# A PROBABILISTIC APPROACH TO THE ESTIMATION OF LIFETIME DISTRIBUTION OF ALLOY 800 SG TUBING

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## Abstract

Alloy 800 has been used for steam generator (SG) tubing for more than 30 years, primarily in CANDU reactors and in reactors in Germany. Extensive laboratory testing and in-service experience suggest that the Alloy 800 tubing has excellent resistance to corrosion-related degradation under appropriate operating conditions. In planning refurbishment of CANDU stations, a key concern is the longevity of existing SGs up to the 60 year lifetime of the refurbished plant. The paper reviews an existing methodology based on the concept of the improvement factor, and estimates it based on data specific to CANDU operating conditions. The paper presents a more advanced probabilistic approach to estimate the degradation free lifetime distribution of Alloy 800 tubing, which is used to quantify the probability of degradation during the service life and to evaluate the impact of potential occurrences of degradation on reliability of SG tubing.

## 1 Introduction

CANDU reactors employ Alloy 800 tubing in SGs, which has demonstrated excellent resistance to in-service degradation modes, in particular stress corrosion cracking (SCC). As many CANDU plants are approaching the end of life, degradation free performance of Alloy 800 SG tubing in the remaining and extended plant life is of critical concern to the nuclear utility industry. If it can be demonstrated with high probability that the lifetime of SG tubing would exceed 60 years, the replacement of SGs would not be required during refurbishment of the plant and considerable monetary benefits can be realized.

However, the estimation of lifetime distribution of Alloy 800 tubing is quite difficult due to lack of data regarding corrosion-related in-service degradation. There are two possible approaches to modeling the distribution. Firstly, a distribution can be developed heuristically by estimating perceived improvement in the lifetime of Alloy 800 tubing compared to another alloy for which ample service performance data are available, such as Alloy 600 traditionally used for SG tubing in many PWR SGs. Secondly, a distribution can be derived from a more mechanistic modeling of the degradation process. In this approach, assumptions need to be made about the probability that a corrosive environment could occur (in the domain of electrochemical corrosion potential and pH), and how corrosive the environment might be in terms of corrosion rate. Laboratory studies have been carried out over a range of potential and pH under SG crevice chemistry conditions. On the other hand, it is possible to calculate crevice chemistries expected in operating SGs, for instance from SG blowdown chemistry or hideout return data. However, verification that these calculations are actually truly representative of in-service conditions inside

SG crevices has not been possible, and SG-specific assumptions have to be made as to the range of pH and potential that could occur if a probabilistic approach is to be attempted.

The objective of this paper is to present an advanced probabilistic model of the lifetime distribution that combines some prior estimates of the lifetime distribution with in-service performance of SGs in CANDU reactors.

## 2 Degradation- Free Lifetime Distribution

### 2.1 Overview of Existing Approach

Degradation free lifetime (DFL) is defined as the duration of the service life of SG tubing in which no degradation takes place. The onset of degradation is considered to have taken place when 0.05% to 0.1% of the tubes in a SG have experienced an active SCC degradation mode which requires significant maintenance attention, such as tube plugging [1]. In the case of a CANDU plant with 4 SGs and each SG having approximately 4000 tubes, degradation of 8 or more tubes would imply the end of degradation life of the SG tubing in that plant. Conventionally, the DFL (*t*) is modelled by the Weibull probability distribution with cumulative distribution given as

$$F_T(t) = 1 - \exp\left(-\left(\frac{x}{\alpha}\right)^{\beta}\right) \tag{1}$$

where $\alpha$ is the scale parameter and $\beta$ is the shape parameter, also referred to as the slope of the Weibull plot.

The current approach relies on a concept of a Demonstrated Improvement Factor (DIF) to quantify the benefit of improved design and materials with reference to the performance of Alloy 600MA tubing. The DIF is defined as the ratio of the median DFL of the Alloy 800 tubing to the median DFL of Alloy 600 MA tubing.

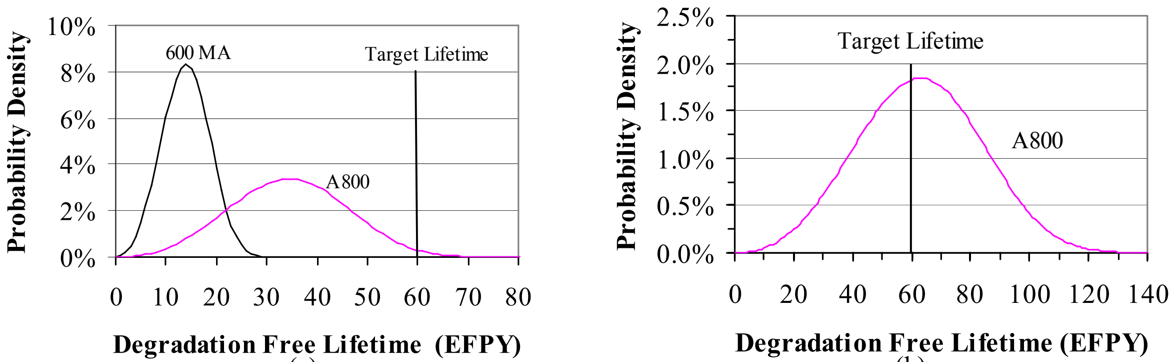
The performance of Alloy 800 in CANDU SGs can be evaluated with reference to that of Alloy 600MA tubing in plants with Westinghouse designed SGs with feedrings and kiss rolls at the top-of-tubesheet expansions [1, 2]. Using the in-service performance data, the median DFL of Alloy 600MA tubing was estimated as 13.96 EFPYs at a reference temperature of 613°F (323°C). The Weibull shape parameter was estimated as $\beta = 3.34$ from the slope of the Weibull plot. This lifetime distribution has a coefficient of variation (COV) of 33%. The Weibull lifetime distribution of Alloy 800 is thought of having the same shape parameters as the Alloy 600 MA tubing, i.e., $\beta = 3.34$. Then the scale parameters can be estimated from the following relation derived from the maximum likelihood principle [3]:

$$\alpha = \left(\frac{1}{m}\sum_{k=1}^{n} t_k^{\beta}\right)^{(1/\beta)} \tag{2}$$

Here $t_1$, $t_2$, . . . , $t_m$ denote the time of occurrences of degradation and remaining ($n$-$m$) values denote the operating time of plants without degradation. If no degradation has occurred till present time, $m = 1$ is assumed implying that degradation is imminent.

Table 1: Operating life of CANDU plants with Alloy 800 SG tubing (until June 2007)

| Plant | Operating Life (EFPY) | Plant | Operating Life (EFPY) |
|---|---|---|---|
| Point Lepreau | 20.10 | Embalse | 18.20 |
| Gentilly - 2 | 19.20 | Cernavoda | 9.00 |
| Woolsong - W1 | 21.00 | Darlington - D1 | 13.40 |
| W2 | 9.11 | D2 | 12.62 |
| W3 | 8.40 | D3 | 12.23 |
| W4 | 7.30 | D4 | 12.00 |



(a) (b)

Figure 1: DFL distributions (a) comparison for DIF = 2.06 (b) for DMIF = 4.5

The degradation free lifespan of Alloy 800 tubing in the existing 12 CANDU reactors ranges from 7.3 to 20.1 EFPYs (Table 1). Based on this information and $\beta = 3.34$, the median DFL is calculated as 28.8 EFPYs that results in DIF = 28.8/13.96 = 2.06.

The DFL distributions of the Alloy600MA and Alloy 800 tubing are compared in Figure 1(a). It shows that the probability of degradation free lifetime of Alloy 800 tubing exceeding 60 EFPY is very small (1.19%). It is therefore concluded that the estimated DIF, based on comparisons with "worst-case" performance of Alloy 600 tubing, is not adequate to ensure the longevity of Alloy 800 tubing, and a more refined approach is required to estimate the improvement factor as well as the lifetime distribution.

## 3 Detailed Material Improvement Factors (DMIF)

### 3.1 Concept

Using the Weibull distribution with $\beta = 3.34$, it is possible to back-calculate a target value of the improvement factor corresponding to a specified probability of lifetime exceeding 60 years. Target values of IF for a probability level ranging from 80% to 99% are presented in Table 2. For example, to state with 90% probability that DFL > 60 years, it should be demonstrated that IF $\geq$ 7.6. On the other hand, IF $\geq$ 6 is needed to show that DFL > 60 has 80% probability. A concept of detailed material improvement factor (DMIF) was introduced [1, 2] to refine the estimate of the improvement factor. It is estimated by comparing the experimental data regarding the relative degradation resistance of Alloy 800 versus Alloy 600MA [1]. For example, DMIF can be taken as the ratio of crack depth in Alloy 600MA to crack depth in Alloy 800 in a specimen exposed to the same test conditions.

Table 2: Target values of improvement factors to demonstrate DFL ≥ 60 years with a specified probability

| Specified Probability (%) | Target Improvement Factor |
|---|---|
| 80% | 6.0 |
| 90% | 7.6 |
| 95% | 9.4 |
| 99% | 15.3 |

Based on laboratory test results, Slade et al. [2] compiled DMIFs under a variety of chemical environments (i.e., pH values). They reported an aggregated DMIF of 4.5, which was computed by weighting the DMIF with the relative frequency of occurrence of pH values. Given a DMIF of 4.5, the median lifetime is estimated  63 EFPYs with the Weibull shape parameter of 3.34, as shown in Figure 1(b). From this distribution, the probability of occurrence of degradation before 60 years is 45%, which is rather large.

### 3.2 DMIF Based on the "Safe ECP-pH Zone" Concept

SG tubing is exposed to a varying environment in terms of electro-chemical potential (ECP) and local chemistry conditions. The most probable locations where the tubing materials may be susceptible to environmental degradation are SG crevices or under deposits. This is because non volatile impurities such as chlorides and sulphates can hide out and concentrate in crevices, or under deposits, under heat transfer conditions. Because of the hideout of SG impurities an electrochemical corrosion cell will be formed between the surfaces of tube free span and tube inside the crevice that would result in corrosion degradation in crevices. Mechanisms of SG tubing degradation are well summarized in references [4-6].

For several years the CANDU industry has carried out a variety of SG tubing corrosion tests, coupled with crevice chemistry testing and modeling, in order to provide a basis for understanding existing SG degradation, for predicting and anticipating future degradation, and for ensuring appropriate materials selection for new SGs. Although a number of short- and long-term autoclave tests with CERT, U-bends, C-rings, capsules, etc. have been carried out, a key factor in being able to compare and contrast the results of these tests has been that they were carried out in a consistent set of chemistries, based on hideout return data from Bruce NGS, where most of the CANDU SG tubing degradation has occurred. As part of a project to be able to evaluate quickly the effect of a variety of SG chemistries on SG tubing behaviour, electrochemical polarization tests were carried out. The corrosion susceptibility of Alloy 800, Alloy 600, Alloy 690 and Alloy 400 has been evaluated by performing a series of electrochemical measurements under the plausible SG secondary side crevice conditions [7].

Based on these electrochemical data, recommended safe ECP/pH zones for minimizing the corrosion degradation of the SG alloys were defined for SG alloys under CANDU operating conditions (Figure 2). Accelerated crevice corrosion tests and CERT tests have been also carried out to verify and revise the safe ECP/pH zones defined by electrochemical analyses [8].

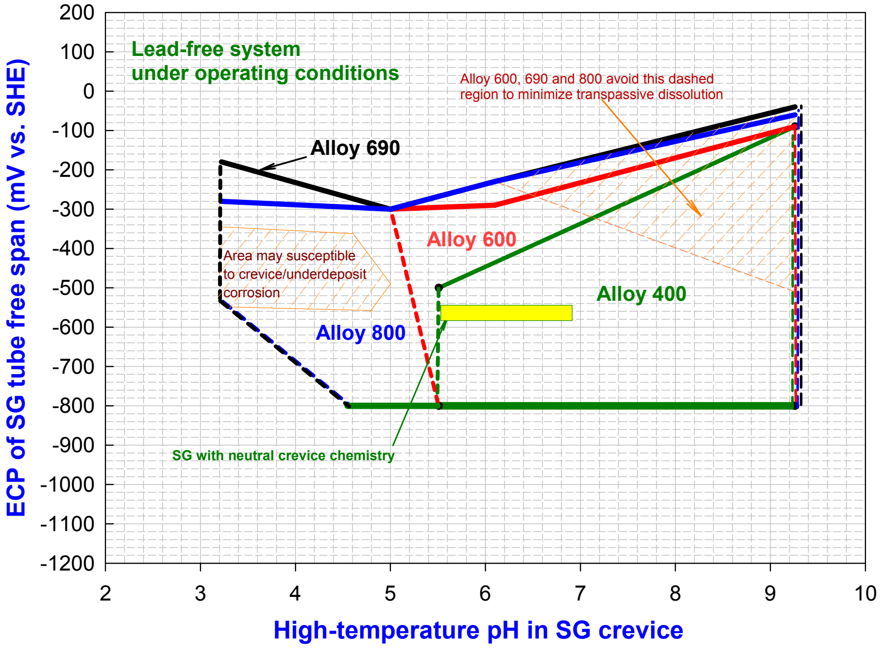


Figure 2: Recommended ECP/pH zone with minimized corrosion for SG alloys at CANDU SG operating temperature

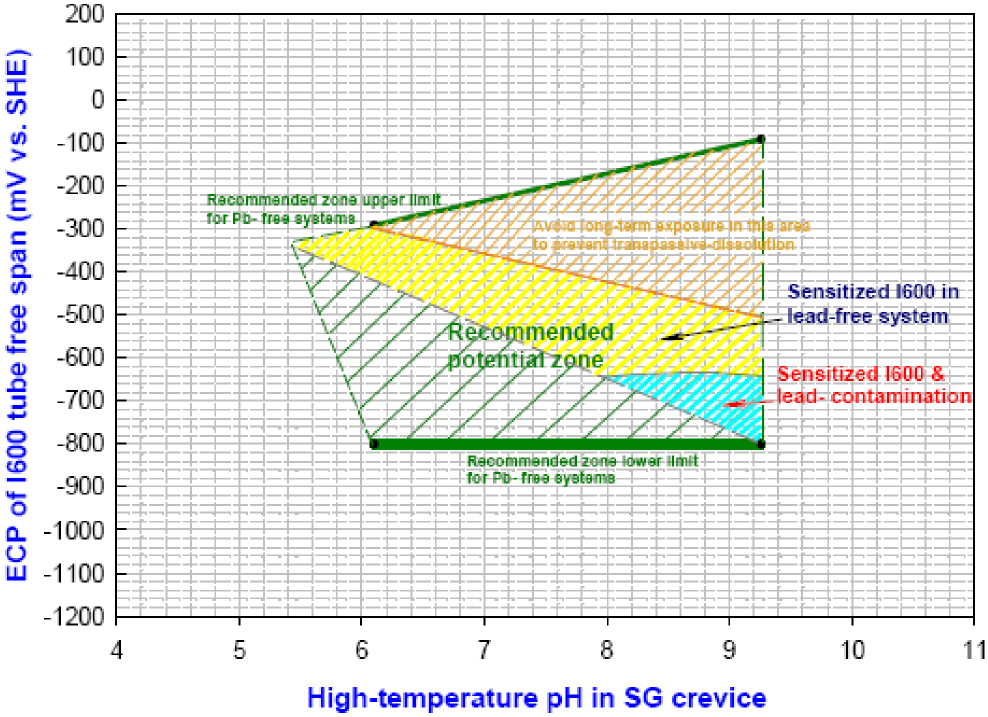


Figure 3: Effects of sensitization and lead contamination on the acceptable ECP zone for Alloy 600 under CANDU SG operating conditions

Alloy 600 MA has numerous degradation issues, especially if it is sensitized [9-11]. Figure 3 shows how sensitization affects the operating margin of Alloy 600 under SG operating conditions in the presence and absence of lead contamination.

Table 3: Improvement factors derived from Safe ECP-pH Zone for Alloys 800 and 600

| No | Case | Improvement Factor |
|---|---|---|
| 1 | Lead free conditions | |
| 1.1 | Not sensitized Alloy 600MA | 1.46 |
| 1.2 | Sensitized Alloy 600MA | 3.40 |
| 2 | Lead contamination | |
| 2.1 | Not sensitized Alloy 600MA | 2.66 |
| 2.2 | Sensitized Alloy 600MA | 20.14 |

Since the area of the safe ECP-pH zone for an alloy characterizes its aggregate resistance to degradation under diverse chemical environments, the ratio of the safe zone areas of Alloy 800 to Alloy 600MA is proposed as a more comprehensive estimate of the material improvement factor (DMIF), and results are presented in Table 3. Under lead-free conditions, the DMIF of Alloy 800 with reference to non-sensitized Alloy 600 is 1.46, which increases to 3.4 in comparison with sensitized Alloy 600. It is believed that Alloy 600 tubing in the Bruce NGS SGs is generally sensitized and some lead contamination is present in the steam generator. In such case, the improvement factor turns out to be quite high (over 20 as shown by case 2.2 in Table 3). It implies that the median lifetime of Alloy 800 tubing can be as high as 260 years.

# 4 Proposed Model

## 4.1 Approach

Although the parameters of the Weibull lifetime distribution of Alloy 800 tubing are not known precisely, engineering judgement suggests that parameters of Alloy 600 MA distribution can provide some guidance about its distribution. The concept of an improvement factor applies a linear scaling to the median lifetime of Alloy 600MA without changing the Weibull shape parameter ($\beta$), which means the coefficient of variation of Alloy 800 is the same as that of the Alloy 600MA (33%). The constancy of the Weibull shape parameter is a significant assumption in the current approach, since the composition and microstructure of Alloy 800 and its response to chemically aggressive environments is mechanistically different than that of Alloy 600MA.

It can be concluded that there are uncertainties associated with Weibull shape parameter and median lifetime of Alloy 800. The paper presents a Bayesian approach to build the probabilistic model by incorporating some information with the available in-service performance in a systematic manner [12].

For example, it is proposed that the most likely value of the Weibull shape parameter is 3.34, though some uncertainty to this value is assigned through a gamma distribution given as

$$f(\beta\,|\,\lambda,p)=\lambda^{p}\beta^{p-1}e^{-\lambda\beta}/\Gamma(p) \qquad\qquad \beta>0 \tag{3}$$

where $\lambda$ and $p$ are the scale and shape parameters, which are related to mean and variance as $p/\lambda$ and $p/\lambda^2$, respectively. The mean of β is taken as 4 and a coefficient of variation of 40%, which implies that with 90% probability the shape parameter (β) ranges from 1.77 to 6.13 and the mode (i.e. most likely value) is 3.4 (Figure 4a).

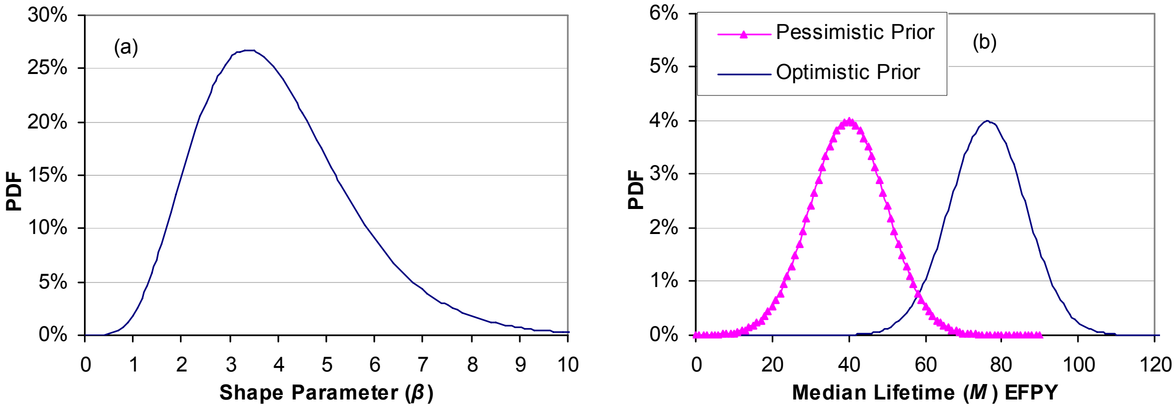


Figure 4: Prior distributions of (a) Weibull shape parameter, (b) two priors for the median lifetime

In a similar manner, the median life (*M*) of Alloy 800 is considered an uncertain quantity with a mean (μ) and standard deviation (σ). The Gaussian distribution truncated at 0 is chosen to model the median life as [12]

$$f(M\,|\,\mu,\sigma)=(1/K\sqrt{2\pi}\sigma)\exp\left(-\frac{1}{2}\left(\frac{M-\mu}{\sigma}\right)^{2}\right) \qquad 0\le M<\infty \tag{4}$$

where $K=\left(\int_{-\mu/\sigma}^{\infty}(2\pi)^{-1/2}\exp(-u^{2}/2)du\right)$ is a normalizing constant.

Two different prior distributions are proposed in this paper: (1) an optimistic prior which assigns 95% exceedance probability to the median life of 60 EFPY, and (2) a pessimistic prior with an expected value of median life as 40 EFPY. In both cases, the standard deviation of 10 EFPY is assigned and resulting distributions are plotted in Figure 4(b).

The scale parameter (α) of the Weibull distribution is related with the median values as $M=\alpha\exp(c/\beta)$, where $c=\ln\ln 2=-0.366$. From the theory of transformation of random variables, the distribution of α can be derived as:

$$f(\alpha\,|\,\beta,\mu,\sigma)=(Ke^{c/\beta}/\sqrt{2\pi}\sigma)\exp\left(-\frac{1}{2}\left(\frac{\alpha e^{c/\beta}-\mu}{\sigma}\right)^{2}\right), \qquad 0\le\alpha<\infty \tag{5}$$

Since α and β are random variables, the reliability function in an average sense is given as

$$S(x) = \iint e^{-(x/\alpha)^{\beta}} f(\alpha) f(\beta) d\alpha d\beta \tag{6}$$

Based on the optimistic prior of median lifetime, the expected survival probability (or reliability) curve was computed and plotted in Figure 5. It shows that the probability of lifetime of Alloy 800 exceeding 60 EFPY is about 70%. It is however a prior or notional probability, which should be confirmed with available data.

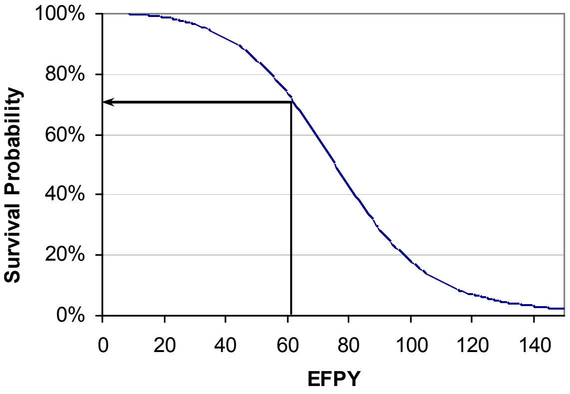


Figure 5: Prior Reliability function of Alloy 800 SG tubing

## 4.2 Reliability updating using observed data

A sample of lifetime data, referred to as *z,* in general consists of two parts: (1) *r* values, ( $x_1, x_2, ..., x_r$ ), of complete lifetime, and (2) (*n-r*) values, ( $s_1, s_2, ..., s_{n-r}$ ), of right censored survival times. The statistical likelihood of observing this sample is given as

$$L(z \mid \alpha, \beta) = \left\{ \prod_{i=1}^{r} \left( \frac{\beta}{\alpha} \right) \left( \frac{x_i}{\alpha} \right)^{\beta - 1} \exp\left\{ - \left( \frac{x_i}{\alpha} \right)^{\beta} \right\} \right\} \left\{ \prod_{j=1}^{n-r} \exp\left\{ - \left( \frac{s_j}{\alpha} \right)^{\beta} \right\} \right\} \tag{7}$$

Given a sample of data the prior distribution of β and *M* can be updated using the Bayes' theorem, which leads to a joint posterior distribution as

$$\tilde{f}(M, \beta \mid z) = \frac{L(z \mid \alpha, \beta) f(M) f(\beta)}{\iint L(z \mid \alpha, \beta) f(M) f(\beta) dM d\beta} \tag{8}$$

The marginal distribution of the median lifetime can be obtained by integrating the joint distribution (Eq.8) with respect to β as

$$\tilde{f}(M \mid z) = \int \tilde{f}(M, \beta \mid z) d\beta \tag{9}$$

Similarly, the posterior of β can be obtained by integrating out $M$ from Eq.(9). The posterior joint distribution $\tilde{f}(\alpha,\beta\,|\,z)$ can be derived by replacing $M$ with α in Eq.(8). Numerical integration is required in evaluating equations 8 and 9. The reliability function of the Alloy 800 can be updated by using the posterior joint distribution of α and β as

$$\tilde{S}(x\,|\,z) = \iint \exp(-(x/\alpha)^{\beta})\tilde{f}(\alpha,\beta\,|\,z)\,d\alpha\,d\beta \qquad (10)$$

## 5 Numerical Analysis and Results

### 5.1 Updating based on current service experience

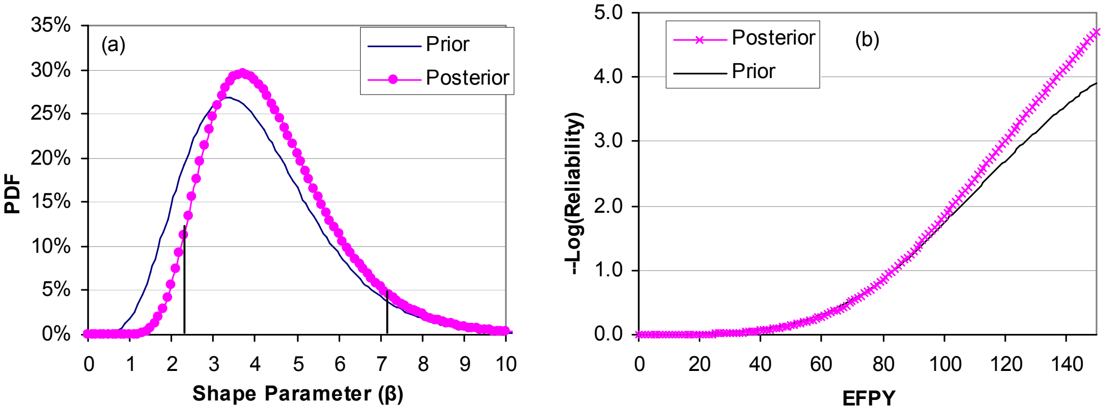


Figure 7: Updated distributions of (a) shape parameter (b) reliability function

The objective of this section is to use the in-service performance of Alloy 800 tubing in CANDU SGs along with some prior estimates to predict the probability of degradation free lifetime exceeding certain age. In the service life of the CANDU fleet, no incidence of OD SCC degradation has been reported (Table 1). Using this information, a likelihood function was written using Eq.(7) and then the Bayesian updating model was applied as described in Section 4.

The posterior distributions of the shape parameter and the reliability function were first obtained using the optimistic prior of median life (mean 75 EFPY). The posterior mean of the shape parameter is slightly increased to 4.4 (Figure 7a). The logarithmic plots in Figure 7(b) show that the updated reliability has not changed much until 80 EFPY. The prior probability of surviving till age 30 is 96% and its updated value increases to 98%. Similarly, in case of reliability up to 60 EFPY, its prior estimate increases from 71% to 74%. After age 80, the posterior reliability decreases as compared to the prior estimate. It appears that the current in-service data are not in conflict with prior belief about the longevity of Alloy 800 tubing.

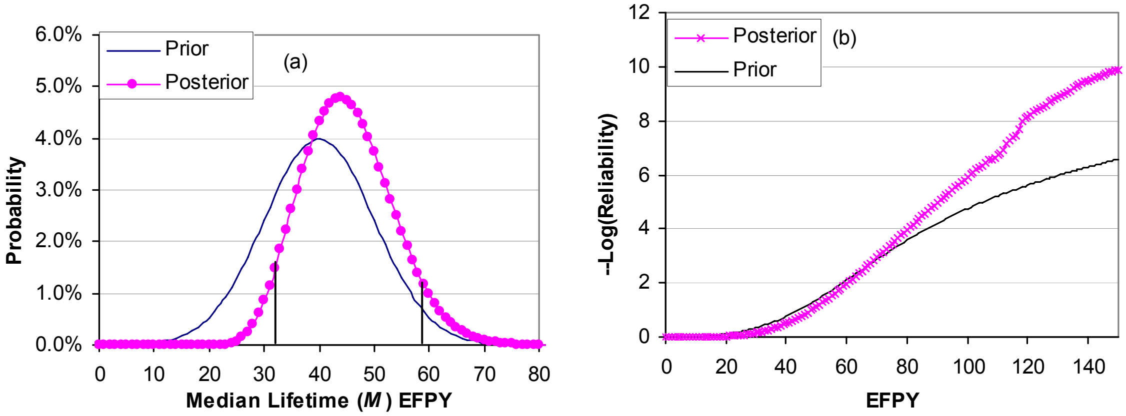


Figure 8: Updated distributions obtained from pessimistic priors (a) Median lifetime, (b) reliability function

In the second case, results as shown in Figure 8 were computed using a pessimistic prior of median life (mean 40 EFPY). It shows that the prior reliability of Alloy 800 tubing at age 30 is 70%, and at age 60 EFPY it is 12%. The updated reliability at age 30 significantly increases to 86%. However, reliability at 60 EFPY increases slightly to 14%. It means, in case of a pessimistic prior, longer in-service data are needed to make a significant change in the prior information. The posterior mean of the shape parameter is 5. The posterior mean of median lifetime increases to 45.15 EFPY and 90% credible interval varies from 32 to 59 EFPY (Figure 8a).

## 5.2 Updating based on potential future degradation

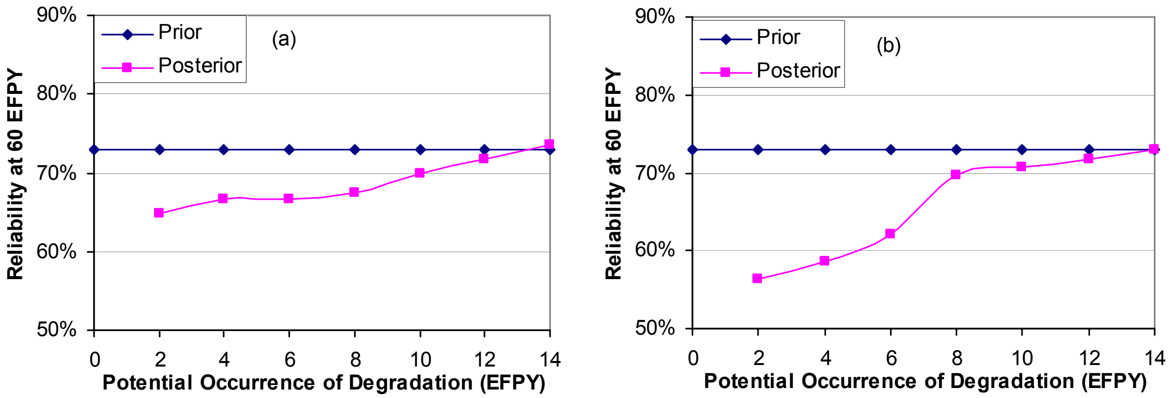


Figure 9: Updated reliability of Alloy 800 tubing at 60 EFPY given the occurrence of degradation (a) in an old CANDU plant (b) in a newer CANDU plant

The proposed model can be applied to investigate the impact of future occurrences of degradation on the reliability of SG tubing. For example, if the Alloy 800 tubing in an early generation CANDU plant (for instance, Wolsong 1, 21 EFPY) experiences SCC degradation in some future time (*t*) and the rest of the plants operate without degradation, the updated reliability at age 60 EFPY can be computed as a function of the time of occurrence of degradation. Figure

9(a) shows that if degradation occurs in year 2, the reliability will drop to about 65% from the prior estimate of 73%. The drop in reliability becomes smaller as the potential occurrence of degradation is postponed farther in the future. Figure 9(b) shows similar results assuming the occurrence of degradation in Darlington reactor D1. The reliability drops by 15% (from 73% to 58%), if degradation would occur in year 2. The reason being that operating life of Darlington 1 is relatively short (13.4 EFPY).

## 6 Summary

This paper has summarized the in-service performance and safe ECP-pH zone derived from laboratory test data for Alloy 800 SG tubing in CANDU SG service, with the intent of describing an approach to develop a more quantifiable estimate of in-service life of Alloy 800 SG tubing, in particular for those reactors planning refurbishment without SG replacement.

In an existing approach, the lifetime distribution of Alloy 800 tubing is derived with reference to that of Alloy 600 MA tubing by scaling its median lifetime by an improvement factor (IF) and assuming an identical value the Weibull shape parameter for both alloys. From the degradation free performance of Alloy 800 tubing in the CANDU fleet, the IF is estimated to be 2.06. The paper shows that within this approach, the improvement factors in the range of 2 to 5 are not sufficient to demonstrate with probability that Alloy 800 tubing will survive till age 60. For CANDU specific operating conditions, the paper presents a new set of detailed material improvement factors (DMIF) estimated through the comparison of safe ECP-pH zones for Alloy 800 and 600MA alloys. Depending on lead contamination, the DMIF values can range from 3 to 20 with reference to sensitized Alloy 600 MA.

This paper presents a more general probabilistic model in which assumptions of the existing approach are relaxed. In the proposed approach, the median lifetime and the Weibull shape parameter of Alloy 800 tubing are considered as uncertain quantities. Prior information about these variables is presented in form of probability distributions, which are updated through the information about in-service performance of Alloy 800 tubing in a CANDU fleet worldwide. Some preliminary results show that performance of Alloy 800 tubing is consistent with a prior belief of its lifetime exceeding 60 years. If we begin with a more pessimistic belief that median lifetime about 40 years, the current degradation free performance significantly improves reliability in the near term. This model can also be applied to evaluate the impact of a potential occurrence of degradation in a CANDU plant in future.

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