Zero Failure Data Analysis for Alloy 690 PWSCC Initiation Time Prediction

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1. Introduction

Alloy 690 has been used as replacement of Alloy 600 for components of nuclear reactors, such as reactor pressure vessel head penetration nozzles in pressurized water reactors (PWRs) and steam generator tubing. Compared to its predecessor, Alloy 690 offers much better resistance to primary water stress corrosion cracking (PWSCC) in the primary system of PWRs [1]. There has not been PWSCC observed in Alloy 690-based components in PWRs to date. Regardless of its excellent resistance to SCC, developing an ability to predict PWSCC initiation time of Alloy 690 is indispensable for an effective maintenance of nuclear reactors.

Statistical modeling has been used for various lifetime analysis, including PWSCC initiation time prediction. However, the high PWSCC resistance of Alloy 690 brings challenge to acquire data concerning with PWSCC initiation time, which is needed for constructing a statistical model. Until recently, PWSCC tests on Alloy 690 have not been able to generate PWSCC in tested specimens, and some of tests are still under way with having no clues when PWSCC will occur. Therefore, methods that can deal with the absence of failure in the test are proposed in this work with an intention to predict PWSCC initiation time of Alloy 690.

2. Methods and Results

The techniques used in this work are based on a zero-failure test plan. It is assumed that the PWSCC initiation time of Alloy 690 obeys Weibull distribution.

2.1 Weibull distribution

Weibull distribution [2] has been commonly used as the probabilistic models for PWSCC initiation time prediction. The probability and cumulative density functions of the two-parameter Weibull distribution are given by Equations (1) and (2), respectively,

$$f(t;\eta,\beta) = \frac{\beta}{\eta}\left(\frac{\beta}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \tag{1}$$

$$F(t;\eta,\beta) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \tag{2}$$

where, t is time, $\eta > 0$ is the scale parameter and $\beta > 0$ is the shape parameter of the Weibull distribution [2]. Equations (1) and (2) describe the PWSCC initiation as a function of time

2.3 Zero-Failure Test Plan

A zero-failure test plan has been used for reliability demonstrations [3]. It can be used to demonstrate that a new product has an improved lifetime and that a certain reliability objective has been achieved. The product's lifetime can be represented by Weibull scale parameter η. The reliability objective can be defined as a desired reliability (e.g. 0.9, 0.95, or 0,99 etc.) at a specific time duration. In a zero-failure test plan, the test is designed such that if the test resulted in no failures in all tested specimens, the test objective has been achieved. To make such a plan, the number of specimens to be tested, how long each specimen needs to be tested, and a certain level of confidence need to be specified.

A zero-failure test plan to prove that a new product has an improved lifetime can mathematically be expressed as:

$$P(\eta > \eta_0 | no\ failure) \geq (1-\alpha), \tag{7}$$

where η is new product's scale parameter, η_0 is old product's or expected scale parameter and $(1-\alpha)$ is the level of confidence. The test plan is developed to allow failures at least in one tested specimen with confidence $(1-\alpha)$. Then the following expression can be written:

$$1 - e^{-n\left(T/\eta_0\right)^{\beta}} = 1 - \alpha \tag{8}$$

The Equation (8) can be used to determine the number of specimens n and time duration T for the test. A zero-failure test plan to prove that a certain reliability objective has been achieved can be expressed as:

$$P\left(T_\gamma > t_\gamma \middle| no\ failure\right) \geq (1-\alpha), \tag{9}$$

where t_γ is the time goal when material reliability is γ and T_γ is time at which material reliability is γ. Determining the number of tested specimens and test duration can be done by using Weibull based reliability function, expressed as:

$$\gamma = \exp\left[-\left(\frac{t_\gamma}{\eta}\right)^{\beta}\right], \tag{10}$$

By rearranging Equation (10), η can be expressed as:

$$\eta = \frac{t_\gamma}{(-(\log(\gamma))^{1/\beta})} \tag{11}$$

Putting Equation (11) into (8), the following equation will be obtained:

$$1 - e^{-n\left(T \Big/ \frac{t_\gamma}{(-(\log(\gamma))^{1/\beta})}\right)^{\beta}} = 1 - \alpha \qquad (12)$$

If the test duration T is specified beforehand, number of specimens n can be determined from Equation (11) and vice versa.

2.4 PWSCC Initiation Time Prediction

Equation (12) can also be used to predict the PWSCC initiation time of Alloy 690. Instead of directly predicting the SCC initiation time, this way can tell us, depending on the data, whether Alloy 690 surpasses a reliability goal at a certain operation time. Being reliable here means that the material will not experience PWSCC. From a PWSCC test on Alloy 690, all variables in Equation (10) needed to calculate the level of confidence can be determined except for β. One EPRI MRP report suggested β value to be 5 for Alloy 690 [1]. In this work, various values of β will also be used to see how it affects the calculation. As an example, data taken from PWSCC test done in [4] are used (see Table I). The test was done on thermally treated Alloy 690 under 360°C water with 500 ppm B and 2 ppm Li. Test was done with constant load at ~ 500 MPa.

Fig. 1 shows the level of confidence $(1 - \alpha)$ as a function of time t_γ with β = 5 if reliability goal γ = 0.95 is chosen. It is clearly seen that the level of confidence decreases as the time increases. The level of confidence here can be interpreted as our confidence that the material reliability is 0.95 with β = 5. To interpret this result, for example, the operation time at which we can believe that the material's reliability is 0.95 with high confidence, e.g. 90%, is ~86340 hours. Fig. 2 shows the effect of β value on the level of confidence when reliability is 95% and operation time is 78440 hours (9 years). It is shown that the level of confidence increases as β value increases.

Table I: Data from [4]

Number of specimens	Test duration (hour)
18	123,000

2.5 Factor of Improvement

Thanks to abundant PWSCC initiation data of Alloy 600, it is possible to determine the factor of improvement (FOI) for PWSCC initiation of Alloy 690 relative to that of Alloy 600. The work on determining the FOI has been done using Weibayes and Weibull analyses [1]. Weibayes is used for Alloy 690 while Weibull is used for Alloy 600. FOI in this approach is the ratio of η obtained from Alloy 690 Weibayes assuming that a failure is

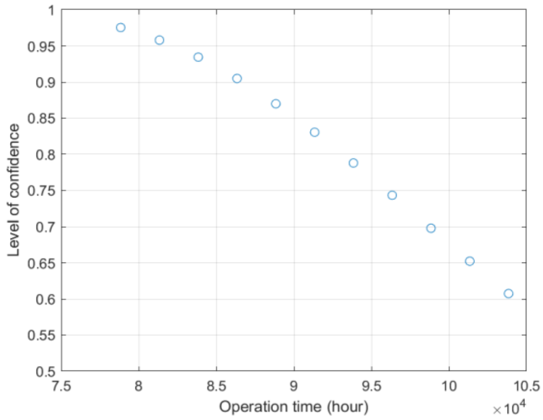

Fig. 1. The level of confidence as a function of operation time $\boldsymbol{t_\gamma}$ with $\boldsymbol{\beta}$ = 5 if reliability goal $\boldsymbol{\gamma}$ = 0.95 is chosen

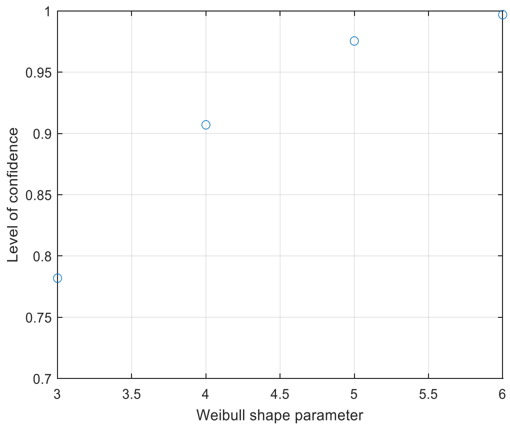

Fig. 2. The level of confidence as a function of $\boldsymbol{\beta}$ when reliability is 95% and operation time is 78440 hours

assumed to occur immediately if the test continues and β = 5 to η obtained from Alloy 600 Weibull analysis, which can be expressed as:

$$FOI = \frac{Weibayes\ (r = 1, \beta = 5.0)\ \eta,\ Alloy\ 690}{Weibull\ \eta,\ Alloy\ 600}, (13)$$

where r here is number of failure.

In the current work, we use zero-failure test plan approach to determine the FOI. Equation (8) can be used to estimate the value of η. Instead of determining directly the value of η, this way allows to determine the level of confidence that η value is greater than a certain value.

As an example, data taken from an EPRI report [1] are used and shown in Table II. All the specimens were thermally treated (TT) and tested under the same conditions. The FOI in Table II is obtained by Equation (13).

Table II: Data from [1]

Material	Number of specimens	Test duration (hours)	η (hours)	FOI
690TT	16	100,000	174,110	15.5
600TT	12	Up to all specimens cracked	11,199	

Fig. 3 shows the level of confidence as a function of η value and a decreasing function is seen. It can be seen that the level of confidence is low (~63%) for the FOI to be greater than ~174,000 hours, which is not in agreement with the FOI obtained by Equation (13). If, for example, 90% of confidence is chosen, η value will be greater than 147,360.4 hours with this level of confidence. Then we can say that with a confidence level of 90%, the FOI is greater than 13.2.

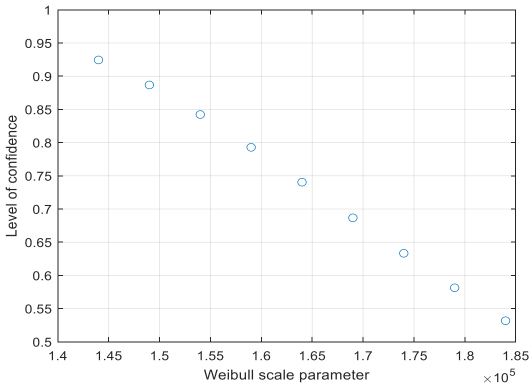

Fig. 3. The level of confidence as a function of $\boldsymbol{\eta}$ value.

3. Conclusions

Zero-failure test plan can be used for prediction of PWSCC initiation of Alloy 690. In the current work, the data are taken from only one test for each technique. However, there have been actually plenty of PWSCC initiation tests on Alloy 690 although there is a lack of coordination, i.e. conducted under various testing conditions. These tests have yielded useful data but the variety of testing conditions such as temperature, load and water chemistry makes it challenging to take the available data into account. In the future, a model that can consider factors such as temperature and load will be pursued in order to be able to take as much as available data as possible.

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