
</tr>
</tbody>
</table>
Sensitivity analysis of the parameters affecting FAC is carried out and the results are shown in Figures 1 through 5. From Figure 1, it is seen that FAC decreases with increase in pH, a behavior in agreement with Vinod et al. [15] but with differing rates, as the models used are different. While Kastner’s model [1] is used in this paper, Vinod et al. [15] employ the model as propounded by Abdulssalam and Stanley [4]. FAC also decreases with increase in the chromium content, as shown in Figure 2.

Figure 1: FAC Rate vs. pH

Figure 2: FAC Rate vs. Chromium content

Figure 3: FAC Rate vs. Flow Velocity

Figure 4: FAC Rate vs. Oxygen Content

Figure 5: FAC Rate vs. Temperature

Figure 6: FAC rate vs. Exposure Time
FAC rate increases with increase in Flow Velocity and Oxygen content, as depicted in Figure 3 and Figure 4, respectively. FAC increases with increase in Temperature up to 422 K and from then on decreases as shown in Figure 5.

The results of FAC for single phase outlet feeder (whose parameters are given in Table 2) for a straight section and an elbow are shown in Figure 6, which illustrates the behavior of FAC rates with exposure time for a single phase flow for the example case. It is seen from Figure 6 that FAC rate increases with exposure period, and is higher in the elbow section than in the straight section.

Figure 7 shows the results of reliability analysis of the selected outlet feeder with the following details:

- Erosion corrosion rate: 0.0252 mm/yr
- Modeling error: 1
- Initial thickness of feeder $t_0$: 6.75mm
- Minimum required thickness $t_{min}$: 5.4 mm

As expected, the reliability of the system decreases with exposure period, as depicted in Figure 6. Initially the reliability index is high and decreases to a minimum of 3.57 at the end of 25th year.

Using the data in Table 3 for the example case, the results of reliability evaluation for different coefficients of variation of the estimated corrosion rates (R) are shown in Figure 8. The impact of modeling error is further demonstrated in Figure 9.

![Figure 7: Reliability Index vs. Exposure Period for the Outlet Feeder](image)

![Figure 8: Reliability Index with COV(R) at Different Exposure Period](image)

![Figure 9: Reliability Index with COV ($A_t$) at Different Exposure Period](image)
Table 3 shows the details of the FAC parameters used in reliability assessment considering it as a series system, assuming 8 components which are correlated. Variation of probability of failure with exposure time for different correlations of components (0, 0.5 and 0.95) is presented in Figure 10.

Table 3: FAC parameter for reliability evaluation of outlet feeder

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean corrosion rate (mm/year) ( \mu ) (R)</td>
<td>0.0252</td>
</tr>
<tr>
<td>2</td>
<td>COV of rate ( \text{COV}(R) )</td>
<td>0.254</td>
</tr>
<tr>
<td>3</td>
<td>Mean of modeling error ( \mu ) (( A_i ))</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>COV of modeling error ( \text{COV}(A_i) )</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>Nominal thickness of pipe ( t_n ) (mm)</td>
<td>6.75</td>
</tr>
<tr>
<td>6</td>
<td>Minimum thickness ( t_{\text{min}} ) (mm)</td>
<td>5.40</td>
</tr>
</tbody>
</table>

![Figure 10: Failure Probabilities at Different Exposure Periods](image)

5. Results and Discussion

Flow accelerated corrosion is a phenomenon that results in the metal loss from piping vessels and equipments made of carbon steel. It occurs under such conditions of flow and geometry of material which are common in high energy piping and tubing in nuclear power plants. Figure 1 indicates that erosion corrosion rate is high in the case of elbow sections than in straight sections. Erosion corrosion is sensitive to factors like temperature, exposure period, flow velocity, material, pH value of the fluid and oxygen content. Erosion corrosion reduces with increase in pH and increases with increase in flow velocity and oxygen content. This effect is shown in Figures 1 through 6. Erosion corrosion initially increases at a faster rate and then gradually over the remaining operating period.

As expected, reliability of the system decreases with time as indicated in Figure 7. It is seen from Figure 8 and Figure 9 that reliability of the system decreases with increase in COV of the FAC rate (R) and the modeling error (\( A_i \)) respectively. Further, it could be noticed that in the beginning years of the system’s life, the decrease is comparatively significant to that towards the end of its service life (normally 40 years).
Figure 10 illustrates that probability of failure is almost zero until 20 years and then increases with increased exposure period. Also, the probability of failure decreases with increase in the correlation coefficient between safety margins of different sections which are susceptible to FAC.

6. Conclusions

Erosion corrosion is one of the major degradation mechanisms acting in certain critical components in PHT piping system of PHWR. A model for the reliability of corroded pipeline considering uncertainty is presented. The factors affecting FAC are discussed and from the study it is seen that the FAC rate increases with increase in fluid velocity, oxygen content and decrease in pH level of the fluid (Heavy water) and chromium content in the component. Reliability is affected by degree of uncertainty in the parameters of model. The COV of variables R and A<sub>t</sub> is a measure of uncertainty present and hence sensitivity analysis is conducted to demonstrate the effect of variation in COV of R and A<sub>t</sub>. It is observed from the study that reliability decreases with increase in COV of the variables and the sensitivity of Reliability decreases with increased exposure period. From the study, it is concluded that an accurate estimation of COV is required during short exposure periods. Hence there is a need to monitor and control the parameters like temperature, flow velocity, pH and oxygen content, accurately to avoid failure of pipelines against thinning due to erosion corrosion. The methodology is illustrated with an outlet feeder on PHT of PHWR.

References


