A PROBABILISTIC DEGRADATION MODEL FOR THE ESTIMATION OF THE REMAINING LIFE DISTRIBUTION OF FEEDERS

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ABSTRACT

Wall thinning due to flow accelerated corrosion (FAC) is a pervasive form of degradation in the outlet feeder pipes of the primary heat transport system of CANDU reactors. The prediction of the end-of-life of a feeder from wall thickness measurement data is confounded by the sampling and temporal uncertainties associated with the FAC degradation phenomenon. Traditional regression-based statistical methods deal with only the sampling uncertainties, leaving the temporal uncertainties unresolved. This paper presents an advanced probabilistic model, which is able to integrate the temporal uncertainties into the prediction of lifetime. In particular, a random gamma process model is proposed to model the FAC process and it is calibrated with a set of wall thickness measurements using the method of maximum likelihood. This information can be used to establish an optimum strategy for inspection and replacement of feeders.

Keywords: *flow-accelerated corrosion, feeder thinning, end of life, renewal theory, gamma process, life-cycle management*

1 Introduction

1.1 *FAC Degradation*

Feeder pipes that connect fuel channels and headers are important parts of the primary heat transport system of a CANDU reactor. High temperature (about 310-312 °C) heavy water flows out of individual CANDU channels via the feeder pipes into outlet headers and then goes to steam generators. After heat exchange in the steam generators, the lower-temperature (typically 266°C) heavy water flows back to inlet header and is then distributed to fuel channels through inlet feeders.

Flow accelerated corrosion is a process whereby the normally protective oxide layer on carbon steel dissolves into a stream of flowing water or wet steam (Dooley and Chexal, 2000). It is an electrochemical corrosion enhanced by mass transfer in flowing water. FAC can be generally divided into two subsequent processes (Figure 1): (1) the production of soluble ferrous ions at the oxide-water interface, and (2) the transfer of the ferrous ions into the bulk water across the diffusion boundary layer. It is thus expected that any facto rs that influence the iron oxidation, dissolution of magnetite and diffusion and transfer of ferrous ions can affect the rate of FAC. Those factors include the fluid velocity, pipe configuration, water temperature, water chemistry (e.g. pH value) and metallurgical variables such as chromium content in the steel.

The feeder thinning due to FAC is observed exclusively in the outlet feeders and not in the

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inlet feeders because the ferrous ion concentration is saturated in the inlet and it is highly unsaturated in the outlet feeders due to temperature rise. The greater concentration gradient between the oxidation layer and bulk flow provides a big driving force for FAC.

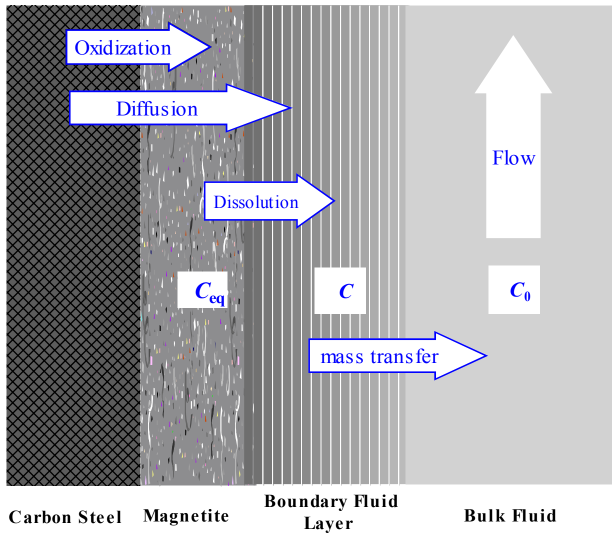

Figure 1: FAC process consisting of two subsequent processes. The first process produces soluble ferrous ions at the oxide-water interface which are separated into three simultaneous actions: 1) metal oxidation, 2) diffusion of ferrous species from the iron surface to the boundary fluid layer through the porous oxide layer, and 3) dissolution of magnetite oxide layer. The second process involves the transfer of the ferrous ions into the bulk fluid across the boundary layer

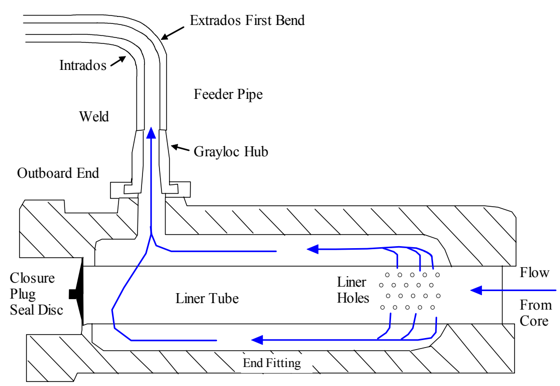

Figure 2: Illustration of end-fitting and outlet feeder pipe (from Burrill and Cheluget, 1999)

All outlet feeder pipes (SA 106 Grade B carbon steel) have typical nominal diameter of either 2.0" or 2.5" at the reactor face. The water is mildly alkaline ($10.2 < pH_a < 10.8$) and contains dissolved deuterium. The flow leaves the end-fitting annulus via a right-angle turn and enters a Grayloc hub (SA 105 carbon steel), resulting in a disturbed turbulent flow at the entrance to the outlet feeder pipe, which triggers the flow-accelerated corrosion downstream of the hub especially at the first bend (Figure 2). The operating flow velocity in individual pipes varies with channel power from 8 to 18 m/s (Burrill and Cheluget, 1999).

The bending process during pipe fabrication causes thinning at the extrados and thickening at the intrados. Depending upon the bending process and radius of the bend (bending angles), the difference in thickness between intrados and extrados can be up to 25% (Kumar 2004). It is presumed that the extrados at the 1st bend of the feeder pipe is most vulnerable to FAC because of the enhanced turbulence and the lower wall thinning allowance.

Several empirical FAC models have been reported in the literature based on different interpretations of the FAC mechanism (Berge et al., 1980; Burrill, 1995; Burrill and Cheluget 1999; Lang, 2000). Berge et al. (1980) expressed the FAC, R, rate as

$$R = \frac{1}{1/(2k_d) + 1/k_m}\left(C_{eq} - C_0\right) \qquad (1)$$

where k_d = magnetite dissolution coefficient, k_m = mass transfer coefficient, C_{eq} and C_0 the concentration of ferrous ion in the metal surface and bulk water, respectively. When mass transfer controls the FAC, which is common for CANDU systems, the following linear relationship was proposed by Ducreaux (1983):

$$R \approx k_m\left(C_{eq} - C_0\right) \qquad (2)$$

Since the mass transfer coefficient k_m is usually expressed as a power function of the flow velocity (Berger and Hau, 1977), the FAC rate in general can be expressed as a power function of the flow velocity, i.e., $R \propto V^{\alpha}$, where V denotes the flow velocity. These observations can be used for developing a probabilistic model of the FAC process.

1.2 *Life-Cycle Management Issues*

Wall thinning of feeders due to flow accelerated corrosion (FAC) is a life-limiting degradation phenomenon. The nominal end of life is defined as the time when the wall thickness has been reduced to the minimum acceptable wall thickness. The inspection data show that wall-thinning data exhibit considerable scatter, and it suffers from both sampling and temporal uncertainties. The sampling uncertainty arises from the fact that inspection sample is generally a small portion of the overall population. Due to the small sample size, the determination of representative distribution type becomes difficult, resulting in the modelling error. Another consequence of small sample size is that it hinders an accurate estimation of the distribution parameters, and they should ideally be treated as random variables. The extrapolation of finite sample estimates to the population therefore suffers from aforementioned uncertainties. The effect of the temporal uncertainty is that the rate of degradation becomes randomly variable with age.

Because of uncertainties associated with FAC, a precise determination of the end of life is not possible. An adequate consideration of uncertainties is mandatory for safe and efficient life-cycle management of the feeder system. The paper proposes a probabilistic model to account for uncertainties associated with FAC and estimate the distribution of remaining lifetime. This information can be used to establish an optimum time of feeder replacement.

2 Wall Thickness Data

The paper presents a probabilistic analysis of a set of wall thickness data from feeder pipes that are typical to a CANDU 6 PHTS. The data involve measurements from the extrados of type VI outlet bends (type VI defines the geometrical configuration). The sample consists of 284 measurements of minimum wall thickness near the bend extrados taken from 193 feeders at six inspection outages. As indicated in Table 1, about 70 percent of the inspected bends were measured only once whereas less than 4 percent were measured more than three times. There is only one bend that was measured at all six inspection outages, and its deterioration path is plotted as a thick line in Figure 3 (a).

The loss of wall thickness of the bend demonstrates a nearly linear trend over time. This linear relationship is also verified by the other four bends with five measurements as shown in Figure 3(a). Based on this observation, the assumption of mean deterioration being linear over time is justified.

Table 1: Ratio of Repeated Measurements

Number of Repeated Measurements	Number of Pipes	Percentage (%)
1	132	68.4
2	44	22.8
3	10	5.2
4	2	1.0
5	4	2.1
6	1	0.5
Total	193	100.0

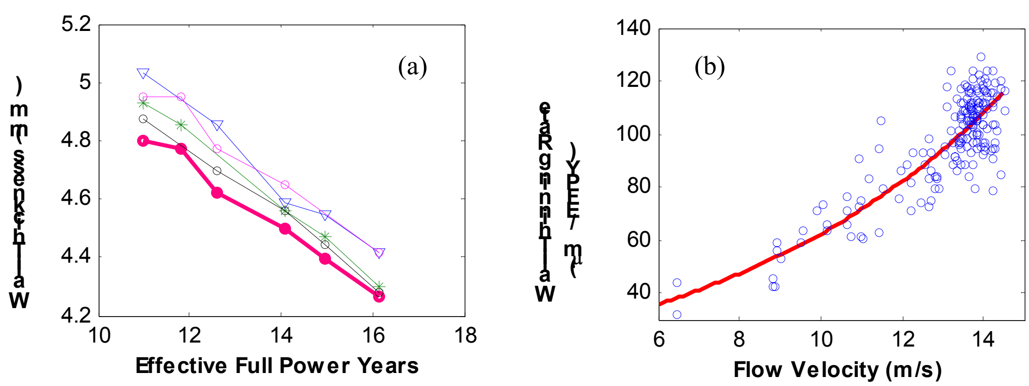

Figure 3: Scatter plot of wall thickness measurements. (a) Linear trend of wall thinning over time, and (b) Nonlinear relationship of wall thinning rate against flow velocity.

As discussed in the last section, the FAC rate and thus the wall thinning rate are influenced by many factors, among them the flow velocity being the most significant contributor due to its greatest variability. This is even more correct for the present case in which other factors such as geometry (bend type), coolant temperature and pH are nearly constant for all feeders. One of our main objectives is to find out the correlation of the wall-thinning rate with the flow velocity. From thermal-hydraulic analysis, the flow velocity at the first bend of the outlet feeder can be calculated. The time-averaged flow velocity from both one- and two-phase flow is used. Figure 3(b) plots the thinning rate against the flow velocity. The thinning rates are calculated from the measured wall thickness loss divided by the corresponding effective full power years; for feeders that were measured several times, the average values are used. The scatter-plot shows great variability and a nonlinear trend of the wall thinning rate with flow velocity is observed. It is seen that most of the feeders experience a heavy water flow velocity of 12 to 14 m/s.

The initial feeder wall thickness of the inspected pipes is not known. However, recent measurements of the wall thickness from 17 spare bends that had not been installed provide the baseline for initial wall thickness. Figure 4 shows that the variation in the initial wall thickness is very small and so only the mean value, 6.223 mm, is used as a constant initial thickness in the subsequent analysis.

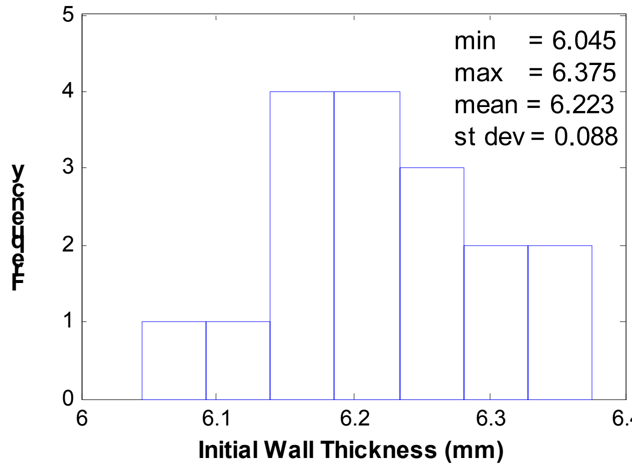

Figure 4: Histogram for the initial wall thickness

3 Probabilistic Model of FAC

3.1 *Degradation as a Random Process*

The loss of wall thickness due to FAC is a slow, incremental process of mass loss by electrochemical and diffusion reactions. The inspection however measures the remaining wall thickness from which a cumulative loss of wall thickness can be obtained. Such degradation can be conceptually modeled in the following manner.

The amount of wall thickness loss at any k^{th} instant, referred to as the incremental damage, is uncertain, so it is modeled as a positive random variable denoted as X_k. Suppose n increments of damage occur in a time interval from 0 to t. The total damage observed up to time t, denoted as $Y(t)$, is a sum of these increments

$$Y(t) = X_1 + X_2 + ... + X_n \tag{3}$$

The distribution of X_k is somewhat difficult to estimate from small samples and infrequent inspections. The least informed (or unbiased) choice is the exponential distribution, as it requires the knowledge of only the average amount of damage increment. Assuming that damage increments are independent from one another, the cumulative damage is gamma distributed. Here another source of uncertainty is the number of damage increments, n, in the time interval $(0, t)$. It can often be assumed to follow a Poisson process, such that the number n can be taken as a Poisson distributed random variable. This model is referred to as stochastic compound Poisson process.

In cases where degradation takes place in very small increments almost continuously over time, a limiting form of the compound Poisson process can be derived in which the Poisson rate of damage occurrence approaches infinity in any finite time interval as the size of the increment tends to zero (Dufresne, Gerber and Shiu, 1991). Such a process is referred to as a stochastic gamma process, which is in principle a continuous-time Markov process with independent and gamma distributed increments. The gamma process is ideal for modeling degradation progressing with frequent occurrence of very small increments, such as corrosion, creep and wear of components (Cinlar et al. 1977, van Noortwijk and Klatter 1999, Lawless and Crowder 2004).

A stationary gamma process, denoted by $X(t)$, has two basic parameters: a shape parameter η and scale parameter δ. By definition, the deterioration at time t is gamma distributed as

$$f_{X(t)}(x) = \frac{(x/\delta)^{\eta t-1}}{\delta\,\Gamma(\eta t)} e^{-x/\delta} \tag{4}$$

The mean deterioration path is given as

$$E[X(t)] = \eta\delta\, t \tag{5}$$

which is a linear function of time with mean deterioration rate $\eta\delta$. Moreover, its increments at disjointed time intervals are independent and each increment, $\Delta X(t)=X(t+\Delta t)-X(t)$, is also distributed, i.e.,

$$f_{\Delta X(t)}(x) = \frac{(x/\delta)^{\eta\,\Delta t-1}}{\delta\,\Gamma(\eta\Delta t)} e^{-x/\delta} \tag{6}$$

Data presented in Section 2 show that wall thinning is reasonably linear over time, so it can be modeled as a stationary gamma process.

Suppose the end of life is defined when the damage exceeds a limit or failure threshold, denoted as x_F. Due to the monotonic nature of the sample path of the gamma process, the lifetime distribution can be obtained as:

$$F_T(t) = \Pr\{X(t) \ge x_F\} = 1 - \int_0^{x_F} \frac{(x/\delta)^{\eta t-1}}{\delta\,\Gamma(\eta t)} e^{-x/\delta} dx = 1 - GA(x_F; \eta t, \delta) \tag{7}$$

where $GA(x; \beta_0, \beta_1)$ the cumulative distribution function at x of a gamma random variable with shape parameter β_0 and scale parameter β_1.

3.2 *Statistical Analysis*

This section describes the estimation of parameters of the gamma process model through maximum likelihood analysis of inspection data. To model the effect of flow velocity on the thinning rate, the scale parameter δ is taken as an exponential function of the flow velocity, i.e., $\delta = e^{\alpha_0+\alpha_1 V}$.

Given inspection data we can estimate the process parameters by using the method of maximum likelihood. In particular, let $X(t) = w_0 - W(t)$ be the wall thickness loss in which $W(t)$ is the actual wall thickness at time t and w_0 the initial wall thickness. Suppose we inspect a number M of components, each being inspected n_i times at different instances. Then we have a dataset (w_{ij}, t_{ij}, V_i) ($i=1,\ldots,M, j=1,\ldots,n_i$) of the wall thickness w_{ij} at different time t_{ij} and associated flow velocity V_i for each pipe. From Eq. (6) and the assumption of stationary independent increments of gamma process, the likelihood function for one component with flow velocity V_i is expressed as

$$L_i(\eta,\alpha_0,\alpha_1) = \prod_{j=1}^{n_i} \frac{\left(\Delta w_{ij}\right)^{\eta\Delta t_{ij}-1}}{\delta^{\eta\Delta t_{ij}}\Gamma\left(\eta\Delta t_{ij}\right)} e^{-\Delta w_{ij}/\delta} = \prod_{j=1}^{n_i} \frac{\left(\Delta w_{ij}\right)^{\eta\Delta t_{ij}-1}}{\Gamma\left(\eta\Delta t_{ij}\right)} \exp\left\{-\eta\Delta t_{ij}\left(\alpha_0+\alpha_1 V_i\right)-\Delta w_{ij}e^{-\alpha_0+\alpha_1 V_i}\right\} \tag{8}$$

in which $\Delta w_{ij} = w_i(t_{i,j-1})$-$w_i(t_{ij})$, $\Delta t_{ij} = t_{ij} - t_{i,j-1}$, $w_i(t_{i0}) = w_0$ and $t_{i0} = 0$. Hence, the complete log-likelihood for M components is

$$l(\eta,\alpha_0,\alpha_1) = \sum_{i=1}^{M}\sum_{j=1}^{n_i}\left[\left(\eta\Delta t_{ij}-1\right)\ln\Delta w_{ij} - \ln\Gamma\left(\eta\Delta t_{ij}\right) - \eta\Delta t_{ij}\left(\alpha_0+\alpha_1 V_i\right) - \Delta w_{ij}e^{-\alpha_0+\alpha_1 V_i}\right] \tag{9}$$

The maximum likelihood estimates (*m.l.e.*) of the parameters are shown below with standard errors in parentheses:

$$\tilde{\eta} = 5.2567(0.4465),\ \tilde{\alpha}_0 = -5.8121(0.1156),\ \tilde{\alpha}_1 = 0.1386(0.0058) \tag{10}$$

and the estimated correlation matrix of the *m.l.e.* is

$$Corr(\tilde{\eta},\tilde{\alpha}_0,\tilde{\alpha}_1) = \begin{bmatrix} 1 & -0.749 & -0.022 \\ & 1 & -0.675 \\ sym & & 1 \end{bmatrix} \tag{11}$$

The maximized log-likelihood $l\left(\tilde{\eta},\tilde{\alpha}_0,\tilde{\alpha}_1\right) = 212.1$.

3.3 *Test for Damage Incubation Period*

To test whether or not a statistically significant damage incubation period exists, the likelihood ratio test can be applied. The incubation period t_0 implies

$$X_0(t) = W(t) - w_0 = \begin{cases} 0, & t \le t_0 \\ X(t-t_0), & t > t_0 \end{cases} \tag{12}$$

where $X(t)$ is the gamma process.

The null hypothesis is (NH) H_0: $t_0 = 0$ and the alternative hypothesis (AH) H_1: $t_0 \neq 0$. Under the AH, the log-likelihood function of the dataset is the same as Eq. (9) except for the initial time of the i^{th} component being $t_{i0} = t_0$. The *m.l.e.* of the parameters are given with standard errors in parentheses as:

$$\hat{\eta} = 5.9195(0.4981),\ \hat{\alpha}_0 = -5.8323(0.1112),\ \hat{\alpha}_1 = 0.1382(0.0057),\ \hat{t}_0 = 1.3062(0.3174) \tag{13}$$

and the estimated correlation matrix of the *m.l.e.* is

$$Corr(\hat{\eta},\hat{\alpha}_0,\hat{\alpha}_1,\hat{t}_0) = \begin{bmatrix} 1 & -0.700 & -0.023 & 0.195 \\ & 1 & -0.665 & 0.098 \\ & & 1 & -0.045 \\ sym & & & 1 \end{bmatrix} \tag{14}$$

The maximized log-likelihood $l\left(\hat{\eta},\hat{\alpha}_0,\hat{\alpha}_1,\hat{t}_0\right) = 219.2$.

The likelihood ratio statistic for testing the hypothesis H_0 is defined to be twice the difference between the two maximum log-likelihoods (Lawless, 2003):

$$\Lambda(t_0) = 2l\left(\hat{\eta}, \hat{\alpha}_0, \hat{\alpha}_1, \hat{t}_0\right) - 2l\left(\tilde{\eta}, \tilde{\alpha}_0, \tilde{\alpha}_1\right) = 14.2 \tag{15}$$

Since $\Lambda(t_0) = \chi^2_{(1)}$, we have p = 0.0002, which suggests significant evidence against the null hypothesis, implying that an incubation period does exist. Therefore, the alternative model with an incubation period is adopted for the remaining lifetime prediction.

The mean wall thinning rate is estimated to be 0.0174exp(0.1382V). For a feeder pipe with flow velocity of, say 14 m/s, the mean wall thinning rate is 0.12 mm/EFPY. Approximately, the mean lifetime of the feeder can be estimated as $0.4w_{\text{th}}/0.12$ = 20.7 EFPY.

3.4 *Prediction of the Remaining Lifetime Distribution*

From (7), the lifetime distribution for a component with flow velocity V is expressed as

$$F_T(t) = \Pr\{X(t) \geq w_0 - w_{th}\} = 1 - GA\left(w_0 - w_{th}; \hat{\eta}(t - \hat{t}_0), \hat{\delta}\right) \tag{16}$$

for $t \geq \hat{t}_0$, in which $\hat{\delta} = \exp\left(\hat{\alpha}_0 + \hat{\alpha}_1 V\right)$ and w_{th} is the critical wall thickness, below which the end of life is defined. In this study we choose $w_{th} = 0.6w_0$ for illustration purposes only.

Suppose the remaining wall thickness of a currently inspected feeder is w_s, then the remaining lifetime is the time interval in which the thickness reduces from w_s to w_{th}. It is obtained as

$$F_T(t \mid w_s) = \Pr\{X(t) \geq w_0 - w_{th} \mid W(s) = w_s\} = 1 - GA\left(w_s - w_{th}; \hat{\eta}(t - s), \hat{\delta}\right) \tag{17}$$

for $t \geq s \geq \hat{t}_0$.

In case of an un-inspected feeder, its remaining wall thickness is unknown and Eq.(17) can not be used. Traditionally, the remaining lifetime of a feeder that has survived up to the time of inspection can be obtained as a conditional distribution given below:

$$F_T(t \mid s) = \Pr\{T \leq t \mid T > s\} = 1 - \frac{GA\left(w_0 - w_{th}; \hat{\eta}(t - \hat{t}_0), \hat{\delta}\right)}{GA\left(w_0 - w_{th}; \hat{\eta}(s - \hat{t}_0), \hat{\delta}\right)} \tag{18}$$

But even this cannot be used in the study because the un-inspected feeders may have wall thickness less than the failure threshold but are still surviving. Under this circumstance, the only thing one can do is to use the lifetime distribution from Eq. (16) and take the corresponding probability at the future time as the failure probability up to that point of time.

To account for sampling uncertainties, the confidence band can be constructed through Monte Carlo simulations. Parameters $(\eta, \alpha_0, \alpha_1, t_0)$ are modeled as a multivariate normal distribution with mean value in Eq. (13) and correlation matrix of Eq. (14). Simulated values of the parameters are plugged into the corresponding equation for the (remaining) lifetime distribution given above.

4 Numerical Results and Discussion

4.1 *Lifetime Distribution of Feeders*

The lifetime distribution of a randomly selected feeder with initial thickness of 6.223 mm, end of life threshold w_{th} = 3.734 mm and flow velocity of 14.22 m/s is estimated from Eq.(16), and it is plotted in Figure 5(a). The survival function and the confidence bounds are plotted in Figure 5(b). The mean lifetime, i.e., area under the survival function, is estimated as 21. 6 EFPY. This lifetime refers to the time it takes for the wall thickness of the selected feeder to reach 3.734 mm, the chosen failure threshold.

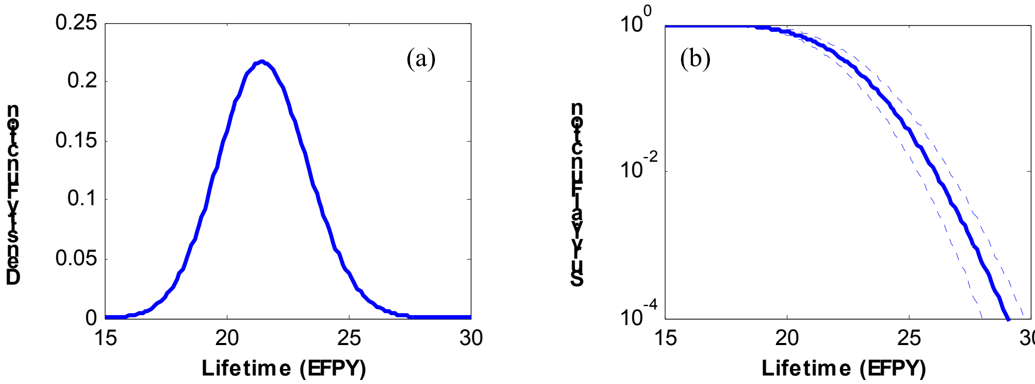

Figure 5: Feeder lifetime distribution. (a) Probability density, and (b) survival functions with 95% confidence bands

4.2 *Remaining Life of Inspected Feeders*

As an example, the remaining life distribution of the feeder bend inspected six times (the bend with measurements shown in Figure 3(a)) is derived using Eq.(17) by substituting the value of wall thickness of w_s = 4.267mm at the latest outage16.15 EFPY and the flow velocity of 14.22 m/sec. The distribution and the survival curves are shown in Figure 6. The mean remaining life is estimated as 4.5 EFPY with standard deviation of 0.7 EFPY. Essentially, it is the mean duration for wall thickness to decrease from 4.267 mm to 3.734 mm, the chosen failure threshold.

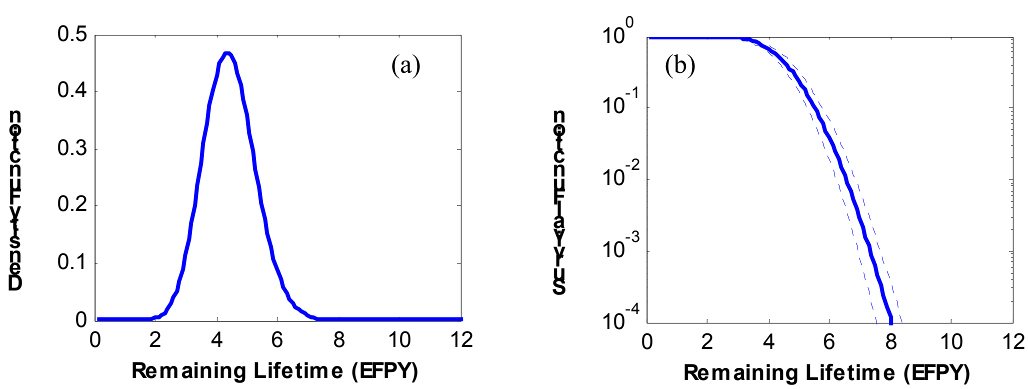

Figure 6: Remaining life distribution of selected feeder bend. (a) Probability density, and (b) survival functions with 95% confidence bands

5 Conclusion

The paper presents an advanced probabilistic model, which integrates sampling and temporal uncertainties into the prediction of lifetime distribution of feeders. In the proposed approach, the flow accelerated corrosion (FAC) is modeled as a random gamma process and the model parameters are calibrated with a set of wall thickness measurements using the method of maximum likelihood. The dependence of FAC rate on flow velocity is systematically incorporated by treating it as a statistical covariate. The gamma process with independent damage increments captures the temporal uncertainty and the influence of the sampling uncertainty is incorporated through Monte Carlo simulations.

The proposed model is effectively applied to estimate the remaining life of inspected and un-inspected feeders. The proposed risk-based approach is expected to improve the life-cycle management of feeder systems.

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