ELECTRIC POWER RESEARCH INSTITUTE

Steam Generator Management Program: Improvement Factors for Pressurized Water Reactor Steam Generator Tube Materials

LICENSED MATERIAL

PORTIONS TRANSLATED

Steam Generator Management Program: Improvement Factors for Pressurized Water Reactor Steam Generator Tube Materials

1019044

Final Report, December 2009

EPRI Project Manager
S. Choi

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Dominion Engineering, Inc.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This report was prepared by

Dominion Engineering, Inc.
11730 Plaza America Drive #310
Reston, VA 20190

Principal Investigators
C. Marks
J. Gorman
C. Anderson
M. Dumouchel

This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

Steam Generator Management Program: Improvement Factors for Pressurized Water Reactor Steam Generator Tube Materials. EPRI, Palo Alto, CA: 2009. 1019044.

REPORT SUMMARY

This report updates previously developed improvement factors associated with the use of advanced alloys for PWR steam generator tube materials. It discusses improvement factors for thermally treated Alloy 600 (Alloy 600TT), thermally treated Alloy 690 (Alloy 690TT), and Alloy 800 nuclear grade (Alloy 800NG) with respect to mill annealed Alloy 600 (Alloy 600MA) steam generator tubing.

Background

Predictions of performance gains associated with the use of advanced alloys have been made in the past through the use of *improvement factors*. EPRI report 1003589 developed and presented improvement factors for Alloy 600TT and Alloy 690TT. However, due to the short length of field experience relative to expected failure times, these estimates of improvement factors, which were based on field experience, may be overly conservative.

Objectives

- To summarize the current knowledge of the improvement in corrosion resistance gained from using various grades of tubing
- To provide a basis for assessing appropriate modifications to the current water chemistry guidelines to reflect alloy-specific improvements in degradation resistance.

Approach

In the preparation of this report, the project team:

- Updated plant experience-based improvement factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG tubing to reflect recent corrosion events and additional operating time without a significant number of failures.
- Supplemented this plant experience analysis by consideration of the relative performance of steam generator tube plugs made of Alloy 600TT and Alloy 690TT.
- Updated laboratory-based improvement factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG vs. Alloy 600MA to include results of recent studies per a literature review.
- Compiled a summary of experiments performed to date in model boilers with sodium contamination. Model boiler testing programs are believed to be a reasonable simulant of actual plant performance, as they more closely resemble the stress, material, and thermal-hydraulic conditions that occur in plants, although the chemistries achieved in these tests may be more aggressive than those likely to be experienced during normal operation.

Results

The evaluations described in this report have resulted in the derivation of conservative improvement factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG relative to Alloy 600MA. These improvement factors can be used in conjunction with experience gained with Alloy 600MA to establish conservative estimates of the rates of future tube degradation in PWR steam generators. Because these estimates are conservative, they do not provide best estimate predictions, i.e., they are considered likely to over predict actual tube degradation. Because the degree of conservatism varies between data sets, these improvement factors are not appropriate for use in comparing the relative performance of the three alloys. However, because of their conservative nature, these improvement factors are expected to be useful in establishing the extent to which utilities may rely upon the corrosion resistant nature of these alloys, for example, by use of less stringent chemistry guidelines or by increases in inspection intervals.

EPRI Perspective

This report represents an ongoing effort by EPRI to assist utilities in evaluating the likelihood of future degradation of steam generators. It provides an update to previous reports, including EPRI reports 1003589, *Pressurized Water Reactor Generic Tube Degradation Predictions* (2003) and 1013640, *Alloy 690 Improvement Factor Update: Application of an Improvement Factor to the Evaluation of a Chemistry Upset at Ginna NPP* (2006). It provides a complement to EPRI report 1009801 (MRP-111), *Resistance to Primary Water Stress Corrosion Cracking of Alloys 690, 52, and 152 in Pressurized Water Reactors* and its revision, EPRI report 1018130 (MRP-237). It is expected that the models developed here will aid both in economic calculations and in the development of technical bases for determining suitable in-service inspection intervals and suitable alloy-specific chemistry specifications.

Keywords

Steam generators
Materials degradation
Alloy 600MA
Alloy 600TT
Alloy 690TT
Alloy 800NG
Improvement factor
SG tube
Steam Generator Management Program
Chemistry guideline bases
Steam generator degradation
PWR

ACKNOWLEDGMENTS

The authors wish to thank the following individuals who reviewed drafts of this report and provided useful insights. Their contributions have made this a more useful analysis.

Rick Eaker
Consultant to EPRI

Oscar Flores
Sothern California Edison

Ken Johnson
Duke Power

Yucheng Lu
AECL

Sandra Pagan
OPG

Steve Sawochka
NWT Corp.

Jim Stevens
Luminant

Additionally, the efforts of Paul Spekkens (OPG) in making several proprietary COG reports available to the authors are gratefully acknowledged.

LIST OF ACRONYMS

ALARA	=	As low as reasonably achievable
AVT	=	All volatile treatment
A&V	=	Axial and volumetric
CEA	=	Commisariat à l`Énergie Atomique (the French Atomic Energy Commission)
CGR	=	Crack growth rate
CL	=	Cold leg
CLT	=	Constant load test
CERT	=	Constant extension rate test, also known as slow strain rate test (SSRT)
CIEMAT	=	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EDF	=	Électricité de France
EFPY	=	Effective full production years
EPRI	=	Electric Power Research Institute
HL	=	Hot leg
ID	=	Inner diameter
IF_R	=	Improvement Factor (relative)
IGA	=	Intergranular attack
IGASCC	=	Intergranular stress corrosion cracking
KAERI	=	Korea Atomic Energy Research Institute
LBI	=	Large but indeterminate

LT	=	Long term
MA	=	Mill annealed
MEA	=	Methoxyethylamine
MRP	=	Materials reliability program
NRC	=	Nuclear regulatory commission
OD	=	Outer diameter
OTSG	=	Once-through steam generator
ppm	=	Parts per million
ppb	=	Parts per billion
PWR	=	Pressurized water reactor
PWSCC	=	Primary water stress corrosion cracking
RUB	=	Reverse U-bend (stress corrosion cracking specimens made from split half steam generator tubing, hence also known as split tube U-bend specimens
SBI	=	Small but indeterminate
SCC	=	Stress corrosion cracking
SG	=	Steam generator
TT	=	Thermal treatment

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION AND OVERVIEW

The first generation of steam generators (SGs) in commercial PWRs of US design, those tubed with mill-annealed Alloy 600 (Alloy 600MA), has experienced significant degradation of the heat transfer tubes through numerous modes. This degradation has resulted in reductions in output and reliability concerns that have led to steam generator replacement (or planned replacement) at most plants with SGs of this generation. The second generation of steam generators used a thermal treatment of Alloy 600 (Alloy 600TT), which has demonstrated an improvement in performance over the mill-annealed condition. However, laboratory testing has indicated that Alloy 600TT is susceptible to corrosion as well, although it is more resistant than Alloy 600MA. While stress corrosion cracking began to occur relatively early in the operational life of Alloy 600MA steam generators, indications of SCC in SGs in US plants tubed with Alloy 600TT have only been observed after a much longer period of operation (see section 3.2.1).

Thermally treated Alloy 690 (Alloy 690TT) was later developed to have improved corrosion resistance over Alloy 600TT. In US plants, most replacement SGs are tubed with Alloy 690TT. Although plant experience is still limited, no indications of cracking have been observed in Alloy 690TT plants to date. Laboratory test results also indicate a substantial improvement in performance over Alloy 600TT, although the alloy may have some susceptibility to corrosion in specific environments.

Another advanced alloy, nuclear grade Alloy 800 (Alloy 800NG), has been used in many non-US plants. This alloy is expected to have corrosion resistance similar to or better than that of Alloy 600TT (although the improvement over Alloy 600MA is due to compositional differences, not thermal treatment). The field data compiled by EPRI from plants with Alloy 800NG are somewhat limited; however, it is included in this report for comparison on the basis of its widespread international use.

Predictions of performance gains associated with the use of advanced alloys have been made in the past through the use of *improvement factors*. Improvement factors for Alloy 600TT and Alloy 690TT were developed and presented in a previous EPRI report, 1003589 [1]. However, due to the short length of field experience relative to expected failure times, the parts of these improvement factors that were based on field experience may be overly conservative. This report updates the previously developed improvement factors associated with the use of advanced alloys. Improvement factors for thermally treated Alloy 600 (Alloy 600TT), thermally treated Alloy 690 (Alloy 690TT), and Alloy 800 nuclear grade (Alloy 800NG) with respect to mill annealed Alloy 600 (Alloy 600MA) steam generator tubing are discussed in this report.

The overall improvement factor for advanced alloys vs. Alloy 600MA tubes in SGs is probably made up of several multiplicative factors, as follows:

- The “material” improvement factor that is the focus of this report.
- A “design” improvement factor that takes into account the reduced susceptibility to corrosion that is provided by the better design and manufacturing features of steam generators with newer alloy tubes that were not in many early Alloy 600MA steam generators, but not including the tube material change. The changes that contribute to this “design” improvement factor include changes to minimize impurity concentration in crevices (e.g., elimination of deep TTS crevices, use of alternate line-contact tube support geometries, and use of modified thermal hydraulic designs that minimize sludge accumulation) and changes to minimize the likelihood of tube support corrosion that can worsen crevice conditions and can cause denting, e.g., use of stainless steel supports.
- A “chemistry” improvement factor that takes into account the reduced ingress of impurities, oxidants, and corrosion products into steam generators that have resulted from plant design and chemistry changes that have occurred over the years.
- Possible proprietary design and material changes that are not well documented in the open literature and are mainly associated with improved specifications (such as tighter tolerances on minor alloying elements or tube in tubesheet expansion geometries).

Due to improvements in design and water chemistry, the actual performance gains observed by plants may be higher than the material improvement factors calculated based on laboratory testing presented in this report. It must also be recognized that some changes in the factors listed above were essentially simultaneous, so that observed benefits cannot be conclusively assigned to a single change. However, this simultaneity also makes separation of these effects less critical in predicting future tube degradation in the newer generation steam generators.

Because of these complicating factors, it is important to emphasize that the improvement factors recommended in this report are conservatively based on the most robust data sets available. In some cases, this means that different bases and different degrees of conservatism are used in assessing different alloys. Thus, the perspective used here is to provide the technical bases needed to justify differences in operating with alternate SG tube material (for example, changes to chemistry or inspection practices). The improvement factors developed here are not intended for use in making material selections for future applications.

The purpose of this report is to summarize the current knowledge of the improvement in corrosion resistance gained from using various grades of tubing and to provide a basis for assessing appropriate modifications to the current water chemistry guidelines to reflect alloy-specific improvements in degradation resistance. A summary of conclusions developed in the body of this report is given in Chapter 2. Chapter 3 updates the previous plant experience based improvement factors to reflect current data, while Chapter 4 provides new improvement factors based on the field performance of tube plugs. Material improvement factors for advanced alloys based on the results of laboratory testing are described in Chapter 5. Model boiler data on the relative corrosion of tubing alloys in strongly caustic solutions are reviewed in Chapter 6.

2 CONCLUSIONS AND RECOMMENDATIONS

2.1 Introduction

The following tasks were performed in the preparation of this report:

- Plant experience based improvement factors have been updated to reflect recent corrosion events and additional operating time without a significant number of failures of Alloy 600TT, Alloy 690TT, and Alloy 800NG tubing.
- The plant experience analysis was supplemented by consideration of the relative performance of steam generator tube plugs made of Alloy 600TT and Alloy 690TT.
- Laboratory-based improvement factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG vs. Alloy 600MA were updated to include results of recent studies per a literature review.
- A summary of experiments performed to date in model boilers with sodium contamination was compiled. Model boiler testing programs are believed to be a reasonable simulant of actual plant performance, as they more closely resemble the stress, material, and thermal-hydraulic conditions that occur in plants (although the chemistries achieved in these tests may not be realistic).

The updated improvement factors developed in this report are summarized below. A comparison of improvement factors derived from different sources and using different methods is also given in this chapter.

2.2 Summary of Improvement Factors

This report discusses the development of relative improvement factors (IF_R) for Alloy 600TT, Alloy 690TT, and Alloy 800NG. Improvement factors for Alloy 600TT have been updated to reflect recent plant experience and laboratory test programs evaluating the corrosion resistance of this alloy. In general, the bases for making predictions regarding the long-term performance of steam generators tubed with Alloy 690TT have not significantly changed since the publication of the *Alloy 690 Improvement Factor Update* (Reference [2]). The estimated improvement factors have been increased to take into account additional plant experience without statistically significant failures that has accumulated since the previous assessment was published. Additional laboratory test results have also been incorporated. Alloy 690TT is expected to significantly outperform Alloy 600MA under steam generator conditions (both primary and secondary side). The estimated improvement factors for Alloy 800NG have been made based on laboratory testing and accumulated plant experience.

Specific chapters of this report address each of the following issues and are subdivided by alloy:

- Material improvement factors derived from plant steam generator tubing experience data are discussed in Chapter 3.
- Material improvement factors derived from plant tube plug experience data are discussed in Chapter 4.
- Material improvement factors derived from laboratory testing are discussed in Chapter 5.
- Material improvement factors derived from model boiler testing in strong caustic environments are discussed in Chapter 6.

The findings from each of these chapters/subsections are summarized in Section 2.2.2. The next section, Section 2.2.1, discusses the nature of determining improvement factors in the absence of failure data.

2.2.1 Improvement Factors in the Absence of Failure

In Section 2.2.2, improvement factors derived from plant experience are discussed. These improvement factors are derived using a previously developed statistical technique (see References [1], [2], [4], [5], and [7], for example), have been widely considered in the industry, and the improvement factors thus derived have generally been accepted as a valid basis for making chemistry, inspection, and other long-term planning decisions. However, there are some peculiarities of the method which can result in somewhat counter intuitive results. Most of these are associated with determining improvement factors in the absence of significant failure data. The next few paragraphs provide some explanation of how these calculations are made and some of the consequences of the assumptions. Appendix A discusses an alternate technique, which has not received significant review and is therefore not used as the basis for the improvement factors derived in this report. However, this alternate analysis does demonstrate that the techniques actually used in this report are conservative.

The plant experience based improvement factors are defined as the ratio of the median times to failure for the two populations. The median time to failure is the time required for half of the plants in the population to reach some failure criterion (a fraction of tubes failed by the mechanism under consideration). For plants tubed with Alloy 600MA, defining the median time to failure is straightforward, since a failure criterion can be defined such that more than half the plants have actually failed. For Alloys 600TT, 690TT, and 800NG, there has been, at most, only one plant that has reached one of the failure criteria, and for most mechanisms, no plant has reached the failure criterion. Therefore, in order to predict a median time to failure for these plant populations, it has been assumed (unless it is already known to be the case) that there has already been one plant that has reached the failure criterion. In all cases, this is either a known fact (i.e., one plant has reached the criterion) or a conservative assumption (i.e., the advanced alloy is assumed to have performed worse than it actually has). The extent to which this assumption is conservative is illustrated by the alternative method discussed in Appendix A. For Alloys 600TT, 690TT, and 800NG for all cases (whether a plant has reached the failure criterion or not), the median time to failure has been calculated making the further assumption that the distribution of times to reach the failure criterion will be similar to that for Alloy 600MA.

The assumption that the new alloys have a distribution in failure times similar to that for Alloy 600MA cannot be justified using plant experience since there are not sufficient failure data for the newer alloys. However, it is considered reasonable based on laboratory performance of these alloys. As a consequence of this assumption, the predicted median time to failure can be much greater than the actual performance lifetime. This is considered reasonable and is a direct consequence of the assumption of similarity of distributions. The absence of early failures indicates that the median failure will not occur for a considerable time. This is especially significant for the stress corrosion cracking mechanisms considered here since there can be a large difference in the time to first failure and the time to median failure (often a factor of five or higher). The distribution of failure times can be a factor even when one plant has reached the failure criterion if this plant is young compared to the whole population, since this indicates that the failure was either anomalous (not indicative of the whole population) or the distribution is very wide (meaning a very long time between the earliest failure and the median failure).

Because a single plant is assumed to have reached the failure criterion, this methodology can predict a longer time to median failure for larger populations than for smaller. For example, assuming that one plant out of a group of ten has just failed puts the current failure percentage of 10% a distance of 40% from the median failure percentage of 50%, while assuming that one plant out of 50 has just failed puts the current failure percentage of 2% a distance of 48% away from the median failure percentage of 50%. This type of difference leads to significant differences in the predicted times to reach the median failure percentage of 50%, and leads to difficulties in comparing plant experience based improvement factors between two populations for which no significant failures have occurred. Both improvement factors are conservative, but there are different degrees of conservatism.

2.2.2 Material Improvement Factors Derived from Plant Experience Data

The estimated material improvement factors derived from plant experience continue to increase due to additional accumulated experience. General stress corrosion cracking in Alloy 600TT, Alloy 690TT, and Alloy 800NG appears to be minimal, although possible trends in Alloy 600TT PWSCC and ODSCC and Alloy 800NG ODSCC have been observed and are discussed in Section 3.2. In general, improvement factors have been developed separately for primary water (which is a well defined plant environment) and secondary water (which is an ill defined plant environment due to the concentration of impurities in crevices). The following improvement factors were derived from plant experience data:

- The estimated plant experience based improvement factor for Alloy 600TT in primary environments (PWSCC) is > 10.5 (note that this value does not apply to the highly cold worked kiss rolls in French plant, but does apply to the less heavily cold worked and stressed Alloy 600TT in US plants). This value is expected to increase with continued operation without significant failures. However, it should be noted that this value may include the effects of SG design changes that were implemented essentially concurrently, in the US, with the use of Alloy 600TT (e.g., hydraulic expansion in the tubesheet). Note that this analysis does not address PWSCC associated with bulges or tube ends (see Section 3.2.1.2). These degradation mode are expected to be either limited in extent (i.e., isolated cases associated with manufacturing anomalies) or addressed by alternative repair criteria (e.g., for SCC in the tubesheet that does not degrade the primary to secondary pressure boundary).

- The estimated plant experience based improvement factor for Alloy 690TT in primary environments (PWSCC) is > 9.5. This value is expected to increase with continued operation without significant failures.
- The estimated plant experience based improvement factor for Alloy 800NG in primary environments (PWSCC) is > 9.5. This value is expected to increase with continued operation without significant failures.
- The estimated plant experience based improvement factor for Alloy 600TT in secondary environments is > 2.5. This is a conservative lower bound based on the analysis of TSP IGA/SCC occurrence. This value is expected to increase with continued operation without statistically significant failures, even though one plant has already reached the failure criterion. Estimated improvement factors for specific degradation modes are given in Section 3.
- The estimated plant experience based improvement factor for Alloy 690TT in secondary environments is > 5. This is a conservative lower bound based on predictions of circumferential TTS ODSCC occurrence. This improvement factor is expected to increase as additional plant experience without failure accumulates. Estimated improvement factors for specific degradation mechanisms and future predictions are given in Section 3.3.3.
- The estimated plant experience based improvement factor for Alloy 800NG in secondary environments is > 7. This is a conservative lower bound based on predictions of circumferential OD TTS SCC occurrence. This improvement factor may increase as additional plant experience without statistically significant failures accumulates. Estimated improvement factors for specific degradation modes and future predictions are given in Section 3.3.4.

EPRI is continuing to assess alternate methods of determining improvement factors from plant data for materials which have not exhibited significant cracking.

2.2.3 Material Improvement Factors Derived from Laboratory Testing

In general, the use of laboratory data to develop improvement factors results in a high degree of conservatism due to the aggressive nature of testing. It was previously estimated that the degree of conservatism in using laboratory data would lead to a reduction in the IF_R by at least a factor of two [4]. In general, improvement factors have been developed separately for primary water (with a well defined plant environment consistently simulated in laboratory tests) and secondary water (ill defined in the plants and simulated with a significant variety of chemistries in laboratory tests). The following improvement factors were derived from laboratory test data:

- The estimated laboratory testing based improvement factor for Alloy 600TT in primary environments (PWSCC) is 1.6. Note that this value is thought to be low due to the aggressive material conditions often used in laboratory testing (e.g., high strains in U-bend tests) which are not thought to be representative of plant conditions.
- The estimated laboratory testing based improvement factor for Alloy 690TT in primary environments (PWSCC) is > 126.

- The estimated laboratory testing based improvement factor for Alloy 800NG in primary environments (PWSCC) is >20. However, it should be noted that this improvement factor is based on many fewer tests than those for Alloys 600TT and 690TT.
- The estimated laboratory testing based improvement factor for Alloy 600TT in secondary environments is 2.6. This is the average value of the environment-weighted improvement factor function developed in Section 5.5.2.1. It should be noted that this factor is expected to be much lower than the actual improvement factor since most laboratory testing includes cold working of test specimens (formation of U-bends or RUBS) which eliminates much of the benefit of thermal treatment.
- In general, the estimated laboratory testing based improvement factor for Alloy 690TT in secondary environments is 120. As for Alloy 600TT, this is the average value of the environment-weighted improvement factor function developed in Section 5.5.2.2. In extreme environments (those at $pH_T < 5$ or > 9.5), the observed improvement was substantially lower. However, data on the pH distribution (discussed in Section 5.3) indicate that these conditions seldom occur during normal PWR operation and therefore should be weighted less in predicting tube degradation rates. Moreover, laboratory testing usually includes some cold work of the test specimen removing much of the advantage of thermal treatment. Because of this, it is possible that the experimentally determined improvement factors taken as data points for this analysis underestimate the actual improvement factor. However, the advantages of thermal treatment for Alloy 690 are not as well understood as for Alloy 600.
- The estimated laboratory testing based improvement factor for Alloy 800NG in secondary environments is >10. Tests in caustic lead-contaminated environments ($pH_T \geq 10.3$) show a much lower improvement factor under those conditions. There is also one test series (in which Alloy 800NG did not crack) that implies improvement factors of >300 over a wide range of environments. However, other results in some of those environments (in which Alloy 800NG did crack) imply lower improvement factors.

2.2.4 Material Improvement Factors Derived from Model Boiler Testing in Caustic Environments

Material factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG in secondary environments contaminated with sodium based on the results of model boiler tests using the concept of integrated exposure are discussed in Chapter 6. Conclusions from these evaluations are:

- An evaluation based on two methods of calculating integrated exposure indicate that the model boiler tests support improvement factors relative to Alloy 600MA of 2.5 to 21.3 for Alloy 600TT (IF_R = 21.3 based on the preferred method) and of 12.6 to 45.3 for Alloy 690TT (45.3 by the preferred method). The IF_R calculated for Alloy 800NG-NP was 4.3 to 4.1, and was 10.1 to 31.0 for Alloy 800NG-P[1]. It should be noted that these boiler tests almost exclusively assessed caustic environments.

[1] Two work conditions of Alloy 800NG were evaluated in Chapter 6: Alloy 800NG-NP refers to Alloy 800NG in the conventional mill-annealed condition, and Alloy 800NG-P refers to Alloy 800NG with 4% cold work (not expected to affect corrosion resistance) and glass bead peening following the mill anneal. The glass bead peening step is performed to impart additional resistance to ODSCC, and therefore warrants a separate IF_R estimate.

As the estimated IF_R values for the advanced alloys (Alloys 600TT, 690TT, and 800NG-P) are based on tests in which only partial cracking was induced, the above IF_Rs are believed to be conservative. This conservatism is offset by the low number of tests in which cracking was observed, which reduces the confidence of these estimates.

2.3 Comparison of Improvement Factors Derived by Different Methods

The use of each method (analysis based on plant experience, laboratory data, or model boiler data) has strengths and weaknesses as discussed below.

The use of plant experience data is more representative of conditions that actually occur in the field. Furthermore, the large sample size of some plant populations helps to normalize for isolated defects (which may skew laboratory results). However, the length of operating experience is still lower than the expected time to cracking for the advanced alloys, resulting in calculated improvement factors that are pessimistically low. These factors will become more accurate as plant experience without failures accumulates. The limited number of chemistry upsets also makes it difficult to quantify the effect of a specific contaminant at elevated concentrations from field data.

The use of laboratory data for the development of improvement factors has the advantage that the environment being studied is completely controlled (i.e., the effect of design differences and differences between operating conditions are eliminated). However, the rate of corrosion seen in the laboratory may not accurately reflect what occurs in the field. This would occur if the relationship between the aggressiveness of the environment and rate of corrosion is not linear (as is suspected in some cases). In addition, many experiments are performed using specimens with high plastic strains or cold work. Plastic strains and cold work partially eliminate the improvements due to thermal treatment, making the resulting improvement factor unrealistically low.

The model boiler data are perhaps the most robust in that samples are more representative of plant components than typical laboratory tests (i.e., the samples are tubes in the as-manufactured condition and are subjected to realistic stresses and thermal-hydraulic conditions). Also, the test durations are generally substantially in excess of the Alloy 600MA failure time. However, a limited number of model boiler tests were performed under reducing conditions, and few of these were successful in initiating SCC in the advanced alloys. In addition, the model boiler tests were generally performed in much more aggressive chemical environments than are expected to occur in plants.

2.4 Recommended Overall Improvement Factors

Based on analysis of the improvement factors calculated above and engineering judgment, the following improvement factors are recommended for use in predicting tube degradation in PWR SGs.

- Alloy 600TT PWSCC: IF_R ~ 1.6. This is a conservative value based on laboratory data. Plant experience would suggest a considerably higher value.
- Alloy 690TT PWSCC: IF_R ~ 125. This value, based on laboratory data, will result in no degradation predicted for this mechanism during plant life, even with multiple life extensions.
- Alloy 800NG PWSCC: IF_R ~ 9.5. This is a minimum indicated by plant experience. Continued good performance by Alloy 800NG will result in an increased value.
- Alloy 600TT Secondary Environments: IF_R ~ 2.5. This is the lower limit of the laboratory and plant-experience based improvement factors and is therefore conservative.
- Alloy 690TT Secondary Environments: IF_R ~ 45. This value is estimated from the IF_R predicted by the model boiler tests, using Method B. This is a more conservative estimate than the IF_R calculated based on the full range of laboratory testing and should be considered a lower bound. Due to the lack of observed SCC in Alloy 690TT to date, the IF_R calculated from plant experience data is not representative of degradation rates at this time.
- Alloy 800NG Secondary Environments: IF_R ~10. This improvement factor was determined from the laboratory test data, but is in general agreement with the lower bound identified by plant experience, where there have been limited failures observed in Alloy 800NG tubed plants to date.

A summary of improvement factors derived in this study is given Table 2-1.

Table 2-1
Summary of Recommended Improvement Factors

IF_R Determined Based On:	Alloy 600TT	Alloy 690TT	Alloy 800NG	Notes
Plant Experience				In general, these alloys have not demonstrated sufficient degradation in the field to allow the development of robust improvement factors. Therefore, these values are all minimums which are expected to increase as additional operating time is accumulated. Because these values are all minimums with different degrees of conservatism it is not possible to directly compare the values given for the different alloys.
Primary-side SCC	>10.5	>9.5	>9.5	
Secondary-side SCC	>2.5	>5	>7	
Laboratory Testing				Laboratory testing often introduces unrealistic conditions in order to accelerate failures. Because these accelerating factors may affect different materials differently, comparing different alloys using these types of tests is not straightforward. Uncertainty regarding actual secondary side environments makes these improvement factors less certain.
Primary (including AVT/pure water results)	1.6	> 126	> 20**	
Secondary (Environment-weighted)*	2.2	120	>10****	
Model Boiler Testing				The model boiler tests reviewed here were all based on caustic environments. Thus the environments tested are not likely to be a good representation of actual conditions.
Integrated Exposure	21.3	45.3	4.1 / 31.0 ***	
OVERALL RECOMMENDATIONSt				These recommendations are not made on a common basis and therefore cannot be directly compared. In particular, no conclusions should be drawn regarding the relative performance of Alloy 690TT and Alloy 800NG. Instead, these values are recommended as lower bounds on the improvement factor that are sufficiently conservative for use in chemistry and inspection decisions.
Primary-side	**1.6**	**125**	**10**	
Secondary-side	**2.5**	**40**	**10**	

* Includes experimental data from tests in caustic, chloride, sulfate, lead, and oxidizing environments.

** Many fewer tests were reviewed than for other conditions.

*** Conventional mill-annealed Alloy 800NG / Alloy 800NG with glass bead peening. Note that the 31.0 value probably does not apply to the expansion transition since the benefits of peening are most likely negated by the plastic strains in this region.

**** One series of tests implies an improvement factor of >300, but is contradicted by other testing.

t Based mostly on direct comparisons of laboratory results. The Alloy 690TT secondary side IF_R is discounted due to limited operating experience and more limited test data. The Alloy 800NG primary side IF_R is discounted due to the small number of tests.

3
PLANT STEAM GENERATOR TUBING EXPERIENCE BASED IMPROVEMENT FACTORS

In this chapter, the relative performance of Alloy 600MA versus that of Alloy 600TT, Alloy 690TT, and Alloy 800NG is evaluated by comparing the field performance of these alloys where they have been used for steam generator tubes. This comparison is made by comparing the rates of failure experienced in steam generators tubed with each alloy. In previous studies, improvement factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG have already been developed [1, 2, 5, and 7, for example]. At the time of the previous analyses, little cracking in the new alloys had been observed; the reported improvement factors were therefore developed making the conservative assumption that one plant had already reached the failure criterion. Since to date no statistically relevant failures have been observed in plants with Alloy 690TT and Alloy 800NG[2] and only one plant has reached the failure criterion for only one mechanism for Alloy 600TT, these factors have proven to be pessimistic. The improvement factors for these alloys presented in this chapter have been updated to take into account the plant experience that has accumulated since publishing those earlier reports.

The use of plant experience based improvement factors is generally considered more indicative of actual performance than laboratory test based factors when sufficient plant operating data are available for a robust analysis. Laboratory studies are generally performed in highly aggressive environments to accelerate the rate of failure events, whereas plant experience-based factors capture the performance of the as installed material condition under actual water chemistry and operating conditions. Additionally, laboratory test specimens are often cold worked, changing the nature of crack initiation and significantly increasing stress levels. These effects can make laboratory test results very conservative. However, since the operating time for steam generators tubed with advanced alloys is relatively short compared to the expected onset of statistically significant failures, the improvement factors calculated from plant data may be overly conservative. It is recommended that both strategies be taken into account when determining overall improvement factors.

Note that comparing the plant experience based improvement factors for different alloys that have not experienced significant failure (e.g., Alloy 690TT versus Alloy 800NG) is not always appropriate. In these cases, the calculated improvement factor is the lower bound which is supported by the statistical method chosen. Thus, the differences in values are as likely to be due

[2] At the time this report was written, DEI was made aware of the planned publication of data which would indicate that the first Alloy 800NG plant had reached the failure criterion for TSP OD SCC in 2005. This data was not published in time for formal inclusion in this report. However, it should be noted that because of the assumption of imminent failure of the first plant, the calculated median times to failure and thus the improvement factor for this failure mode is not affected by a single unit reaching the failure criterion (essentially, a single unit having failed is the conservative assumption made in the absence of failures, so the first failure does not significantly affect the calculation results).

to the particulars of the plant population (number of plants, range of operating times, temperatures, etc.) rather than the actual material. As is discussed in Section 1, the plant based material improvement factors are generally convoluted with other factors, such as changes in design geometry or chemistry practices.

3.1 Methodology

Field performance was quantified by comparing the times to reach a mechanism-specific degradation threshold, henceforth referred to as the *failure criterion*. The improvement factor is determined by directly comparing the median time to reach the degradation threshold for each alloy, or the time at which half the units have reached the failure criterion. The approach used to determine these median times to cracking is described below.

For Alloy 600MA, the determination of a median time to the failure criterion is relatively straightforward due to the large number of failures observed with that alloy. For data sets in which a large number of failures are observed (i.e., the degradation threshold has been reached in most cases), a Weibull distribution can be used to describe the time to failure criterion. This distribution is defined by the following equation:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad \textbf{Eq. 3-1}$$

Where *F(t)* is the fraction of units to reach the failure criterion at time *t* and β and θ are fitted parameters. By plotting the time to failure versus number of units failed, β and θ can be obtained through some fitting routine (such as least squares). The median time to degradation threshold is then found by setting *F(t)* = 0.5.

At this time, for US units with Alloy 600TT tubing, the failure criterion has been reached at only one unit and for only one SCC mode. No generic corrosion degradation has yet been observed in any US SGs with Alloy 690TT tubing or in any international SGs with Alloy 800NG tubing. Therefore, predictions for corrosion degradation mechanisms must be developed from experience using other mathematical formulations. It is anticipated that the modes of degradation that will eventually be observed will be the same as those observed in earlier types of steam generators, but delayed in time because of the improved corrosion resistance of the tube material and the effects of other design feature improvements.

For alloys whose cumulative plant experience contains insufficient or no instances of reaching the failure criterion, a Weibayes analysis is used to predict time to failure. For this analysis, the most likely value of θ is determined from the following equation:

$$\theta = \left(\frac{\sum_{i=1}^{n} x_i^{\beta}}{r} \right)^{\frac{1}{\beta}} \qquad \textbf{Eq. 3-2}$$

Where *r* is the number of units that have reached the failure criterion, x_i are the accumulated times for each unit (either operating time or time to reach the failure criterion), and *n* is the number of units. Because only one plant (for only one mode) with Alloy 600TT and no plants with Alloy 690TT or Alloy 800NG have reached the failure criterion, it is assumed that failure of the first unit has occurred or is imminent (*r* is arbitrarily close to 1, this is the assumption which makes the first failure of little consequence in the calculation of the median time to failure). This is a conservative assumption, and, as the time without an increase in the number of failures increases, the median time to failure will increase and thus the improvement factor will increase as well. In this method, β is assumed to be equal to the value for Alloy 600MA, meaning that the failures for other tubing materials will have the same distribution as those for Alloy 600MA but that the initial failures will occur after a longer time period. Note that this methodology makes the calculated improvement factor sensitive to the number of plants in the population group as well as their distribution in ages. For example, the assumption that one plant has reached the failure criterion has a greater effect on Alloy 800NG plants (1 failure out of 16 total) than on Alloy 690TT plants (1 failure out of 53 total).

The calculated median times to failure are adjusted to a common temperature using the Arrhenius equation before the improvement factor is determined. The improvement factor is then a simple ratio of the median time to failure of the alloy under consideration to the original alloy.

3.1.1 Data Sets Considered

The calculation of plant experience based improvement factors requires careful population selection to maximize the extent to which the observed improvement is caused by the tube material differences and not by other design differences. Ideally, the tubing material is the only design change between the plants compared. Several non-material design features have been shown to significantly impact degradation rates, specifically the tube support design and the method of tubesheet expansion. The method of tubesheet expansion is generally taken into account when selecting plant populations for calculating improvement factors for primary water stress corrosion cracking (PWSCC) and secondary-side stress corrosion cracking at the top of tubesheet (OD TTS IGA/SCC). Methods of expansion include “WEXTEX” or explosive expansion, hydraulic expansion, roll (full- or partial depth) expansion, kiss roll expansion (not used in the US but used at some non-US plants, primarily French, but also sometimes used elsewhere, such as South Korea and Belgium), and partial hydraulic or mechanical expansions at both the bottom and top of the tubesheet. Tube support design primarily affects stress corrosion cracking at the tube to tube support intersection (TSP IGA/SCC). Common tube support designs include broached hole supports, drilled hole supports, eggcrate supports, and lattice grid supports. (Note that it is customary to refer to all of these designs as tube support plates –TSPs–, even though not all are plates.) Inevitably, there are some design changes (for example, tighter tolerances on the depth of the tubesheet crevice) that may significantly affect degradation and yet are not well documented or vary so much that it would not be possible to define a distinct population that was large enough for statistical analysis.

Degradation thresholds used to calculate improvement factors are generally defined for a specific corrosion mechanism (for example, 0.05% hot leg tubes with tube support plate IGA/SCC), and are only meaningful when all other aspects of the design remain constant. In general, the threshold for failure (e.g., 0.05% or 0.1%) has been selected for the convenience of the mathematical treatment, specifically so that the time required for most units to "fail" is quantifiable (neither too short nor too long to determine from the experience base). This report discusses corrosion arising from the following mechanisms:

- Axial primary-side intergranular attack/stress corrosion cracking (IGA/SCC) at the expansion zone transition (Axial EZ PWSCC)

  For axially-oriented primary water stress corrosion cracking (PWSCC) in hot leg tube expansion transitions, the failure criterion was defined as 0.1% of the tubes with HL axial PWSCC defects. The time scales for the various plants were adjusted for differences in operating hot leg temperature to a reference temperature of 609°F using an Arrhenius equation with an activation energy (*Q*) of 50 kcal/mole. This activation energy is based on previous studies performed for EPRI [114].

- Circumferential primary-side IGA/SCC at the expansion zone transition (Circ. EZ PWSCC)

  The failure criterion for circumferentially oriented primary water stress corrosion cracking was defined as the time to reach 0.1% of tubes with HL circumferential PWSCC. In addition, the time scales for the plants were adjusted to a reference temperature of 609°F using an Arrhenius equation with an activation energy (*Q*) of 50 kcal/mole.

- Axial and volumetric secondary-side IGA/SCC at the top of tubesheet (OD TTS A&V IGA/SCC)

  The failure criterion for axial and volumetric secondary-side IGA/SCC at the top of tubesheet was defined as the time at which cracking was observed in the outer diameter of 0.1% of tubes. Reference temperatures are defined for specific plant populations in the body of this chapter.

- Circumferential secondary-side IGA/SCC at the top of tubesheet (OD TTS Circ. SCC)

  For the analysis of feedring plants, the failure criterion for circumferentially oriented IGA/SCC at the top of tubesheet (sludge pile) was defined as the time at which cracking was observed in 0.05% of tubes. The time at which cracking was observed in 0.1% of tubes was used as the failure criterion for preheater plants (Alloy 600MA and Alloy 600TT only). This difference is based on mathematical convenience, i.e., so that the failure criterion was not reached in too short or too long a time to adequately quantify.

- IGA/SCC at the tube support plate intersection (HL TSP IGA/SCC)

  The failure criterion for this degradation mechanism was defined as the time to 0.05% cracking at the tube to tube support plate intersection for the majority of the analyses presented. The preheater plant populations (Alloy 600MA and Alloy 600TT) were analyzed using a 1.0% TSP IGA/SCC degradation threshold. This difference is based on mathematical convenience, i.e., so that failure criterion was not reached in too short or too long a time to adequately quantify.

In this report, circumferential and axial/volumetric degradation modes were modeled separately because of higher regulatory concern for circumferential cracks and because different factors of improvement were observed in some cases for different defect orientations.

Since actual repairs due to wear at anti-vibration bar (AVB) support locations (“AVB wear”) and repairs due to other causes such as preventive repairs, wear caused by loose parts, etc., (“miscellaneous”) have been performed in significant numbers (relative to SCC indications) in the more corrosion resistant tubing, these mechanisms do not require the formulation of improvement factors. That is, there is ample evidence that tubing material does not affect these types of repair.

The plant populations considered for each improvement factor are given in Table 3-1. Populations with the same tubing material are divided for the following reasons:

- For PWSCC at the top of the tubesheet, units with different expansion methods (hard rolled, kiss rolled, hydraulically expanded, explosively expanded, etc.) are separated because these methods impart significantly different stress patterns.
- For ODSCC at the top of the tubesheet, units with different expansion methods are separated because these methods result in different stress distributions and in different crevice geometries.
- For ODSCC at all locations, preheater units are treated separately from feedring units because the presence of a preheater results in different thermal hydraulics. This changes patterns of deposition and accumulation of impurities as well as the temperature of the secondary side water entering the hot leg side of the tube bundle. For example, at the TSP it is often observed that the first ODSCC indications occur on the hot leg side at the first tube support plate. In a preheater unit, the difference between the secondary side hot and cold leg temperatures in the SG are greater. That is if two units are operating at the same primary hot and cold leg temperatures, at the first tube support plate the tubes in the preheater plant will be hotter on the hot leg and colder on the cold leg.
- For ODSCC at the tube support plates (TSPs), units with broached hole TSPs are treated differently from units with drilled hole TSPs, since the thermal hydraulics of the support geometry are thought to significantly affect impurity accumulation and deposition in these locations.

Table 3-1
Plant Populations Analyzed to Determine Material IF_R

Degradation Mech.	SG Tubing Material	Plant Population
Axial EZ PWSCC	Alloy 600LTMA	Westinghouse, WEXTEX
		Westinghouse, HE
	Alloy 600TT	Westinghouse, HE
	Alloy 690TT	Westinghouse, HE
	Alloy 800NG	KWU Plants
Circ. EZ PWSCC	Alloy 600LTMA	Westinghouse, WEXTEX
		Westinghouse, HE
	Alloy 600TT	Westinghouse HE
	Alloy 690TT	Westinghouse, HE
	Alloy 800NG	KWU Plants
A&V TTS OD IGA/SCC	Alloy 600LTMA	French Feedring, KR
		Westinghouse Feedring, HE
		Preheater, KR
		Preheater, FDR
	Alloy 600TT	French Feedring, KR
		Westinghouse Feedring, HE
		Westinghouse Preheater, HE
	Alloy 690TT	Westinghouse, HE
	Alloy 800NG	KWU Plants
Circ. TTS OD IGA/SCC	Alloy 600LTMA	French Feedring, KR
		Westinghouse Feedring, HE
		Preheater, HR
		Preheater FDR
	Alloy 600TT	French Feedring, Kiss Roll
		Westinghouse Feedring, HE
		Westinghouse Preheater, HE
	Alloy 690TT	Westinghouse, HE
	Alloy 800NG	KWU Plants
TSP IGA/SCC	Alloy 600LTMA	DH-Feedring
		BH-Feedring
		DH-Preheater
	Alloy 600TT	Westinghouse Feedring, BH
		Westinghouse Preheater, BH
	Alloy 690TT	Westinghouse, HE
	Alloy 800NG	KWU Plants

Note that the population of KWU plants includes only original European units, and excludes Angra 2 and replacement steam generators.

3.1.2 Trends for a Single Plant/Mode

For each plant, the field data collected were analyzed to determine the operating time in EFPY to reach a defined percentage of the tubes with defects. The time scales for the various plants were adjusted for differences in operating hot leg temperature to a specified reference temperature using an Arrhenius equation with a known activation energy (Q). This activation energy is based on previous studies performed for EPRI [114].

For each plant analyzed, records from each outage were obtained from the EPRI SGDD [161] and other sources reviewed for incidences of tube repairs due to one of the five mechanisms above. Once the cumulative number of repaired tubes for a single degradation mechanism reached a defined percentage of the total tubes in the plant (the degradation threshold or *failure criterion* discussed earlier in this section), one of the following courses of action was taken:

- For cases in which the degradation threshold was exceeded, the actual time at which the degradation threshold was reached was interpolated using a Weibull fit to the inspection data.
- For cases in which the degradation threshold was surpassed on the first inspection, the time to degradation threshold was extrapolated backwards from the first inspection using a Weibull fit to the later inspection data.

The Weibull fit is performed by solving the Weibull equation for β and θ using the known points and then solving the equation for t (time to threshold) at the percent failure of interest. This method is further discussed at the beginning of this section.

For plants that have not yet reached the degradation threshold, the operating time in effective full power years (EFPY) at a defined reference temperature is found by adjusting the plant reported operating time for the last inspection using the Arrhenius equation and the activation energy for the specific degradation mechanism. This time becomes an input into the Weibayes equation to determine the Weibull distribution for predicted time to failure (x_i in Equation 3-2).

3.1.3 Trends for Groups and Median Ranking

Once a plant population is selected, the individual plant times to failure are plotted and fit to a Weibull distribution as described in the beginning of this section.

If no failures have occurred, r is assumed to be unity for the determination of θ (i.e., the first failure is assumed to be imminent). In this case, θ^* is a conservative 63% lower confidence bound on the true value of θ (i.e., there is at least 63% confidence that the true Weibull distribution lies to the right of the Weibayes line). If failures have occurred and Weibayes is used, θ^* is the maximum likelihood estimator of the true value of θ.

In order to perform the Weibayes analyses, it was assumed that the Weibull slope for the distribution of time to cracking is the same for all groups of plants for a particular type of tube degradation. This assumes that the spread of times to cracking among a group of similarly designed plants will be the same for newer generation SGs as it was for earlier design SGs. This is not necessarily a conservative assumption, as some of the reasons for the large range of times to cracking in the original SGs (material variability, chemistry differences, etc.) have been better controlled in second generation and later design SGs due to such things as improved industry guidelines for chemistry control and tubing manufacture. (That is, early failures which give warning of future trends may have been eliminated by better controls.) However, since for the Weibayes analysis it is conservatively assumed that the first failure is imminent among a group of plants, the potential non-conservatism introduced by using the slope from the earlier generation SGs is compensated by the conservatism of the imminent first failure assumption and is not considered to be of much importance. Alternatively, slower to initiate materials might inherently have more distribution in initiation times, making the assumption of an identical slope conservative.

Since the Weibayes analysis uses a maximum likelihood method to determine the characteristic time θ for the newer generation SGs, it was decided that a maximum likelihood method should also be used to determine the parameters β and θ of the earlier generation SGs. This ensures that a consistent calculational approach is used when determining the factors of improvement.

For a Weibull distribution with a censored sample (i.e., failure data plus suspension data), the maximum likelihood estimates of the parameters β and θ are as follows [115]:

$$\frac{\sum_{i=1}^{n} x_i^{b^*} \ln(x_i)}{\sum_{i=1}^{n} x_i^{b^*}} - \frac{1}{r}\sum_{i=1}^{r} \ln(x_i) - \frac{1}{b^*} = 0 \qquad \textbf{Eq. 3-3}$$

where b^* is the maximum likelihood estimate of β
n is the total sample size (number of failures (r) + number of suspensions (k))
$x_1, x_2, \ldots, x_n$ are the operating times accumulated by units 1, 2,…,n
r is the number of failures

The value of θ is obtained from Equation 3-2.

Units censored (suspended) at times t_i are assigned the values $x_{r+i} = t_i$. Thus, the second term in Equation 3-3 sums the logarithms of the failure times only. The maximum likelihood estimates are found by solving Equation 3-3 first for b^* using an iterative procedure, and then using this result to solve Equation 3-2 for θ.

The median time to the specified percentage failure can then be solved for $F(t) = 0.5$ from the Weibull probability distribution.

It should be noted that the degree of conservatism in the predicted median time for alloys which have not exhibited cracking will be a function of the distribution in operating times and the number of plants in the population. Thus, it is not possible to directly compare the plant based improvement factors for two alloys which have not shown cracking. In such a case, the comparison would merely be a statistical manipulation of the operating times for the units in each population.

3.2 Possible Emerging Trends

3.2.1 Alloy 600TT SCC

At the time EPRI 1003589 [1] was completed in 2003, there had been a single instance of SCC occurring in Alloy 600TT tubing at a US plant. Indications of axial ODSCC were detected by bobbin coil and confirmed by Plus Point and Ultrasonic (UT) techniques in Alloy 600TT tubing at Seabrook during the May 2002 steam generator inspections. All of the indications were located at quatrefoil TSP intersections, and both hot leg and cold leg locations were affected over a range of elevations. However, the root cause evaluation determined that the cracking was the result of cold work during manufacturing and did not represent a new generic issue in Alloy 600TT tubing and that active cracking was not occurring at Seabrook [116].

Subsequent to the 2002 report of indications at the TSPs at Seabrook, there have been a few additional indications at TSPs and in the tubesheet area. The current trends for these mechanisms are discussed below.

3.2.1.1 Trends in Alloy 600TT IGA/SCC at TSP Elevations

Upon detection of SCC at Seabrook in May 2002, two of the affected tubes were pulled for metallurgical analysis to characterize the degradation and identify the root cause. Examination of the tubes showed IGA/SCC was present. However, the root cause of the tube cracking was determined to be high residual hoop stress in a small number of tubes caused by cold working that was not relieved by subsequent heat treatment during the manufacturing process. In response, an examination of the ECT data for tubes in rows 1 though 10 in all four Seabrook steam generators was performed (ECT signatures are influenced by cold working). The review showed that all 15 of the cracked tubes had distinct ECT signatures that differed from the other tubes. Rather than the flat region defined by entrance and exit “blips” expected for the U-bend region, the degraded tubes exhibited a distinct shift to the left, an “offset signal.” Based on these results, Seabrook developed an ECT screening technique to identify all tubes with high residual hoop stresses. In addition to the 15 cracked tubes repaired during OR08, six more tubes were identified with the characteristic offset bobbin signal. Although no crack indications had been detected in these tubes during OR08, it was decided to inspect and preventively plug these tubes during OR09. Of the six tubes plugged, 3 were observed to have axial ODSCC at the time of repair. No further IGA/SCC has been observed.

Subsequently, both Braidwood 2 and Byron 2 found limited numbers of tubes in their Model D5 SGs with the offset signal, though only Braidwood 2 identified tubes as having stress corrosion cracking [117].

Because this type of degradation is thought to be possible in the near term only in the limited number of atypical tubes characterized by the ECT offset signal [118], the generic predictions in EPRI 1003589 and subsequent reports are not affected by the Seabrook findings—except to the extent that a particular plant may have atypical tubes that exhibit the aforementioned material anomaly.

3.2.1.2 Trends in Alloy 600TT IGA/PWSCC at/below Top of Tubesheet

Eddy current testing (ECT) has identified primary side crack-like indications at several units with Alloy 600TT tubing. ECT indications consistent with primary water stress corrosion cracking have been observed in the tubesheet regions at Catawba 2 [121] and Vogtle 1 [122]. Catawba 2, which had operated for approximately 14.7 EFPY at the time, found three discrete circumferential indications in a bulged area within the tubesheet region of one tube during an outage in 2004.[117] During a 2005 outage, Vogtle 1 found three circumferential indications on the inside diameter of two tubes that were associated with bulges.[117, 119, 123]

During the 2004 Catawba 2 outage, nine additional tubes were found to have circumferentially oriented indications in the tack expansion region, and a few hundred tubes were found to have indications in the tube-to-tubesheet weld. In six of the tubes with weld indications, the indications, reflecting either single or multiple cracks, extended into the parent tube. The subsequent 2006 and 2007 inspections resulted in the finding of several additional indications in the tack expansion area, including 10 indications on the cold leg side of the SG.[119]

During a recent Braidwood 2 outage, A2R13 (Spring 2008), nearly 300 tubes exhibited ECT detectable indications within the bottom one inch of the tubesheet (at the approximate locations of the tube-end welds), with 16 requiring repair and the remainder exempted from repair by an alternate repair criterion (ARC) applicable for that outage. During the most recent Byron 2 outage, B2R14 (Fall 2008), ECT indications of cracks were detected in 65 tubes on the hot-leg side within the bottom ¼ inch of the tube.

Surry 2, Vogtle 2, and Wolf Creek also all detected flaws by ECT near the tube-end welds during their respective 2008 inspections, with the numbers of indications found ranging from about 30 to over 250 [120]. This degradation mode was also present during the most recent outage at Comanche Peak 2.

Primary water stress corrosion cracking has been detected by Plus Point ECT in Alloy 600TT sleeves at Oconee 1 and 3 over three inspections at each plant (no tubes have been pulled for metallurgical examination of the ECT indications). However, the cracking has occurred in double rolled joints in the sleeves. The rolling method used to lock the sleeve into the tube produces significantly higher tube residual stresses than the hydraulic tube expansion method used to expand Alloy 600TT tubes in the tubesheet in the US. Therefore, this experience does not indicate that significant SCC is imminent in US plants with Alloy 600TT. Furthermore, the Oconee plants have a “once-through” design that is substantially different from the recirculating designs considered in the development of improvement factors for this report.

In non-US plants with Alloy 600TT tubing, there have been some instances of both PWSCC and OD IGA/SCC. However, none of this experience is known to directly apply to US plants with Alloy 600TT tubing because of differences in design and operating experience of the steam generators. For example, there has been significant PWSCC detected in French and South Korean plants with mechanical kiss roll tube expansions. However, kiss rolling produces significantly higher cold work and residual stresses than the hydraulic expansion method used in the US. Therefore, this experience indicates only that Alloy 600TT tubing is susceptible to PWSCC in high stress/high cold work conditions. During a recent EPRI visit to South Korea it was learned that the Korean utility is reporting that PWSCC and ODSCC has been detected in

Alloy 600TT tubing at Kori 3; however, the circumstances regarding the cracking are not known (i.e., if the cracking is as a result of some abnormal event or occurred during normal operation). There have been no instances of cracking of Alloy 600TT sleeves in any international plants.

3.2.1.3 Trends in Alloy 600TT OD Cracking at the Top of the Tubesheet (TTS)

In 2006, Vogtle 1 found 17 tubes with circumferential indications and one with an axial indication on the OD surface at the TTS. Due to resource limitations (vendor personnel and equipment) and the inaccessible physical locations of the tubes, a tube pull was not performed during the outage. However, based on evaluations of *in situ* inspections using several techniques, the indications were concluded to be caused by secondary side SCC [120]. About a dozen similar indications were also identified during the 2008 SG inspection, and two tubes were removed for metallurgical examination. Metallurgical examination confirmed that the flaws were in fact circumferential and axial ODSCC.[182] The circumferential OD IGA/SCC at the TTS is the single incidence of an SCC mode reaching the failure criterion defined in this study at a unit with Alloy 600TT tubing.

Lastly, in 2007 Catawba 2 identified eight tubes with axially oriented OD indications in one steam generator. The indications were located slightly above the top of the tubesheet in the sludge pile region [122]. It is understood that inspections in Spring 2009 did not find additional significant indications of this type and it is therefore assumed that the 2007 results do not represent the start of an active mode of degradation.

3.2.2 Alloy 800NG TS ODSCC[3]

The corrosion mechanisms that are considered most likely to affect steam generators with 800NG tubing are the OD mechanisms at the top of the tubesheet, i.e., axial and volumetric IGA/SCC and circumferential SCC. This is based on (1) service experience indicating that ID mechanisms are unlikely to be significant and (2) the known aggressive chemistries that can develop under sludge piles and in crevices at the TTS. Other modes, such as axial IGA/SCC at supports and in the deep tubesheet crevice, are also possible.

The industry experience with corrosion in 800NG tubes is summarized below:

- During operation of Siemens steam generators using phosphate water chemistry, significant wastage was experienced. At Point Lepreau, some pitting and wastage was experienced during its early operation when phosphate water chemistry was used. Since conversion of the Siemens units and Point Lepreau to AVT water chemistry, these corrosion mechanisms have ceased being significant. For this reason, wastage and pitting are not considered further in this document.

[3] At the time this report was written, it was noted that publication was planned of data which would indicate the first Alloy 800NG plant had reached the failure criterion for TSP OD SCC in 2005. This data was not published in time for formal inclusion in this report. However, it should be noted that because of the assumption of imminent failure of the first plant, the calculated median times to failure and thus the improvement factor for this failure mode is not affected by a single unit reaching the failure criterion (essentially, a single unit having failed is the conservative assumption made in the absence of failures, so the first failure does not significantly affect the calculation results).

- The first confirmed occurrence of IGA/SCC in SGs with 800NG tubing was reported by Biblis B. This case occurred in 1981, and involved axial ODSCC at a tube with a mechanical dent and cold work at the TTS [159].
- In the past several years, about 50 tubes in four Siemens units have been identified with possible OD attack with crack-like indications between the upper and lower expansion zones (the tubes had hard rolls at the bottom and top of the tubesheet). Two tubes were pulled from Biblis A (October 2006). Destructive examination confirmed that the indications were the result of axial OD IGA/SCC.[160]
- Circumferential crack-like indications attributed to ODSCC were similarly detected in the transitions zone at the top of the tubesheet of 29 tubes in the cold leg of one SG at Almaraz Unit II [184], and some non-specified number of similar indications were detected in hot leg areas [183]. Denting indications had also been detected in these areas.
- Axial flaw indications have been found at Unterweser within the support grid region and just above the tube support plate. These flaws are believed to be the result of an aging mechanism rather than individual chemical excursions [181].

The recent detection of IGA/SCC in the tubesheet region of KWU/Siemens design SGs and also at TTS and support elevations may indicate that in-service cracking of Alloy 800NG tubes in SGs has a substantial potential for occurring as SG life is extended. If so, future inspection programs for plants with Alloy 800NG tubing will need to take this into account. Because significant differences exist in the expansion method used in different steam generator models (for example, low stress hydraulic expansion at Point Lepreau versus high stress mechanical hard roll at Biblis, and glass bead peening of the tube OD surfaces for later Siemens units), the potential for eventual occurrence of this type of SCC may be unit specific. However, it should be noted that hydraulic tube expansion was performed at Almaraz Unit 2, where ODSCC indications were also observed.

3.3 Improvement Factors

The main results of the evaluations performed for this report are shown in Table 3-2, which shows the demonstrated improvement factors for Alloy 800NG, Alloy 600TT, and Alloy 690TT versus Alloy 600MA.

Table 3-2
Estimated Improvement Factors for Advanced Alloys Based on Plant Experience

Mechanism	600MA		600TT			690TT			800NG		
	Design Group*	Median Time to Failure (EFPY)	Design Group*	Median Time to Failure (EFPY)	IF_R	Design Group	Median Time to Failure (EFPY)	IF_R	Design Group	Median Time to Failure (EFPY)	IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	West. (All HE)	115.8	>14.2	West. (All)	102.9	>12.6	KWU (All)	103.1	>12.7
	West. (HE)**	10.9			*>10.7*			*>9.5*			*>9.5*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	West. (All HE)	116.2	>11.8	West. (All)	102.8	>10.4	KWU (All)	102.8	>10.4
	West. (HE)**	10.9			*>10.7*			*>9.5*			*>9.5*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	West. Preheater (HE)	20.9	>2.3	West. (All)	48.9	>5.4	KWU (All)	59.6	>6.6
	West. Preheater (KR)**	14.9			*>1.4*			*>3.3*			*>4.0*
	West. Feedring (KR)	8.4	West. Feedring (KR)	64.0	>7.6			>5.8			>7.1
	West. Feedring (HE)**	15.9	West. Feedring (HE)	58.5	*>3.7*			*>3.1*			*>3.7*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	West. Preheater (HE)	17.7	>3.2	West. (All)	29.4	>5.3	KWU (All)	42.4	>7.6
	West. Preheater (KR)**	5.8			*>3.1*			*>5.1*			*>7.3*
	West. Feedring (KR)	13.9	West. Feedring (KR)	40.6	>2.9			>2.1			>3.1
	West. Feedring (HE)**	15.7	West. Feedring (HE)	39.7	*~2.5*			*>1.9*			*>2.7*
TSP IGA/SCC	West. Preheater (DH)	8.2	West. Preheater (BH)	21.0	>2.6	West. (All)	106.0	>13.0	KWU (All)	110.8	>13.6
	West. Feedring (DH)	8.3	West. Feedring (BH)	121.5	>14.7			>12.8			>13.4
	West. Feedring (BH)**	25.7			*>4.7*			*>4.1*			*>4.3*

**Labels in parenthesis indicate the tube-in-tubesheet expansion method or TSP geometry:*

WEXTEX = Explosive Expansion — *FDR = Full-Depth Roll* — *DH = Drilled Hole (TSP)*

HE = Hydraulic Expansion — *KR = Kiss Roll* — *BH = Broached Hole (TSP)*

***This population includes three (3) or fewer plants. Thus, IF_R estimates cannot be made with confidence. Calculated IF_R values are italicized to indicate low confidence.*

600TT/600MA Primary Side IF_R >10.5 — Justification: Expansion method a major factor. Lower value adds robustness but not overly conservative with respect to other values.

690TT/600MA Primary Side IF_R >9.5 — Justification: Expansion method a major factor. Lower value adds robustness but not overly conservative with respect to other values.

800NG/600MA Primary Side IF_R >9.5 — Justification: Expansion method a major factor. Lower value adds robustness but not overly conservative with respect to other values.

600TT/600MA Secondary Side IF_R >2.5 — Justification: Most values compromised (concurrent design change or inspection transient); lower value is very robust.

690TT/600MA Primary Side IF_R >5 — Justification: Most values concurrent with design change; medium value add robustness.

800NG/600MA Primary Side IF_R >7 — Justification: Most values concurrent with design change; medium value add robustness.

Note: Individual IF_R values have different degrees of conservatism. It is not valid to compare values.

3.3.1 Alloy 600MA Degradation

Extensive field data are available for Alloy 600MA tubing. For each mode of degradation, a population of Alloy 600MA tubed plants was analyzed using a Weibull analysis to provide a baseline from which to measure improvements in performance for other materials. In general, the populations of Alloy 600MA tubed plants considered in this report were Westinghouse design plants with Alloy 600MA tubing and WEXTEX tube in tubesheet expansions and Westinghouse design plants with hydraulic tube in tubesheet expansions (HE). Significantly more data are available from plants with Alloy 600MA and WEXTEX expansions. However, the majority of plants tubed with advanced alloys have hydraulic tube in tubesheet expansions, and therefore this population is preferable for determining material improvement factors independent of design changes. For development of the improvement factor for Alloy 600TT, a population of French feedring plants was originally selected to minimize differences in design; this is further discussed in Section 3.3.2.1.

The failure criterion for each degradation mechanism was defined such that a significant portion of the Alloy 600MA WEXTEX plants had reached the degradation threshold. For these plants, the median times to failure were fit to a Weibull distribution as described in Section 3.1. For the Alloy 600MA HE plants, a Weibayes approach was used to develop a distribution of the time to cracking since only two plants (Callaway and South Texas 2) have this particular tube material and expansion method combination.

It should also be noted that South Texas 2 operating time for PWSCC modes was suspended after one operating cycle, when peening of the hot leg tube expansion region was performed. The peening is believed to have been performed early enough in life that essentially no tubes should be susceptible to PWSCC. This data point was therefore categorized as a “suspended cycle” for analyses of primary-side degradation modes. If the 9.4 years during which the plant continued operating without reaching the failure criterion are considered in the analysis, the median time to failure for Westinghouse Alloy 600MA HE plants increases to 19.75 EFPY. This would result in significantly reduced calculated improvement factors. However, because Callaway reached the degradation threshold within this time period while operating at a lower temperature, it is likely that the failure criterion would have been reached had peening not been performed.

The median times to failure for specific degradation mechanisms are discussed in the remainder of this section.

3.3.1.1 Axially Oriented PWSCC in Hot Leg Expansion Transitions

For axially-oriented primary water stress corrosion cracking (PWSCC) in hot leg tube expansion transitions, field data were collected for cracking in Westinghouse design plants with Alloy 600MA tubing and with WEXTEX tube in tubesheet expansions and with hydraulic tube in tubesheet expansions. These data were analyzed to determine the median time to 0.1% hot leg axial PWSCC. The plant time scales were adjusted to a reference hot leg temperature of 609°F.

The WEXTEX Alloy 600MA plant data for axially oriented PWSCC are given in Figure 3-3. The Weibull analysis of these data is shown in Figure 3-4, which gives the median time to failure for Westinghouse design plants with Alloy 600MA tubing and WEXTEX expansions to be about 8.14 EFPY.

Data for Westinghouse design plants with Alloy 600MA tubing and hydraulic tube in tubesheet expansions include only two plants, and only one of them has observed 0.1% axial PWSCC. Therefore, a Weibayes approach was used to develop a distribution of the time to cracking. The data for Alloy 600MA HE plants are shown in Figure 3-5. As seen in the Weibayes plot shown in Figure 3-6, the median time to failure for these plants is 10.9 EFPY.

3.3.1.2 Circumferential PWSCC in Hot Leg Expansion Transitions

For circumferentially-oriented PWSCC in hot leg tube expansion transitions, field data were collected from Westinghouse design plants with Alloy 600MA tubing and with WEXTEX expansion transitions. These are the same groups of plants that were analyzed for time to axial PWSCC as discussed above in Section 3.3.1.1. The data were analyzed to determine the operating time to reach 0.1% of tubes with HL circumferential PWSCC at each plant. In addition, the time scales for the plants were adjusted to a reference temperature of 609°F using an Arrhenius equation with an activation energy (Q) of 50 kcal/mole.

Figure 3-7 shows the field data for cracking in Alloy 600MA tubed plants with WEXTEX expansion transitions. The plot of the Weibull distribution fit to the time-to-failures data for these plants is shown in Figure 3-8, which indicates that the median time to cracking for this population is 9.9 EFPY. Field data for Alloy 600MA plants with hydraulic expansion transitions are shown in Figure 3-9. The median time to cracking for the HE plants was found to be 10.9 EFPY using the Weibayes method, as seen in Figure 3-10.

3.3.1.3 Axial and Volumetric Secondary-side IGA/SCC at Top of Tubesheet (TTS)

For axial and volumetric secondary-side IGA/SCC occurring at the top of the tubesheet, field data were collected from the following Alloy 600MA-tubed plant populations:

- Westinghouse Alloy 600MA Feedring Plants with Hydraulic Expansions and FDBs
- French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs
- European Alloy 600MA Preheater Plants with Kiss Rolls and FDBs
- Westinghouse Alloy 600MA Preheater Plants with Full Depth Hard Roll Expansions and FDBs

Field data for axial and volumetric secondary-side stress corrosion cracking occurring at the top of tubesheet (OD TTS A&V IGA/SCC) in Westinghouse design hydraulic expansion plants are shown in Figure 3-11. The median time to cracking for these two plants is 15.9 EFPY, as shown on the plot of the Weibayes function, Figure 3-12. Given a larger data set, these median times to failure could be used to develop material improvement factors for nuclear grade Alloy 800 (Alloy 800NG) and thermally treated Alloy 690 (Alloy 690TT), as the majority of these plants have hydraulic expansion transitions. Because only two Westinghouse-design feedring plants with hydraulic expansions are tubed with Alloy 600MA, other plant experience data sets are considered in the determination of IF_Rs in this report.

In order to minimize the effect of design changes on the improvement factor calculated for thermally treated Alloy 600TT, field data were collected from French feedring plants with analogous designs but different tubing materials (either Alloy 600MA or Alloy 600TT). Both plant populations have kiss rolled tube in tubesheet expansions and flow distribution baffles (FDBs). The data for the French feedring plants tubed with Alloy 600MA are shown in Figure 3-13. Because the majority of these plants had reached the defined degradation threshold, the median time to IGA/SCC was determined by fitting the time-to-reach-failure data to a Weibull distribution. The median time to failure was found to be 8.39 EFPY, as shown in Figure 3-14.

Two populations of plants with feedwater preheaters (as opposed to the feedring design) were also analyzed for hot leg OD TTS A&V IGA/SCC. These SGs are treated separately from the other Westinghouse models because of performance differences resulting from their preheater design. Experience in plants with Alloy 600MA tubing has been that feedring design SGs experience tube degradation at a different rate than preheater design SGs. The reason for this is probably the different thermal hydraulics of the two types of SGs; therefore, it is expected that the two designs will continue to experience different rates of degradation in second-generation plants.

Field data collected from European preheater plants with Alloy 600MA tubing and kiss-roll expansion transitions are shown in Figure 3-15. Due to the lack of observed cracking of this mode in these plants, the Weibayes method was used to determine the median time to failure. For these plants, the median time to IGA/SCC was 14.91 EFPY, as shown in Figure 3-16.

The second group of preheater plants consists of all US Westinghouse design plants with Alloy 600MA tubing and full-depth hard rolled expansion transitions. Field data collected for these plants are shown in Figure 3-17. Determination of the median time to failure was performed by fitting the data to a Weibull distribution, as the majority of the plants in this group had reached the degradation threshold. The median time to failure was 9.05 EPFY, as shown by the Weibull plot in Figure 3-18.

3.3.1.4 Circumferential Secondary-Side IGA/SCC at Top of Tubesheet

For circumferential secondary-side IGA/SCC occurring at the top of the tubesheet, field data were collected from the following Alloy 600MA-tubed plant populations:

- Westinghouse Alloy 600MA Feedring Plants with Hydraulic Expansions and FDBs
- French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs
- European Alloy 600MA Preheater Plants with Kiss Rolls and FDBs
- Westinghouse US Alloy 600MA Preheater Plants with Full Depth Hard Roll Expansions and FDBs

These are the same groups analyzed for axial and volumetric secondary-side TTS IGA/SCC in section 3.3.1.3.

The field data collected for the Westinghouse feedring plants with hydraulic expansions (HE) are shown in Figure 3-19. The associated Weibayes function is shown in Figure 3-20. The median time to failure was determined to be 15.7 EFPY.

The field data collected for the French feedring plants with kiss-roll expansions (KR) are shown in Figure 3-21. The Weibull distribution of the times to failure is shown in Figure 3-22. The median time to failure for these plants was determined to be 13.86 EFPY.

The field data collected for the European Westinghouse design preheater plants with kiss-roll expansions are shown in Figure 3-23. The Weibull distribution of the times to failure is shown in Figure 3-24. The median time to failure for these plants was determined to be 5.79 EFPY.

The field data collected for the Westinghouse design preheater plants with full-depth roll expansions are shown in Figure 3-25. The Weibull distribution of the times to failure is shown in Figure 3-26. The median time to failure for these plants was determined to be 5.59 EFPY.

3.3.1.5 IGA/SCC at Tube Support Plate Intersection

Modifications to the design of the tube support plate have been shown to have a significant effect on the rate of observed IGA/SCC at the tube-tube support plate intersection. For this reason, the performance of plants with drilled hole versus broached hole tube support plate geometries is analyzed in this section. A design improvement factor for tube support plate geometry that is independent from the material improvement factor was determined in addition to the material improvement factor.

Data for stress corrosion cracking at the tube support plate intersection were collected from US Westinghouse design feedring plants with Alloy 600MA tubing and either drilled hole tube supports or broached hole tube supports. In some newer plants with Alloy 690TT or Alloy 800NG tubing, a lattice tube support geometry is used; however no data exist for this geometry in Westinghouse-type Alloy 600MA plants. The field data for plants with carbon steel drilled hole support plates are shown in Figure 3-27. The Weibull distribution for these data is plotted in Figure 3-28 . The median time to failure for these plants was found to be 8.26 EFPY. A schematic of the typical drilled-hole support plate geometry is shown in Figure 3-1.

Later plants shifted to stainless steel broached hole tube support plates to reduce the potential for impurities to concentrate and form aggressive environments at the tube to tube support intersection and to avoid denting. This tube support plate geometry is shown in Figure 3-2. The field data for these plants are shown in Figure 3-29 . Only one unit, Callaway, operated with broached hole tube support plates and Alloy 600MA tubes. TSP IGA/SCC was not observed at this unit. The Weibayes distribution based on the single plant with broached hole TSPs and Alloy 600MA tubes is plotted in Figure 3-30. The median time to failure was found to be 25.71 EFPY, a considerable improvement over the drilled hole geometry.

Westinghouse design preheater plants with Alloy 600MA tubing and drilled hole tube supports were also analyzed. The data from these plants are shown in Figure 3-31. From fitting a Weibull distribution to these data, the median time to failure was 8.15 EFPY, similar to the median time to failure found for the Westinghouse feedring plants. The Weibull plot for this function is shown in Figure 3-32.

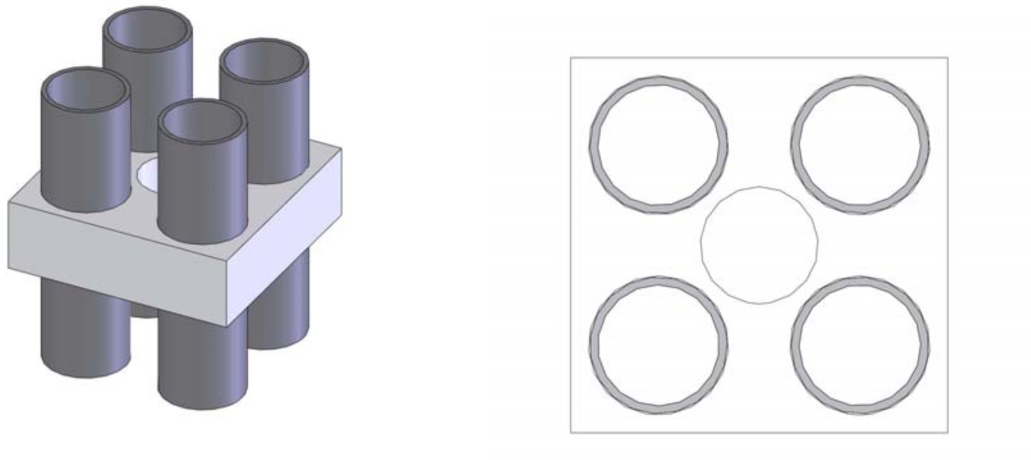

Figure 3-1
Drilled Hole Support Plate

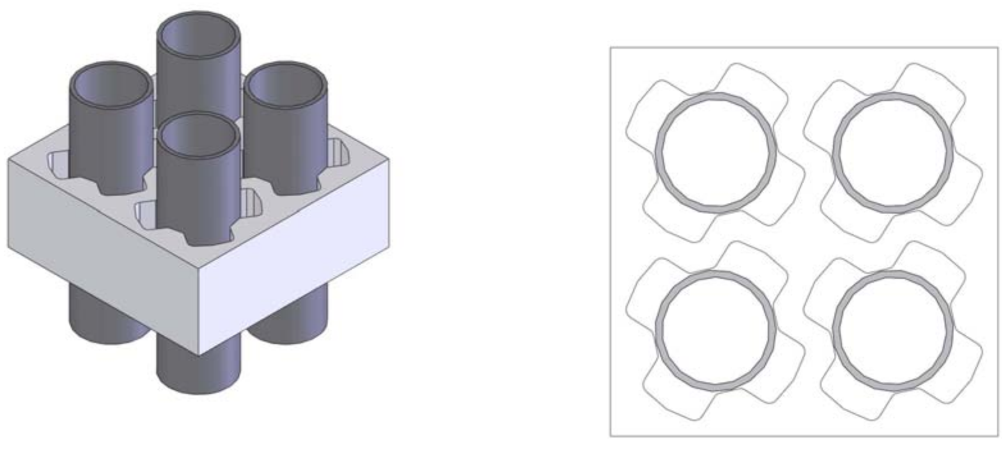

Figure 3-2
Broached Hole Tube Support Plate

3.3.1.6 Summary

The calculated median times to failure for the plant groups and degradation modes discussed in this section are shown in Table 3-3.

Table 3-3
Median Times to Failure for Alloy 600MA Plant Populations

	Plant Population	Median Time to Failure (EFPY)
Axial EZ PWSCC	West. (WEXTEX)	8.1
	West. (HE)	10.9
Circ. EZ PWSCC	West. (WEXTEX)	9.9
	West. (HE)	10.9
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1
	West. Preheater (KR)	14.9
	West. Feedring (KR)	8.4
	West. Feedring (HE)	15.9
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6
	West. Preheater (KR)	5.8
	West. Feedring (KR)	13.9
	West. Feedring (HE)	15.7
TSP IGA/SCC	West. Preheater (DH)	8.2
	West. Feedring (DH)	8.3
	West. Feedring (BH)	25.7

It is important to note that the failure criterion is defined differently for each degradation mechanism, and thus degradation times cannot be compared across mechanisms.

No. Plants = 12 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 12	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (orig.)	3/86	22.70 R	19.05	2.92	603	14.99	2.29	2.29	1	1	12	1.00	0.0565
Sequoyah 2	6/82	26.23	18.80	3.95	609	18.80	3.95	3.95	2	1	11	2.00	0.1371
Sequoyah 1 (orig.)	7/80	23.00 R	14.10	4.72	609	14.10	4.72	4.72	3	1	10	3.00	0.2177
Salem 2 (orig.)	10/81	26.48 R	10.80	6.46	602	8.17	4.89	4.89	4	1	9	4.00	0.2984
North Anna 2 (orig.)	12/80	14.28 R	11.40	4.37	618	16.24	6.23	6.23	5	1	8	5.00	0.3790
Farley 1 (orig.)	12/77	22.23 R	17.06	7.33	607	15.76	6.77	6.77	6	1	7	6.00	0.4597
Salem 1 (orig.)	6/77	18.25 R	10.70	9.83	602	8.09	7.43	7.43	7	1	6	7.00	0.5403
Diablo Canyon 1	5/85	23.32	18.60	11.17	603	14.64	8.79	8.79	8	1	5	8.00	0.6210
Trojan	5/76	16.65 S	9.05	8.84	615	11.47	11.20	11.20	9	1	4	9.00	0.7016
Beaver Valley 1 (orig.)	10/76	29.35 R	18.40	12.44	607	16.99	11.49	11.49	10	1	3	10.00	0.7823
North Anna 1 (orig.)	6/78	14.57 R	8.48		618	12.08		12.08	11	0		10.00	
Fessenheim 1 (orig.)	12/77	25.10 R	17.50		613	20.50		20.50	12	0		10.00	
				Ave. Thot=	609								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with LTMA Alloy 600 tubing and full depth WEXTEX expansions.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. DC2, NA2 value computed by extrapolating from first detection using a slope of b = 2.

Figure 3-3
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 600MA WEXTEX Plants

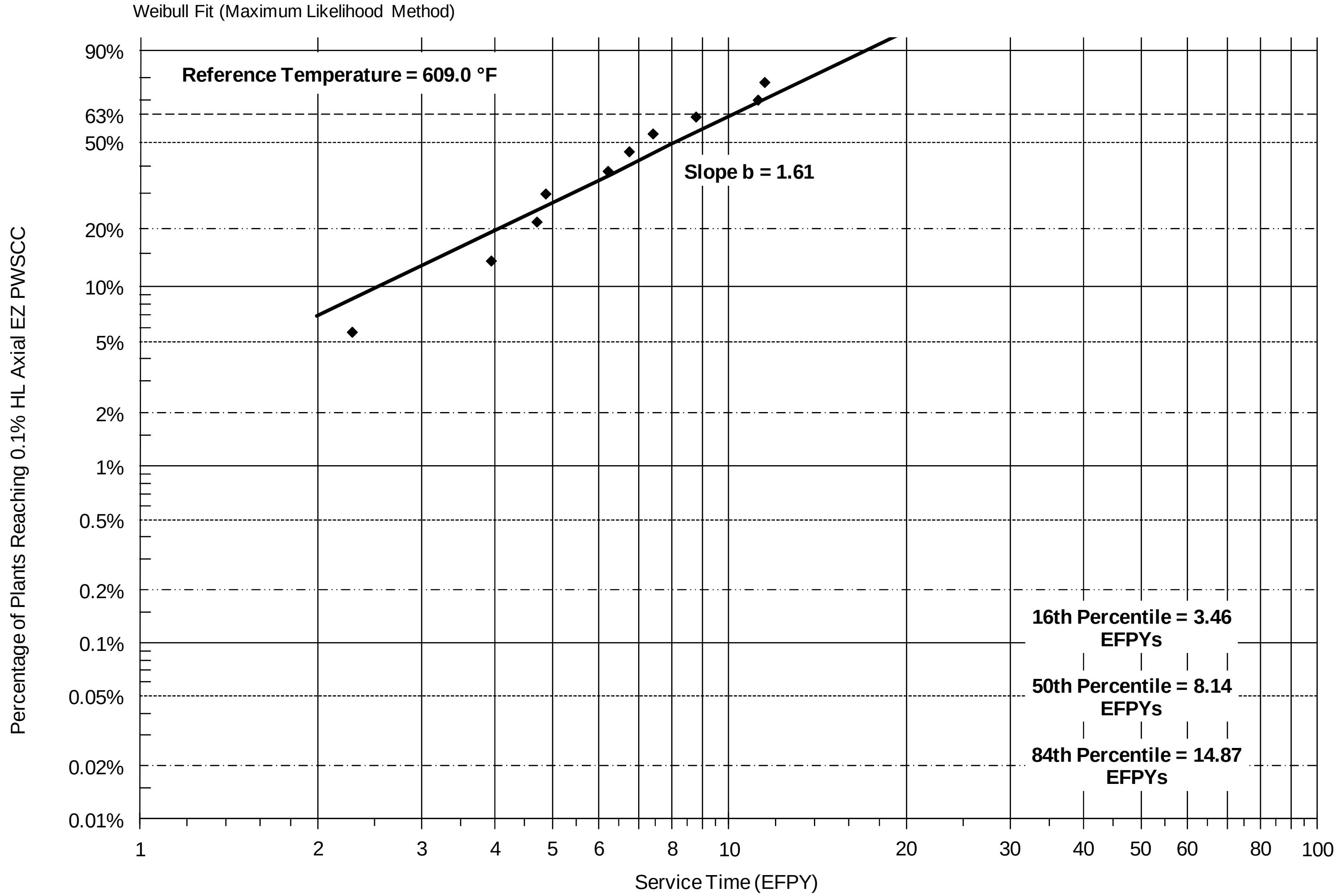

Figure 3-4
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 600MA WEXTEX Plants - Weibull Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 2 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 2	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
South Texas 2 (orig.)	6/89	14.0 R	0.90		624	1.62		1.62	1	0		0.00	
Callaway (orig.)	12/84	20.8 R	16.70	9.36	618	23.80	13.34	13.34	2	1	1	1.50	0.5000
				Ave. Thot=	621								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with LTMA Alloy 600 tubing and full depth hydraulic expansions.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. STP 2 suspended at EOC 1, when HL peening performed.

Figure 3-5
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 600MA HE Plants

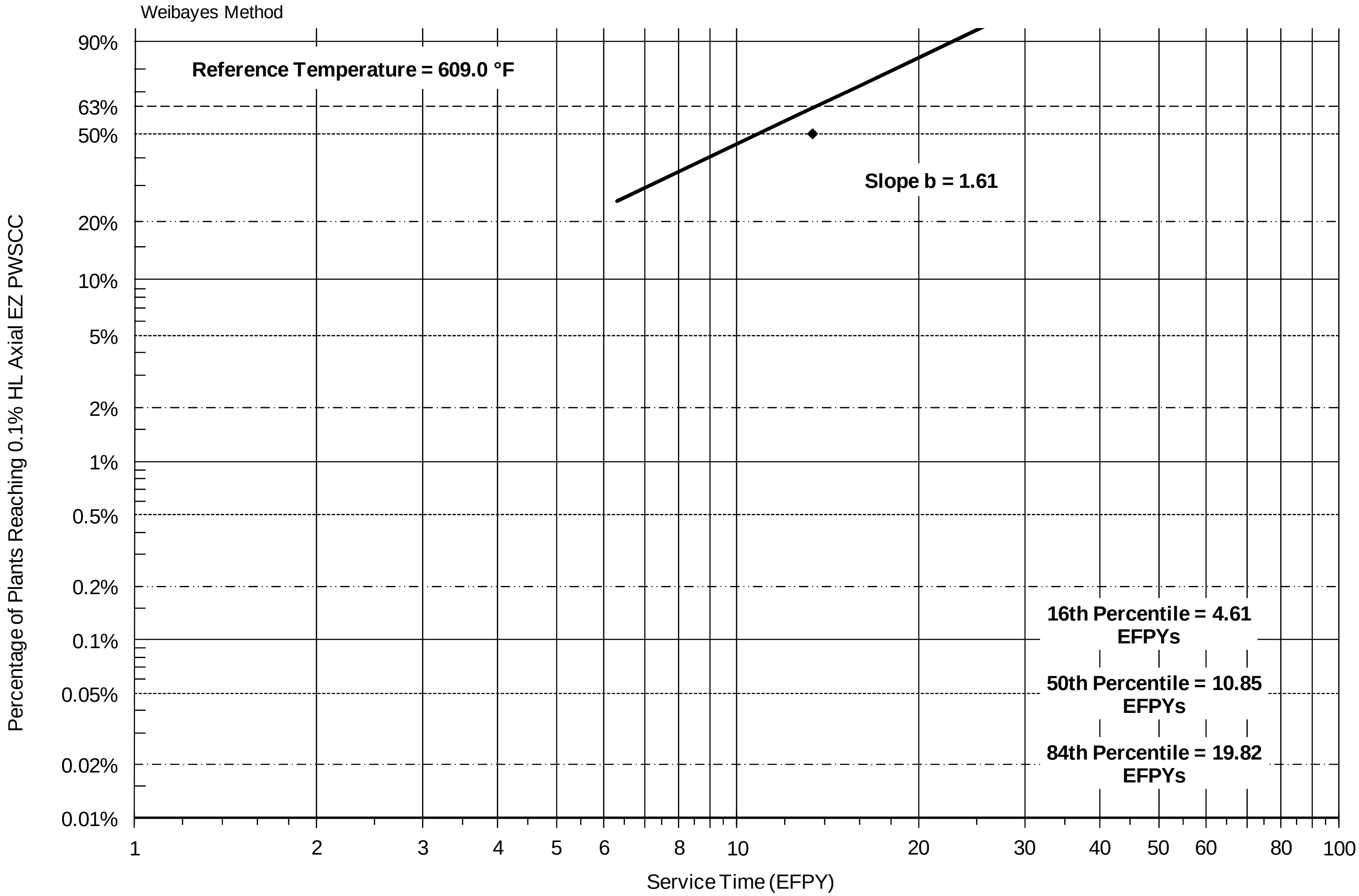

Figure 3-6
Time to 0.1% Axial PWSCC - All Westinghouse Design Alloy 600MA HE Plants - Weibayes Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 12 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 12	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Fessenheim 1 (orig.)	12/77	25.10 R	17.50	2.39	613	20.50	2.80	2.80	1	1	12	1.00	0.0565
Sequoyah 1 (orig.)	7/81	23.00 R	14.10	4.23	609	14.10	4.23	4.23	2	1	11	2.00	0.1371
North Anna 1 (orig.)	6/78	14.57 R	8.48	3.59	618	12.09	5.11	5.11	3	1	10	3.00	0.2177
Trojan	5/76	16.65 S	9.05	4.97	615	11.47	6.30	6.30	4	1	9	4.00	0.2984
Farley 1 (orig.)	12/77	22.23 R	17.06	7.42	607	15.75	6.85	6.85	5	1	8	5.00	0.3790
Salem 1 (orig.)	6/77	18.25 R	10.70	10.62	602	8.09	8.03	8.03	6	1	7	6.00	0.4597
North Anna 2 (orig.)	12/80	14.28 R	9.42	5.70	618	13.43	8.12	8.12	7	1	6	7.00	0.5403
Salem 2 (orig.)	10/81	26.48 R	10.80		602	8.17		8.17	8	0		7.00	
Sequoyah 2	6/82	26.23	18.80	11.63	609	18.80	11.63	11.63	9	1	4	8.20	0.6371
Diablo Canyon 1	5/85	23.32	18.60		603	14.64		14.64	10	0		8.20	
Diablo Canyon 2 (orig.)	3/86	22.70 R	19.05		603	14.99		14.99	11	0		8.20	
Beaver Valley 1 (orig.)	10/76	29.35 R	18.40		607	16.99		16.99	12	0		8.20	

Ave. Thot= 609

Reference Temperature

609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with LTMA Alloy 600 tubing and full depth WEXTEX expansions.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. Fes 1 value computed by extrapolating from first detection using a slope of b = 2.

Figure 3-7
Time to 0.1% HL Circumferential EZ PWSCC - All Westinghouse Design Alloy 600MA WEXTEX Plants

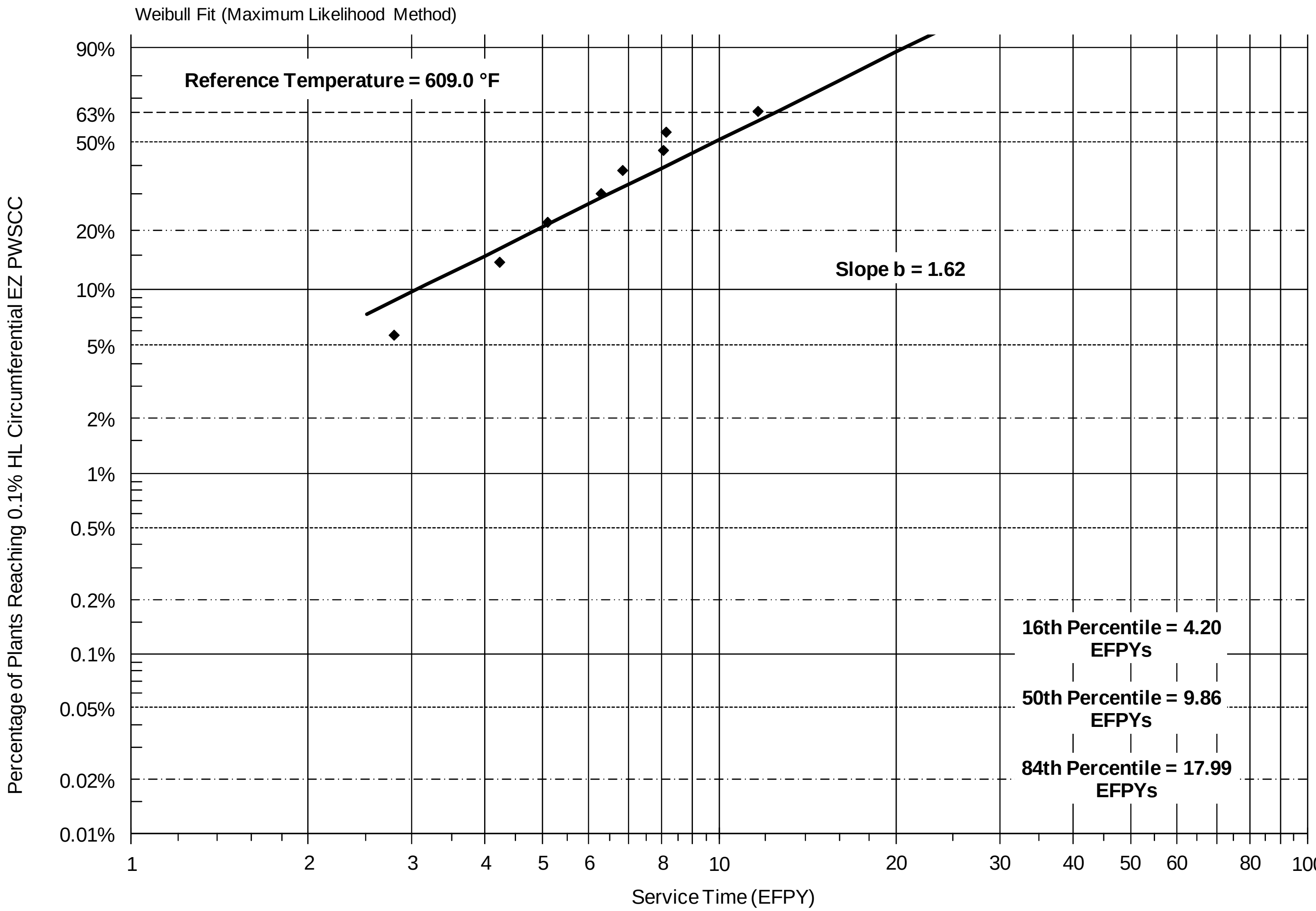

Figure 3-8
Time to 0.1% HL Circumferential EZ PWSCC - All Westinghouse Design Alloy 600MA WEXTEX Plants – Weibull Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 2 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 2	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
South Texas 2 (orig.)	6/89	14 R	0.90		624	1.62		1.62	1	0		0.00	
Callaway (orig.)	12/84	20.8 R	16.70	9.38	618	23.80	13.37	13.37	2	1	1	1.50	0.5000
				Ave. Thot=	621								

Reference Temperature
609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with LTMA Alloy 600 tubing and full depth hydraulic expansions.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. STP 2 suspended at EOC 1, when HL peening performed.

Figure 3-9
Time to 0.1% HL Circumferential EZ PWSCC - All Westinghouse Design Alloy 600MA HE Plants

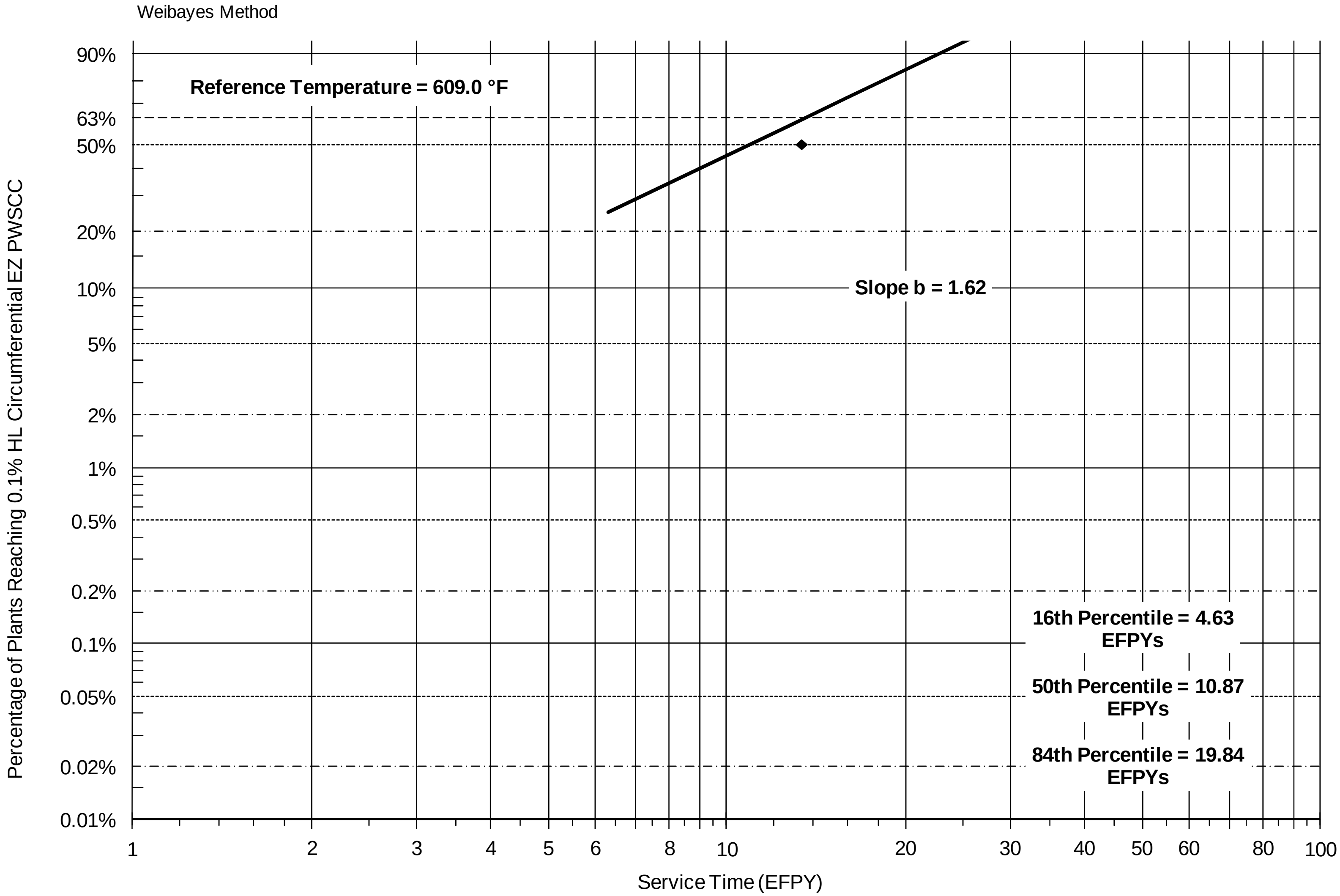

Figure 3-10
Time to 0.1% HL Circumferential EZ PWSCC - All Westinghouse Design Alloy 600MA HE Plants – Weibayes Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 2 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to Detect IGA/SCC or to Last ISI	N= 2	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Callaway (orig.)	12/84	20.8 R	16.70	8.34	618	20.64	10.31	10.31	1	1	2	1.00	0.2917
South Texas 2 (orig.)	6/89	14.00 R	10.30		624	16.37		16.37	2	0		1.00	
				Ave. Thot=	621								

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with SGs with LTMA Alloy 600 tubing, hydraulic expansions, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-11
Time to 0.1% HL OD TTS A&V IGA/SCC – Westinghouse Alloy 600MA Feedring Plants with Hydraulic Expansions and FDBs

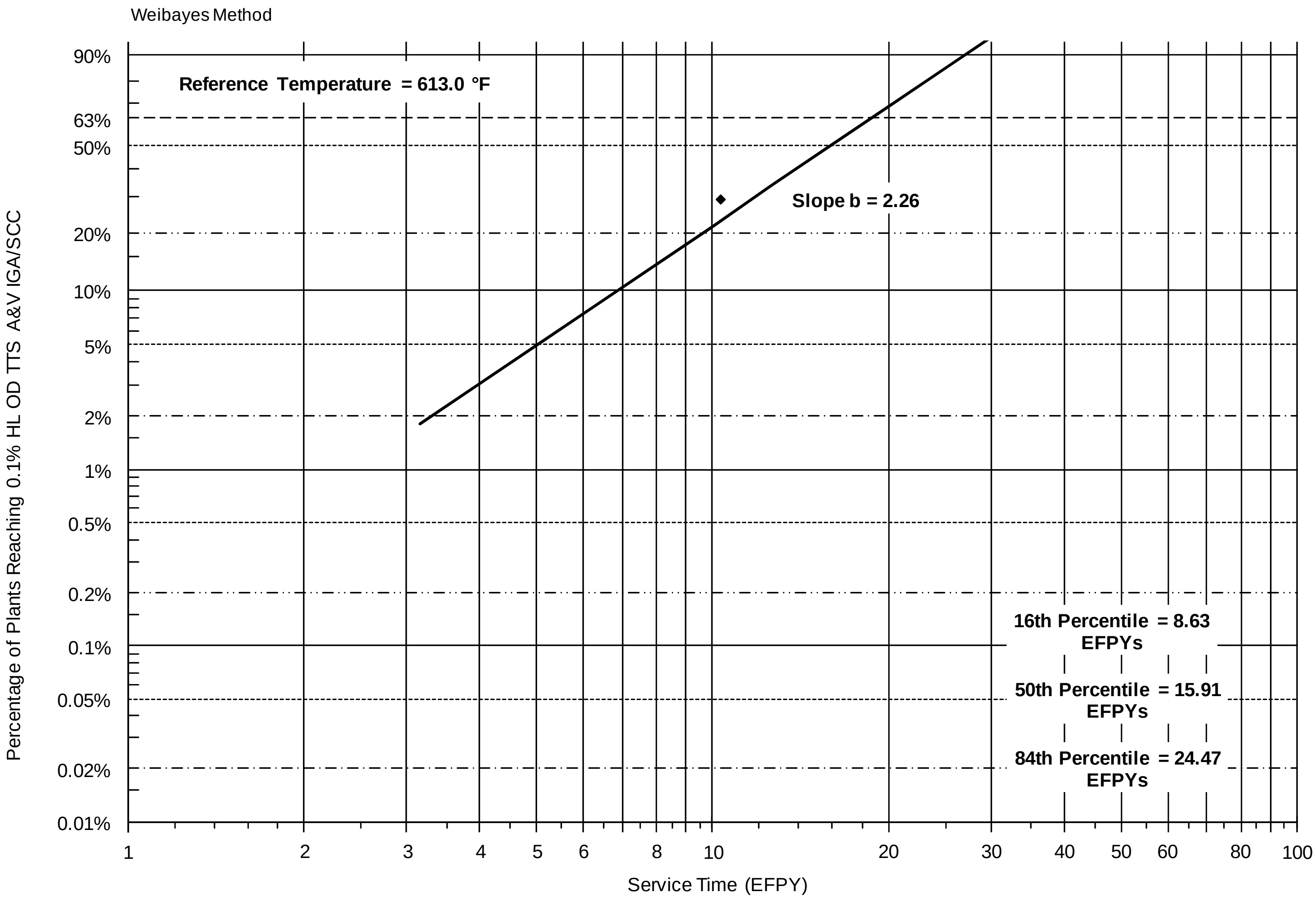

Figure 3-12
Time to 0.1% HL OD TTS A&V IGA/SCC – Westinghouse Alloy 600MA Feedring Plants with Hydraulic Expansions and FDBs – Weibayes Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 14 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to Detect IGA/SCC	Adjusted EDYs to Detect IGA/SCC or to Last ISI	N= 14	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1	Qty @ First Detection
Tricastin 3	5/81	20.70 R	17.31	3.75	613	17.31	3.75	3.75	1	1	14	1.00	0.0486	0.0131
Gravelines B3	6/81	27.27	20.61	4.75	613	20.61	4.75	4.75	2	1	13	2.00	0.1181	0.0068
Dampierre 3 (orig.)	5/81	14.51 R	11.80	5.02	613	11.80	5.02	5.02	3	1	12	3.00	0.1875	0.0019
Blayais 1	12/81	26.77	14.57	5.43	613	14.57	5.43	5.43	4	1	11	4.00	0.2569	0.0040
Tricastin 1 (orig.)	12/80	18.00 R	14.48	6.68	613	14.48	6.68	6.68	5	1	10	5.00	0.3264	0.0026
Dampierre 4	11/81	26.85	19.80	7.09	613	19.80	7.09	7.09	6	1	9	6.00	0.3958	0.0014
Tricastin 4	11/81	26.85	15.74	7.93	613	15.74	7.93	7.93	7	1	8	7.00	0.4653	0.0013
Dampierre 2	2/81	27.60	14.35	8.28	613	14.35	8.28	8.28	8	1	7	8.00	0.5347	0.0010
Tricastin 2 (orig.)	12/80	16.43 R	12.94	8.97	613	12.94	8.97	8.97	9	1	6	9.00	0.6042	0.0009
Gravelines B2 (orig.)	12/80	15.76 R	12.09	9.10	613	12.09	9.10	9.10	10	1	5	10.00	0.6736	0.0006
Gravelines B1 (orig.)	12/80	13.19 R	9.11		613	9.11		9.11	11	0		10.00		0.0004
St. Laurent B1 (orig.)	8/83	12.07 R	9.26		613	9.26		9.26	12	0		10.00		
Gravelines B4 (orig.)	10/81	18.78 R	14.56	10.57	613	14.56	10.57	10.57	13	1	2	11.67	0.7894	0.0003
St. Laurent B2 (orig.)	8/83	23.60 R	17.30		613	17.30		17.30	14	0		11.67		

Ave. Thot= 613

Reference Temperature

613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to French plants with SGs with LTMA Alloy 600 tubing, kiss rolls, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-13
Time to 0.1% HL OD TTS A&V IGA/SCC - French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs

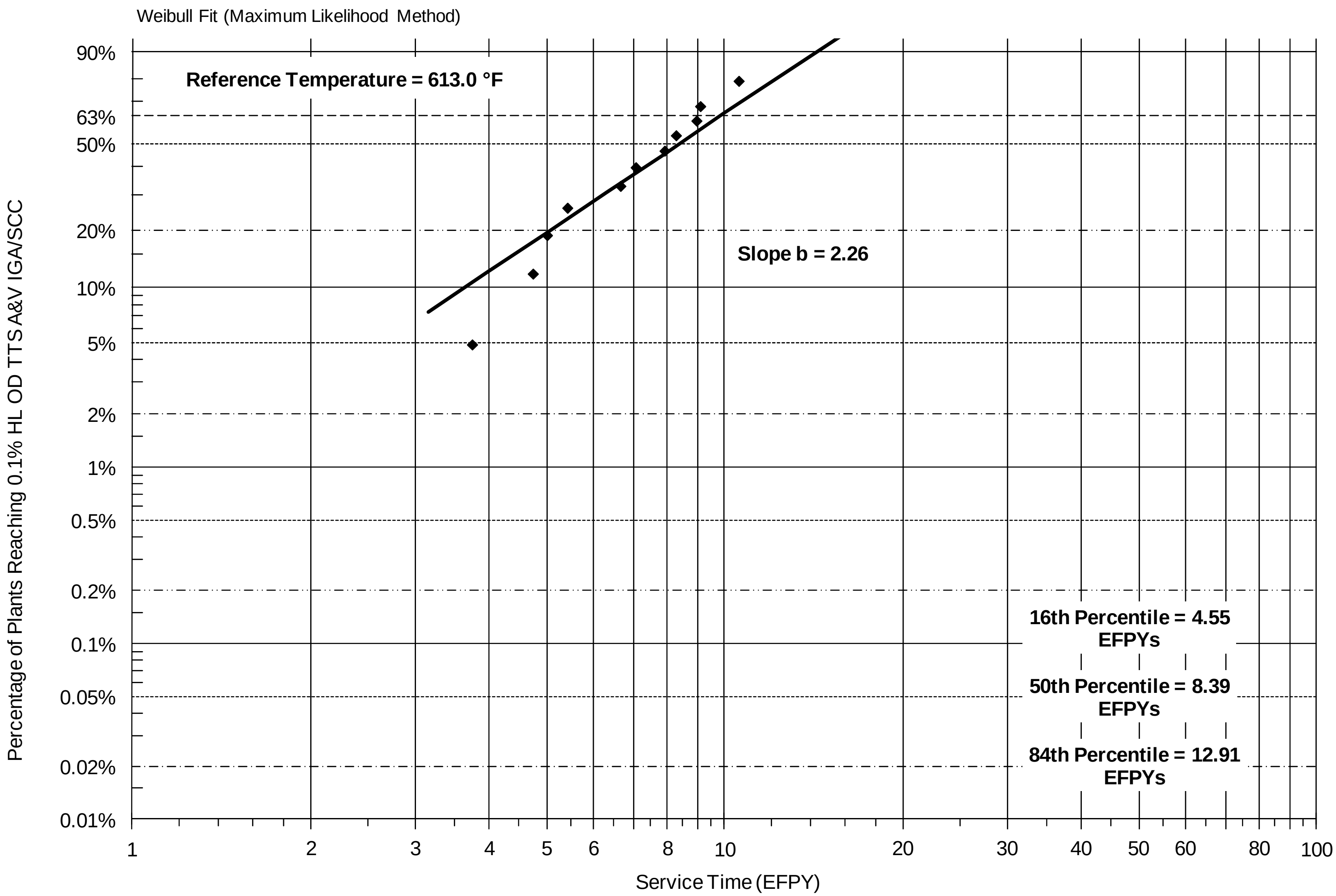

Figure 3-14
Time to 0.1% HL OD TTS A&V IGA/SCC - French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs - Weibull Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 3 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 3	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Ringhals 3 (orig.)	9/81	13.77 R	9.70		610	6.91		6.91	1	0		0.00	
Doel 4 (orig.)	7/85	10.76 R	8.87		619	9.25		9.25	2	0		0.00	
Tihange 3 (orig.)	9/85	12.75 R	9.90		626	13.83		13.83	3	0		0.00	
				Ave. Thot=	618								

Reference Temperature

618.0 °F = 598.72 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to Westinghouse design plants with preheater-type SGs with LTMA Alloy 600 tubing, kiss roll expansions, and a FDB.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-15
Time to 0.1% HL OD TTS A&V IGA/SCC - Alloy 600MA Preheater Plants with Kiss Roll Expansions and a FDB

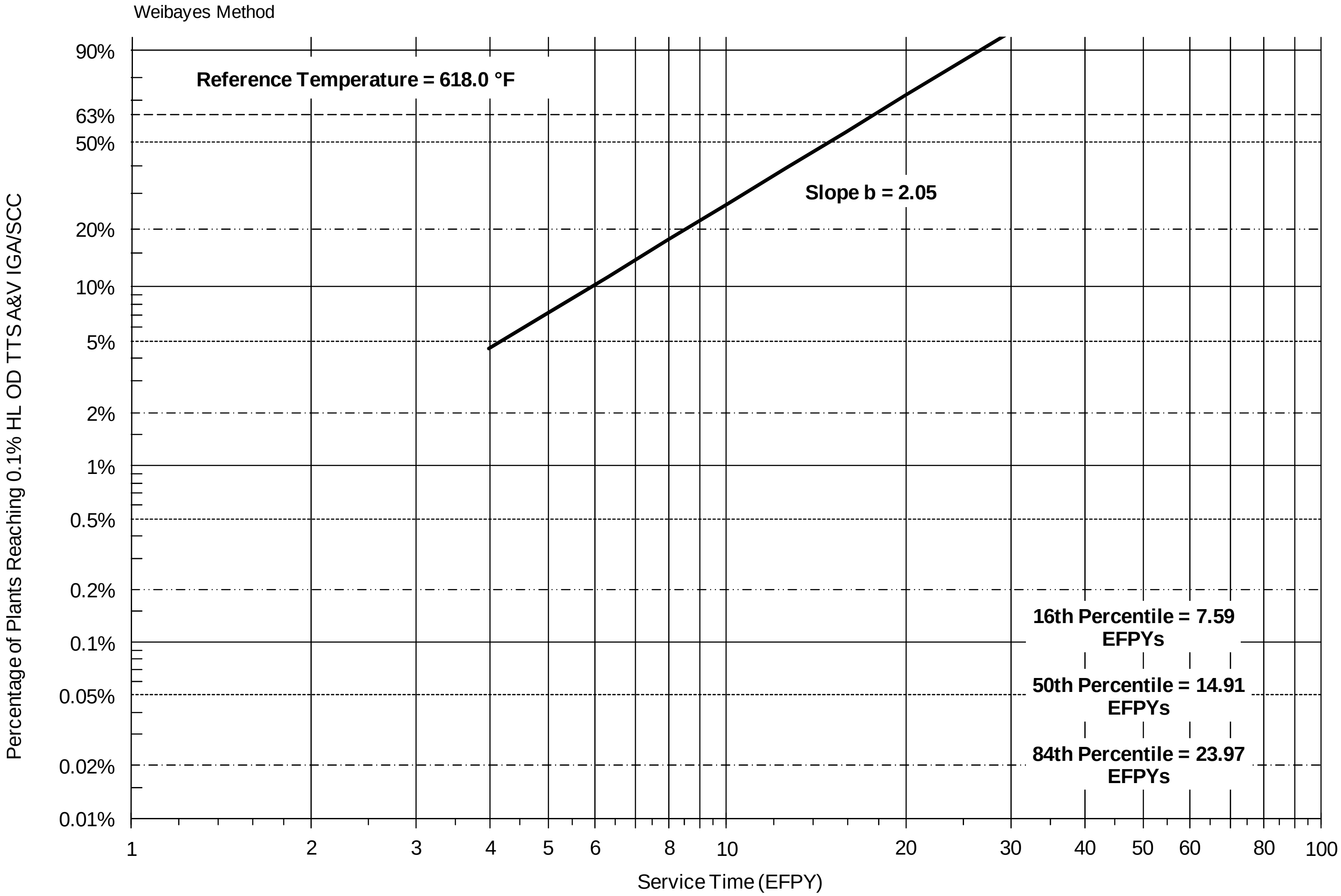

Figure 3-16
Time to 0.1% HL OD TTS A&V IGA/SCC - Alloy 600MA Preheater Plants with Kiss Roll Expansions and a FDB - Weibayes Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 9 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 9	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Braidwood 1 (orig.)	7/88	10.20 R	7.17	6.25	608	4.69	4.08	4.08	1	1	9	1.00	0.0745
Byron 1 (orig.)	9/85	12.19 R	8.85	7.68	608	5.78	5.02	5.02	2	1	8	2.00	0.1809
McGuire 2 (orig.)	3/84	13.60 R	9.36	6.06	618	9.36	6.06	6.06	3	1	7	3.00	0.2872
Summer (orig.)	1/84	10.70 R	7.43	5.89	619	7.68	6.09	6.09	4	1	6	4.00	0.3936
Catawba 1 (orig.)	6/85	11.01 R	7.11	6.95	618	7.11	6.95	6.95	5	1	5	5.00	0.5000
Watts Bar 1	5/96	10.00 R	9.36		617	8.97		8.97	6	0		5.00	
South Texas 1 (orig.)	8/88	11.76 R	8.37		620	9.11		9.11	7	0		5.00	
Harris (orig.)	5/87	14.43 R	9.29		619	9.69		9.69	8	0		5.00	
Comanche Peak 1	7/90	16.68 R	13.00		618	13.00		13.00	9	0		5.00	

Ave. Thot= 616

Reference Temperature
618.0 °F = 598.72 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to U.S. Westinghouse plants with preheater-type SGs with LTMA Alloy 600 tubing, full depth hard roll expansions, and a FDB.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-17
Time to 0.1% HL OD TTS A&V IGA/SCC - US Westinghouse Alloy 600MA Preheater Plants with Full Depth Hard Roll Expansions and a FDB

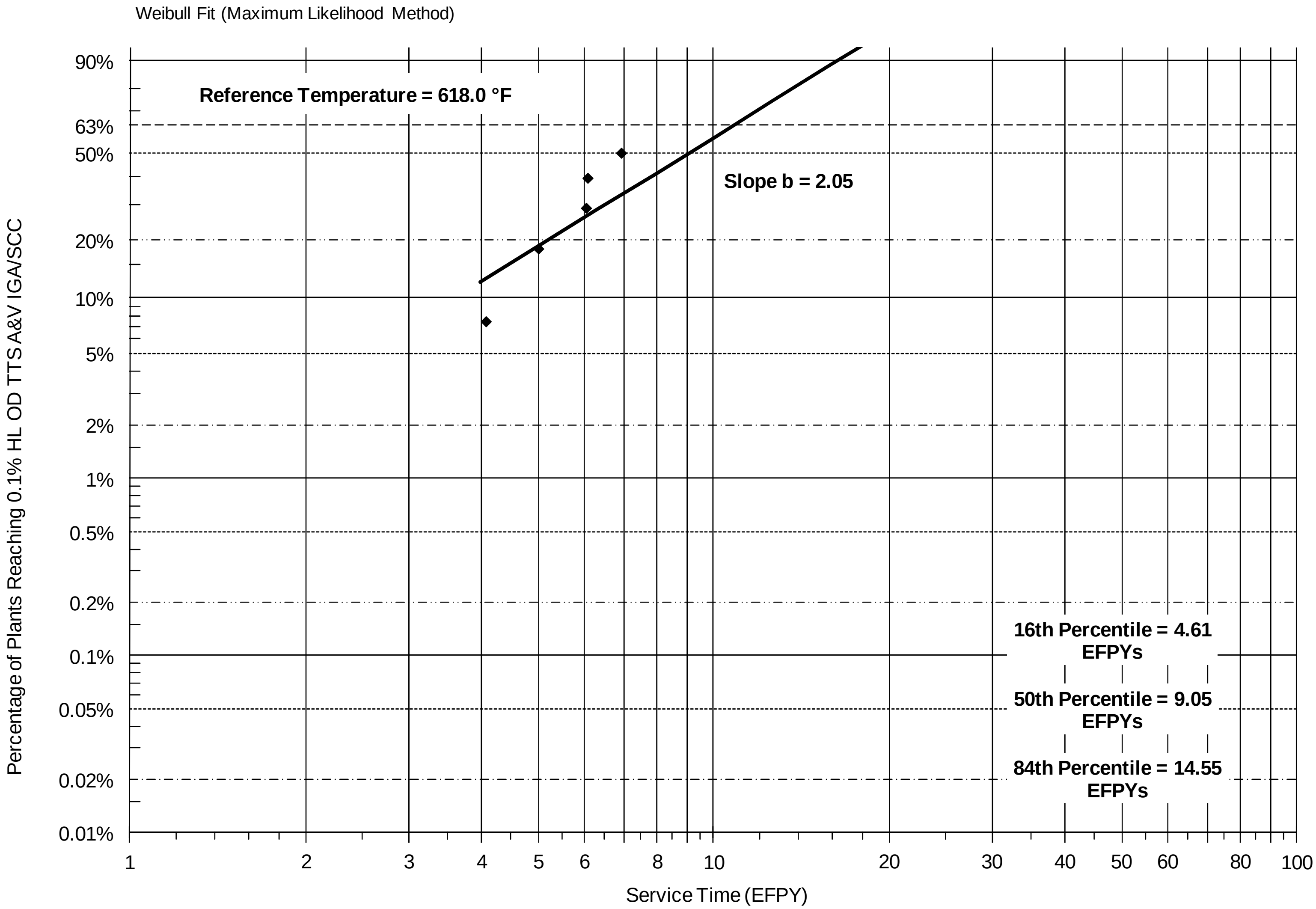

Figure 3-18
Time to 0.1% HL OD TTS A&V IGA/SCC - US Westinghouse Alloy 600MA Preheater Plants with Full Depth Hard Roll Expansions and a FDB - Weibull Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 1 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 1	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Callaway (orig.)	12/84	20.81 R	16.70	8.99	618	20.64	11.11	11.11	2	1	2	0.67	0.2619
South Texas 2 (orig.)	6/89	14.00 R	10.30		624	16.37		16.37	1	0		0.00	
				Ave. Thot=	621								

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with LTMA Alloy 600 tubing, hydraulic expansions, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-19
Time to 0.05% HL OD TTS Circumferential SCC - All Westinghouse Design Alloy 600MA Plants with Hydraulic Expansions and FDBs

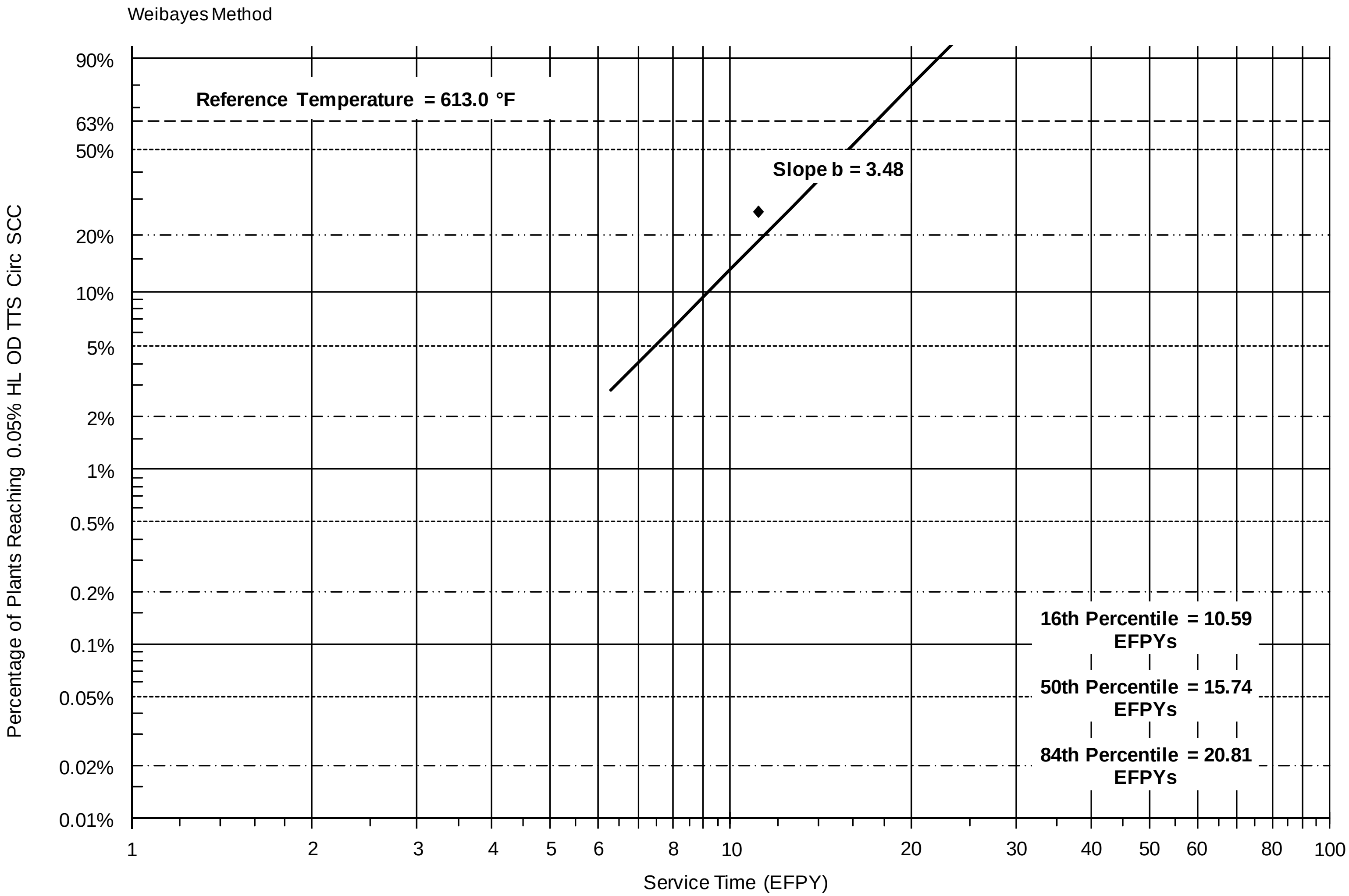

Figure 3-20
Time to 0.05% HL OD TTS Circumferential SCC - All Westinghouse Design Alloy 600MA Plants with Hydraulic Expansions and FDBs - Weibayes Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Dampierre 3 (orig.)	5/81	14.51 R	10.88	7.28	613	10.88	7.28	7.28	1	1	16	1.00	0.0427
Dampierre 4	11/81	26.85	19.80	7.50	613	19.80	7.50	7.50	2	1	15	2.00	0.1037
St. Laurent B2 (orig.)	6/81	22.30 R	17.30	8.18	613	17.30	8.18	8.18	3	1	14	3.00	0.1646
Doel 3 (orig.)	10/82	10.70 R	8.40		613	8.40		8.40	4	0		3.00	
Gravelines 1 (orig.)	12/80	13.19 R	9.11		613	9.11		9.11	5	0		3.00	
St. Laurent B1 (orig.)	8/83	12.07 R	9.26	9.34	613	9.26	9.34	9.34	6	1	11	4.17	0.2358
Dampierre 2 (orig.)	2/81	24.00 R	18.66	11.50	613	18.66	11.50	11.50	7	1	10	5.33	0.3069
Tricastin 4 (orig.)	11/81	22.90 R	19.18	11.59	613	19.18	11.59	11.59	8	1	9	6.50	0.3780
Gravelines 2 (orig.)	12/80	15.76 R	12.09		613	12.09		12.09	9	0		6.50	
Tricastin 2 (orig.)	12/80	16.43 R	12.94		613	12.94		12.94	10	0		6.50	
Tricastin 1 (orig.)	12/80	18.00 R	14.61	14.36	613	14.61	14.36	14.36	11	1	6	8.00	0.4695
Gravelines 4 (orig.)	10/81	18.78 R	14.56	14.61	613	14.56	14.61	14.61	12	1	5	9.50	0.5610
Blayais 1	12/81	26.77	15.94	15.99	613	15.94	15.99	15.99	13	1	4	11.00	0.6524
Tricastin 3 (orig.)	5/81	20.70 R	17.33		613	17.33		17.33	14	0		11.00	
Tihange 2 (orig.)	3/83	18.29 R	14.85		617	17.59		17.59	15	0		11.00	
Gravelines 3	6/81	27.27	16.23	17.99	613	16.23	17.99	17.99	16	1	1	14.00	0.8354

Ave. Thot= 613

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse feedring design SGs with LTMA Alloy 600 tubing, kiss rolls, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-21
Time to 0.05% HL OD TTS Circumferential SCC - All French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs

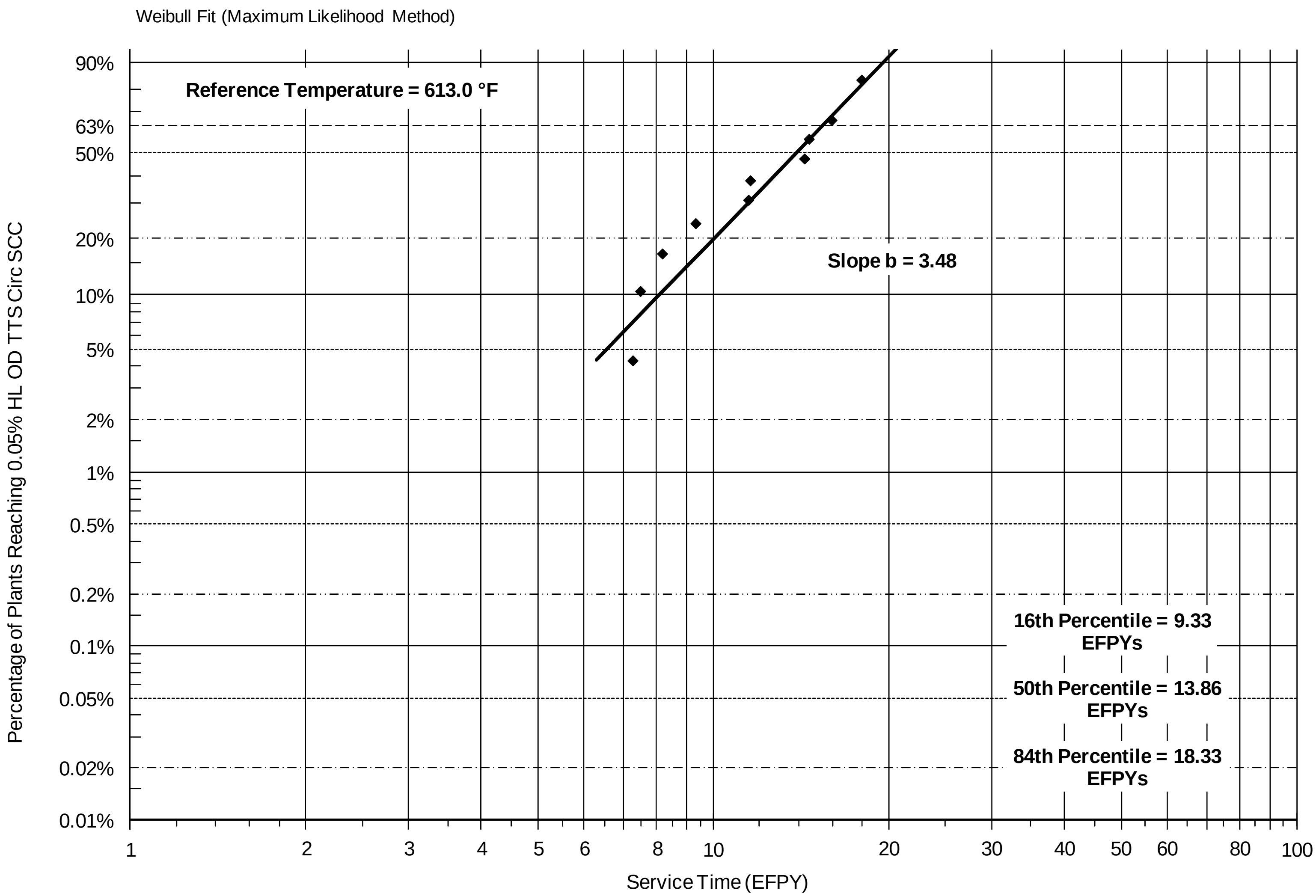

Figure 3-22
Time to 0.05% HL OD TTS Circumferential SCC - All French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 3 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% TTS SCC	Adjusted EDYs to 0.1% TTS SCC or to Last ISI	N= 3	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Doel 4 (orig.)	7/85	10.76 R	8.87	4.11	619	9.25	4.29	4.29	1	1	3	1.00	0.2059
Ringhals 3 (orig.)	9/81	13.77 R	7.31		610	5.20		5.20	2	0		1.00	
Tihange 3 (orig.)	9/85	12.75 R	9.90	4.98	626	13.83	6.95	6.95	3	1	1	2.50	0.6471
				Ave. Thot=	618								

Reference Temperature

618.0 °F = 598.72 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to Westinghouse design plants with preheater-type SGs with LTMA Alloy 600 tubing, kiss roll expansions, and a FDB.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-23
Time to 0.1% HL OD TTS Circumferential SCC - Westinghouse Design Alloy 600MA Preheater Plants with Kiss Roll Expansions and a FDB

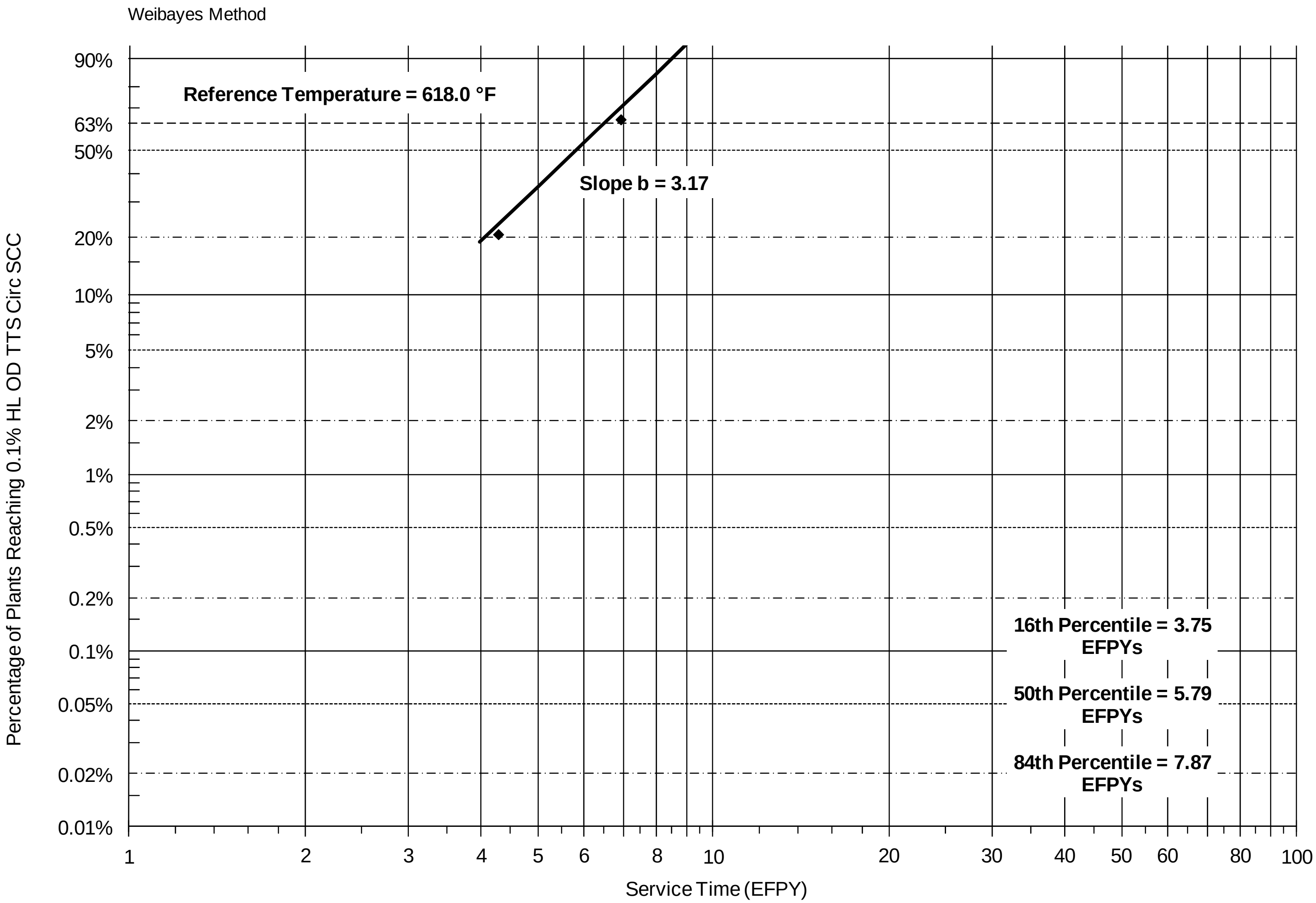

Figure 3-24
Time to 0.1% HL OD TTS Circumferential SCC - Westinghouse Design Alloy 600MA Preheater Plants with Kiss Roll Expansions and a FDB

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 9 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% TTS SCC	Adjusted EDYs to 0.1% TTS SCC or to Last ISI	N= 9	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Braidwood 1 (orig.)	7/88	10.20 R	7.17	5.12	608	4.69	3.35	3.35	1	1	9	1.00	0.0745
Summer (orig.)	1/84	10.70 R	7.43	3.91	619	7.68	4.05	4.05	2	1	8	2.00	0.1809
Watts Bar 1	5/96	10.00 R	9.36	4.45	617	7.86	4.26	4.26	3	1	7	3.00	0.2872
South Texas 1 (orig.)	8/88	11.76 R	8.37	4.11	620	9.11	4.47	4.47	4	1	6	4.00	0.3936
Byron 1 (orig.)	9/85	12.19 R	8.85	7.17	608	5.78	4.69	4.69	5	1	5	5.00	0.5000
Comanche Peak 1	7/90	11.00 R	8.20	5.25	618	8.20	5.25	5.25	6	1	4	6.00	0.6064
Catawba 1 (orig.)	6/85	11.01 R	7.11		618	7.11		7.11	7	0		6.00	
Harris (orig.)	5/87	14.43 R	9.29	7.16	619	9.69	7.47	7.47	8	1	2	7.33	0.7482
McGuire 2 (orig.)	3/84	13.60 R	9.36	8.68	618	9.36	8.68	8.68	9	1	1	8.67	0.8901
				Ave. Thot=	616								

Reference Temperature
618.0 °F = 598.72 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to U.S. Westinghouse plants with preheater-type SGs with LTMA Alloy 600 tubing, full depth hard roll expansions, and a FDB.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-25
Time to 0.1% HL OD TTS Circumferential SCC - US Westinghouse Alloy 600MA Preheater Plants with Full Depth Hard Roll Expansions and a FDB

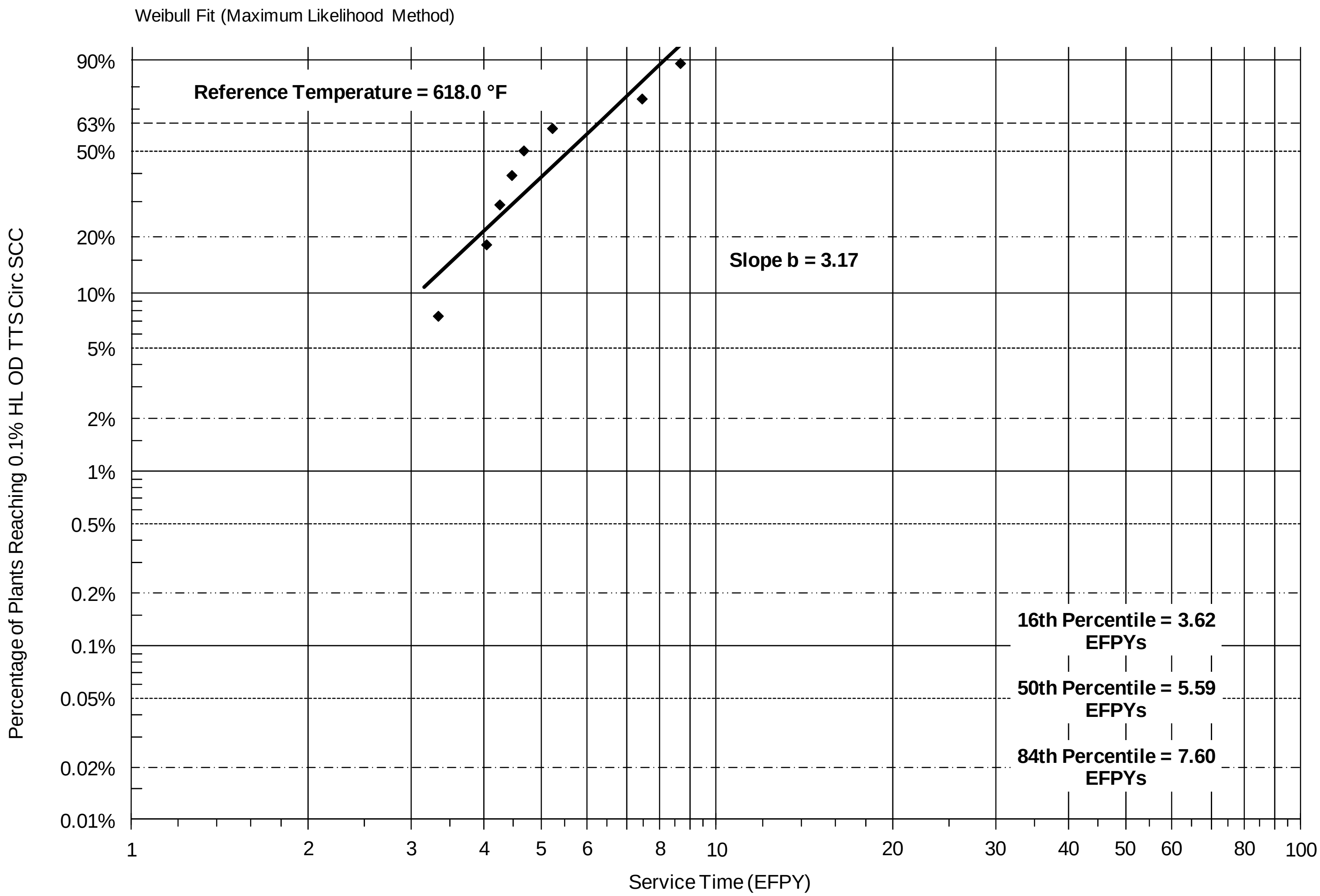

Figure 3-26
Time to 0.1% HL OD TTS Circumferential SCC - US Westinghouse Alloy 600MA Preheater Plants with Full Depth Hard Roll Expansions and a FDB - Weibull Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Farley 2 (orig.)	7/81	19.81 R	15.34	2.66	607	16.72	2.90	2.90	1	1	16	1.00	0.0427
Beaver Valley 1 (orig.)	10/76	29.30 R	19.60	3.01	607	21.36	3.28	3.28	2	1	15	2.00	0.1037
Indian Point 3 (orig.)	8/76	12.52 R	6.47		590	3.35		3.35	3	0		2.00	
Cook 1 (orig.)	8/75	22.08 R	12.07	4.90	599	9.30	3.78	3.78	4	1	13	3.07	0.1690
Beaver Valley 2	11/87	20.81	16.90	4.54	607	18.42	4.95	4.95	5	1	12	4.14	0.2343
Diablo Canyon 2	3/86	22.70 R	19.05	6.61	603	17.47	6.06	6.06	6	1	11	5.21	0.2997
Diablo Canyon 1	5/85	23.32	18.60	7.16	603	17.06	6.57	6.57	7	1	10	6.29	0.3650
Salem 2	10/81	26.90	16.00	8.25	602	14.05	7.24	7.24	8	1	9	7.36	0.4303
Farley 1 (orig.)	12/77	22.23 R	17.13	6.70	607	18.67	7.30	7.30	9	1	8	8.43	0.4956
Salem 1 (orig.)	6/77	18.25 R	10.70	8.37	602	9.39	7.35	7.35	10	1	7	9.50	0.5610
Trojan	5/76	16.65 S	9.05	5.30	615	13.88	8.12	8.12	11	1	6	10.57	0.6263
North Anna 2 (orig.)	12/80	14.28 R	9.42	5.23	618	16.41	9.10	9.10	12	1	5	11.64	0.6916
North Anna 1 (orig.)	6/78	14.57 R	8.48	5.72	618	14.77	9.96	9.96	13	1	4	12.71	0.7570
Prairie Island 2	12/74	33.74	27.50		590	14.26		14.26	14	0		12.71	
Sequoyah 1 (orig.)	7/81	23.00 R	14.10	14.10	609	16.75	16.75	16.75	15	1	2	14.14	0.8441
Sequoyah 2	6/82	26.23	18.80	18.80	609	22.33	22.33	22.33	16	1	1	15.57	0.9312

Ave. Thot= 605

Reference Temperature

605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to U.S. Westinghouse plants with feedring-type SGs with LTMA Alloy 600 tubing, drilled hole carbon steel TSPs, which never used phosphate water chemistry.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-27
Time to 0.05% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600MA Drilled Hole Feedring Plants

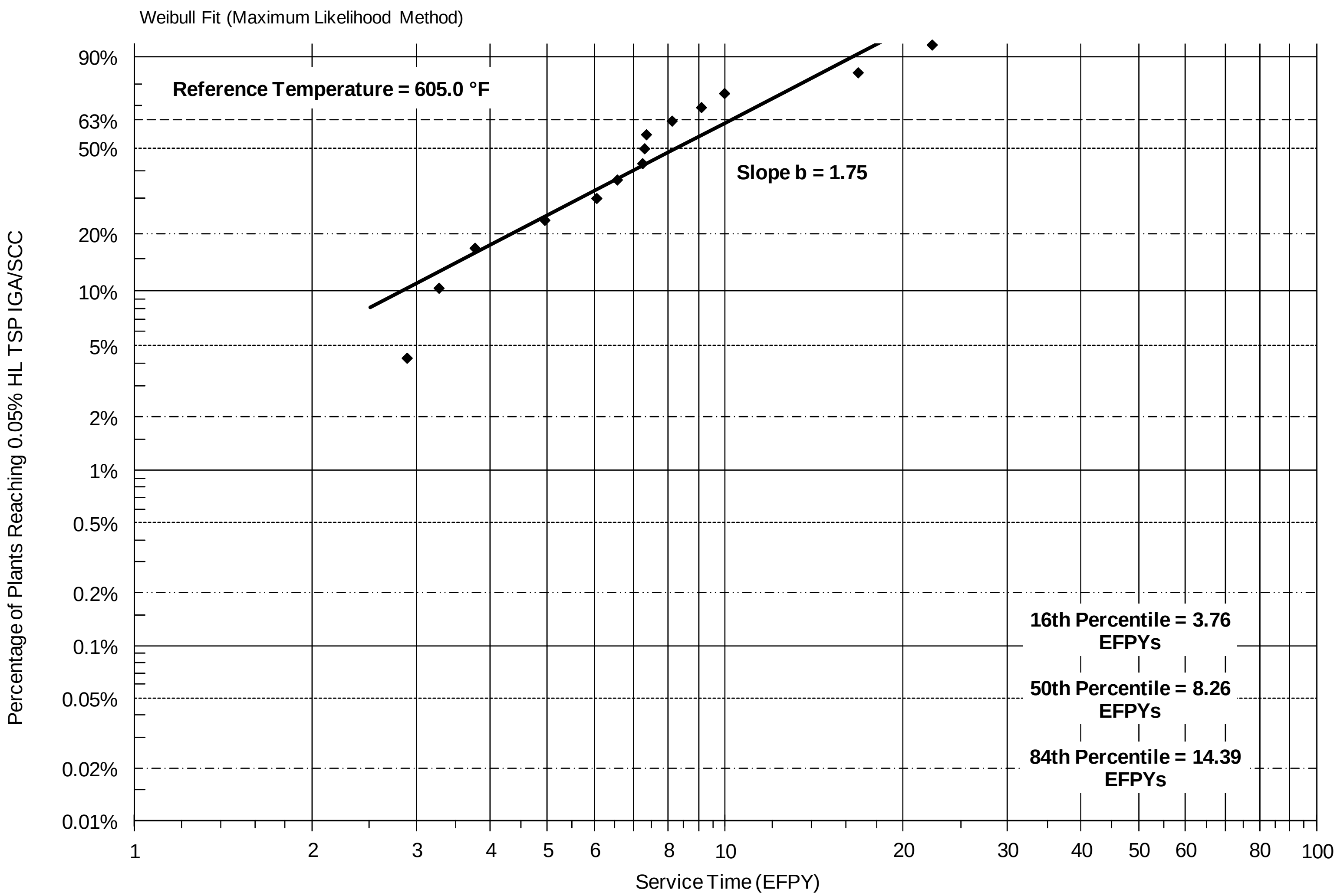

Figure 3-28
Time to 0.05% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600MA Drilled Hole Feedring Plants - Weibull Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 1 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 1	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Callaway	12/84	20.81 R	16.70		618	29.08		29.08	1	0		0.00	
				Ave. Thot=	618								

Reference Temperature
605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to U.S. Westinghouse plants with feedring-type SGs with LTMA Alloy 600 tubing and broached hole stainless steel TSPs.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-29
Time to 0.05% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600MA Broached Hole Feedring Plants

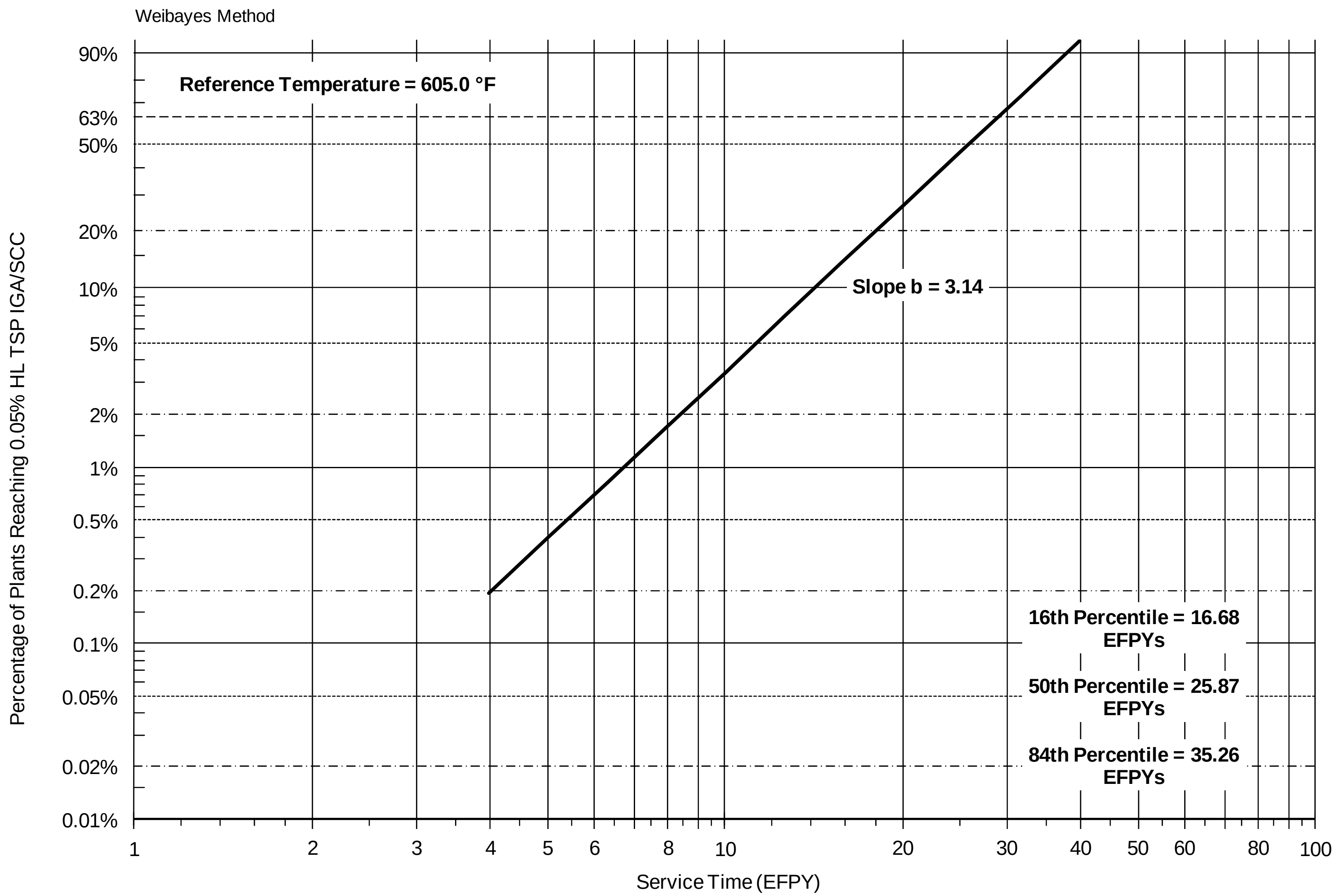

Figure 3-30
Time to 0.05% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600MA Broached Hole Feedring Plants – Weibayes Analysis

Plant Steam Generator Tubing Experience Based Improvement Factors

No. Plants = 10 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 1.0% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 1% IGA/SCC	Adjusted EDYs to 1% IGA/SCC or to Last ISI	N= 10	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Braidwood 1 (orig.)	7/88	10.20 R	7.17	3.72	608	4.69	2.43	2.43	1	1	10	1.00	0.0673
Byron 1 (orig.)	9/85	12.19 R	8.85	5.44	608	5.78	3.56	3.56	2	1	9	2.00	0.1635
Catawba 1 (orig.)	6/85	11.01 R	7.11	4.10	618	7.11	4.10	4.10	3	1	8	3.00	0.2596
Summer (orig.)	1/84	10.70 R	7.43	6.70	619	7.68	6.93	6.93	4	1	7	4.00	0.3558
Comanche Peak 1 (orig.)	7/90	16.68 R	13.00	8.50	618	13.00	8.50	8.50	5	1	6	5.00	0.4519
McGuire 1 (orig.)	12/81	15.26 R	9.24	8.57	618	9.24	8.57	8.57	6	1	5	6.00	0.5481
Watts Bar 1 (orig.)	5/96	10.00 R	9.36		617	8.97		8.97	7	0		6.00	
South Texas 1 (orig.)	8/88	11.76 R	8.37		620	9.11		9.11	8	0		6.00	
McGuire 2 (orig.)	3/84	13.60 R	9.36		618	9.36		9.36	9	0		6.00	
Harris (orig.)	5/87	14.43 R	9.29		619	9.69		9.69	10	0		6.00	

Ave. Thot= 616

Reference Temperature
618.0 °F = 598.72 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to U.S. Westinghouse plants with preheater-type SGs with LTMA Alloy 600 tubing and drilled hole carbon steel TSPs.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-31
Time to 1% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600MA Drilled Hole Preheater Plants

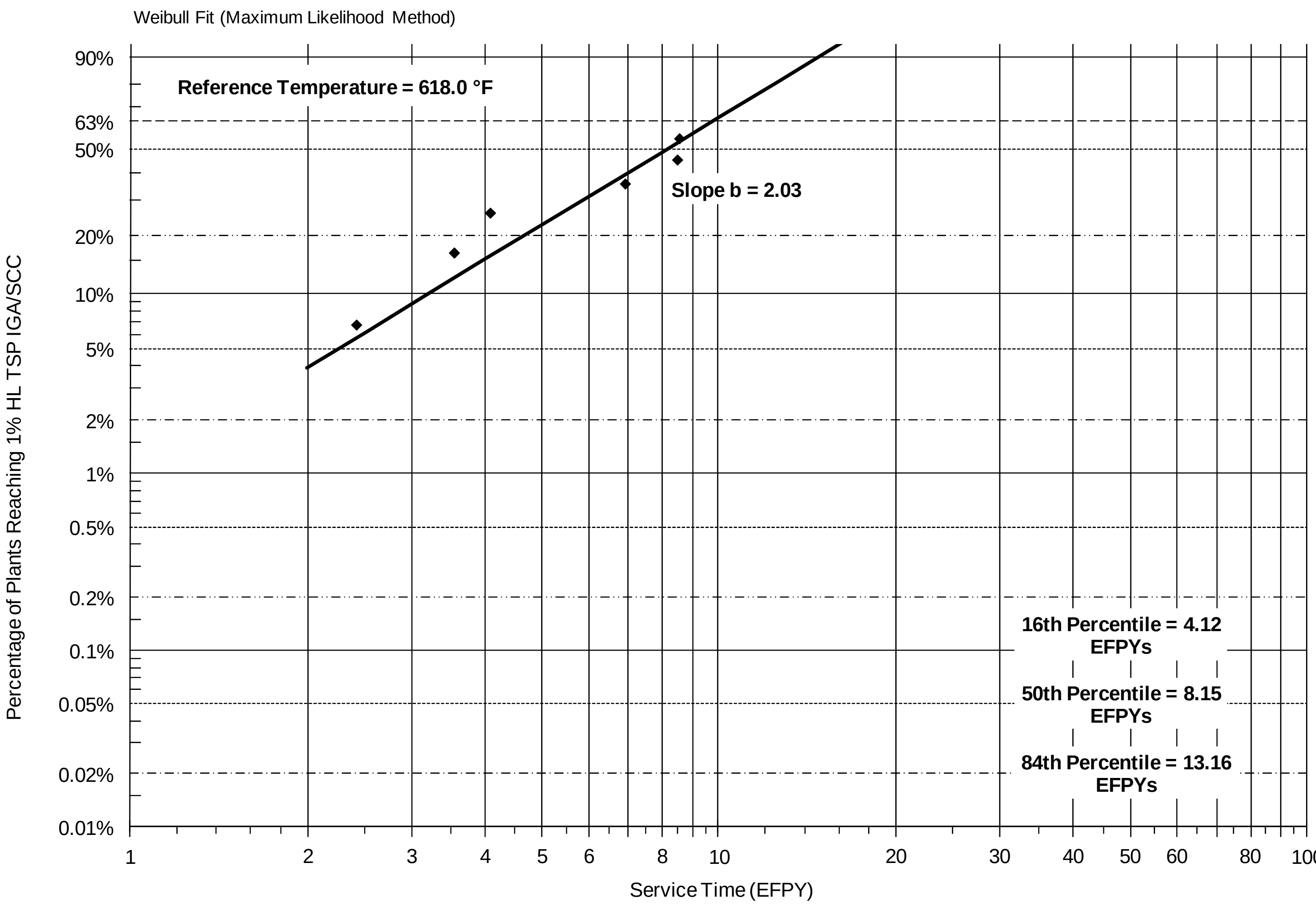

Figure 3-32
Time to 1% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600MA Drilled Hole Preheater Plants - Weibull Analysi

3.3.2 Alloy 600TT versus Alloy 600MA

Evaluation of the improvement factor for Alloy 600TT relative to Alloy 600MA is discussed in the following subsections.

3.3.2.1 French Feedring Experience

Due to the number of non-material design improvements made in the industry, care was taken to select plant populations such that the tubing material is the only design change between the plants compared. For this reason, data from two populations of French steam generators having kiss rolled tube in tubesheet expansions and essentially the same design were originally considered for analysis of the improvement gains associated with Alloy 600TT tubing compared to Alloy 600MA. These populations encompassed a significant number of units (14 SGs tubed with Alloy 600MA, 28 with Alloy 600TT) to allow a robust determination of degradation statistics. The field data collected for French feedring plants with Alloy 600TT tubing and kiss roll expansions for secondary-side axial and volumetric IGA/SCC at the top of the tubesheet (OD TTS A&V IGA/SCC) are shown in Figure 3-33. The associated Weibayes function for the Alloy 600TT tubed plants is plotted in Figure 3-34. The corresponding data for plants analyzed for secondary-side circumferential IGA/SCC at the top of tubesheet are shown in Figure 3-35, and the Weibayes function is plotted in Figure 3-36.

The large number of tube cracking data available from the French feedring plants supported the decision to determine a factor of improvement for the change in tubing material to Alloy 600TT from Alloy 600MA for the time to ODSCC based on these plants. However, when analyzing the data, it was discovered that there was a change in inspection technology from bobbin coil to RPC at about the time that the majority of cracking was first discovered in the Alloy 600MA plants. This meant that the first use of RPC often detected significant levels of cracking (10% or more tubes cracked in some cases). These levels are significantly higher than the levels of cracking in some of the Alloy 600TT plants, and it became difficult to estimate the time to a level of cracking such as 1% or 2% tubes failed at many plants (where valid comparisons of the median time to cracking could be made between the two tube materials). In addition, inspections of all SGs are not performed during every outage at French units, making assessment of the level of cracking as a function of time for a particular plant difficult. Despite these caveats, the comparison between these two populations is considered a strong indicator of the improvement factor attributable to Alloy 600TT tubing relative to Alloy 600MA tubing because of the size and similarity of these plant populations.

It should also be noted that it is likely that the change from Alloy 600MA to Alloy 600TT in the French feedring units was accompanied by other subtle changes in the material, such as tighter specifications on minor constituents (e.g., carbon) and impurities, changes to the mill annealing process (such as penultimate and final annealing temperature), or slightly different material strength requirements. While improvements due to these changes would be expected to be generally encompassed by an Alloy 600TT versus Alloy 600MA improvement factor, it is possible that these subtle changes were different in the French units than in the US units, which typically used tubing supplied by a different vendor.

From the Weibayes plot shown in Figure 3-34, the median time to 0.1% axial and volumetric secondary-side SCC at the TTS was found to be 64 EFPY for French kiss roll plants tubed with Alloy 600TT. The lower bound on the material improvement factor for axial and volumetric ODSCC is then determined to be 64/8.4 = 7.6 (this is a lower bound because the mechanism has not affected the Alloy 600TT units to date). For circumferentially oriented SCC at this location, the median time to failure (0.05% of tubes with SCC) was determined to be 41 EFPY (shown in Figure 3-36). The lower bound on the improvement factor for circumferentially oriented cracking is then 41/14 = 2.9 (again, this is a lower bound because this mechanism has not yet occurred in the Alloy 600TT units).

The improvement factors based on French kiss rolled plant experience may be conservative compared to the US HE plant experience because the high cold work and residual stress imparted by kiss rolling removes much of the improvement provided by thermal treatment. For comparison, predictions of ODSCC in US Alloy 600TT plants based on US Alloy 600TT plants are given in the following section. Improvement factors for the remaining degradation mechanisms are also determined based on the field data from Westinghouse design plants with Alloy 600TT tubing.

3.3.2.2 Westinghouse Design Alloy 600TT Experience

Significantly greater improvement factors are expected for lower cold work and residual stress situations, such as hydraulic expansions as used in the US for Westinghouse design plants with Alloy 600TT tubing. These data were therefore assessed. The results of the analysis of time to cracking for each degradation mechanism are discussed in the following subsections.

3.3.2.2.1 Axially Oriented PWSCC in Hot Leg Expansion Transitions

Data for Westinghouse design plants with Alloy 600TT tubing and hydraulic tube in tubesheet expansions are shown in Figure 3-37. The degradation threshold was defined as 0.1% of tubes indicating hot-leg OD top-of-tubesheet axial and volumetric IGA/SCC. This definition was chosen such that the degradation mechanism was not impacted by other design changes, and that the threshold value was met by the majority of Alloy 600MA plants. None of the Alloy 600TT plants have experienced any PWSCC at this location; therefore, a Weibayes approach was used to develop a distribution of the time to cracking. The slope of the Weibull distribution was assumed to be the same as that calculated for the plants with Alloy 600MA tubing and WEXTEX expansions (β = 1.61 as shown on Figure 3-4). As before, all plant time scales were adjusted to a reference hot leg temperature of 609°F. A Weibull distribution was then fit to the plant operating time data using the Weibayes method. The plot of the distribution is shown on Figure 3-38. As shown on the figure, the median time to 0.1% axial PWSCC at Westinghouse design plants with Alloy 600TT tubing and hydraulic expansions was shown to be about 116 EFPY, assuming that the first failure among the plants is imminent.

Comparing this result to the result of 10.9 EFPY for plants with Alloy 600MA tubing and hydraulic expansions, the lower bound on the improvement factor for time to 0.1% axial PWSCC in Alloy 600TT tubing relative to the time to cracking in Alloy 600MA tubing (with a similar tube expansion method) can be shown to be about 116/10.9 = 10.7. Comparing the Alloy 600TT/hydraulic expansion result to the Alloy 600MA/WEXTEX result also gives a combined material plus design lower bound on the improvement factor of 116/8.1 = 14.2.

3.3.2.2.2 Circumferentially Oriented PWSCC in Hot Leg Expansion Transitions

Data for the Westinghouse design HE plants with Alloy 600TT tubing analyzed for primary-side circumferential IGA/SCC at the top of tubesheet are shown in Figure 3-39. The degradation threshold for this mechanism was defined as the time when circumferential stress corrosion cracking is observed in 0.1% of tubes. As above, the slope of the Weibull distribution was assumed to be the same as that calculated for the plants with Alloy 600MA tubing and WEXTEX expansions (β = 1.62 as shown on Figure 3-8) and all plant time scales were adjusted to a reference hot leg temperature of 609°F. The median time to failure as determined by the Weibayes method was found to be 116 EFPY, as shown in Figure 3-40.

The lower bound on the improvement factor calculated for plants with Alloy 600TT tubing relative to plants with Alloy 600MA can therefore be determined as 116/10.9 = 10.7. Comparing the Alloy 600TT/hydraulic expansion result to the Alloy 600MA/WEXTEX result also gives a lower bound on the combined material plus design improvement factor of 116/9.9 = 11.8.

3.3.2.2.3 Axial and Volumetric Secondary-side IGA/SCC at Top of Tubesheet (TTS)

Plant populations with feedwater SGs and with feedring SGs (more common in the US) were analyzed separately for the time to reach 0.1% axial and volumetric secondary-side stress corrosion cracking because of the anticipated differences in observed cracking rates due to design features. In general, a slower rate of cracking has been observed in feedring plants, which is thought to result from the addition of “cold” feedwater near the top of the tube sheet, reducing boiling and the resulting impurity concentration in this area. The plant time scales were adjusted to a reference hot leg temperature of 613°F for the feedring plants, and 618°F for the preheater plants.

The field data for Westinghouse design feedring plants with Alloy 600TT tubing and hydraulic expansions are shown in Figure 3-41. Because no plants have yet reached the failure criterion, the Weibayes method was used to determine the median time to failure. This was found to be 58.5 EFPY, as shown in the plot in Figure 3-42. Comparing this value to the median time to failure determined for Westinghouse feedring Alloy 600MA HE plants, the lower bound on the material improvement factor was determined to be 58.5/15.9 = 3.7.

The field data for Westinghouse design preheater plants with Alloy 600TT tubing and hydraulic expansions are shown in Figure 3-43. This group includes the Westinghouse plants with preheater design Model D5 SGs (such as Catawba 2), all of which have Alloy 600TT tubing. This population consists of only four plants, none of which have reached the failure criterion, so a Weibayes method was used to predict the median time to failure. Based on the accumulated plant experience as of 2008, the median time to failure was determined to be 20.9 EFPY. The Weibull distribution for this data is shown in Figure 3-44. Because of the lack of data for preheater plants with Alloy 600MA tubing and hydraulic expansions, a material improvement factor cannot be determined. A lower bound on the material plus design improvement factor can be found by comparing the median time to failure in preheater Alloy 600TT HE plants to that observed in preheater Alloy 600MA plants with full-depth roll (FDR) expansions as 20.9/9.1 = 2.3.

Although the median time to failure for preheater plants appears to be lower than that for feedring plants, this is because no plant has reached the degradation threshold at present. Because the Weibayes method assumes that the first instance of failure is imminent, the difference in improvement factors may be due to insufficient experience in preheater plants. Additional experience without observed cracking may show these improvement factors to be overly conservative.

3.3.2.2.4 Circumferential Secondary-side IGA/SCC at Top of Tubesheet

The same plant populations were analyzed for circumferential stress corrosion cracking as for the axial and volumetric TTS IGA/SC discussed in section 4.3.2.2.3. For feedring plants, the failure criterion was defined to be the time to cracking observed in 0.05% of hot leg tubes at the top of tubesheet, adjusted to a reference temperature of 613°F. This failure criterion was used to determine the median time to failure for feedring plants with Alloy 600MA tubing and HE expansions. The field data for circumferential OD cracking collected from Westinghouse design feedring plants with Alloy 600TT tubing and hydraulic expansions are shown in Figure 3-45. Since only one Alloy 600TT plant has reached the failure criterion, the Weibayes method was used to predict the median time to failure, as shown in Figure 3-46. The median time to failure was found to be 39.7 EFPY. The improvement factor for Alloy 600TT over Alloy 600MA can be shown to be 39.7/15.7 = 2.5.

For the Westinghouse design preheater plants, the failure criterion was defined as observed cracking in 0.05% hot leg tubes at the top of the tubesheet. Plant time scales were adjusted to a reference temperature of 618°F. The field data collected for the Westinghouse design preheater plants are shown in Figure 3-47. As above, the Weibayes method was used to determine the median time to failure, which was found to be 17.7 EFPY. The Weibull function is shown in Figure 3-48. Comparing the median time to failure to that for Alloy 600MA preheater plants with full depth roll expansions, the lower bound on the material plus design factor can be shown to be 17.7/5.6 = 3.2. Again, estimated improvement factors for Alloy 600TT will continue to increase as long as no failures are observed.

3.3.2.2.5 IGA/SCC at Tube Support Plate Intersection

Two populations were analyzed for stress corrosion cracking at the tube to tube support plate intersection. The first population consisted of Westinghouse Alloy 600TT feedring plants with broached hole tube support plates. The failure criterion for these plants was defined to be 0.05% tubes with observed cracking at the tube support plate intersection, with time scales adjusted to a reference temperature of 605°F. The field data collected from these plants are shown in Figure 3-49. As before, the median time to failure was determined from the Weibayes method, the plot of which is shown in Figure 3-50. The median time to failure was found to be 121.5 EFPY. Comparing this value to the median time to failure for Alloy 600MA feedring plants with broached hole tube supports, the lower bound on the alloy improvement factor can be shown to be 121.5/25.7 = 4.7.

A second plant population consisted of Westinghouse preheater plants with Alloy 600TT tubing and hydraulic expansions and broached hole tube supports. The failure criteria for this population was defined as 0.1% tubes with observed cracking at the tube support plate intersection. The field data collected for this population are shown in Figure 3-51. The Weibull distribution produced from the Weibayes method is plotted in Figure 3-52 and shows the median time to failure to be 21.0 EFPY. Comparing this value to the median time to failure for Alloy 600MA preheater plants with drilled hole tube supports, a lower bound on the material plus design improvement factor can be shown to be 21.0/8.15 = 2.6.

3.3.2.3 Summary of Alloy 600TT Plant Experienced Based Improvement Factors

The material improvement factors estimated for Alloy 600TT with respect to various degradation mechanisms is shown in Table 3-4. Comparison of the improvement factors derived from the French plants and Westinghouse plants are in relative agreement. Both indicate that the use of Alloy 600TT provides greater relative resistance to axial and volumetric ODSCC than to circumferential cracking. However, this indication is not statistically robust since, to date, only one plant with 600TT has experience circumferential IGA/SCC at the TTS at the threshold level (none have for axial and volumetric IGA/SCC at the TTS).

Table 3-4
Estimated Material Improvement Factors for Alloy 600TT

Degradation Mech.	Alloy 600MA Plant Population	Median Time to Failure (EFPY)	Alloy 600TT Plant Population	Median Time to Failure (EFPY)	IF_R
Axial EZ PWSCC	West. (WEXTEX)	9.9	West. (All HE)	115.8	>14.2
	West. (HE)	10.9			>10.7
Circ. EZ PWSCC	West. (WEXTEX)	9.1	West. (All HE)	116.2	>11.8
	West. (HE)	14.9			>10.7
A&V TTS OD IGA/SCC	West. Preheater (FDR)	8.4	West. Preheater (HE)	20.9	>2.3
	West. Preheater (KR)	15.9			>1.4
	West. Feedring (KR)	5.6	West. Feedring (KR)	64.0	>7.6
	West. Feedring (HE)	5.8	West. Feedring (HE)	58.5	3.7*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	13.9	West. Preheater (HE)	17.7	>3.2
	West. Preheater (KR)	15.7			>3.1
	West. Feedring (KR)	8.2	West. Feedring (KR)	40.6	>2.9
	West. Feedring (HE)	8.3	West. Feedring (HE)	39.7	2.5*
TSP IGA/SCC	West. Preheater (DH)	25.7	West. Preheater (BH)	21.0	>2.6
	West. Feedring (DH)	0.0	West. Feedring (BH)	121.5	>14.7
	West. Feedring (BH)	0.0			>4.7

**As discussed in Section 3.2.1.3, one axial indication and 17 circumferential indications of SCC have been identified at Vogtle 1. Multiple axial indications of SCC were identified at Catawba in 2007, although this degradation mode is not considered active. These IF_{Rs} are therefore less conservative than others given in this table.*

As of 2008, the plant experience-based improvement factor for Alloy 600TT versus Alloy 600MA for PWSCC is conservatively estimated to be greater than 10.5. This is based on the data for Westinghouse Alloy 600TT plants with hydraulic expansions versus hydraulic expansion Westinghouse plants tubed with Alloy 600MA. For secondary-side corrosion mechanisms, the plant experience-based improvement factor is estimated to be about 3.7 and 2.5 for A&V and circumferential SCC, respectively. As these degradation modes have already been observed in 600TT, these values are less conservative than the other improvement factors presented in Table 3-4. The improvement factor for Alloy 600TT versus Alloy 600MA for SCC at tube support plate elevations is estimated to be greater than 2.6 based on the data for Westinghouse-design preheater plants (bounding case).

No. Plants = 28 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 28	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Bugey 5 (repl.)	8/93	15.04	10.13		613	10.13		10.13	1	0		0.00	
Cattenom 4	12/91	16.76	12.70		616	14.42		14.42	2	0		0.00	
Cattenom 3	2/91	17.59	13.55		616	15.39		15.39	3	0		0.00	
Penly 1	12/90	17.76	13.59		616	15.43		15.43	4	0		0.00	
Chinon B4	4/88	20.43	15.49		613	15.49		15.49	5	0		0.00	
Golfech 1	2/91	17.59	13.96		616	15.85		15.85	6	0		0.00	
Nogent 2	5/89	19.35	14.12		616	16.04		16.04	7	0		0.00	
Chinon B3	3/87	21.52	16.40		613	16.40		16.40	8	0		0.00	
Cattenom 2	2/88	20.60	14.45		616	16.41		16.41	9	0		0.00	
Belleville 1	6/88	20.27	14.65		616	16.64		16.64	10	0		0.00	
Belleville 2	1/89	19.68	14.74		616	16.74		16.74	11	0		0.00	
Flamanville 2	3/87	21.52	14.89		616	16.91		16.91	12	0		0.00	
Nogent 1	2/88	20.60	15.18		616	17.24		17.24	13	0		0.00	
Cattenom 1	4/87	21.44	15.25		616	17.32		17.32	14	0		0.00	
St-Alban 2	3/87	21.52	15.40		616	17.49		17.49	15	0		0.00	
Paluel 3	2/86	22.60	15.57		616	17.68		17.68	16	0		0.00	
Cruas 4	2/85	23.60	17.95		613	17.95		17.95	17	0		0.00	
Gravelines 6	10/85	22.93	18.02		613	18.02		18.02	18	0		0.00	
St-Alban 1	5/86	22.35	15.87		616	18.02		18.02	19	0		0.00	
Paluel 4	6/86	22.27	15.94		616	18.10		18.10	20	0		0.00	
Gravelines 5	1/85	23.68	18.11		613	18.11		18.11	21	0		0.00	
Cruas 2	4/85	23.44	18.20		613	18.20		18.20	22	0		0.00	
Cruas 3	9/84	24.02	18.45		613	18.45		18.45	23	0		0.00	
Flamanville 1	12/85	22.77	16.27		616	18.48		18.48	24	0		0.00	
Cruas 1	4/84	24.44	18.94		613	18.94		18.94	25	0		0.00	
Blayais 4 (SG 3)	10/83	24.94	19.19		613	19.19		19.19	26	0		0.00	
Paluel 1	12/85	22.77	17.20		616	19.53		19.53	27	0		0.00	
Paluel 2	12/85	22.77	17.22		616	19.56		19.56	28	0		0.00	

Ave. Thot= 615

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to French plants with SGs with TT Alloy 600 tubing, kiss rolls, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-33
Time to 0.1% HL OD TTS A&V IGA/SCC - French Alloy 600TT Feedring Plants with Kiss Rolls and FDBs

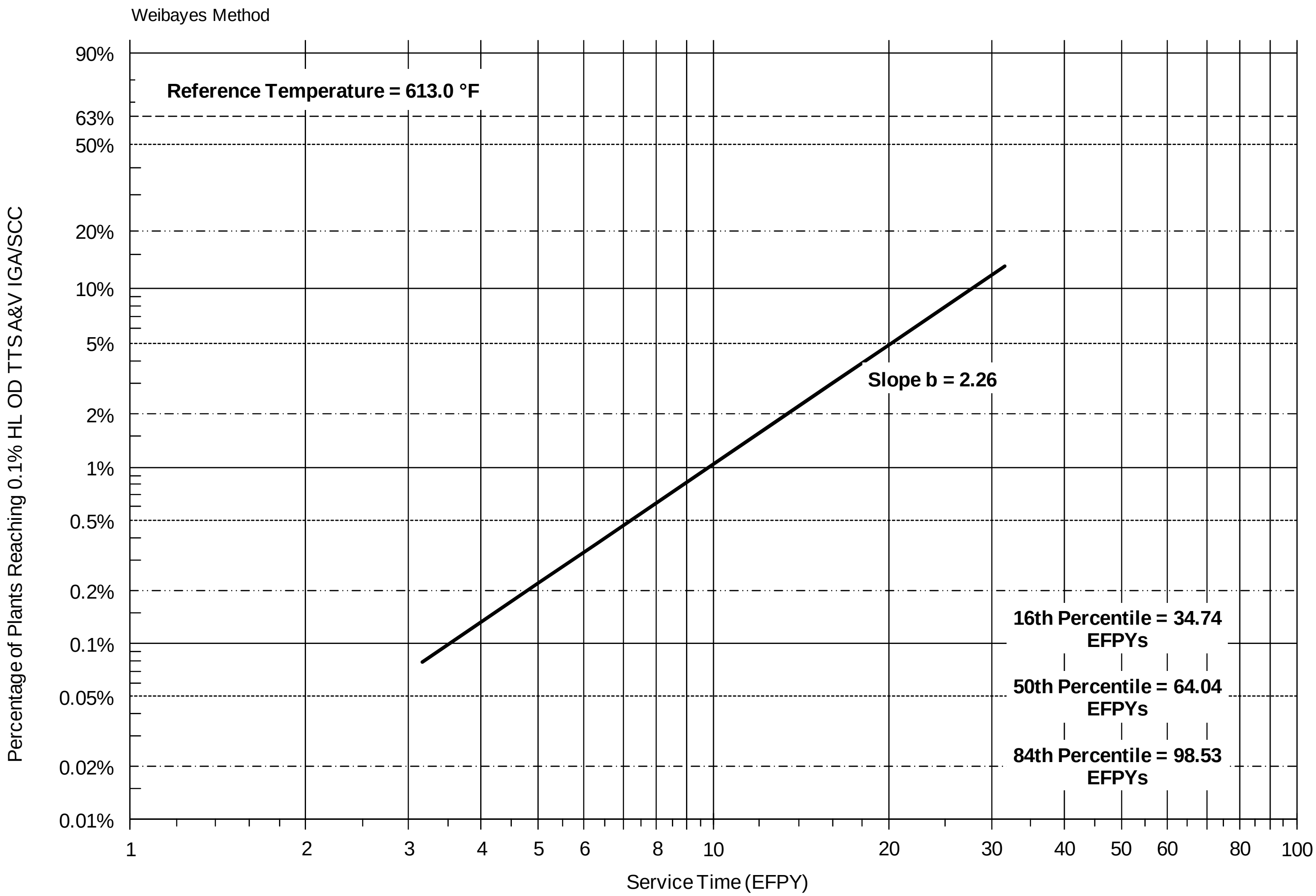

Figure 3-34
Time to 0.1% HL OD TTS A&V IGA/SCC - French Alloy 600TT Feedring Plants with Kiss Rolls and FDBs – Weibayes Analysis

No. Plants = 30 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 30	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Ulchin 2	9/89	18.93	8.30		613	8.30		8.30	1	0		0.00	
Ulchin 1	9/88	19.99	8.90		613	8.90		8.90	2	0		0.00	
Bugey 5 (repl.)	8/93	15.04	10.13		613	10.13		10.13	3	0		0.00	
Cattenom 4	12/91	16.76	12.70		616	14.42		14.42	4	0		0.00	
Cattenom 3	2/91	17.59	13.55		616	15.39		15.39	5	0		0.00	
Penly 1	12/90	17.76	13.59		616	15.43		15.43	6	0		0.00	
Chinon B4	4/88	20.43	15.49		613	15.49		15.49	7	0		0.00	
Golfech 1	2/91	17.59	13.96		616	15.85		15.85	8	0		0.00	
Nogent 2	5/89	19.35	14.12		616	16.04		16.04	9	0		0.00	
Chinon B3	3/87	21.52	16.40		613	16.40		16.40	10	0		0.00	
Cattenom 2	2/88	20.60	14.45		616	16.41		16.41	11	0		0.00	
Belleville 1	6/88	20.27	14.65		616	16.64		16.64	12	0		0.00	
Belleville 2	1/89	19.68	14.74		616	16.74		16.74	13	0		0.00	
Flamanville 2	3/87	21.52	14.89		616	16.91		16.91	14	0		0.00	
Nogent 1	2/88	20.60	15.18		616	17.24		17.24	15	0		0.00	
Cattenom 1	4/87	21.44	15.25		616	17.32		17.32	16	0		0.00	
St-Alban 2	3/87	21.52	15.40		616	17.49		17.49	17	0		0.00	
Paluel 3	2/86	22.60	15.57		616	17.68		17.68	18	0		0.00	
Cruas 4	2/85	23.60	17.95		613	17.95		17.95	19	0		0.00	
Gravelines 6	10/85	22.93	18.02		613	18.02		18.02	20	0		0.00	
St-Alban 1	5/86	22.35	15.87		616	18.02		18.02	21	0		0.00	
Paluel 4	6/86	22.27	15.94		616	18.10		18.10	22	0		0.00	
Gravelines 5	1/85	23.68	18.11		613	18.11		18.11	23	0		0.00	
Cruas 2	4/85	23.44	18.20		613	18.20		18.20	24	0		0.00	
Cruas 3	9/84	24.02	18.45		613	18.45		18.45	25	0		0.00	
Flamanville 1	12/85	22.77	16.27		616	18.48		18.48	26	0		0.00	
Cruas 1	4/84	24.44	18.94		613	18.94		18.94	27	0		0.00	
Blayais 4 (SG 3)	10/83	24.94	19.19		613	19.19		19.19	28	0		0.00	
Paluel 1	12/85	22.77	17.20		616	19.53		19.53	29	0		0.00	
Paluel 2	12/85	22.77	17.22		616	19.56		19.56	30	0		0.00	
				Ave. Thot=	615								

Reference Temperature

613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse feedring design SGs with TT Alloy 600 tubing, kiss rolls, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-35
Time to 0.05% HL OD TTS Circumferential SCC - French Alloy 600TT Feedring Plants with Kiss Rolls and FDBs

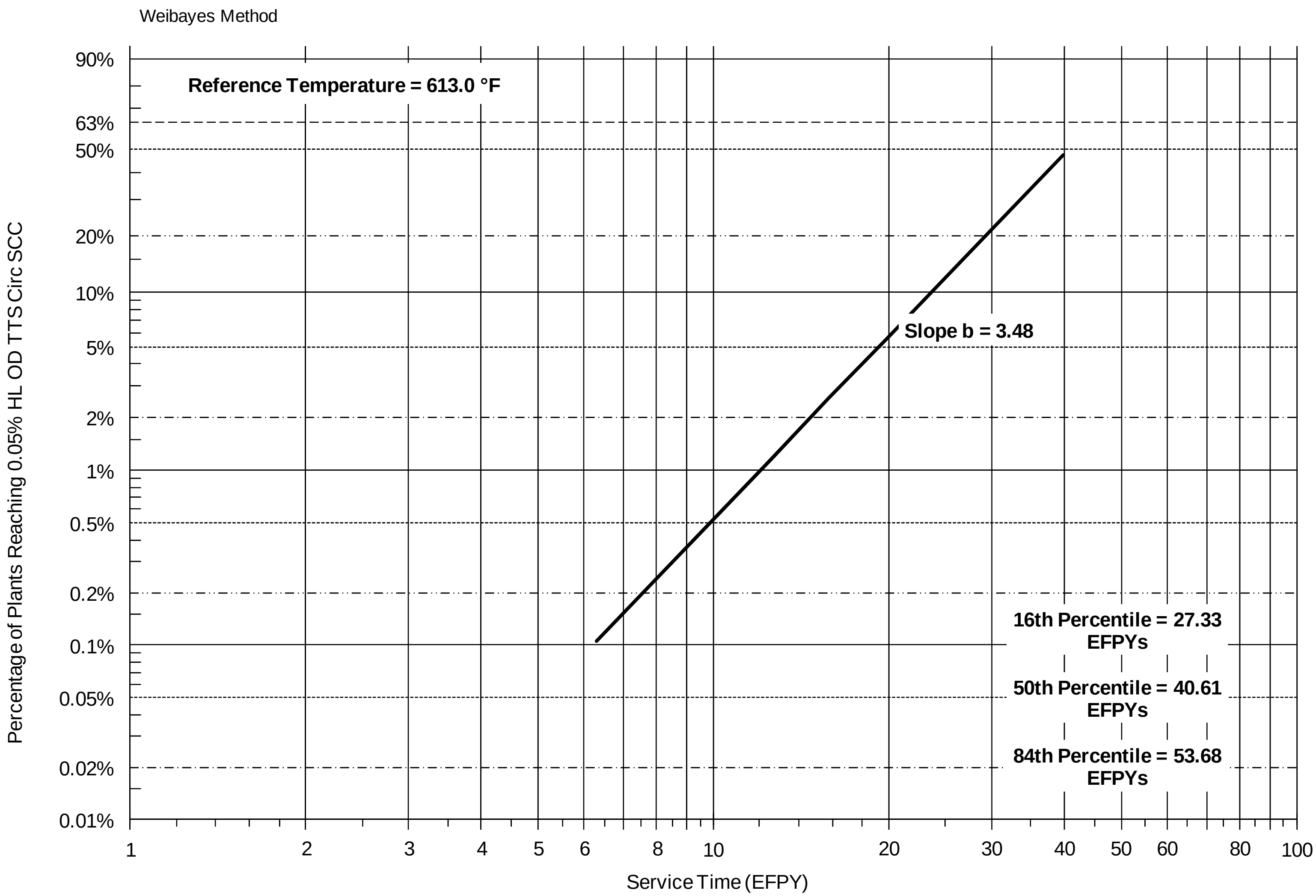

Figure 3-36
Time to 0.05% HL OD TTS Circumferential SCC - French Alloy 600TT Feedring Plants with Kiss Rolls and FDBs - Weibayes Analysis

No. Plants = 25 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 25	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Salem 1 (repl.)	11/97	10.84	7.90		602	5.97		5.97	1	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	19.00		597	11.74		11.74	2	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	18.1 (est.)		599	12.13		12.13	3	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	18.40		599	12.33		12.33	4	0		0.00	
Robinson 2 (repl.)	10/84	23.93	18.20		604	14.91		14.91	5	0		0.00	
Braidwood 2	10/88	19.93	17.10		608	16.43		16.43	6	0		0.00	
Byron 2	8/87	21.05	17.20		608	16.53		16.53	7	0		0.00	
Tomari 2	4/91	17.40	14.40		613	16.87		16.87	8	0		0.00	
Surry 1 (repl.)	7/81	27.19	20.00		605	17.05		17.05	9	0		0.00	
Comanche Peak 2	8/93	15.10	11.90		619	17.63		17.63	10	0		0.00	
Tomari 1	6/89	19.21	15.60		613	18.27		18.27	11	0		0.00	
Surry 2 (repl.)	9/80	28.02	22.00		605	18.76		18.76	12	0		0.00	
Seabrook	7/90	18.18	13.80		617	18.91		18.91	13	0		0.00	
Sendai 2	11/85	22.78	18.50		610	19.25		19.25	14	0		0.00	
Tsuruga 2	2/87	21.55	15.10		617	20.69		20.69	15	0		0.00	
Millstone 3	4/86	22.40	15.19		617	20.82		20.82	16	0		0.00	
Vogtle 2	5/89	19.30	16.00		617	21.93		21.93	17	0		0.00	
Catawba 2	8/86	22.10	17.50 (est.)		615	22.17		22.17	18	0		0.00	
Kori 3	9/85	23.02	16.70		619	24.74		24.74	19	0		0.00	
Vandellos 2	3/88	20.52	16.30		620	25.11		25.11	20	0		0.00	
Yonggwang 2	6/87	21.24	17.00		619	25.19		25.19	21	0		0.00	
Kori 4	4/86	22.44	17.10		619	25.34		25.34	22	0		0.00	
Vogtle 1	5/87	21.27	18.50		617	25.35		25.35	23	0		0.00	
Yonggwang 1	8/86	22.04	18.40		619	27.26		27.26	24	0		0.00	
Wolf Creek	9/85	23.02	19.20		618	27.36		27.36	25	0		0.00	
				Ave. Thot=	612								

Reference Temperature

609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with TT Alloy 600 tubing and full depth hydraulic expansions.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. Kori 2 excluded because it experienced denting at the TTS.
7. Sendai 1, Takahama 3 and 4 excluded because the A600 TT tubing was installed with a full depth hard roll as well as a hydraulic expansion.

Figure 3-37
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 600TT HE Plants

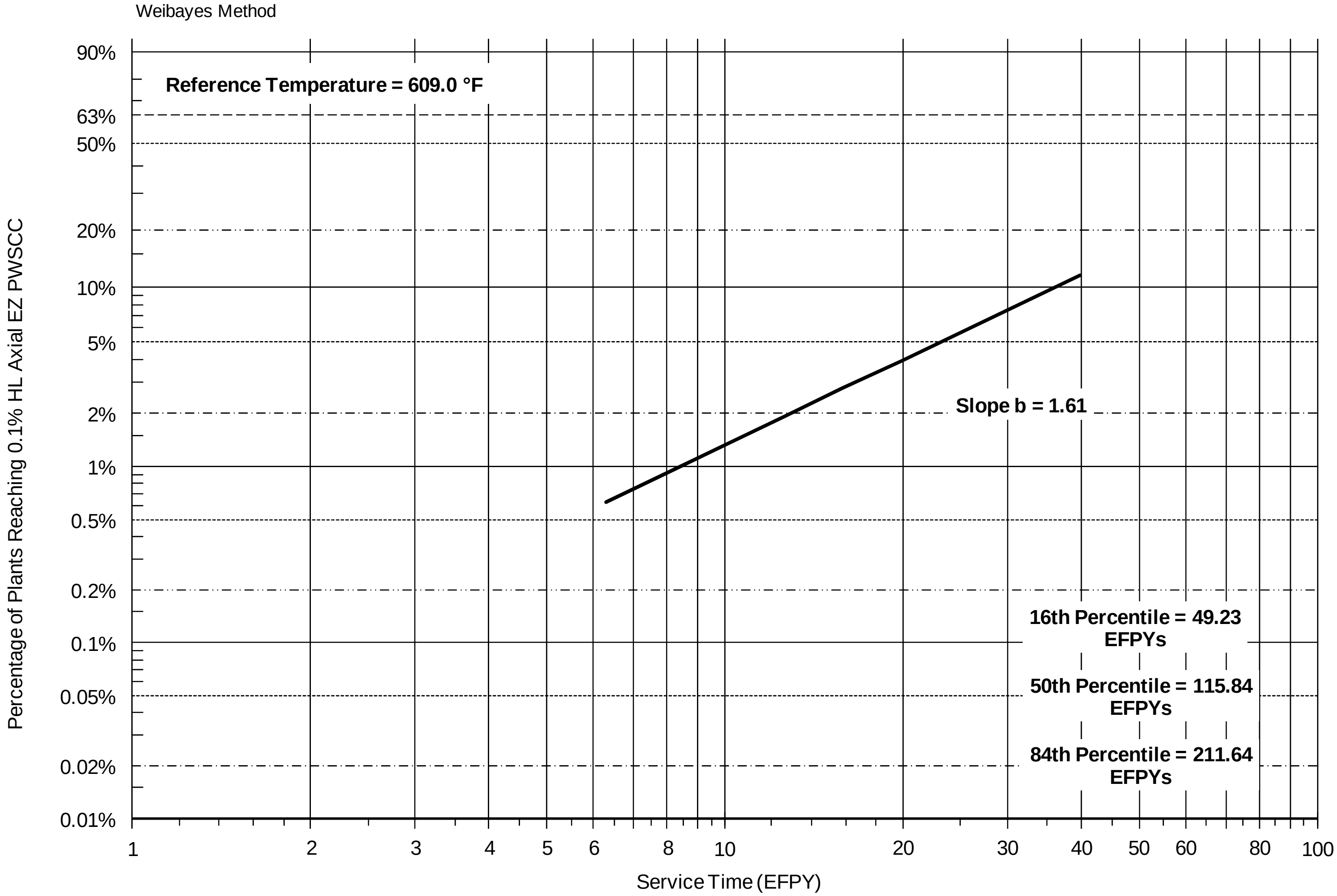

Figure 3-38
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 600TT HE Plants - Weibayes Analysis

No. Plants = 25 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 25	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Salem 1 (repl.)	11/97	10.84	7.90		602	5.97		5.97	1	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	19.00		597	11.74		11.74	2	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	18.10		599	12.13		12.13	3	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	18.40		599	12.33		12.33	4	0		0.00	
Robinson 2 (repl.)	10/84	23.93	18.10		604	14.83		14.83	5	0		0.00	
Braidwood 2	10/88	19.93	17.10		608	16.43		16.43	6	0		0.00	
Byron 2	8/87	21.05	17.20		608	16.53		16.53	7	0		0.00	
Tomari 2	4/91	17.40	14.40		613	16.87		16.87	8	0		0.00	
Surry 1 (repl.)	7/81	27.19	20.00		605	17.05		17.05	9	0		0.00	
Comanche Peak 2	8/93	15.10	11.90		619	17.63		17.63	10	0		0.00	
Tomari 1	6/89	19.21	15.60		613	18.27		18.27	11	0		0.00	
Seabrook	7/90	18.18	13.80		617	18.54		18.54	12	0		0.00	
Surry 2 (repl.)	9/80	28.02	22.00		605	18.76		18.76	13	0		0.00	
Sendai 2	11/85	22.78	18.50		610	19.25		19.25	14	0		0.00	
Tsuruga 2	2/87	21.55	15.10		617	20.69		20.69	15	0		0.00	
Millstone 3	4/86	22.40	15.19		617	20.82		20.82	16	0		0.00	
Catawba 2	8/86	22.10	17.50		615	22.17		22.17	17	0		0.00	
Kori 3	9/85	23.02	16.70		619	24.74		24.74	18	0		0.00	
Vandellos 2	3/88	20.52	16.30		620	25.11		25.11	19	0		0.00	
Yonggwang 2	6/87	21.24	17.00		619	25.19		25.19	20	0		0.00	
Kori 4	4/86	22.44	17.10		619	25.34		25.34	21	0		0.00	
Vogtle 2	5/89	19.30	18.50		617	25.35		25.35	22	0		0.00	
Vogtle 1	5/87	21.27	18.50		617	25.35		25.35	23	0		0.00	
Yonggwang 1	8/86	22.04	18.40		619	27.26		27.26	24	0		0.00	
Wolf Creek	9/85	23.02	19.20		618	27.36		27.36	25	0		0.00	
				Ave. Thot=	612								

Reference Temperature

609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with TT Alloy 600 tubing and full depth hydraulic expansions.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. Kori 2 excluded because it experienced denting at the TTS.
7. Sendai 1, Takahama 3 and 4 excluded because the A600 TT tubing was installed with a full depth hard roll as well as a hydraulic expansion.

Figure 3-39
Time to 0.1% HL Circumferential PWSCC - All Westinghouse Alloy 600TT HE Plants

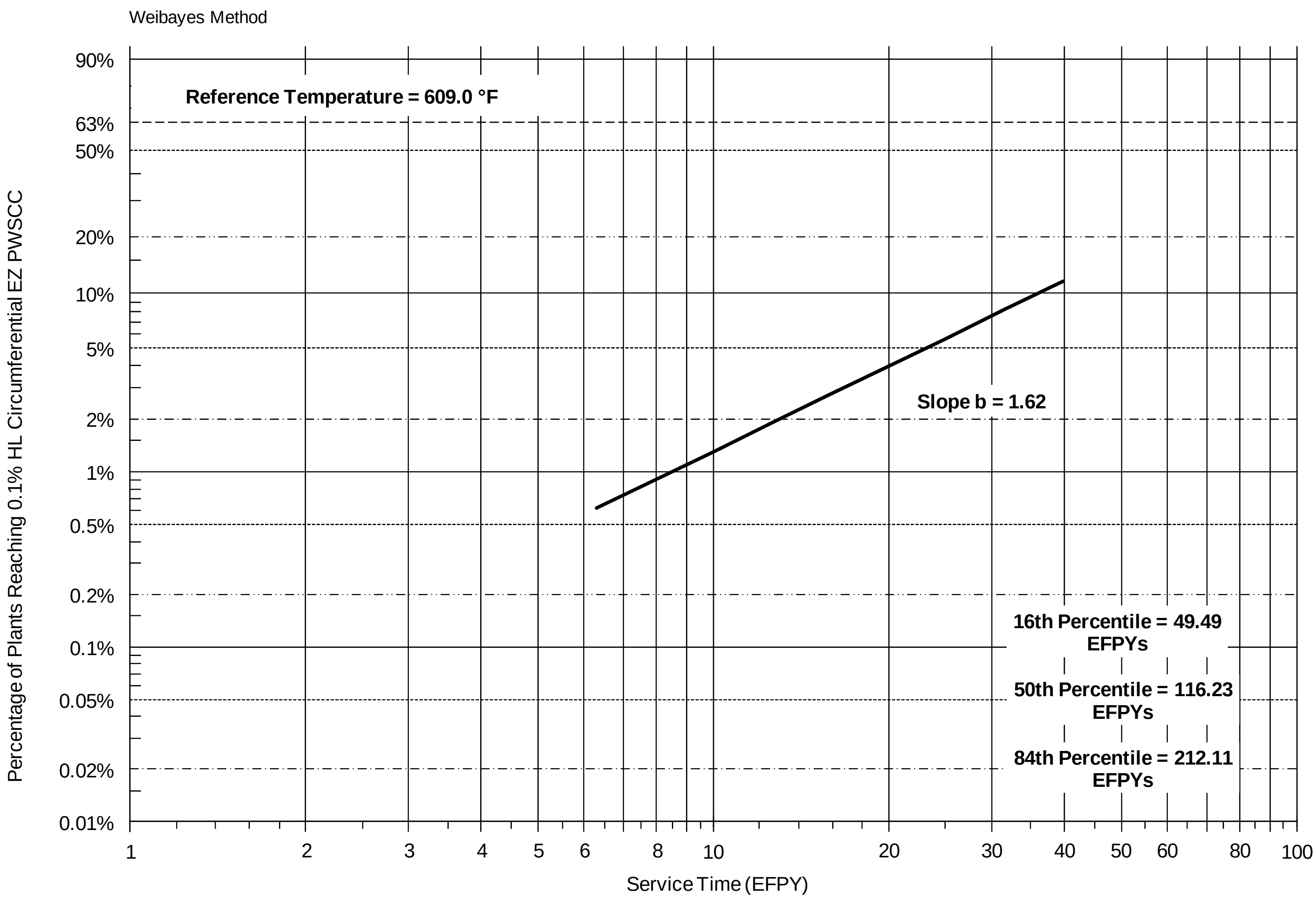

Figure 3-40
Time to 0.1% HL Circumferential PWSCC - All Westinghouse Alloy 600TT HE Plants – Weibayes Analysis

No. Plants = 24 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 24	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Salem 1 (repl.)	11/97	10.84	7.90		602	4.92		4.92	1	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	13.60		597	6.82		6.82	2	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	18.10		599	9.90		9.90	3	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	18.40		599	10.06		10.06	4	0		0.00	
Takahama 3	1/85	23.64	17.70		601	10.56		10.56	5	0		0.00	
Takahama 4	6/85	23.26	19.10		601	11.40		11.40	6	0		0.00	
Robinson 2 (repl.)	10/84	23.93	18.10		604	12.30		12.30	7	0		0.00	
Sendai 1	7/84	24.18	19.30		604	13.12		13.12	8	0		0.00	
Surry 1 (repl.)	7/81	27.19	20.00		605	14.20		14.20	9	0		0.00	
Tomari 2	4/91	17.40	14.40		613	14.40		14.40	10	0		0.00	
Tomari 1	6/89	19.21	15.60		613	15.60		15.60	11	0		0.00	
Surry 2 (repl.)	9/80	28.02	22.00		605	15.61		15.61	12	0		0.00	
Seabrook	7/90	18.18	13.80		617	16.01		16.01	13	0		0.00	
Sendai 2	11/85	22.78	18.50		610	16.28		16.28	14	0		0.00	
Tsuruga 2	2/87	21.55	15.10		617	17.89		17.89	15	0		0.00	
Millstone 3	4/86	22.40	15.19		617	18.00		18.00	16	0		0.00	
Vogtle 2	5/89	19.30	16.00		617	18.96		18.96	17	0		0.00	
Vogtle 1 (7)	5/87	21.27	16.00		617	18.96		18.96	18	0		0.00	
Kori 3	9/85	23.02	16.70		619	21.52		21.52	19	0		0.00	
Yonggwang 2	6/87	21.24	17.00		619	21.91		21.91	20	0		0.00	
Vandellos 2	3/88	20.52	16.30		620	21.91		21.91	21	0		0.00	
Kori 4	4/86	22.44	17.10		619	22.04		22.04	22	0		0.00	
Yonggwang 1	8/86	22.04	18.40		619	23.72		23.72	23	0		0.00	
Wolf Creek	9/85	23.02	19.20		618	23.73		23.73	24	0		0.00	
				Ave. Thot=	610								

Reference Temperature

613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse feedring design SGs with TT Alloy 600 tubing, hydraulic expansions, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. Kori 2 excluded because it experienced denting at the TTS.
7. One indication of axial TTS SCC was identified at Vogtle 1 in 2006. This was the first indication of this mode of SCC observed in Alloy 600TT SG tubing.

Figure 3-41
Time to 0.1% HL OD TTS A&V IGA/SCC - Westinghouse Design Alloy 600TT Feedring Plants with Hydraulic Expansions and FDBs

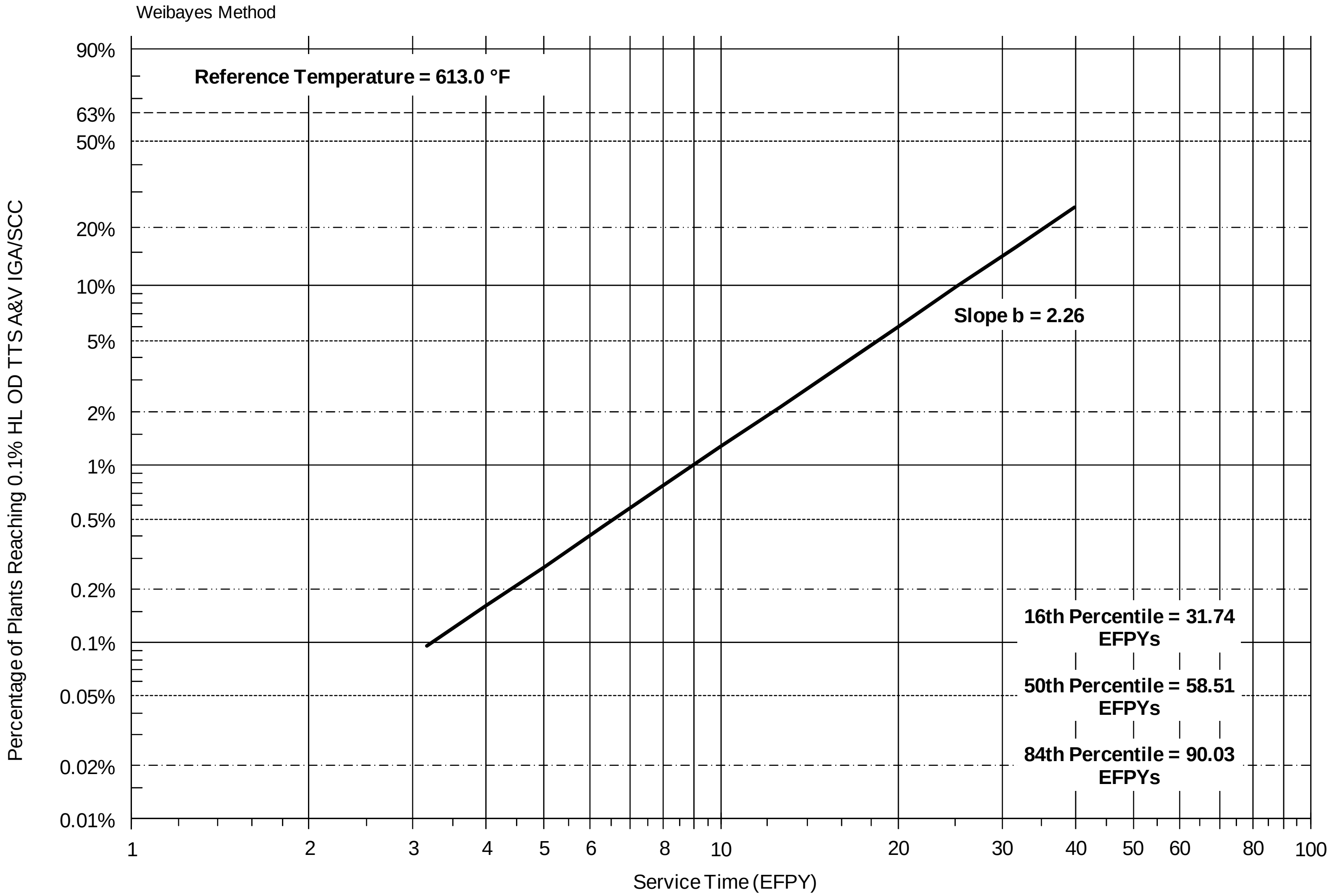

Figure 3-42
Time to 0.1% HL OD TTS A&V IGA/SCC - Westinghouse Design Alloy 600TT Feedring Plants with Hydraulic Expansions and FDBs – Weibayes Analysis

No. Plants = 4 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% TTS SCC	Adjusted EDYs to 0.1% TTS SCC or to Last ISI	N= 4	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Braidwood 2	10/88	19.93	17.10		608	11.18		11.18	1	0		0.00	
Byron 2	8/87	21.05	17.20		608	11.24		11.24	2	0		0.00	
Comanche Peak 2	8/93	15.10	11.90		619	12.41		12.41	3	0		0.00	
Catawba 2 (6)	8/86	22.10	17.50		615	15.42		15.42	4	0		0.00	

Ave. Thot= 613

Reference Temperature
618.0 °F = 598.72 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to U.S. Westinghouse plants with preheater-type SGs with TT Alloy 600 tubing, hydraulic expansions, and a FDB.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. Eight indications of axial ODSCC were identified in one SG at Catawba 2 in 2007. No additional indications of this type were found in Spring 2009 inspections, indicating that this degradation mode is not currently active at Catawba 2.

Figure 3-43
Time to 0.1% HL OD TTS A&V IGA/SCC - US Westinghouse Alloy 600TT Preheater Plants with Hydraulic Expansions and a FDB

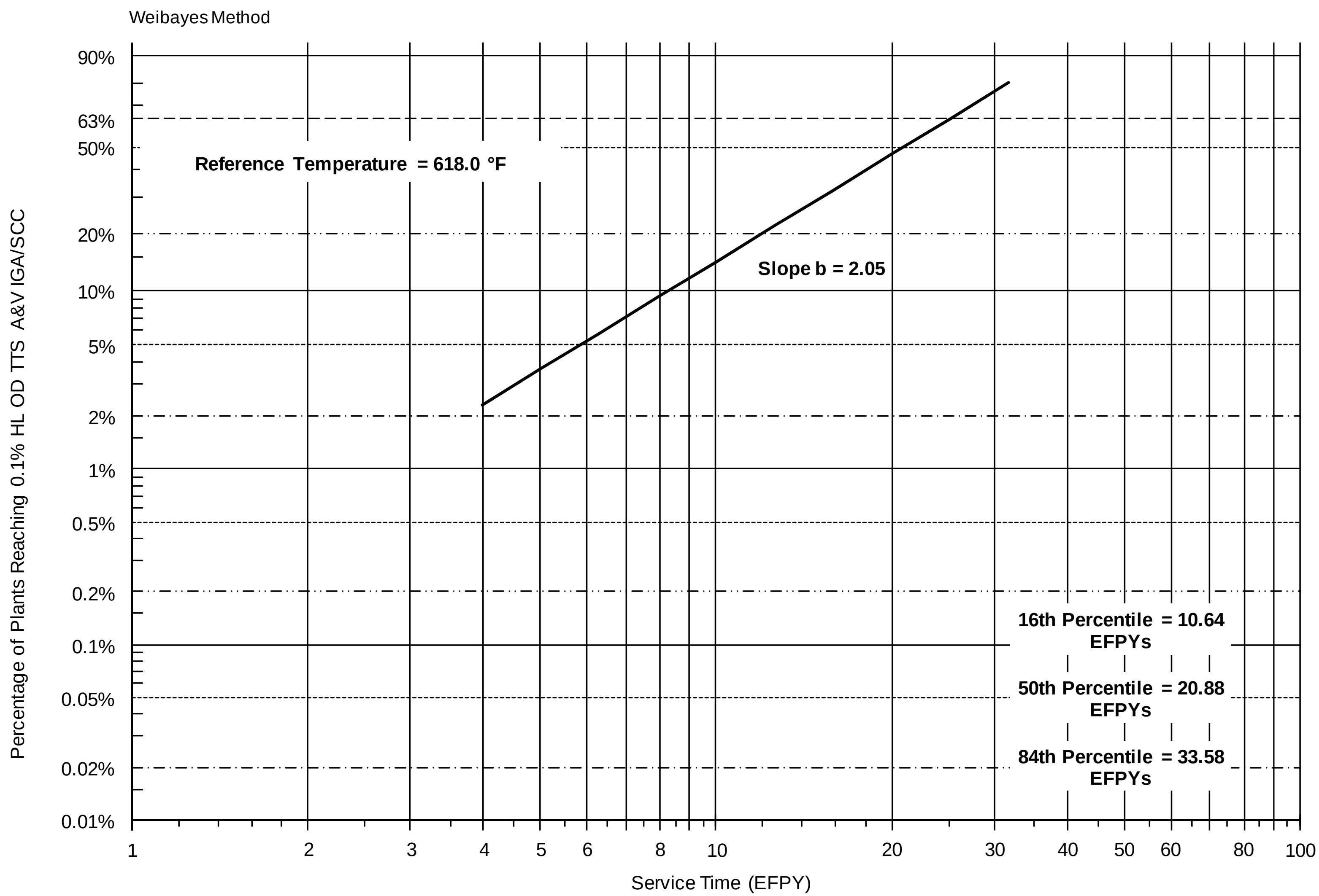

Figure 3-44
Time to 0.1% HL OD TTS A&V IGA/SCC - US Westinghouse Alloy 600TT Preheater Plants with Hydraulic Expansions and a FDB – Weibayes Analysis

No. Plants = 24 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 24	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Salem 1 (repl.)	11/97	10.84	7.90		602	4.92		4.92	1	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	19.00		597	9.52		9.52	2	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	18.10		599	9.90		9.90	3	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	18.40		599	10.06		10.06	4	0		0.00	
Takahama 3	1/85	23.64	17.70		601	10.56		10.56	5	0		0.00	
Takahama 4	6/85	23.26	19.14		601	11.42		11.42	6	0		0.00	
Robinson 2 (repl.)	10/84	23.93	18.10		604	12.30		12.30	7	0		0.00	
Sendai 1	7/84	24.18	19.30		604	13.12		13.12	8	0		0.00	
Surry 1 (repl.)	7/81	27.19	20.00		605	14.20		14.20	9	0		0.00	
Tomari 2	4/91	17.40	14.40		613	14.40		14.40	10	0		0.00	
Tomari 1	6/89	19.21	15.60		613	15.60		15.60	11	0		0.00	
Surry 2 (repl.)	9/80	28.02	22.00		605	15.61		15.61	12	0		0.00	
Seabrook	7/90	18.18	13.80		617	16.01		16.01	13	0		0.00	
Sendai 2	11/85	22.78	18.50		610	16.28		16.28	14	0		0.00	
Tsuruga 2	2/87	21.55	15.10		617	17.89		17.89	15	0		0.00	
Millstone 3	4/86	22.40	15.19		617	18.00		18.00	16	0		0.00	
Vogtle 2	5/89	19.30	16.00		617	18.96		18.96	17	0		0.00	
Vogtle 1	5/87	21.27	18.50	17.10	617	21.92	20.26	20.26	18	1	7	3.13	0.1158
Kori 3	9/85	23.02	16.70		619	21.52		21.52	19	0		3.13	
Yonggwang 2	6/87	21.24	17.00		619	21.91		21.91	20	0		3.13	
Vandellos 2	3/88	20.52	16.30		620	21.91		21.91	21	0		3.13	
Kori 4	4/86	22.44	17.10		619	22.04		22.04	22	0		3.13	
Yonggwang 1	8/86	22.04	18.40		619	23.72		23.72	23	0		3.13	
Wolf Creek	9/85	23.02	19.20		618	23.73		23.73	24	0		3.13	

Ave. Thot= 610

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse feedring design SGs with TT Alloy 600 tubing, hydraulic expansions, and flow distribution baffles.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. Kori 2 excluded because it experienced denting at the TTS.

Figure 3-45
Time to 0.05% HL OD TTS Circumferential SCC - Westinghouse Design Alloy 600TT Feedring Plants with Hydraulic Expansions and FDBs

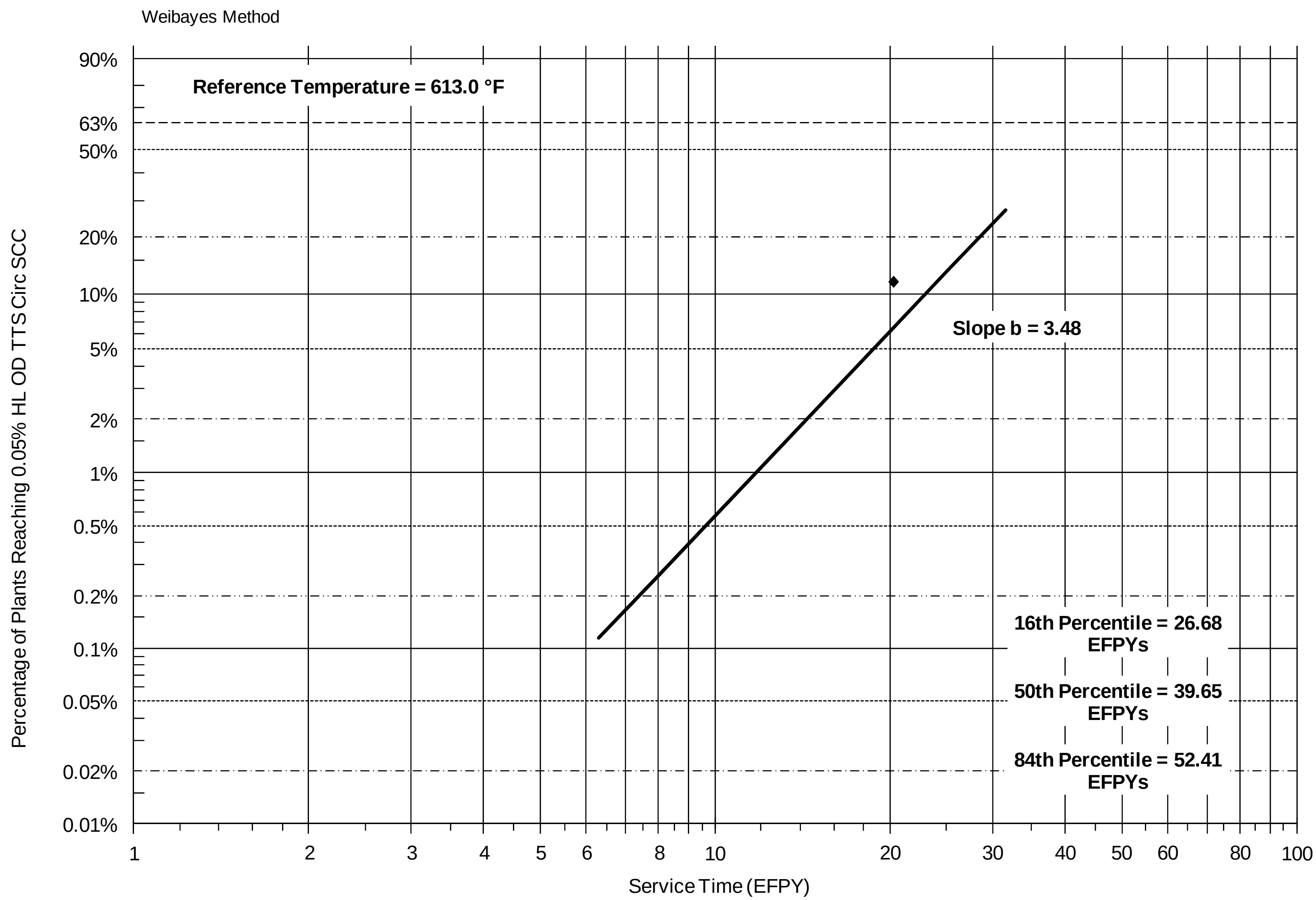

Figure 3-46
Time to 0.05% HL OD TTS Circumferential SCC - Westinghouse Design Alloy 600TT Feedring Plants with Hydraulic Expansions and FDBs - Weibayes Analysis

No. Plants = 4 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% TTS SCC	Adjusted EDYs to 0.1% TTS SCC or to Last ISI	N= 4	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Braidwood 2	10/88	19.93	17.10		608	11.18		11.18	1	0		0.00	
Byron 2	8/87	21.05	17.20		608	11.24		11.24	2	0		0.00	
Comanche Peak 2	8/93	15.10	11.90		619	12.41		12.41	3	0		0.00	
Catawba 2	8/86	22.10	17.50		615	15.42		15.42	4	0		0.00	
				Ave. Thot=	613								

Reference Temperature
618.0 °F = 598.72 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to U.S. Westinghouse plants with preheater-type SGs with TT Alloy 600 tubing, hydraulic expansions, and a FDB.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-47
Time to 0.1% HL OD TTS Circumferential SCC - US Westinghouse Alloy 600TT Preheater Plants with Hydraulic Expansions and a FDB

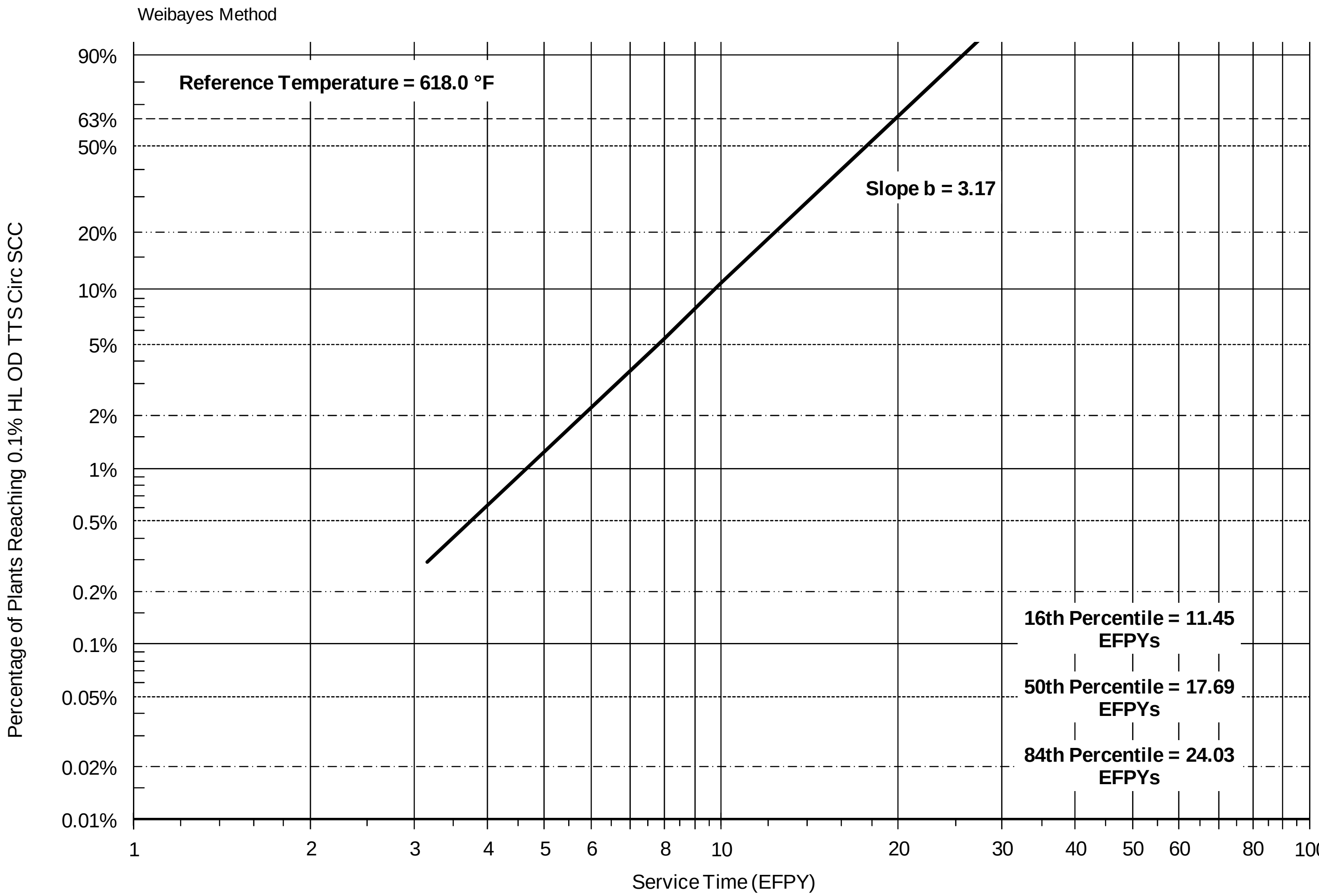

Figure 3-48
Time to 0.1% HL OD TTS Circumferential SCC - US Westinghouse Alloy 600TT Preheater Plants with Hydraulic Expansions and a FDB - Weibayes Analysis

No. Plants = 25 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 25	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Salem 1 (repl.)	11/97	10.84	7.90		602	6.94		6.94	1	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	19.00		597	13.42		13.42	2	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	18.1 (est.)		599	13.95		13.95	3	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	18.40		599	14.18		14.18	4	0		0.00	
Takahama 3	1/85	23.64	17.70		601	14.88		14.88	5	0		0.00	
Takahama 4	6/85	23.26	19.14		601	16.09		16.09	6	0		0.00	
Robinson 2 (repl.)	10/84	23.93	18.10		604	17.33		17.33	7	0		0.00	
Sendai 1	7/84	24.18	19.30		604	18.48		18.48	8	0		0.00	
Surry 1 (repl.)	7/81	27.19	20.00		605	20.00		20.00	9	0		0.00	
Tomari 2	4/91	17.40	14.40		613	20.29		20.29	10	0		0.00	
Tomari 1	6/89	19.21	15.60		613	21.98		21.98	11	0		0.00	
Surry 2 (repl.)	9/80	28.02	22.00		605	22.00		22.00	12	0		0.00	
Seabrook	7/90	18.18	13.80		617	22.55		22.55	13	0		0.00	
Sendai 2	11/85	22.78	18.50		610	22.93		22.93	14	0		0.00	
Tsuruga 2	2/87	21.55	15.10		617	25.20		25.20	15	0		0.00	
Millstone 3	4/86	22.40	15.19		617	25.35		25.35	16	0		0.00	
Vogtle 2	5/89	19.30	16.00		617	26.71		26.71	17	0		0.00	
Kori 3	9/85	23.02	16.70		619	30.33		30.33	18	0		0.00	
Yonggwang 2	6/87	21.24	17.00		619	30.87		30.87	19	0		0.00	
Vandellos 2	3/88	20.52	16.30		620	30.87		30.87	20	0		0.00	
Vogtle 1	5/87	21.27	18.50		617	30.88		30.88	21	0		0.00	
Kori 4	4/86	22.44	17.10		619	31.05		31.05	22	0		0.00	
Kori 2	7/83	25.12	20.30		616	32.48		32.48	23	0		0.00	
Yonggwang 1	8/86	22.04	18.40		619	33.41		33.41	24	0		0.00	
Wolf Creek	9/85	23.02	19.20		618	33.43		33.43	25	0		0.00	
				Ave. Thot=	611								

Reference Temperature

605.0 °F = 591.49 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to Westinghouse plants with feedring-type SGs with TT Alloy 600 tubing and broached hole stainless steel TSPs.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-49
Time to 0.05% Hot Leg TSP IGA/SCC – Westinghouse Alloy 600TT Broached Hole Feedring Plants

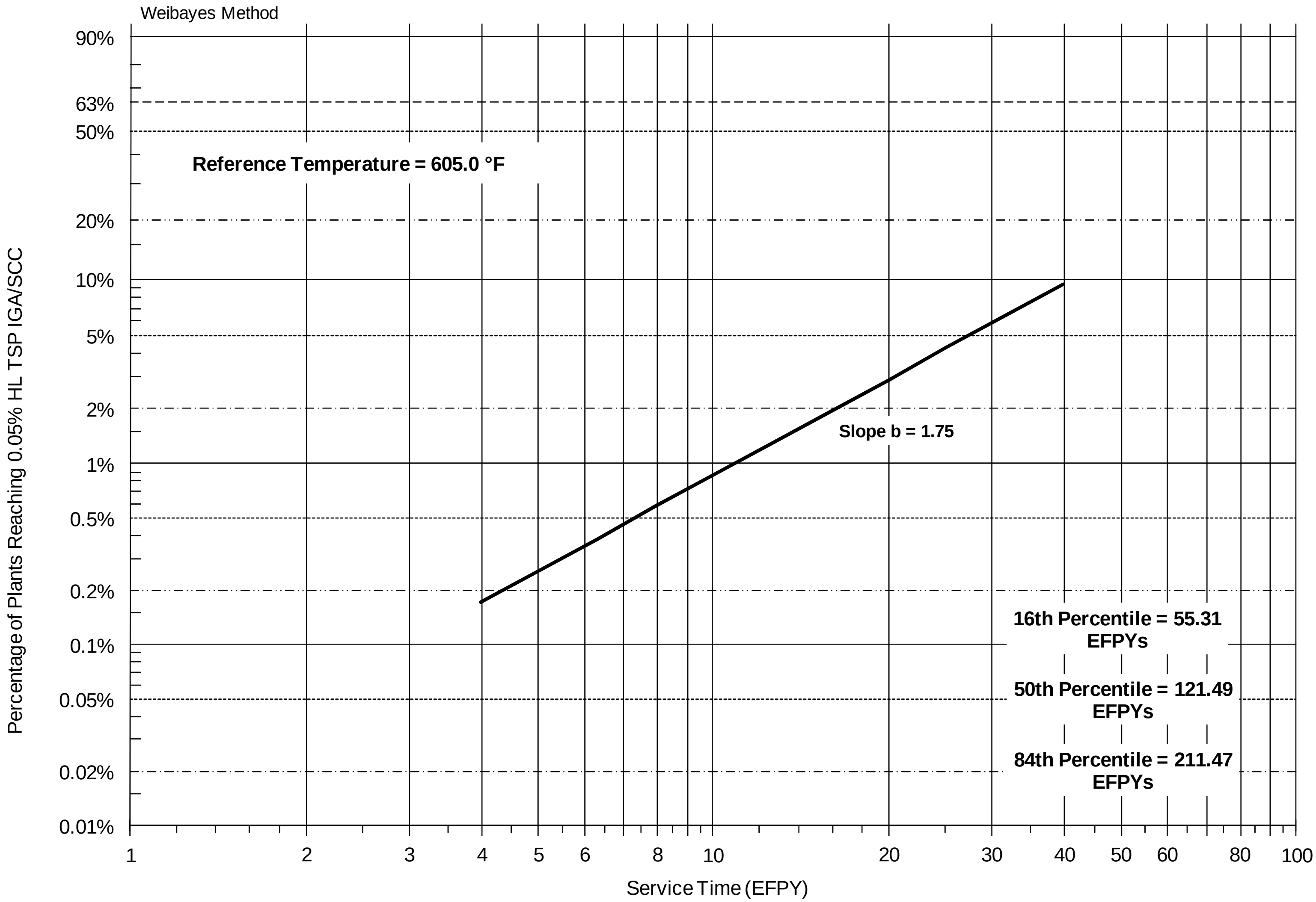

Figure 3-50
Time to 0.05% Hot Leg TSP IGA/SCC – Westinghouse Alloy 600TT Broached Hole Feedring Plants – Weibayes Analysis

No. Plants = 4 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 1.0% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 1% IGA/SCC	Adjusted EDYs to 1% IGA/SCC or to Last ISI	N= 4	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Braidwood 2	10/88	19.93	17.10		608	11.18		11.18	1	0		0.00	
Byron 2	8/87	21.05	17.20		608	11.24		11.24	2	0		0.00	
Comanche Peak 2	8/93	15.10	11.90		619	12.41		12.41	3	0		0.00	
Catawba 2	8/86	22.10	17.50		615	15.42		15.42	4	0		0.00	
				Ave. Thot=	613								

Reference Temperature

618.0 °F = 598.72 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to U.S. Westinghouse plants with preheater-type SGs with TT Alloy 600 tubing and broached hole stainless steel TSPs.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-51
Time to 1% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600TT Drilled Hole Preheater Plants

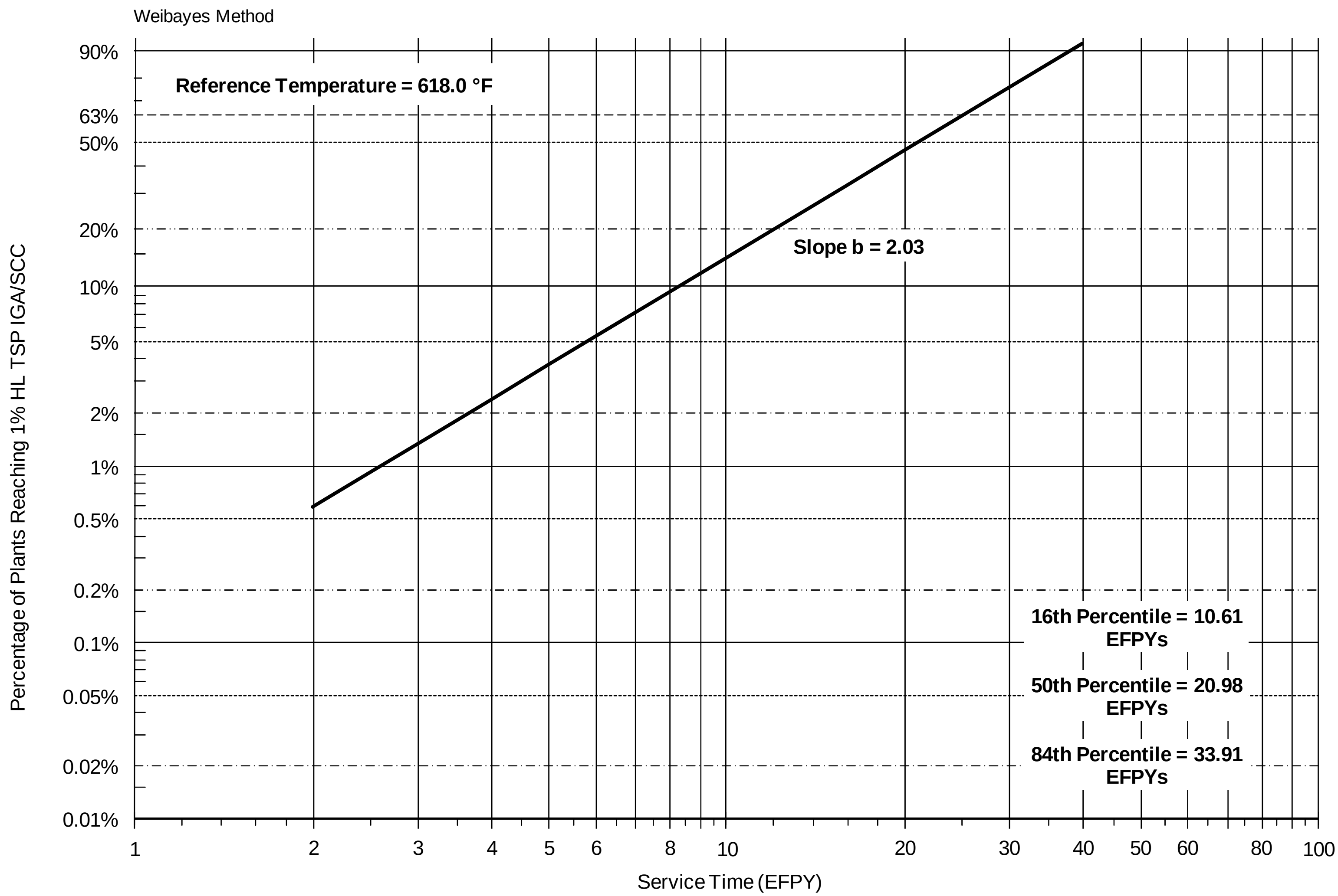

Figure 3-52
Time to 1% Hot Leg TSP IGA/SCC - US Westinghouse Alloy 600TT Drilled Hole Preheater Plants – Weibayes Analysis

3.3.3 Alloy 690TT versus Alloy 600MA

As discussed earlier in this report, in the absence of observed failures, field performance based improvement factors are calculated from the current length of operating experience. In these situations, the first incidence of failure is assumed to be imminent. Because Alloy 690TT has been in use for a relatively short period of time, the improvement factors derived from plant experience are generally lower than those for Alloy 800NG and Alloy 600TT at this time.

As no stress corrosion cracking has been observed in plants tubed with Alloy 690TT, the Weibayes method was used to predict the median times to failure for these plants. The failure criterion used for each degradation mechanism was identical to that used in analyzing the performance of Alloy 600TT HE plants. The data collected on Alloy 690TT experience to date in all Westinghouse design plants with Alloy 690TT tubing and their respective Weibull plots for various degradation mechanisms are given at the end of this section.

3.3.3.1 Axial Primary-side IGA/SCC at the Expansion Transition (Axial EZ PWSCC)

The median time to failure is currently estimated to be 102.9 EFPY for axial PWSCC. The field data for all Westinghouse design Alloy 690TT plants with respect to axial PWSCC are shown in Figure 3-58. The Weibull plot developed for this data is given in Figure 3-59.

3.3.3.2 Circumferential Primary-side IGA/SCC at the Expansion Transition (Circ. EZ PWSCC)

The median time to failure is currently estimated to be 102.8 EFPY for circumferential PWSCC. The field data for all Westinghouse design Alloy 690TT plants with respect to Circ. PWSCC are shown in Figure 3-60. The Weibull plot developed for this data is given in Figure 3-61.

3.3.3.3 Axial and volumetric secondary-side IGA/SCC at the top of tubesheet (OD TTS A&V IGA/SCC)

The median time to failure is estimated to be 48.9 EFPY for A&V secondary-side IGA/SCC at the top of tubesheet. The field data for all Westinghouse design Alloy 690TT plants analyzed for OD TTS A&V IGA/SCC are shown in Figure 3-62. The Weibull plot developed for this data is given in Figure 3-63.

3.3.3.4 Circumferential secondary-side IGA/SCC at the top of tubesheet (OD TTS Circ. SCC)

The median time to failure for Alloy 690 tubed SGs is estimated to be 29.4 EFPY with respect to circumferential secondary-side IGA/SCC at the top of the tubesheet. The field data analyzed for this degradation mechanism are given in Figure 3-64. The Weibayes method was used to develop the Weibull distribution for the data, shown in Figure 3-65.

3.3.3.5 IGA/SCC at the tube support plate intersection (HL TSP IGA/SCC)

For IGA/SCC at the tube support plate intersection, the median time to failure for Alloy 690 tubed SGs is estimated to be 106 EFPY. The field data analyzed for this degradation mechanism are given in Figure 3-66. The Weibayes method was used to develop the Weibull distribution for the data, shown in Figure 3-67.

3.3.3.6 Conclusions

The calculated material improvement factors for Alloy 690TT vs. Alloy 600MA for each degradation mechanism are shown in Table 3-5. For comparison, the material plus design improvement factor for PWSCC in Alloy 690TT vs. Alloy 600MA with WEXTEX expansion transitions is also shown.

Table 3-5
Estimated Material Improvement Factors for Alloy 690TT vs. Alloy 600MA

Degradation Mode	600MA		690TT		
	Design Group	Median Time to Failure (EFPY)	Design Group	Median Time to Failure (EFPY)	IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	West. (All)	102.9	>12.6
	West. (HE)	*>10.9*			*>9.5*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	West. (All)	102.8	>10.4
	West. (HE)	*>10.9*			*>9.5*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	West. (All)	48.9	>5.4
	West. Preheater (KR)	*>14.9*			*>3.3*
	West. Feedring (KR)	8.4			>5.8
	West. Feedring (HE)	*>15.9*			*>3.1*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	West. (All)	29.4	>5.3
	West. Preheater (KR)	*>5.8*			*>5.1*
	West. Feedring (KR)	13.9			>2.1
	West. Feedring (HE)	*>15.7*			*>1.9*
TSP IGA/SCC	West. Preheater (DH)	8.2	West. (All)	106.0	>13.0
	West. Feedring (DH)	8.3			>12.8
	West. Feedring (BH)	25.7			*>4.1*

Italicized IF_R values indicate low confidence.

All improvement factors are estimated in the absence of significant degradation of Alloy 690TT.

Plant experience to date indicates a lower bound on the improvement factor of about 1.9, limited by the predictions for circumferential OD IGA/SCC at the TTS in units with Alloy 690TT tubed steam generators. The material improvement factors calculated for TTS IGA/SCC have the potential to be overly conservative because of the relatively high slope assumed for the Weibayes analysis. For these mechanisms, the slope was assumed to be the same as that of the French kiss roll plants tubed with Alloy 600MA, since this is the conservative assumption. For other degradation mechanisms, the slope of the Weibull distribution was determined from that of the Westinghouse Alloy 600MA tubed plants with WEXTEX tube in tubesheet expansions. (Note that the range in improvement factors is generally due to differences in the performance of Alloy 600MA, rather than to the assumptions made in the analysis.)

As experience with Alloy 690TT accumulates, the calculated plant experienced based improvement factor will increase. Table 3-6 presents the current improvement factors calculated for various degradation modes and the improvement factors that would be calculated at various future times should no failures be observed.

3.3.3.7 Weibayes Modeling

As plant experience with Alloy 690TT accumulates without failure, the improvement factor will continue to increase. Figure 3-53 through Figure 3-57 show the predicted median time to failure for each degradation mechanism as a function of time without failure based on the Weibayes models developed in this report. From these functions, the improvement factors that would be calculated at a given point in the future can be found (assuming no failures have yet occurred). The anticipated improvement factors for Alloy 690TT in 2012 and 2020 are shown in Table 3-6.

Table 3-6
Relative Improvement Factors - Alloy 690TT SGs versus Alloy 600MA Design Group

Degradation Mechanism	Alloy 600MA Design Group	Alloy 690TT IF_R Assuming 1 Imminent Failure in 2008	Alloy 690TT IF_R Assuming 1 Imminent Failure in 2012	Alloy 690TT IF_R Assuming 1 Imminent Failure in 2020
Axial EZ PWSCC	Feedring Alloy 600MA Wextex Expansions	13.2	17.4	26.1
Circumferential EZ PWSCC	Feedring Alloy 600MA Wextex Expansions	10.7	14.3	21.6
HL TTS OD A&V SCC	Feedring Alloy 600MA Kiss Roll FDBs	6.0	7.9	11.9
HL TTS OD Circumferential SCC	Feedring Alloy 600MA Kiss Roll FDBs	2.2	2.8	4.3
HL TSP IGA/SCC	Feedring Alloy 600MA Drilled Hole No Phosphate	13.1	17.5	26.2

The operating time required to verify a given improvement factor can also be calculated. Times to verify an IF_R of 5, 10, 20, and 30 are given in Table 3-7.

Table 3-7
Required Operating Time for Verification of a Given Improvement Factor

Degradation Mechanism	Alloy 600MA Design Group	Year of First 690TT Plant Reaching Failure Criterion $IF_R = 5$	Year of First 690TT Plant Reaching Failure Criterion $IF_R = 10$	Year of First 690TT Plant Reaching Failure Criterion $IF_R = 20$	Year of First 690TT Plant Reaching Failure Criterion $IF_R = 30$
Axial EZ PWSCC	Feedring Alloy 600 MA Wextex Expansions	2000	2005	2014	2024
Circumferential EZ PWSCC	Feedring Alloy 600 MA Wextex Expansions	2002	2007	2018	2029
HL TTS OD A&V SCC	French Feedring Alloy 600MA Kiss Roll FDBs	2006	2016	2037	2057
HL TTS OD Circumferential SCC	Feedring Alloy 600MA Kiss Roll FDBs	2025	2054	2112	2170
HL TSP IGA/SCC	Feedring Alloy 600MA Drilled Hole No Phosphate	2001	2005	2014	2024

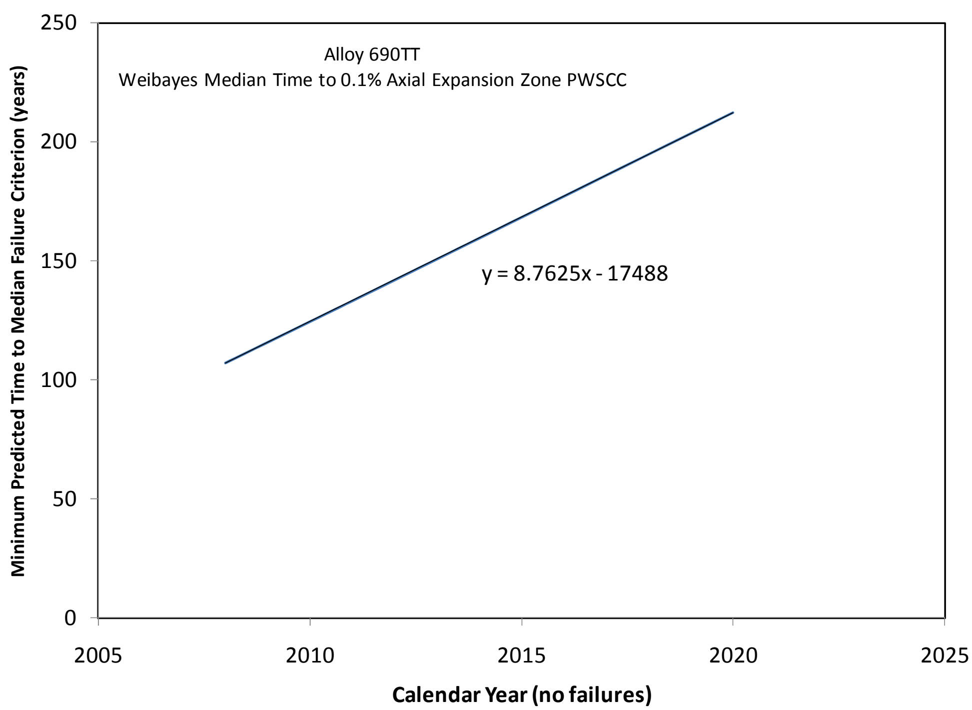

Figure 3-53
Alloy 690TT Axial EZ PWSCC Median Time to Failure Criterion – With No Future Failures

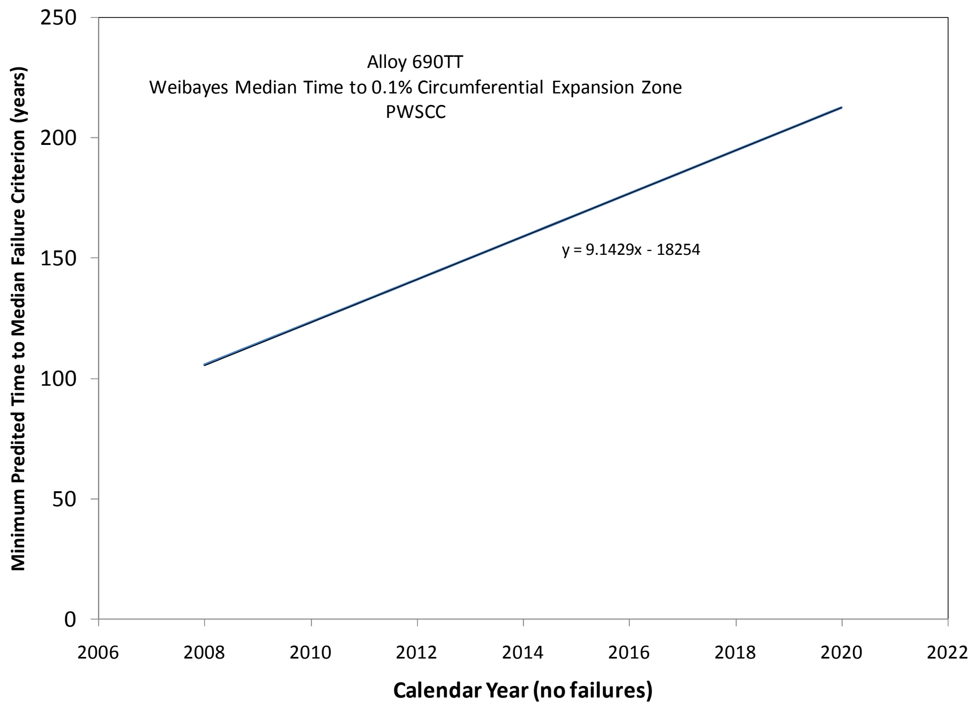

Figure 3-54
Alloy 690TT Circumferential EZ PWSCC Median Time to Failure Criterion - With No Future Failures

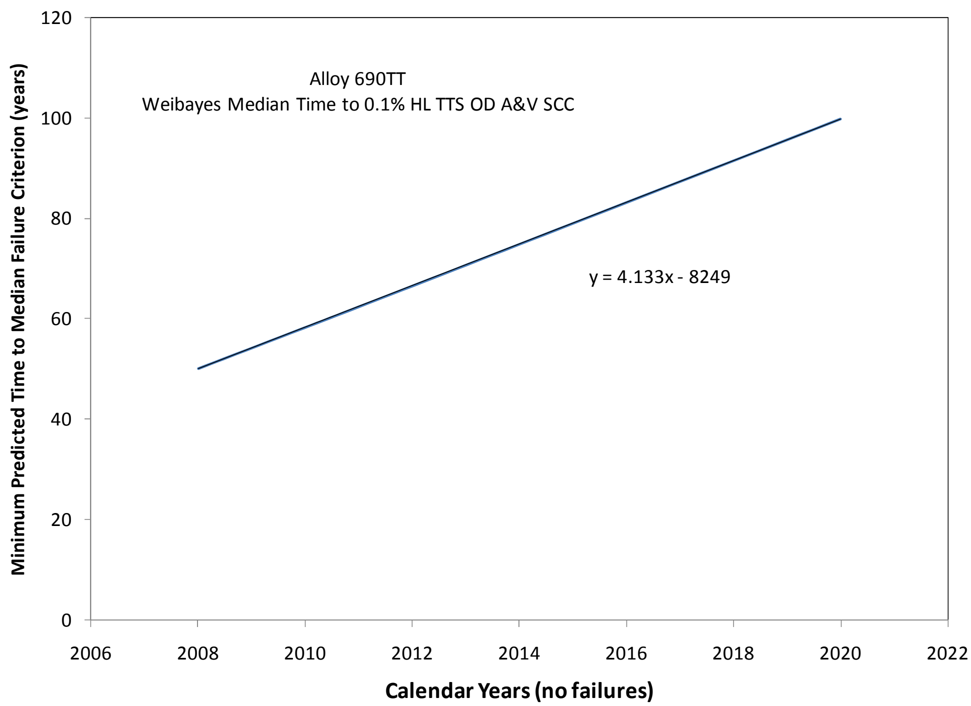

Figure 3-55
Alloy 690TT HL TTS OD A&V SCC Median Time to Failure Criterion - With No Future Failures

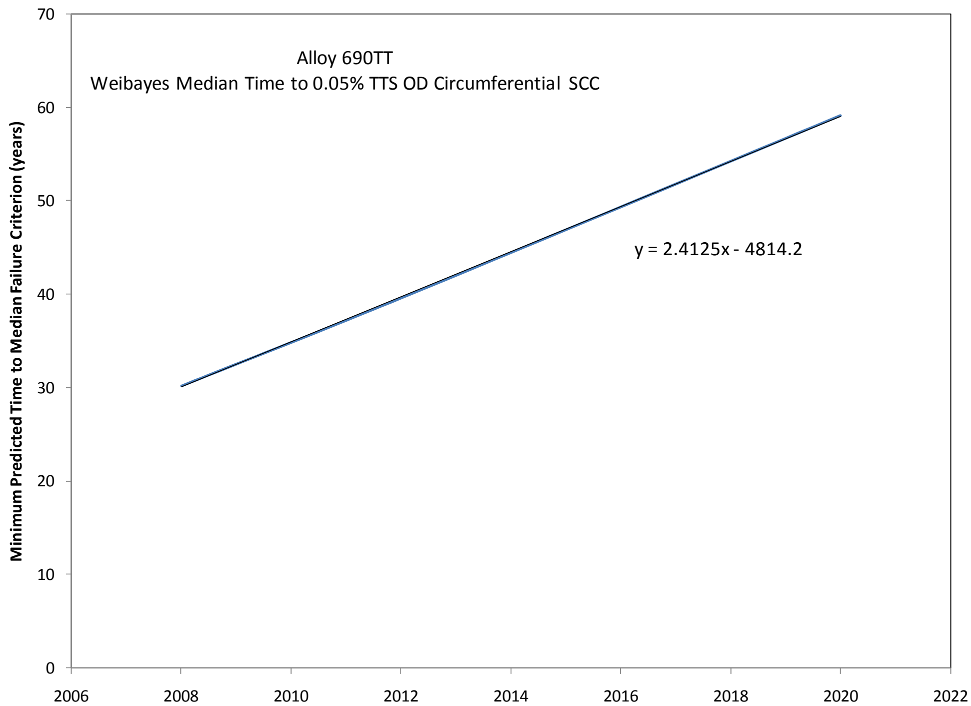

Figure 3-56
Alloy 690TT HL TTS OD Circ. SCC Median Time to Failure Criterion - With No Future Failures

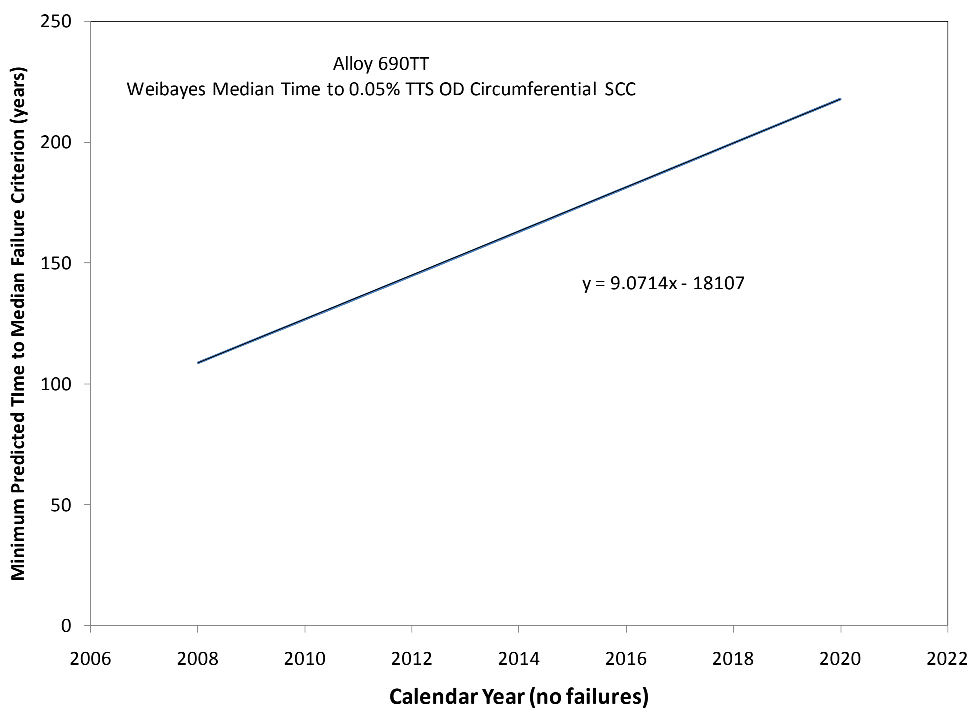

Figure 3-57
Alloy 690TT HL TSP IGA/SCC Median Time to Failure Criterion - with No Future Failures

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41		2.41	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90		4.90	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41		5.41	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59		5.59	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76		5.76	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80		5.80	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03		6.03	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28		6.28	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56		6.56	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12		7.12	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	7.19		7.19	12	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19		7.19	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63		7.63	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78		8.78	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83		8.83	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84		8.84	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87		8.87	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95		8.95	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60		9.60	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66		9.66	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78		9.78	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79		9.79	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88		9.88	24	0		0.00	
Sizewell B	2/95	13.59	7.30		617	10.00		10.00	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04		10.04	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07		10.07	27	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29		10.29	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30		10.30	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83		10.83	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89		10.89	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09		11.09	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30		11.30	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76		11.76	34	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15		12.15	35	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38		12.38	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42		12.42	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42		12.42	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53		12.53	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65		12.65	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74		12.74	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05		13.05	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33		13.33	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52		13.52	44	0		0.00	
Golfech 2	3/94	14.52	10.63		616	14.01		14.01	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50		14.50	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77		14.77	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97		14.97	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49		15.49	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58		15.58	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81		16.81	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27		17.27	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78		17.78	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91		18.91	54	0		0.00	
				Ave. Thot=	612								

Reference Temperature

609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-58
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 690TT Plants

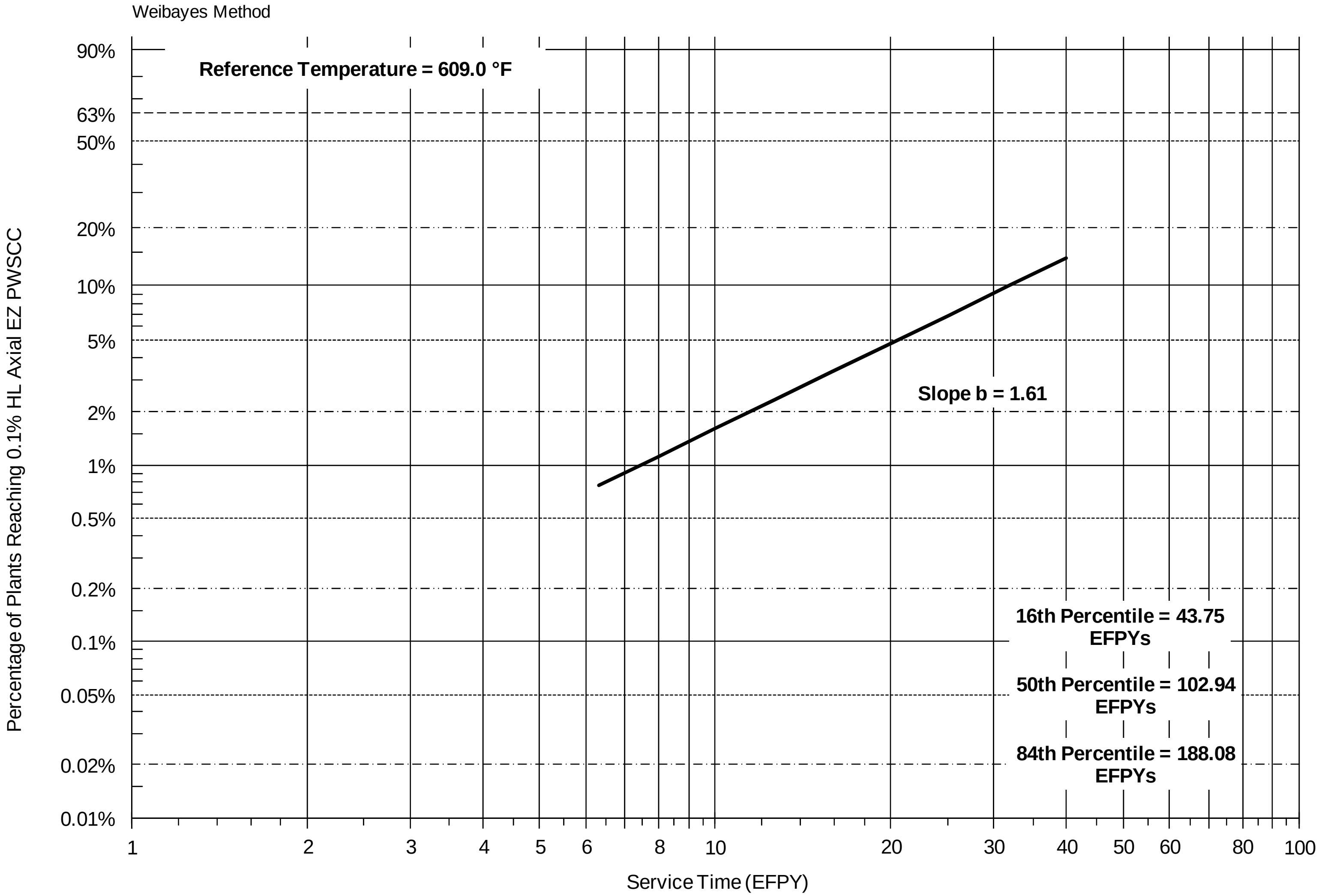

Figure 3-59
Time to 0.1% HL Axial EZ PWSCC - All Westinghouse Design Alloy 690TT Plants – Weibayes Analysis

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41		2.41	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.00		589	4.90		4.90	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41		5.41	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59		5.59	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76		5.76	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80		5.80	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03		6.03	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28		6.28	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56		6.56	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12		7.12	11	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19		7.19	12	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	7.19		7.19	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63		7.63	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78		8.78	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83		8.83	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84		8.84	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87		8.87	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95		8.95	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60		9.60	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66		9.66	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78		9.78	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79		9.79	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88		9.88	24	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04		10.04	25	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07		10.07	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29		10.29	27	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30		10.30	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83		10.83	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89		10.89	30	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09		11.09	31	0		0.00	
Sizewell B	2/95	13.59	7.30		620	11.24		11.24	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30		11.30	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76		11.76	34	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15		12.15	35	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38		12.38	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42		12.42	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42		12.42	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.7 (est.)		613	12.53		12.53	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65		12.65	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74		12.74	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05		13.05	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33		13.33	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52		13.52	44	0		0.00	
Golfech 2	3/94	14.52	10.83		616	14.27		14.27	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50		14.50	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77		14.77	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97		14.97	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49		15.49	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58		15.58	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81		16.81	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27		17.27	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78		17.78	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91		18.91	54	0		0.00	

Ave. Thot= 612

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-60
Time to 0.1% HL Circumferential PWSCC – All Westinghouse Design Alloy 690TT Plants

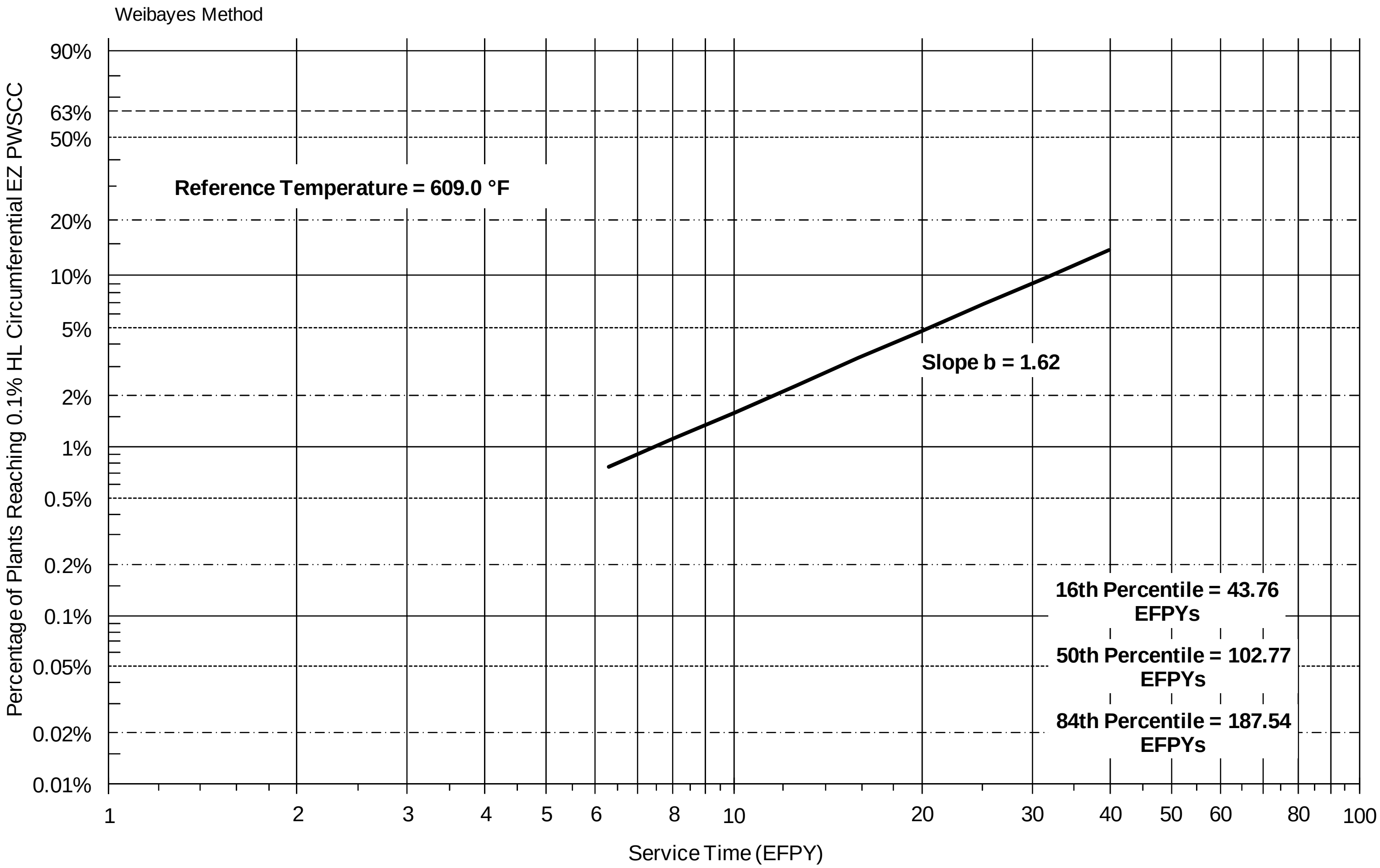

Figure 3-61
Time to 0.1% HL Circumferential PWSCC – All Westinghouse Design Alloy 690TT Plants – Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93		1.93	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.00		589	3.87		3.87	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35		4.35	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54		4.54	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70		4.70	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95		4.95	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21		5.21	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25		5.25	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26		5.26	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85		5.85	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02		6.02	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14		6.14	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.70		603	6.31		6.31	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41		7.41	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43		7.43	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47		7.47	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.52		613	7.52		7.52	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64		7.64	18	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20		8.20	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.20		613	8.20		8.20	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25		8.25	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36		8.36	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60		8.60	23	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66		8.66	24	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68		8.68	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90		8.90	26	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04		9.04	27	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30		9.30	28	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65		9.65	29	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68		9.68	30	0		0.00	
Sizewell B	2/95	13.59	7.30		620	9.81		9.81	31	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42		10.42	32	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57		10.57	33	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57		10.57	34	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60		10.60	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60		10.60	36	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.7 (est.)		613	10.70		10.70	37	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80		10.80	38	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02		11.02	39	0		0.00	
Ikata 3	12/94	13.72	11.54		613	11.54		11.54	40	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56		11.56	41	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60		11.60	42	0		0.00	
Golfech 2	3/94	14.52	10.83		616	12.30		12.30	43	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49		12.49	44	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77		12.77	45	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78		12.78	46	0		0.00	
Penly 2	11/92	15.84	11.51		616	13.07		13.07	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30		13.30	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39		13.39	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72		14.72	50	0		0.00	
Ohi 4	2/93	15.59	12.60		617	14.93		14.93	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47		15.47	52	0		0.00	
Ohi 3	12/91	16.72	13.80		617	16.35		16.35	53	0		0.00	
				Ave. Thot=	612								

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-62
Time to 0.1% HL OD TTS A&V IGA/SCC - All Westinghouse Design Alloy 690TT Plants

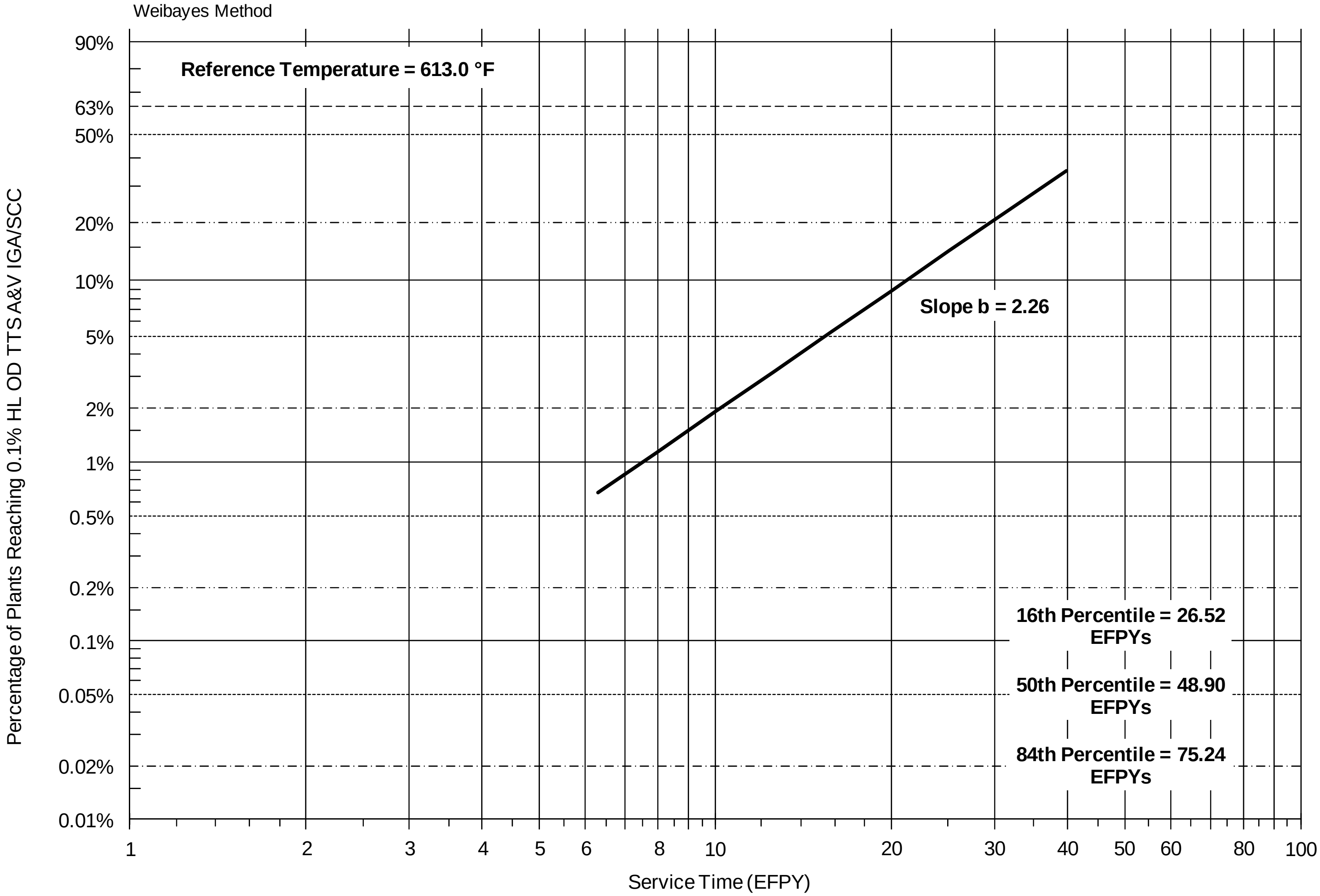

Figure 3-63
Time to 0.1% HL OD TTS A&V IGA/SCC - All Westinghouse Design Alloy 690TT Plants - Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93		1.93	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.00		589	3.87		3.87	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35		4.35	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54		4.54	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70		4.70	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95		4.95	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21		5.21	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25		5.25	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26		5.26	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85		5.85	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02		6.02	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14		6.14	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.70		603	6.31		6.31	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41		7.41	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43		7.43	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47		7.47	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.52		613	7.52		7.52	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64		7.64	18	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20		8.20	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.20		613	8.20		8.20	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25		8.25	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36		8.36	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60		8.60	23	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66		8.66	24	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68		8.68	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90		8.90	26	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04		9.04	27	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30		9.30	28	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65		9.65	29	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68		9.68	30	0		0.00	
Sizewell B	2/95	13.59	7.30		620	9.81		9.81	31	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42		10.42	32	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57		10.57	33	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57		10.57	34	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60		10.60	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60		10.60	36	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.7 (est.)		613	10.70		10.70	37	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80		10.80	38	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02		11.02	39	0		0.00	
Ikata 3	12/94	13.72	11.54		613	11.54		11.54	40	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56		11.56	41	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60		11.60	42	0		0.00	
Golfech 2	3/94	14.52	10.83		616	12.30		12.30	43	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49		12.49	44	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77		12.77	45	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78		12.78	46	0		0.00	
Penly 2	11/92	15.84	11.51		616	13.07		13.07	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30		13.30	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39		13.39	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72		14.72	50	0		0.00	
Ohi 4	2/93	15.59	12.60		617	14.93		14.93	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47		15.47	52	0		0.00	
Ohi 3	12/91	16.72	13.80		617	16.35		16.35	53	0		0.00	

Ave. Thot= 612

Reference Temperature

613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-64
Time to 0.05% HL OD TTS Circumferential SCC - All Westinghouse Design Alloy 690TT Plants

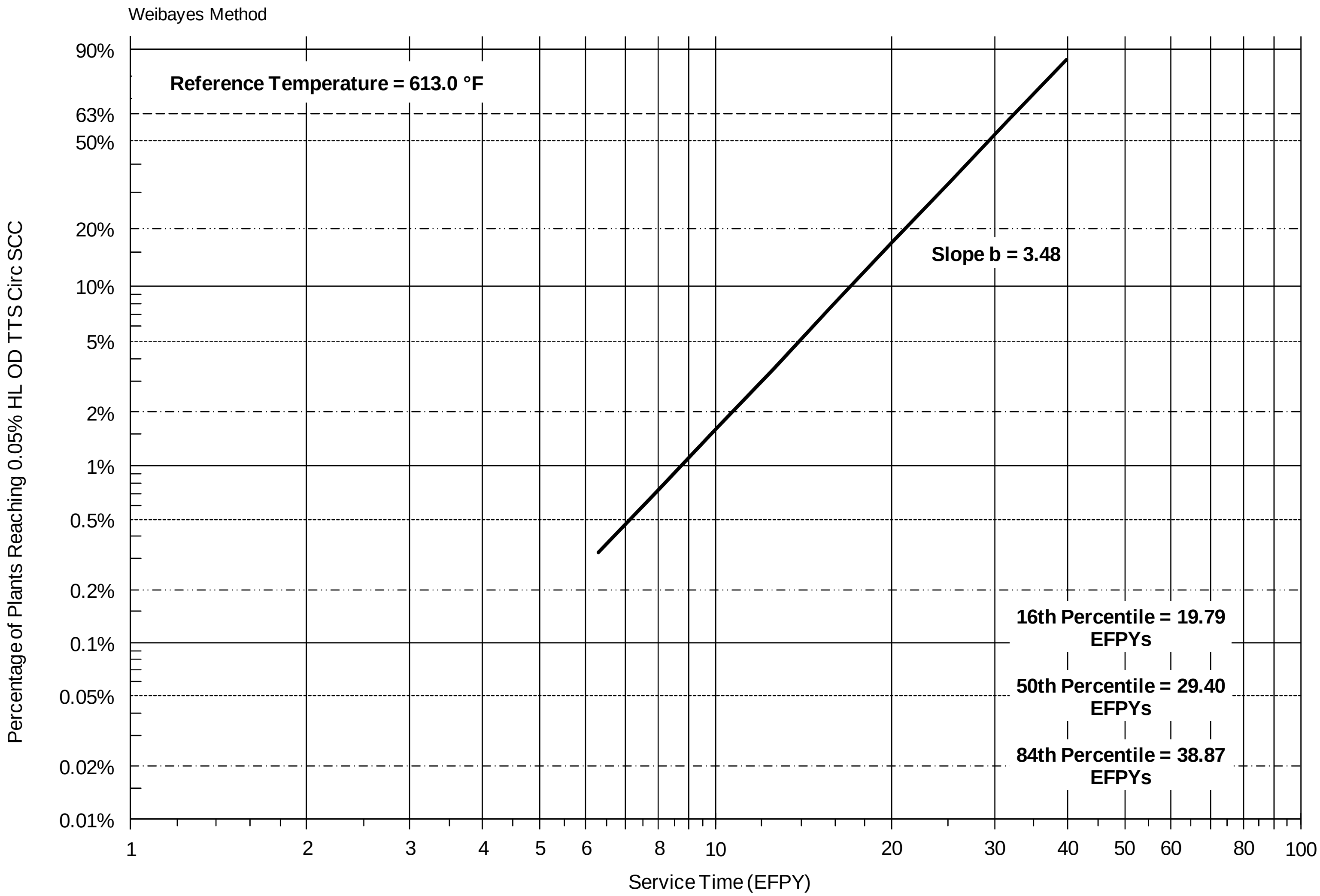

Figure 3-65
Time to 0.05% HL OD TTS Circumferential SCC - All Westinghouse Design Alloy 690TT Plants - Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.72		2.72	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.00		589	5.46		5.46	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	6.13		6.13	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	6.39		6.39	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	6.63		6.63	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	6.97		6.97	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	7.34		7.34	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	7.40		7.40	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	7.41		7.41	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	8.24		8.24	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	8.48		8.48	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	8.65		8.65	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.70		603	8.90		8.90	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	10.44		10.44	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	10.47		10.47	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	10.53		10.53	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.52		613	10.60		10.60	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	10.76		10.76	18	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	11.55		11.55	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.20		613	11.55		11.55	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	11.62		11.62	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	11.78		11.78	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	12.12		12.12	23	0		0.00	
Civaux 2	1/00	8.67	5.23		625	12.21		12.21	24	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	12.23		12.23	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	12.53		12.53	26	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	12.74		12.74	27	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	13.10		13.10	28	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	13.60		13.60	29	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	13.64		13.64	30	0		0.00	
Sizewell B	2/95	13.59	7.30		620	13.83		13.83	31	0		0.00	
Chooz B2	4/97	11.43	6.29		625	14.68		14.68	32	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	14.89		14.89	33	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	14.89		14.89	34	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	14.93		14.93	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	14.93		14.93	36	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.7 (est.)		613	15.08		15.08	37	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	15.22		15.22	38	0		0.00	
Genkai 4	7/97	11.11	9.30		617	15.52		15.52	39	0		0.00	
Ikata 3	12/94	13.72	11.54		613	16.26		16.26	40	0		0.00	
Chooz B1	8/96	12.09	6.98		625	16.29		16.29	41	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	16.34		16.34	42	0		0.00	
Golfech 2	3/94	14.52	10.83		616	17.33		17.33	43	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	17.60		17.60	44	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	18.00		18.00	45	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	18.01		18.01	46	0		0.00	
Penly 2	11/92	15.84	11.51		616	18.42		18.42	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	18.74		18.74	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	18.86		18.86	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	20.74		20.74	50	0		0.00	
Ohi 4	2/93	15.59	12.60		617	21.03		21.03	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	21.79		21.79	52	0		0.00	
Ohi 3	12/91	16.72	13.80		617	23.03		23.03	53	0		0.00	

Ave. Thot= 612

Reference Temperature
605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-66
Time to 0.05% HL TSP IGA/SCC - All Westinghouse Design Alloy 690TT Plants

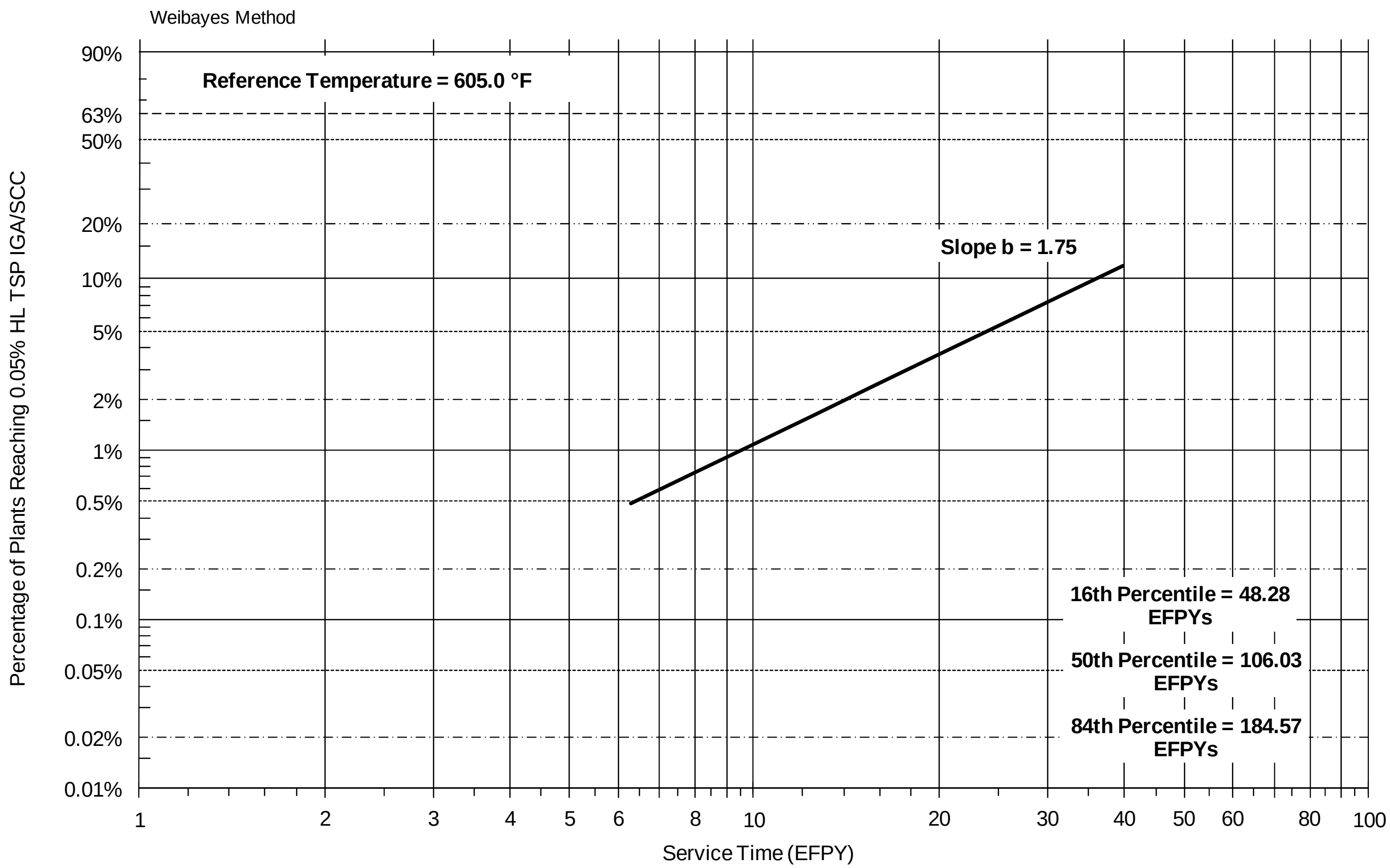

Figure 3-67
Time to 0.05% HL TSP IGA/SCC - All Westinghouse Design Alloy 690TT Plants - Weibayes Analysis

3.3.4 Alloy 800NG versus Alloy 600MA

3.3.4.1 Alloy 800 Experience

At the present time, no US steam generators are tubed with Alloy 800NG. Worldwide operating experience is that corrosion of Alloy 800NG tubes has been so minimal that developing predictions of future corrosion involves high uncertainty.[4] The limited experience of corrosion in Alloy 800NG tubes is summarized in Section 3.2.2.

3.3.4.2 Improvement Factor Estimates

The material improvement factor that can be expected for plants with Alloy 800 nuclear grade (Alloy 800NG) tubing was determined based on field data from 16 KWU plants. Due to the lack of general corrosion experience in these plants, the Weibayes method was used to predict the future distribution of failures (as before, the first failure is assumed to be imminent). The Weibayes analysis was based on the cumulative operating experience through September 1, 2008. The results of this analysis are given for various cracking mechanisms in the following subsections.

3.3.4.2.1 Axial primary-side IGA/SCC at the Expansion Transition (Axial EZ PWSCC)

The median time to failure is currently estimated to be 103.1 EFPY for axial PWSCC in plants with Alloy 800NG tubing. The field data for all KWU Alloy 800NG plants with respect to axial PWSCC are shown in Figure 3-73. The Weibull plot developed for this data is given in Figure 3-74.

3.3.4.2.2 Circumferential Primary-side IGA/SCC at the Expansion Transition (Circ. EZ PWSCC)

The median time to failure is currently estimated to be 102.8 EFPY for circumferential PWSCC in plants with Alloy 800NG tubing. The field data for the KWU plants with respect to circumferential PWSCC are shown in Figure 3-75. The Weibull plot developed for this data is given in Figure 3-76.

3.3.4.2.3 Axial and Volumetric Secondary-side IGA/SCC at the Top of Tubesheet (OD TTS A&V IGA/SCC)

The median time to failure for these plants is estimated to be 59.6 EFPY for A&V secondary-side IGA/SCC at the top of tubesheet. The field data for all KWU Alloy 800NG plants analyzed

[4] At the time this report was written, DEI was made aware of the planned publication of data which would indicate the first Alloy 800NG plant had reached the failure criterion for TSP OD SCC in 2005. This data was not published in time for formal inclusion in this report. However, it should be noted that because of the assumption of imminent failure of the first plant, the calculated median times to failure and thus the improvement factor for this failure mode is not affected by a single unit reaching the failure criterion (essentially, a single unit having failed is the conservative assumption made in the absence of failures, so the first failure does not significantly affect the calculation results).

for OD TTS A&V IGA/SCC are shown in Figure 3-77. The Weibull plot developed for this data is given in Figure 3-78.

3.3.4.2.4 Circumferential Secondary-side IGA/SCC at the Top of Tubesheet (OD TSS Circ. SCC)

The median time to failure for Alloy 800NG tubed SGs is estimated to be 42.4 EFPY with respect to circumferential secondary-side IGA/SCC at the top of the tubesheet. The field data analyzed for this degradation mechanism are given in Figure 3-79. The Weibayes method was used to develop the Weibull distribution for the data, shown in Figure 3-80.

3.3.4.2.5 IGA/SCC at the Tube Support Plate Intersection (HL TSP IGA/SCC)

For IGA/SCC at the tube support plate intersection, the median time to failure for Alloy 800NG tubed SGs is estimated to be 111 EFPY. The field data analyzed for this degradation mechanism are given in Figure 3-81. The Weibayes method was used to develop the Weibull distribution for the data, shown in Figure 3-82.

Estimates of the improvement factor for Alloy 800NG versus Alloy 600MA are given in Table 3-8.

Table 3-8
Estimated Material Improvement Factors for Alloy 800NG versus Alloy 600MA

Degradation Mode	600MA		800NG		
	Plant Population	Median Time to Failure (EFPY)	Design Group	Median Time to Failure (EFPY)	IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	KWU (All)	103.1	>12.7
	West. (HE)	10.9			*>9.5*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	KWU (All)	102.8	>10.4
	West. (HE)	10.9			*>9.5*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	KWU (All)	59.6	>6.6
	West. Preheater (KR)	14.9			*>4.0*
	West. Feedring (KR)	8.4			>7.1
	West. Feedring (HE)	15.9			*>3.7*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	KWU (All)	42.4	>7.6
	West. Preheater (KR)	5.8			*>7.3*
	West. Feedring (KR)	13.9			>3.1
	West. Feedring (HE)	15.7			*>2.7*
TSP IGA/SCC	West. Preheater (DH)	8.2	KWU (All)	110.8	>13.6
	West. Feedring (DH)	8.3			>13.4
	West. Feedring (BH)	25.7			*>4.3*

Italicized IF_R values indicate low confidence.
All improvement factors are estimated in the absence of significant degradation of Alloy 800NG.

3.3.4.3 Weibayes Modeling

As plants with Alloy 800NG continue to operate without failure, the improvement factor will continue to increase. Figure 3-68 through Figure 3-72 show the predicted median time to failure for each degradation mechanism as a function of time without failure based on the Weibayes models developed in this report. From these functions, the improvement factors that would be calculated at a specified future date can be found (assuming no failures have yet occurred). The anticipated improvement factors for Alloy 800NG in 2012 and 2020 are shown in Figure 3-10 below. As an alternative approach, the time without failures at which various improvement factors could be calculated is shown in Table 3-10.

Table 3-9
Relative Improvement Factors - Alloy 800NG versus Alloy 600MA

Degradation Mechanism	Alloy 600MA Design Group	Alloy 690TT IF_R Assuming 1 Imminent Failure in 2008	Alloy 690TT IF_R Assuming 1 Imminent Failure in 2012	Alloy 690TT IF_R Assuming 1 Imminent Failure in 2020
Axial EZ PWSCC	Feedring Alloy 600 MA Wextex Expansions	12.8	14.8	18.8
Circumferential EZ PWSCC	Feedring Alloy 600 MA Wextex Expansions	10.6	12.2	15.5
HL TTS OD A&V SCC	French Feedring Alloy 600MA Kiss Roll	7.2	8.3	10.5
HL TTS OD Circumferential SCC	Feedring Alloy 600MA Kiss Roll FDBs	3.1	3.6	4.5
HL TSP IGA/SCC	Feedring Alloy 600MA Drilled Hole No Phosphate	13.5	15.6	19.9

Table 3-10
Required Operating Time for Verification of a Given Improvement Factor – Alloy 800NG versus Alloy 600MA

Degradation Mechanism	Alloy 600MA Design Group	Year of First 800NG Plant Reaching Failure Criterion $IF_R = 5$	Year of First 800NG Plant Reaching Failure Criterion $IF_R = 10$	Year of First 800NG Plant Reaching Failure Criterion $IF_R = 20$	Year of First 800NG Plant Reaching Failure Criterion $IF_R = 30$
Axial EZ PWSCC	Feedring Alloy 600 MA Wextex Expansions	1992	2002	2022	2042
Circumferential EZ PWSCC	Feedring Alloy 600 MA Wextex Expansions	1995	2007	2031	2055
HL TTS OD A&V SCC	Feedring Alloy 600MA Kiss Roll FDBs	2000	2018	2053	2088
HL TTS OD Circumferential SCC	Feedring Alloy 600MA Kiss Roll FDBs	2024	2064	2145	2226
HL TSP IGA/SCC	Feedring Alloy 600MA Drilled Hole No Phosphate	1992	2002	2020	2039

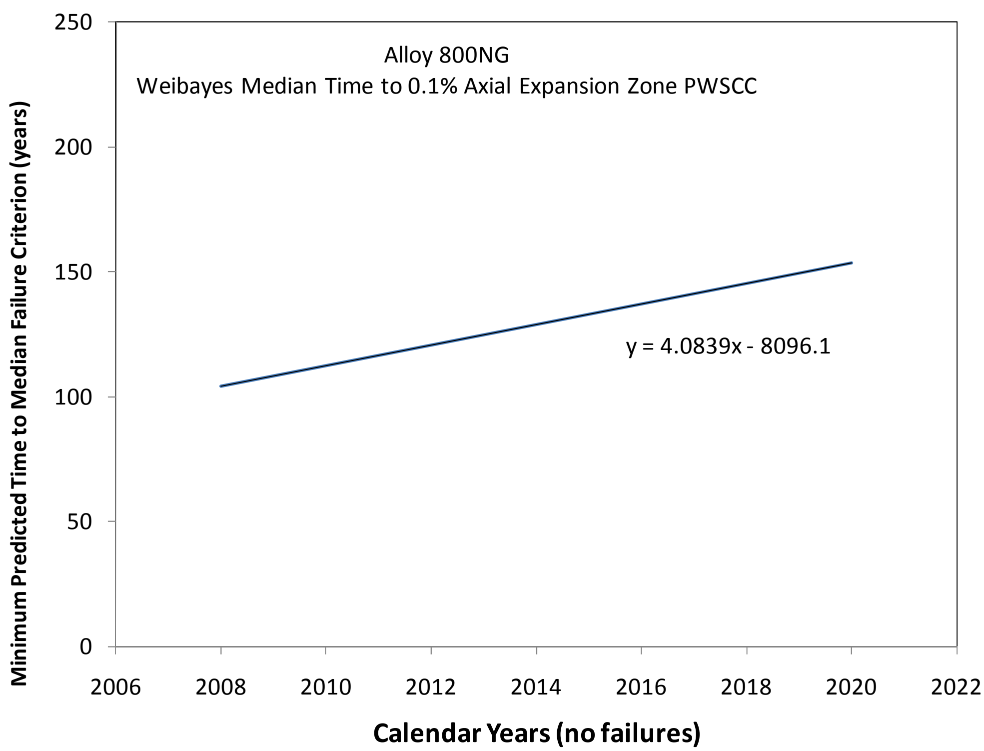

Figure 3-68
Alloy 800NG Weibayes Median Time to 0.1% Axial PWSCC

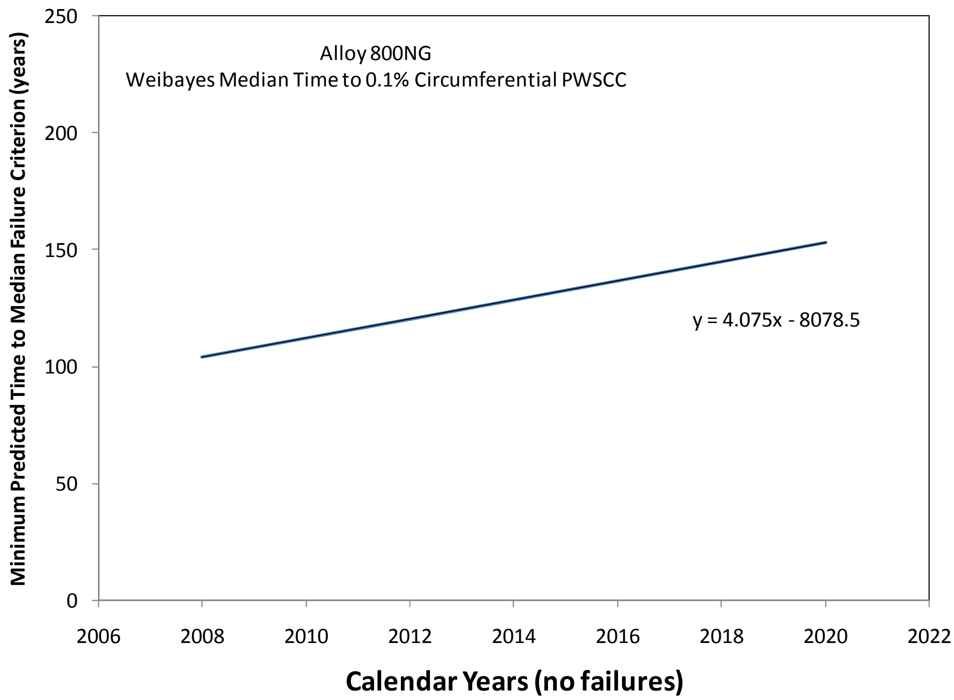

Figure 3-69
Alloy 800NG Weibayes Median Time to 0.1% Circumferential PWSCC

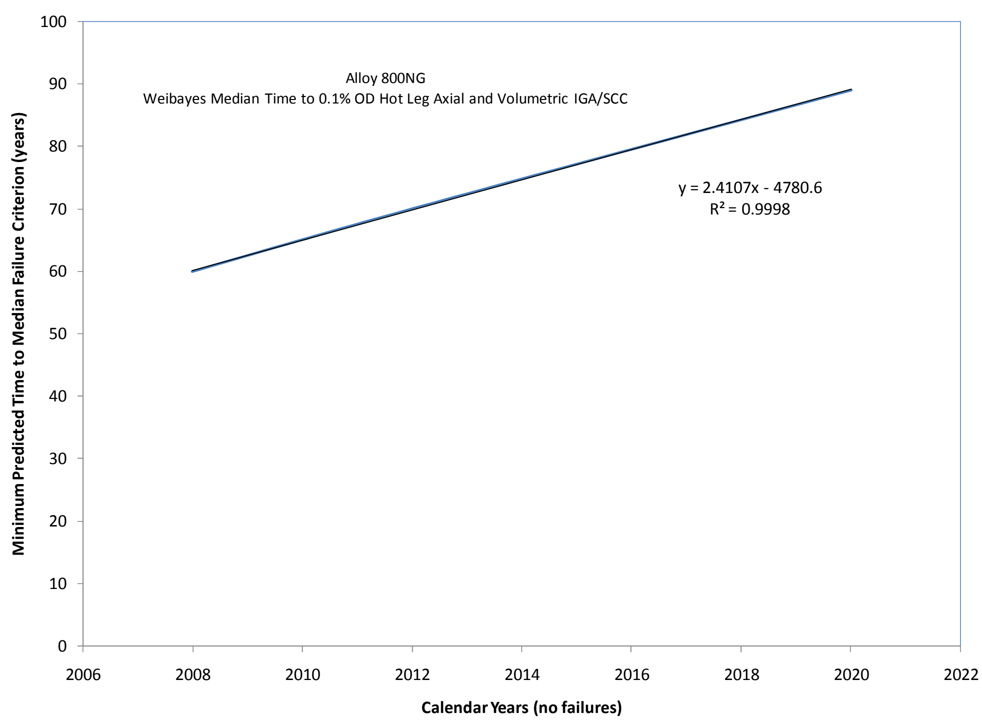

Figure 3-70
Alloy 800NG Weibayes Median Time to 0.1% HL OD A&V IGA/SCC

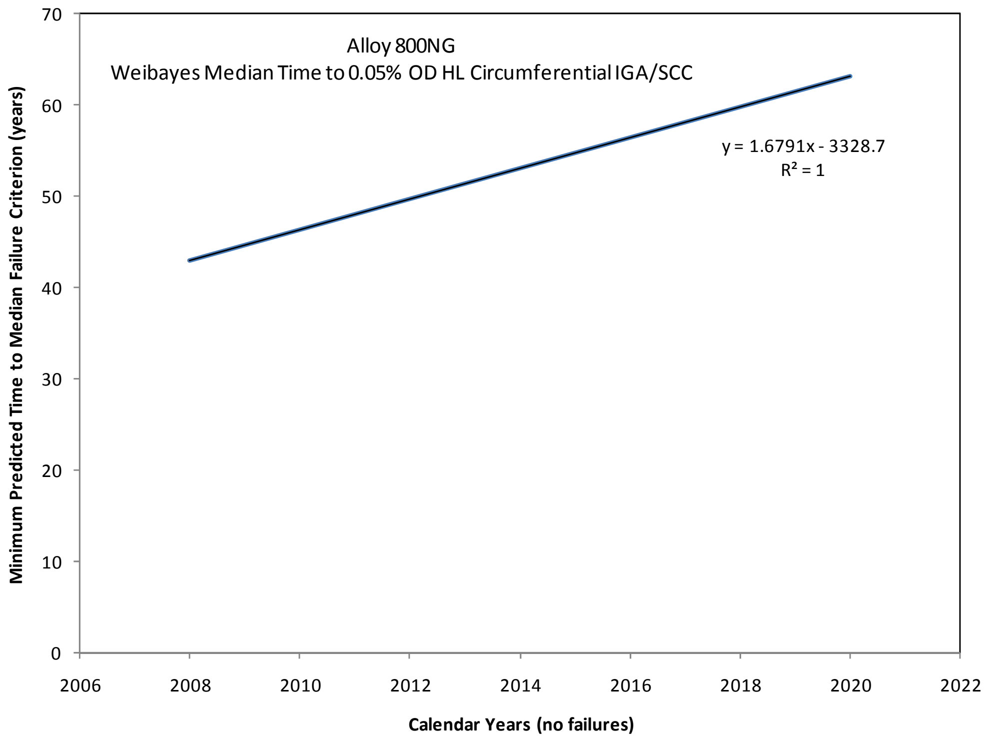

Figure 3-71
Alloy 800NG Weibayes Median Time to 0.05% HL OD Circ. IGA/SCC

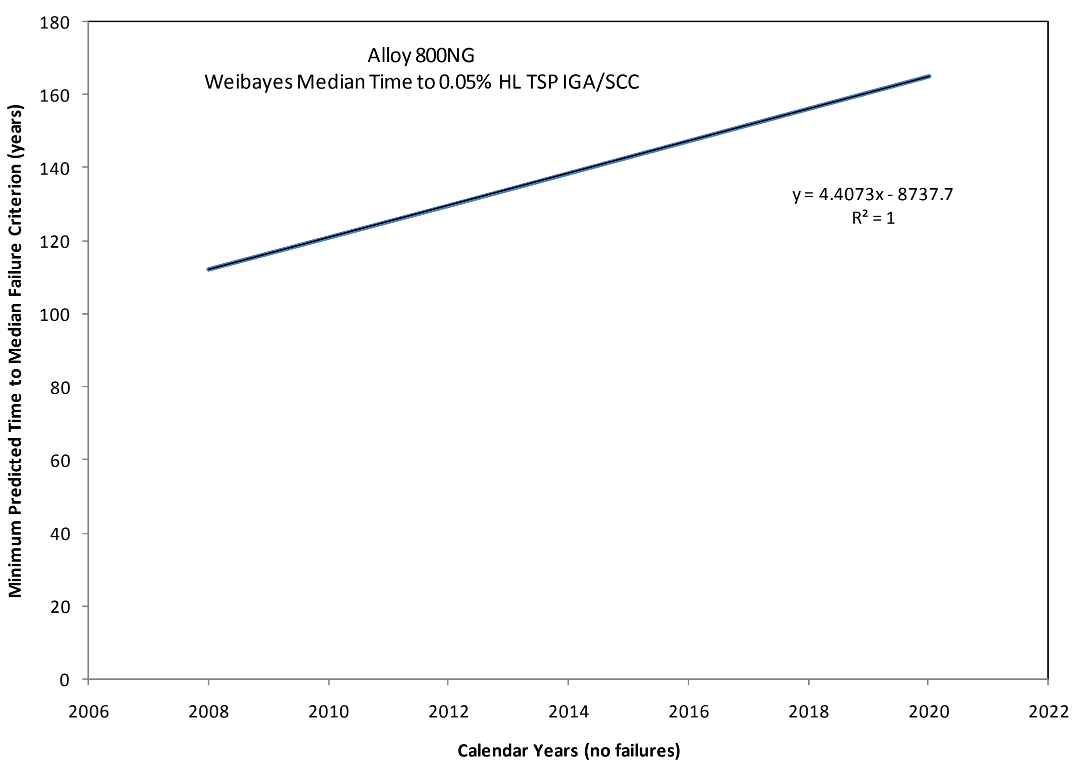

Figure 3-72
Alloy 800NG Weibayes Median Time to 0.05% HL TSP IGA/SCC

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Obrigheim (repl.)	9/83	25.02	19.44		589	8.66		8.66	1	0		0.00	
Biblis A	8/74	34.11	23.74		596	14.08		14.08	2	0		0.00	
Stade	1/72	36.69	29.3		597	18.10		18.10	3	0		0.00	
Unterweser	10/78	29.94	23.4		604	19.17		19.17	4	0		0.00	
Biblis B	4/76	32.44	22.2		607	20.50		20.50	5	0		0.00	
Gösgen	2/79	29.60	20		610	20.81		20.81	6	0		0.00	
Isar 2	1/88	20.68	16.54		615	20.96		20.96	7	0		0.00	
Neckarwestheim 2	1/89	19.68	16.3		616	21.48		21.48	8	0		0.00	
Emsland	4/88	20.43	17.2		616	22.67		22.67	9	0		0.00	
Trillo	8/88	20.10	16.18		619	23.97		23.97	10	0		0.00	
Brokdorf	10/86	21.93	17.64		618	25.14		25.14	11	0		0.00	
Borssele	7/73	35.19	28.42		606	25.22		25.22	12	0		0.00	
Neckarwestheim 1	6/76	32.27	24.8		612	27.93		27.93	13	0		0.00	
Grohnde	8/84	24.10	20.1		620	30.96		30.96	14	0		0.00	
Grafenrheinfeld	12/81	26.77	21.9		618	31.21		31.21	15	0		0.00	
Philippsburg 2	12/84	23.77	19.3		622	32.13		32.13	16	0		0.00	

Ave. Thot= 610

Reference Temperature

609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with KWU design SGs with Alloy 800 tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. EFPYs as of September 8, 2009. EDYs adjusted as required to account for temperature and/or power changes at Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-73
Time to 0.1% HL Axial EZ PWSCC - All KWU Design Alloy 800NG Plants

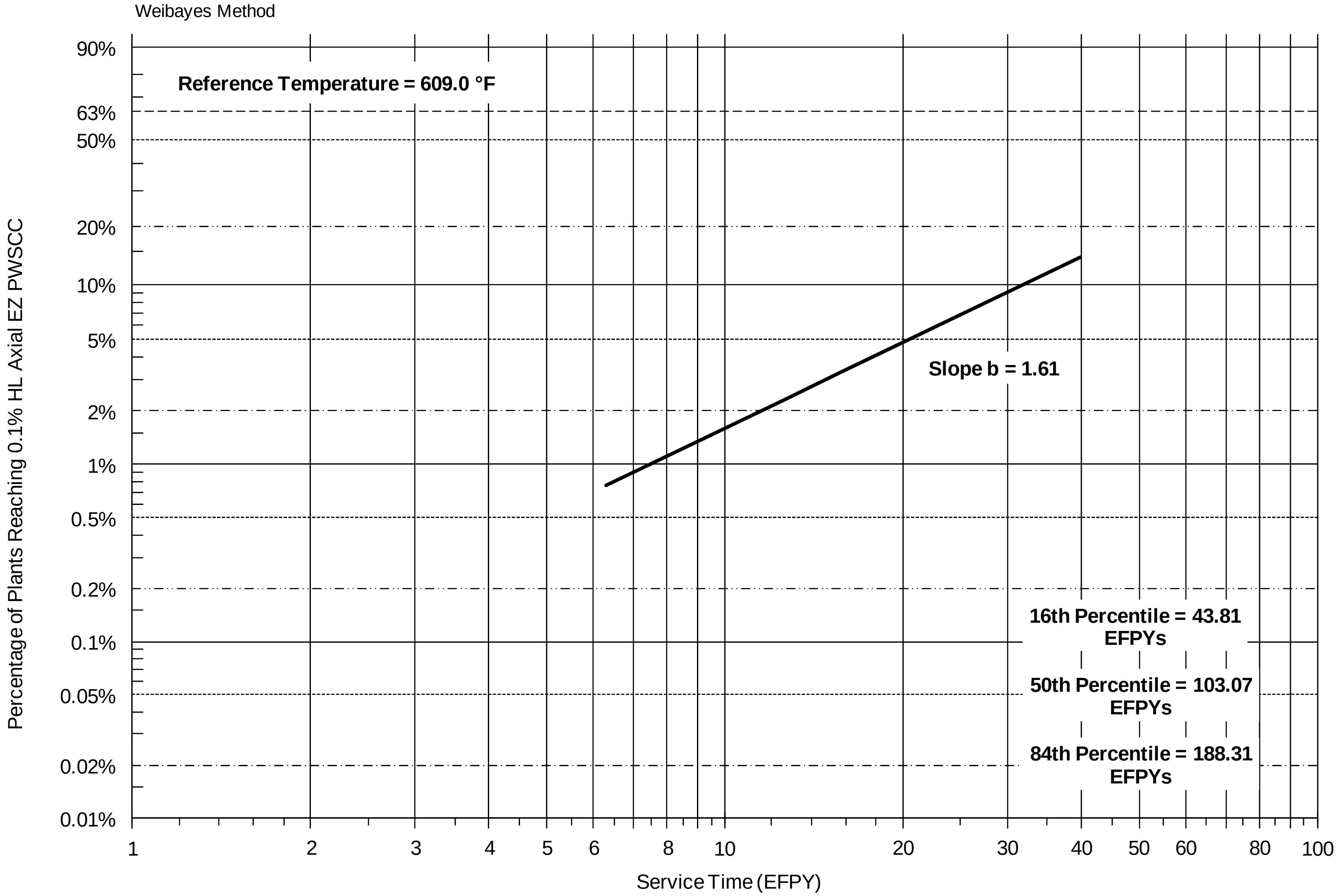

Figure 3-74
Time to 0.1% HL Axial EZ PWSCC - All KWU Design Alloy 800NG Plants – Weibayes Analysis

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Obrigheim (repl.)	9/83	25.02	19.44		589	8.66		8.66	1	0		0.00	
Biblis A	8/74	34.11	23.74		596	14.08		14.08	2	0		0.00	
Stade	1/72	36.69	29.3		597	18.10		18.10	3	0		0.00	
Unterweser	10/78	29.94	23.4		604	19.17		19.17	4	0		0.00	
Biblis B	4/76	32.44	22.2		607	20.50		20.50	5	0		0.00	
Gösgen	2/79	29.60	20		610	20.81		20.81	6	0		0.00	
Isar 2	1/88	20.68	16.54		615	20.96		20.96	7	0		0.00	
Neckarwestheim 2	1/89	19.68	16.3		616	21.48		21.48	8	0		0.00	
Emsland	4/88	20.43	17.2		616	22.67		22.67	9	0		0.00	
Trillo	8/88	20.10	16.18		619	23.97		23.97	10	0		0.00	
Brokdorf	10/86	21.93	17.64		618	25.14		25.14	11	0		0.00	
Borssele	7/73	35.19	28.42		606	25.22		25.22	12	0		0.00	
Neckarwestheim 1	6/76	32.27	24.8		612	27.93		27.93	13	0		0.00	
Grohnde	8/84	24.10	20.1		620	30.96		30.96	14	0		0.00	
Grafenrheinfeld	12/81	26.77	21.9		618	31.21		31.21	15	0		0.00	
Philippsburg 2	12/84	23.77	19.3		622	32.13		32.13	16	0		0.00	
				Ave. Thot=	610								

Reference Temperature

609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with KWU design SGs with Alloy 800 tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. EFPYs as of September 8,2009. EDYs adjusted as required to account for temperature and/or power changes at Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-75
Time to 0.1% HL Circumferential EZ PWSCC - All KWU Design Alloy 800NG Plants – Weibayes Analysi

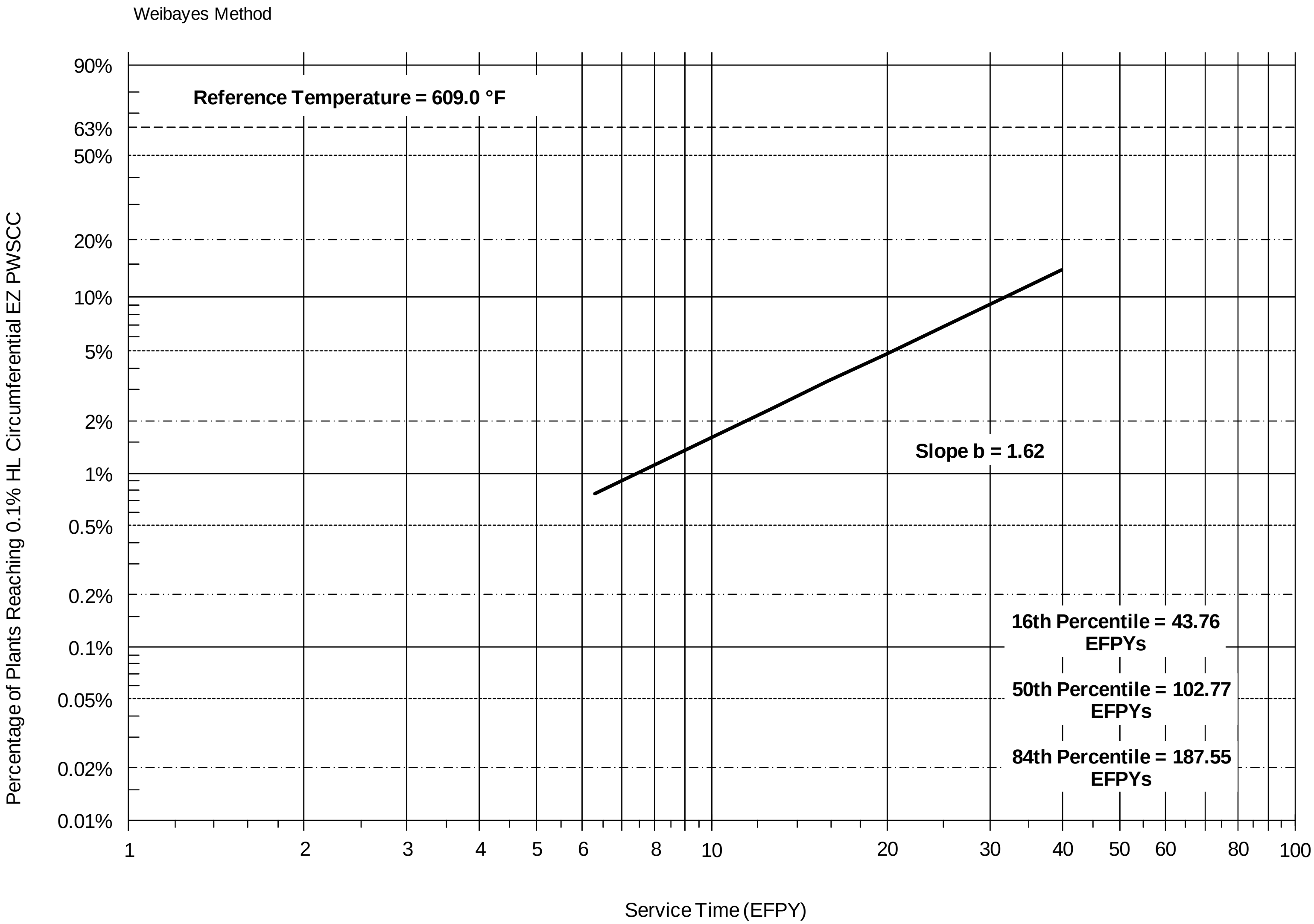

Figure 3-76
Time to 0.1% HL Circumferential EZ PWSCC - All KWU Design Alloy 800NG Plants – Weibayes Analysis

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Obrigheim (repl.)	9/83	25.02	19.44		589	6.84		6.84	1	0		0.00	
Biblis A	8/74	34.11	23.74		596	11.39		11.39	2	0		0.00	
Stade	1/72	36.69	29.3		597	14.68		14.68	3	0		0.00	
Unterweser	10/78	29.94	23.4		604	15.91		15.91	4	0		0.00	
Biblis B	4/76	32.44	22.2		607	17.17		17.17	5	0		0.00	
Isar 2	1/88	20.68	16.54		615	18.01		18.01	6	0		0.00	
Neckarwestheim 2	1/89	19.68	16.3		616	18.51		18.51	7	0		0.00	
Emsland	4/88	20.43	17.2		616	19.53		19.53	8	0		0.00	
Trillo	8/88	20.10	16.18		619	20.85		20.85	9	0		0.00	
Borssele	7/73	35.19	28.42		606	21.06		21.06	10	0		0.00	
Gösgen	2/79	29.60	24.42		610	21.49		21.49	11	0		0.00	
Brokdorf	10/86	21.93	17.64		618	21.80		21.80	12	0		0.00	
Neckarwestheim 1	6/76	32.27	24.8		612	23.77		23.77	13	0		0.00	
Grafenrheinfeld	12/81	26.77	21.9		618	27.06		27.06	14	0		0.00	
Grohnde	8/84	24.10	20.1		620	27.02		27.02	15	0		0.00	
Philippsburg 2	12/84	23.77	19.3		622	28.21		28.21	16	0		0.00	

Ave. Thot= 610

Reference Temperature

613.0 °F = 595.94 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with KWU design SGs with Alloy 800 tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. EFPYs as of September 8, 2009. EDYs adjusted as required to account for temperature and/or power changes at Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-77
Time to 0.1% HL OD TTS A&V IGA/SCC - All KWU Design Alloy 800NG Plants

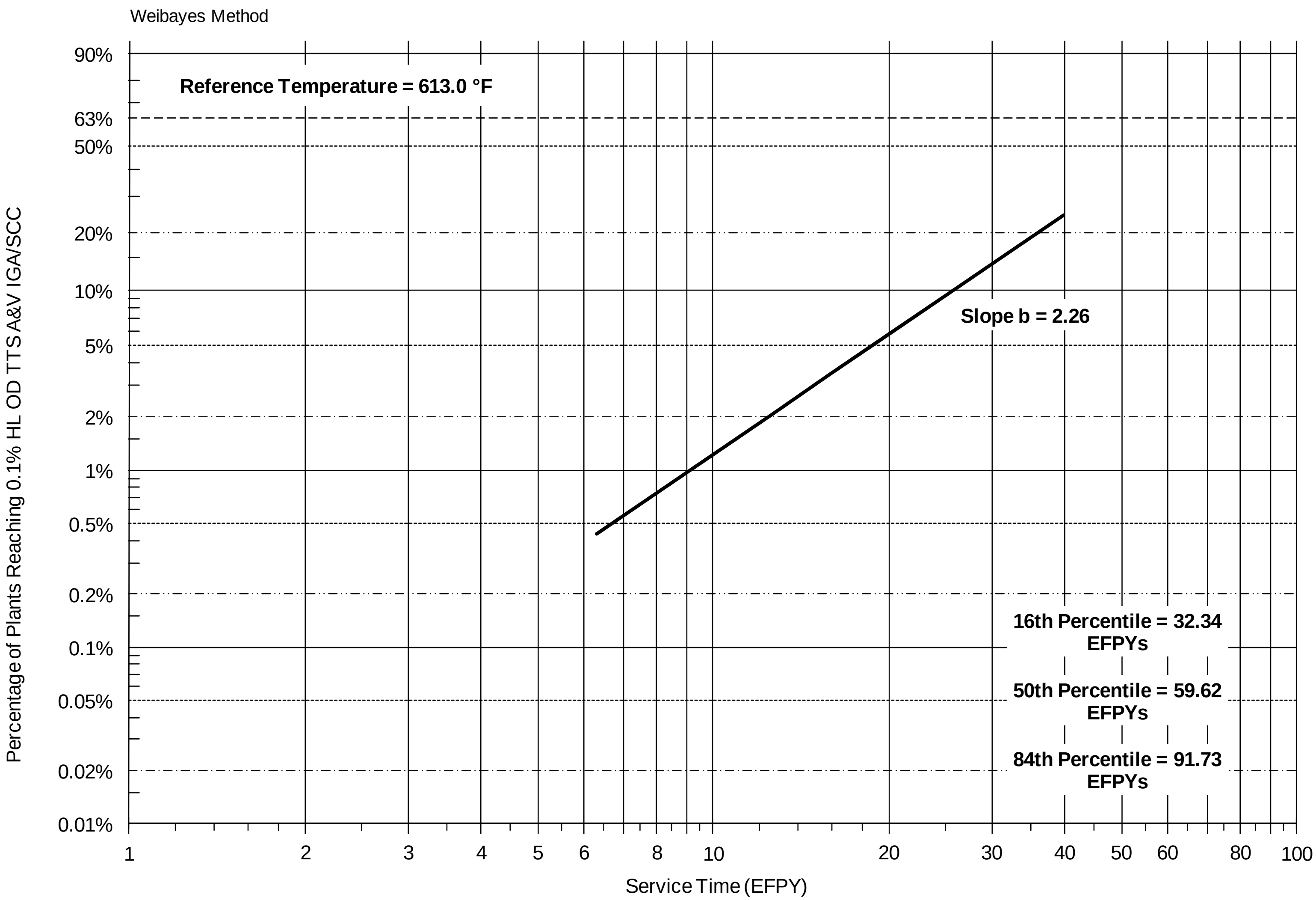

Figure 3-78
Time to 0.1% HL OD TTS A&V IGA/SCC - All KWU Design Alloy 800NG Plants – Weibayes Analysis

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Obrigheim (repl.)	9/83	25.02	19.44		589	6.84		6.84	1	0		0.00	
Biblis A	8/74	34.11	23.74		596	11.39		11.39	2	0		0.00	
Stade	1/72	36.69	29.3		597	14.68		14.68	3	0		0.00	
Unterweser	10/78	29.94	23.4		604	15.91		15.91	4	0		0.00	
Biblis B	4/76	32.44	22.2		607	17.17		17.17	5	0		0.00	
Neckarwestheim 2	1/89	19.68	16.3		616	18.51		18.51	6	0		0.00	
Isar 2	1/88	20.68	16.54		615	18.01		18.01	7	0		0.00	
Emsland	4/88	20.43	17.2		616	19.53		19.53	8	0		0.00	
Trillo	8/88	20.10	16.18		619	20.85		20.85	9	0		0.00	
Borssele	7/73	35.19	28.42		606	21.06		21.06	10	0		0.00	
Gösgen	2/79	29.60	24.42		610	21.49		21.49	11	0		0.00	
Brokdorf	10/86	21.93	17.64		618	21.80		21.80	12	0		0.00	
Neckarwestheim 1	6/76	32.27	24.8		612	23.77		23.77	13	0		0.00	
Grafenrheinfeld	12/81	26.77	21.9		618	27.06		27.06	14	0		0.00	
Grohnde	8/84	24.10	20.1		620	27.02		27.02	15	0		0.00	
Philippsburg 2	12/84	23.77	19.3		622	28.21		28.21	16	0		0.00	
				Ave. Thot=	610								

Reference Temperature

613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with KWU design SGs with Alloy 800 tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. EFPYs as of September 8, 2009. EDYs adjusted as required to account for temperature and/or power changes at Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-79
Time to 0.05% HL OD TTS Circumferential SCC - All KWU Design Alloy 800NG Plants

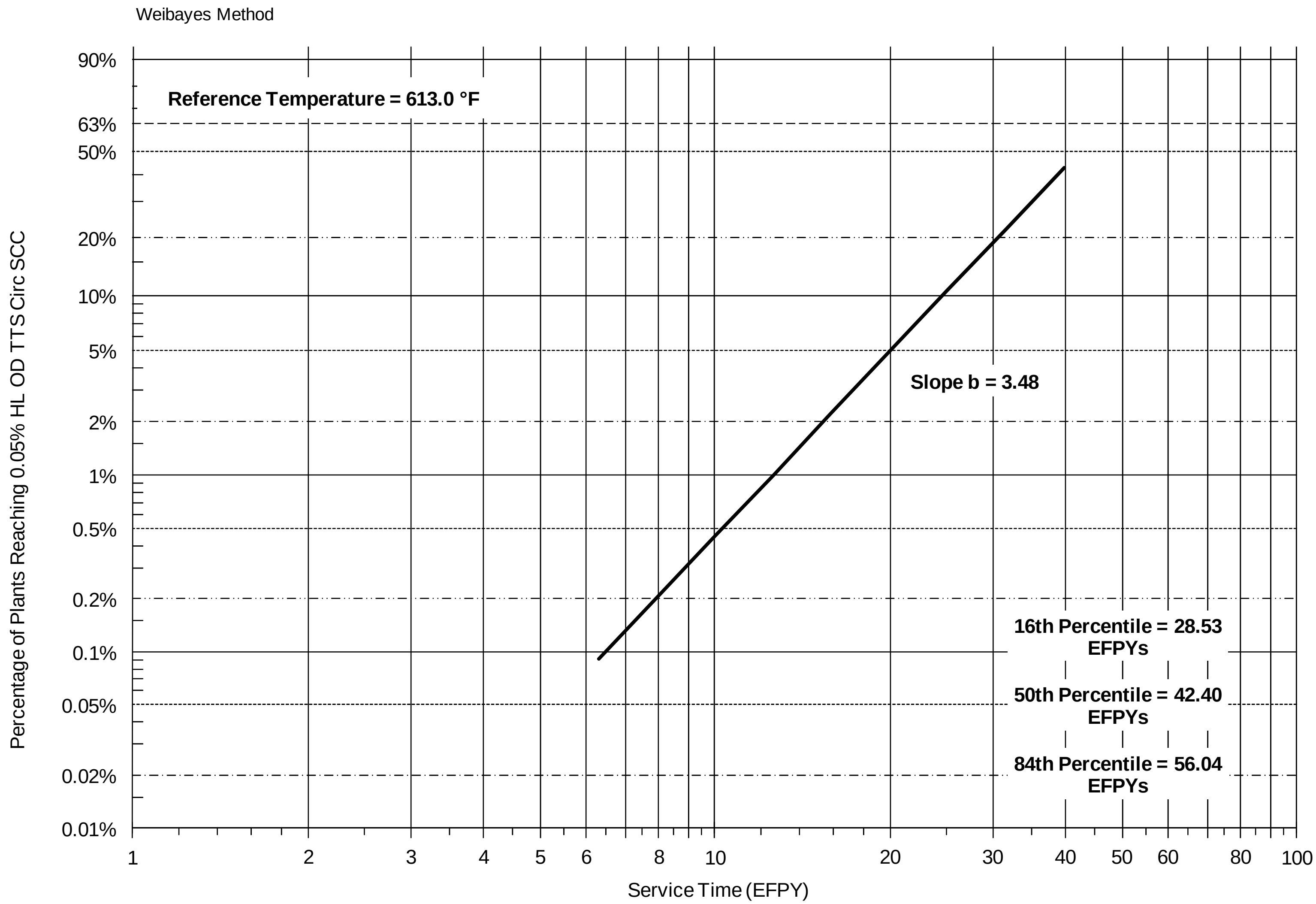

Figure 3-80
Time to 0.05% HL OD TTS Circumferential SCC - All KWU Design Alloy 800NG Plants - Weibayes Analysis

No. Plants = 16 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 16	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Obrigheim (repl.)	9/83	25.02	19.44		589	9.64		9.64	1	0		0.00	
Biblis A	8/74	34.11	23.74		596	16.04		16.04	2	0		0.00	
Stade	1/72	36.69	29.3		597	20.69		20.69	3	0		0.00	
Unterweser	10/78	29.94	23.4		604	22.41		22.41	4	0		0.00	
Biblis B	4/76	32.44	22.2		607	24.20		24.20	5	0		0.00	
Gösgen	2/79	29.60	20		610	24.79		24.79	6	0		0.00	
Isar 2	1/88	20.68	16.54		615	25.37		25.37	7	0		0.00	
Neckarwestheim 2	1/89	19.68	16.3		616	26.08		26.08	8	0		0.00	
Emsland	4/88	20.43	17.2		616	27.52		27.52	9	0		0.00	
Trillo	8/88	20.10	16.18		619	29.38		29.38	10	0		0.00	
Borssele	7/73	35.19	28.42		606	29.67		29.67	11	0		0.00	
Brokdorf	10/86	21.93	17.64		618	30.71		30.71	12	0		0.00	
Neckarwestheim 1	6/76	32.27	24.8		612	33.49		33.49	13	0		0.00	
Grohnde	8/84	24.10	20.1		620	38.07		38.07	14	0		0.00	
Grafenrheinfeld	12/81	26.77	21.9		618	38.13		38.13	15	0		0.00	
Philippsburg 2	12/84	23.77	19.3		622	39.75		39.75	16	0		0.00	
				Ave. Thot=	610								

Reference Temperature

605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with KWU design SGs with Alloy 800 tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. EFPYs as of September 8, 2009. EDYs adjusted as required to account for temperature and/or power changes at Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 3-81
Time to 0.05% HL TSP IGA/SCC - All KWU Design Alloy 800NG Plants

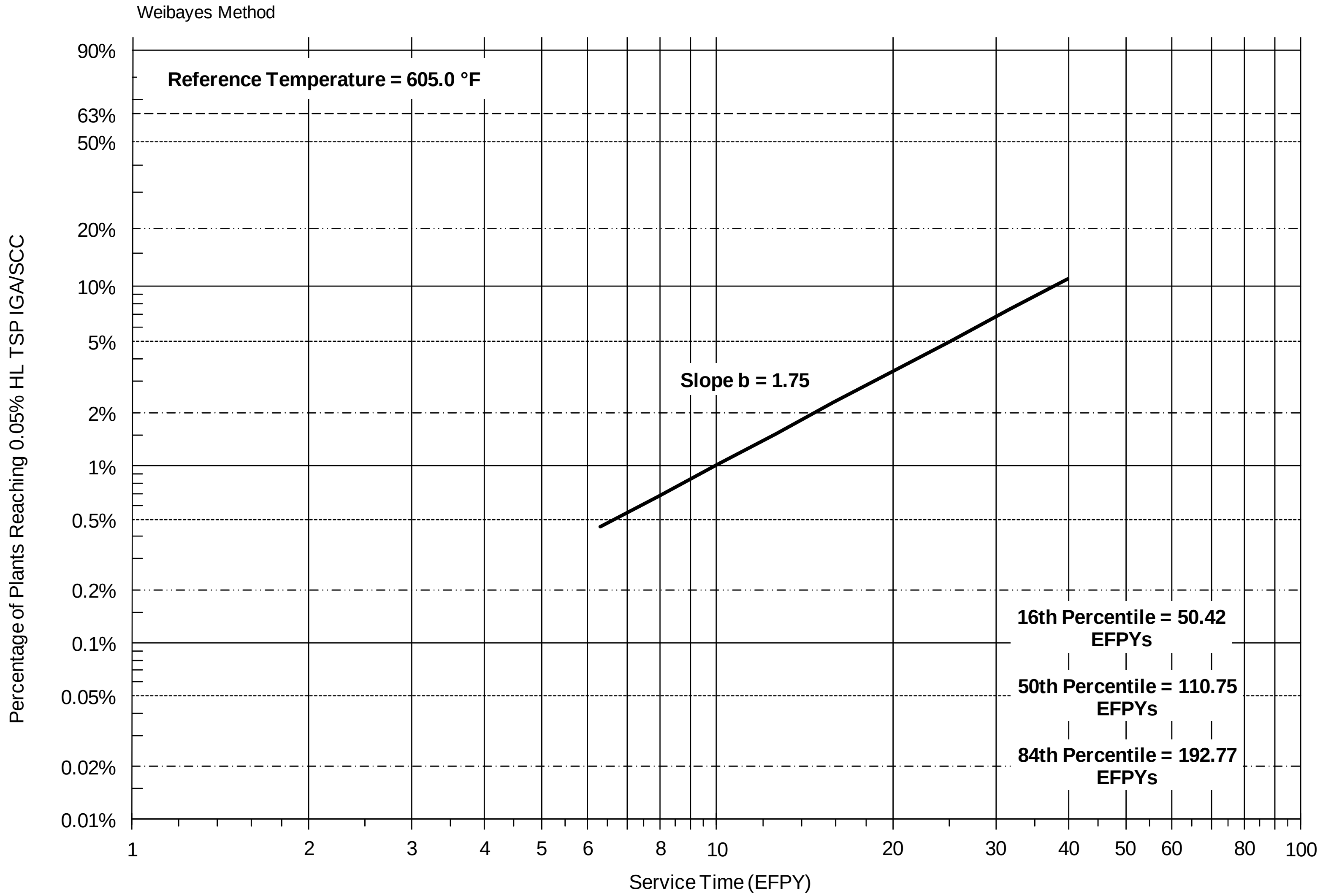

Figure 3-82
Time to 0.05% HL TSP IGA/SCC - All KWU Design Alloy 800NG Plants - Weibayes Analysis

3.3.5 Design Improvement Factors

Design improvements have also been known to affect corrosion rates. In this section, design improvement factors were estimated when data on plant populations with the same tubing material but with design differences were available. Based on analysis of the field data collected for plants with Alloy 600MA and Alloy 600TT tubing, the following design improvement factors (IF_Rs) were estimated for tube in tubesheet expansion mechanisms and tube support plate geometries.

- Hydraulic Expansions vs. WEXTEX Expansions – PWSCC Mechanisms

  This factor was determined to be 1.0 (no improvement). This is based on the results of the analyses for PWSCC in Westinghouse design Alloy 600MA tubed plants with WEXTEX and HE expansion mechanisms. The ratio between median time to failure was found to be 1.3 in the axial direction, and 1.1 (slight improvement) circumferential direction. Due to the limited data for HE Westinghouse Alloy 600MA plants, this slight performance increase is not considered significant.

- Hydraulic Expansions vs. Kiss Roll Expansions – HL OD TTS A&V IGA/SCC

  The IF_R for hydraulic over kiss roll expansion was determined to be about 1.9 (some improvement), based on the analysis of secondary-side A&V IGA/SCC in Alloy 600MA- and Alloy 600TT-tubed feedring plants. It should be noted that limited data were available for HE Westinghouse Alloy 600MA plants. This improvement factor is not currently supported by the ratio between the median time to failure from plants with Alloy 600TT tubing and KR or HE expansions; however, this is due to the shorter cumulative operating experience of the HE plants rather than observed failures.

- Hydraulic Expansions vs. Kiss Roll Expansions – HL OD TTS Circumferential SCC

  This factor was determined to be 1.1 (slight improvement), based on the data for the hydraulically expanded Alloy 600MA tubes at Callaway versus the data for the plants with Alloy 600MA kiss rolled tubes. Section 4.3.2.1 discusses possible reasons for this result.

- Kiss Roll Expansions vs. Full Depth Hard Roll Expansions (Preheater Plants) – HL OD TTS A&V IGA/SCC

  This factor was determined to be 1.0 (no improvement). The observed factor of improvement for kiss rolled Alloy 600MA preheater plants versus US preheater plants with Alloy 600MA full depth hard rolled tubes was 1.6. However, the kiss roll data were from a small number (3) of international plants which use different inspection techniques and scopes than are typically used in the US, so there is some uncertainty in the result of the calculation. Therefore, applying engineering judgment, it was considered that a best estimate design improvement factor of 1.0 was appropriate for kiss roll expansions versus full depth hard roll expansions for preheater plants.

- Kiss Roll Expansions vs. Full Depth Hard Roll Expansions (Preheater Plants) – HL OD TTS Circumferential SCC

  This factor was determined to be 1.0 (no improvement), based on the data for the kiss rolled Alloy 600MA preheater plants versus the data for the US preheater plants with Alloy 600MA full depth hard rolled tubes.

- Stainless Steel Broached Hole TSPs vs. Carbon Steel Drilled Hole TSPs

  This factor was determined to be about 3, based on the feedring plant data for the Alloy 600MA tubing and stainless steel broached hole TSP at Callaway versus the US Alloy 600MA carbon steel drilled hole TSP data for time to 0.05% cracking. However, it should be noted that this is based on data from one plant only (for stainless steel broached hole TSPs) and that TSP cracking had not occurred at the last in service inspection at this plant.

3.3.6 Summary of Material Improvement Factors

The material factors estimated for Alloy 600TT, Alloy 690TT, and Alloy 800NG are summarized in Table 3-2.

The service-demonstrated improvement factors for Alloy 800NG are generally larger than those for Alloy 690TT because Alloy 690TT has been used for fewer years of service. However, the improvement factors for both Alloy 690TT and Alloy 800NG remain relatively low compared to their anticipated performance benefits. In this regard, it is important to understand that, since neither Alloy 800NG nor Alloy 690TT have experienced significant service-induced IGA/SCC, while Alloy 600MA has, the calculated service-demonstrated improvement factors will increase for these alloys as long as degradation of the type being considered is not detected at significant levels in these alloys. Although these factors will continue to be conservative for many years, these results confirm that significant benefits result from material improvements.

4
STEAM GENERATOR TUBE PLUG PLANT EXPERIENCE BASED IMPROVEMENT FACTORS

The performance of Alloys 600TT and 690TT steam generator (SG) tube plugs is evaluated in this chapter in an effort to determine the level of improvement associated with Alloy 690TT relative to Alloy 600TT with respect to the initiation of axial and circumferential primary water stress corrosion cracking (PWSCC). This evaluation is made by comparison of the rates of failure of plugs composed of these alloys as determined by their performance in the field. The improvement factors determined from plug experience are then compared to improvement factors for highly stressed Alloy 600TT relative to Alloy 600MA to determine an improvement factor for Alloy 690TT relative to Alloy 600MA. In addition to mechanical and rolled plugs composed of Alloys 600TT and 690TT, plugs composed of Alloys 600MA and 800NG, and other plug types, such as welded plugs, have also been installed in the industry [161]. However, due to a lack of available operational performance data, it was only possible to evaluate the operating experience of mechanical and rolled plugs composed of Alloys 600TT and 690TT.

Reference [162] and its revisions [163, 164] document an extensive study performed by Westinghouse Electric Corporation in the late 1980s and early 1990s in an effort to characterize and quantify the susceptibility to PWSCC of its own mechanical plugs fabricated from Alloy 600TT. This study was based on both operating experience and laboratory studies of Alloy 600TT mechanical plugs, but it did not include any Weibull statistical analyses of Alloy 600TT data. There was also no attempt to determine an improvement factor for Alloy 690TT relative to Alloy 600TT as 690TT mechanical plugs from this vendor were not yet commercially available at the time Revision 1 of Reference [162] was published.

The use of plant experience based improvement factors is generally considered to provide a more representative indication of actual performance when sufficient failure data are available for a robust analysis. Laboratory studies are generally performed in highly aggressive environments to accelerate the rate of failure events, whereas plant experience-based factors capture the performance of the as-installed material condition under actual water chemistry and operating conditions. However, improvement factors calculated from plant data are conservative due to the fact that the operating times for Alloy 690TT tube plugs are short compared to the expected onset of failure. Specifically, limited operating time with Alloy 690TT reduces the lower bound on the improvement factor relative to materials with significant failure data.

4.1 Methodology

In the SG tubing analysis, it was possible to fit a Weibull distribution to the failure data at each unit and to then calculate the time required to reach the mechanism-specific failure criterion by substituting the Weibull slope and characteristic time into Equation 3-1 and solving for the time required to reach a given degradation threshold. Such an analysis, when applied to steam generator tubing, requires information regarding the service lifetime of each tube in the population, the reason why each tube was removed from service, and the inspection history of the population, which is widely available in the SGDD. High quality data are generally obtained from multiple 100% inspections of tubes at a given unit using a consistent inspection technique. Data obtained from partial inspections are less desirable as they introduce uncertainty into the analysis. When failed tubes are found in a partial inspection sample, it is assumed that the fraction of failed tubes in the population must be equal to the fraction of failed tubes in the inspection sample. Application of this assumption to small samples in which failures were observed generally leads to an unrealistic description of the cumulative failures in the population and does not provide a useful result. Failure data obtained using different inspection techniques (presumably with different detection levels) over the lifetime of a given population have also been observed to yield less useful information. Changing the inspection technique used to evaluate a given population generally leads to a so-called inspection transient, making the meaningful comparison of data before and after the change more difficult if not impossible.

For this analysis of SG plugs, as in the SG tube analysis, field performance was quantified by comparing the times to reach a mechanism-specific failure criterion, with the improvement factor defined as the ratio of the median time to reach the failure criterion for a given degradation mode for two different alloys. However, unlike the SG tube analysis, it was not possible to define the failure criterion as a specific fraction of components failed because data of comparable quality were not available. Many units performed visual inspections of plugs to detect cracking, but these examinations were generally not considered to provide sufficient evidence that cracking was or was not present. Visual inspections, which attempt to identify leaking plugs, were considered to be an insufficient method of crack detection for the following reasons:

- Cracks in plugs may not always be visible, especially when the plugs remain installed in the generators.
- Plugs with cracks that have not grown through-wall would not be expected to leak, and plugs with through-wall cracks may not leak at flow rates large enough to be detected.
- Plug leakage does not necessarily mean that the suspect plug is cracked (i.e., the plug could exhibit leakage if it were improperly installed, which has been observed in the industry [180], it could appear to be leaking if there were primary coolant trapped above the expander in mechanical plugs, etc.) [162].

The majority of the useful available data related to plug failures came from small partial inspection samples which were evaluated by eddy current testing and/or destructive examination. Some other useful data were obtained from visual inspections in which visible cracks were evident, substantial boric acid buildup was present around the plug, and/or prolonged leakage from the plug was observed long after the steam generator had been drained.

In light of the nature of the available data, the failure criterion for SG tube plugs was not defined as the time required to reach a given fraction of plug failures caused by a given degradation mode, rather it was defined as the time when a particular degradation mode was first detected in the plugs at a given unit. Note that the time at which a degradation mode was first detected at a unit refers to the shortest of the service times of the plugs failed by that degradation mode at that unit. Also note that for the purpose of this analysis, the plugs that were installed in the original and the replacement steam generators at a given unit, the plugs fabricated from Alloys 600TT and 690TT, and mechanical and rolled plugs are all considered to be distinct populations (i.e., a given unit could have up to six different plug populations), which would each have a unique failure or suspension time.

Acceptable inspections which indicated the absence of a particular degradation mode were treated as suspensions. The suspension times were defined as the age of the oldest plug that was examined during the inspection. For example, if eddy current testing during a given outage were performed on plugs that were installed during different earlier outages, and the test results indicated that a particular degradation mode was not present, the suspension time would be the age, in EDY, of the oldest plug examined.

The choice of the earliest failure time to characterize the onset of PWSCC and the longest service time to characterize the absence of PWSCC leads to higher estimates of the improvement factors than other choices might. However, as the majority of available plug data at a given unit are from inspections of plugs of the same age, the possible non-conservative impact of this choice is considered to be minor. Also note that the suspension points (inspections in which failures of a given mode were not observed) used to determine the lower bound improvement factor values presented in Table 4-6 were from inspections of populations of plugs of the same age.

Following the determination of the plug median times to failure[5] for Alloys 600TT and 690TT, Alloy 690TT to Alloy 600TT mode-specific improvement factors were calculated. Alloy 690TT to Alloy 600MA improvement factors were determined by comparison of the Alloy 690TT to Alloy 600TT plug improvement factors with various different Alloy 600TT to Alloy 600MA improvement factors, such that the Alloy 690TT to Alloy 600MA improvement factor for a given degradation mode was simply the product of the appropriate Alloy 690TT to Alloy 600TT and Alloy 600TT to Alloy 600MA improvement factors. Note that the determination of unique Alloy 600TT to Alloy 600MA improvement factors based on plug cracking analyses was not possible as data related to Alloy 600MA plug cracking were essentially unavailable. As PWSCC has been observed in a number of different Alloy 600MA plugs types [165], the absence of data on Alloy 600MA is presumed to be due to a deficiency in record availability and to the early replacement of most Alloy 600MA plugs that were susceptible to cracking, not to the absence of cracking in the plugs. Note that high quality Alloy 600MA plug cracking data are not expected to exist as PWSCC was only identified in Alloy 600MA plugs by evidence of leakage. It was possible to perform eddy current examinations of some plugs types, but this type of inspection was generally not performed on Alloy 600MA plugs [165].

4.1.1 Data Sets Considered

As discussed in Section 3.1.1, careful population selection is necessary in the development of meaningful improvement factors. In similar fashion to the SG tubes, it has been observed that non-material design features have a significant effect on degradation rates, specifically the design of the plug and the method in which a given plug is installed in the tube. For example, extensive cracking of mechanical and rolled plugs fabricated from Alloy 600TT has occurred, while there has been no reported cracking of most types of welded plugs fabricated from Alloys 600MA, 600TT, and 690TT, and Inco 82 [165].

[5] As discussed below, Alloy 690TT has not been observed to crack. Therefore, the median time to failure is a statistical determination and does not imply any actual failures.

Operating experience seems to suggest that mechanical and rolled plugs are characterized by differing susceptibilities to axial cracking (rolled plugs appear to be less susceptible to axial cracking than mechanical plugs). Therefore, the analyses discussed in Section 4.1 were performed for mechanical and rolled plugs treated as a single population, and for mechanical and rolled plugs treated as separate populations. It is also possible that variations in plug installation parameters, such as the distance of expander travel in mechanical plugs and the length of the roll expansion zone in rolled plugs, could also lead to variations in susceptibility to PWSCC, but an investigation of these sources of variability was not possible with the available data. Variations in these parameters would be expected to impact the times required to initiate PWSCC if they led to differences in the magnitudes of the resultant residual stresses formed. Reference [162] states that differences in the distance of expander travel in mechanical plugs would affect the stress distribution, which could impact the location and orientation of PWSCC, but it would not be expected to significantly affect the magnitudes of the stresses, and therefore, the times required to initiate PWSCC. Results of plug SCC laboratory testing demonstrated that the distance of expander travel in mechanical plugs had an insignificant effect on the time to failure of the specimens examined, and the distinction between expander travel between plugs was removed from the presentation of plug corrosion data [164]. It is expected that variability in these parameters between alloys is not likely to be significant and that these factors contribute to the scatter in the data, but not an actual difference.

The SG tubing degradation thresholds used to calculate improvement factors were defined as the time required to reach a given failure fraction, which were determined as described in Section 3.1.2. As discussed in Section 4.1, the plug failure criterion was defined as the time that a specific degradation mode was first observed at a given unit due to the nature of the failure data derived from partial inspections and to the lack of information regarding the lifetimes of all other plugs at a given unit. It was not possible to determine fractional degradation thresholds analogous to those of SG tubing.

This report discusses plug corrosion arising from the following mechanisms:

- Axial primary-side intergranular stress corrosion cracking (SCC) in the plug (Axial Plug PWSCC)

  The failure criterion for axially-oriented primary water stress corrosion cracking (PWSCC) in steam generator tube plugs was defined as the time of the first observance of plug axial PWSCC defects at a given unit. The time scales for the various units were adjusted for differences in operating hot leg temperature to a reference temperature of 609°F using an Arrhenius equation with an activation energy (Q) of 50 kcal/mole. This activation energy is based on previous studies performed for EPRI [112].

- Circumferential primary-side intergranular SCC (Circ. Plug PWSCC)

  The failure criterion for circumferentially oriented PWSCC was defined as the time of the first observance of plug circumferential PWSCC defects at each unit. The time scales for the plants were adjusted to a reference temperature of 609°F using an Arrhenius equation with an activation energy (Q) of 50 kcal/mole.

Circumferential and axial degradation modes were modeled separately because of higher regulatory concern for circumferential cracks, which could lead to a plug top release (PTR) event, similar to that observed at North Anna 1, for both mechanical and rolled plugs.

4.1.2 Trends for Alloy 600TT Plug Cracking

The median time to the failure criterion for Alloy 600TT plugs was determined as follows. For calculational consistency with the analyses performed for SG tubing, a degradation-mode-specific maximum likelihood estimator (MLE) for the Weibull slope, b^*, for each Alloy 600TT plug population in which failures were observed was determined as described in Section 3.1.3 using Equation 3-3. Equation 3-3 is repeated here for convenience as Equation 4-1:

$$\frac{\sum_{i=1}^{n} x_i^{b^*} \ln(x_i)}{\sum_{i=1}^{n} x_i^{b^*}} - \frac{1}{r}\sum_{i=1}^{r} \ln(x_i) - \frac{1}{b^*} = 0 \qquad \textbf{Eq. 4-1}$$

where all variables are as defined in Section 3.1.3. The value of b^* was then used to determine the characteristic time parameter, θ, for a given plug population and degradation mode using the Weibayes Equation, as described in Section 3.1, which is repeated here:

$$\theta = \left(\frac{\sum_{i=1}^{n} x_i^{\beta}}{r} \right)^{\frac{1}{\beta}} \qquad \textbf{Eq. 4-2}$$

where all variables are as defined in Section 3.1. The median time to reach the failure criterion for a particular plug population and degradation mode was determined by substituting the relevant Weibull slope and characteristic life parameters into the Weibull distribution (Equation 3-1, which is repeated here as Equation 4-3) and solving for the time, t, at a cumulative failure fraction, F, of 0.5.

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad \textbf{Eq. 4-3}$$

4.1.3 Trends for Alloy 690TT Plugs

Similarly to Alloy 690TT SG tubing, cracking of Alloy 690TT plugs has not been observed in operating steam generators. In US plants installation of rolled plugs fabricated from this material began in the early- to mid-1980s [161], and mechanical 690TT plugs became available in the Fall of 1989 [164]. As there have been no reports of PWSCC in Alloy 690TT plugs, a Weibayes approach is appropriate. Inherent to this approach is the assumption that at each unit, a crack was present in one of the oldest installed plugs which was just below the limit of detection. Installation and removal dates of Alloy 690TT plugs of each type (i.e., mechanical and rolled) at a given unit were identified using information obtained from utility personnel and from information that is available in the SGDD. Alloy 690TT plugs have been removed from service for a number of reasons such as improper installation (when installation tolerances were not met or tubes were plugged by mistake), reclamation of plugged tubes by sleeving, and reclamation of plugged tubes by alternate repair criteria. In some cases the SGDD specifies that plugs were removed for sleeving operations or other reasons, but it does not specify when such plugs were installed. Therefore, in the absence of additional information from utility personnel, the removal date of a given plug was determined as follows:

- The removal date of a given plug was assumed to be the time of steam generator replacement or the most recent outage time for the following cases:
  - Plugs installed after the latest sleeving and/or unplugging campaign at a given unit
  - Plugs of a given type (i.e., mechanical or rolled) installed during a given outage prior to future sleeving and/or unplugging campaigns in a quantity exceeding the number of tubes unplugged and/or sleeved during these future campaigns as specified in the SGDD
- The removal date of a given plug was assumed to be unknown for the following case:
  - Plugs of a given type (i.e., mechanical or rolled) installed during a given outage prior to future sleeving and/or unplugging campaigns in a quantity *not* exceeding the number of tubes unplugged and/or sleeved during these future campaigns as specified in the SGDD

It is expected that these assumptions have led to additional conservatisms in the values of the improvement factors derived in this chapter as it is possible that plugs assumed to have an unknown lifetime were in fact not removed from service during a sleeving and/or unplugging campaign.

The SGDD also indicates that several different Alloy 690TT plug types have been installed in US units. For the purpose of the analysis presented in this chapter, it was assumed that the following plug types have susceptibilities to PWSCC that are similar to that of mechanical plugs:

- Mechanical, welded
- Sentinel

It was assumed that the following plug types have susceptibilities to PWSCC that are similar to that of rolled plugs:

- Rolled, stabilizer
- Rolled, welded
- Sleeve plug, rolled

Degradation-mode-specific median times to the failure criterion (the first instance of cracking) for each Alloy 690TT plug population were then determined using the same method described in Section 4.1.2 and the appropriate Weibull slope determined for Alloy 600TT plugs.

4.1.4 Residual Stress Contribution

The simultaneous presence of three separate conditions, an aggressive chemical environment, a susceptible material, and residual tensile stress, is required in order for PWSCC to take place. In this chapter, and elsewhere in this report, it is assumed that primary coolant environments are well defined and that the effect of variations in primary coolant chemistry between units is negligible with respect to the initiation of PWSCC in Alloys 600TT and 690TT. Differences in operating temperature between units are expected to have a significant impact on the times required to initiate PWSCC, and operating times are therefore adjusted to a reference temperature prior to any Weibull analyses between units and between cycles with different operating temperatures at a given unit. It is also assumed in this chapter that the impact of variations in microstructural characteristics of a given alloy is small compared to the effect of differences in residual stress levels between mechanical and rolled plugs. This assumption is supported by the fact that cracking of Alloy 600TT plugs has been observed in plugs with microstructures that were considered to range from highly resistant to PWSCC to highly susceptible to PWSCC [164, 174 , 175].

Differences in residual stress levels imparted during the installation of mechanical and rolled plugs are expected to have a strong impact on the susceptibility of these plugs to the initiation of PWSCC. Operating experience has shown that PWSCC does not readily occur at tensile stresses below a threshold value of about 35 ksi (240 MPa) in low-temperature mill annealed Alloy 600 (Alloy 600LTMA) tubing.[6] Residual axial and hoop tensile stresses induced by mechanical and kiss roll expansion processes typically exceed this value, and hydraulic expansion generally induces peak axial and hoop residual tensile stresses below 35 ksi. Laboratory data and operational experience have shown that the threshold stress for Alloy 600TT is greater than 35 ksi [167].

Reference [164] states that the rate of initiation of PWSCC in Alloy 600 is directly proportional to the 4^{th} power (the time to initiate PWSCC is inversely proportional to the 4^{th} power) of the absolute value of the residual tensile stress in primary coolant environments. Other studies have observed that a stress exponent value of 6 or 7 may be a more appropriate description of the impact of residual tensile stress on PWSCC, and that other factors in addition to the magnitude of the residual stress also have an important effect on the time required to initiate PWSCC. These additional factors include the amount of cold work and the ratio of the applied stress to the material yield strength [166]. At a given level of residual stress (maximum residual stresses in mechanical plugs are expected to be approximately constant and essentially independent of the initial material yield strength [164]), increases in material yield strength caused by cold work would be expected to increase the time required to initiate PWSCC. In situations where the residual stress imparted to the material is a fixed percentage of the material yield strength, for example in expansion transitions in rolled plugs, higher strength materials would be expected to initiate PWSCC at a higher rate than would lower strength materials [166]. Heat-to-heat variations in material yield strength are expected to be present for both Alloys 600TT and 690TT and would be expected to contribute to the inherent variability in the observed times to initiate PWSCC in mechanical and rolled plugs.

4.1.5 Rolled Plug Finite Element Analysis

Measured values of residual stresses present in mechanical and rolled plugs were not available to DEI, but it was possible to develop a finite element analysis (FEA) model using publicly available installation parameters for a Combustion-Engineering-design rolled plug [177, 178].

[6] The term threshold is use here in a practical sense, indicating that below the threshold SCC is not of engineering significance. In the absolute sense, i.e., that there is a stress below which SCC will never occur, a true threshold is considered unlikely.

4.1.5.1 Finite Element Analysis Model

In order to calculate the residual stresses associated with a mechanically rolled steam generator tube plug, a finite element model of the tube geometry and a portion of the surrounding tubesheet material was prepared using ANSYS Revision 11 [168]. The model considered a limited axial extent of the tube and tubesheet geometry, rather than the entire 21-inch tubesheet length. The hydraulic expansion of the steam generator tube was simulated, followed by a displacement-based expansion simulating the rolling process. Application of operating conditions after the rolling process was also considered. Additional details of the finite element models used in this evaluation are provided below.

4.1.5.1.1. Model Geometry

The FEA model includes a portion of the axial length of the steam generator tube and tubesheet as well as the tube plug. The analyses were performed using two-dimensional axisymmetric models, and the tube and tubesheet were modeled using PLANE42 4-node planar elements. Both the hydraulic expansion of the steam generator tube and the roll expansion of the plug, as simulated, occurred over the entire tube circumference at the same time. Therefore, the roll expansion was simulated as a progressively increasing expansion of a ring contacting the plug inner diameter.

The model geometry is shown in Figure 4-1. As shown in this figure, the model comprised a 2.5-inch length of a steam generator tube plug, a steam generator tube, and a portion of the tubesheet. The model included a 0.875-inch OD by 0.050-inch wall thickness steam generator tube expanded into a 0.890-inch ID tubesheet hole. The plug was also 0.050-inch thick. The height of the cylindrical portion of the roller is 1.25 inches, and the roller includes a short chamfer region at the top for contact stability.

The tubesheet surrounding the tube was represented by a sleeve of material with a 1.69-inch outer diameter. The actual steam generator tubesheet is an array of holes and tubes, which results in a different elastic compliance than a solid block of material. Considerable industry effort was made in the early 1990s to develop an equivalent diameter (solid) sleeve of tubesheet material that would represent the stiffness of the entire tubesheet with holes. The equivalent sleeve method permits an axisymmetric analysis of a single tube in a tubesheet, rather than requiring three-dimensional analyses of the full steam generator geometry. The outer diameter of the sleeve for this model was calculated based on the methodology developed by Chaaban in Reference [169].

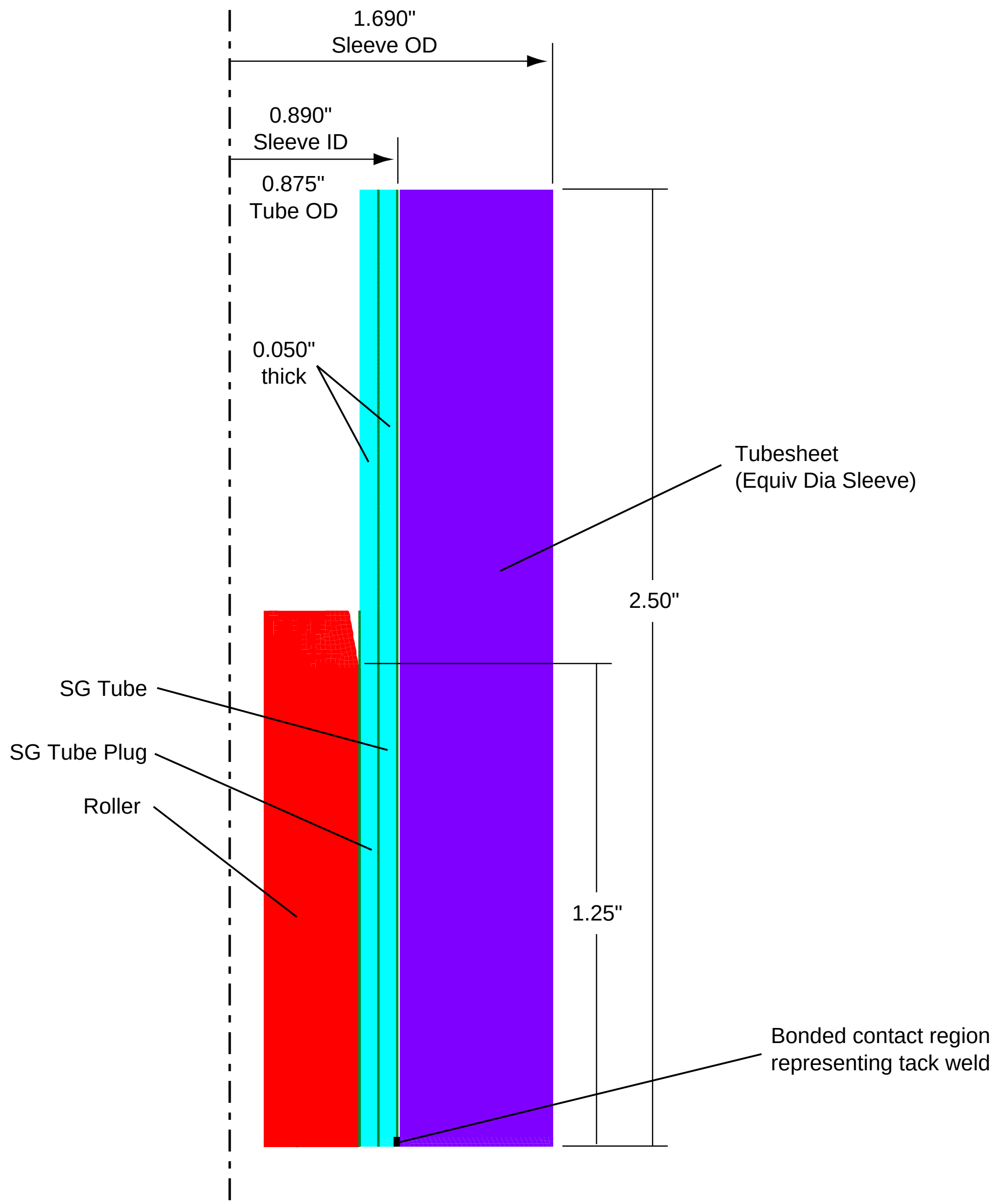

Figure 4-1
Tube Plug FEA Geometry

4.1.5.1.2 Boundary Conditions and Loads

In order to properly approximate the material hardening conditions in the steam generator tube, against which the tube plug is embedded, the installation process of the steam generator tube was first simulated, followed by the plug roll expansion. The initial load step in the model had the steam generator tube hydraulically expanded into the tubesheet using an expansion pressure of 33,300 psi; the initial tack roll was not simulated. A 0.025-inch high region of the tube and tubesheet were allowed to come into bonded contact once they touched; this region represented the tack weld between the tube and tubesheet after expansion. The expansion pressure was then removed. The tube plug and the roller were not affected during this operation.

After removing the hydraulic expansion pressure, the plug was expanded into the tube by moving the roller radially outwards. The roller moves a radial distance equal to the gap between the tube ID and the plug OD created by the hydraulic expansion, plus an additional 0.006 inches (12% of the tube wall thickness). The roller was then backed away from the plug by a small amount. After the roll expansion, a uniform operating temperature of 600°F (316°C) was applied to the entire model; the through-wall temperature gradient and variations in operating temperature were not considered in the model. Primary pressure of 2,235 psig was applied to the inside surface of the plug, and the axial end cap load was applied at the top surface of the plug as a tensile pressure. Contact between the tube OD and the tubesheet hole ID, between the plug OD and the tube ID, and between the roller OD and the plug ID, was modeled using CONTA171 and TARGE169 surface contact pairs. The surfaces were assumed to have a friction coefficient of 0.4.

The top surfaces of the plug, tube, and tubesheet were coupled in the axial direction to enforce plane bending; however, this boundary condition was also sufficiently remote from the regions of interest to not affect the results. The bottom surface of the roller was held in the axial direction. The remaining bottom edges were allowed to be free surfaces.

4.1.5.1.3 Material Properties

Two primary materials were used for the tube expansion models: the steam generator tube and plug were made of Alloy 600 and the tubesheet was made of SA-508 low alloy steel forging. Both materials used isotropic hardening for plasticity. The roller was assumed not to plastically deform under loading; it had the elastic properties of the low alloy steel material. The elastic modulus, the coefficient of thermal expansion and the Poisson’s ratio for both materials were taken from the 2007 ASME BPV Code [170]. The stress strain curve data for Alloy 600 were taken from Reference [171], using a 44 ksi room temperature yield strength. The stress strain curve data for the tubesheet material were based on data for mild steel in Reference [172], used in conjunction with a 69 ksi room temperature yield strength.

4.1.5.2 Analysis Results

Axial and hoop stress plots of the tube plug, tube, and tubesheet at operating conditions after installation of the plug are shown in Figure 4-2 and Figure 4-3, respectively. The results show considerable compressive stresses in the region of the roll expansion, and tensile stresses above the expansion. Plots of the axial and hoop stress on the ID surface of the plug as a function of elevation within the plug are shown in Figure 4-4. According to these data, the maximum axial stress on the plug ID surface is 37.7 ksi, and the maximum hoop stress on the plug ID surface is 41.1 ksi.

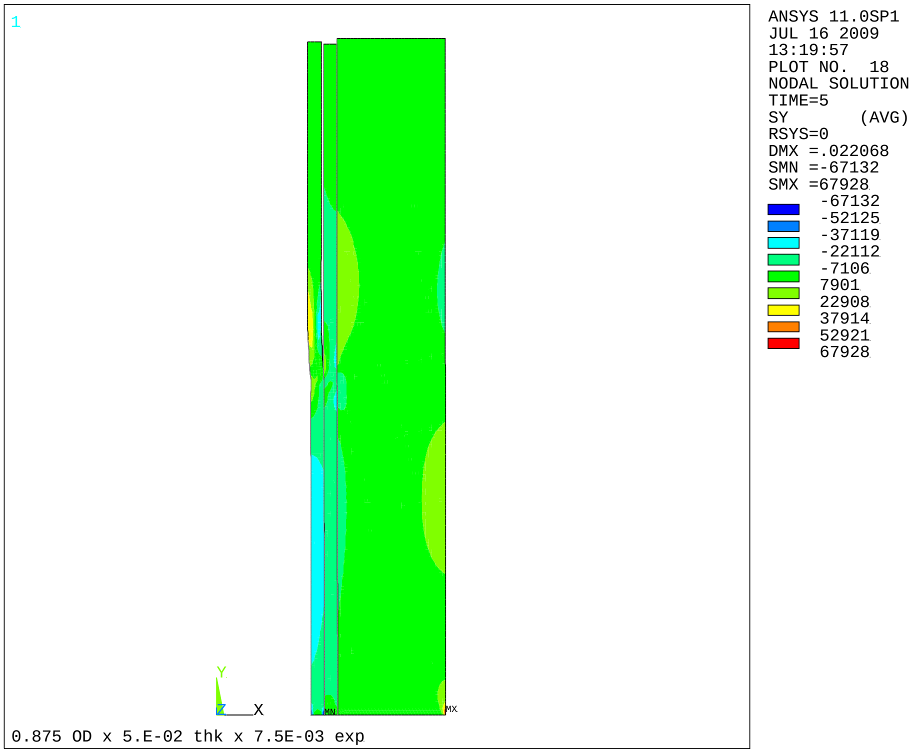

Figure 4-2
FEA Model Axial Stress Predictions

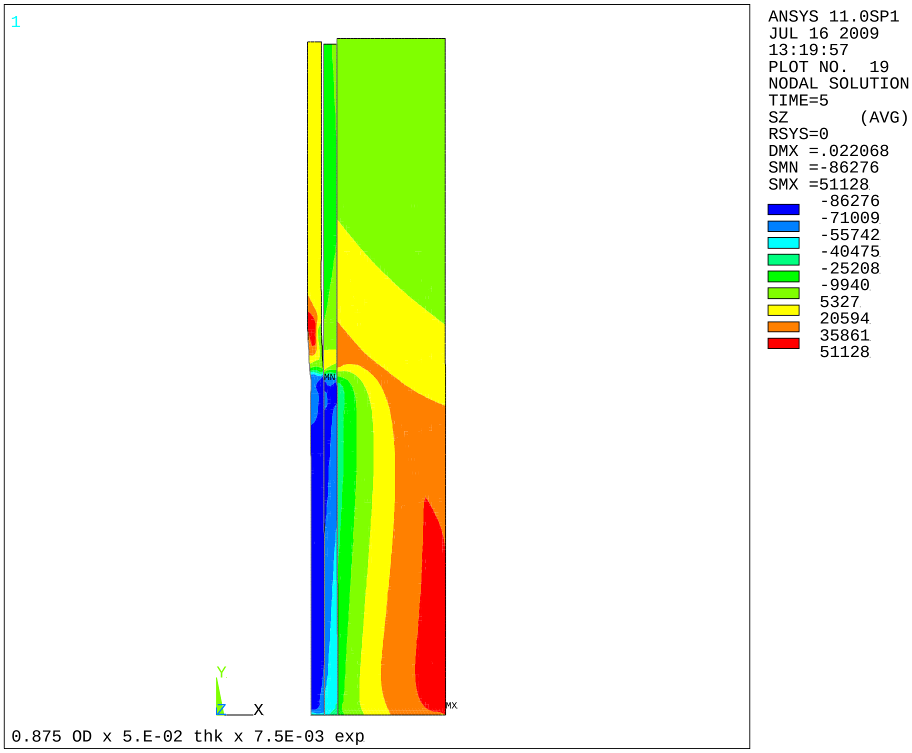

Figure 4-3
FEA Model Hoop Stress Predictions

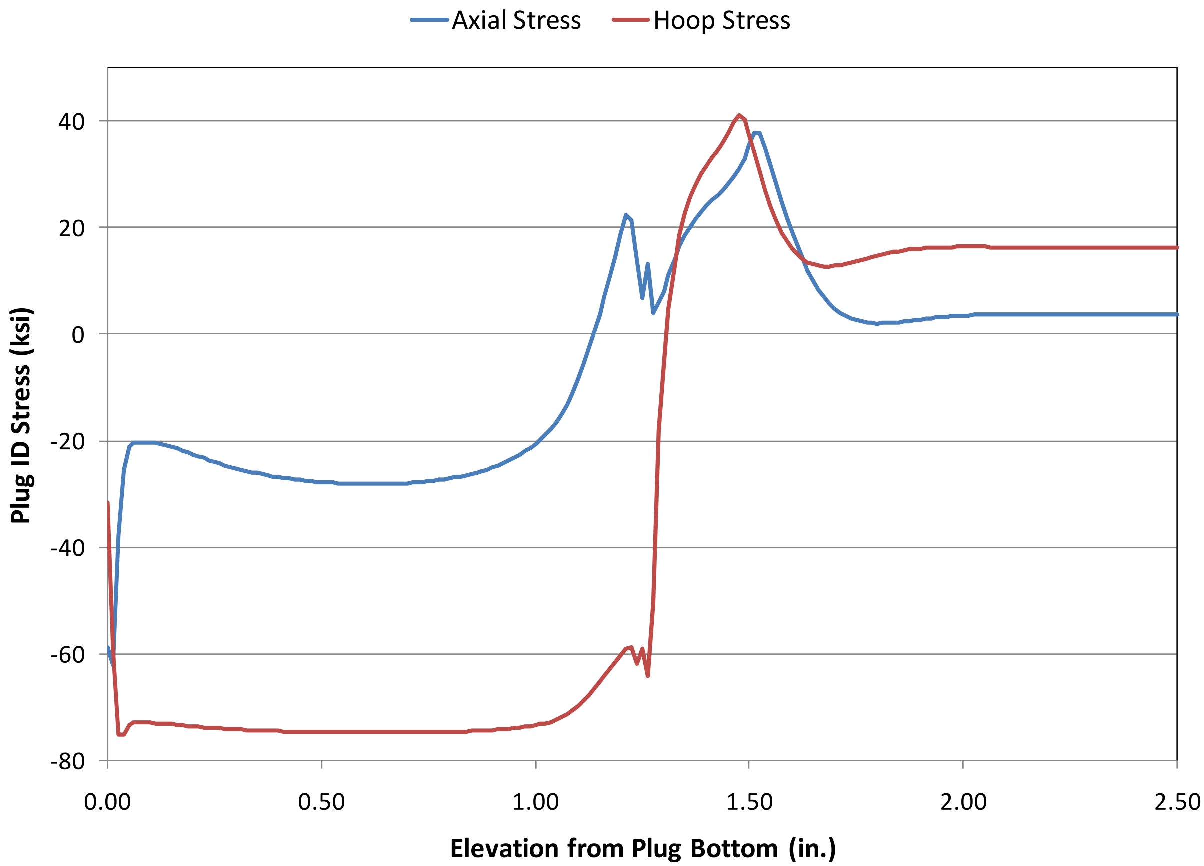

Figure 4-4
FEA Model Inner Diameter Stress Predictions

These results show qualitative agreement with measured and calculated residual stress values for kiss roll (maximum axial and hoop stresses of 38 and 49 ksi, respectively) and normal roll (maximum axial and hoop stresses of 45-49 and 54-62 ksi, respectively) expanded tubing as the maximum tensile stresses in the plug are at the expansion transition and the maximum hoop stress exceeds the maximum axial stress [166]. It should also be noted that these maximum tensile stress values exceed the threshold residual stress value for PWSCC initiation discussed in Section 4.1.4, and that both axial and circumferential PWSCC has been observed in rolled plugs.

4.1.6 Stress Indexing Analysis

The power-law relationship between the rate of initiation of PWSCC and the magnitude of residual tensile stresses present in a material can be used to predict failure times of other specimens of the same material with different levels of residual stress. Specifically, the relationship between the times required for two specimens to crack is given by the following equation:

$$\frac{t_1}{t_2} = \left(\frac{\sigma_1}{\sigma_2}\right)^n \quad \textbf{Eq. 4-4}$$

where t_1 and t_2 are the respective times required for each of the specimens to initiate PWSCC, σ_1 and σ_2 are the respective residual tensile stresses present in each specimen, and n is the stress exponent discussed in Section 4.1.4.

For comparison purposes, it is of interest to estimate PWSCC rate acceleration factors for axial and circumferential cracking for various different levels of residual stress relative to hydraulically expanded Alloy 600TT SG tubing using Equation 4-4. Reference [167] provides prototypical values of 32.6 and 35.5 ksi, respectively, for the maximum residual hoop and axial tensile stresses present in hydraulically expanded Alloy 600TT SG tubing. The median times to reach the failure criterion for hydraulically expanded Alloy 600TT tubing given in Section 3.3.2.2 are 116.0 EFPY for axial PWSCC and 114.0 EFPY for circumferential PWSCC. Note that a direct comparison of these times to the relevant plug cracking times is not applicable as the SG tubing and plug failure criteria are different (the failure criterion for SG tubing was defined as the time to reach 0.1% cumulative failure by PWSCC and the criterion for plugs was the time of the first detection of PWSCC), so relative time predictions were not determined. Using a stress exponent value of 4 as recommended for mechanical plugs in Reference [164], Table 4-1 lists several predictions for relative rates of cracking for Alloy 600TT at a constant temperature relative to hydraulically expanded Alloy 600TT tubing. For example, stress indexing analysis applied to the FEA model calculations would predict that axial PWSCC in Alloy 600TT rolled plugs would initiate about 2.5 times faster than in hydraulically expanded tubing of the same material.

Table 4-1
Prototypical PWSCC Stress Acceleration Factors Relative to Hydraulic Expansion PWSCC

Degradation Mech.	Material Condition	Hydraulic Expansion Reference Values	Plug Values	
		Stress Orientation and Magnitude (ksi)	Maximum Residual Tensile Stress (ksi)	Stress Acceleration Factor
Axial PWSCC	Rolled Plug	Hoop, 32.6	41.1	2.5
	Kiss Roll Expanded Tube		49	5.1
	Normal Roll Expanded Tube		58	10.0
Circ. PWSCC	Rolled Plug	Axial, 35.5	37.7	1.3
	Kiss Roll Expanded Tube		38	1.3
	Normal Roll Expanded Tube		47	3.1

The residual stress values provided for the rolled plug were determined in the FEA analysis discussed in Section 4.1.5 and the prototypical stress values for kiss roll and normal roll expansion transitions for Alloy 600 tubing were obtained from Reference [166].

4.2 Possible Emerging Trends

There are no emerging trends relevant to the plugging analyses presented in this chapter, as essentially 100% of Alloy 600TT mechanical and rolled plugs have been removed from service by repair, replacement, or steam generator replacement, and degradation of Alloy 690TT plugs has not been reported. It is possible that a more extensive analysis could be performed if more data were available. However, the collection of additional data is outside the scope of this project and is not expected to provide enough additional understanding to warrant the anticipated cost.

4.3 Improvement Factors

The main results of the evaluations performed for SG tube mechanical and rolled plugs are presented in Table 4-2, which shows the demonstrated improvement factors for Alloy 690TT relative to Alloy 600TT.

Table 4-2
Recommended Improvement Factors for Advanced Alloy 690TT versus Alloy 600TT Based on Plant Experience with SG Tube Plugs

Degradation Mech.	Failure Criterion	Plant Population	Median Time to Failure (EFPY)	Material IF_R vs. A600TT*
Axial PWSCC	Time to First Observed PWSCC	A690TT Mechanical Plugs	139.3	87.5
Circ. PWSCC	Time to First Observed PWSCC	A690TT Mechanical and Rolled Plugs	126.9	64.4
		A690TT Mechanical Plugs	82.5	39.9
		A690TT Rolled Plugs	62.0	60.7

*All improvement factors are estimated in the absence of significant degradation of Alloy 690TT and are type-to-type IFs, e.g., rolled Alloy 600TT to rolled Alloy 690TT.

4.3.1 Alloy 600TT Degradation

A limited number of field data are available regarding Alloy 600TT steam generator tube plugs. For each degradation mode, a population of Alloy 600TT plugs, all mechanical and rolled plugs and mechanical and rolled plugs separately, was evaluated using a Weibull or Weibayes analysis. The analyses were used to provide a baseline for comparisons with analogous populations of Alloy 690TT plugs. Alloy 690TT mechanical and rolled plugs have been widely installed, the majority of which remain in service in steam generators that have not been replaced, at US plants, so it is useful to evaluate the performance history of both mechanical and rolled Alloy 600TT tube plugs.

The failure criterion for each degradation mechanism was defined as the earliest observation of plug failure at a given unit. For these units, the times to first cracking were fit to a Weibull distribution as described in Section 4.1.2.

Note that Reference [173] indicates that axial cracking has been observed in Alloy 600TT rolled plugs. However, as there were no quantitative data available for axial PWSCC in rolled plugs, the median time to the failure criterion was determined using a Weibayes approach using the Weibull slope for axial cracking of WEXTEX-expanded SG tubing presented in Figure 3-4.

Also note that plug cracking was observed in three plugs installed in the cold leg at Calvert Cliffs 1 [164], but the crack orientation was not determined, so it was not possible to include this unit in the evaluation. These three plugs were found to be leaking after approximately 0.35 EDY (using an activation energy of 50 kcal/mole and a reference temperature of 609°F) of operation.

Circumferential cracking was observed at St. Lucie 1 in 1994. A sample of the 15 leaking plugs detected at St. Lucie 1 was removed and subjected to further analysis [176]. Since the results of this analysis were unavailable, it was not possible to include the St. Lucie 1 data in the axial PWSCC analysis.

The median times to failure for specific degradation mechanisms are discussed in the remainder of this section.

4.3.1.1 Axially Oriented PWSCC

Field data for axially-oriented PWSCC in mechanical and rolled tube plugs were gathered from NRC documentation, plug technical reports, and information received from utility personnel. These data were analyzed to determine the times at which this degradation mode was first observed, or when inspections showed that axial cracking was not present, at several units that had installed mechanical and rolled plugs. Unit-specific time scales were adjusted to a reference temperature of 609°F using an activation energy of 50 kcal/mole.

Mechanical and rolled plugs were first analyzed as a single population as discussed in Section 4.3.1.1.1. The available data for axial cracking of mechanical and rolled plugs suggests that these plug types are characterized by different susceptibilities to this degradation mode as axial cracking was not observed during inspection of rolled plugs at three units with rolled plugs (McGuire 1 and 2, and Summer) [175, 179]. As a result, mechanical and rolled plug axial cracking were also analyzed separately in Sections 4.3.1.1.2 and 4.3.1.1.3, respectively.

4.3.1.1.1 Combined Population of Mechanical and Rolled Plugs

The available data for axially-oriented PWSCC in mechanical and rolled Alloy 600TT steam generator tube plugs are given in Figure 4-5 and the Weibull analysis of these data is presented in Figure 4-6. As indicated on the plot in Figure 4-6, the median time to the failure criterion for Alloy 600TT mechanical and rolled plugs is about 3.2 EFPY.

4.3.1.1.2 Mechanical Plugs

The analysis of axially-oriented cracking of Alloy 600TT mechanical plugs as a unique population was performed by excluding inspection data for rolled plugs from McGuire 1 and 2, and Summer. The data are presented in Figure 4-7 and the Weibull analysis of these data is presented in Figure 4-8. The median time required for mechanical plugs at these units to reach the failure criterion is about 1.6 EFPY.

4.3.1.1.3 Rolled Plugs

The analysis of axially-oriented cracking of Alloy 600TT rolled plugs is based on eddy current inspection data from McGuire 1 and 2, and Summer, in which axial cracking was not present. These data are presented in Figure 4-9 and the Weibayes analysis is presented in Figure 4-10. Assuming a slope of 1.61 (the slope calculated for axial PWSCC of WEXTEX expanded Alloy 600MA tubing), the calculated median time required to reach the failure criterion at these units is about 9.6 EFPY.

4.3.1.2 Circumferentially Oriented PWSCC

Field data for circumferentially-oriented PWSCC in mechanical and rolled tube plugs were also gathered from documentation from utilities archived in NRC databases, plug technical reports, and information received from utility personnel. The available data were analyzed to determine the times at which circumferential cracking was first observed or when inspection data did not indicate the presence of circumferential cracking. Time scales were adjusted to 609°F with an activation energy of 50 kcal/mole. Note that circumferential cracking of rolled plugs was detected using eddy current testing at McGuire 1 and Summer, but the ages of the failed plugs were not available, so it was not possible to include these two units in the analysis.

4.3.1.2.1 Combined Population of Mechanical and Rolled Plugs

The available field data for circumferentially-oriented PWSCC in all Alloy 600TT mechanical and rolled plugs is presented in Figure 4-11. The Weibull analysis of these data yielded a median time to reach the failure criterion of about 2.0 EFPY, as presented in Figure 4-12.

4.3.1.2.2 Mechanical Plugs

For the analysis of Alloy 600TT mechanical plugs as a unique population, the circumferential PWSCC detected at McGuire 2 was excluded from the larger combined population discussed in Section 4.3.1.2.1. The field data used for this analysis are presented in Figure 4-13 and the Weibull analysis of these data is presented in Figure 4-14. As indicated on the plot in Figure 4-14, the median time to reach the failure criterion calculated for this population and failure mode was about 2.1 EFPY.

4.3.1.2.3 Rolled Plugs

An analogous analysis was performed for circumferential cracking of Alloy 600TT rolled plugs. It was not possible to include the data from McGuire 1 and Summer as quantitative data related to circumferential PWSCC of rolled plugs at these units were not available. These data are presented in Figure 4-15 and the Weibayes analysis is presented in Figure 4-16. Assuming a slope of 1.62 (the slope calculated for circumferential PWSCC of WEXTEX expanded Alloy 600MA tubing), the calculated median time required to reach the failure criterion at these units is about 1.0 EFPY.

4.3.1.3 Summary

The calculated median times to failure for the plant groups and degradation modes discussed in this section are shown in Table 4-3.

Table 4-3
Median Times to Failure for Alloy 600TT Plug Populations

Degradation Mech.	Failure Criterion	Plant Population	Median Time to Failure (EFPY)
Axial PWSCC	Time to First Observed PWSCC	A600TT Mechanical Plugs	1.6
Circ. PWSCC	Time to First Observed PWSCC	A600TT Mechanical and Rolled Plugs	2.0
		A600TT Mechanical Plugs	2.1
		A600TT Rolled Plugs	1.0

Standard stress indexing analysis alone as discussed in Section 4.1.6 would predict that axial cracking of rolled plugs would occur roughly two times faster than would circumferential cracking. It is unlikely that this discrepancy is the result of inconsistencies in the FEA model as its results qualitatively agree with measured residual stress values (i.e., residual hoop stresses are expected to be greater than residual axial stresses following roller expansion processes) for kiss roll and normal roll expansion techniques [166]. These results suggest that a standard stress indexing approach may not be valid in the analysis of tube plug failures and lifetime predictions.

Time to First Observed Axial PWSCC - Mechanical and Rolled A600 TT Plugs

No. Plants = 11 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to First PWSCC	Adjusted EDYs to First PWSCC or to Last ISI	N= 11	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Connecticut Yankee (6)	1/68	28.85 S	1.20	1.20	585	0.45	0.45	0.45	1	1	11	1.00	0.0614
Indian Point 2 (orig.)	8/74	25.85 R	1.34	1.34	588	0.57	0.57	0.57	2	1	10	2.00	0.1491
Sequoyah 1 (orig.)	7/80	23.00 R	1.10	1.10	609	1.10	1.10	1.10	3	1	9	3.00	0.2368
Millstone 2 (orig.)	12/75	16.51 R	2.10	1.80	598	1.35	1.16	1.16	4	1	8	4.00	0.3246
North Anna 1 (orig.)	6/78	14.57 R	1.16	1.16	618	1.65	1.65	1.65	5	1	7	5.00	0.4123
North Anna 2 (orig.)	12/80	14.28 R	1.52	1.52	618	2.17	2.17	2.17	6	1	6	6.00	0.5000
Farley 2 (orig.)	7/81	19.81 R	2.50	2.50	607	2.31	2.31	2.31	7	1	5	7.00	0.5877
Bugey 5 (orig.)	7/79	14.15 R	4.37		613	5.12		5.12	8	0		7.00	
McGuire 2 (orig.)	3/84	13.60 R	4.20		618	5.98		5.98	9	0		7.00	
Summer (orig.)	1/84	10.70 R	4.10		619	6.07		6.07	10	0		7.00	
McGuire 1 (orig.)	12/81	15.26 R	4.40		618	6.27		6.27	11	0		7.00	
				Ave. Thot=	608								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. The crack morphology was not determined as all cracked plugs were repaired with PIP and none were removed. It is assumed that at least one of the plugs had an axially-oriented crack.

Figure 4-5
Time to First Axial PWSCC – Alloy 600TT Mechanical and Rolled Tube Plugs

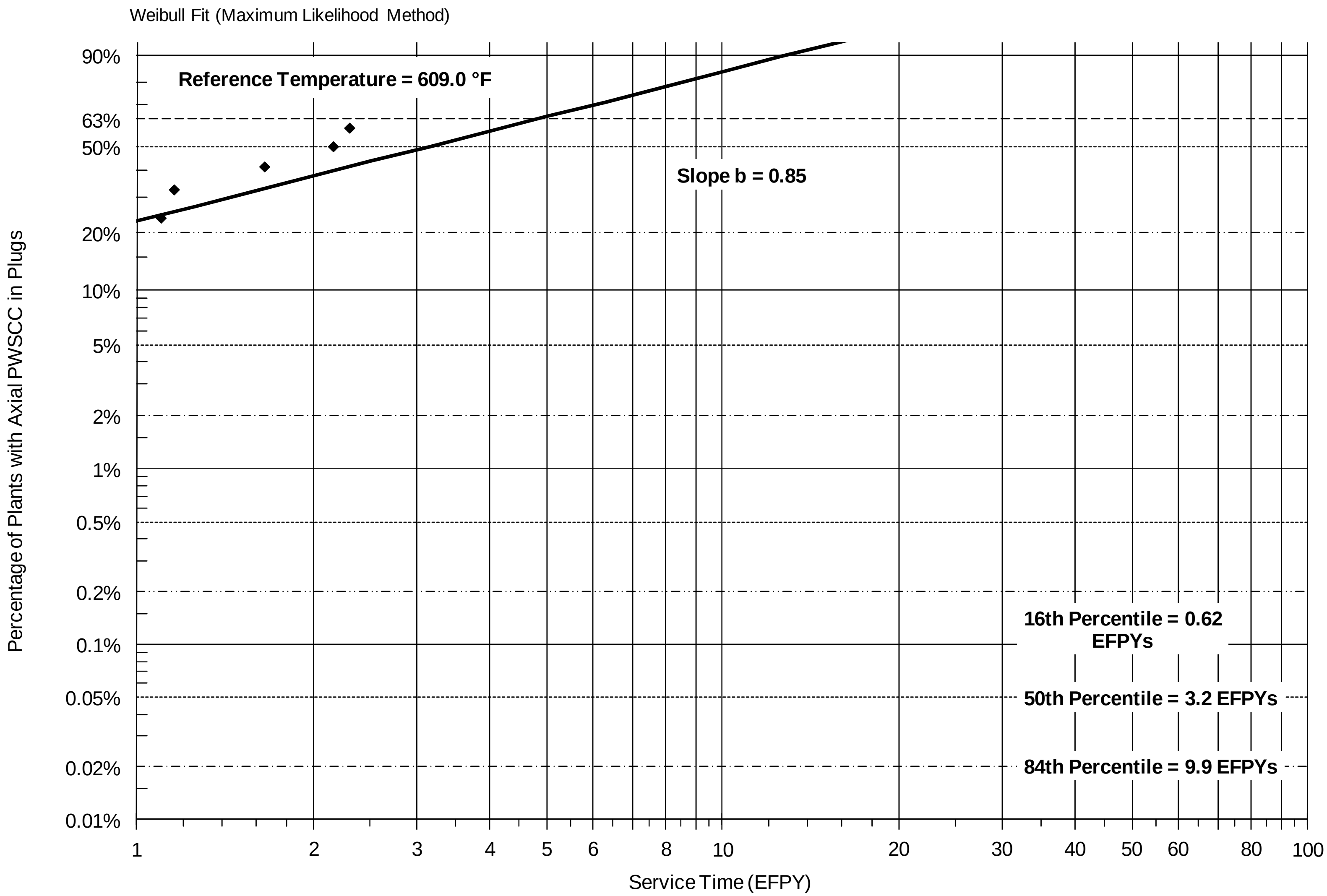

Figure 4-6
Time to First Axial PWSCC – Alloy 600TT Mechanical and Rolled Tube Plugs - Weibull Analysis

Time to First Observed Axial PWSCC - Mechanical A600 TT Plugs

No. Plants = 8 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to First PWSCC	Adjusted EDYs to First PWSCC or to Last ISI	N= 8	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Connecticut Yankee (6)	1/68	28.85 S	1.20	1.20	585	0.45	0.45	0.45	1	1	8	1.00	0.0833
Indian Point 2 (orig.)	8/74	25.85 R	1.34	1.34	588	0.57	0.57	0.57	2	1	7	2.00	0.2024
Sequoyah 1 (orig.)	7/80	23.00 R	1.10	1.10	609	1.10	1.10	1.10	3	1	6	3.00	0.3214
Millstone 2 (orig.)	12/75	16.51 R	2.10	1.80	598	1.35	1.16	1.16	4	1	5	4.00	0.4405
North Anna 1 (orig.)	6/78	14.57 R	1.16	1.16	618	1.65	1.65	1.65	5	1	4	5.00	0.5595
North Anna 2 (orig.)	12/80	14.28 R	1.52	1.52	618	2.17	2.17	2.17	6	1	3	6.00	0.6786
Farley 2 (orig.)	7/81	19.81 R	2.50	2.50	607	2.31	2.31	2.31	7	1	2	7.00	0.7976
Bugey 5 (orig.)	7/79	14.15 R	4.37		613	5.12		5.12	8	0		7.00	
				Ave. Thot=	605								

Reference Temperature
609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. The crack morphology was not determined as all cracked plugs were repaired with PIP and none were removed. It is assumed that at least one of the plugs had an axially-oriented crack.

Figure 4-7
Time to First Axial PWSCC –Alloy 600TT Mechanical Tube Plugs

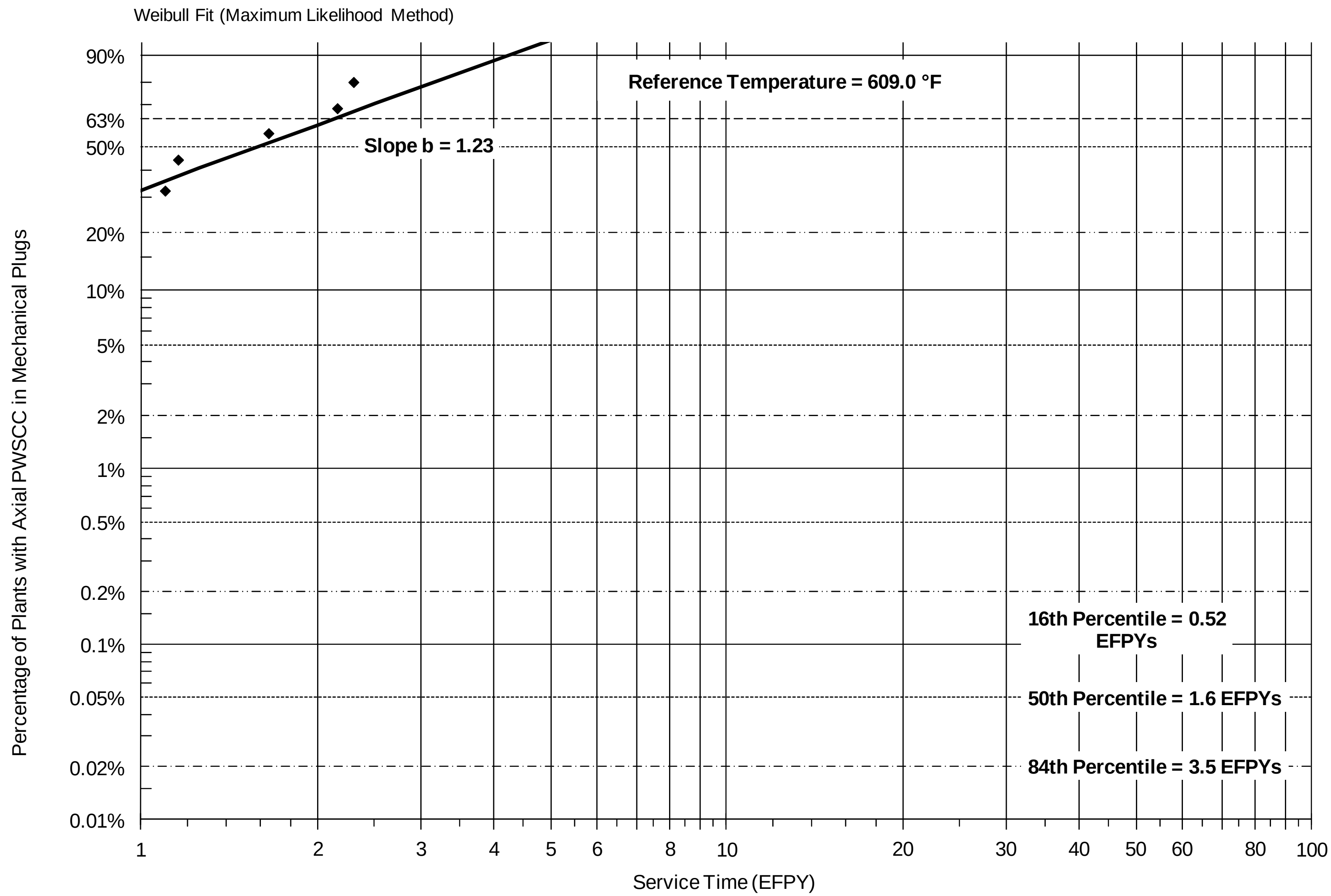

Figure 4-8
Time to First Axial PWSCC – Alloy 600TT Mechanical Tube Plugs-Weibull Analysis

Time to First Observed Axial PWSCC - Rolled A600 TT Plugs

No. Plants = 3 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to First PWSCC	Adjusted EDYs to First PWSCC or to Last ISI	N= 3	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
McGuire 2 (orig.)	3/84	13.60 R	4.20		618	5.98		5.98	1	0		0.00	
Summer (orig.)	1/84	10.70 R	4.10		619	6.07		6.07	2	0		0.00	
McGuire 1 (orig.)	12/81	15.26 R	4.40		618	6.27		6.27	3	0		0.00	

Ave. Thot= 618

Reference Temperature

609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-9
Time to First Axial PWSCC – Alloy 600TT Rolled Tube Plugs

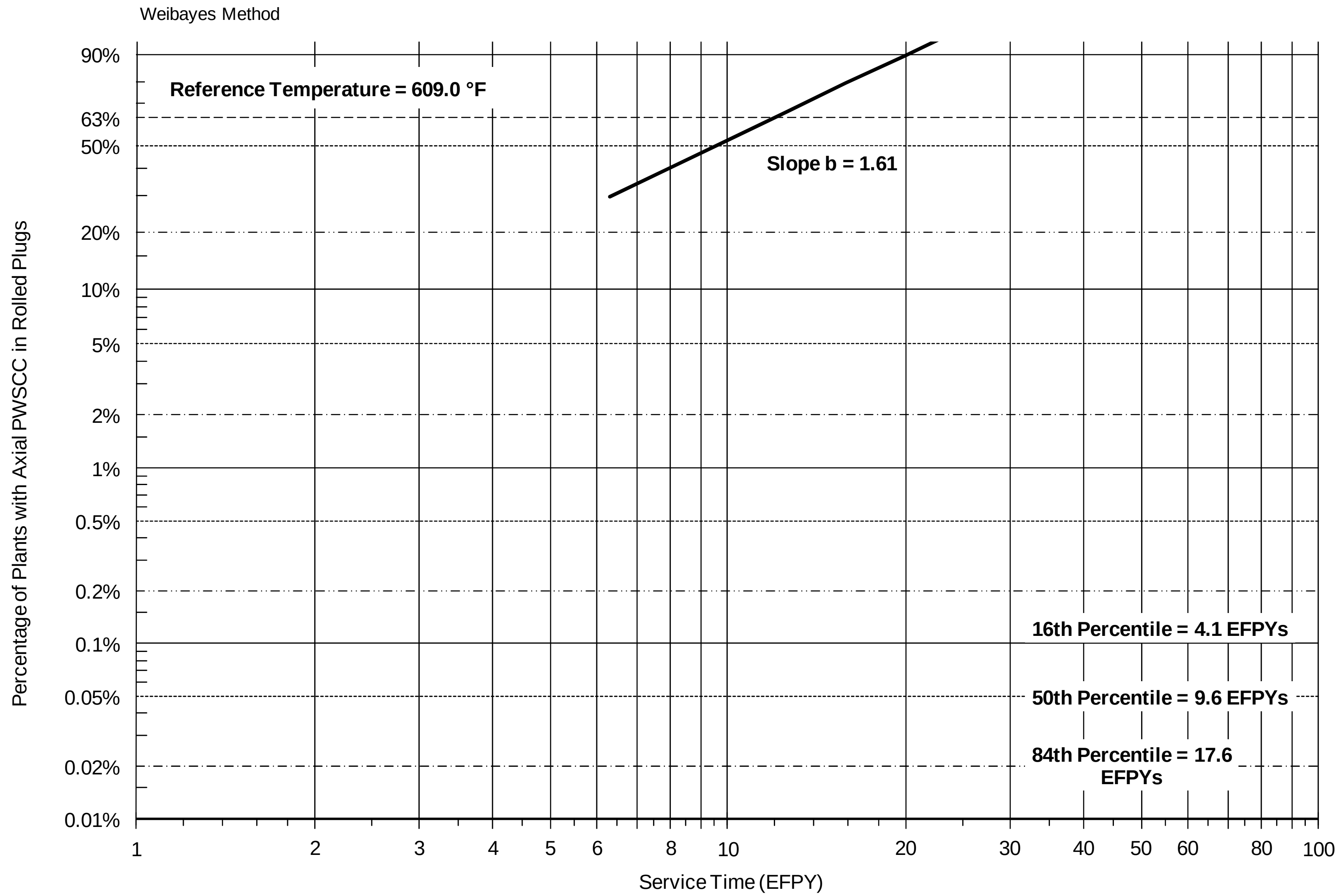

Figure 4-10
Time to First Axial PWSCC – Alloy 600TT Rolled Tube Plugs-Weibayes Analysis

Time to First Observed Circumferential PWSCC - Mechanical and Rolled A600 TT Plugs

No. Plants = 10 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to First PWSCC	Adjusted EDYs to First PWSCC or to Last ISI	N= 10	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Connecticut Yankee	1/68	28.85 S	1.20	1.20	585	0.45	0.45	0.45	1	1	10	1.00	0.0673
Indian Point 2 (orig.)	8/74	25.85 R	1.34		588	0.57		0.57	2	0		1.00	
Sequoyah 1 (orig.)	7/80	23.00 R	1.10	1.10	609	1.10	1.10	1.10	3	1	8	2.11	0.1741
Millstone 2 (orig.)	12/75	16.51 R	2.10	1.80	598	1.35	1.16	1.16	4	1	7	3.22	0.2810
McGuire 2 (orig.)	3/84	13.60 R	4.20	0.90	618	5.98	1.28	1.28	5	1	6	4.33	0.3878
North Anna 1 (orig.)	6/78	14.57 R	1.16	1.16	618	1.65	1.65	1.65	6	1	5	5.44	0.4947
North Anna 2 (orig.)	12/80	14.28 R	1.52	1.52	618	2.17	2.17	2.17	7	1	4	6.56	0.6015
Farley 2 (orig.)	7/81	19.81 R	2.50	2.50	607	2.31	2.31	2.31	8	1	3	7.67	0.7083
St. Lucie 1 (orig.)	8/83	24.18 R	6.70	6.70	599	4.49	4.49	4.49	9	1	2	8.78	0.8152
Bugey 5 (orig.)	7/79	14.15 R	4.37	4.37	613	5.12	5.12	5.12	10	1	1	9.89	0.9220

Ave. Thot= 605

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. The crack morphology was not determined as all cracked plugs were repaired with PIP and none were removed. It is assumed that at least one of the plugs had a circumferentially-oriented crack.

Figure 4-11
Time to First Circumferential PWSCC – All Alloy 600TT Mechanical and Rolled Tube Plugs

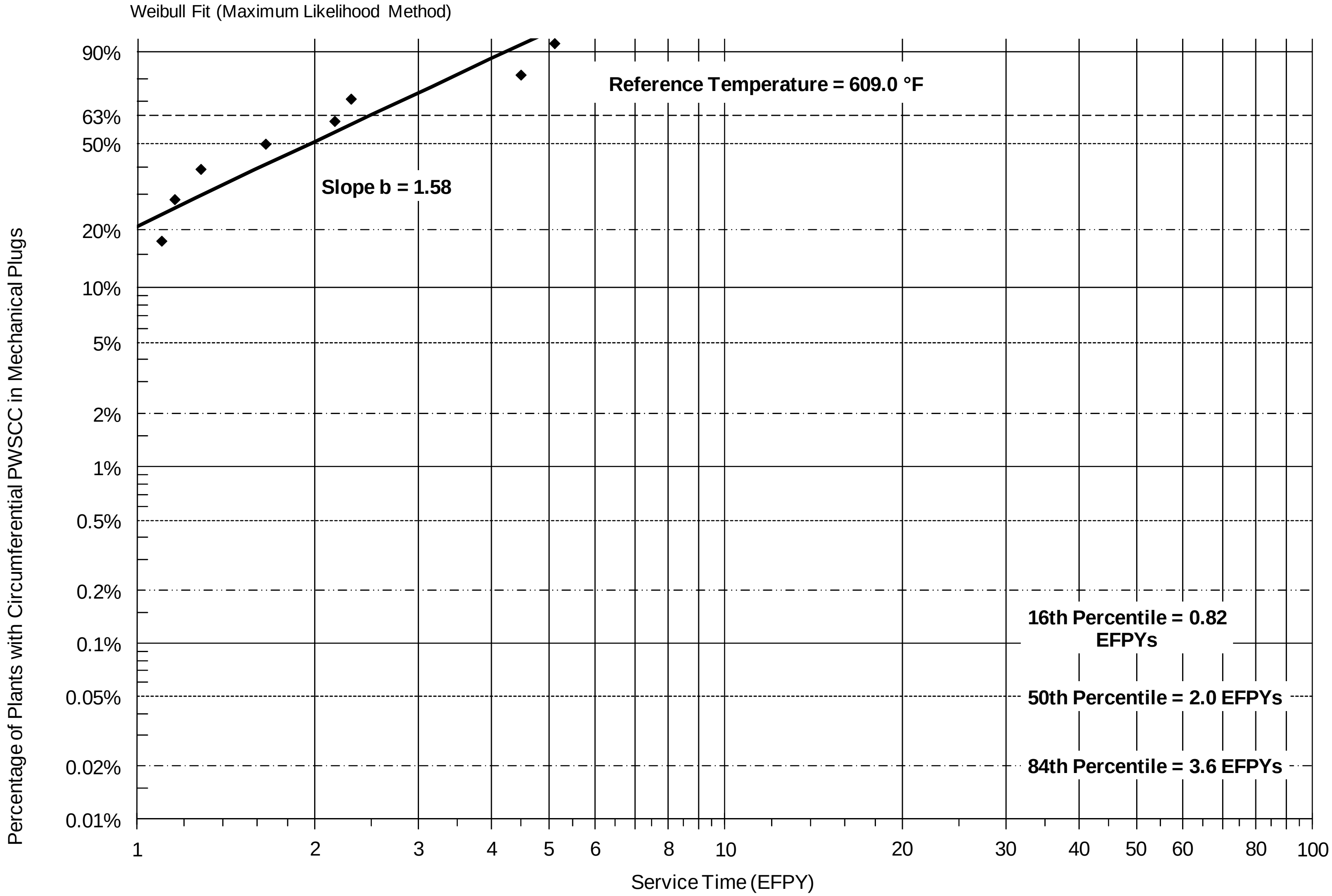

Figure 4-12
Time to First Circumferential PWSCC – Alloy 600TT Mechanical and Rolled Tube Plugs-Weibull Analysis

Time to First Observed Circumferential PWSCC - Mechanical A600 TT Plugs

No. Plants = 9 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to First PWSCC	Adjusted EDYs to First PWSCC or to Last ISI	N= 9	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Connecticut Yankee	1/68	28.85 S	1.20	1.20	585	0.45	0.45	0.45	1	1	9	1.00	0.0745
Indian Point 2 (orig.)	8/74	25.85 R	1.34		588	0.57		0.57	2	0		1.00	
Sequoyah 1 (orig.)	7/80	23.00 R	1.10	1.10	609	1.10	1.10	1.10	3	1	7	2.13	0.1941
Millstone 2 (orig.)	12/75	16.51 R	2.10	1.80	598	1.35	1.16	1.16	4	1	6	3.25	0.3138
North Anna 1 (orig.)	6/78	14.57 R	1.16	1.16	618	1.65	1.65	1.65	5	1	5	4.38	0.4335
North Anna 2 (orig.)	12/80	14.28 R	1.52	1.52	618	2.17	2.17	2.17	6	1	4	5.50	0.5532
Farley 2 (orig.)	7/81	19.81 R	2.50	2.50	607	2.31	2.31	2.31	7	1	3	6.63	0.6729
St. Lucie 1 (orig.)	8/83	24.18 R	6.70	6.70	599	4.49	4.49	4.49	8	1	2	7.75	0.7926
Bugey 5 (orig.)	7/79	14.15 R	4.37	4.37	613	5.12	5.12	5.12	9	1	1	8.88	0.9122

Ave. Thot= 604

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.
6. The crack morphology was not determined as all cracked plugs were repaired with PIP and none were removed. It is assumed that at least one of the plugs had a circumferentially-oriented crack.

Figure 4-13
Time to First Circumferential PWSCC – Alloy 600TT Mechanical Tube Plugs

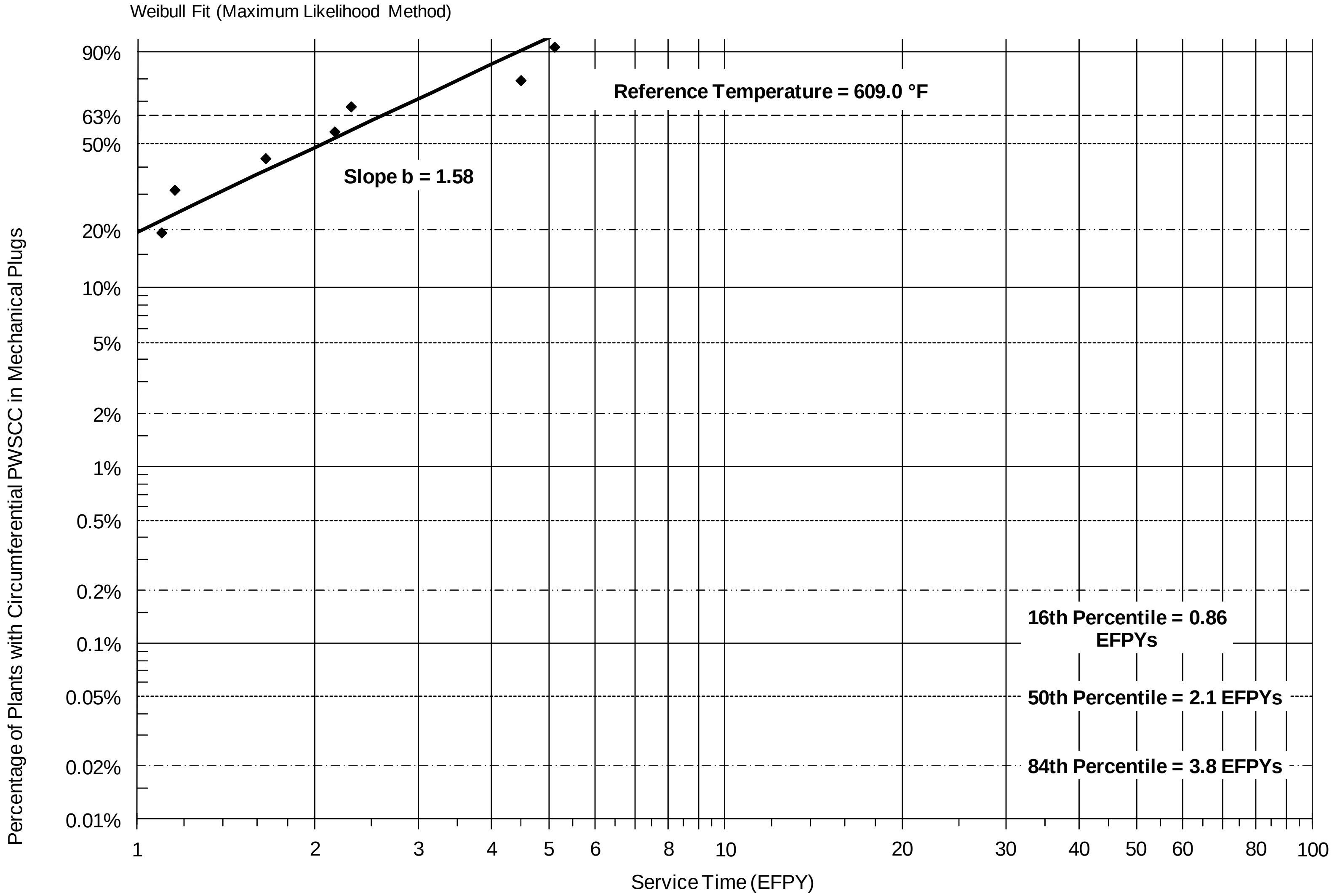

Figure 4-14
Time to First Circumferential PWSCC – Alloy 600TT Mechanical Tube Plugs-Weibull Analysis

Time to First Observed Circumferential PWSCC - Rolled A600 TT Plugs

No. Plants = 1 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to First PWSCC	Adjusted EDYs to First PWSCC or to Last ISI	N= 1	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
McGuire 2 (orig.)	3/84	13.60 R	4.20	0.90	618	5.98	1.28	1.28	1	1	1	1.00	0.5000
				Ave. Thot=	618			1.28					

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-15
Time to First Circumferential PWSCC – Alloy 600TT Rolled Plugs

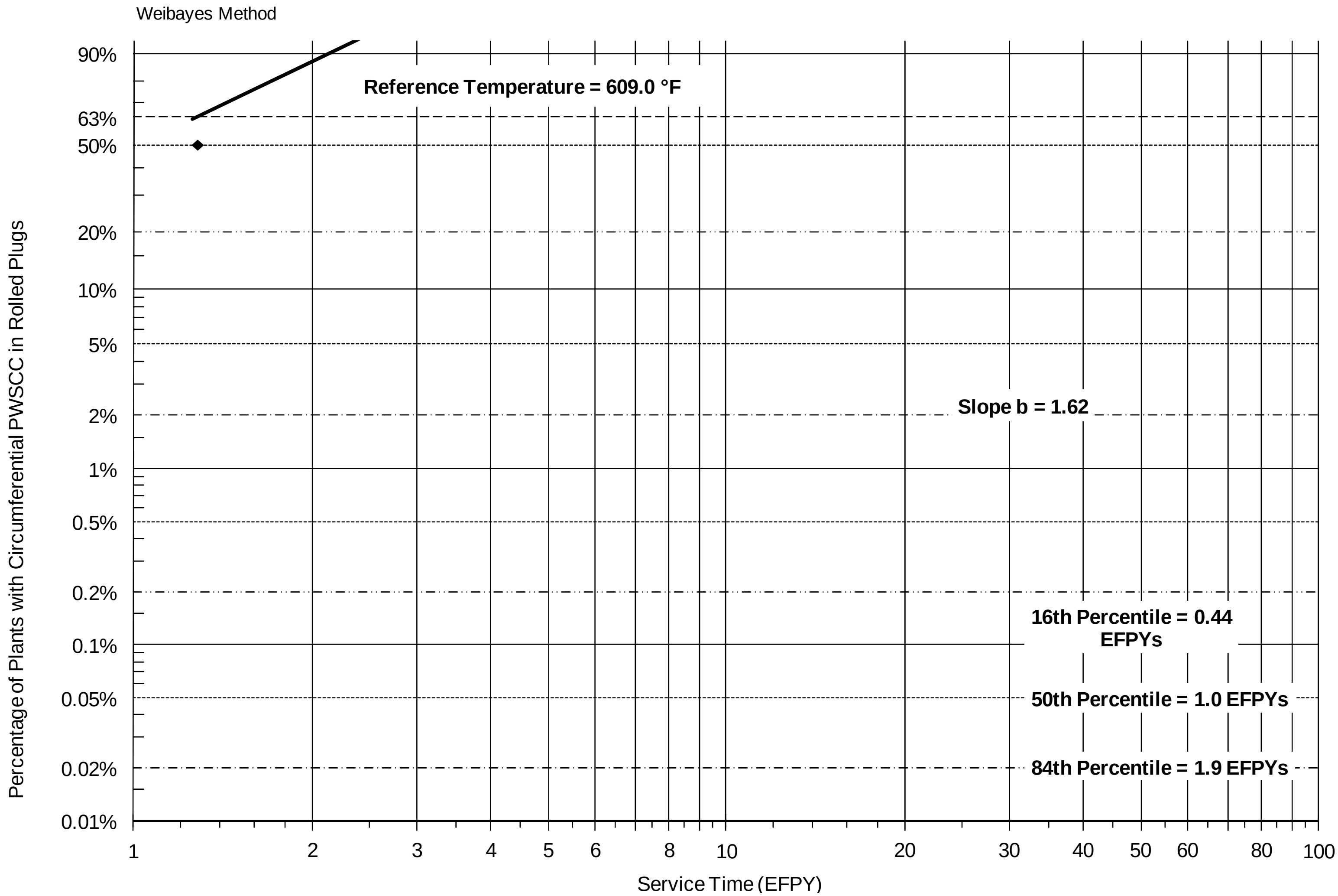

Figure 4-16
Time to First Circumferential PWSCC – Alloy 600TT Rolled Plugs-Weibayes Analysi

4.3.2 Alloy 690TT versus Alloy 600TT

Improvement factors for degradation modes in which no failures have been observed are calculated from the current length of operating experience. Since no failures have been reported for such degradation modes, it is necessary to assume that the first incidence of failure is imminent. SG tube plug degradation provides a unique opportunity to evaluate the performance of Alloy 690TT relative to Alloy 600TT as the performance of the former has been far superior to the latter in the context of SG tube plugs installed across the industry. For SG tubing, failures of Alloy 600TT have not been numerous enough to demonstrate the superiority of Alloy 690TT.

As no stress corrosion cracking has been observed in mechanical and rolled plugs fabricated from Alloy 690TT, the Weibayes method was used to predict the median times to failure for plants with these plugs installed. In order to make meaningful comparisons with the Alloy 600TT baseline results presented in Section 4.3.1, the same failure criterion was used for Alloy 690TT plugs as was used for Alloy 600TT plugs (i.e., the time of the first incidence of PWSCC at a given unit) and the same plug populations (i.e., a combined population of mechanical and rolled plugs, and unique populations of mechanical and rolled plugs) were evaluated.

4.3.2.1 Axially-Oriented PWSCC

4.3.2.1.1 Combined Population of Mechanical and Rolled Plugs

Based on the Weibayes analysis for axially-oriented PWSCC of mechanical and rolled Alloy 690TT plugs, the median time to the failure criterion is approximately 776.7EFPY. The field data for this population and the corresponding Weibayes plot are given in Figure 4-17 and Figure 4-18. Note that this median time to failure value is based on a Weibull slope derived from the combined population of Alloy 600TT mechanical and rolled plugs. In light of the fact that the operating experience data suggest that mechanical and rolled plugs have differing levels of susceptibility to axial PWSCC, this value is not considered to be a realistic lifetime prediction for axially-oriented PWSCC of Alloy 690TT plugs.[7]

4.3.2.1.2 Mechanical Plugs

The Weibayes analysis corresponding to Alloy 690TT mechanical plugs as a unique population yields a median time to failure of about 139.3 EFPY. The data used in this analysis and the corresponding Weibayes plot are presented in Figure 4-19 and Figure 4-20, respectively.

[7] By treating the two Alloy 600TT populations as one population, the variation in initiation times is increased. When applying this variation to Alloy 690TT, this leads to a prediction of a large lag between initial observations of PWSCC and reaching the median time to failure.

4.3.2.1.3 Rolled Plugs

The analogous Weibayes analysis for Alloy 690TT rolled plugs indicates a median time to failure of about 67.9 EFPY. The data evaluated in this analysis are given in Figure 4-21 and the Weibayes plot is presented in Figure 4-22.

4.3.2.2 Circumferentially Oriented PWSCC in Hot Leg Expansion Transitions

4.3.2.2.1 Combined Population of Mechanical and Rolled Plugs

The data analyzed and the corresponding Weibayes analysis for circumferential PWSCC of the combined plug population are given in Figure 4-23 and Figure 4-24, respectively. As shown on the plot in Figure 4-24, the calculated median time to reach the failure criterion for this mechanism and population is about 126.9 EFPY.

4.3.2.2.2 Mechanical Plugs

The median time to failure for circumferentially-oriented PWSCC of Alloy 690TT mechanical plugs is approximately 82.5 EFPY. The data used in this analysis are given in Figure 4-25 and the Weibayes plot of these data is presented in Figure 4-26.

4.3.2.2.3 Rolled Plugs

The field data analyzed for circumferential PWSCC of Alloy 690TT rolled plugs are presented in Figure 4-27. The Weibayes method was applied to these data and was used to generate the plot given in Figure 4-28. As presented in Figure 4-28, the median time to reach the failure criterion for this population and degradation mode is about 62.0 EFPY.

4.3.2.3 Summary of Alloy 690TT Tube Plug Plant Experience Based Improvement Factors

The calculated material improvement factors for Alloy 690TT vs. Alloy 600TT for each degradation mechanism are shown in Table 4-4.

Table 4-4
Estimated Material Improvement Factors for Alloy 690TT vs. Alloy 600TT

Degradation Mech.	Failure Criterion	Plant Population	Median Time to Failure (EFPY)	Material IF_R vs. A600TT*
Axial PWSCC	Time to First Observed PWSCC	A690TT Mechanical Plugs	139.3	87.5
Circ. PWSCC	Time to First Observed PWSCC	A690TT Mechanical and Rolled Plugs	126.9	64.4
		A690TT Mechanical Plugs	82.5	39.9
		A690TT Rolled Plugs	62.0	60.7

*All improvement factors are estimated in the absence of significant degradation of Alloy 690TT and are type-to-type IFs, e.g., rolled Alloy 600TT to rolled Alloy 690TT.

According to the results given in Table 4-4, plant experience indicates a lower bound on the improvement factor for axial PWSCC of about 7.1. As this improvement factor is based on no cracking in either material, it is only a ratio of service times and is not considered to be representative of the level of improvement of Alloy 690TT relative to Alloy 600TT. Table 4-4 indicates an upper bound on the improvement factor for axial PWSCC of about 250. This value is not considered to be a valid description of the material improvement factor because it is based on an analysis of mechanical and rolled plugs as a single population, which seem to be characterized by different susceptibilities to axially-oriented PWSCC.

The remaining material improvement factor values for axial and circumferential PWSCC are roughly comparable in value and are minimum bounds since Alloy 690TT plugs have not cracked. Based on the discussion in this section, material improvement factor values for axial and circumferential PWSCC of 90 and 40, respectively, are considered to be conservative measures of the performance of Alloy 690TT relative to Alloy 600TT. These values are based on the assumption of a single imminent failure of one of the oldest Alloy 690TT plugs at each unit. This assumption is considered to be conservative as PWSCC of Alloy 690TT tubing and plugs has not been observed in operating steam generators.

Time to First Axial PWSCC - Mechanical and Rolled A690 TT Plugs

No. Plants = 83 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 83	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
ANO 1 (repl.)	11/05	2.80	0.10		603	0.08		0.08	1	0		0.00	
Ginna (orig.)	7/70	25.77 R	0.70		589	0.31		0.31	2	0		0.00	
Prairie Island 1 (repl.)	9/04	4.00	1.60		590	0.74		0.74	3	0		0.00	
ANO 1 (orig.)	12/74	30.77 R	1.10		603	0.87		0.87	4	0		0.00	
Calvert Cliffs 1 (orig.)	5/75	26.85 R	1.68		594	0.92		0.92	5	0		0.00	
Calvert Cliffs 2 (orig.)	4/77	25.95 R	1.80		594	0.98		0.98	6	0		0.00	
Calvert Cliffs 2 (repl.)	4/03	5.37	1.80		595	1.03		1.03	7	0		0.00	
Braidwood 1 (orig.)	7/88	10.20 R	1.24		608	1.19		1.19	8	0		0.00	
Oconee 1 (repl.)	10/03	4.92	1.50		604	1.23		1.23	9	0		0.00	
Ginna (repl.)	6/96	12.26	3.00		589	1.34		1.34	10	0		0.00	
Watts Bar 1 (repl.)	10/06	1.88	1.20		614	1.46		1.46	11	0		0.00	
Prairie Island 1 (orig.)	12/73	30.71 R	3.30		590	1.53		1.53	12	0		0.00	
Millstone 2 (orig.)	12/75	16.51 R	2.47		598	1.59		1.59	13	0		0.00	
Beaver Valley 1 (repl.)	2/06	2.55	1.50		611	1.62		1.62	14	0		0.00	
Palo Verde 3 (repl.)	10/07	0.84	1.50		612	1.69		1.69	15	0		0.00	
Cook 1 (orig.)	8/75	22.08 R	2.68		599	1.80		1.80	16	0		0.00	
Comanche Peak 1	7/90	16.68 R	1.30		618	1.85		1.85	17	0		0.00	
Watts Bar 1 (orig.)	5/96	10.00 R	1.40		617	1.92		1.92	18	0		0.00	
Cook 1 (repl.)	6/00	8.18	5.20		586	2.05		2.05	19	0		0.00	
Palo Verde 1 (repl.)	10/05	2.84	2.00		611	2.16		2.16	20	0		0.00	
Oconee 2 (repl.)	6/04	4.25	2.80		604	2.29		2.29	21	0		0.00	
Indian Point 2 (repl.)	7/00	8.18	5.40		589	2.41		2.41	22	0		0.00	
Kewaunee (orig.)	6/74	27.33 R	5.20		590	2.41		2.41	23	0		0.00	
Prairie Island 2 (orig.)	12/74	33.74	6.10		590	2.83		2.83	24	0		0.00	
Harris (orig.)	5/87	14.43 R	1.92		619	2.84		2.84	25	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	5.60		593	2.94		2.94	26	0		0.00	
Byron 1 (repl.)	2/98	10.59	2.90		610	3.02		3.02	27	0		0.00	
ANO 2 (repl.)	9/00	7.97	2.70		607	2.49		2.49	28	0		0.00	
Catawba 1 (orig.)	6/85	11.01 R	2.20		618	3.13		3.13	29	0		0.00	
Indian Point 2 (orig.)	8/74	25.85 R	7.63		588	3.26		3.26	30	0		0.00	
Point Beach 2 (orig.)	10/72	24.05 R	5.60		597	3.46		3.46	31	0		0.00	
ANO 2 (orig.)	11/80	19.88 R	4.20		607	3.88		3.88	32	0		0.00	
Palisades (repl.)	3/91	17.52	12.40		583	4.31		4.31	33	0		0.00	
South Texas 1 (repl.)	5/00	8.34	3.00		620	4.62		4.62	34	0		0.00	
Diablo Canyon 1	5/85	23.32	6.00		603	4.72		4.72	35	0		0.00	
Beaver Valley 1 (orig.)	10/76	29.35 R	5.30		607	4.89		4.89	36	0		0.00	
Salem 2 (orig.)	10/81	26.48 R	6.60		602	4.99		4.99	37	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	8.20		597	5.07		5.07	38	0		0.00	
Palo Verde 3 (orig.)	1/88	19.82 R	3.18		621	5.09		5.09	39	0		0.00	
McGuire 1 (orig.)	12/81	15.26 R	3.60		618	5.13		5.13	40	0		0.00	
Palo Verde 2 (repl.)	11/03	4.80	3.60		618	5.13		5.13	41	0		0.00	
Vogtle 2	5/89	19.30	3.60		618	5.13		5.13	42	0		0.00	
Waterford 3	9/85	23.02	8.04		599	5.38		5.38	43	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.30		599	5.56		5.56	44	0		0.00	
McGuire 2 (orig.)	3/84	13.60 R	4.10		618	5.84		5.84	45	0		0.00	
Sequoyah 1 (repl.)	3/03	5.47	5.40		611	5.85		5.85	46	0		0.00	
Davis Besse	7/78	30.19	6.90		608	6.63		6.63	47	0		0.00	
Callaway (orig.)	12/84	20.8 R	4.90		618	6.99		6.99	48	0		0.00	
Salem 1 (repl.)	11/97	10.84	9.40		602	7.11		7.11	49	0		0.00	
Crystal River 3	3/77	31.53	9.30		603	7.32		7.32	50	0		0.00	
Harris (repl.)	10/01	6.92	5.10		619	7.56		7.56	51	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	7.40		610	7.70		7.70	52	0		0.00	
Oconee 3 (orig.)	12/74	29.85 R	8.60		607	7.94		7.94	53	0		0.00	
Cook 2 (repl.)	3/89	19.52	10.10		606	8.96		8.96	54	0		0.00	
Fort Calhoun	9/73	34.96	18.00		593	9.45		9.45	55	0		0.00	
Millstone 3	4/86	22.40	7.10		617	9.73		9.73	56	0		0.00	
Summer (repl.)	12/94	13.76	6.70		619	9.93		9.93	57	0		0.00	
Oconee 1 (orig.)	7/73	30.24 R	10.90		607	10.07		10.07	58	0		0.00	
Sequoyah 1 (orig.)	7/80	23.00 R	10.10		609	10.10		10.10	59	0		0.00	
TMI1	9/74	34.02	13.00		603	10.23		10.23	60	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	16.90		597	10.44		10.44	61	0		0.00	
Oconee 2 (orig.)	9/74	29.52 R	11.50		607	10.62		10.62	62	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	14.30		602	10.81		10.81	63	0		0.00	
Robinson 2 (repl.)	10/84	23.93	13.50		604	11.06		11.06	64	0		0.00	
North Anna 1 (repl.)	4/93	15.43	9.70		613	11.36		11.36	65	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	15.10		602	11.42		11.42	66	0		0.00	
Wolf Creek	9/85	23.02	8.10		618	11.54		11.54	67	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15		12.15	68	0		0.00	
Sequoyah 2	6/82	26.23	12.20		609	12.20		12.20	69	0		0.00	
McGuire 1 (repl.)	5/97	11.35	8.30		619	12.30		12.30	70	0		0.00	
St. Lucie 2 (orig.)	8/83	24.18 R	18.70		599	12.53		12.53	71	0		0.00	
Diablo Canyon 2 (orig	3/86	22.70 R	17.10		603	13.46		13.46	72	0		0.00	
Beaver Valley 2	11/87	20.81	15.60		606	13.84		13.84	73	0		0.00	
Vogtle 1	5/87	21.27	9.80		618	13.96		13.96	74	0		0.00	
Surry 2 (repl.)	9/80	28.02	17.80		605	15.18		15.18	75	0		0.00	
San Onofre 2	8/83	25.10	15.54		609	15.54		15.54	76	0		0.00	
Surry 1 (repl.)	7/81	27.19	18.90		605	16.12		16.12	77	0		0.00	
San Onofre 3	4/84	24.44	16.18		609	16.18		16.18	78	0		0.00	
Braidwood 2	10/88	19.93	16.84		611	18.23		18.23	79	0		0.00	
Byron 2	8/87	21.05	17.59		611	19.04		19.04	80	0		0.00	
Comanche Peak 2	8/93	15.10	13.00		619	19.26		19.26	81	0		0.00	
Catawba 2	8/86	22.10	15.41		615	19.53		19.53	82	0		0.00	
Seabrook	7/90	18.18	14.30		618	20.38		20.38	83	0		0.00	
				Ave. Thot=	606								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-17
Time to First Axial PWSCC – Alloy 690TT Mechanical and Rolled Tube Plugs

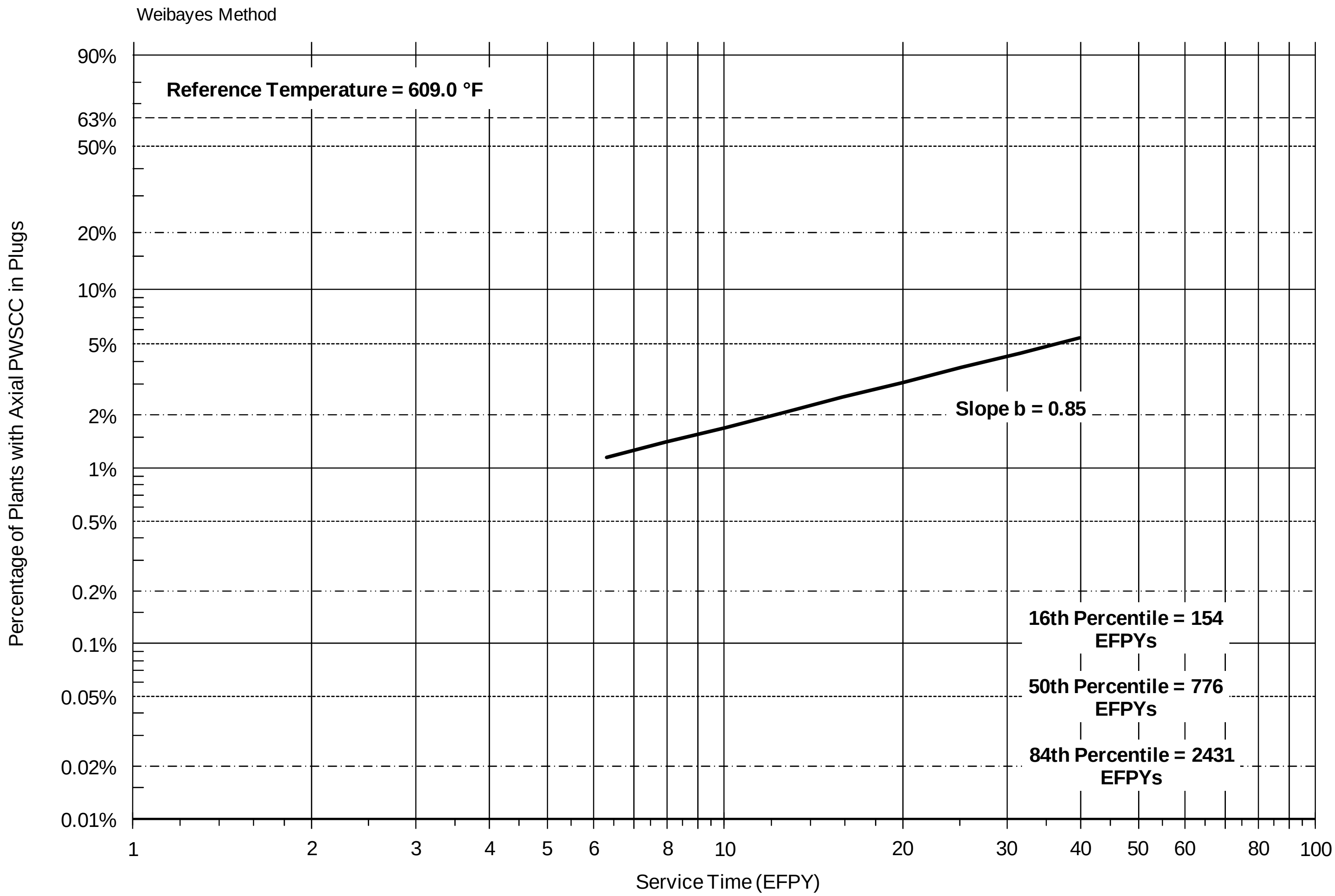

Figure 4-18
Time to First Axial PWSCC – Alloy 690TT Mechanical and Rolled Tube Plugs-Weibayes Analysis

Time to First Axial PWSCC - Mechanical A690 TT Plugs

No. Plants = 45 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 45	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Waterford 3	9/85	23.02	1.14		599	0.76		0.76	1	0		0.00	
Braidwood 1 (orig.)	7/88	10.20 R	1.24		608	1.19		1.19	2	0		0.00	
Ginna (repl.)	6/96	12.26	3.0		589	1.34		1.34	3	0		0.00	
Millstone 2 (orig.)	12/75	16.51 R	2.47		598	1.59		1.59	4	0		0.00	
Beaver Valley 1 (repl.)	2/06	2.55	1.50		611	1.62		1.62	5	0		0.00	
Cook 1 (orig.)	8/75	22.08 R	2.68		599	1.80		1.80	6	0		0.00	
Comanche Peak 1	7/90	16.68 R	1.30		618	1.85		1.85	7	0		0.00	
Kewaunee (orig.)	6/74	27.33 R	4.00		590	1.86		1.86	8	0		0.00	
Watts Bar 1 (orig.)	5/96	10.00 R	1.40		617	1.92		1.92	9	0		0.00	
Indian Point 2 (repl.)	7/00	8.18	5.40		589	2.41		2.41	10	0		0.00	
Harris (orig.)	5/87	14.43 R	1.92		619	2.84		2.84	11	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	5.60		593	2.94		2.94	12	0		0.00	
Byron 1 (repl.)	2/98	10.59	2.90		610	3.02		3.02	13	0		0.00	
Indian Point 2 (orig.)	8/74	25.85 R	7.63		588	3.26		3.26	14	0		0.00	
Point Beach 2 (orig.)	10/72	24.05 R	5.6		597	3.46		3.46	15	0		0.00	
Palisades (repl.)	3/91	17.52	10.10		583	3.51		3.51	16	0		0.00	
Harris (repl.)	10/01	6.92	2.90		619	4.30		4.30	17	0		0.00	
South Texas 1 (repl.)	5/00	8.34	3.00		620	4.62		4.62	18	0		0.00	
Beaver Valley 1 (orig.)	10/76	29.35 R	5.30		607	4.89		4.89	19	0		0.00	
Palo Verde 2 (repl.)	11/03	4.80	3.60		618	5.13		5.13	20	0		0.00	
Vogtle 2	5/89	19.30	3.60		618	5.13		5.13	21	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.30		599	5.56		5.56	22	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	7.40		610	7.70		7.70	23	0		0.00	
Cook 2 (repl.)	3/89	19.52	10.10		606	8.96		8.96	24	0		0.00	
Fort Calhoun	9/73	34.96	18.00		593	9.45		9.45	25	0		0.00	
Sequoyah 1 (orig.)	7/80	23.00 R	10.10		609	10.10		10.10	26	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	16.90		597	10.44		10.44	27	0		0.00	
Byron 2	8/87	21.05	9.87		611	10.68		10.68	28	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	14.30		602	10.81		10.81	29	0		0.00	
Robinson 2 (repl.)	10/84	23.93	13.50		604	11.06		11.06	30	0		0.00	
North Anna 1 (repl.)	4/93	15.43	9.70		613	11.36		11.36	31	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	15.10		602	11.42		11.42	32	0		0.00	
Wolf Creek	9/85	23.02	8.10		618	11.54		11.54	33	0		0.00	
Catawba 2	8/86	22.10	9.51		615	12.05		12.05	34	0		0.00	
Sequoyah 2	6/82	26.23	12.20		609	12.20		12.20	35	0		0.00	
St. Lucie 2 (orig.)	8/83	24.18 R	18.70		599	12.53		12.53	36	0		0.00	
Beaver Valley 2	11/87	20.81	14.60		606	12.96		12.96	37	0		0.00	
Diablo Canyon 2 (orig	3/86	22.70 R	17.10		603	13.46		13.46	38	0		0.00	
Vogtle 1	5/87	21.27	9.80		618	13.96		13.96	39	0		0.00	
Surry 2 (repl.)	9/80	28.02	17.80		605	15.18		15.18	40	0		0.00	
San Onofre 3	4/84	24.44	15.97		609	15.97		15.97	41	0		0.00	
Surry 1 (repl.)	7/81	27.19	18.90		605	16.12		16.12	42	0		0.00	
Braidwood 2	10/88	19.93	16.84		611	18.23		18.23	43	0		0.00	
Comanche Peak 2	8/93	15.10	13.00		619	19.26		19.26	44	0		0.00	
Seabrook	7/90	18.18	14.30		618	20.38		20.38	45	0		0.00	
				Ave. Thot=	606								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-19
Time to First Axial PWSCC –Alloy 690TT Mechanical Tube Plugs

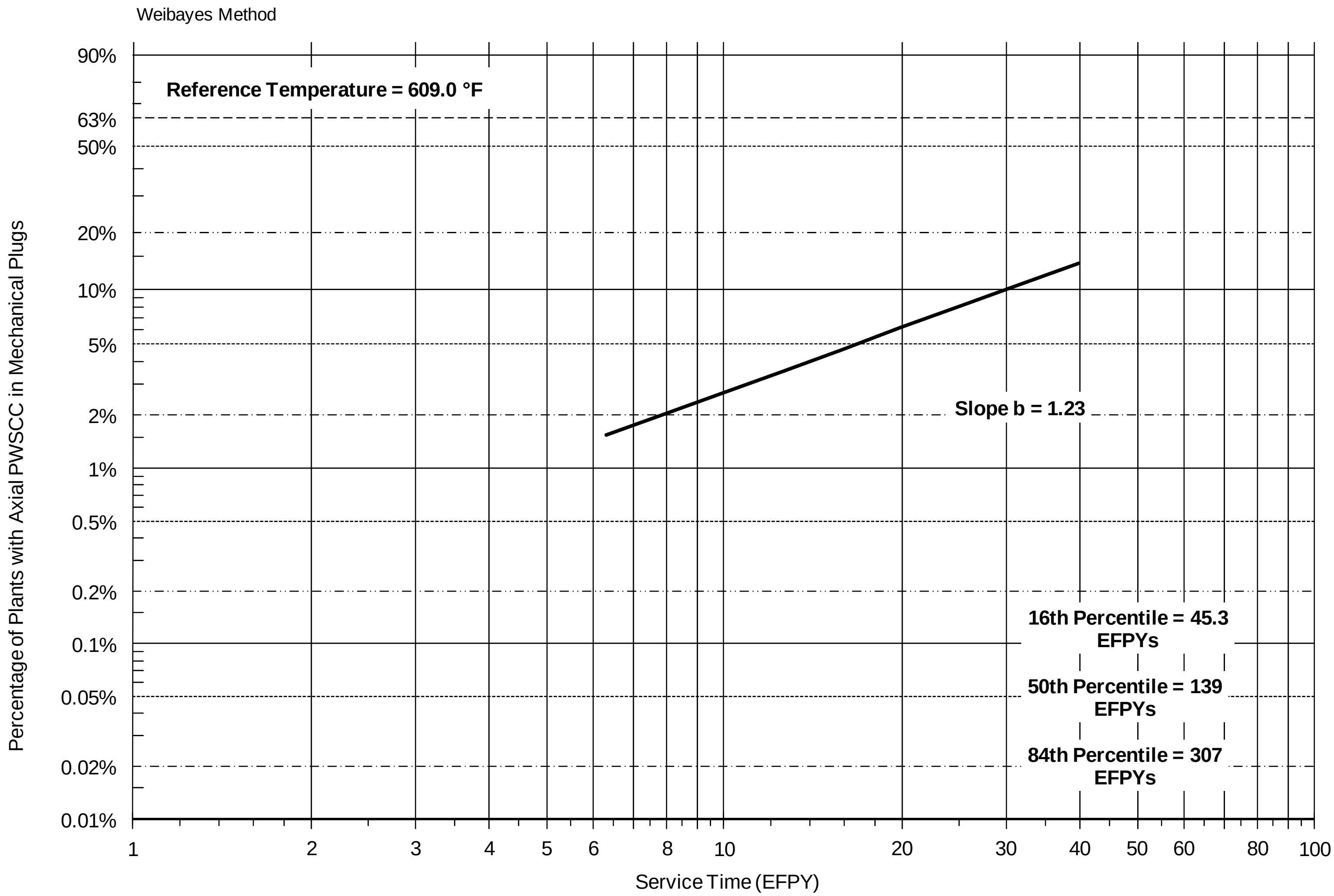

Figure 4-20
Time to First Axial PWSCC – Alloy 690TT Mechanical Tube Plugs-Weibayes Analysis

Time to First Axial PWSCC - Rolled A690 TT Plugs

No. Plants = 57 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to First PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 57	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
ANO 1 (repl.)	11/05	2.80	0.10		603	0.08		0.08	1	0		0.00	
Cook 1 (orig.)	8/75	22.08 R	0.26		599	0.18		0.18	2	0		0.00	
Ginna (orig.)	7/70	25.77 R	0.70		589	0.31		0.31	3	0		0.00	
Prairie Island 1 (repl.)	9/04	4.00	1.6		590	0.74		0.74	4	0		0.00	
ANO 1 (orig.)	12/74	30.77 R	1.10		603	0.87		0.87	5	0		0.00	
Calvert Cliffs 1 (orig.)	5/75	26.85 R	1.68		594	0.92		0.92	6	0		0.00	
Calvert Cliffs 2 (orig.)	4/77	25.95 R	1.80		594	0.98		0.98	7	0		0.00	
Calvert Cliffs 2 (repl.)	4/03	5.37	1.80		595	1.03		1.03	8	0		0.00	
Oconee 1 (repl.)	10/03	4.92	1.50		604	1.23		1.23	9	0		0.00	
Watts Bar 1 (repl.)	10/06	1.88	1.20		614	1.46		1.46	10	0		0.00	
Prairie Island 1 (orig.)	12/73	30.71 R	3.3		590	1.53		1.53	11	0		0.00	
Palo Verde 3 (repl.)	10/07	0.84	1.50		612	1.69		1.69	12	0		0.00	
Cook 1 (repl.)	6/00	8.18	5.20		586	2.05		2.05	13	0		0.00	
Palo Verde 1 (repl.)	10/05	2.84	2.00		611	2.16		2.16	14	0		0.00	
Oconee 2 (repl.)	6/04	4.25	2.80		604	2.29		2.29	15	0		0.00	
Surry 2 (repl.)	9/80	28.02	2.70		605	2.30		2.30	16	0		0.00	
Surry 1 (repl.)	7/81	27.19	2.80		605	2.39		2.39	17	0		0.00	
Kewaunee (orig.)	6/74	27.33 R	5.20		590	2.41		2.41	18	0		0.00	
Sequoyah 1 (orig.)	7/80	23.00 R	2.70		609	2.70		2.70	19	0		0.00	
Prairie Island 2 (orig.)	12/74	33.74	6.1		590	2.83		2.83	20	0		0.00	
ANO 2 (repl.)	9/00	7.97	2.70		607	2.49		2.49	21	0		0.00	
Catawba 1 (orig.)	6/85	11.01 R	2.20		618	3.13		3.13	22	0		0.00	
Robinson 2 (repl.)	10/84	23.93	4.70		604	3.85		3.85	23	0		0.00	
ANO 2 (orig.)	11/80	19.88 R	4.20		607	3.88		3.88	24	0		0.00	
Palisades (repl.)	3/91	17.52	12.40		583	4.31		4.31	25	0		0.00	
Diablo Canyon 1	5/85	23.32	6.00		603	4.72		4.72	26	0		0.00	
North Anna 1 (repl.)	4/93	15.43	4.20		613	4.92		4.92	27	0		0.00	
Salem 2 (orig.)	10/81	26.48 R	6.60		602	4.99		4.99	28	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	8.20		597	5.07		5.07	29	0		0.00	
Palo Verde 3 (orig.)	1/88	19.82 R	3.18		621	5.09		5.09	30	0		0.00	
McGuire 1 (orig.)	12/81	15.26 R	3.60		618	5.13		5.13	31	0		0.00	
Waterford 3	9/85	23.02	8.04		599	5.38		5.38	32	0		0.00	
McGuire 2 (orig.)	3/84	13.60 R	4.10		618	5.84		5.84	33	0		0.00	
Sequoyah 1 (repl.)	3/03	5.47	5.40		611	5.85		5.85	34	0		0.00	
Davis Besse	7/78	30.19	6.90		608	6.63		6.63	35	0		0.00	
Sequoyah 2	6/82	26.23	6.80		609	6.80		6.80	36	0		0.00	
Cook 2 (repl.)	3/89	19.52	7.70		606	6.83		6.83	37	0		0.00	
Callaway (orig.)	12/84	20.8 R	4.90		618	6.99		6.99	38	0		0.00	
Salem 1 (repl.)	11/97	10.84	9.40		602	7.11		7.11	39	0		0.00	
Crystal River 3	3/77	31.53	9.30		603	7.32		7.32	40	0		0.00	
Harris (repl.)	10/01	6.92	5.10		619	7.56		7.56	41	0		0.00	
Oconee 3 (orig.)	12/74	29.85 R	8.60		607	7.94		7.94	42	0		0.00	
St. Lucie 2 (orig.)	8/83	24.18 R	12.10		599	8.11		8.11	43	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	13.50		597	8.34		8.34	44	0		0.00	
Diablo Canyon 2 (orig	3/86	22.70 R	10.70		603	8.42		8.42	45	0		0.00	
Millstone 3	4/86	22.40	7.10		617	9.73		9.73	46	0		0.00	
Summer (repl.)	12/94	13.76	6.70		619	9.93		9.93	47	0		0.00	
Oconee 1 (orig.)	7/73	30.24 R	10.90		607	10.07		10.07	48	0		0.00	
TMI1	9/74	34.02	13.00		603	10.23		10.23	49	0		0.00	
Oconee 2 (orig.)	9/74	29.52 R	11.50		607	10.62		10.62	50	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15		12.15	51	0		0.00	
McGuire 1 (repl.)	5/97	11.35	8.30		619	12.30		12.30	52	0		0.00	
Beaver Valley 2	11/87	20.81	15.60		606	13.84		13.84	53	0		0.00	
San Onofre 2	8/83	25.10	15.54		609	15.54		15.54	54	0		0.00	
San Onofre 3	4/84	24.44	16.18		609	16.18		16.18	55	0		0.00	
Byron 2	8/87	21.05	17.59		611	19.04		19.04	56	0		0.00	
Catawba 2	8/86	22.10	15.41		615	19.53		19.53	57	0		0.00	

Ave. Thot= 605

Reference Temperature
609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with at least one TT Alloy 600 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-21
Time to First Axial PWSCC – Alloy 690TT Rolled Tube Plugs

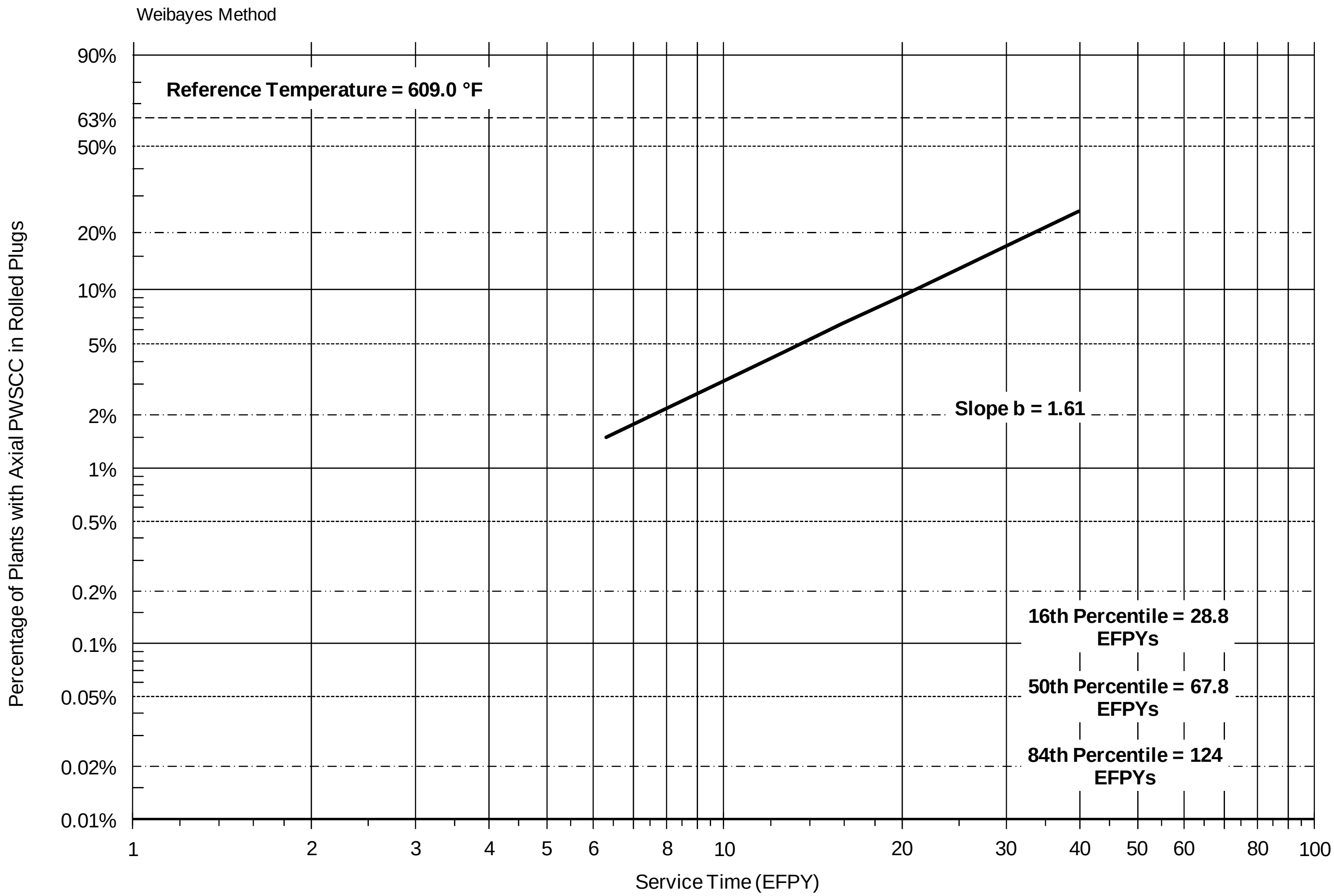

Figure 4-22
Time to First Axial PWSCC – Alloy 690TT Rolled Tube Plugs-Weibayes Analysis

Time to First Circumferential PWSCC - Mechanical and Rolled A690 TT Plugs

No. Plants = 83 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 83	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
ANO 1 (repl.)	11/05	2.80	0.10		603	0.08		0.08	1	0		0.00	
Ginna (orig.)	7/70	25.77 R	0.70		589	0.31		0.31	2	0		0.00	
Prairie Island 1 (repl.)	9/04	4.00	1.60		590	0.74		0.74	3	0		0.00	
ANO 1 (orig.)	12/74	30.77 R	1.10		603	0.87		0.87	4	0		0.00	
Calvert Cliffs 1 (orig.)	5/75	26.85 R	1.68		594	0.92		0.92	5	0		0.00	
Calvert Cliffs 2 (orig.)	4/77	25.95 R	1.80		594	0.98		0.98	6	0		0.00	
Calvert Cliffs 2 (repl.)	4/03	5.37	1.80		595	1.03		1.03	7	0		0.00	
Braidwood 1 (orig.)	7/88	10.20 R	1.24		608	1.19		1.19	8	0		0.00	
Oconee 1 (repl.)	10/03	4.92	1.50		604	1.23		1.23	9	0		0.00	
Ginna (repl.)	6/96	12.26	3.00		589	1.34		1.34	10	0		0.00	
Watts Bar 1 (repl.)	10/06	1.88	1.20		614	1.46		1.46	11	0		0.00	
Prairie Island 1 (orig.)	12/73	30.71 R	3.30		590	1.53		1.53	12	0		0.00	
Millstone 2 (orig.)	12/75	16.51 R	2.47		598	1.59		1.59	13	0		0.00	
Beaver Valley 1 (repl.)	2/06	2.55	1.50		611	1.62		1.62	14	0		0.00	
Palo Verde 3 (repl.)	10/07	0.84	1.50		612	1.69		1.69	15	0		0.00	
Cook 1 (orig.)	8/75	22.08 R	2.68		599	1.80		1.80	16	0		0.00	
Comanche Peak 1	7/90	16.68 R	1.30		618	1.85		1.85	17	0		0.00	
Watts Bar 1 (orig.)	5/96	10.00 R	1.40		617	1.92		1.92	18	0		0.00	
Cook 1 (repl.)	6/00	8.18	5.20		586	2.05		2.05	19	0		0.00	
Palo Verde 1 (repl.)	10/05	2.84	2.00		611	2.16		2.16	20	0		0.00	
Oconee 2 (repl.)	6/04	4.25	2.80		604	2.29		2.29	21	0		0.00	
Indian Point 2 (repl.)	7/00	8.18	5.40		589	2.41		2.41	22	0		0.00	
Kewaunee (orig.)	6/74	27.33 R	5.20		590	2.41		2.41	23	0		0.00	
Prairie Island 2 (orig.)	12/74	33.74	6.10		590	2.83		2.83	24	0		0.00	
Harris (orig.)	5/87	14.43 R	1.92		619	2.84		2.84	25	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	5.60		593	2.94		2.94	26	0		0.00	
Byron 1 (repl.)	2/98	10.59	2.90		610	3.02		3.02	27	0		0.00	
ANO 2 (repl.)	9/00	7.97	2.70		607	2.49		2.49	28	0		0.00	
Catawba 1 (orig.)	6/85	11.01 R	2.20		618	3.13		3.13	29	0		0.00	
Indian Point 2 (orig.)	8/74	25.85 R	7.63		588	3.26		3.26	30	0		0.00	
Point Beach 2 (orig.)	10/72	24.05 R	5.60		597	3.46		3.46	31	0		0.00	
ANO 2 (orig.)	11/80	19.88 R	4.20		607	3.88		3.88	32	0		0.00	
Palisades (repl.)	3/91	17.52	12.40		583	4.31		4.31	33	0		0.00	
South Texas 1 (repl.)	5/00	8.34	3.00		620	4.62		4.62	34	0		0.00	
Diablo Canyon 1	5/85	23.32	6.00		603	4.72		4.72	35	0		0.00	
Beaver Valley 1 (orig.)	10/76	29.35 R	5.30		607	4.89		4.89	36	0		0.00	
Salem 2 (orig.)	10/81	26.48 R	6.60		602	4.99		4.99	37	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	8.20		597	5.07		5.07	38	0		0.00	
Palo Verde 3 (orig.)	1/88	19.82 R	3.18		621	5.09		5.09	39	0		0.00	
McGuire 1 (orig.)	12/81	15.26 R	3.60		618	5.13		5.13	40	0		0.00	
Palo Verde 2 (repl.)	11/03	4.80	3.60		618	5.13		5.13	41	0		0.00	
Vogtle 2	5/89	19.30	3.60		618	5.13		5.13	42	0		0.00	
Waterford 3	9/85	23.02	8.04		599	5.38		5.38	43	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.30		599	5.56		5.56	44	0		0.00	
McGuire 2 (orig.)	3/84	13.60 R	4.10		618	5.84		5.84	45	0		0.00	
Sequoyah 1 (repl.)	3/03	5.47	5.40		611	5.85		5.85	46	0		0.00	
Davis Besse	7/78	30.19	6.90		608	6.63		6.63	47	0		0.00	
Callaway (orig.)	12/84	20.8 R	4.90		618	6.99		6.99	48	0		0.00	
Salem 1 (repl.)	11/97	10.84	9.40		602	7.11		7.11	49	0		0.00	
Crystal River 3	3/77	31.53	9.30		603	7.32		7.32	50	0		0.00	
Harris (repl.)	10/01	6.92	5.10		619	7.56		7.56	51	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	7.40		610	7.70		7.70	52	0		0.00	
Oconee 3 (orig.)	12/74	29.85 R	8.60		607	7.94		7.94	53	0		0.00	
Cook 2 (repl.)	3/89	19.52	10.10		606	8.96		8.96	54	0		0.00	
Fort Calhoun	9/73	34.96	18.00		593	9.45		9.45	55	0		0.00	
Millstone 3	4/86	22.40	7.10		617	9.73		9.73	56	0		0.00	
Summer (repl.)	12/94	13.76	6.70		619	9.93		9.93	57	0		0.00	
Oconee 1 (orig.)	7/73	30.24 R	10.90		607	10.07		10.07	58	0		0.00	
Sequoyah 1 (orig.)	7/80	23.00 R	10.10		609	10.10		10.10	59	0		0.00	
TMI1	9/74	34.02	13.00		603	10.23		10.23	60	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	16.90		597	10.44		10.44	61	0		0.00	
Oconee 2 (orig.)	9/74	29.52 R	11.50		607	10.62		10.62	62	0		0.00	
Turkey Point 4 (repl.)	5/83	25.36	14.30		602	10.81		10.81	63	0		0.00	
Robinson 2 (repl.)	10/84	23.93	13.50		604	11.06		11.06	64	0		0.00	
North Anna 1 (repl.)	4/93	15.43	9.70		613	11.36		11.36	65	0		0.00	
Turkey Point 3 (repl.)	4/82	26.44	15.10		602	11.42		11.42	66	0		0.00	
Wolf Creek	9/85	23.02	8.10		618	11.54		11.54	67	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15		12.15	68	0		0.00	
Sequoyah 2	6/82	26.23	12.20		609	12.20		12.20	69	0		0.00	
McGuire 1 (repl.)	5/97	11.35	8.30		619	12.30		12.30	70	0		0.00	
St. Lucie 2 (orig.)	8/83	24.18 R	18.70		599	12.53		12.53	71	0		0.00	
Diablo Canyon 2 (orig	3/86	22.70 R	17.10		603	13.46		13.46	72	0		0.00	
Beaver Valley 2	11/87	20.81	15.60		606	13.84		13.84	73	0		0.00	
Vogtle 1	5/87	21.27	9.80		618	13.96		13.96	74	0		0.00	
Surry 2 (repl.)	9/80	28.02	17.80		605	15.18		15.18	75	0		0.00	
San Onofre 2	8/83	25.10	15.54		609	15.54		15.54	76	0		0.00	
Surry 1 (repl.)	7/81	27.19	18.90		605	16.12		16.12	77	0		0.00	
San Onofre 3	4/84	24.44	16.18		609	16.18		16.18	78	0		0.00	
Braidwood 2	10/88	19.93	16.84		611	18.23		18.23	79	0		0.00	
Byron 2	8/87	21.05	17.59		611	19.04		19.04	80	0		0.00	
Comanche Peak 2	8/93	15.10	13.00		619	19.26		19.26	81	0		0.00	
Catawba 2	8/86	22.10	15.41		615	19.53		19.53	82	0		0.00	
Seabrook	7/90	18.18	14.30		618	20.38		20.38	83	0		0.00	

Ave. Thot= 606

Reference Temperature
609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with at least one TT Alloy 690 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-23
Time to First Circumferential PWSCC – Alloy 690TT Mechanical and Rolled Tube Plugs

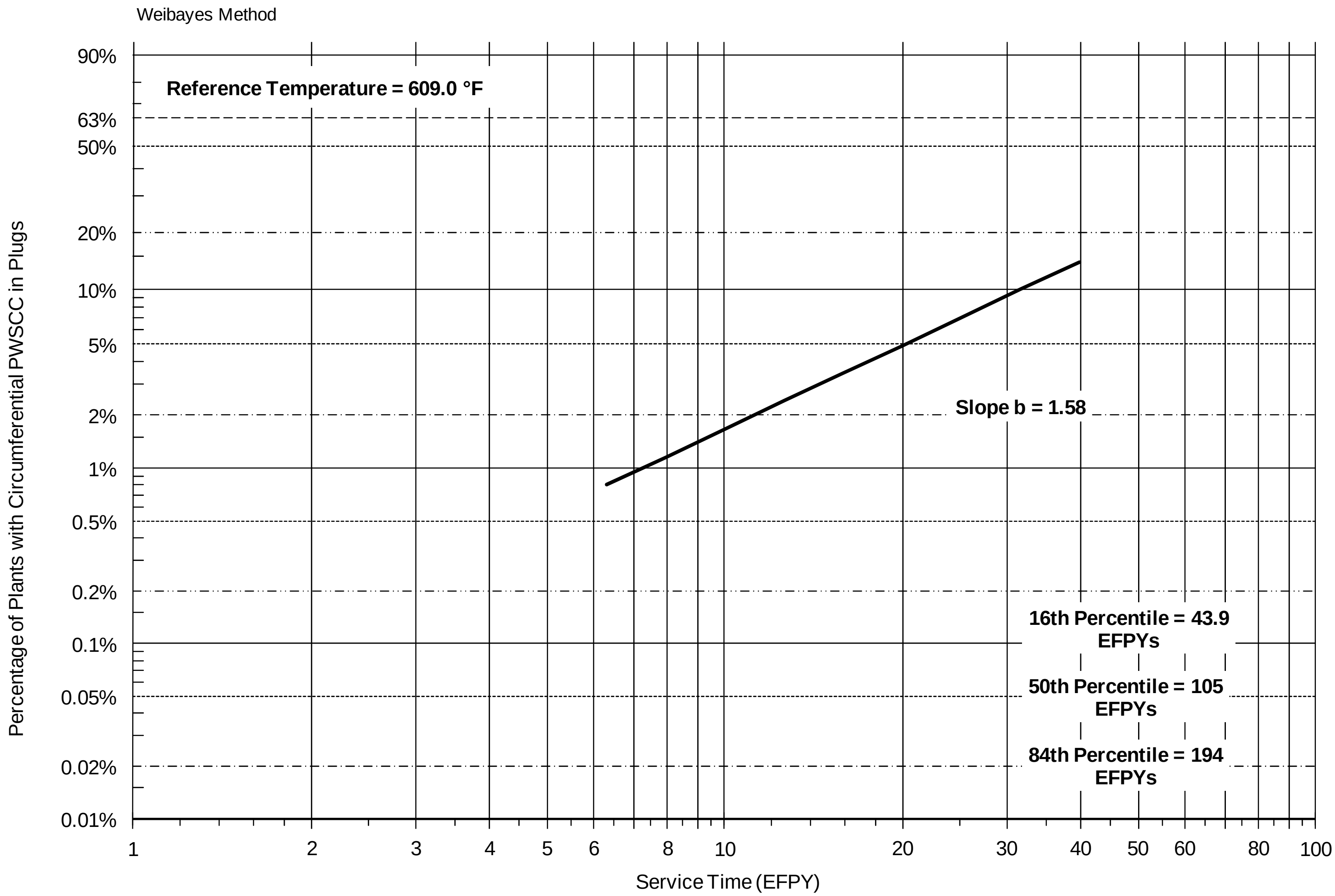

Figure 4-24
Time to First Circumferential PWSCC – Alloy 690TT Mechanical and Rolled Tube Plugs-Weibayes Analysis

Time to First Circumferential PWSCC - Mechanical A690 TT Plugs

No. Plants = 45 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 45	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Waterford 3	9/85	23.02	1.14		599	0.76		0.76	1	0			0.00
Braidwood 1 (orig.)	7/88	10.20 R	1.24		608	1.19		1.19	2	0			0.00
Ginna (repl.)	6/96	12.26	3.0		589	1.34		1.34	3	0			0.00
Millstone 2 (orig.)	12/75	16.51 R	2.47		598	1.59		1.59	4	0			0.00
Beaver Valley 1 (repl.)	2/06	2.55	1.50		611	1.62		1.62	5	0			0.00
Cook 1 (orig.)	8/75	22.08 R	2.68		599	1.80		1.80	6	0			0.00
Comanche Peak 1	7/90	16.68 R	1.30		618	1.85		1.85	7	0			0.00
Kewaunee (orig.)	6/74	27.33 R	4.00		590	1.86		1.86	8	0			0.00
Watts Bar 1 (orig.)	5/96	10.00 R	1.40		617	1.92		1.92	9	0			0.00
Indian Point 2 (repl.)	7/00	8.18	5.40		589	2.41		2.41	10	0			0.00
Harris (orig.)	5/87	14.43 R	1.92		619	2.84		2.84	11	0			0.00
Indian Point 3 (repl.)	6/89	19.27	5.60		593	2.94		2.94	12	0			0.00
Byron 1 (repl.)	2/98	10.59	2.90		610	3.02		3.02	13	0			0.00
Indian Point 2 (orig.)	8/74	25.85 R	7.63		588	3.26		3.26	14	0			0.00
Point Beach 2 (orig.)	10/72	24.05 R	5.6		597	3.46		3.46	15	0			0.00
Palisades (repl.)	3/91	17.52	10.10		583	3.51		3.51	16	0			0.00
Harris (repl.)	10/01	6.92	2.90		619	4.30		4.30	17	0			0.00
South Texas 1 (repl.)	5/00	8.34	3.00		620	4.62		4.62	18	0			0.00
Beaver Valley 1 (orig.)	10/76	29.35 R	5.30		607	4.89		4.89	19	0			0.00
Palo Verde 2 (repl.)	11/03	4.80	3.60		618	5.13		5.13	20	0			0.00
Vogtle 2	5/89	19.30	3.60		618	5.13		5.13	21	0			0.00
St. Lucie 1 (repl.)	1/98	10.67	8.30		599	5.56		5.56	22	0			0.00
Braidwood 1 (repl.)	9/98	9.98	7.40		610	7.70		7.70	23	0			0.00
Cook 2 (repl.)	3/89	19.52	10.10		606	8.96		8.96	24	0			0.00
Fort Calhoun	9/73	34.96	18.00		593	9.45		9.45	25	0			0.00
Sequoyah 1 (orig.)	7/80	23.00 R	10.10		609	10.10		10.10	26	0			0.00
Point Beach 1 (repl.)	3/84	24.52	16.90		597	10.44		10.44	27	0			0.00
Byron 2	8/87	21.05	9.87		611	10.68		10.68	28	0			0.00
Turkey Point 4 (repl.)	5/83	25.36	14.30		602	10.81		10.81	29	0			0.00
Robinson 2 (repl.)	10/84	23.93	13.50		604	11.06		11.06	30	0			0.00
North Anna 1 (repl.)	4/93	15.43	9.70		613	11.36		11.36	31	0			0.00
Turkey Point 3 (repl.)	4/82	26.44	15.10		602	11.42		11.42	32	0			0.00
Wolf Creek	9/85	23.02	8.10		618	11.54		11.54	33	0			0.00
Catawba 2	8/86	22.10	9.51		615	12.05		12.05	34	0			0.00
Sequoyah 2	6/82	26.23	12.20		609	12.20		12.20	35	0			0.00
St. Lucie 2 (orig.)	8/83	24.18 R	18.70		599	12.53		12.53	36	0			0.00
Beaver Valley 2	11/87	20.81	14.60		606	12.96		12.96	37	0			0.00
Diablo Canyon 2 (orig	3/86	22.70 R	17.10		603	13.46		13.46	38	0			0.00
Vogtle 1	5/87	21.27	9.80		618	13.96		13.96	39	0			0.00
Surry 2 (repl.)	9/80	28.02	17.80		605	15.18		15.18	40	0			0.00
San Onofre 3	4/84	24.44	15.97		609	15.97		15.97	41	0			0.00
Surry 1 (repl.)	7/81	27.19	18.90		605	16.12		16.12	42	0			0.00
Braidwood 2	10/88	19.93	16.84		611	18.23		18.23	43	0			0.00
Comanche Peak 2	8/93	15.10	13.00		619	19.26		19.26	44	0			0.00
Seabrook	7/90	18.18	14.30		618	20.38		20.38	45	0			0.00
				Ave. Thot=	606								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 690 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-25
Time to First Circumferential PWSCC – Alloy 690TT Mechanical Tube Plugs

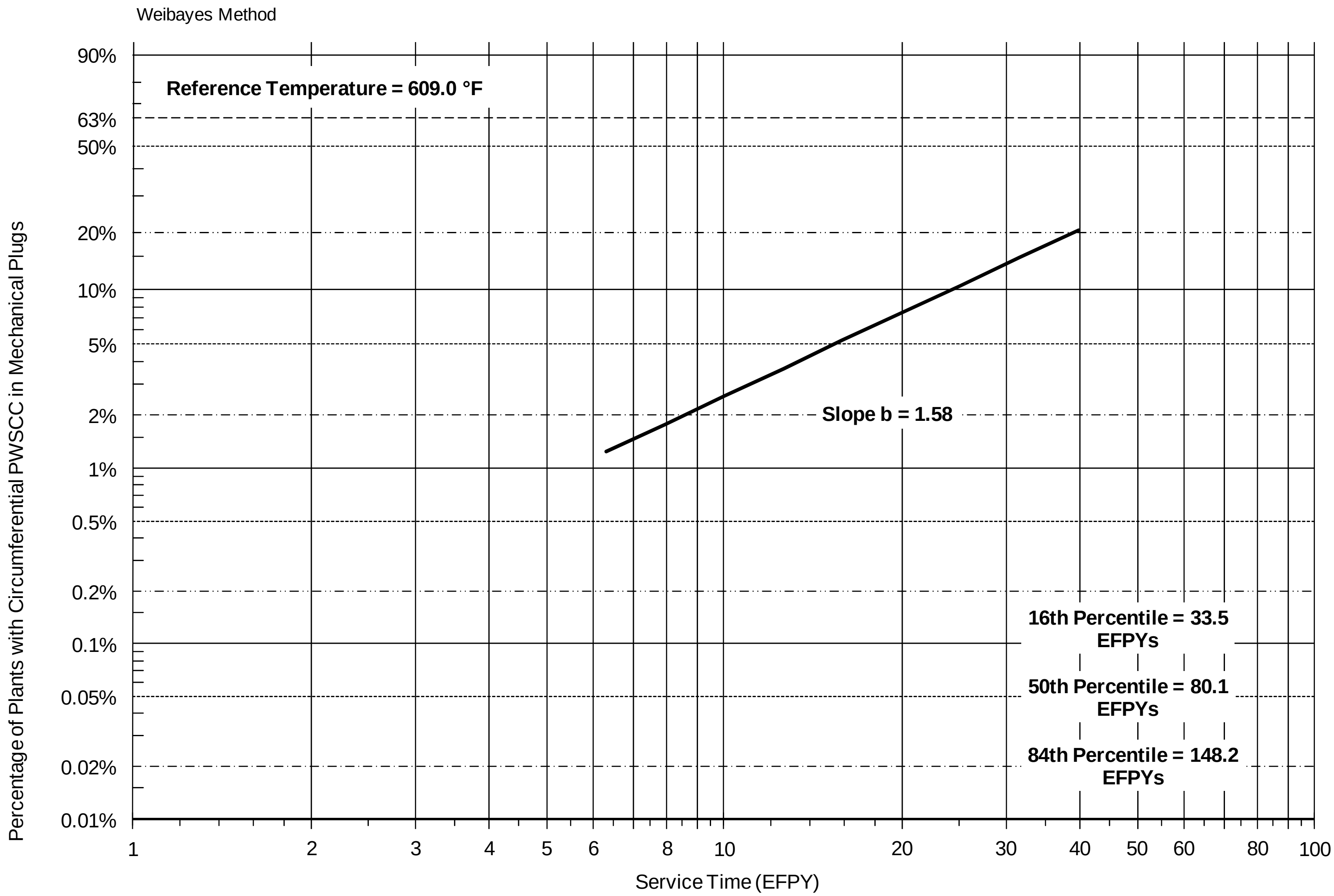

Figure 4-26
Time to First Circumferential PWSCC – Alloy 690TT Mechanical Tube Plugs-Weibayes Analysis

Time to First Circumferential PWSCC - Rolled A690 TT Plugs

No. Plants = 57 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs of Oldest Plug (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 57	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
ANO 1 (repl.)	11/05	2.80	0.10		603	0.08		0.08	1	0		0.00	
Cook 1 (orig.)	8/75	22.08 R	0.26		599	0.18		0.18	2	0		0.00	
Ginna (orig.)	7/70	25.77 R	0.70		589	0.31		0.31	3	0		0.00	
Prairie Island 1 (repl.)	9/04	4.00	1.6		590	0.74		0.74	4	0		0.00	
ANO 1 (orig.)	12/74	30.77 R	1.10		603	0.87		0.87	5	0		0.00	
Calvert Cliffs 1 (orig.)	5/75	26.85 R	1.68		594	0.92		0.92	6	0		0.00	
Calvert Cliffs 2 (orig.)	4/77	25.95 R	1.80		594	0.98		0.98	7	0		0.00	
Calvert Cliffs 2 (repl.)	4/03	5.37	1.80		595	1.03		1.03	8	0		0.00	
Oconee 1 (repl.)	10/03	4.92	1.50		604	1.23		1.23	9	0		0.00	
Watts Bar 1 (repl.)	10/06	1.88	1.20		614	1.46		1.46	10	0		0.00	
Prairie Island 1 (orig.)	12/73	30.71 R	3.3		590	1.53		1.53	11	0		0.00	
Palo Verde 3 (repl.)	10/07	0.84	1.50		612	1.69		1.69	12	0		0.00	
Cook 1 (repl.)	6/00	8.18	5.20		586	2.05		2.05	13	0		0.00	
Palo Verde 1 (repl.)	10/05	2.84	2.00		611	2.16		2.16	14	0		0.00	
Oconee 2 (repl.)	6/04	4.25	2.80		604	2.29		2.29	15	0		0.00	
Surry 2 (repl.)	9/80	28.02	2.70		605	2.30		2.30	16	0		0.00	
Surry 1 (repl.)	7/81	27.19	2.80		605	2.39		2.39	17	0		0.00	
Kewaunee (orig.)	6/74	27.33 R	5.20		590	2.41		2.41	18	0		0.00	
Sequoyah 1 (orig.)	7/80	23.00 R	2.70		609	2.70		2.70	19	0		0.00	
Prairie Island 2 (orig.)	12/74	33.74	6.1		590	2.83		2.83	20	0		0.00	
ANO 2 (repl.)	9/00	7.97	2.70		607	2.49		2.49	21	0		0.00	
Catawba 1 (orig.)	6/85	11.01 R	2.20		618	3.13		3.13	22	0		0.00	
Robinson 2 (repl.)	10/84	23.93	4.70		604	3.85		3.85	23	0		0.00	
ANO 2 (orig.)	11/80	19.88 R	4.20		607	3.88		3.88	24	0		0.00	
Palisades (repl.)	3/91	17.52	12.40		583	4.31		4.31	25	0		0.00	
Diablo Canyon 1	5/85	23.32	6.00		603	4.72		4.72	26	0		0.00	
North Anna 1 (repl.)	4/93	15.43	4.20		613	4.92		4.92	27	0		0.00	
Salem 2 (orig.)	10/81	26.48 R	6.60		602	4.99		4.99	28	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	8.20		597	5.07		5.07	29	0		0.00	
Palo Verde 3 (orig.)	1/88	19.82 R	3.18		621	5.09		5.09	30	0		0.00	
McGuire 1 (orig.)	12/81	15.26 R	3.60		618	5.13		5.13	31	0		0.00	
Waterford 3	9/85	23.02	8.04		599	5.38		5.38	32	0		0.00	
McGuire 2 (orig.)	3/84	13.60 R	4.10		618	5.84		5.84	33	0		0.00	
Sequoyah 1 (repl.)	3/03	5.47	5.40		611	5.85		5.85	34	0		0.00	
Davis Besse	7/78	30.19	6.90		608	6.63		6.63	35	0		0.00	
Sequoyah 2	6/82	26.23	6.80		609	6.80		6.80	36	0		0.00	
Cook 2 (repl.)	3/89	19.52	7.70		606	6.83		6.83	37	0		0.00	
Callaway (orig.)	12/84	20.8 R	4.90		618	6.99		6.99	38	0		0.00	
Salem 1 (repl.)	11/97	10.84	9.40		602	7.11		7.11	39	0		0.00	
Crystal River 3	3/77	31.53	9.30		603	7.32		7.32	40	0		0.00	
Harris (repl.)	10/01	6.92	5.10		619	7.56		7.56	41	0		0.00	
Oconee 3 (orig.)	12/74	29.85 R	8.60		607	7.94		7.94	42	0		0.00	
St. Lucie 2 (orig.)	8/83	24.18 R	12.10		599	8.11		8.11	43	0		0.00	
Point Beach 1 (repl.)	3/84	24.52	13.50		597	8.34		8.34	44	0		0.00	
Diablo Canyon 2 (orig	3/86	22.70 R	10.70		603	8.42		8.42	45	0		0.00	
Millstone 3	4/86	22.40	7.10		617	9.73		9.73	46	0		0.00	
Summer (repl.)	12/94	13.76	6.70		619	9.93		9.93	47	0		0.00	
Oconee 1 (orig.)	7/73	30.24 R	10.90		607	10.07		10.07	48	0		0.00	
TMI1	9/74	34.02	13.00		603	10.23		10.23	49	0		0.00	
Oconee 2 (orig.)	9/74	29.52 R	11.50		607	10.62		10.62	50	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15		12.15	51	0		0.00	
McGuire 1 (repl.)	5/97	11.35	8.30		619	12.30		12.30	52	0		0.00	
Beaver Valley 2	11/87	20.81	15.60		606	13.84		13.84	53	0		0.00	
San Onofre 2	8/83	25.10	15.54		609	15.54		15.54	54	0		0.00	
San Onofre 3	4/84	24.44	16.18		609	16.18		16.18	55	0		0.00	
Byron 2	8/87	21.05	17.59		611	19.04		19.04	56	0		0.00	
Catawba 2	8/86	22.10	15.41		615	19.53		19.53	57	0		0.00	
				Ave. Thot=	605								

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with at least one TT Alloy 690 plug of known lifetime.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Oldest plug inspected for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure 4-27
Time to First Circumferential PWSCC – Alloy 690TT Rolled Tube Plugs

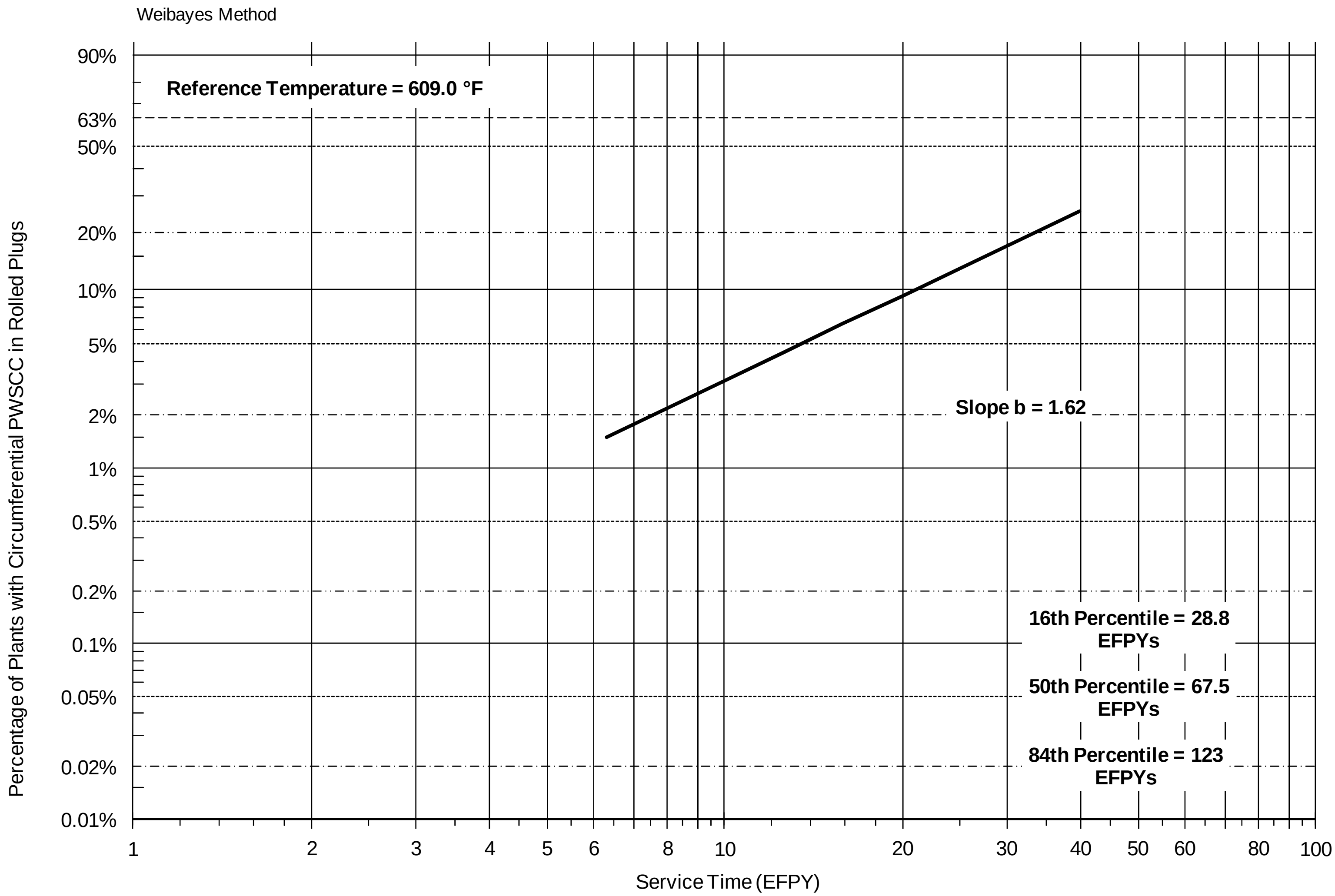

Figure 4-28
Time to First Circumferential PWSCC – Alloy 690TT Rolled Tube Plugs-Weibayes Analysi

4.3.3 Alloy 690TT versus Alloy 600MA

As discussed in Section 4.1, data availability did not permit a direct comparison between the performance of plugs fabricated from Alloys 600MA and 690TT. Improvement factors for the performance of Alloy 690TT relative to that of Alloy 600MA were instead determined by comparing Alloy 690TT to Alloy 600TT improvement factor values with appropriate Alloy 600TT to Alloy 600MA improvement factors.

4.3.3.1 Selection of Alloy 600TT versus Alloy 600MA Improvement Factor

Chapters 3 and 5 discuss the negative impacts of introducing cold work into thermally treated materials. The analyses of plug operating experience presented in this chapter have also shown that the high levels of cold work and residual stress imparted during plug installation seem to have led to accelerated initiation of axial and circumferential PWSCC in Alloy 600TT mechanical plugs and accelerated initiation of circumferential PWSCC in rolled plugs. In addition to improving material microstructure, the thermal treatment process is designed to relax residual stresses present in tubing and other parts following the completion of various cold-working operations, such as tube straightening, during fabrication. The introduction of high levels of residual stress into plugs during installation is necessary to ensure that an effective seal between the plug and the tube is formed.

Based on this information, it is considered conservative and appropriate to use the following laboratory test based improvement factors related to the performance of Alloy 600TT versus Alloy 600MA:

- IF_R = 1.6 (Section 5.5.1.1) for mechanical plugs
- IF_R = 2 (Section 5.5.1.1) for rolled plugs
- IF_R = 1.6 (Section 5.5.1.1) for mechanical and rolled plugs

The most conservative improvement factor (1.6) for the performance of Alloy 600TT relative to Alloy 600MA was chosen for mechanical plugs for the reasons listed above and since it was derived from laboratory testing results which are typically performed under conditions of high stress. It was also chosen because an analogous tubing improvement factor for this expansion method (mandrel expansion) is not available. This is considered to be a conservative selection as the high levels of residual stress present in laboratory specimens (on the order of about 75 ksi) are expected to be higher than those present in mechanical plugs.

An improvement factor of 2 was chosen for rolled plugs for the reasons listed above and because this is the level of improvement observed for PWSCC of Alloy 600TT relative to Alloy 600MA in kiss roll expansion transitions. Kiss rolling is a similar expansion method and the improvement factor value is considered to be a lower bound as the prototypical stresses imparted are greater than those expected for roll expansion of plugs (based on the information presented in Section 4.1.6).

The most conservative value of 1.6 was chosen for the combined population of mechanical and rolled plugs.

4.3.3.2 Alloy 690TT versus Alloy 600MA Improvement Factors

The calculated material improvement factors for Alloy 690TT vs. Alloy 600MA for each degradation mechanism are shown in Table 4-5.

Table 4-5
Estimated Material Improvement Factors for Alloy 690TT vs. Alloy 600MA

Degradation Mech.	Failure Criterion	Plant Population	Material IF_R A600TT/A600MA	Material IF_R A690TT/A600TT*	Material IF_R A690TT/A600MA*
Axial PWSCC	Time to First Observed PWSCC	A690TT Mechanical Plugs	1.6	87.5	140.0
Circ. PWSCC	Time to First Observed PWSCC	A690TT Mechanical and Rolled Plugs	1.6	64.4	103.0
		A690TT Mechanical Plugs	1.6	39.9	63.8
		A690TT Rolled Plugs	2	61	121.4

*All improvement factors are estimated in the absence of significant degradation of Alloy 690TT and are type-to-type IFs, e.g., rolled Alloy 600TT to rolled Alloy 690TT.

According to the results given in Table 4-5, plant experience indicates respective lower and upper bounds on the improvement factor for axially-oriented PWSCC of about 14.1 and 393.5. These values are not considered to be representative of the level of improvement of Alloy 690TT relative to Alloy 600TT for the reasons discussed in Section 4.3.1.3. Therefore, an improvement factor value of 140.0 is considered to be the most representative description of the performance of Alloy 690TT relative to Alloy 600TT. For the reasons discussed in Section 4.3.1.3, it is considered to be a conservative estimate. It is also expected that the choice of 1.6 for the Alloy 600TT to Alloy 600MA improvement factor is conservative.

Table 4-5 shows a lower bound on the improvement factor for circumferentially-oriented PWSCC of about 63.8 for mechanical plugs. This value is limited by the conservatisms discussed in Section 4.3.2.3 and by the conservative choice of 1.6 for the Alloy 600TT to Alloy 600MA improvement factor.

4.3.3.3 Conclusions

Based on the discussion presented in Section 4.3.3, the overall plug-performance-based improvement factor values for Alloy 690TT relative to Alloys 600MA and 600TT for axial and circumferential PWSCC are presented in Table 4-6. These values are considered to be conservative and rigorously demonstrated.

Table 4-6
Plug-Performance-Based Improvement Factors for Alloy 690TT vs. Alloys 600MA and 600TT

Degradation Mech.	Failure Criterion	Material IF_R A690TT/A600MA	Material IF_R A690TT/A600TT
Axial PWSCC	Time to First Observed PWSCC	140.0	87.5
Circ. PWSCC	Time to First Observed PWSCC	63.8	39.9

Note: all improvement factor values are based on essentially no PWSCC in Alloy 690TT and are therefore lower bounds.

The recommended improvement factor values presented above for axial and circumferential PWSCC of Alloys 600MA and 600TT are significantly higher than those developed in the SG tube analyses because very rapid degradation of Alloy 600TT plugs has been observed while degradation of Alloy 690TT plugs has not been detected. The improvement factor values presented in Table 4-6 are expected to increase as mechanical and rolled Alloy 690TT plugs installed across the industry grow older in the absence of PWSCC. However, since some of the Alloy 690TT plugs are installed in Alloy 600MA-tubed SGs that will inevitably be replaced, the values of the recommended improvement factors are not expected to increase linearly as is predicted for SG tube-based improvement factors.

5
LABORATORY TESTING BASED IMPROVEMENT FACTORS

This chapter updates the previously determined laboratory test based improvement factors developed in References [1] and [2]. In Reference [1], laboratory based environment-specific improvement factors were developed for Alloy 600TT and Alloy 690TT versus Alloy 600MA. The improvement factor for Alloy 690TT was reviewed and updated in Reference [2]. The improvement factor for Alloy 800NG based on laboratory testing was developed using the same methodology.

5.1 Methodology

5.1.1 General Approach

This section describes the general approach used to determine experiment-based improvement factors for Alloy 600TT, Alloy 690TT, and Alloy 800NG versus Alloy 600MA. In the sources reviewed, the reported "improvement factor" or IF_R was determined from several types of data:

- Relative depths of cracking, IGA, or pitting for specimens exposed for the same duration to the same test conditions:

  IF_R = Depth of corrosion in Alloy 600MA/ Depth of corrosion in Alloy 600TT, Alloy 690TT, or Alloy 800NG

- Relative apparent crack growth rate for specimens exposed to the same test conditions:

  IF_R = Apparent growth rate in Alloy 600MA/ Apparent growth rate in Alloy 600TT, Alloy 690TT, or Alloy 800NG

- Relative time to cracking or failure under the same test conditions:

  IF_R = Time to crack or fail in Alloy 600TT, Alloy 690TT, or Alloy 800NG / Time to crack or fail in Alloy 600MA

- Relative extent of cracking (e.g., in a SSRT/CERT test):

  IF_R = Area of SCC for Alloy 600MA / Area of SCC for Alloy 600TT, Alloy 690TT, or Alloy 800NG

The environments tested in the laboratory vary between test programs, providing data at a range of conditions. In general, test environments were separated into primary/AVT/water (i.e., water relatively free of concentrated contaminants), caustic contaminated, lead contaminated, chloride contaminated, sulfur contaminated, and environments containing oxidizing species. However, many of the tests involved several contaminants at the same time, and thus there is considerable overlap.

An important consideration with regard to evaluating improvement factors from laboratory tests is that laboratory tests using either C-rings, U-bends, or RUBs can change the relative performance of the alloys because they involve the application of high levels of cold work and stress. For example, the application of high levels of cold work and stress removes some of the benefit provided by thermal treatment (which removes some cold work and stress imparted to the material after the final mill anneal through straightening, for example), thus making the difference between Alloy 600TT (and probably Alloy 690TT) and either Alloy 600MA or Alloy 800NG less in C-ring, U-bend, and RUB tests than in service. In addition, the IF_R calculation methodology discussed above assumes that the corrosion acceleration effects of the higher laboratory stresses and cold work are equal for each alloy which may not always be correct. However, this effect should not be as significant a factor for the Alloy 800NG vs. Alloy 600MA comparison, since neither of these alloys has been thermally treated.

An alternate approach, based on regions of susceptibility, was considered but not used. Several techniques are available to investigate the stability of oxide films in various environments, such as cyclic polarization testing or measurements of the hydrogen concentration in oxide films formed during exposure to specific environments. While these tests are useful tools for identifying environmental conditions in which an alloy is susceptible to stress corrosion cracking, for example, there are some challenges in deriving improvement factors from this type of data.

5.1.2 Sources Reviewed

Laboratory testing relevant to the behavior of Alloy 600MA, Alloy 600TT, Alloy 690TT, and Alloy 800 was previously reviewed in Reference [1], Reference [2], and Reference [7]. The results of laboratory test programs referenced by these documents are discussed in Section 5.2 for each of the three alloys. These results are supplemented with a review of the literature since EPRI report 1013640 [2] was published in 2006, including material from the International Conference on Water Chemistry of Nuclear Reaction Systems [8].

5.1.3 Determination of Time to Failure

The time to failure was defined by the party conducting each test program. References for each laboratory test program are given in Chapter 7 of this report or are included in the specific EPRI report referenced.

Because of limited numbers of samples and limited durations of tests, the comparisons of the results of tests of Alloy 800NG, Alloy 600MA, Alloy 600TT, and Alloy 690TT samples sometimes produce indeterminate answers. For example, there may be measurable crack depths in the Alloy 600MA samples but no cracks in the Alloy 800NG samples. Indicating that $IF_R = \infty$ would be misleading, since it is possible that use of more samples and longer durations would result in some finite cracking of the Alloy 800NG samples. To allow an approximate quantification, an estimated improvement factor was calculated assuming that an uncracked specimen had a flaw at the lower level of detection (5 µm for metallurgical examination). This approach of quantifying an estimated improvement factor (rather than using a "large but indeterminate" or LBI designation) was used wherever possible for sulfur, lead and "oxidizing species" contaminated environments. This was done to aid in developing a quantitative assessment of the chemistry weighted improvement factor discussed in Section 5.4.

In past reports, two general strategies were used in analyzing laboratory data. In Reference [1] laboratory data are evaluated using minimum times to failure (or test length, in the case of no failure). In Reference [105] laboratory data are evaluated using Weibayes statistics. For example, in one data set in which Alloy 600MA and Alloy 690TT RUB specimens were tested [3], the following data were obtained:

- Alloy 600MA earliest failure 1,050 hr
- Alloy 690TT no failure maximum test time 25,000 hr
- Alloy 600MA Weibull time constant 1,118 hr
- Alloy 690TT Weibayes time constant (assumed β=5) 59,700 hr

From these data, the two previous analyses computed the following improvement factors:

$$IF_R > \frac{Test\ Time\ with\ No\ Alloy\ 690TT\ Failures}{Time\ to\ First\ Alloy\ 600MA\ Failure} > \frac{25000}{1050} > 25\ \text{(Reference [1])} \qquad \textbf{Eq. 5-1}$$

$$IF_R = \frac{\theta_{Weibayes}\left(Alloy\ 690TT\right)}{\theta_{Weibull}\left(Alloy\ 600MA\right)} = \frac{59700}{1118} = 53.4\ \text{(Reference [105])} \qquad \textbf{Eq. 5-2}$$

Both methods represent reasonable estimates in the absence of enough data to calculate actual values. Each also has drawbacks. The methodology of Reference [1] (Equation 5-1) is overly simplistic. It does not attempt to account for the distribution in Alloy 600MA failures. For example, an anomalously early failure would significantly increase the estimated improvement factor. Likewise, it does not account for early failures of Alloy 690TT. In the absence of any failures at all, the possibility of early failures (due to various experimental differences) would lead to the conclusion that the likely typical failure time is actually much more than the experimental duration. These issues are well captured by the use of Weibull and Weibayes statistics.

Alternatively, the use of Equation 5-2, as in Reference [105], presents other problems. First, the experimental works considered generally used too few specimens for rigorous application of statistical approaches. Second, the Weibayes analysis used to characterize the time for Alloy 690TT failures requires an assumption of a Weibull slope (shape parameter, β). Reference [105] assumes that this slope is 5. This assumption introduces additional uncertainty.

For many of the test programs reviewed, Reference [105] uses Equation 5-1 to estimate the improvement factor, in recognition of the small number of data points. Additionally, Reference

[105] compared improvement factors calculated using Equation 5-1 with those calculated using Equation 5-2 and found little difference in the overall magnitude of the improvement factor. In general, Equation 5-1 was used to develop laboratory improvement factors for this report.

5.1.4 Prototypical Environment Categories

In order to develop improvement factors that are more representative of conditions experienced during plant operation, environment-weighted improvement factors were developed to reflect the relative frequency at which each environment is experienced in plants. For the purpose of this report and past improvement factor analyses, the reported laboratory test environments were separated into primary, pure, and AVT water; caustic contaminated; lead contaminated; chloride contaminated; sulfur contaminated; and oxidizing environments. This last category is included specifically to address a possible trend of SCC observed in Alloy 690TT under oxidizing conditions. Many of the tests involved several contaminants at the same time, and thus there is considerable overlap.

Because the rate of corrosion depends significantly on the pH of the environment, the data reviewed were also organized by at-temperature pH (pH_T). Previous reports developed environment-weighed improvement factors based on the relative frequency of occurrence of pH_T values in crevices. To develop this weighted improvement factor, it is necessary to determine the relative frequency of occurrence of different pH ranges, determine the appropriate improvement factor for each pH range, and then convolute the two to obtain a weighted improvement factor.

5.2 Experimental Improvement Factors By Testing Environment

5.2.1 Alloy 600TT versus Alloy 600MA

Laboratory experiment-based improvement factors for thermally treated Alloy 600 versus mill-annealed Alloy 600 were previously developed in EPRI report TR-108501[5] to predict the tube degradation rates in Westinghouse design D5 and F models (which have Alloy 600TT tubing).

The following chemistries were considered in Reference [5]. A summary of the experiments reviewed and associated improvement factors is provided in table form below for the following chemistries:

- Pure, primary, and AVT water environments - Table 5-1
- Caustic contaminated environments - Table 5-2
- Chloride contaminated environments - Table 5-3
- Sulfur contaminated environments - Table 5-4
- Lead contaminated environments - Table 5-5

An additional category, environments containing oxidizing species, was added due to trends seen in SCC in Alloy 690TT.

Note that in the analyses that follow, an improvement factor is typically described for a given environment over a wider range of pH_T than is strictly applicable. For example, an improvement factor is given for low pH_T in sodium/caustic contaminated environments. In fact, the improvement factor for pure/primary/AVT water is used in this range, as indicated, for example, in Figure 5-1. This extension of IF_R beyond the applicable range is merely a construct to facilitate the determination of an overall improvement factor as a function of pH_T, as discussed in Section 5.5.

Table 5-1
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in AVT and Primary Water Environments

Organization	Date	Environment, Test Type	Primary or AVT?	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
Westinghouse	1980s	pure H2O + H2, RUB	Primary	360	1,500	> 3	25
		Primary water, RUB	Primary	360	time to cracking	1.5 - 3	
Japanese	1980s	Primary water, RUB	Primary	360	10,000	2.5	16
B&W	1980s	Split U-bend	AVT	316	4	1.5	36
French	1987	Pure water + H2, RUB	Primary	360	LT	> 4.3	11
Swedish	1987	Pure water + H2, RUB	Primary	365	not given	1.6	40
Westinghouse	1990	Primary water, RUB	Primary	360	not given	3 - > 5	24
Swedish	1991	Pure water + H2	Primary	365	23,000	1.4 - 16	39
Japanese	1995	Primary water, pH = 7.1 - 7.3, CERT	Primary	370	not given	1.5 -2	12
		Primary water, RUB	Primary	320	not given	1.6 - 3	
		Primary water, constant load	Primary	340	not given	1.05	

Table 5-1 (continued)
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in AVT and Primary Water Environments

Organization	Date	Environment, Test Type	Primary or AVT?	Temp (°C)	Time (hours)	Improvement Factor, IFR	Ref.
French	2005	Complex* AVT, pH_T = 5.2, C-ring	AVT	320	up to 4000	4.9	26
		Complex + morpholine, pH_T = 5.3, C-ring	AVT	320	up to 4000	> 14**	
		Complex + morpholine, no CH_3COOH, pHT = 5.4, C-ring	AVT	320	up to 4000	9.8	
		Complex, no CH_3COOH, pHT = 6, C-ring	AVT	320	up to 4000	> 11	
		0.008M $Ca_3(PO_4)_2$, pHT = 5.9, C-ring	AVT	320	up to 4000	2.5	
		Complex + Elevated NH_3OH, pH_T = 6, C-ring	AVT	320	up to 4000	> 4.7**	
		Complex* AVT, Al/Si = 0.05, pH_T = 5.2, C-ring	AVT	320	up to 4000	4.5	
		Complex* AVT, pH_T = 5.2, C-ring	AVT	305	up to 4000	IND	
		Complex* AVT, pH_T = 5.2, C-ring	AVT	312.5	up to 4000	0.78	
		Complex* AVT, pH_T = 5.2, C-ring	AVT	335	up to 4000	> 3**	

* Complex = 0.103M SiO_2, 0.013M Al_2O_3, $1.7*10^4$ M CH_3COOH, 0.008M $Ca(PO_4)_2$

** No cracking in 600TT; 0.003 max CGR assumed (lowest reported crack growth rate)

Table 5-2
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in Caustic Environments

Organization	Date	Caustic Conc (%NaOH), Test Type	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
EDF	1981	0.4-10, C-ring	350	[time to achieve crack depth]	1.2	7
Westinghouse	late 1970s - early 1980s	10, C-ring	315	up to 168	4.0 - 36	10,14,25
		10, C-ring	315	6570	1.4	
		10, C-ring	316	LT	18	
		50, C-ring	343	LT	3.7	
		10 + CuO, C-ring	316	LT	1.03	
		10, C-ring	343	LT	3.1	
		10, C-ring	316	LT	17.9	
		50, C-ring	343	LT	4.1	
		50, C-ring	316	LT	3.3	
Westinghouse, EDF, Framatome, CEA	early 1980s	10, C-ring	315	2000	up to 46	15
		10, C-ring	332	2000	up to 8.7	
Mitsubishi	1980s	10, C-ring	325, 343	not given	6.4 - 6.6	16
Westinghouse	1980s	10, Crack growth rate	288,343	not given	16 at 288°C, 4.2 at 343°C	17
		10, C-ring (low, mid, high stress)	316	not given	1.0 (low), 2.5 (mid), 30-100 (high)	
INCO	1987	10, U-bend	350	not given	4.4	22
B&W	1988	10, C-ring	288	not given	8.0 - 10	23
Westinghouse	1990	10, C-ring	332	4680	10	24
UK	1990	30 + 10% Na_2SO_4, C-ring	350	12,000	1.5 - 2	38
		10, C-ring	305	not given	3.2 - 7	
KAERI	2004	10, RUB	315	1440	Indeterminate	70

LT = Long-term

Table 5-3
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in Chloride Contaminated Environments

Organization	Date	Environment, Test Type	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
Westinghouse	1980s	C-ring, pH_T = 3.5, 127,000 ppm $FeCl_2$	332	5000	indeterminate	22
Japanese	1980s	double U-bend	288-300	4000	indeterminate	35
		double C-ring	288	3,000	indeterminate	35
INCO	1980s	AVT + chloride + O_2, C-ring	316	12432	indeterminate	55
Japanese*	1992	$pH_{25°C}$ = 4.5, $PbCl_2$ (3000 ppm or 300 ppm), C-ring	340	2500	5 - 6	20
MEA	1994	C-ring, $pH_{315°C}$ = 2.7, equimolar Cl and SO_4 ions	315	not given	1.1	27
		C-ring, 1.636m NaCl, $pH_{315°C}$ = 3.9	315	not given	3.8	27
		C-ring, 1.90m NaCl, $pH_{315°C}$ = 3.1	315	not given	2	27

*The test environment included both chloride and lead.

Table 5-4
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in Sulfate Contaminated Environments

Organization	Date	Environment, Test Type	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
Westinghouse	1980s	80,000 ppm Na_2SO_4 + H2SO4, pH_T = 6.6* - C-ring	332	5000	3.6, > 16	25
		80,000 ppm SO_4 + H2SO4, pH_T = 5.6* - C-ring	332	2000	1.6, 3.1	
		10,000 ppm SO_4, pH_T ~ 6.6*, C-ring	332	4000	17, > 33	
CERL	1983	0.2M $NaHSO_4$ + 0.4M $FeSO_4$ + 0.4 Na_2SO_4, C-ring	290, 315	up to 3584	1.3,3.1	17
INCO	1985	750 ppm sulfate, 10% NaOH, C-ring	316	not given	4.9	55
MEA	1994	C-ring, $pH_{315°C}$ = 2.7, equimolar Cl and SO_4 ions	315	not given	1.1	27
		0.491m $(NH_4)_2SO_4$, 0.0467m H_2SO_4, pH_T = 3.2*, C-ring	318	ST	5.5	
		1.0m $(NH_4)_2SO_4$, 0.4685m H_2SO_4, pH_T = 3.1*, C-ring	311	ST	2.4	

ST = Short-term

*The MultEQ sulfate species model has been revised since the time that these reports were published. Re-evaluation of these test conditions may therefore result in slightly different pH values.

Table 5-5
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in Lead Contaminated Environments

Organization	Date	Environment, Test Type	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
Westinghouse	1979	Morpholine + hydrazine + lead, C-ring	332	1350	LBI	14
B&W	1990	Lead contaminated, C-ring*	324	~4000	0.7 - 100	63
Japanese	1992	pH = 4.5, PbCl2, Cc-ring	340	2500	5 - 6	20
Spanish	1994	4% NaOH + 0.01M PbO, C-ring	320	2000	8.5	65
		4% NaOH + 0.002M PbO, C-ring			1.5	
		4% NaOH + 0.004M PbO, C-ring			4	
		AVT + 0.01M01M PbO, C-ring			1.44	
		AVT +0.002M PbO, C-ring			0.7	
Japanese	1994	AVT + 100 ppm Pb as PbO, C-ring	320	4000	1.4, 2.4	29
		AVT + 10 ppm Pb as PbO, C-ring			20, 3.4	
		AVT + 1 ppm Pb as PbO, C-ring			32, 2.3	
French	1994	10% NaOH, 1% PbO	350	Avg. time to failure	1.5	30

Table 5-5 (continued)
Summary of Laboratory Test Indicated Improvement Factors for Alloy 600TT vs. Alloy 600MA in Lead Contaminated Environments

Organization	Date	Environment, Test Type	Temp (°C)	Time (hours)	Improvement Factor, IFR	Ref.
Teledyne	2007	500 ppm Pb + 1.5 M Na_2SO_4, 0.01M Fe_3O_4, 0.05M Al_2O_3, 0.3M SiO_2, 0.15M KOH, 0.04M HCl, $pH_{330°C}$ = 9; RUB	330	Up to 4260	4.1	31
		3M NaCl + 0.16M NaOH + 500 ppm Pb as PbO (pH_T = 9); RUB	330	Up to 4320	2.5	
		3M NaCl + 500 ppm Pb as PbO (pH_T = 7); RUB	330	Up to 4820	2.3	
		3M NaCl + 500 ppm Pb as $PbCl_2$ (pHT = 5); RUB	330	Up to 3875	1.5	

LBI = Large But Indeterminate

*See Table 3-6

Table 5-6
B&W Canister Experiments on Degradation of Alloy 600TT [5, 59]]

Canister	Environment	pH_T	IF_R
1	AVT + 0.1m PbO	7.4	1.3
3	AVT + 0.1m $PbSiO_3$	-	0.7
4	AVT + 0.1m $Pb(H_2BO_3)_2$	6.8	~100
5	AVT + 1.0m $PbCl_2$ + 0.1m PbO	5.3	LBI
6	1.0m NaOH	9.9	1.1
7	Morpholine + 1.0m NaOH + 0.1m PbO + 3.0m H_3BO_3	6.7	0.9
8	Morpholine + 0.1m $NaHSO_4$ + 0.1m $PbSO_4$ + 0.3m H_3BO_3	2.2	no cracking
9	1.0m NaOH + 0.1m PbO	9.9	3.8
11	1.0m NaOH + 0.1m PbS	9.9	0.7
12	0.2m $PbCl_2$	3.8	LBI

Improvement factors for Alloy 600TT versus Alloy 600MA as a function of pH were previously developed for EPRI in Reference [4]. In this case, the experimental IF_Rs were determined from the laboratory data on stress corrosion cracking of Alloy 600MA and Alloy 600TT published in Appendix A of Reference [5]. These data are broken down by pH in Table 5-7 with sources referenced (reference numbers refer to Chapter 7 of this report). However, these previous analyses did not attempt to distinguish among the various environments given in Section 5.1.4.

In order to effectively capture the likelihoods of the various environments actually being present, the experimental data available were assessed as functions of pH for each of the prototypical environments considered. The formulation of these functions is discussed in the following subsections.

Table 5-7
Improvement Factor Data for Alloy 600TT vs. Alloy 600MA from Reference [5]

Contaminants	pH_T	IF_R (Alloy 600TT/Alloy 600MA)	Reference
Cl/SO_4	2.7	1.1	6
	3.9	3.8	
	3.1	2	
Na	10.4	2.6	7
	10.5	3.5	
	10.5	5.6	
	10.4	5.8	
Na	10.4	4	10
	10.4	1.4	14
	10.4	18	
	10.5	3.7	
Na/CuO	10.4	1.03	
Na	10.4	3.1	14
	10.4	17.9	
	10.5	4.1	
	10.5	3.3	
Na	10.4	1.06	15
	10.4	1.4	
Na	10.4	6.4	16
	10.4	6.5	
Na	10.4	4.2	17
	10.4	16	
Na/SO_4	6.6	3.6	25
	5.6	1.6	
	5.6	3.1	
	6.6	17	
$Na/SO_4/Fe$*	3.5	1.3	17
	3.5	3.1	
Na/SO_4	3.2	5.5	6
	3.1	2.4	
Pb	7.4	1.3	19
Pb/H_3BO_3	6.8	3	
Pb/Na	9.9	1.5	
Pb/Cl	4.5	5	20

*This solution was composed of 0.2M $NaHSO_4$ + 0.4M $FeSO_4$ + 0.4 Na_2SO_4

Table 5-8 below shows experimental data by pH_T and environment.

Table 5-8
Experimentally Determined Improvement Factors for Alloy 600TT versus Alloy 600MA by pH and Environment

pH_T Range	AVT/Pure/Primary Water	Caustic Polluted	Chloride Polluted	Sulfate Polluted	Lead Polluted	Oxidizing Material
2.5 - 3			1.1 (1)	1.1 (1)		
3 - 3.5			2 (1)	2 (1)		
3.5 - 4			3.8 (1)	3.8 (1), 1.3 (3), 3.1 (3)		
4 - 4.5						
4.5 - 5			5 (6)		5 (6)	
5 - 5.5						
5.5 - 6				1.6, 3.1		
6 - 6.5						
6.5 - 7	1.4-16, 1.5-2, 1.5-3, 1.6, 1.6-3, 2.5, 3, 3-5, 4.3			3.6, 17	3 (4)	
7 - 7.5					1.3	
7. 5 - 8						
8 - 8.5						
8.5 - 9						
9 - 9.5						
9.5-10		1.5 (5)			1.5 (5)	
10 - 10.5		1.06, 1.4, 1.4, 2.6, 3.1, 3.3, 3.5, 3.7, 4, 4.1, 4.2, 5.6, 5.8, 6.4, 6.5, 16, 18, 17.9		1.6 (2), 3.1 (2), 3.6 (2), 17 (2)		1.03 (CuO)

(1) Sulfate and chloride contaminated solution
(2) Caustic and sulfur contaminated solution
(3) This solution was composed of 0.2M $NaHSO_4$ + 0.4M $FeSO_4$ + 0.4 Na_2SO_4
(4) H_3BO_3 also present
(5) Lead contaminated and caustic solution
(6) Lead and chloride contaminated solution

5.2.1.1 Alloy 600TT/Alloy 600MA PWSCC IF_R

The laboratory data on Alloy 600TT/Alloy 600MA improvement factors (given in Figure 5-1) are by definition determined over a limited range of pH values. A typical value for primary water is 1.6. The data used in this evaluation are shown in Table 5-1 and the selection of this value is discussed further in Section 5.5.1.1.

5.2.1.2 Alloy 600TT/Alloy 600MA Caustic ODSCC IF_R as a Function of pH

The various improvement factors which have been calculated using laboratory test data are given in Table 5-8. For caustic environments, most data are at a pH_T of 10.5. In the absence of other data, it is assumed that the effect of sodium is defined by the following:

- An improvement factor of 1 at $pH_T = 10.5$, which bounds the data at that pH. It is not readily apparent why some tests result in a low factor of improvement while others are high. Therefore, it is not possible to quantify the extent to which this choice is conservative.
- At $pH_T = 9.9$, the improvement factor in the presence of lead was found to be 1.5. The effect of lead is not well understood, but it is assumed that it is not likely to increase the improvement factor.
- The IF_R was assumed to be linear from (10.5,1) through (9.9,1.5) to 1.6, the value observed for relatively dilute solutions (see Section 5.2.1.1).
- For lower values of pH, the improvement factor was assumed to be 1.6.

Figure 5-1 shows the relationship resulting from the combination of the above. Section 3.2.1.1 further discusses the selection of these values.

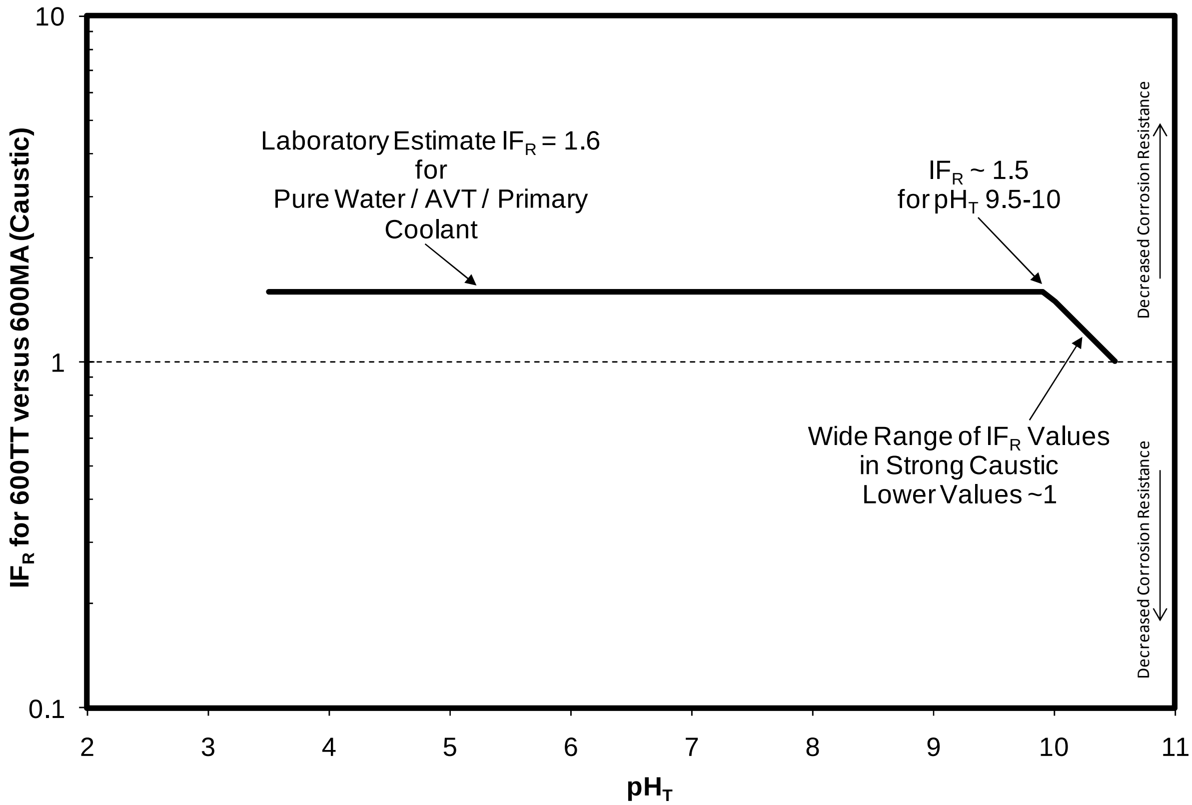

Figure 5-1
Alloy 600TT/Alloy 600MA IF_R as a Function of pH_T for Sodium Contaminated Environments

5.2.1.3 Alloy 600TT/Alloy 600MA Chloride ODSCC IF_R as a Function of pH

The various improvement factors which have been calculated using laboratory test data from chloride environments are given in Table 5-3. These data are plotted against pH_T in Figure 5-2. Most of the available data are at low pH. To model higher pH effects, the following steps were taken:

- Excluding the one outlier (as indicated in Figure 5-2), the data were fit to a parabola fixed at (5.5, 1.6). This point was chosen so that for pH values from neutral (~5.5 at secondary temperatures) through 7.4 (primary chemistry) and up to the limits considered here, the improvement factor could be set at 1.6, the value determined for relatively dilute solutions. Exclusion of the outlier may result in a conservative assessment, but the extent of conservatism cannot be quantified.
- Above pH_T = 5.5, the improvement factor was assumed to be 1.6, the value for relatively dilute solutions (see Section 5.2.1.1).

The resulting relationship between the improvement factor and pH_T for chloride environments is also given in Figure 5-2.

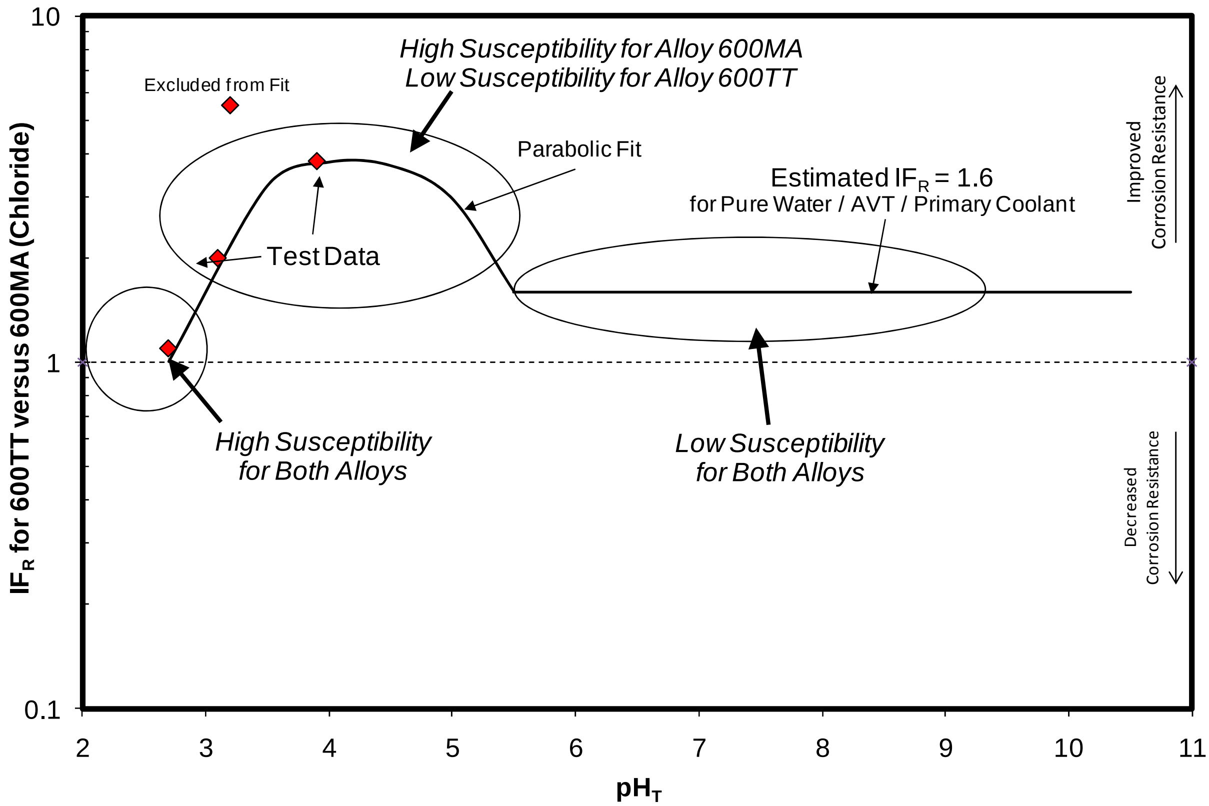

Figure 5-2
Alloy 600TT/Alloy 600MA IF_R as a Function of pH_T for Chloride Environments

The resulting function has a maximum around pH_T = 4. This should not be interpreted as a minimum in SCC susceptibility of Alloy 600TT, but rather a maximum in the difference in susceptibility between Alloy 600TT and Alloy 600MA as indicated by the shaded ellipses in Figure 5-2.

5.2.1.4 Alloy 600TT/Alloy 600MA Sulfate ODSCC IF_R as a Function of pH

The laboratory-based improvement factors for sulfate environments (summarized in Table 5-4) are plotted in Figure 5-3. Also plotted is a fit based on the same principles as that for chloride (see Section 5-14), i.e., a parabolic fit below pH_T = 5.5 and 1.6 above.

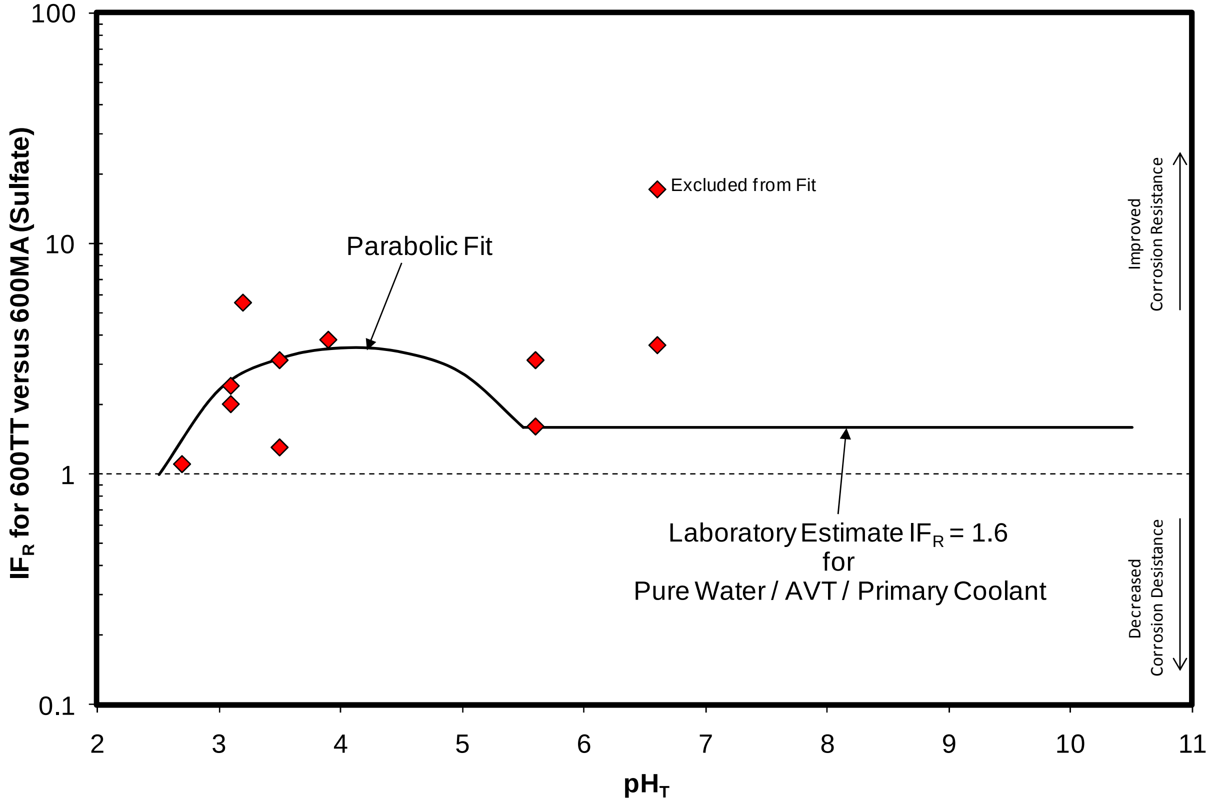

Figure 5-3
Alloy 600TT/Alloy 600MA IF_R as a Function of pH for Sulfate Environments

5.2.1.5 Alloy 600TT/Alloy 600MA Lead ODSCC IF_R as a Function of pH_T

The improvement factor data for lead contaminated environments are plotted in Figure 5-4. The data may show some slight trend toward higher improvement factors at higher and lower pH_T. However, for the calculations made in this report, the logarithmic mean of all of the data is used to characterize the IF_R over the entire range of pH_T, as shown in Figure 5-4.

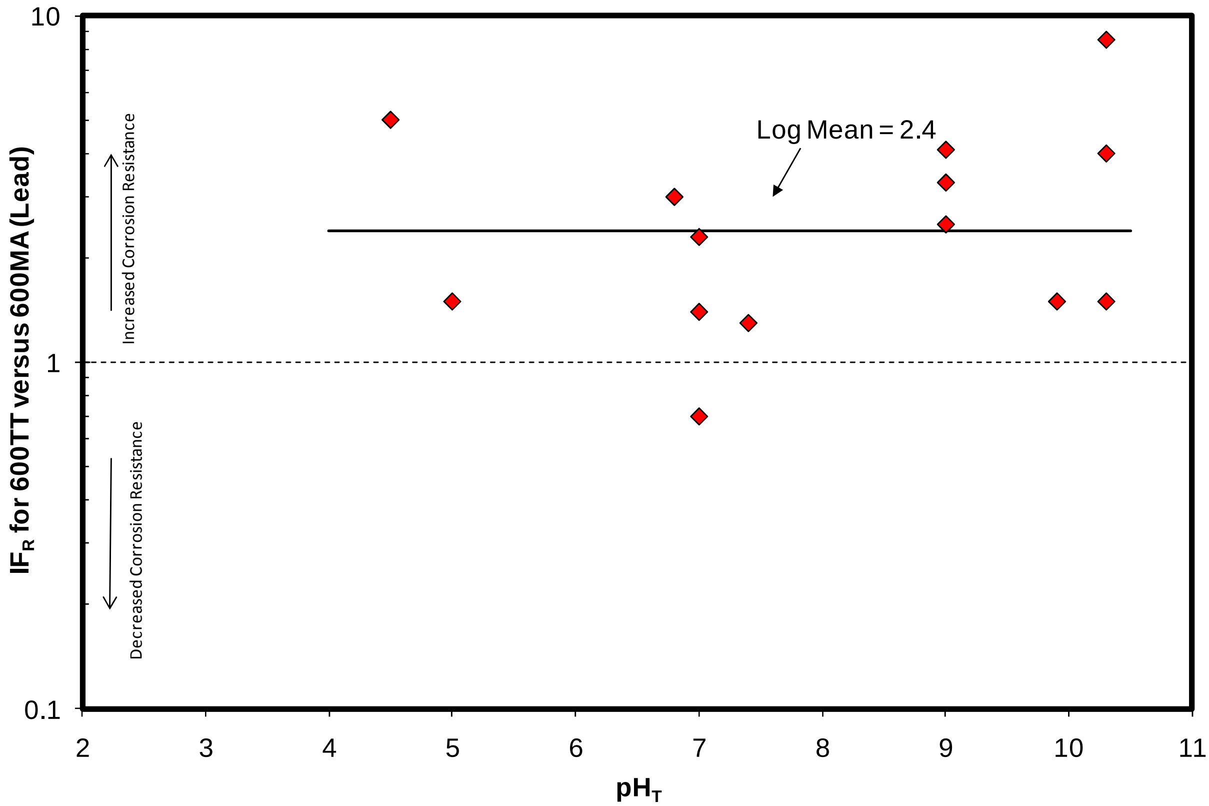

Figure 5-4
Alloy 600TT/Alloy 600MA IF_R as a Function of pH for Lead Contaminated Environments

5.2.1.6 Alloy 600TT/Alloy 600MA ODSCC IF_R for Oxidizing Environments as a Function of pH

Improvement factors for oxidizing environments are plotted in Figure 5-5. The small number of data points and the data scatter do not provide a sufficient data set to estimate a difference between Alloy 600MA and Alloy 600TT under oxidizing conditions. In assessing the effect of oxidizing conditions on an overall improvement factor, an IF_R of unity (no difference) was used.

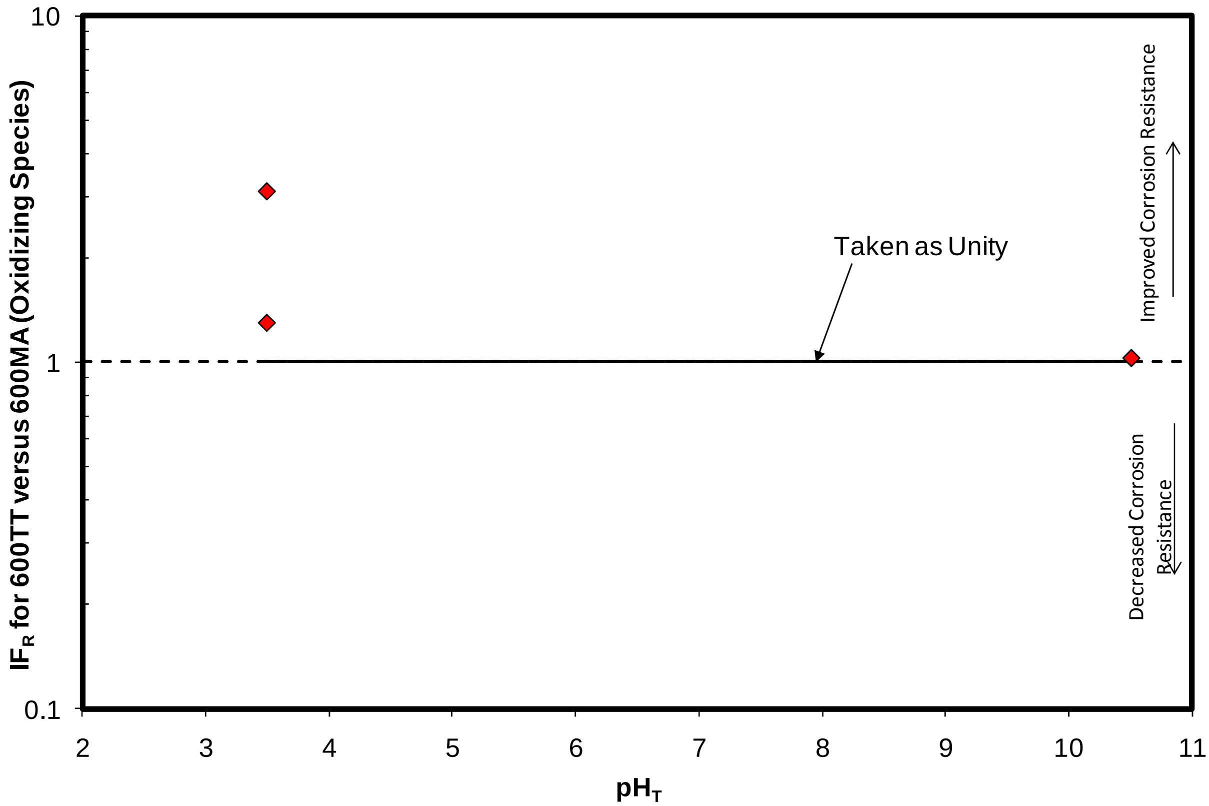

Figure 5-5
Alloy 600TT/Alloy 600MA IF$_R$ as a Function of pH$_T$ for Oxidizing Environments

5.2.2 Alloy 690TT versus Alloy 600MA

In developing generic predictions for Alloy 690 SG tube degradation, the improvement factors developed from actual plant experience are considered overly conservative because the experience with Alloy 690 has not been long enough to quantitatively assess the longer life expectancy of Alloy 690. Furthermore, field experience is complicated by additional design changes and chemistry improvements that were implemented concurrently with the change to Alloy 690TT. Therefore, laboratory testing, in which Alloy 600MA and Alloy 690TT are directly compared, is useful in determining the improvement factor as a function of operating chemistry. In Reference [1], the laboratory testing described in the literature was reviewed and chemistry-specific improvement factors were determined. Reference [2] updated the laboratory experiment based improvement factor determined for Alloy 690TT.

The same chemistries considered in Section 3.2.1 are considered in this section for Alloy 690TT. These are as follows:

- Pure, primary, and AVT water environments - Table 5-9
- Caustic contaminated environments - Table 5-10
- Chloride contaminated environments - Table 5-11

- Sulfur contaminated environments - Table 5-12
- Lead contaminated environments - Table 5-13
- Environments containing oxidizing species - Table 5-14

The accompanying tables give the results of the literature review performed in Reference [5], supplemented with the results of the literature review performed in Reference [2]. This includes a review of the relevant literature through 2005.

Literature Review of Sources Published Since 2005

In order to update the improvement factors developed in Reference [2], a review of the literature published after 2005 was performed. This review included a search of multiple databases plus specific review of the proceedings of the International Conference on Water Chemistry of Nuclear Reactor Systems.

KAERI Results – 2006

Kim, et al. [86], reported in 2006 the results of comparative tests in which reverse U-bend specimens (RUBs) of Alloys Alloy 600MA, Alloy 600TT, Alloy 600HTMA, Alloy 690TT, and Alloy 800NG were immersed in a 10% NaOH solution at 315°C with or without1000 ppm lead in the form of PbO.

- In the tests without lead addition, cracking in all Alloy 600MA materials (MA, TT, and HTMA) was observed after 40 days, while no cracking was observed in Alloy 690 after 60 days. One Alloy 800NG sample cracked after 30 days and one was found to be cracked after 60 days. These data correspond to an improvement factor for Alloy 690TT vs. Alloy 600MA of at least 1.5 ($IF_R > 1.5$).
- In tests in which 1000 ppm lead was added, cracking was observed in Alloy 690TT after 10 days. Cracking was observed in Alloy 800 samples after 30 days, and only one Alloy 600 sample had cracked after 40 days. These observations correspond to an improvement factor of < 0.25 for Alloy 690TT vs. Alloy 600MA, and an IF_R of < 0.75 for Alloy 800NG vs. Alloy 600MA.

Japanese and Mitsubishi Results – 2006

Yamamoto, et al. [87], reported in 2006 the results of tests on crack growth rate under stress in Alloy 600HTMA, Alloy 600TT and Alloy 690TT in simulated primary water at temperatures ranging from 290°C to 360°C. Crack growth was induced in both Alloy 600 alloys but could not be induced in Alloy 690TT after 4000 hrs. These results show a qualitative improvement in Alloy 690TT over Alloy 600MA. The difficulty in initiating stress corrosion cracking in Alloy 690TT for crack growth rate tests is a common observance when testing this material.

Rockwell Scientific Results – 2006

Lumsden and McIlree [88] reported in 2006 the results of comparative tests in which RUBs of Alloy 600MA, Alloy 600TT and Alloy 690TT were immersed in a solution containing 500 ppm lead at $pH_{330°C}$ = 5, 7, or 9 and 330°C. All four Alloy 600MA specimens had cracked after 720 hours, and cracking was observed in both Alloy 600TT samples after 3840 hours. Cracking was observed in one Alloy 690TT sample after 2900 hours, corresponding to an improvement factor of 4. However, this could be due to an anomalous fabrication as no cracking has been observed in 4 additional Alloy 690TT samples after 4320 hours (2 samples) or 3200 hours (2 samples).

Teledyne Scientific and Imaging Results – 2007

In 2007, EPRI published a report [31] on the results of research (performed by Teledyne Scientific and Imaging Company) on factors affecting lead-induced SCC in Alloy 600 and Alloy 690TT tubing. RUB specimens of Alloy 600MA, Alloy 600TT, and Alloy 690TT were exposed to solutions containing 50 or 500 ppm Pb as pBO in a complex environment, or 500 ppm Pb as PbO or $PbCl_2$ at a $pH_{330°C}$ = 5, 7, and 9. Of the Alloy 690TT specimens tested, 2 of 8 cracked in the pH = 9 tests, and no SCC occurred in the lower pH environments. Cracking was detected in 600MA specimens in all three simple pH environments containing Pb. PbSCC was likewise detected in 600TT specimens in all three simple test solutions, although slower crack growth rates were observed than for the mill-annealed specimens.

Materials Reliability Program (MRP) Interim Report – 2008

In August 2008, EPRI published a summary of the results of research on crack growth rate (CGR) of Alloy 690TT PWSCC [105] since 2004. The conclusions from this report are discussed in section 5.5.1.2.

Conclusions from New Literature

The improvement factors given by recent experimental results generally lie within the range of improvement factors previously reported and incorporated into Reference [2]. However, the reported experimental improvement factors in lead-contaminated environments vary widely and have been found to be both above and below unity. The mechanism by which lead contamination enhances corrosion is currently not well understood. The lowest reported improvement factor was 0.044 [73]. The negative effect of lead on performance of Alloy 690TT in caustic environments is supported by the results reported by Kim [86] described above. These data, when considered with the data given in [2], indicate that the improvement factor in caustic lead solutions is quite low and imply that consideration of lead contaminated caustic environments separately from neutral or acidic lead contaminated environments may be warranted.

Table 5-9
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in AVT/Primary Water Environments

Organization	Date	Environment, Test type	Primary or AVT?	Temp (•C)	Time (hours)	Improvement Factor, IF_R	Reference
INCO	1979	Deaerated pH_{RT} 10 water, Double U-bend	Probably primary	316	10,080	> 1.3	21
Westinghouse	1981	Pure water & pure water + NH_3, RUB	AVT	360	up to 5400	> 2.7	32
EDF	1985	Pure water + H_2, RUB	Primary	360	11000	> 11	33,34
Westinghouse	1985	Primary water, RUBs & Roll Tr.	Primary	360	13000	> 8.7	35
Japanese	1985	RUBs & CL - Primary water	Primary	360	12000	> 40 & > 7	16
B&W	1986	RUBs - AVT water	AVT	288 - 360	1Alloy 8000 - 9Alloy 6000	> 1.6, > 8, & > 44	36
Kobe Steel	1987	H_2 saturated water, U-bend	Primary	330	3000	1.3	37
British	1990	Pure steam with H_2, RUB	Primary	400	1000	> 10	38
Swedish	1991	Pure water + H_2, RUB	Primary	365	22000	> 25	39,40
University of Newcastle	1997	Hydrogen/steam RUB	Primary	380	13824	>9.8	41
Japanese	1997	Primary water, RUB	Primary	360	10000	> 44	42
Westinghouse, EDF, Framatome, CEA	1985	Primary water (beginning + end of cycle), RUB	Primary	360	13,000 or 16,000	> 6.4	43
British	1999	Primary water, RUB	Primary	not given	7500	> 1.4	44
EDF	2003	Primary water, CERT	Primary	360	up to 2208	Indeterminate	45
French (CEA, EDF)	2003	Primary water, pure water, RUB	Primary	325 - 360	up to 90,000	> 18	46

Table 5-9 (continued)
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in AVT/Primary Water Environments

Organization	Date	Environment, Test type	Primary or AVT?	Temp (•C)	Time (hours)	Improvement Factor, IFR	Reference
Framatome ANP (Germany)	2004	Steam, RUB	Primary	400	9720	> 27	46
Framatome ANP (France)	2004	Pure water, Pure water + H_2, Roll Tr.	Primary	360	100000	> 125	46
Japanese and Mitsubishi	2006	Primary water (1Alloy 800 ppm B, 3.5 ppm Li, 30 cc/kg H2)	Primary	290 - 360	not given	Qualitative*	87
French**	2005	Complex, pHT = 5.2, C-ring	AVT	320	up to 4000	> 16.3	26
		Complex + morpholine, pHT = 5.3, C-ring	AVT	320	up to 4000	> 14	
		Complex + morpholine, no CH3COOH, pHT = 5.4, C-ring	AVT	320	up to 4000	> 11	
		Complex, no CH3COOH, pHT = 6, C-ring	AVT	320	up to 4000	> 16.3	
		0.008M Ca3(PO4)2, pHT = 5.9, C-ring	AVT	320	up to 4000	> 9.3	
		Complex + Elevated NH3OH, pHT = 6, C-ring	AVT	320	up to 4000	> 4.7	
		Complex* AVT, Al/Si = 0.05, pHT = 5.2, C-ring	AVT	320	up to 4000	> 6	
		Complex* AVT, pHT = 5.2, C-ring	AVT	312.5	up to 4000	> 8.3	
		Complex* AVT, pHT = 5.2, C-ring	AVT	335	up to 4000	> 3.3	

* Based on time to initiate SCC in a crack growth rate test.
** No cracking observed in any 690TT specimens. IF_R is therefore estimated using an assumed max. crack growth rate of < 0.003 um/h (this was the lowest reported CGR)

"Complex" Environment = 0.103M SiO_2, 0.013M Al_2O_3, $1.7*10^{4}$ M CH_3COOH, 0.008M $Ca(PO_4)_2$

Table 5-10
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Caustic Environments

Organization	Date	Caustic Conc. (%NaOH), Type Test	Temp (•C)	Time (hours)	Improvement Factor, IF_R	Reference
West. (Alloy 690MA vs. Alloy 600MA)	1973	10, U-bend	316	1176	0.09	47
INCO (SA & Q Alloy 690 & Alloy 600)	1976	50, Frac. Mech.	316	336	<1	48
INCO (Alloy 690S vs. Alloy 600MA)	1977	50, U-bends	316	1680	0.1	49
INCO (Alloy 690MA vs. Alloy 600MA)	1979	10, U-bends	300	655	>1	21
INCO (Alloy 690MA vs. Alloy 600MA)	1979	50, U-bends	300	655	<1	21
West. (Alloy 690MA vs. Alloy 600MA)	1980	10-50, U-bend	~330	2200 - 5592	LBI	50
EDF	1981	10, Frac. Mech.	350	not reported	40	51
EDF (Alloy 690MA vs. Alloy 600MA)	1981	• 4, C-ring	350	not reported	LBI	51
EDF (Alloy 690MA vs. Alloy 600MA)	1981	10, C-ring	350	not reported	5	51
EDF (Alloy 690MA vs. Alloy 600MA)	1981	20, C-ring	350	not reported	2	51
INCO (Alloy 690MA vs. Alloy 600MA)	1982-3	50, U-bend	316	9000	5	52,53
INCO (Alloy 690MA vs. Alloy 600MA)	1982-3	1, U-bend	316	9400	LBI	52,53
INCO	1982-3	10, CERT	288-300	not reported	2	52,53
W, EDF, Fram., CEA	1985	10, C-ring	315	1000	LBI to 200	54
W, EDF, Fram., CEA	1985	10, C-ring	332	4000	~6 to LBI	54
W, EDF, Fram., CEA	1985	10, C-ring	315	2000	20	54
MHI and Sumitomo	1985	10, C-ring	325 & 343	500 & 1500	LBI	16

Table 5-10 (continued)
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Caustic Environments

Organization	Date	Caustic Conc. (%NaOH), Type Test	Temp (•C)	Time (hours)	Improvement Factor, IFR	Reference
INCO	1985	10, C-ring	316	1680 - 8200	> 2.9	55
ENEL (Alloy 690MA vs. Alloy 600MA)	1986	NaOH in FW, MB	~290	816	1.5	56
CE	1987	NaOH in FW, MB	332	1128	2.5 to > 5	57
INCO	1987	10, U-bend	350	4152	> 5.8	58
Rockwell	1987	50, C-ring	320	120	LBI	59
MHI	1989	10, C-ring	343	1500	LBI	61
British	1990	30, Unstressed C-ring	350	12000	6.5	38
British	1990	10, C-ring	305	1000	86	38
Westinghouse	1990	10, C-ring	343	500 - 1000	40 - 298	62
Westinghouse	1990	NaOH in FW, MB	not rep.	7608	25	62
B&W	1991	4, C-ring	324	4073	8	63
CIEMAT	1993	10, C-ring	350	1000	19 to 40	64
CIEMAT	1994	4, C-ring	320	2000	LBI	65
EDF	1995	10, various	350	1000	3 to >10	66
CIEMAT	1996	4, C-ring	320	1000	LBI	67
Sumitomo	1997	10, SSRT	300	CERT	3.7	68
Sumitomo	1997	10, C-ring	325	1000	> 10	68
CRIEPI	1999	10, C-ring	350	10000	> 20	69
KAERI	2004	10, RUB	315	1440	> 1.5*	70,71
Japanese	2005	10, C-ring	350	240	> 20	72
Bettis	2005	10, STUB	307	2000	> 8.1	73
KAERI	2006	10, RUB	315	1440	> 1.5	86

Table 5-11
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Chloride Environments

Organization	Date	Environment, Test Type	Temp (•C)	Time (hours)	Improvement Factor, IF_R	Ref.
Westinghouse	1980	Oxygenated water with 100 ppm chlorides, C-rings	330	10,578	Indeterminate (no cracking)	50
Japanese	1985	100 - 500 ppm chlorides, Double U-bends and C-rings	288 - 300	1000 - 4000	Indeterminate (no cracking)	16
INCO	1985	AVT + oxygen + 500 ppm chlorides, C-rings	316	12,400	Indeterminate (no cracking)	55
Westinghouse	1985	12.7% $FeCl_2$, C-rings	332	5000	Indeterminate (no cracking)	17
CE	1985	AVT + chloride contamination, Model Boiler	282	12,650	> 6	74
Kobe Steel	1987	Aerated pH 4 water with chlorides, Double U-bend	300	1000	LBI (no cracking of Alloy 690TT)	37
CIEMAT	1993	Deaerated AVT water with 50 ppm NaCl + 50 ppm $CuCl_2$, C-ring	350	1000	LBI (no cracking of Alloy 690TT)	64
MEA	1994	AVT water with Cl^- + $SO_4^=$ at $PH_{315°C}$ 2.7, C-ring	315	100	20	75
MEA	1994	1.636m NaCl, 0.082m Na_2SO_4, 0.100m $(NH_4)_2SO_4$, $PH_{315°C}$ 3.9, C-rings	315	71.5 - 96	LBI	75
MEA	1994	1.90m NaCl, 0.05m Na_2SO_4, 0.02m $(NH_4)_2SO_4$, $PH_{315°C}$ 3.1, C-rings	315	98	20	75
EDF	1997	50 g/l chlorides at pH_T 2, U-bend	250	2000	LBI (Alloy 690TT did not crack)	185
EDF	1997	50 g/l chlorides plus 3% boric acid at pH_T 2, U-bend	250	288 - 1500	LBI (Alloy 690TT did not crack)	185
EDF (Alloy 690MA)	1997	Boiling $MgCl_2$ at pH_T 1, C-ring or U-bend	153	288 - 1500	0.2	185
Japanese	2005	38 ppm HCl $pH_{335°C}$ ~3, C-ring	350	360	> 3	72

LBI = Large But Indeterminate

Table 5-12
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Sulfate Environments

Organization	Date	Environment, Test type	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
CE (Alloy 690MA)	1983	Sulfate faulted MB	300	8760	6, LBI	76
CERL	1983	Acid sulfates, C-rings pH_T ~ 3.6	290 - 350	4400	148 - 254	77
CERL	1983	Acid sulfates, CERT pH_T ~ 2.8	305	not given	14 to 15	77
INCO	1985	SO_4 cont. 10% NaOH, C-ring pH_T ~ 10.2	316	up to 8232	> 2.9	55
Westinghouse	1985	8% Na_2SO_4, pH_{RT} 2 to 10, C-ring	332	5000	pH324°C 6.0 - 200 pH324°C 7.1 - 100 pH324°C 8.0 - 20	17
Kobe Steel	1987	Boiling ferric sulfate - sulfuric acid	Boiling temp.	120	LBI	37
CEA	1989	Resin fines contaminated MB	~300	8Alloy 600	LBI	78
CIEMAT	1993	50% NaOH + 5% $Na_2S_2O_3$, C-rings pH_T ~ 10.5	350	1000	Indeterminate, but Alloy 690TT more susceptible, < 1	64
CIEMAT	1993	Na_2SO_4 and $FeSO_4$ solutions, C-rings pH_T ~ 4.4	350	1000	205	64
MEA	1994	0.491m $(NH_4)_2SO_4$ + 0.0467m H_2SO_4, $pH_{318°C}$ 3.2, C-rings	318	207.5	8	75
Laborelec	1997/8	Acid sulfates, capsule with hard roll pH_T ~ 4.4	320	up to 711	220	79
Laborelec	1997/8	Acid sulfates with copper oxides, capsule with hard roll pH_T ~ 4.4	320	up to 711	~ 0.3	79
Laborelec	1997/8	Acid sulfates with copper metal, capsule with hard roll pH_T ~ 4.4	320	up to 711	~ 1	79
EDF	1998/ 2000/1	Sulfate solutions, some with copper oxides, pH_T 5 - 9.5, C-ring	320	2500 - 3000	pH_T 5: 2.4, 19, 75 pH_T 6: 2.6, 19 pH_T 8: 4	80, 81, 82
CEA	1999	Na_2SO_4 polluted MB	300	Alloy 8000	LBI	83

LBI = Large But Indeterminate

Table 5-13
Summary of Laboratory Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Lead Contaminated Environments

Organization	Date	Environment, Type Test	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
Westinghouse	1980	Water + PbO, U-bend, estimated pH_T ~ 7	330	29,500	15	50
B&W	1991	Lead contaminated environments, C-ring	324	~ 4000	pH_T 2.2 - 1 pH_T 3.8 - 1.2 pH_T 4.5 - 20 pH_T 6.7 - 200 pH_T 6.8 - 10 pH_T 7.4 - 110 pH_T 9.9 - 0.4, 9	63
Japanese	1992	Lead chlorides pH_T 4.5, C-ring	340	up to 2500	2	20
CEA	1992	Lead polluted AVT, Model boiler, estimated pH_T ~ 7	284	9007	6 and 28	101,102
CIEMAT	1993	4 to 10% NaOH with lead, C-ring, pH_T ~ 10.3	350	500 to 1000	0.1 to 1.6	64
CIEMAT	1993	0.75 M Na_2SO_4 + 0.25 M $FeSO_4$ + 0.1 M PbO, C-ring, pH_T ~ 6.3	350	500	220	
Japanese	1994	AVT + lead species, C-ring, estimated pH_T ~ 7	320	4000	107	29
CIEMAT	1994	4% NaOH + lead species, C-ring, pH_T ~ 10.2	320	2000	20 to 37	67
		AVT + lead species, C-ring, estimated pH_T ~ 7	320	2000	15 & 81	
French	1994	10% NaOH + 1% PbO, capsule, pH_T ~ 10.3	350	up to ~ 3000	0.23	30
French	1995	110g/l NaOH + 10 g/l PbO, C-ring & RUB, pH_T ~ 10.3	350	5000	0.15	66
Korean	1997	1 M NaOH and 100 ppm lead, C-ring, pH_T ~ 10.2	340	480	1000	103
		1 M NaOH and 5000 ppm lead, C-ring, pH_T ~ 10.2	340	480	1.6	
CEA	1997	AVT + resin liquor + lead oxide, Model boiler	295	6072	LBI	153

Table 5-13 (continued)
Summary of Laboratory Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Lead Contaminated Environments

Organization	Date	Environment, Type Test	Temp (•C)	Time (hours)	Improvement Factor, IFR	Ref.
CEA	1993	Pure water + 1% PbO, RUB	325	5000	5	104
KAERI	2004	1000 ppm lead + 10% NaOH, RUB	315	1920	< 0.13	70, 71
Bettis	2005	1% PbO + 10% NaOH, STUB	307	500	0.044	73
KAERI	2006	10% NaOH + 1000 ppm lead as PbO	315	1000	< 0.25	86
Rockwell	2006	500 ppm Pb + 6 ppm H2, pH330C = 5, 7, or 9	330	3840	4	89
Teledyne	2007	500 ppm Pb + 1.5 M Na2SO4, 0.01M Fe3O4, 0.05M Al2O3, 0.3M SiO2, 0.15M KOH, 0.04M HCl, pH330C = 9; RUB	330	up to 4260	> 4.3	31
		3M NaCl + 0.16M NaOH + 500 ppm Pb as PbO (pHT = 9); RUB	330	up to 4320	3.9	
		3M NaCl + 500 ppm Pb as PbO (pHT = 7); RUB	330	up to 4820	> 4.3	
		3M NaCl + 500 ppm Pb as PbCl2 (pHT = 5); RUB	330	up to 3875	> 2.0	

LBI = Large But Indeterminate

Table 5-14
Summary of Laboratory Test Indicated Improvement Factors for Alloy 690TT vs. Alloy 600MA in Oxidizing Environments

Organization	Date	Environment, Test type	Temp (°C)	Time (hours)	Improvement Factor, IF_R	Ref.
Laborelec	1997-1998	Acid sulfates w/ copper oxides, capsule w/ hard roll, pHT ~ 4.4	320	up to 711	~ 0.3	79
		Acid sulfates w/ copper metal, capsule w/ hard roll, pH_T ~ 4.4			~ 1	
KAPL	2005	AVT + oxidizing sludge w/ 2% PbO	not given	2,000	not available*	85

* Not reported. Test cited for information only and not explicitly used in subsequent evaluations.

5.2.2.1 Alloy 690TT/Alloy 600MA PWSCC IF_R

The data on Alloy 690TT/Alloy 600MA improvement factors (given in Table 5-9) are by definition determined over a limited range of pH values. An improvement factor of > 125 was determined to best represent this population. The selection of this value is discussed further in Section 5.5.1.2.

5.2.2.2 Alloy 690TT/Alloy 600MA Caustic ODSCC IF_R as a Function of pH

The various improvement factors which have been calculated using laboratory test data are given in Table 5-10. For caustic environments, most data are at a pH of 10.3 (10% caustic solution). The following data were considered in developing a pH dependent improvement factor for caustic solutions:

- The IF_R was assumed to be that of Alloy 690TT in primary conditions (> 125) for pH_T = 3.5 through pH_T = 7.4 (the upper limit of allowable pH for the primary system). For the pH to fall within this range, the hydroxide caustic concentration is very low and neutral conditions are assumed to dominate.
- Most data for caustic test environments were at an estimated pH of 10.3 (corresponding to 10% NaOH in solution). The median IF_R of 10 was taken as representative for these data (see Table 5-9 for data).
- One value of 6.5 was reported as the IF_R at a pH_T = 10.5.
- The IF_R was assumed to be a linear function in the pH range from 7.4 to 10.5. A linear fit was made to the three data points, with one end fixed at 7.4.

Figure 5-6 shows the relationship resulting from the combination of the above. The relationship between pH_T of 7.4 and 10 is quite subjective due to a lack of data in this range.

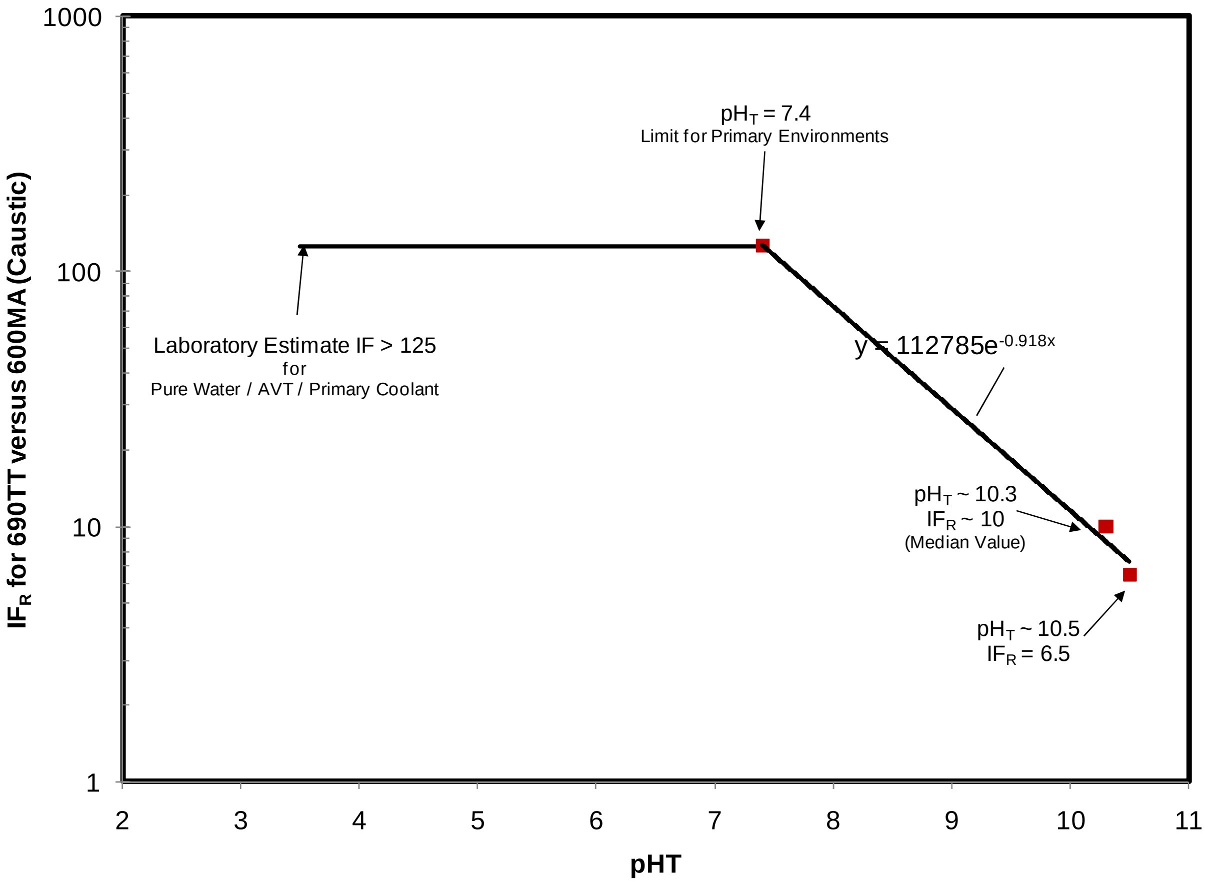

Figure 5-6
Alloy 690TT/Alloy 600MA IF_R as a Function of pH_T for Sodium Contaminated Environments

5.2.2.3 Alloy 690TT/Alloy 600MA Chloride ODSCC IF_R as a Function of pH

The various improvement factors which have been calculated using laboratory test data from chloride environments are given in Table 5-11. These data are plotted against pH in Figure 5-7. Most of the available data are at low pH. To model higher pH effects, the following steps were taken:

- The function was approximated by a best-fit line through the lower two points ($pH_T < 2$). In this range, the improvement factor is less than 1, indicating reduced resistance to corrosion compared to Alloy 600MA.
- The relationship between pH_T and IF_R was taken to be linear in the range from 2 to 5.5.
- Above $pH_T = 5.5$, the improvement factor was assumed to be 125, the value for relatively dilute solutions (see Section 5.2.2.1).

- Data for Alloy 690MA was not considered relevant. The improvement factor for Alloy 690MA is expected to be lower than that of Alloy 690TT, which is consistent with this data point.

The resulting relationship between the improvement factor and pH is shown in Figure 5-7. The relationship between pH_T 2 and 5.5 is considered somewhat speculative because of the lack of available data in this range.

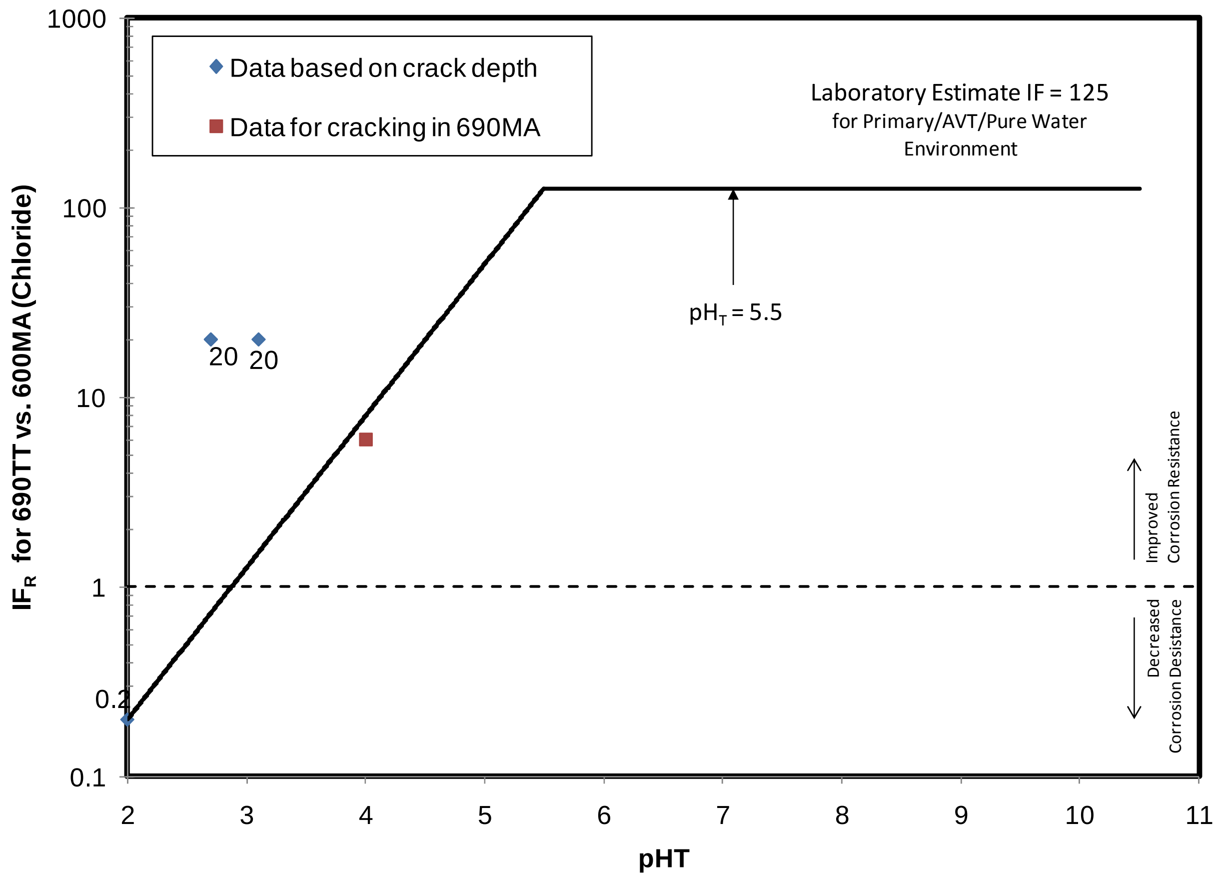

Figure 5-7
Alloy 690TT IF_R as a Function of pH in Chloride Contaminated Environments

5.2.2.4 Alloy 690TT/Alloy 600MA Sulfate ODSCC IF_R as a Function of pH

The improvement factors for environments containing sulfate are plotted in Figure 5-8. Based on the large scatter in the data and the absence of actual cracking of Alloy 690TT, it is inferred that the presence of sulfates does not substantially affect the performance of Alloy 690TT. Therefore, an IF_R of 125 was assumed valid for the primary side pH range (< 7.4).

Extensive ODSCC was observed in Alloy 690TT at a pH_T of 10.5 (in a 50% caustic solution contaminated with sulfur at approximately the same levels as observed in Alloy 600MA). An improvement factor of ~1 (no improvement) was therefore taken as a bound at high pH. In the absence of data, the relationship between pH and IF_R between primary and high pH conditions was assumed to be linear.

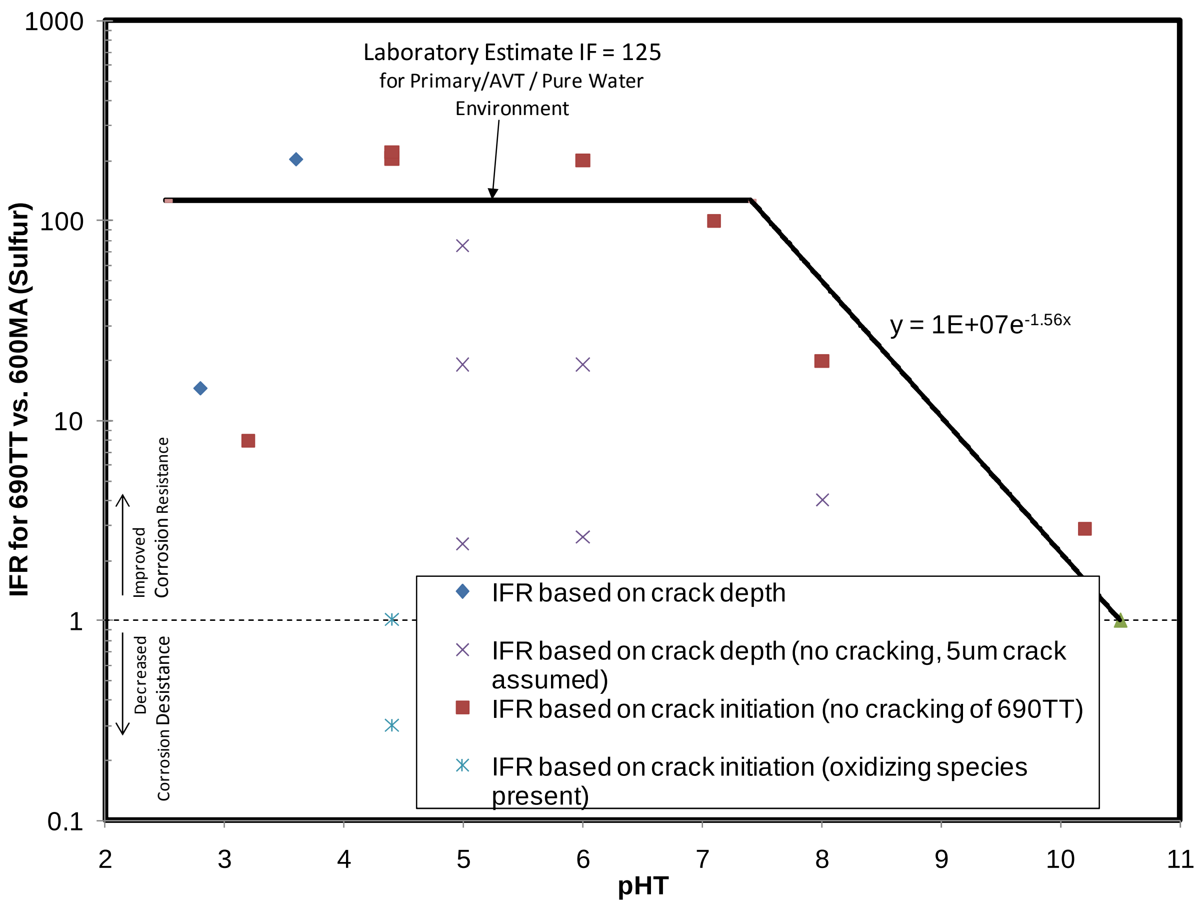

Figure 5-8
Alloy 690TT IF_R as a Function of pH in Sulfur Contaminated Environments

5.2.2.5 Alloy 690TT/Alloy 600MA Lead ODSCC IF_R as a Function of pH

The improvement factors for lead contaminated environments are plotted as a function of pH in Figure 5-9. The only cracking observed in Alloy 690TT occurred in highly caustic environments or those with chloride contamination (low pH). These data were therefore taken to bound the distribution, and a parabola was fit to encompass the remainder of the data. The values within the distribution are conservatively low, as no cracking was observed. The improvement factors calculated for these data would continue to increase with increased test duration until actual cracking was observed. Outside of the bounds of the parabola, the improvement factor was taken as unity based on the observed data points.

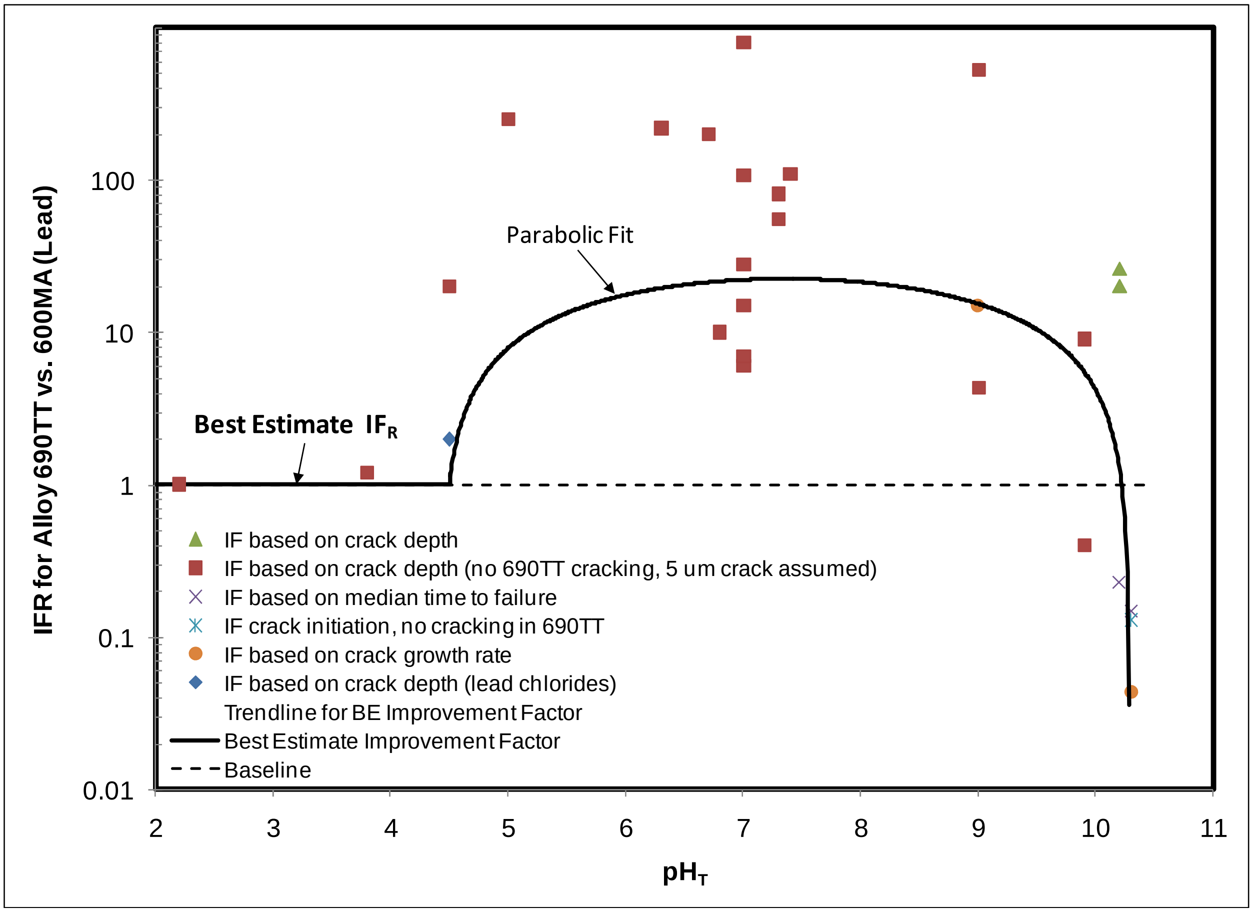

Figure 5-9
Alloy 690TT IF_R as a Function of pH in Lead Contaminated Environments

5.2.2.6 Alloy 690TT/Alloy 600MA ODSCC in the Presence of Oxidizing Species

Due to the limited test data available, the effect of oxidizing species on the performance of Alloy 690TT cannot be estimated with any degree of confidence at this time. The improvement factor is thus indeterminate.

5.2.3 Alloy 800NG versus Alloy 600MA

This section contains summaries of the results of the review of corrosion test data for Alloy 800NG in specific chemical environments, including summary tables of improvement factors. The same chemistries considered in Section 5.2.1 are considered in this section for Alloy 800NG.

- Pure, primary, and AVT water environments - Table 5-15
- Caustic contaminated environments - Table 5-16
- Chloride contaminated environments - Table 5-17
- Sulfur contaminated environments - Table 5-18
- Lead contaminated environments - Table 5-19
- Environments containing oxidizing species - Table 5-20

The results of laboratory tests pertaining to the performance of Alloy 800NG and Alloy 600MA are summarized in the corresponding tables.

In addition to these environments, there is a significant body of experimental work reported by the CANDU Owners Group (COG) that uses complex crevice chemistries. The data from these works are discussed in Section 5.2.3.7.

Table 5-15
Summary of Alloy 800NG Laboratory Testing In Pure, Primary and AVT Water Environments

Testing Org.	Date	Environment, Type Test	pH_T	Temp (°C)	Time (hours)	IF_R vs. Alloy 600MA	Ref.	NG Tested?
Siemens	1972	Obrigheim secondary side, expansions	6.1	265	18000	~10	90	Yes
Indian	1981	Pure water, U-bends of Alloy 800SA and Alloy 600MA	5.6	315	1600	Not Quantified*	91	Yes
		Pure water, U-bends of Alloy 800SA and Alloy 600 heavily sensitized (~Alloy 600TT)	5.6	315	1600	Not Quantified*		
Kobe Steel	1987	Primary water, H_2 sat'd	Primary	330	3000	>26, >18, >34	37	Yes

* After 1600 hrs, cracking macroscopically observed in Alloy 600MA but not in Alloy 800NG. No complete metallographic (microscopic) analyses performed.

Table 5-16
Summary of Alloy 800NG Laboratory Testing in Caustic Environments

Organization	Date	Environment, Type Test	Temp (°C)	Time (hours)	IF_R vs. Alloy 600MA	Ref.	NG Tested?
Westinghouse	1976	10, C-ring	316	4800	15	92	Yes
Westinghouse	1976	50, C-ring	316	4800	0.5	92	Yes
INCO	1976	50, Frac. Mech.	316	336	0.02	48	Unknown
Atomenergi	1976	20%, and 20% +5%NaCl, U-bend	325	2000	36	93	No
EDF	1977	0.4, various	350	various	LBI	94	Unknown
EDF	1977	4, various	350	various	LBI	94	Unknown
EDF	1977	10, various	350	various	LBI	94	Unknown
EDF	1977	50, various	350	various	0.2	94	Unknown
INCO	1984	10, C-ring	316	10,920	60	27	Unknown
MHI	Mid 1980s	10, C-ring	325	500	51	16	Yes
Westinghouse	Mid 1980s	10, C-ring	332	---	23	17	Yes
Westinghouse	Mid 1980s	10% with 1% CuO, C-ring	332	---	2	17	Yes
CE	1987	Caustic forming water, model boiler tubes	316	1128	0.48	57	Yes
Rockwell	1988	50% + 1% Na_2CO_3, C-ring	320 & 350	120 & 240	0.2	95	No
Siemens	1992	10, U-bend	350	1900	7.6	96	Unknown
Siemens	1992	10+ Na_2CO_3 or CuO, U-bend	350	1900	2.7	96	Unknown
Siemens	1992	50+ Na_2CO_3, U-bend	350	700	0.04	96	Unknown
Siemens	1992	10+ Na_2SO_4 Na_2CO_3, CuO, or Fe_3O_4,U-bend	350	---	0.86	96	Unknown
CIEMAT	1993	10 and 10+0.01% CuO, C-ring	350	1000	0.64	64	Unknown
CIEMAT	1994	4, C-ring	320	2000	1.5	65	Yes
EDF	1995	Various	350	1000	> 10	66	Yes
CIEMAT	1996	4, C-ring	320	1500	1.7	67	Yes
Japanese	1997	10+2% Na_2CO_3, C-ring	350	10,000	> 127	69	Unknown

LBI = Large But Indeterminate

Table 5-17
Summary of Alloy 800NG Laboratory Testing in Chloride Contaminated Environments

Organization	Date	Environment, Type Test	Temp (°C)	Time (hours)	IF_R vs. Alloy 600MA	Ref.	NG Tested?
Westinghouse	1985	12.7% $FeCl_2$, C-rings (pH_T~4.1)	332	5000	SBI (<0.0167)	17	Yes
CE	1985	MB with seawater contamination, pH_T ~ 4	~ 300	---	>1	74	Unknown
Kobe Steel	1987	1000 ppm Cl^- (pH_T~5.7)	300	1000	10	37	Yes
CIEMAT	1993	50 ppm NaCl plus 50 ppm $CuCl_2$ (pH_T ~ 2.1)	350	500	0.33	64	Unknown

SBI = Small But Indeterminate

Table 5-18
Summary of Alloy 800NG Laboratory Testing in Sulfur Contaminated Environments

Organization	Date	Environment, Type Test	Temp (°C)	Time (hours)	IF_R vs. Alloy 600MA	Ref.	NG Tested?
INCO	1984	10% NaOH, 750 ppm sulfate, C-ring	316	8232	8	27	Unknown
Westinghouse	1985	8% Na_2SO_4, C-ring	332	not given	5.9	17	Yes
Kobe Steel	1987	boiling ferric sulfate-sulfuric acid, Streicher test	500	1200	LBI	37	Yes
Siemens	1992	25% caustic plus 20% FeS (reducing), U-bend	not given	700	0.37	96	Unknown
CIEMAT	1993	0.75 M Na_2SO_4 plus 0.25 M $FeSO_4$, C-ring	350	500	1.3	64	Unknown
AECL	1994	AVT water w/ $NaHSO_4$	320	not given	LBI	97	Unknown
EDF	1998, 2000, 2001	96 ppm SO_4, pH_T ~ 5	320	3000	2.4	80, 81,82	Unknown
		5000 ppm SO_4, pH_T ~ 5			1.55		
		5000 ppm SO_4, pH_T ~ 6			2.6		
		57000 ppm SO_4, pH_T ~ 5			8.3		
		57000 ppm SO_4, pH_T ~ 6			2.5		
		57000 ppm SO_4, pH_T ~ 8			4		
		57000 ppm SO_4, pH_T ~ 9.5			1		

LBI = Large But Indeterminate

Table 5-19
Summary of Laboratory Testing of Alloy 800NG in Lead Contaminated Environments

Organization	Date	Environment, Type Test	Temp (°C)	Time (hours)	IF_R vs. Alloy 600MA	Ref.	NG Tested?
Indian	1981	U-bend, 50% CW, 0.6 ppm Pb	315	1600	LBI	91	Yes
CIEMAT	1993	Caustic, lead contaminated, C-ring	350	500	0.1	64	Unknown
CIEMAT	1994	4% NaOH + 0.01m PbO, C-ring	320	2000	3.40	65	Yes
		4% NaOH + 0.002m PbO, C-ring			1.8		
		4% NaOH + 0.0004m PbO, C-ring			0.1		
		AVT + 0.01m PbO ($pH_{320°C}$ = 7.3), C-ring			8.6		
		AVT + 0.002m PbO ($pH_{320°C}$ = 7.3), C-ring			5		
Japanese	1994	AVT + Pb, C-ring	320	4000	107	29	Unknown
French	1994	10% NaOH and 1% PbO	350	not given	0.02	30	Unknown
AECL	1994	AVT + $NaHSO_4$ + Pb	320	not given	LBI	97	Unknown
French	1995	100 g/l NaOH + 10 g/l PbO, C-ring and RUB	350	2000	0.015	66	Yes
CIEMAT	1996	AVT, 10, 50 and 100 ppm PbO	320	2000	12 -2 (7)	67	Yes

LBI = Large But Indeterminate

Table 5-20
Summary of Laboratory Testing of Alloy 800NG in Oxidizing Environments

Organization	Date	Environment, Type Test	Temp (°C)	Time (hours)	IF_R vs. Alloy 600MA	Ref.	NG Tested?
Westinghouse	Mid 1980s	10% NaOH with 1% CuO, C-ring	332	---	2	17	Yes
Siemens	1992	10% NaOH + Na_2CO_3 or CuO, U-bend	350	1900	2.7	96	Unknown
		10% NaOH + Na_2SO_4, Na_2CO_3, CuO, or Fe_3O_4,U-bend	350	---	< 0.86		
CIEMAT	1993	10% NaOH + 0.01% CuO, C-ring	350	1000	0.43	64	Unknown
		50 ppm NaCl plus 50 ppm $CuCl_2$ (pH_T ~ 2.1)	350	500	0.33		

Experiment-based improvement factors as functions of pH for each environment considered are developed in the subsections that follow.

5.2.3.1 Alloy 800NG/Alloy 600MA PWSCC IF_R

The improvement factors for pure water and uncontaminated all volatile treatment (AVT) secondary system water testing environments are shown in Table 5-15. As can be seen from this table, there are limited data comparing Alloy 800NG to Alloy 600MA in pure water and AVT environments without contaminants. The data that exist indicate that Alloy 800NG is more resistant to corrosion than Alloy 600MA in these environments; however, due to the limited number of data, an estimate of the improvement factor based on experimental data does not have a high degree of confidence. The laboratory based IF_R for Alloy 800NG versus Alloy 600MA is thus indeterminate but likely to be greater than 20. This rationale is discussed further in Section 5.5.1.3.

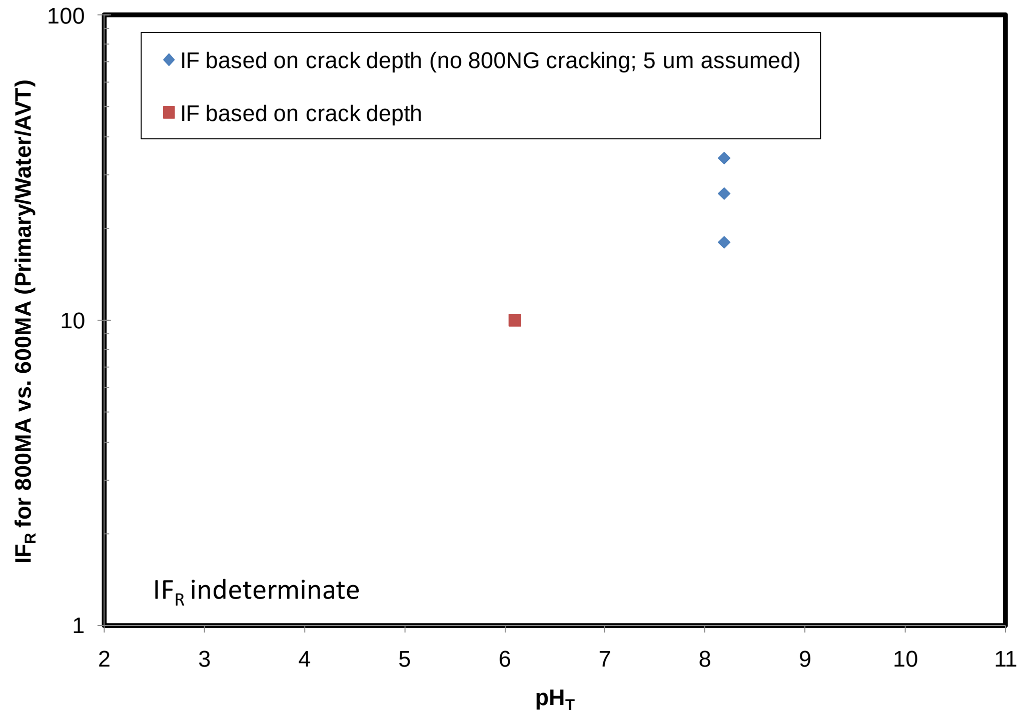

Figure 5-10
Alloy 800NG IF$_R$ in Primary / Water / AVT Environments

5.2.3.2 Alloy 800NG/Alloy 600MA ODSCC IF$_R$ in Caustic Environments

Improvement factors for Alloy 800NG vs. Alloy 600MA in caustic tests are listed in Table 5-16. The improvement factors calculated from the results are plotted as a function of pH in Figure 5-11. In tests in 10% caustic solutions (pH$_T$~10.3) there is evidence that Alloy 800NG is more resistant to SCC than Alloy 600MA. However, in extremely caustic environments (pH$_T$ ~ 10.5), Alloy 800NG appears more susceptible to SCC than Alloy 600MA. Overall, there is significant scatter in the data, preventing estimation of the improvement factor with any degree of confidence.

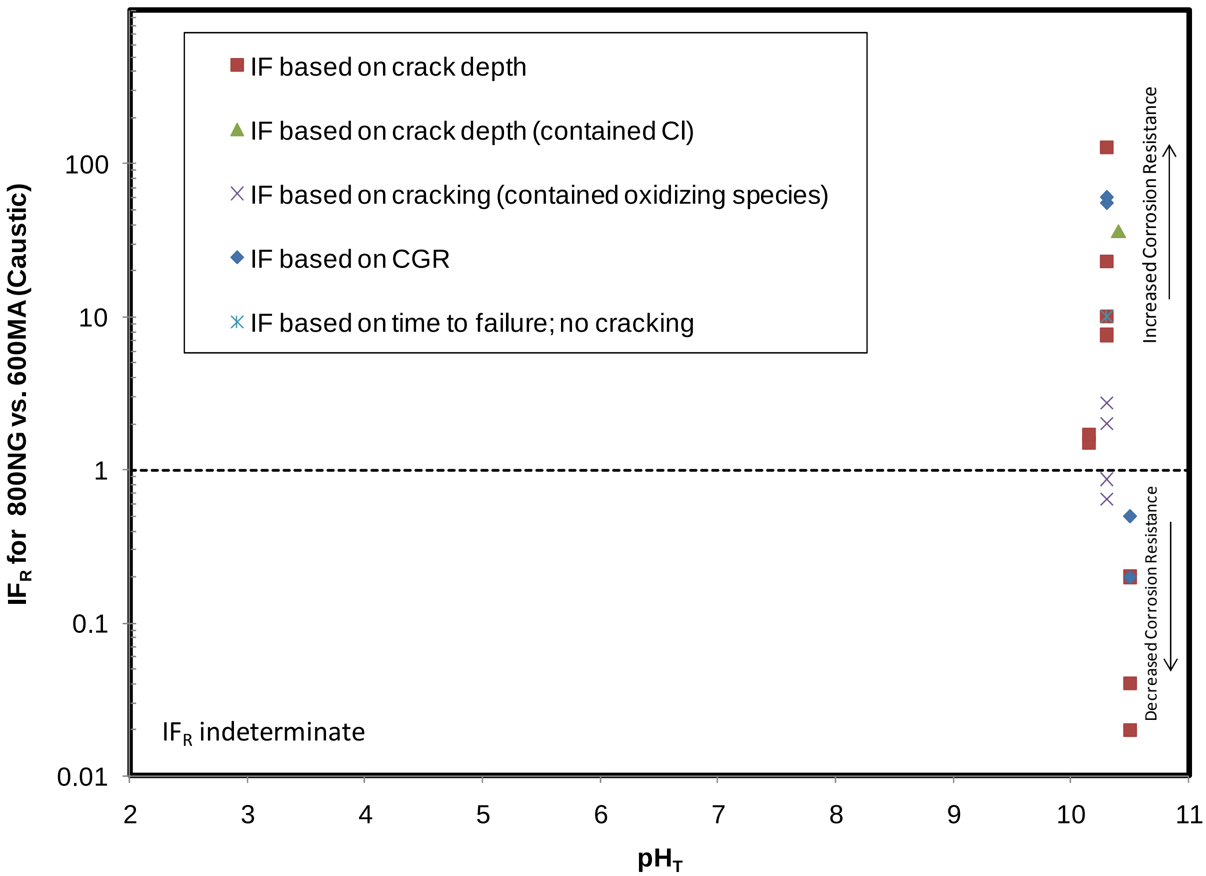

Figure 5-11
Alloy 800NG IF_R as a Function of pH in Sodium Contaminated Environments

5.2.3.3 Alloy 800NG/Alloy 600MA ODSCC IF_R in Chloride Contaminated Environments

Improvement factors for tests of SCC in Alloy 800NG vs. Alloy 600MA performed in chloride contaminated environments are listed in Table 5-17. The calculated improvement factors are plotted as a function of pH in Figure 5-12. Due to differences in test environments and the shortage of available data, the data do not indicate that the use of Alloy 800NG has a significant effect on performance when compared to Alloy 600MA. The improvement factor for these conditions is thus taken to be 1 (no difference).

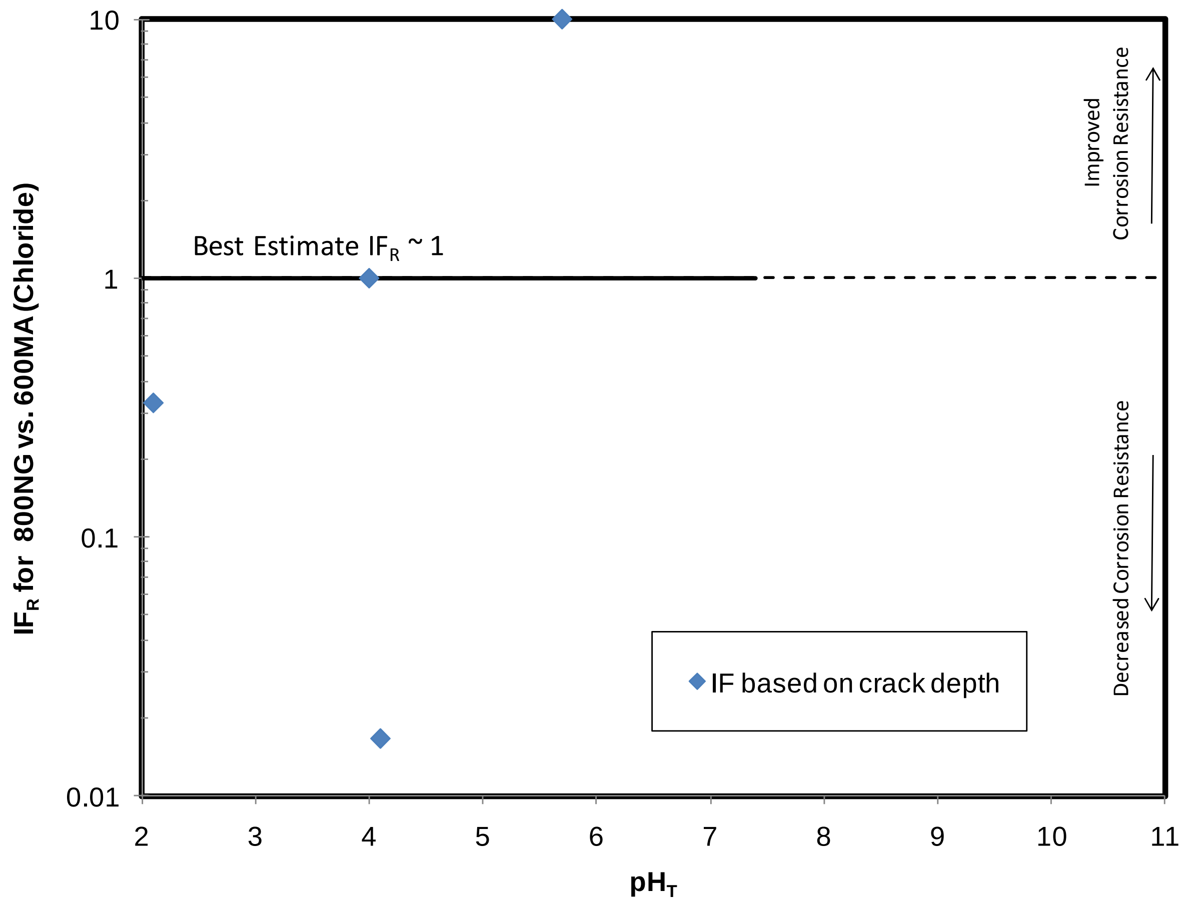

Figure 5-12
Alloy 800NG IF_R as a Function of pH in Chloride Contaminated Environments

5.2.3.4 Alloy 800NG/Alloy 600MA ODSCC IF_R in Sulfur Contaminated Environments

The improvement factors for Alloy 800NG vs. Alloy 600MA and Alloy 690TT for IGA/SCC in sulfur contaminated environments are summarized in Table 5-18. Alloy 800NG generally was more resistant to IGA/SCC in sulfate environments than Alloy 600MA. The improvement factors determined from the experimental results are plotted in Figure 5-13. Test results from model boiler experiments are excluded from this table (discussed in Section 5.2), as are experiments yielding indeterminate data. Data on the performance of Alloy 800NG in low to moderately contaminated environments (≤ 5000 ppm) were considered to be more relevant to potential plant conditions and was therefore weighted significantly more than data for extreme environments in determining an estimate of the improvement factor function.

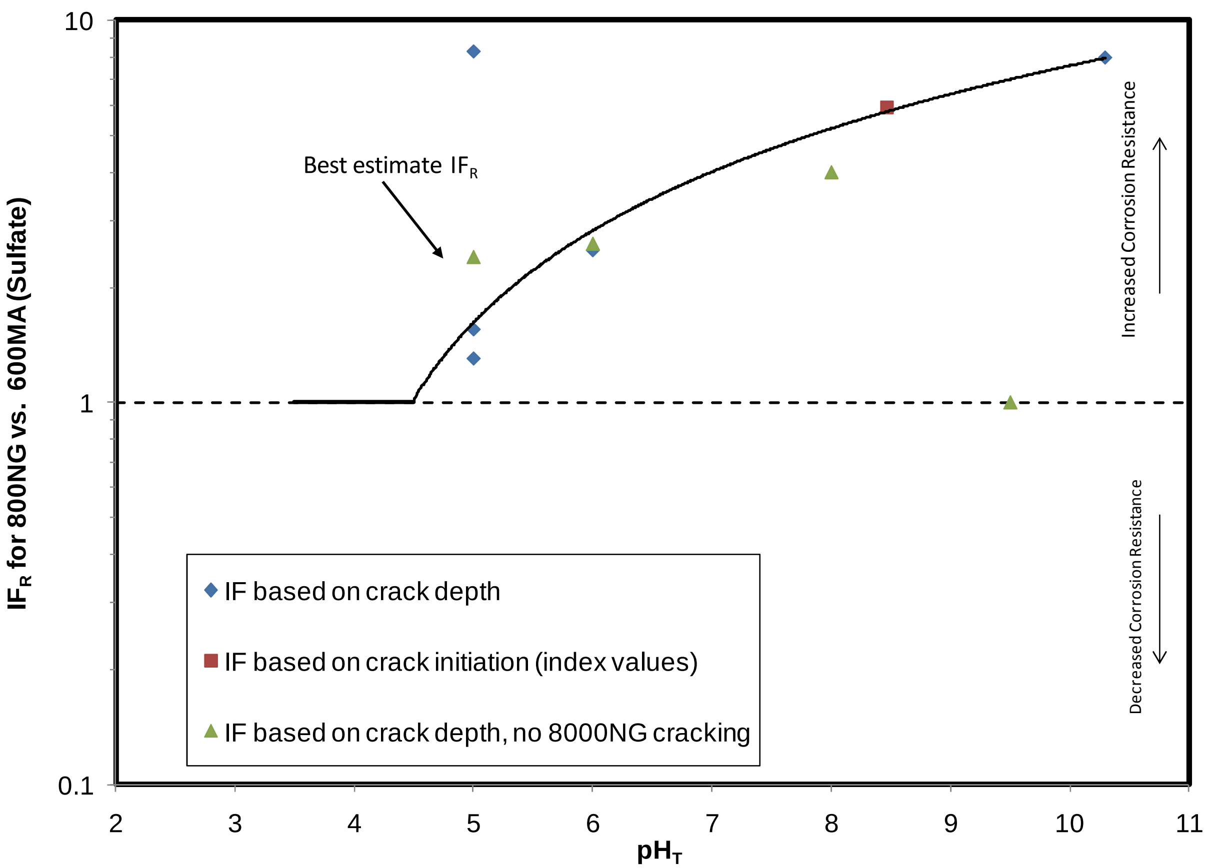

Figure 5-13
Alloy 800NG IF_R as a Function of pH in Sulfur Contaminated Environments

5.2.3.5 Alloy 800NG/Alloy 600MA ODSCC IF_R in Lead Contaminated Environments

The improvement factors for Alloy 800NG vs. Alloy 600MA for IGA/SCC in lead contaminated environments are summarized in Table 5-19. As before, test results from model boiler experiments are excluded from this table (discussed in Section 5.2), as are experiments yielding indeterminate data. The improvement factors determined from the experimental results are plotted as a function of pH in Figure 5-14. A conservative improvement factor of 5 was selected for the moderate pH range, due to the uncertainty in determining the improvement factor for primary water/AVT (near neutral) environments (discussed in Section 5.2.3.1).

As seen in Figure 5-14, Alloy 800NG performs better than Alloy 600MA at moderate pH, but is less resistant to SCC in caustic lead solutions. Since these conditions are not likely to occur during normal plant operation, these were weighted less. However, this increased susceptibility should be kept in mind should such a situation arise.

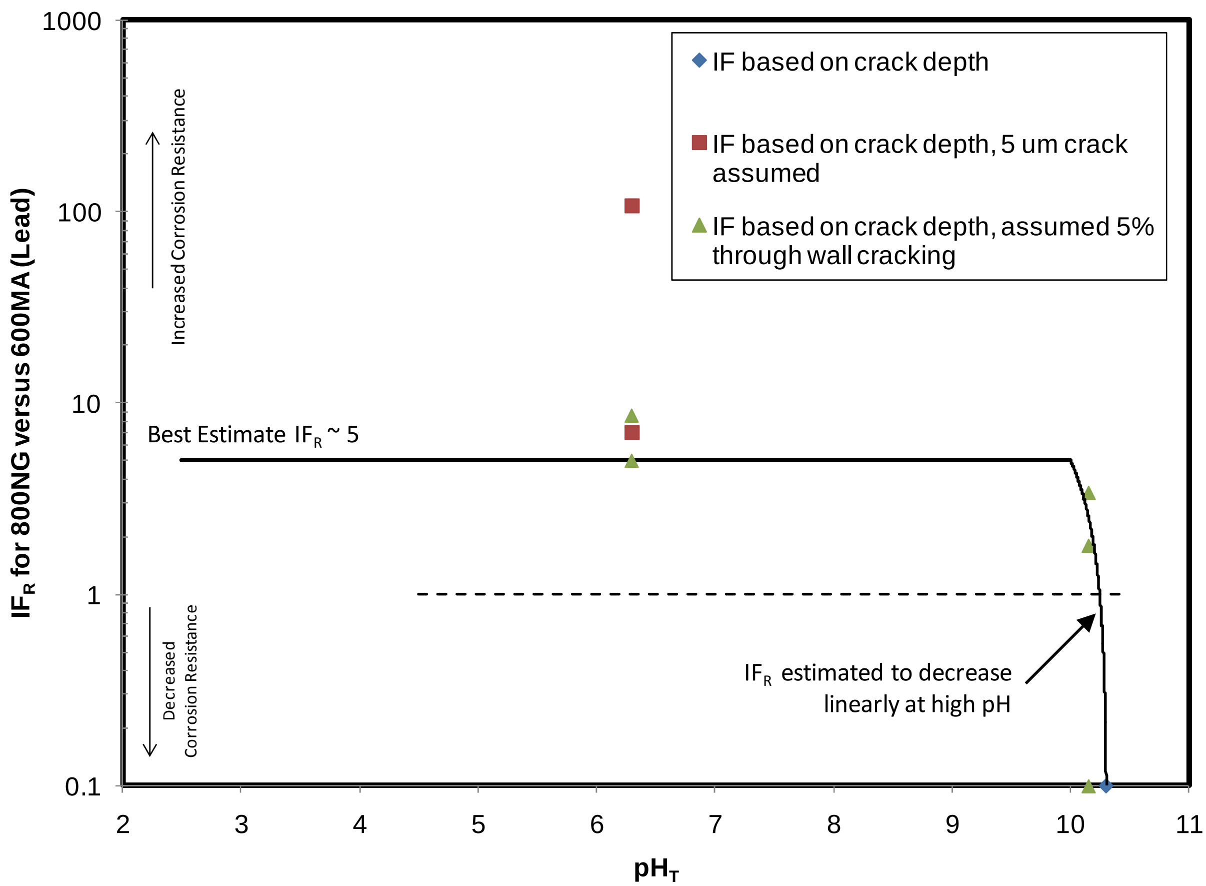

Figure 5-14
Alloy 800NG IF_R as a Function of pH in Lead Contaminated Environments

5.2.3.6 Alloy 800NG/Alloy 600MA ODSCC IF_R in Oxidizing Environments

Laboratory results comparing Alloy 800NG and Alloy 600MA performance in the presence of oxidizing species are limited and exhibit considerable scatter. In addition, these tests were performed at extreme pH values. It is therefore possible that any observed effects may be due to other factors or contaminants. The improvement factor was estimated to be 1 (no difference). The results of these experiments are plotted in Figure 5-15.

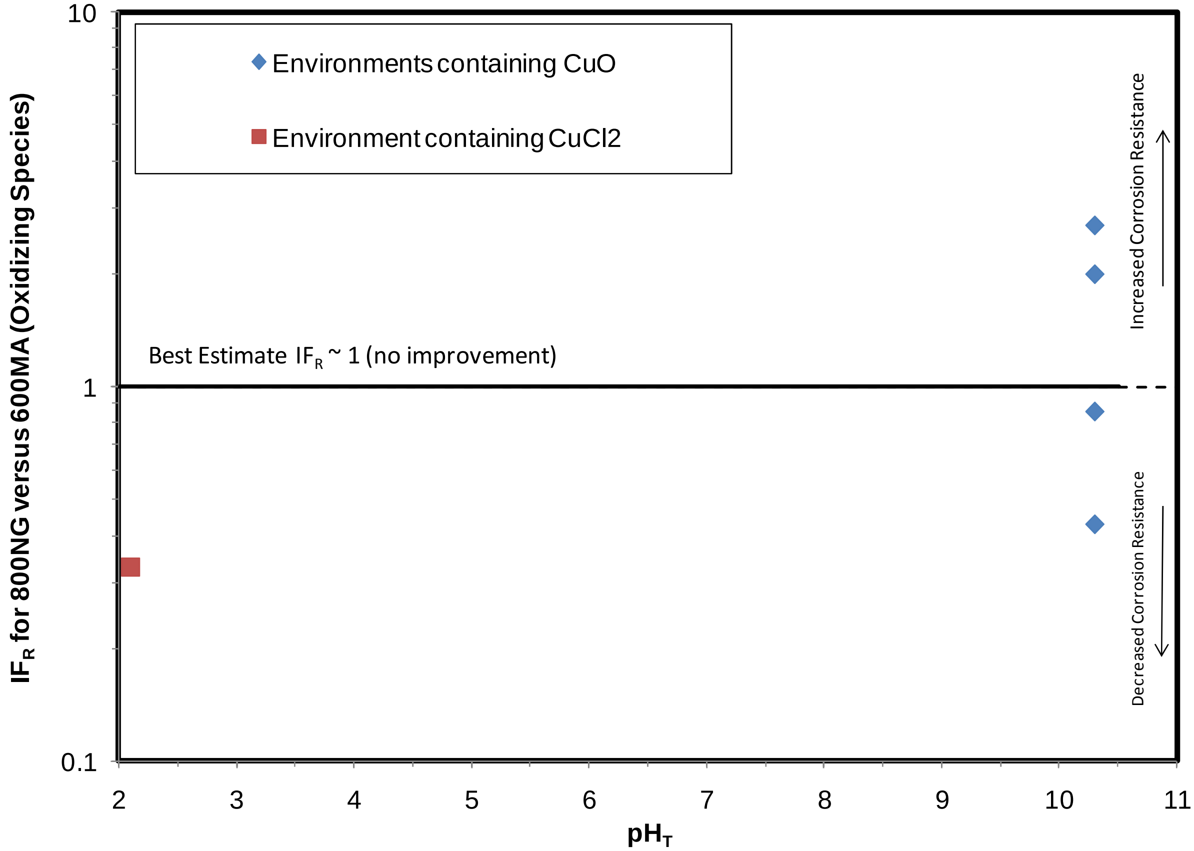

Figure 5-15
Alloy 800NG IF_R as a Function of pH in Oxidizing Environments

5.2.3.7 Alloy 800NG/Alloy 600MA ODSCC IF_R in COG Crevice Chemistries

The CANDU Owners Group (COG) has performed two series of tests which compare the susceptibility to SCC of Alloy 600MA and Alloy 800NG. Both series used three simulated crevice chemistries previously developed by Ontario Power Generation. The compositions of these simulated chemistries are given in Table 5-21.

The first series of tests [186, 187, 188, 189, 190] consisted of C-ring tests conducted at different strains (0.2%, 2%, and 4%[8]) and different temperatures (280°C, 304/305°C[9], and 315°C). The Alloy 600MA tests were conducted for six months (approximately 4,000 hours). The Alloy 800NG tests were conducted for either 4,000 hours or 6,000 hours. For most of the test conditions, neither Alloy 600MA nor Alloy 800NG cracked. For test conditions in which both alloys cracked, an improvement factor was calculated by dividing the Alloy 600MA crack length by the Alloy 800NG crack length. For conditions in which only one alloy cracked, the other was

[8] Tests with Alloy 800NG were only performed at 0.2% and 2% strain. In order to derive an improvement factor in one case, it was necessary to compare an Alloy 600MA sample at 4% to two Alloy 800NG samples, one each at 0.2% and 2% strain.
[9] Tests with Alloy 600MA were performed at 304°C. Tests with Alloy 800NG were performed at 305°C. These tests were treated as being conducted at equivalent temperatures in the analysis performed for this project.

assumed to have an undetected 5 µm crack (as discussed in Section 5.1.1) and an improvement factor was calculated in the same manner. For test conditions under which neither alloy cracked, no improvement factor was calculated. For test conditions in which the Alloy 800NG sample was exposed for 6,000 hours, the ratio of the crack lengths was multiplied by 1.5 to account for the longer exposure of the Alloy 800NG sample.

The calculated improvement factors for Alloy 800NG versus Alloy 600MA based on the COG testing results are given in Table 5-22. (Note that cracking was not observed with either alloy under the basic crevice, BC, conditions, and, therefore, this test condition is not present in Table 5-22.) These results indicate a clear difference between the neutral crevice solution (with improvement factors of at least 10) and the acidic crevice solution (with improvement factors of less than unity, implying more cracking of Alloy 800NG than Alloy 600MA).

Table 5-21
Simulated Crevice Chemistries Used in COG Testing [186]

Solution	Composition	$pH_{305°C}$	$pH_{25°C}$
Neutral Crevice (NC)	0.15 M Na_2SO_4 0.3 M NaCl 0.05 M KCl 0.15 M $CaCl_2$ 0.5 M SiO_2	5.6	8.01
Basic Crevice (BC)	Neutral Crevice Solution plus 0.4 N NaOH	8.86	12.89
Acidic Crevice (AC)	Neutral Crevice Solution plus 0.05 N $NaHSO_4$	3.28	1.5

Table 5-22
Test Results and Calculated Improvement Factors for COG C-Ring Tests

Environment	T (°C)†	Strain (%)	Alloy 600MA Crack Depth (µm)	Alloy 800NG Crack Depth (µm)	Time (hr)	Reference	IF
NC + 100 ppm PbO	304	0.2	66	NI	4000	COG-02-4041	>13.2
		2	84	NI	4000	COG-02-4041	>16.8
NC + 500 ppm PbO	304	0.2	176	25	6000	COG-00-167	10.56
		2	198	NI	4000	COG-00-167	>39.6
	315	0.2	150	NI	6000	COG-00-167	>45.0
		2	189	NI	6000	COG-00-167	>56.7
AC	304	2	NI	100	4000	COG-00-167	<0.05
	315	0.2	Ni	100	4000	COG-00-167	<0.05
		2	NI	215	4000	COG-00-167	<0.02
AC + 500 ppm PbO	304	4	24	85*	6000	COG-00-167	0.42
	315	2	31	70	6000	COG-00-167	0.66

NI = No Indications - 5 µm depth assumed for IF calculation

* Value for 0.2% and 2% strain

† Alloy 800NG testing at 305°C

The second test series [191] used reverse U-bends with simultaneous exposure of Alloy 600MA and Alloy 800NG. These tests were conducted at 305°C, and lasted 8,000 hours. Reference [191] only reports whether or not cracks were observed and whether or not they were through wall. Therefore, it is only possible to provide a lower limit for an improvement factor when there was a through wall crack in one alloy and no cracking in the other. The lower bound on the improvement factor for these cases is about 300. This is derived by dividing the Alloy 600MA thickness of 1524 µm (60 mils) by an assumed detection limit of 5 µm for the uncracked Alloy 800NG. The environments in which this minimum improvement factor was observed were as follows:

- Neutral Crevice Solution
- Neutral Crevice Solution + various lead compounds
  - 500 ppb as lead from PbO, PbS, $PbSO_4$, and $PbSiO_3$ (no cracking observed with $PbCl_2$)
- Basic Crevice Solution
- Basic Crevice Solution + various lead compounds
  - 500 ppb as lead from PbO, PbS, $PbCl_2$, $PbSO_4$, and $PbSiO_3$
- Acid Crevice Solution + various lead compounds
  - 500 ppb as lead from PbO, $PbCl_2$, $PbSO_4$, and $PbSiO_3$ (no cracking observed with PbS)
- AVT Solution + various lead compounds
  - 500 ppb as lead from PbS, and $PbSO_4$ (no cracking observed with $PbCl_2$ or $PbSiO_3$)

Additionally, in AVT solution with PbO, some cracking (which did not go through wall) was also observed.

Interpretation of these results is given in Section 5.5.2.3.

5.2.4 Alloy 690TT versus Alloy 800NG Comparison

Alloy 690TT is currently the preferred material used for replacement steam generator tubing at US plants due to its increased resistance to corrosion relative to Alloy 600MA. Alloy 690TT has a higher chromium content than Alloy 600 (~59%Ni/30%Cr/9%Fe versus ~75% Ni/15% Cr/8%Fe) and is expected to outperform both Alloy 600 and Alloy 800NG.

Alternatively, many European plants have chosen to use Alloy 800NG in steam generator tubes. Alloy 800NG was first developed as an economical alternative to Alloy 600, and is typically composed of 30-35% nickel, 19-23% chromium, and 40+% iron [127]. It has found increasing use in the nuclear industry due to its high temperature strength and improved corrosion resistance in aggressive environments. In particular, Alloy 800NG was selected in by KWU/Siemens for use in plants subsequent to Obrigheim, primarily based on its increased resistance to IGSCC as compared to Alloy 600 (the performance of Alloy 800NG at these 16 plants is analyzed in Section 3.3.4). This group maintains that the resistance of Alloy 800 is comparable to that of Alloy 690TT.

In the light of this debate, it would be useful to determine what benefit, if any, is offered by Alloy 690TT over Alloy 800NG. Analysis of field performance is inconclusive due to the limited operating experience with Alloy 690TT and the absence of statistically significant tube degradation data for either alloy (recently, several cases of apparent IGA/SCC of Alloy 800NG have been reported, but firm data on these cases were not available in time for significant use in this report). Thus, this section focuses on the results of laboratory test programs that compare the performance of Alloy 690TT to that of Alloy 800NG in various environments. Laboratory test programs comparing these two alloys are summarized for the following environments:

- Caustic contaminated environments - Table 5-23
- Chloride contaminated environments -Table 5-24
- Sulfur contaminated environments - Table 5-25
- Lead contaminated environments - Table 5-26

Limited data were available comparing the performance of Alloy 800NG and Alloy 690TT in primary water and oxidizing environments. Direct comparison between these alloys in primary water and AVT environments has been performed in model boiler tests.

Based on a comparison of average IF_R for each environment, the results presented in Table 5-23 through Table 5-26 indicate an improvement factor for Alloy 690TT versus Alloy 800NG of 5–15 (chloride environments: $IF_{R,avg}$~5, sulfate environments: $IF_{R,avg}$~15).

Table 5-23
IF_R for Alloy 690TT versus Alloy 800NG in Caustic Environments

Organization	Date	Caustic Conc. (%NaOH), Type Test	Temp (•C)	Time (hours)	IF_R Alloy 800NG vs. Alloy 690TT	IF_R Alloy 690TT vs. Alloy 800NG	Ref.
Westinghouse	1976	10, C-ring	316	4800	0.25	4	92
		50, C-ring			SBI	LBI	
INCO (Alloy 800SA, Alloy 600Sen, Alloy 690Sen)	1976	50, Frac. Mech.	316	336	0.04	25	48
Atomenergi	1976	20%, and 20% +5%NaCl, U-bend	325	2000	1.2	0.83	93
INCO	1984	10, C-ring	316	10,920	SBI	LBI	27
MHI	Mid 1980s	10, C-ring	325	500	SBI	LBI	16
Westinghouse	Mid 1980s	10, C-ring	332	---	1.9	0.53	17
		10% with 1% CuO, C-ring	332	---	0.05	20	
CE	1987	Caustic forming water, Model boiler tubes	316	1128	0.13	7.69	57
Rockwell	1988	50% + 1% Na_2CO_3, C-ring	320 & 350	120 & 240	0.38	2.63	95
Siemens	1992	10, U-bend	350	1900	1.1	0.91	96
		10+ Na_2SO_4 Na_2CO_3, CuO, or Fe_3O_4,U-bend	350	---	0.46	2.17	
		4, U-bend	320	1000	0.5	2	
CIEMAT	1993	10 and 10+0.01% CuO, C-ring	350	1000	SBI	LBI	64
Siemens	1993	4, C-ring	315	1250	0.07	14.29	99
CIEMAT	1994	4, C-ring	320	2000	SBI	LBI	65

SBI = Small But Indeterminate (< 1)

LBI = Large But Indeterminate (> 1)

Table 5-24
IF_R for Alloy 690TT versus Alloy 800NG in Chloride Environments

Organization	Date	Environment Test Type, ~pH_T	Temp (•C)	Time (hours)	IF_R Alloy 800NG vs. Alloy 690TT	IF_R Alloy 690TT vs. Alloy 800NG	Ref.
Westinghouse	1985	12.7% $FeCl_2$, C-rings (pH_T~4.1)	332	5000	SBI	LBI	17
CE	1985	MB with seawater contamination, pH_T~4	~300	---	< 1	>1	74
Kobe Steel	1987	1000 ppm Cl^- (pH_T~5.7)	300	1000	SBI	LBI	37
CIEMAT	1993	50 ppm NaCl plus 50 ppm $CuCl_2$ (pH_T~2.1)	350	500	0.2	5	64

SBI = Small But Indeterminate (< 1)

LBI = Large But Indeterminate (> 1)

Table 5-25
IF_R for Alloy 690TT versus Alloy 800NG in Sulfur Environments

Organization	Date	Environment, Test Type	Temp (•C)	Time (hours)	IF_R Alloy 800NG vs. Alloy 690TT	IF_R Alloy 690TT vs. Alloy 800NG	Ref.
INCO	1984	10% NaOH + 750 ppm sulfate, C-rings (pH_T~10.3)	316	8232	SBI	LBI	27
CIEMAT	1993	0.75 M Na_2SO_4 + 0.25 M $FeSO_4$, C-rings (pH_T~4.4)	350	500	SBI	LBI	64
Laborelec	1994	Acid sulfates, pH_T ~4.4, capsule	330	3000	SBI	LBI	100
CIEMAT	1994	MB tests with acid sulfates, low pH_T	~300	9500	SBI	LBI	65
EDF	1998-2000	Sulfate, pH_T 5, C-ring	320	~2000 - 3000	0.04, 0.08, Indeterminate	25, 12.5, Indeterminate	80, 81, 82
		Sulfate, pH_T 6, C-ring	320	~2000 - 3000	Indeterminate. 0.12	Indeterminate, 8.33	
CEA	1999	MB with Na_2SO_4 pollutant (pH_T~7)	~300	Alloy 8000	0.08	12.5	83

SBI = Small But Indeterminate (< 1)

LBI = Large But Indeterminate (> 1)

Table 5-26
IF_R for Alloy 690TT versus Alloy 800NG in Lead Environments

Organization	Date	Environment, Test Type, pH_T	Temp (•C)	Time (hours)	IF_R Alloy 800NG vs. Alloy 690TT	IF_R Alloy 690TT vs. Alloy 800NG	Ref
Siemens	1992	caustic with lead, U-bend, pH_T ~ 10.1	320	1000	0.52	1.92	96
CIEMAT	1993	caustic with lead, C-ring, pH_T 10.3	350	---	1	1	64
Siemens	1993	4% caustic with lead, pH_T 10.1	315	750	0.1	10	99
CIEMAT	1994	4% NaOH+0.004m PbO, C-ring, pH_T 10.1	320	2000	SBI	LBI	65
EDF	1994	10% NaOH + lead, Capsule, pH_T 10.3	350	---	0.12	8.33	30
Laborelec	1994	AVT + resin degradation liquor and lead, MB, low pH_T	330	2000	SBI	LBI	100
French	1995	10% NaOH + lead, C-rings and CERT, pH_T 10.3	350	---	0.1	10	66

SBI = Small But Indeterminate (< 1)

LBI = Large But Indeterminate (> 1)

5.3 Distribution of Crevice pH Values

One method used for the estimation of an overall laboratory testing based improvement factor has been to consider laboratory data weighted by the expected relevance of the test environment to actual operating conditions. In this analysis, this weighting has been based on pH, thus requiring an estimate of the distribution of pH_T values in SG crevices. The relative frequency at which each of the pH ranges is experienced in plants is then used as a second input to weight the improvement factors observed in laboratory testing. The three techniques developed to estimate the distribution of pH values in SG crevices are discussed in the subsections below. The last, given in Section 5.3.3, is the currently preferred method, although it is considered somewhat conservative, i.e., it overestimates the probability of extreme pH conditions.

5.3.1 Parabolic pH Distribution

Based on the combined field experience and laboratory data, a distribution of the relative frequency of occurrence of pH_T values was developed in Reference [2]. This distribution is shown in Figure 5-16. The distribution is assumed to be parabolic based on simplicity, the presence of a maximum midway between the extremes, and values of zero at the extremes. In this model, the probability density maximum is midway between the extremes based on the assumption that crevice pH values are most likely to be similar to the bulk values.

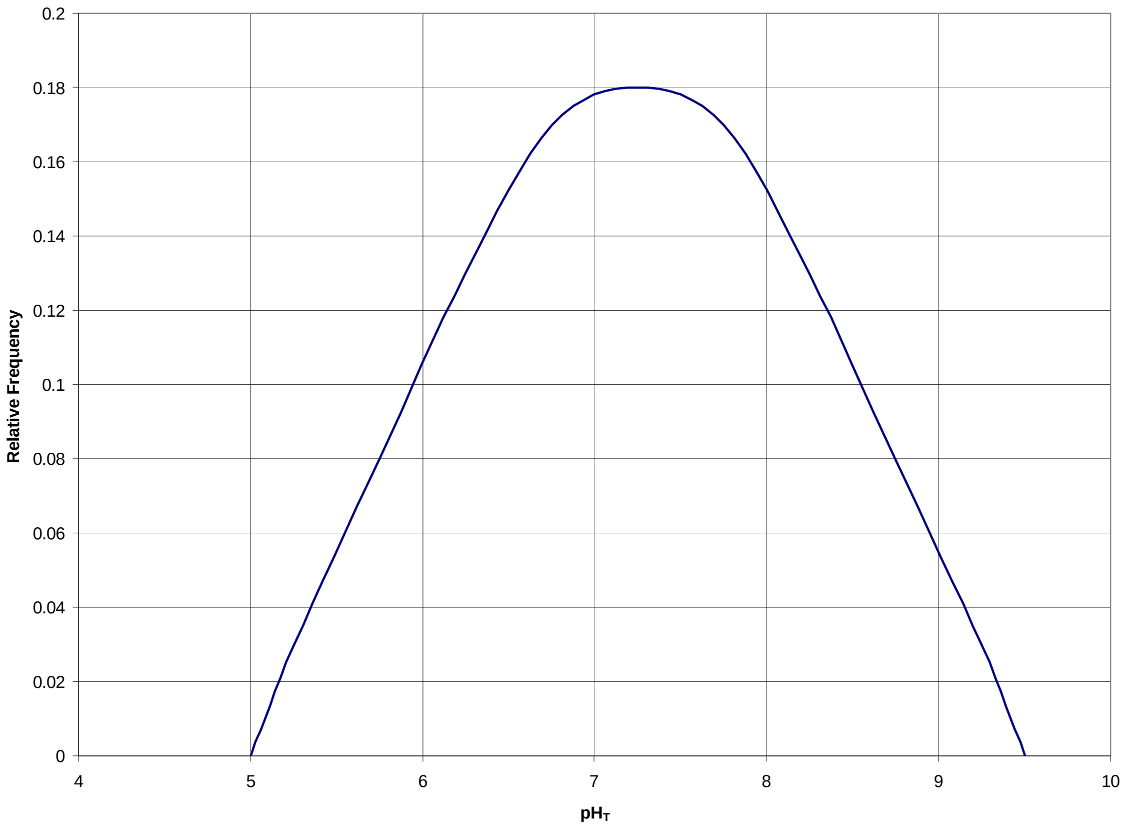

Figure 5-16
Parabolic Distribution of pHT Values in PWR SGs

The reasoning behind the development of this distribution is as follows. The observance of cracking in Alloys Alloy 600TT, Alloy 690TT, and Alloy 800NG when subjected to extreme pH environments has been well documented in laboratory experiments. The lack of significant cracking to date in Alloy 690TT and Alloy 800NG tubing in the field indicates that these conditions must rarely, if ever, occur during normal plant operation. The environments where these three alloys would be expected to have experienced IGA/SCC if they occurred in plants include the following:

- As shown in a review by Vaillant, tests indicate that Alloy 800NG experiences IGA/SCC at 320°C at $pH_T \leq 4.7$ and ≥ 10 in lead polluted environments.[107] Since it appears that all plants have lead pollution, the essentially complete absence of IGA/SCC with Alloy 800NG in service for 30 years provides a strong indication that pH_T values ≤ 4.7 and pH_T values ≥ 10 do not occur in PWR steam generators operated with AVT water chemistry.
- The non-occurrence of $pH_T > 10$ is supported by the absence of IGA/SCC in Alloy 600TT and Alloy 690TT, since these alloys develop IGA/SCC at such high pH_T levels [19].
- Appendix A to TR-108501 contains a survey of the relative performance of Alloy 600TT vs. Alloy 600MA [5]. It indicates that Alloy 600TT is about two or more times slower to crack than Alloy 600MA over the full range of possible secondary side conditions, but that it still has substantial susceptibility to IGA/SCC at high and low pH_T values conditions. The

limited occurence of significant OD IGA/SCC in Alloy 600TT steam generators indicates that these low and high pH_T conditions rarely occur in operating plants.

- Model boiler tests by several organizations have shown that additions of low concentrations of NaOH to the feedwater (without other buffering or complexing additives other than AVT chemicals) cause Alloy 600MA tubes to crack through-wall within two to three weeks. This is over a hundred times faster than seen in the field, and demonstrates that pure caustic environments do not occur in real plants. Model boiler testing is further discussed in Chapter 6.

Based on the above type of observations, it is considered that the crevices in operating PWR steam generators do not experience significant exposure to pH_T values < 5 and > 9.5. Based on this conclusion, and supported by analyses of pulled tube examinations, it is concluded that crevices in steam generators operate mostly in the near neutral to mildly alkaline range (pH_T ~ 6 to 8) with lesser periods between pH_T 5 and 6 and 8 and 9.5. Therefore previous assessments have computed improvement factors weighted assuming that the relative occurrence of crevice pH_T values is about as shown in Figure 5-16.

5.3.2 Hide Out Return (HOR) pH Values

Two sources of hideout return data were reviewed. The first was the data set provided in the Molar Ratio Control Guidelines (MRC GL) generated by NWT [108]. The second was a data set from EDF [109]. The data are shown in Figure 5-17 through Figure 5-20. The following observations were made during the review of the data:

- The calculated pH values extend out of the realistic range on both the acidic and caustic ends. (The establishment of reasonable bounds is discussed in Section 3.3.3.)
- There is some indication that the pH distributions are bimodal. This is consistent with standard models of precipitation. Once precipitation occurs, slight imbalances in non-water (i.e., not H+ or OH-) cations and anions can be magnified with increasing concentration, causing similar starting solutions to diverge to acidic or caustic extremes.
- The goodness of fit for each of the three standard distributions evaluated (normal distribution, log-normal distribution, and bimodal normal distribution) is roughly the same. The bimodal distribution fit is somewhat better, but this is most likely due to the increase in the number of fitted parameters (five versus two).
- There is a substantial difference between the French data and the US data.

Based on statistical evaluations of the two data sets, it is recommended that both the normal distribution calculated from data within the bounds and the random distribution within the bounds be considered. These two distributions are plotted in Figure 5-21 with both sets of data. Note that there is a bias in these fits toward predicting higher pH values than were calculated from the HOR data. This bias is especially pronounced in the low pH region. It is believed that this bias reflects a real error in the calculated pH values. Specifically, it is thought that the calculations from HOR data did not adequately account for the buffering of crevice solutions by dissolved iron. This effect is discussed in Section 3.3.3 with respect to lower bounds on crevice pH values, but it is also expected to moderate the pH in less acidic crevices, albeit to a lesser extent.

Note that the pH values evaluated were those given in the references. They were not subjected to additional screening during the evaluation. In Figure 5-17 through Figure 5-20, fits are based on all of the data. In Figure 5-21, the fit is based only on the data between the upper and lower limits. For this distribution, the mean is equal to 6.8 with a standard deviation of 1.9.

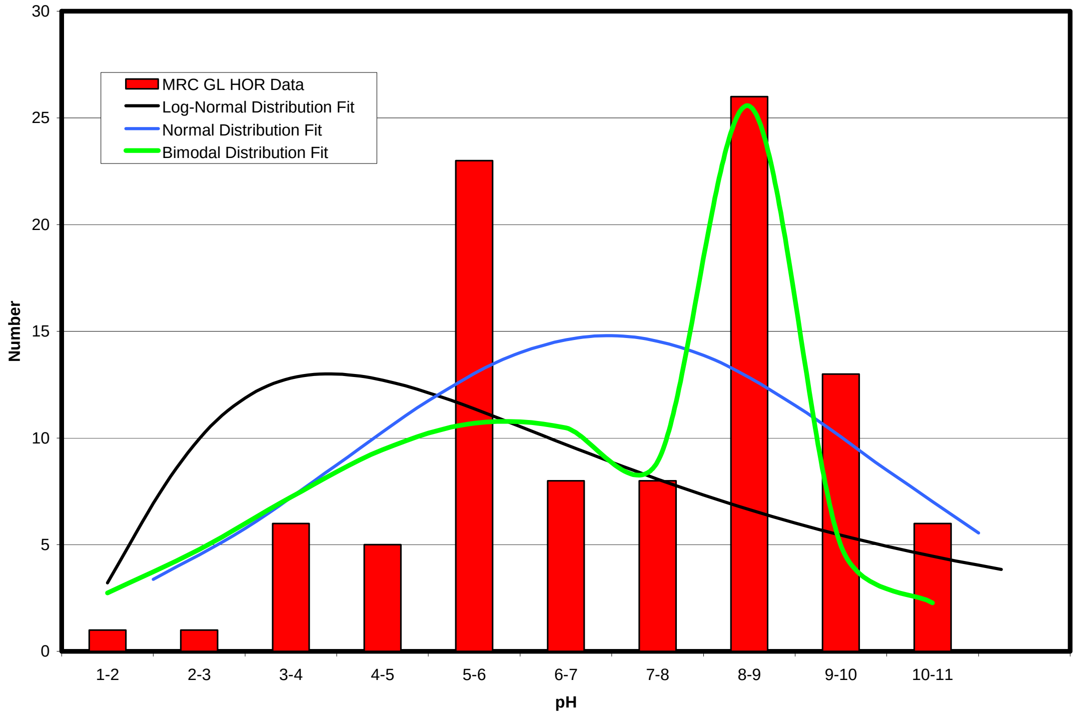

Figure 5-17
Crevice pH_T Distribution from MRC GL Data

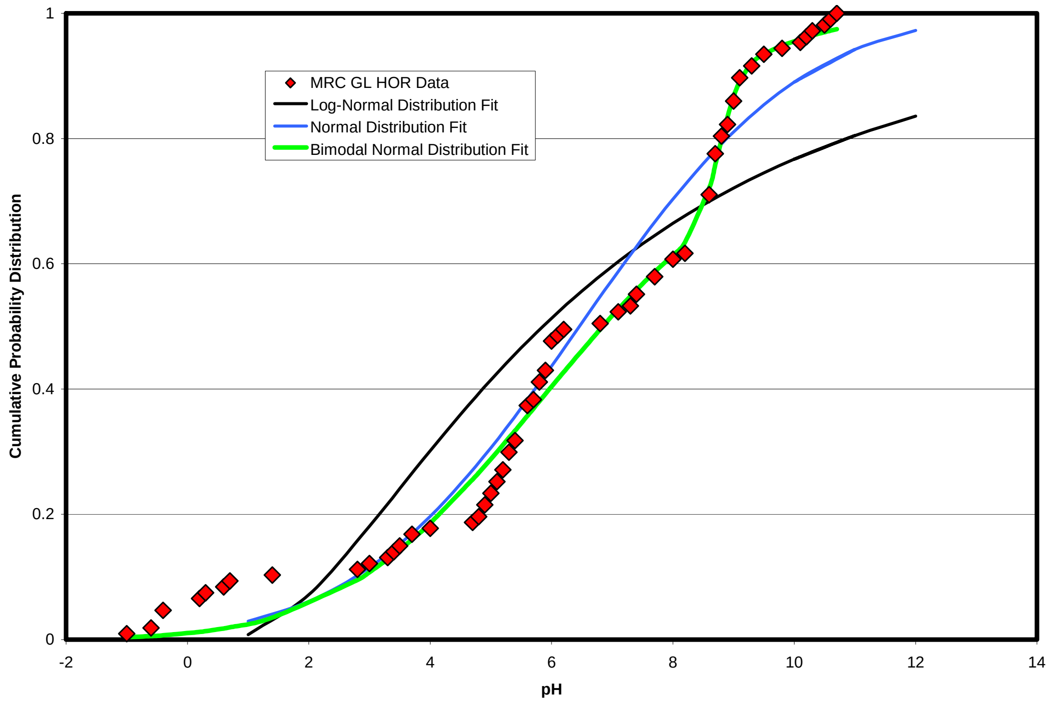

Figure 5-18
Cumulative pH_T Distribution from MRC GL Data

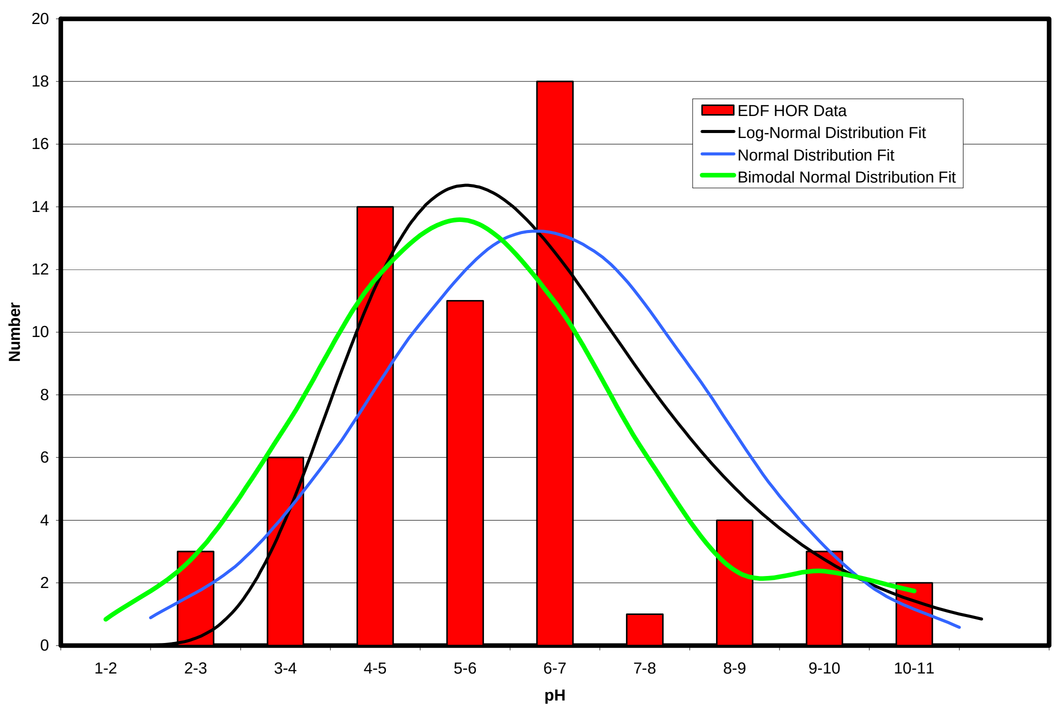

Figure 5-19
Crevice pH_T Distribution from EDF HOR Data

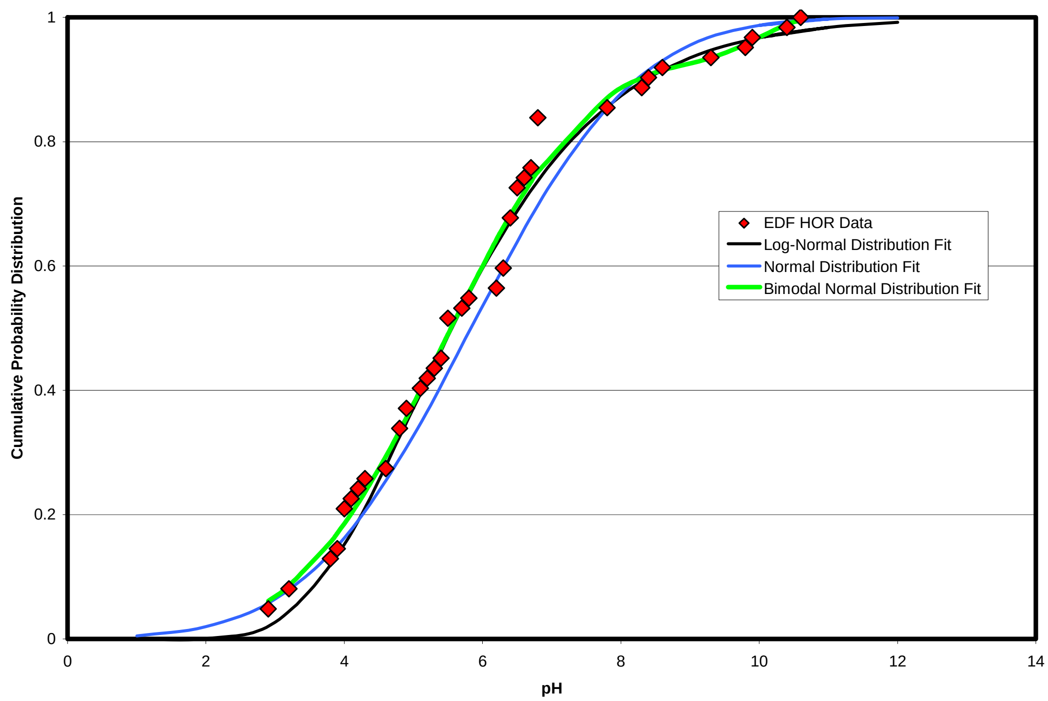

Figure 5-20
Cumulative pH_T Distribution from EDF HOR Data

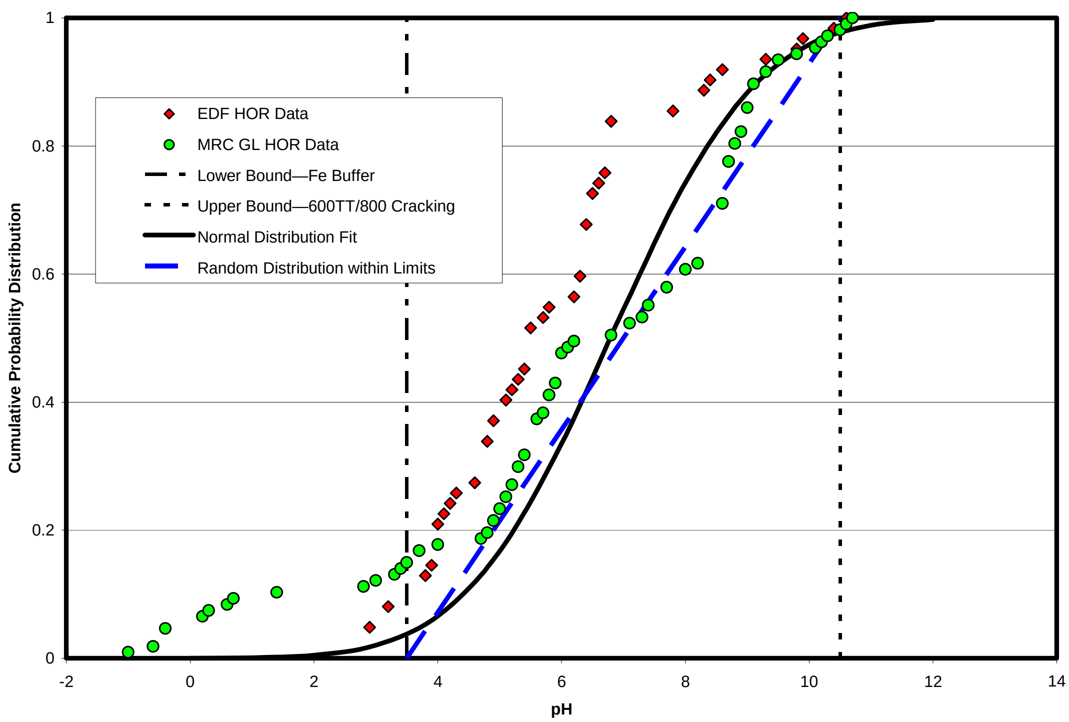

Figure 5-21
Crevice pH_T Cumulative Distributions with Fits

5.3.3 Limits on Crevice pH Values

There are natural limits on the value of the pH in a crevice. For example, in acidic environments, magnetite will dissolve, buffering the solution and preventing the pH from dropping much below 3.5. In caustic environments, anion volatility will decrease as more of the anionic species is present as an anion rather than a volatile compound (HCl will dissociate to H^+ and Cl^- which are non-volatile and thus concentrate along with the cations).

Based on the well documented solubility of magnetite (e.g., Reference 110) a lower pH limit of 3.5 is proposed. Based on the cracking thresholds of Alloy 800NG and Alloy 690TT [9] and the absence of cracking of these alloys in operating steam generators, an upper pH limit of 10.5 is proposed.

The observation of alumino-silicate deposits in crevice regions of pulled tubes has led some to conclude that high pH crevices (≥10) are not realistic [111]. Although this is almost certainly true of the crevices from which these deposits were taken, the extent to which these are generally representative is not clear (deposits from non-crevice areas, more routinely analyzed, do not generally have these species in abundance). A thorough review of this evidence is beyond the scope of this report. However, changing the pH limit from 10.5 to 10.0 has relatively little effect on the resultant improvement factor. Therefore, in the absence of a statistical analysis of the prevalence of alumino-silicates, these data have not been used to form conclusions regarding general pH distributions. Note that including the possibility of pH values between 10.0 and 10.5 is conservative relative to excluding them.

5.3.4 Conclusions Regarding pH Distribution

In general, there appear to be rather few reliable data regarding the pH distribution in SG crevices during operation. The data available appear to be adequately described by a number of different distributions (parabolic, normal, random). For the purposes of this project, the random distribution between limits of 3.5 and 10.5 were chosen. As discussed in Section 5.3.3, there appears to be a good technical basis for the selection of these limits. It is possible that a random distribution is overly conservative relative to the actual distribution, but there are few reliable data available. A random distribution is supported by the HOR data, but these are somewhat suspect.

Based on theoretical considerations (differential ion exchange efficiencies for sodium and chloride, for example, or different volatilities of various impurities) it is possible to make an argument for a higher prevalence of weakly caustic crevices. However, the benefits of substituting any theoretical modeling for the random distribution chosen here are not likely to be large.

5.4 Environmental Weighting Factors

In addition to pH, the type of contaminant has also been demonstrated to significantly affect SCC susceptibility and relative SCC susceptibility. In developing an overall improvement factor, it is necessary to determine how the data from different environments should be treated. Possible approaches include the following:

- Weighting environments by expected prevalence
- Selecting the minimum improvement factor across all environments
- Developing different improvement factors for each environment

To some extent, this project has used each of these options as is discussed in the following subsections.

5.4.1 Primary versus Secondary Chemistry

With respect to the primary side environment, a separate improvement factor is used. This is consistent with the definitive differences between primary and secondary environments. Specifically, the following apply:

- The primary side is very dilute relative to secondary side crevices.
- The primary side environment is known with high certainty, unlike secondary side crevices which are not well characterized (see Section 5.3, for example).
- Some alloys have not cracked under primary conditions (Alloy 690TT and Alloy 800NG), while all alloys have demonstrated high susceptibility in at least some faulted secondary side environments.

In determining an improvement factor for PWSCC, all tests with low impurity concentrations were included.

5.4.2 Weighting for the Secondary Chemistries

In developing an overall improvement factor for the secondary side, different weightings were given to the different types of environment (as defined in Section 5.1.4) as follows:

- Caustic: Weighting = 1. Since the weightings chosen are relevant only in relation to each other, the first weighting is somewhat arbitrary. A value of unity was chosen for simplicity.
- Chloride: Weighting = 0.4 and Sulfate: Weighting = 0.6. As discussed in Section 5.3, the pH distribution is roughly random with no prevalence for acidic or caustic crevices. Therefore, it is assumed that chloride and sulfur contaminated environments (generally more acidic than sodium dominated environments) are, in total, as likely as sodium contaminated environments (i.e., the sum of the weightings for chloride and sulfate is taken as one). Chloride environments were weighted less than sulfate environments due to the volatility of chlorides and hence their lower likelihood of concentrating in crevices. There is little basis for the exact division between chloride and sulfate weightings. However, in general, there is not a substantial difference in the improvements factors for chloride and sulfate environments, so the exact choice of weightings does not significantly affect the assessment.

- Lead: Weighting = 3.2. Analytical transmission electron microscopic (ATEM) analyses of secondary side cracks from pulled tubes at 13 plants indicated that approximately 60% of the cracks examined had significant (5-12%) concentrations of lead at the crack tip. Given the other weightings, selection of 3.2 results in a fractional weighting of 0.6 for lead, equivalent to the fraction of cracks in which lead has been observed.
- Oxidizing: Weighting = 0.1. Modern operating practices, including adherence to the EPRI Guidelines [112], ensures that conditions in the steam generators are reducing, specifically at an electrochemical potential (ECP) just above the 1 atmosphere hydrogen potential. Inevitably, there is some time during startup when there are oxidants present. This time is expected to be short, less than one week. Various upsets may allow the ingress of oxygen into the steam generators (such as a large condenser leak which allows aerated water to enter the secondary system). The weighting chosen is somewhat arbitrary, but is sufficiently small that its specific value does not overly affect the overall improvement factor estimate.

These weightings were used as discussed in Section 5.5 to calculate an overall laboratory testing based improvement factor for secondary side SCC.

5.5 Overall Laboratory Based Improvement Factors

Laboratory based improvement factors were calculated from the data summarized in Section 5.2 using the weighting factors developed in Section 5.3 and Section 5.4. Individual factors were developed for primary and secondary side mechanisms.

5.5.1 Primary Side SCC Improvement Factors

Based on the data discussed in Section 5.2, improvement factors suggested for primary water stress corrosion cracking (PWSCC) are shown in Table 5-27. The bases for these recommendations are discussed in the following subsections.

Table 5-27
Laboratory Testing Based PWSCC Improvement Factors

Alloy	PWSCC IF_R versus 600MA
600TT	1.6
690TT	> 125
800NG	>20*

* Many fewer tests than for other IF_Rs

5.5.1.1 Alloy 600TT versus Alloy 600MA: IF_R = 1.6.

Eleven references provide values for the improvement factor for Alloy 600TT versus Alloy 600MA. These are given in Table 5-1. Five of the references provide a range of improvement factors rather than a single value. If the lowest value is taken from each range, then the median value is 1.6 and six of the values are between 1.4 and 1.6, inclusive. The selection of 1.6 deemphasizes the single result which is substantially lower (1.05) as well as four moderately higher values and the higher values in the ranges. This is a conservative but reasonable evaluation of these data.

As indicated previously, improvement factors for thermally treated materials are expected to be underestimated by laboratory testing because most testing involves cold work of the test sample. However, in the case of PWSCC, the extent to which the improvement factor is underestimated is probably less than it is for ODSCC because the microstructure changes associated with thermal treatment are expected to be a tertiary factor, and these microstructure changes are not much affected by the cold work. (The primary factor is generally thought to be the alloy composition, primarily the bulk chromium content. The secondary factor is generally thought to be the stress levels present in the specific application.) This is supported by the observation that sensitization, which results in lower stresses, grain boundary chromium carbide precipitation, and grain boundary chromium depletion, has generally been observed to result in a net decrease in PWSCC susceptibility [112]. Additional support is given by comparing Alloy 600TT experience with high stress SG designs with Alloy 600MA experience in identical designs, specifically the kiss roll expansion in French feedring SGs, discussed in Section 3.3.2.1, which indicates an improvement factor (for circumferential cracking) of about 2.

5.5.1.2 Alloy 690TT versus Alloy 600MA: IF_R > 125

Results of seventeen comparison tests are given in Table 5-23. In all but one (the Kobe tests [113]) no cracking of Alloy 690TT was observed. Thus each test generated only a minimum bound on the improvement factor. The test which ran the longest relative to the time required to crack Alloy 600MA, and thus generated the least conservative improvement factor, was the Framatome test (given in Appendix B of [46]) , which put a minimum bound of 125 on the improvement factor. In the absence of any PWSCC in realistic environments, this lower bound is considered the most appropriate.

The one test in which Alloy 690TT was observed to crack under primary conditions was reviewed in depth to determine the extent to which this finding was credible, in light of the lack of PWSCC of Alloy 690TT in all other tests [113]. From the reference paper, it appears that the Alloy 690TT material was manufactured specifically for the testing. Furthermore, it was subjected to additional processing (remelting followed by 24 hours at 500°C to simulate service aging). The referenced paper does not provide significant detail regarding deaeration (only specifying hydrogen saturated, with no mention of deoxygenation). In light of these issues and without supporting evidence from other test programs, this test result is not given significant weight.

These test results are supported by the conclusions developed in the 2008 MRP report on CGRs for Alloy 690TT PWSCC [105]. Hickling estimates an IF_R of 40 to 100 for crack initiation in Alloy 690TT versus Alloy 600MA, based on the absence of observed PWSCC originating at a smooth surface in the test programs reviewed. However, it is noted that those estimates are conservative since no actual PWSCC originating at a smooth surface was observed, and the value of 125 remains the least conservative (and therefore most appropriate) improvement factor.

PWSCC crack growth in thick-walled components of the primary system is evaluated in depth in the MRP report. Unlike the thin-walled components of steam generators, in which crack initiation is of greater significance, alloy-specific CGRs are of greater concern in thick-walled components where time to failure is determined by the rate of crack growth. Under normal metallurgical conditions, susceptibility of Alloy 690TT to PWSCC crack growth is extremely low. Conclusions regarding CGRs in thick-walled Alloy 690TT components presented in the report are as follows:

- The calculated IF_R for CGRs in Alloy 690TT versus Alloy 600MA is > 70. This value is expected to be closer to 400 if cold work is taken into consideration.
- Small amounts of intergranular cracking have been induced in Alloy 690TT, however the resulting CGRs are low enough that they are of no engineering significance. This remains true even in most cases where significant cold work (> 10%) has been introduced.
- Possible "bimodal" behavior has been observed with the introduction of high levels of non-homogenous cold work (through uni-directional rolling or tensile straining). This type of cold work can result in rapid intergranular crack growth, potentially at rates nearing those found for Alloy 600MA. It may also alter the observed dependence of CGRs on stress intensity, test temperature, and dissolved H_2 levels. Satisfactory limits of this behavior and its relevance to real plant components have not yet been established. (This behavior is not expected to be relevant to steam generator tubes. Levels of cold work in SG tubes are expected to be lower than those which have lead to more rapid cracking. Additionally, there are some indications that some inhomogenities in microstructure, not present in tubing material, may be necessary for the occurrence of more rapid cracking.)
- Intergranular crack growth has also been observed in Alloy 690 exposed to a supercritical environment containing lithium, boron and hydrogen. However, there is currently no basis for extrapolating CGRs at these conditions down to subcritical temperatures for comparison.

Based on these results, the susceptibility of thick-walled primary side Alloy 690TT components to PWSCC is exceedingly low and is not likely to be a concern for the life of the plant even with multiple life extensions. The current improvement factor estimates will continue to increase as results from longer tests are obtained and experience without cracking accumulates.

5.5.1.3 Alloy 800NG versus Alloy 600MA: IF_R >20

PWSCC relevant testing of Alloy 800NG is summarized in Table 5-15. Based on these data, it is not possible to assign an improvement factor to Alloy 800NG with a high degree of confidence. However, the improvement factor is expected to be at least 20 based on the limited test data available.

5.5.2 Secondary Side SCC Improvement Factors

Based on the data discussed in Section 5.2 and the weighting factors discussed in Sections 3.3 and 5.4, improvement factors are suggested for secondary side SCC in the following subsections.

5.5.2.1 Alloy 600TT versus Alloy 600MA: Secondary Side IF_R

Taking the laboratory based improvement factor functions discussed in Section 5.2.1, the pH weighting factors discussed in Section 3.3, and the environmental weighting factors discussed in Section 5.4, an overall improvement factor for ODSCC of Alloy 600TT versus Alloy 600MA was calculated. Figure 5-22 shows the environment-weighted improvement factor as a function of pH. Because the pH distribution used is a random distribution between 3.5 and 10.5, the pH-weighted improvement factor is equal to the average improvement factor over the range of interest. The value obtained is 2.6.

The following three regions of interest are highlighted in Figure 5-22:

- At low pH, Alloy 600TT is more resistant to SCC than Alloy 600MA. This effect is dominated by the observations regarding chloride and sulfate.
- At intermediate pH values, the improvement factor decreases linearly with pH. This effect is due to the combination of both materials being fairly resistant to SCC in dilute solutions and the improved resistance of Alloy 600TT to lead-related cracking. The difference between the two materials with respect to Pb-SCC decreases with increasing pH, leading to a decrease in the weighted improvement factor.
- At high pH, Alloy 600TT is just as susceptible to SCC as Alloy 600MA, leading to an improvement factor approximating unity at $pH_T = 10.5$.

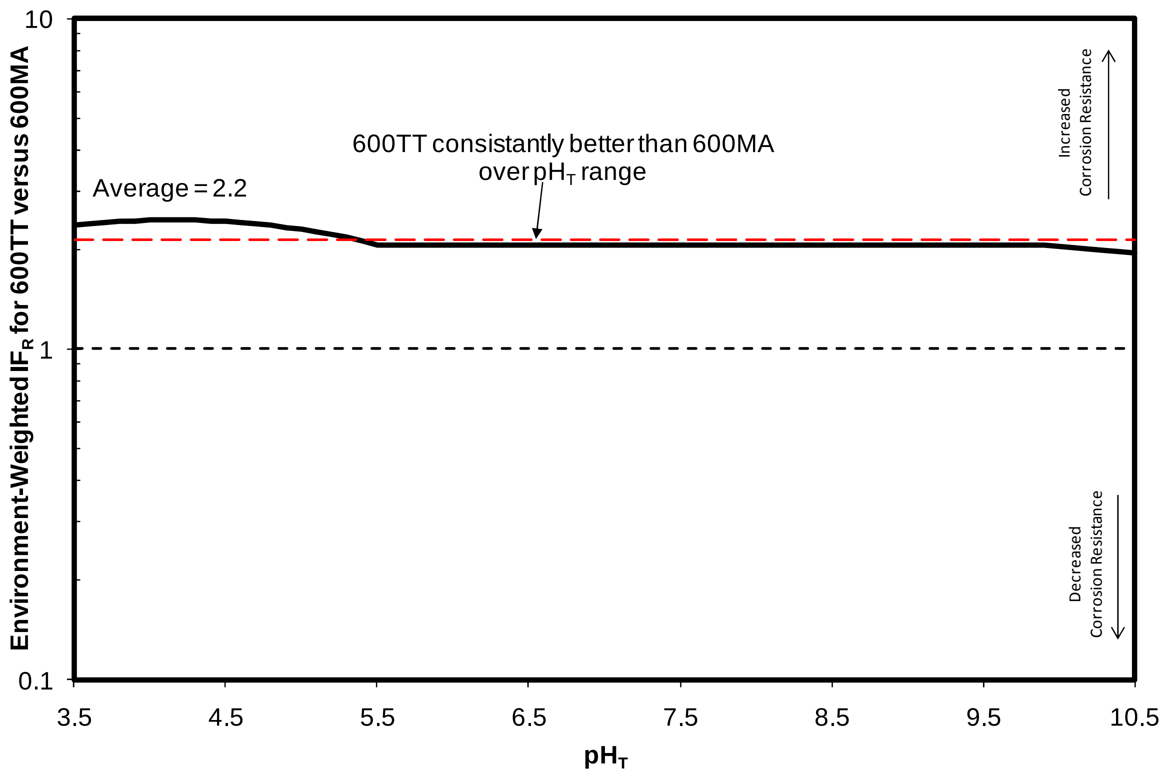

Figure 5-22
Environment-Weighted Improvement Factor for Alloy 600TT versus Alloy 600MA

5.5.2.2 Alloy 690TT versus Alloy 600MA: Secondary Side IF_R

An overall improvement factor function for ODSCC of Alloy 690TT versus Alloy 600MA was calculated as in Section 5.5.2.1 using the improvement factor functions developed in Section 5.2.2 and the previously developed pH and environmental weighting factors. Figure 5-23 shows the overall calculated improvement factor as a function of pH. Assuming the pH distribution for this function is also a random distribution between 3.5 and 10.5, the average improvement factor over this range is 120. This indicates a significant improvement in performance compared to Alloy 600MA. The function has the following characteristics:

- At low pH, increased susceptibility to SCC is observed (relative to the average for the alloy). This is influenced by the observed results for chloride contaminated solutions.
- At pH values approaching neutral, the estimated improvement factor increases substantially due to the increased resistance to SCC in lead contaminated environments observed with Alloy 690TT.
- The observed gain in SCC resistance decreases above the normal primary pH range. It is also off-set by the observed effect of caustic environments on Alloy 690TT, which have been shown to decrease in the performance gap between Alloy 690TT and Alloy 600MA.
- At high pH values, the increased susceptibility of Alloy 690TT to lead-caustic environments results in a substantially reduced improvement factor relative to the average.

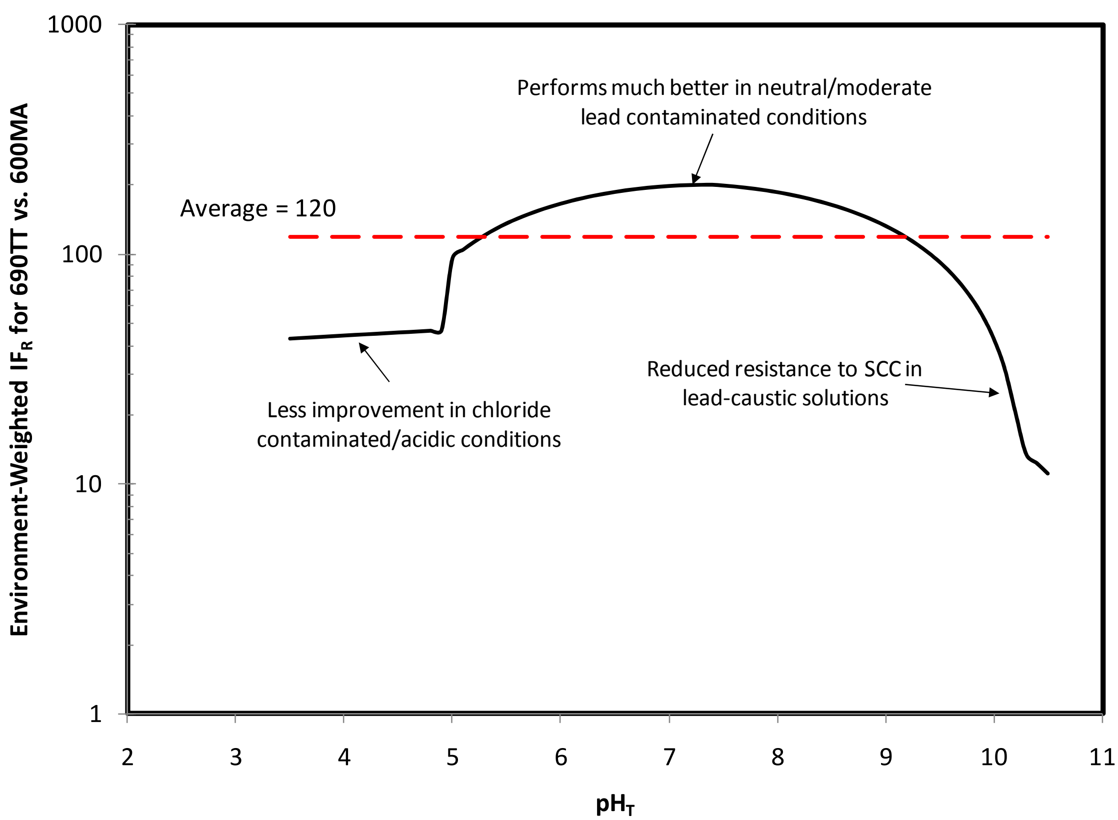

Figure 5-23
Environment-Weighted Improvement Factor for Alloy 690TT versus Alloy 600MA

5.5.2.3 Alloy 800NG versus Alloy 600MA: Secondary Side IF_R

Several approaches to determining an improvement factor are possible using the available data. Some of these are as follows:

- The environment-weighted improvement factor function for ODSCC of Alloy 800NG versus Alloy 600MA could be determined as in Section 5.5.2.1 using the improvement factor functions developed in Section 5.2.3 (which do not include the COG data for more complex environments discussed in Section 5.2.3.7) and the previously developed pH and environmental weighting factors. Figure 5-24 shows the overall calculated improvement factor as a function of pH. Assuming the pH distribution for this function is a random distribution between 3.5 and 10.5, the average of the improvement factor over this range is 4.2.

  This environment-weighted improvement factor for Alloy 800NG is conservatively low for several reasons. First, the lower bound of the improvement factor for lead contaminated environments with moderate pH values was conservatively taken to be 5, due to scatter. No cracking of Alloy 800NG was observed in this pH range, and several test programs resulted in higher experimental improvement factors. The only cracking observed in lead-contaminated environments occurred in 4% and 10% caustic solutions. Because lead was weighted more than the other environments, increasing this estimate for the lower pH range would significantly increase the overall estimated improvement factor. Secondly, the improvement factor for Alloy 800NG in caustic solutions was indeterminate. The effect of an increase in performance in caustic conditions over that of Alloy 600MA therefore does not appear. On the other hand, if Alloy 800NG is more susceptible to corrosion under mildly caustic conditions, the estimated improvement factor could be artificially high. However, laboratory testing has not indicated that this is the case and this situation is considered unlikely.

- The simultaneous testing performed by the COG (see Section 5.2.3.7) could be used as a basis for an improvement factor. This testing implies an improvement factor of >300 over a wide range of environments. However, this improvement factor is based entirely on comparison of crack lengths, which has not generally been used in evaluation of other alloys. Many other test programs include intermediate sampling such that the time at which Alloy 600MA cracked was observed to be less than the total test time. A bound on the improvement factor was determined, e.g., in some Alloy 690TT versus Alloy 600MA cases, by taking the ratio of the total test time to the time at which Alloy 600MA was observed to crack. If these cases were treated in a manner similar to the COG tests, the calculated improvement factor bounds (based on time) would be multiplied by a factor of 300, for example, to account for crack depth. Furthermore, the other COG test series indicates that the improvements factor of 300 may not be reliable, since lower (in some cases much lower) improvement factors were observed in the same environments.

- The COG C-ring data series (see Section 5.2.3.7) could be used to determine an improvement factor. This would be more consistent with assessments for other alloys where estimates are generally based on lower values and tests with actual SCC findings are weighted more. However, this would yield an improvement factor estimate on the order of unity (the log average of <0.05 for the acidic tests and ~10 for the leaded neutral tests). Based on the field performance of Alloy 800NG, an improvement factor of unity is not realistic.

Given these possibilities, an improvement factor of >10 was selected to describe the Alloy 800NG versus Alloy 600MA laboratory results. This value was selected as the most consistent with the neutral C-ring tests, based on a direct comparison of crack lengths. It is also reasonably consistent with the improvement factor calculated using test durations for the non-COG tests (IF ~ 4.2). It is acknowledged that the results of the reverse U-bend tests imply a much higher improvement factor.

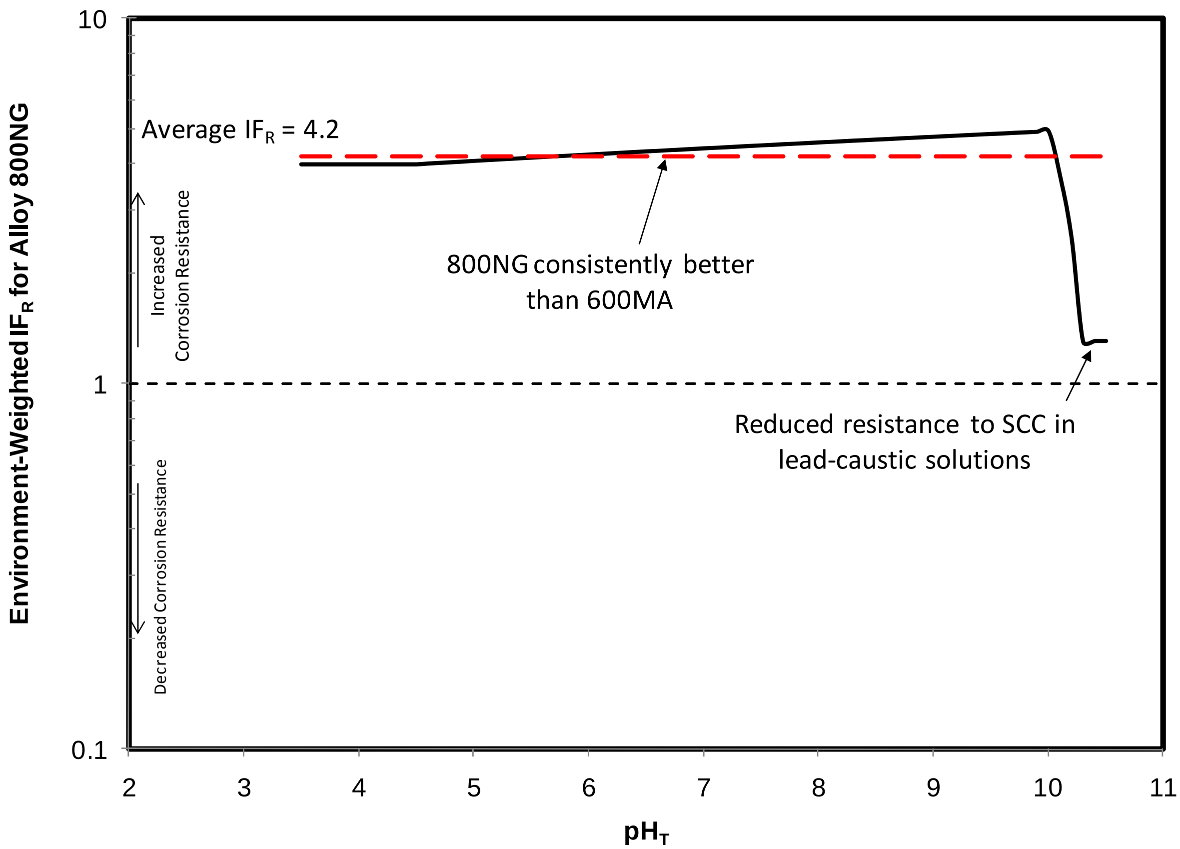

Figure 5-24
Environment-Weighted Improvement Factor for Alloy 800NG versus Alloy 600MA (does not include COG data for complex environments)

6 SECONDARY SIDE INTEGRATED EXPOSURE TO CONCENTRATED CAUSTIC ENVIRONMENTS

6.1 Introduction

The relative changes in risks of tube degradation due to exposure to various chemistries is often addressed in terms of the integrated exposure calculated by integrating the bulk concentration (as measured in the blowdown) over time. Although it is generally recognized that there are other methods, these have not been extensively used. In this chapter, the simple integration method is compared to a double integration method, which accounts for the time in the cycle at which contamination is accumulated. The analyses given here compare model boiler test results for Alloy 600MA, the sodium ingress event at Almaraz, and the results of many model boiler tests conducted with different tube alloys.

Because most model boiler testing evaluated the effects of sodium, this analysis is performed only for the sodium exposure.

6.2 Integrated Exposure Calculations

Two methods of integrated exposure are used in this analysis. Per the terminology of Revision 6 of the EPRI Guidelines [112], these are referred to as Method A and Method B.

6.2.1 Method A: Single Integration Method

The first method is the simple integration of concentration with time, as follows:

$$IE_A = \int_0^t CPdt \qquad \textbf{Eq. 6-1}$$

where C is the concentration of the species of interest (sodium in the analyses performed here), t is the time, and P is a function which relates the rate of mass accumulation in crevices with power production.

Figure 6-1 shows hideout rates (the percentage of feedwater impurity mass that is not removed by blowdown flow) reported in the literature. Note that these are presented here as examples only and do not represent an exhaustive search of the literature. Two sets of data (References [155] – San Jose State University and [156] – CERL) were generated using crevices packed with carbon fiber. One set of data was generated using grown in place oxides which dented the simulated SG tube (Reference [157] – Westinghouse). One set of data was obtained through testing at an operating PWR (Reference [158] – NWT). The three sets of laboratory data were generated using injection of sodium chloride, while the plant test was conducted using potassium chloride. The San Jose State data were obtained by measuring both chloride concentration (by ion chromatography) and combined sodium and chloride concentrations (by conductivity) with good agreement. All of the data were obtained in systems with drilled hole support plate configurations.

Note that sodium hideout rates at plants are typically higher than chloride hideout rates, although they are of the same order of magnitude.

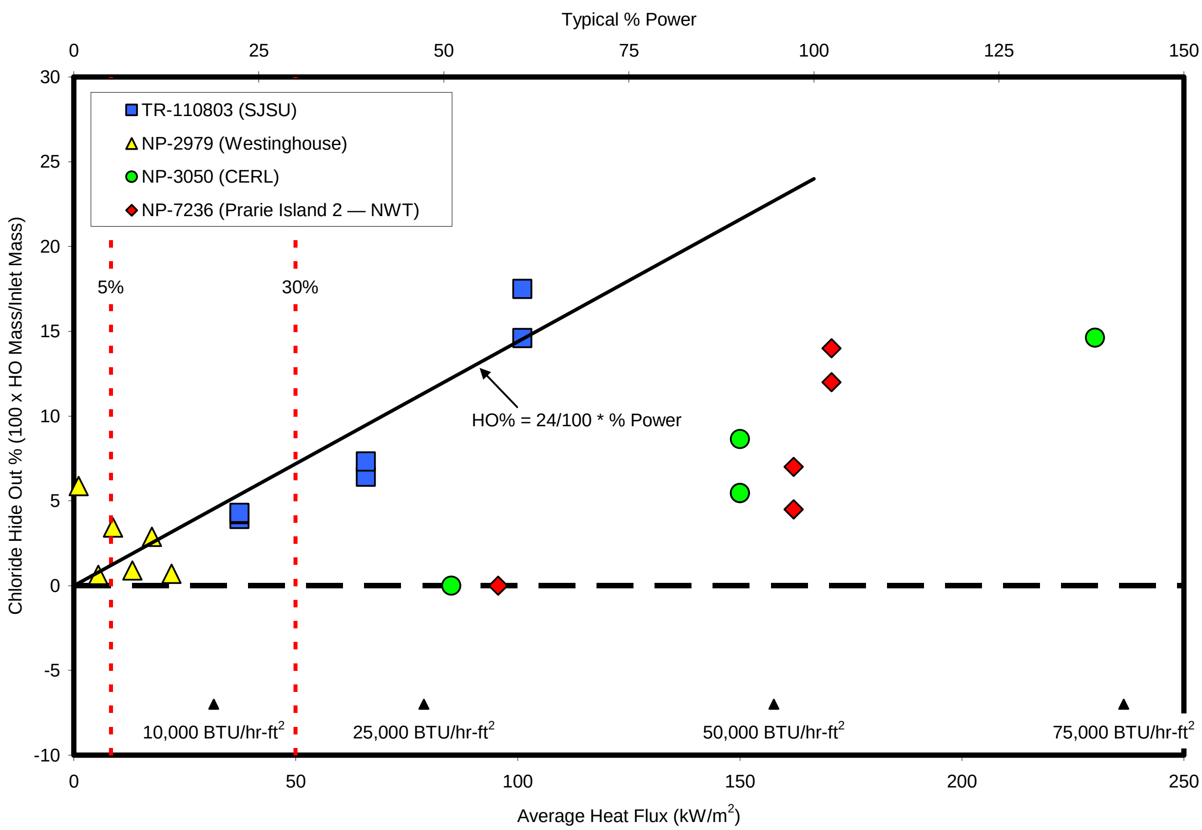

Figure 6-1
Hideout Rate Data from the Literature

For discussion purposes, a more or less arbitrary fit is drawn through the data. This fit is given by the following equation:

$$HO\ (\%) = 0.24\left(\%\ Power\right) \quad \textbf{Eq. 6-2}$$

It is recognized that this relationship is somewhat arbitrary, but it is useful in the following discussions as an order of magnitude estimate.

The constant *P* in Equation 6-1 is conceptually equivalent to the hideout rate as given in Equation 6-2. However, in the discussions considered here the definition of *P* is arbitrarily taken as follows:

$$P = \frac{\%Power}{100} \qquad \textbf{Eq. 6-3}$$

The use of this definition of *P* makes the values calculated using Equation 6-1 somewhat arbitrary. For example, it would be incorrect to use Equation 6-1 to estimate crevice chemistries in SGs for the purpose of comparing the sodium concentration to the concentrations in refreshed autoclave tests.That is, they do not accurately relate to a true mass of sodium accumulated in the SG crevices. However, as a comparative measure, values derived from different sources consistently using this methodology provide a way to meaningfully relate various conditions.

The integrated exposure calculated using Method A is therefore a relative measure of the mass of impurity accumulated in the steam generator. As a relative measure, the units of this integrated exposure are arbitrary. For ease of calculation and consistency with past analyses, units of ppb-days are employed here.

6.2.2 Method B: Double Integration Method

In the conceptualization of Method B flow occluded regions (crevices) are initially steam blanketed and are closer to the primary side temperature than the bulk of the secondary side surfaces due to the lower heat transfer efficiency of steam relative to liquid water (the crevices are “superheated”). With time, some of the impurities entering the steam generator reach the edge of the steam interface, elevating the boiling point of the liquid solution, allowing liquid to exist in the otherwise superheated region. As more impurities accumulate, the volume of fluid that has a high enough concentration to remain in the liquid state increases. Tube degradation is assumed to be caused by contact with this liquid with high impurity concentrations. Therefore, the accumulation of impurities is expected to increase the rate of degradation by increasing the tube surface area exposed to the concentrated solution. The risk of degradation is thus expected to increase with impurity accumulation as well as with the duration of exposure. This conceptualization results in the following definition of the integrated exposure:

$$IE_B = \int_0^t \frac{kA}{V} \int_0^t CPdtdt \qquad \textbf{Eq. 6-4}$$

where the ratio *kA/V* is the tube surface area per mass of accumulated impurity (with *k* being a constant relating the mass of accumulated impurity to the volume of the high concentration crevice solution). Reference [2] discusses the relationship between the wetted tube area and the volume for several crevice geometries. Reference [112] uses an exponential relationship to approximate this function for an eccentric tube/support drilled hole geometry. A simplified case in which the area is not affected by the accumulated mass (i.e., a thin film forms on the tube surface and grows thicker with time rather than extending in area) reduces Equation 6-4 to a reintegration of Equation 6-1. Another simplified case is one in which the relationship between the area and the volume is essentially linear, which yields the following results:

$$IE_B = \kappa \int_0^t \int_0^t CPdtdt \qquad \textbf{Eq. 6-5}$$

Because Method A already considers one limiting case, Equation 6-5 is used for Method B in the analyses presented in this chapter. Because the values of IE_B are used here only for comparative purposes, κ is taken arbitrarily as unity. P is defined by Equation 6-3. The various issues associated with these simplifications are illustrated in Figure 6-2.

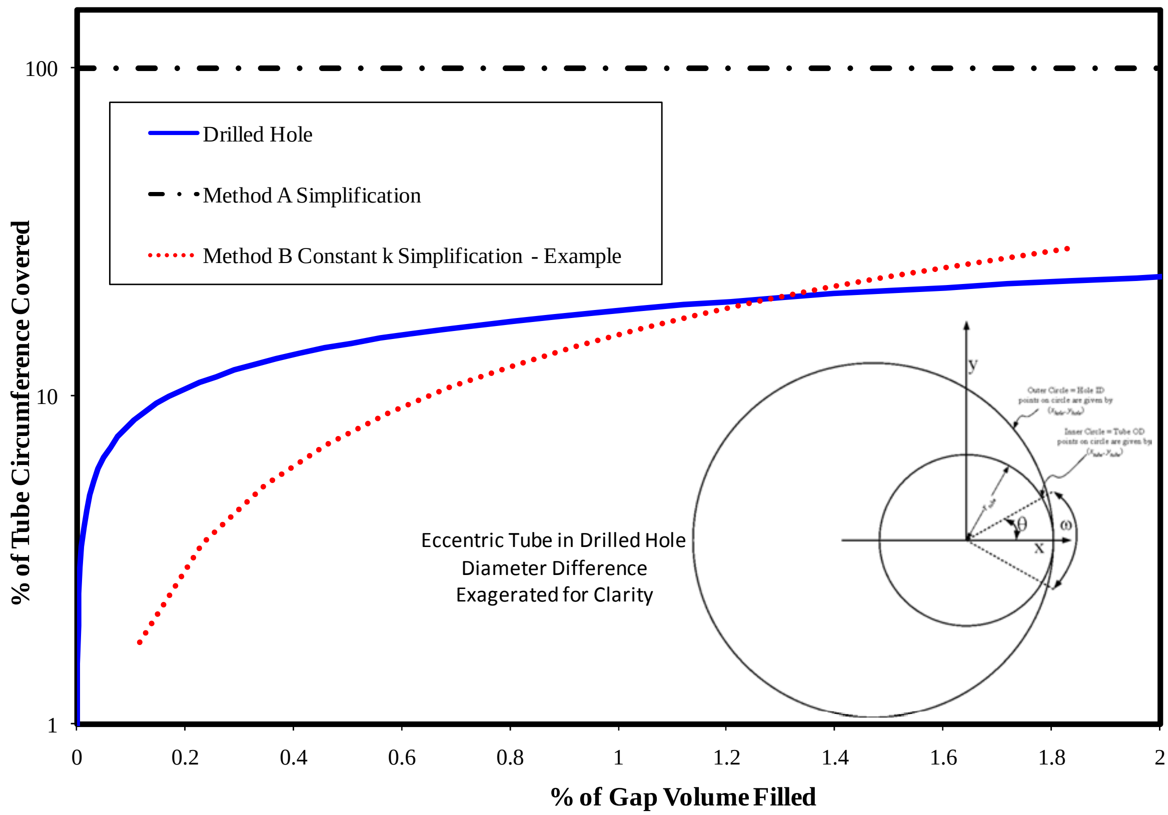

Figure 6-2
Relationship between Liquid Volume and Surface Area Covered for an Eccentric Gap

Note that for a period of constant concentration and full power, Equation 6-5 reduces to the following:

$$IE_B\big|_{C,P} = \frac{1}{2}Ct^2 \qquad \textbf{Eq. 6-6}$$

The integrated exposure calculated using Method B is thus a measure of the duration of exposure to the accumulated mass. Because the integrated exposure is a relative measure, the units are arbitrary. For convenience, ppb-days^2 are used in the present analysis.

6.3 Data Analyzed

The two integrated exposure methods described in the previous section were applied to the following two sets of data:

- Almaraz Tube Rupture Event
- Database of Model Boiler Tests

Each of these data sets is described in the subsections below.

6.3.1 Almaraz Tube Rupture Event

Almaraz Unit 1 experienced a large leak in July 1988 due to a secondary side crack just above the flow distribution baffle. It was attributed to high sodium levels associated with startup of a new condensate polisher system during the April – June time period [124]. A graph showing sodium concentration for the incident on a daily basis is given in Reference [125] and regenerated in Figure 6-3.

The data given in Figure 6-3 were used in Equations 6-1 and 6-5 to evaluate the integrated exposure preceding the tube rupture.

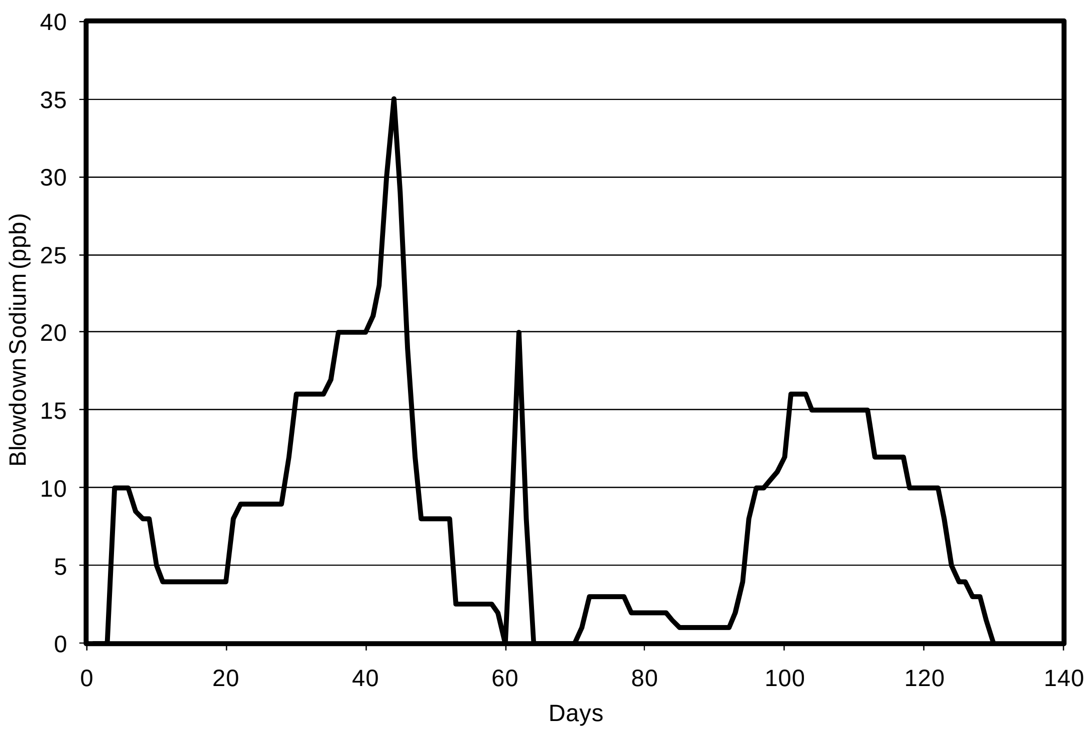

Figure 6-3
Blowdown Sodium preceding the 1988 Almaraz Unit 1 Rupture

6.3.2 Database of Model Boiler Tests

The following references were reviewed to collect information regarding the exposure of SG tubing material to sodium during model boiler tests:

a. C.R. Wolfe and J. B. Prestegiacomo, "Effects of Calcium Hydroxide and Carbonates on IGA and SCC of Alloy 600", Westinghouse Electric Corporation, Pittsburgh, PA: 1983. WCAP - 10273.

b. J. Daret, "Intergranular Attack of Alloy 600 Tubing: Simulation Tests." EPRI-NP-4053. June 1985.

c. J. Daret, "Intergranular Attack of Alloy 600 Tubing: Simulation Tests." EPRI-NP-5377. August 1987.

d. Inhibition of IGA/SCC on Alloy 600 Surfaces Exposed to PWR Secondary Water: Precracking Model Boiler Tests, EPRI, Palo Alto, CA: 1997. 106212-V3.

e. Boric Acid Application Guidelines for Intergranular Corrosion Inhibition, EPRI, Palo Alto, CA: 1987. NP-5558.

f. Corrosion Performance of Alternative Steam Generator Materials and Designs, v1. EPRI, Palo Alto, CA: 1983. NP-3044.

g. PWR Model Steam Generator Corrosion Studies, EPRI, Palo Alto, CA: 1983. NP-3138.

h. R. M. Rentler, "Laboratory Corrosion Test Results for Alloys Alloy 600 and Alloy 690 Steam Generator Tubing Exposed to Faulted Secondary Chemistry Environments," Proceedings: Workshop on Thermally Treated Alloy 690 Tubes for Nuclear Steam Generators, EPRI, Palo Alto, CA: 1986. NP-4665S-SR.

i. J. R. Balavage, "Modular Model Boiler Alternate Materials Test," Appendix B in Alloy 690 for Steam Generator Tubing Applications, EPRI, Palo Alto, CA: 1990. NP-6997-SD.

j. J. R. Balavage and S. J. Gardner, "Material Test Results on Thermally-Treated Alloy 690 and Shot Peened Alloy 800 Steam Generator Tubing," Appendix C in Alloy 690 for Steam Generator Tubing Applications, EPRI, Palo Alto, CA: 1990. NP-6997-SD.

k. Production of Intergranular Attack of Alloy 600, Alloy 690, and Alloy 800 Tubing in Tubesheet Crevices, EPRI, Palo Alto, CA: 1987. NP-5263.

l. J. Daret, et al., "Evidence for the Reduction of Sulfates Under Representative SG Secondary Side Conditions, and for the Role of Reduced Sulfates on Alloy 600 Tubing Degradation," Proceedings of the Ninth International Symposium on Environmental Nuclear Power Systems - Water Reactors, Newport Beach, CA, Aug 1-5, 1999, p567-575, TMS, 1999.

m. Inhibition of IGA/SCC on Alloy 600 Surfaces Exposed to PWR Secondary Water, EPRI, Palo Alto, CA: 1997. TR-106212-V1.

n. S. Tsujikawa, et al., "Study on the IGA/SCC Behavior of Alloy 600 and Alloy 690 SG Tubing Materials in High Temperature Solutions," Proceedings of the ASME/JSME 4th International Conference on Nuclear Engineering (ICONE-4), New Orleans, LA, March 10-14, 1996, ASME, 1996.

The results of these tests were categorized using the following criteria:

- Material tested
- Presence or absence of oxidizing species
- Presence or absence of hydrazine
- Whether or not tubes cracked (versus termination of the experiment before cracking had been observed)

Four different tubing alloys were evaluated in this analysis: Alloy 600MA, Alloy 600TT, Alloy 690TT, and Alloy 800NG. Tests were conducted with Alloy 800NG in both the conventional mill-annealed condition (Alloy 800NG-NP) and having subsequently undergone an OD glass-peening process (Alloy 800NG-P). The glass bead peening process increases the resistance to ODSCC by imparting compressive strain to the tube surfaces, and has been used in many later-generation SGs with Alloy 800NG tubing. With respect to oxides, tests conducted in the presence of any copper oxide or with chromium(III) oxide (Cr_2O_3) were categorized as having oxidizing sludge. Tests with magnetite (Fe_3O_4) or nickel oxide (NiO) were categorized as not having oxidizing sludge.

In deriving material improvement factors for the advanced alloys based on model boiler test data, only tests in which reducing conditions were maintained (i.e. hydrazine was added to the test solution, and no oxidizing species were present) were considered. The tests reviewed in which reducing conditions were maintained are shown in Table 6-1. Due to the considerable amount of test data available for Alloy 600MA, only tests in which throughwall cracking occured were considered in this analysis. For the other alloys, tests terminated without cracking were considered, but noted as not demonstrating cracking.

Table 6-1
Model Boiler Tests Performed Under Reducing Conditions

Ref.	Alloy	Test/Specimen	Chemical Environment	Cracking Observed?
			Alloy 600MA	
a	600MA	11-263	0.17 ppm Na_2CO_3	Yes
a	600MA	12-255	1.7 ppm Na_2CO_3	Yes
a	600MA	12-264	0.3 ppm NaOH	Yes
a	600MA	13-265	0.06 ppm Na_2CO_3, 0.3 ppm NaOH	Yes
b	600MA	AJAX 13-8-600MA	22.9 ppm NaOH, + KOH (9:1), 1 ppm CO_3	Yes
b	600MA	AJAX 13-9-600MA	2.29 ppm NaOH + KOH (9:1), 1 ppm CO_3	Yes
b	600MA	AJAX 15-6-600MA	22.9 ppm NaOH + KOH (9:1), 1.5 ppm SO_4	Yes
b	600MA	AJAX 15-7-600MA	2.29 ppm NaOH + KOH (9:1), 1.5 ppm SO_4	Yes
c	600MA	AJAX 13-10-2 600MA	0.25 mg/l NH_4, NaOH (0.1 mg/l OH-), Na2SiO$_3$ (NaOH: Na_2SiO_3 = 3:1 M); prefaulted with 40wt% NaOH, NaOH:Na_2SiO_3 (6:1)	Yes
c	600MA	AJAX 13-10-4 600MA	0.25 mg/l NH_4, NaOH (0.1 mg/l OH-), Na_2SiO_3 (NaOH: Na_2SiO_3 = 3:1 M); prefaulted with 40wt% NaOH, NaOH:Na_2SiO_3 (6:1)	Yes
c	600MA	AJAX 15-8-3 600MA	AVT + NaOH (0.1 mg/l OH-), Na_2SO_4 (NaOH: Na_2SO_4 = 3:1 M); prefaulted with 40% NaOH, NaOH:Na_2SO_4 (40:1)	Yes
k	600MA	TCSA 4 - 600MA	AVT + average [Na^+] = 19.0 ppm or 1.3 ppm (batch/semi-continuous feed&bleed)	Yes
k	600MA	TCSA 5 - 600MA	AVT + average [Na^+] = 3.0 ppm (semi-continuous feed&bleed), added as Na_2SO_4	Yes
l	600MA	2-600MA	AVT + 0.5 ppm sulfate (as Na_2SO_4)	Yes
			Alloy 600TT	
b	600TT	AJAX 13-8-600TT	22.9 ppm NaOH, + KOH (9:1), 1 ppm CO_3	Partial
b	600TT	AJAX 15-6-600TT	22.9 ppm NaOH + KOH (9:1), 1.5 ppm SO_4	Partial
b	600TT	AJAX 15-7-600TT	2.29 ppm NaOH + KOH (9:1), 1.5 ppm SO_4	Partial
c	600TT	AJAX 13-10-1 600TT	0.25 mg/l NH_4, NaOH (0.1 mg/l OH-), Na2SiO$_3$ (NaOH: Na_2SiO_3 = 3:1 M); prefaulted with 40wt% NaOH, NaOH:Na_2SiO_3 (6:1)	No
c	600TT	AJAX 13-10-3 600TT	0.25 mg/l NH_4, NaOH (0.1 mg/l OH-), Na_2SiO_3 (NaOH: Na_2SiO_3 = 3:1 M); prefaulted with 40wt% NaOH, NaOH:Na_2SiO_3 (6:1)	No
c	600TT	AJAX 15-8-2 600TT	AVT + NaOH (0.1 mg/l OH-), Na_2SO_4 (NaOH: Na_2SO_4 = 3:1 M); prefaulted with 40% NaOH, NaOH:Na_2SO_4 (40:1)	No
c	600TT	AJAX 15-8-4 600TT	AVT + NaOH (0.1 mg/l OH-), Na_2SO_4 (NaOH: Na_2SO_4 = 3:1 M); prefaulted with 40% NaOH, NaOH:Na_2SO_4 (40:1)	No
k	600TT	TCSA 4 - 600TT	AVT + average [Na^+] = 19.0 ppm or 1.3 ppm (batch/semi-continuous feed&bleed), added as Na_2CO_3	Partial
k	600TT	TCSA 5 - 600TT	AVT + average [Na^+] = 3.0 ppm (semi-continuous feed&bleed), added as Na_2SO_4	No
n	600TT	600TT	AVT + 10 ppb Na	No
			Alloy 690	
b	690MA	AJAX 13-8-690MA	22.9 ppm NaOH, + KOH (9:1), 1 ppm CO_3	Partial
b	690MA	AJAX 13-9-690MA	2.29 ppm NaOH + KOH (9:1), 1 ppm CO_3	Partial
b	690MA	AJAX 15-6-690MA	22.9 ppm NaOH + KOH (9:1), 1.5 ppm SO_4	Partial
b	690MA	AJAX 15-7-690MA	2.29 ppm NaOH + KOH (9:1), 1.5 ppm SO_4	Partial
k	690TT	TCSA 4 - 690TT	AVT + average [Na^+] = 19.0 ppm or 1.3 ppm (batch/semi-continuous feed&bleed)	Partial
k	690TT	TCSA 5 - 690TT	AVT + average [Na^+] = 3.0 ppm (semi-continuous feed&bleed), added as Na_2SO_4	No
l	690TT	2-690TT	AVT + 0.5 ppm sulfate (as Na_2SO_4)	No
n	690TT	690TT	AVT + 10 ppb Na	No
			Alloy 800	
k	800NG-MA	TCSA 4 - 800MA (original tube)	AVT + average [Na^+] = 19.0 ppm or 1.3 ppm (batch/semi-continuous feed&bleed)	Yes
k	800NG-MA+P*	TCSA 4 - 800MA (replacement tube)	AVT + average [Na^+] = 3.0 ppm (semi-continuous feed&bleed), added as Na_2SO_4	Partial
l	800NG	2-800NG	AVT + 0.5 ppm sulfate (as Na_2SO_4)	No

* This specimen had 4% cold-work applied and the OD glass bead peened after the mill anneal step. These processing steps were performed on the Alloy 800NG tubing used in some later plants.

As can be seen from Table 6-1, no Alloy 600TT or Alloy 690 (MA or TT) tube specimens experienced throughwall cracking under reducing conditions. Eddy-current indications of SCC of Alloy 600TT and Alloy 690MA (not through-wall) were observed in one test program (Reference b). Improvement factors were determined using the integrated exposure model for Alloy 600TT and 690MA based on these results. These improvement factors are therefore conservative, as the additional time required for the crack to propagate through the remainder of the wall is not considered. It should be noted that the indications of SCC observed in Alloy 690MA were less severe than those in Alloy 600TT specimens, indicating that 690MA in the mill-annealed condition has greater resistance to SCC than Alloy 600TT in caustic-contaminated environments. Alloy 690TT and Alloy 800NG were not evaluated in Reference b.

Through-wall cracking was observed in one test of Alloy 800NG (Reference k). Two work conditions of Alloy 800NG were used in this test program – one with 4% cold work and glass-bead peening of the OD after the mill-anneal (Alloy 800NG-MA+P), and one without peening/cold work (Alloy 800NG-MA). Peening is expected to significantly increase resistance to ODSCC by putting the surface under compressive stress[10]. Considering the limited model boiler tests results available for Alloy 800NG and the expected improvement imparted by peening, these materials are treated separately in this analysis.

It should be noted that only two of the test programs reviewed evaluated the cracking behavior of Alloy 800NG under reducing conditions; this small sample size limits the confidence of the improvement factors estimated from this data set.

6.4 Results

Integrated exposures for the Almaraz event (see Section 6.3.1) and the model boiler tests (see Section 6.3.2) were calculated using both Method A and Method B. Due to the high number of tests resulting in failure of Alloy 600MA tube specimens, only tests in which throughwall cracking was observed are considered for that alloy.

6.4.1 Almaraz Event Integrated Exposures

The Almaraz event resulted in the following integrated exposures:

- Method A: 1,073 ppb-days
- Method B: 71,000 ppb-days[2]

[10] At some locations, such as at roll transitions and dents, this benefit is removed by plastic deformation.

6.4.2 Alloy 600MA Model Boiler Integrated Exposures

The model boiler results for Alloy 600MA are presented in Figure 6-4 (Method A) and Figure 6-5 (Method B) as cumulative distribution plots. The results for the Almaraz event are also presented in these figures. All of the data points given in these figures represent tests in which through wall cracks occurred, i.e., none of the points represent tests terminated before cracking was observed.

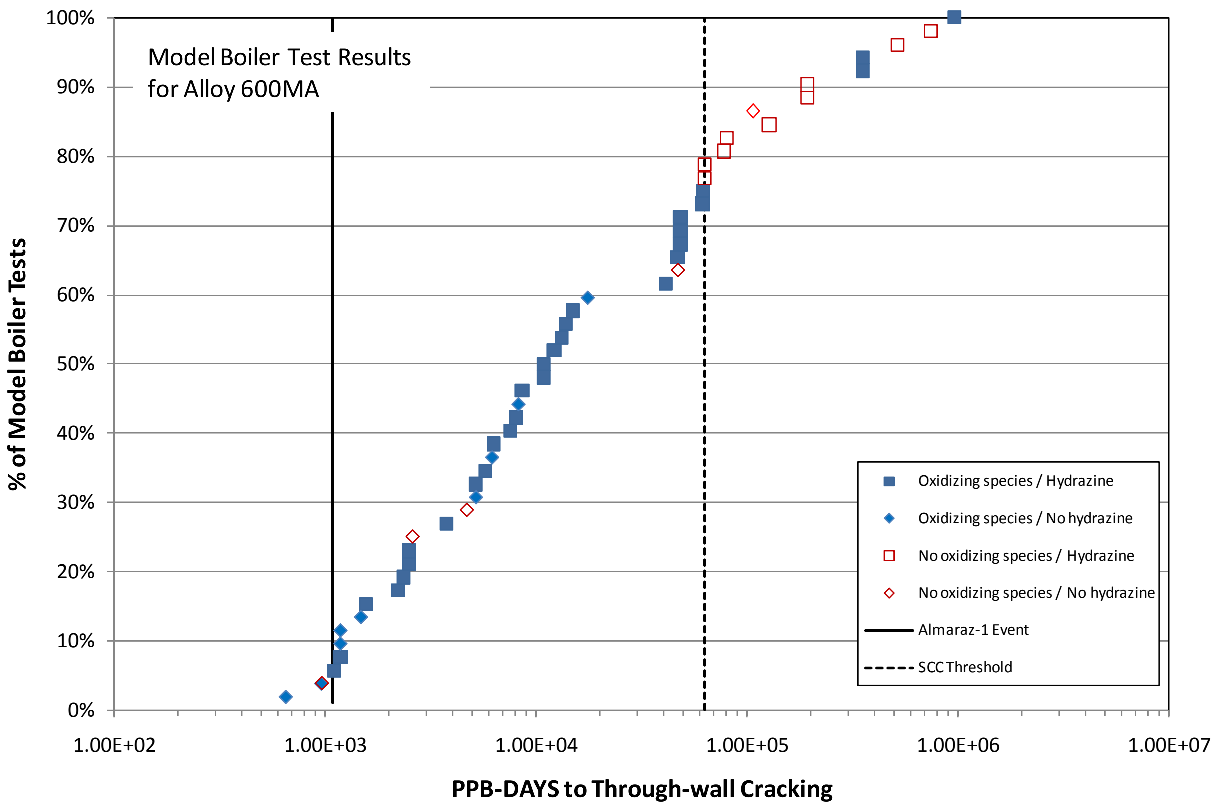

Figure 6-4
Distribution of Integrated Exposure (Method A) for the Model Boiler Tests—Alloy 600MA

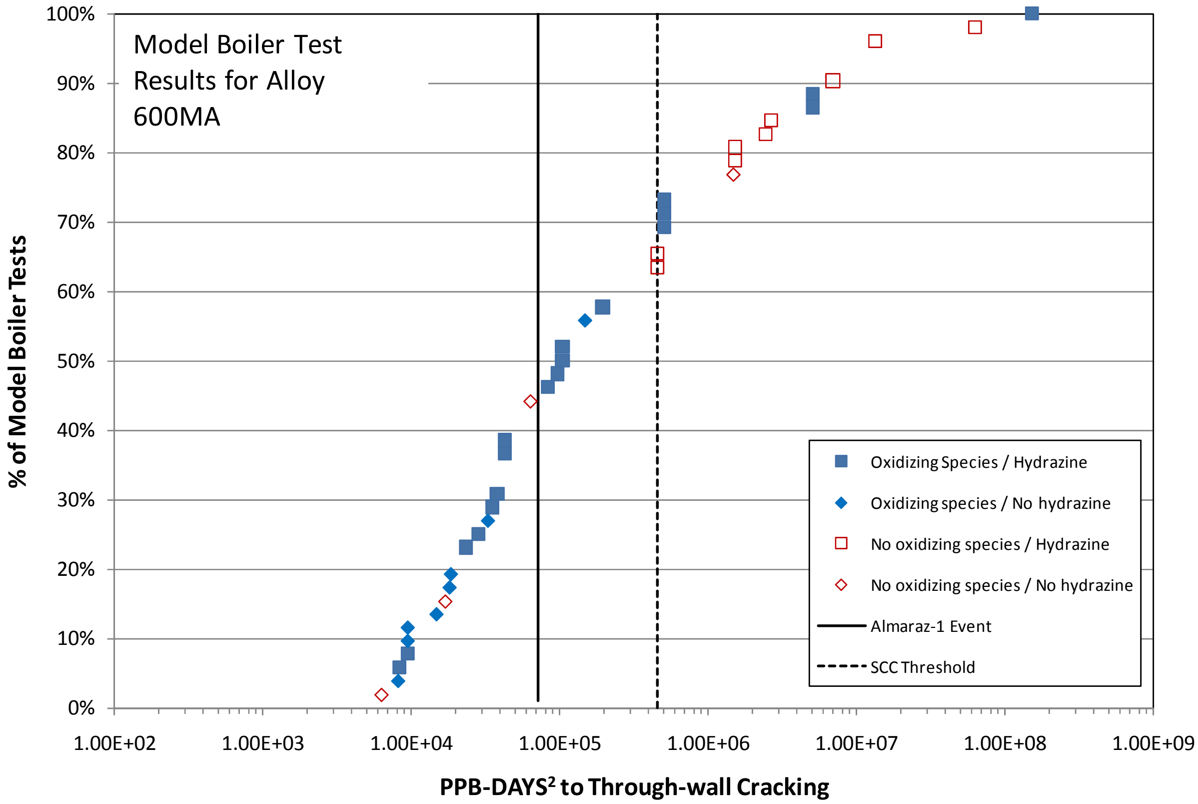

Figure 6-5
Distribution of Integrated Exposure (Method B) for the Model Boiler Tests—Alloy 600MA

It is apparent from inspection of Figure 6-4 and Figure 6-5 that, although numerous tests resulted in early SCC, none of them were conducted under reducing conditions. That is, all of the tests which resulted in cracking with low exposures either had oxidizing sludge present or were conducted without a reducing agent (i.e., without hydrazine). The tests conducted in reducing environments generally required longer exposures before cracking was observed.

For comparison with other alloys, the following values were used to represent the minimum integrated exposure resulting in cracking under reducing conditions:

- Method A: 62,600 ppb-days
- Method B: 456,000 ppb-days^2

The one anomaly in these results is that the Almaraz rupture occurred at an integrated exposure significantly less than that required to cause cracking in the model boiler tests conducted under reducing conditions. In past considerations of the Almaraz event, it has been speculated that the Almaraz event involved oxidizing sludge, specifically, copper oxide which had been left in the steam generators following a chemical cleaning. It is known that copper was left behind (as is somewhat typical of steam generator chemical cleanings that do not include a final copper removal step). However, there is no analytical evidence that this copper was significantly oxidized or that sufficient reducing conditions were not maintained. Nevertheless, the significant difference between the Almaraz experience and the model boiler test results provides some support for the speculation that there were other chemistry factors besides sodium involved in the tube rupture.

6.4.3 Alternate Alloy Model Boiler Integrated Exposures

Model boiler tests with other alloys were considered separately and are discussed in the following subsections.

6.4.3.1 Alloy 600TT Model Boiler Tests

The integrated exposures from the model boiler tests with Alloy 600TT tubing are shown in Figure 6-6 (Method A) and Figure 6-7 (Method B). Also shown are the Alamaraz event and the Alloy 600MA model boiler results. Indications of SCC in Alloy 600TT tubing were observed in two tests conducted under reducing conditions (Reference b and Reference k). The integrated exposures for the earliest failed tube were as follows:

- Method A: 154,000 ppb-days
- Method B: 9,700,000 ppb-days[2]

Comparing these integrated exposures to the minimums for the Alloy 600MA testing yields improvement factors of 2.5 (by Method A) and 21.3 (by Method B). In general, improvement factors derived from model boiler tests are much more likely to be representative of field performance improvement factors than those derived from other laboratory test results, since the benefits of thermal treatment have not been reduced by the addition of cold work, as is generally the case in the autoclave-type tests discussed in Chapter 5. However, since only partial cracking of Alloy 600TT was induced without oxidizing species in a limited number of tests, these estimates are conservative. It should also be noted that, due to the limited number of data points in this sample, the confidence levels associated with IF_Rs derived from 600TT model boiler test data are low.

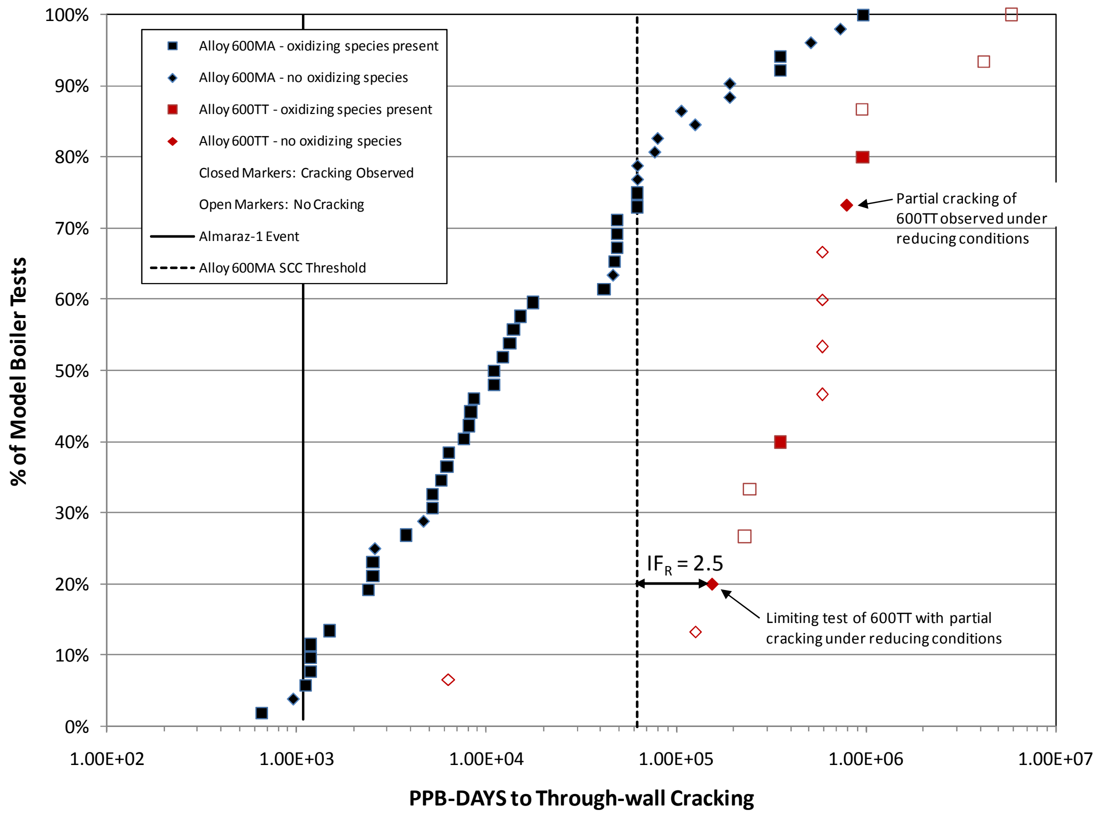

Figure 6-6
Distribution of Integrated Exposure (Method A) for the Model Boiler Tests—Alloy 600TT

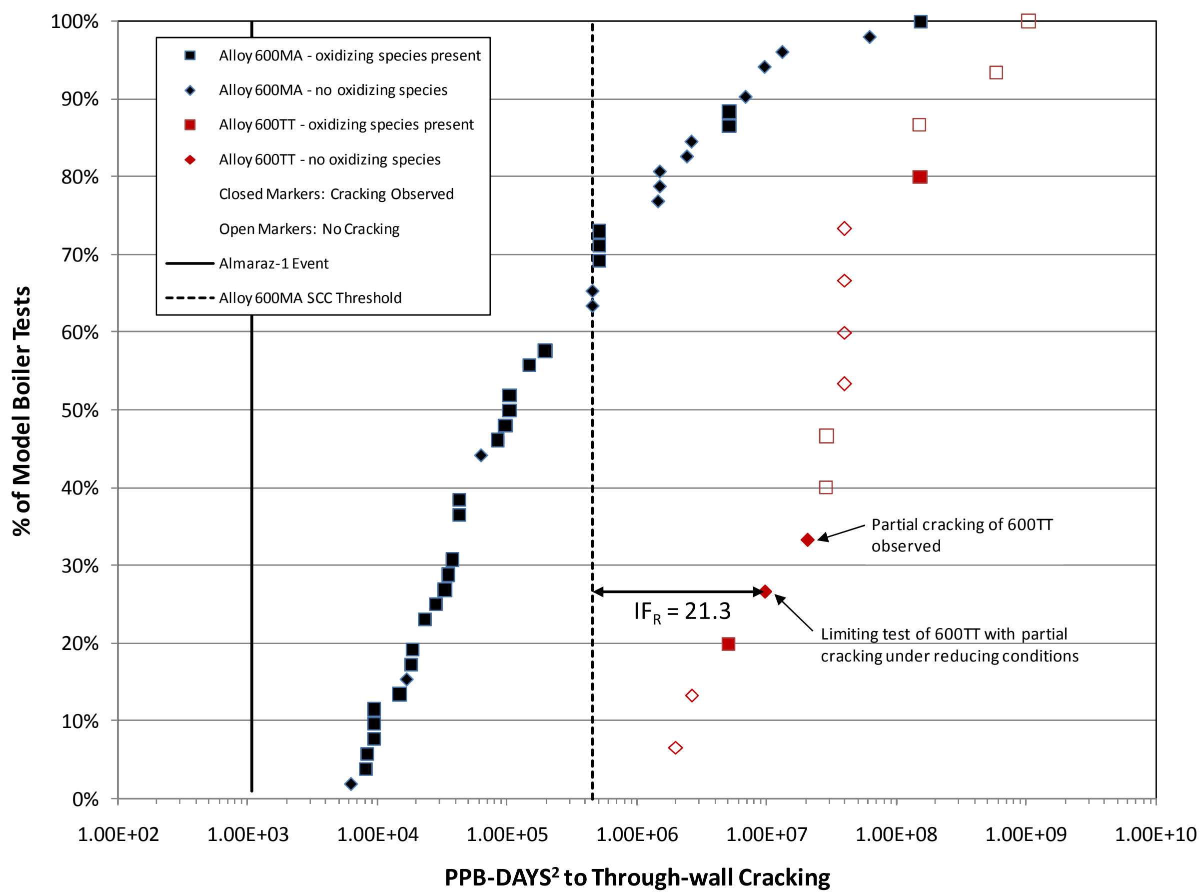

Figure 6-7
Distribution of Integrated Exposure (Method B) for the Model Boiler Tests—Alloy 600TT

6.4.3.2 Alloy 690TT Model Boiler Tests

The integrated exposures from the model boiler tests with Alloy 690TT tubing are shown in Figure 6-8 (Method A) and Figure 6-9 (Method B). Also shown in Figure 6-8 and Figure 6-9 are the Almaraz event and the Alloy 600MA model boiler results. No through-wall cracking was observed in tests performed with Alloy 690TT. Partial cracking of Alloy 690TT under reducing conditions was observed in one test, discussed in EPRI NP-5263 (Reference k). This test resulted in a maximum crack depth of 45% of the wall-thickness, as estimated by ECT. The integrated exposures experienced by this specimen under the testing conditions were as follows:

- Method A: 787,000 ppb-days
- Method B: 20,670,000 ppb-days^2

These data indicate an improvement factor of 12.6 (by Method A) and 45.3 (by Method B). It should be noted that no attempt is made here to account for the differences in the extent of cracking in these two tubing materials or to account for the different times which might be required for a given crack to grow through wall (i.e., the different crack growth rates). These improvement factors are therefore conservative, as they do not take into account the time needed for the crack to propagate through the remainder of the tube wall. Cracking was detected in all cases by eddy current testing. Because the resistance to SCC is considerably increased by thermal treatment, which is performed on all Alloy 690 tubing used in SGs, tests with mill-annealed Alloy 690 (Alloy 690MA) were not included in this analysis.

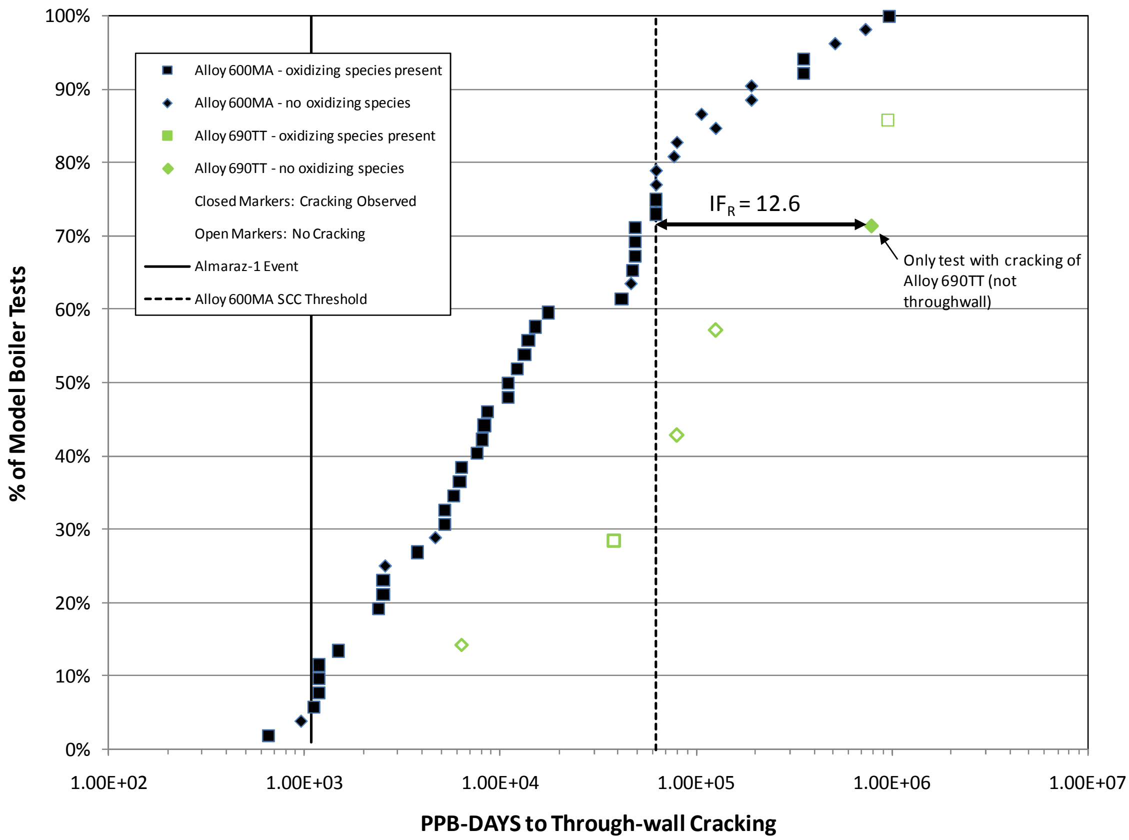

Figure 6-8
Distribution of Integrated Exposure (Method A) for the Model Boiler Tests—Alloy 690TT

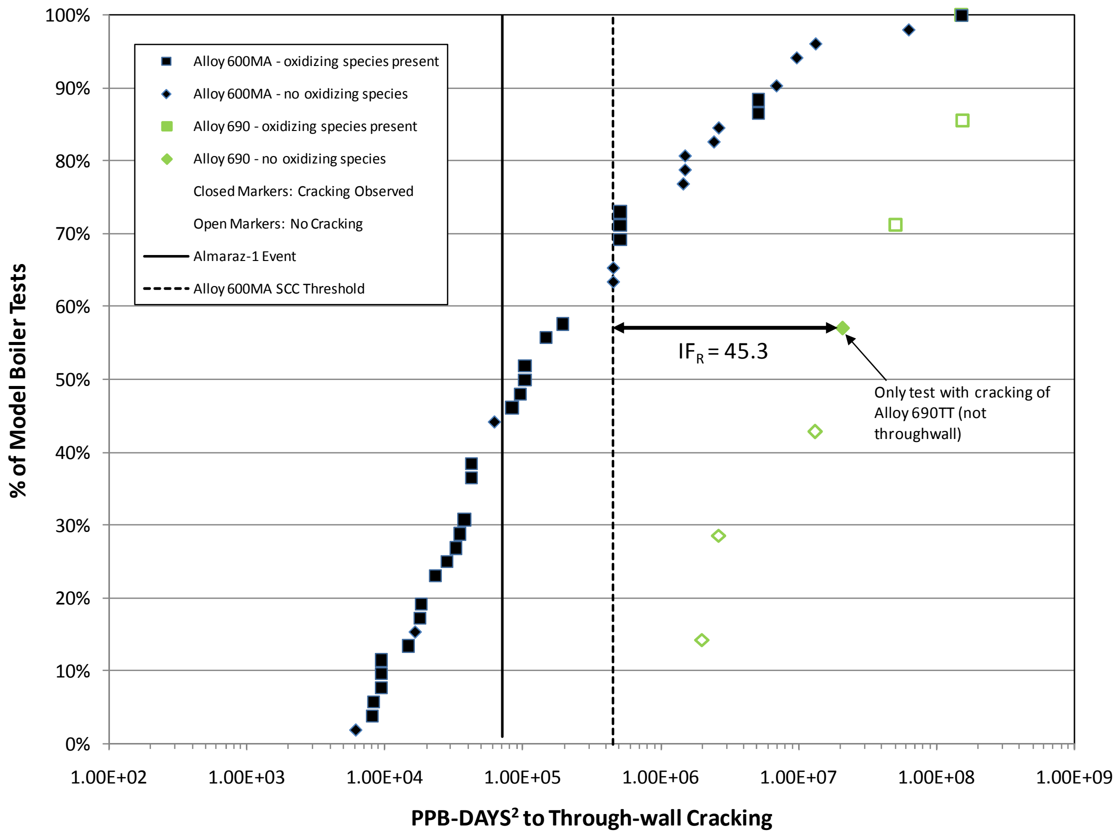

Figure 6-9
Distribution of Integrated Exposure (Method B) for the Model Boiler Tests—Alloy 690TT

6.4.3.3 Alloy 800NG Model Boiler Tests

The integrated exposures from the model boiler tests with Alloy 800NG tubing are shown in Figure 6-10 (Method A) and Figure 6-11 (Method B). Also shown in Figure 6-10 and Figure 6-11 are the Almaraz event and the Alloy 600MA model boiler results. As discussed in the introduction to this section, through-wall cracking under reducing conditions was induced in only one 800NG specimen. This specimen was produced with the conventional mill-annealed thermal treatment, designated Alloy 800NG-NP for the purposes of this report. The integrated exposures experienced by this test specimen prior to tube failure due to SCC are as follows:

- Method A: 266,000 ppb-days
- Method B: 1,860,000 ppb-days^2

These exposures indicate improvement factors for Alloy 800NG-NP, relative to Alloy 600MA, of 4.3 (Method A) and 4.1 (Method B).

The failed specimen was replaced with an Alloy 800NG tubing segment that been treated with 4% coldwork and glass-peened (Alloy 800NG-P), which is expected to impart superior resistance to ODSCC. This tube had a 72% throughwall indication (detected by ECT) after 33 days of exposure. A separate IF_R for Alloy 800NG-P is therefore estimated based on this data. It should be noted that this adds significant conservatism, as the additional time needed reach through-wall cracking is not included. The integrated exposures experienced by this test specimen prior to the detection of SCC are as follows:

- Method A: 635,000 ppb-days
- Method B: 14,130,000 ppb-days[2]

These exposures indicate improvement factors for Alloy 800NG-P, relative to Alloy 600MA, of 10.1 (Method A) and 31.0 (Method B). Note that SCC indications were also observed in Alloy 690TT at this time, a) the Alloy 690TT specimen had undergone an additional 2 weeks of exposure at this time, and b) more severe indications of SCC were observed in the Alloy 800NG-P tube (72% throughwall in the Alloy 800NG-P tube versus 45% throughwall in the Alloy 690TT tube).

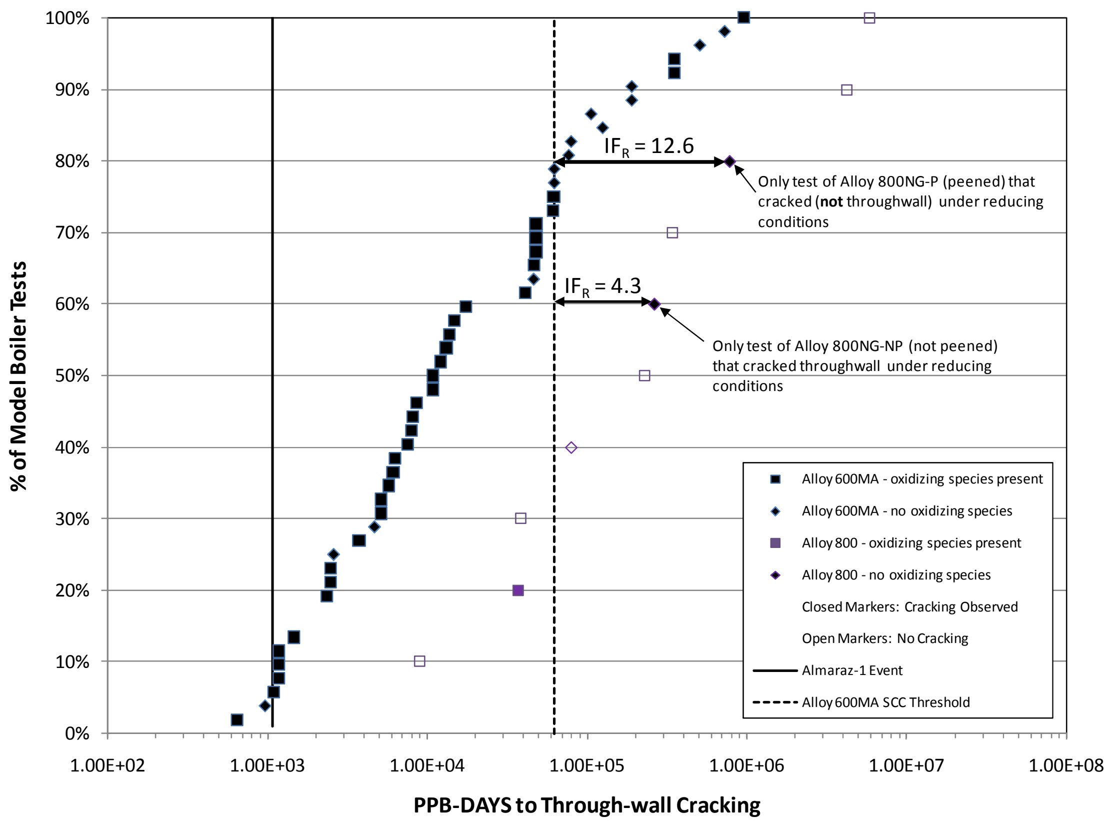

Figure 6-10
Distribution of Integrated Exposure (Method A) for the Model Boiler Tests—Alloy 800NG

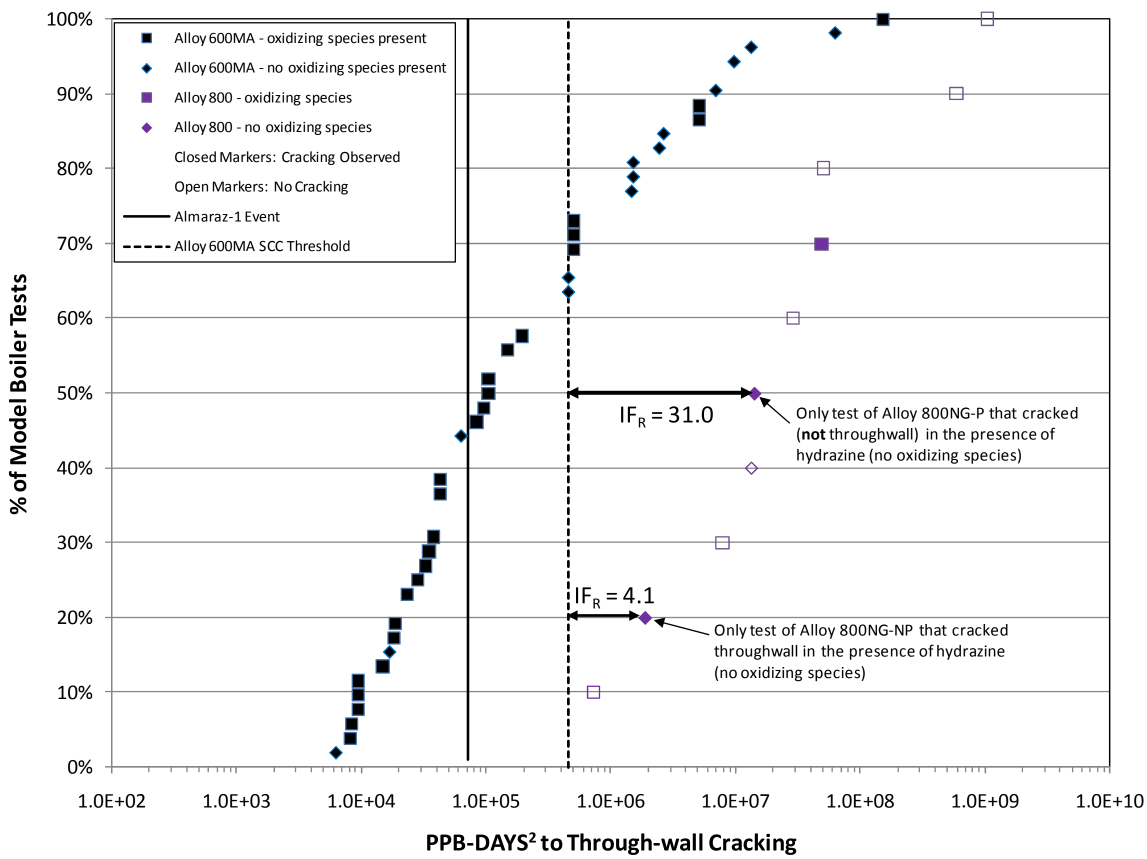

Figure 6-11
Distribution of Integrated Exposure (Method B) for the Model Boiler Tests—Alloy 800NG

6.5 Conclusions Regarding Integrated Exposure to Sodium

For Alloy 600TT, these results indicate it provides an increased margin for exposures to sodium as compared to Alloy 600MA. Different methods of determining the integrated exposure indicate improvement factors relative to Alloy 600MA of 2.5 (by Method A) and 21.3 (by Method B). Alloy 690TT exhibited a greater corrosion resistance relative to the other advanced alloys in caustic environments, leading to IF_R estimates of 12.6 and 45.3, respectively. The improvement factors estimated for Alloy 800NG-NP were slightly lower in comparison (4.3 and 4.1 using Methods A and B, respectively). Improvement factors of 10.1 and 31.0 were estimated for Alloy 800NG-P. Based on the test programs reviewed in this chapter, Alloy 690TT demonstrated the greatest increase in resistance to SCC relative to that of Alloy 600MA in strongly caustic solutions. It should be noted that no cases of throughwall cracking were observed in model boiler tests with Alloys 600TT, 690TT, and 800NG-P. The improvement factors estimated for these alloys are therefore conservative, as the additional time needed reach through-wall cracking in these tube specimens was not considered.

It should be noted that the improvement factors determined in this chapter are derived from a small subset of model boiler tests in which cracking of advanced alloys was observed, and have a relatively high statistical uncertainty.

7
REFERENCES

1. Pressurized Water Reactor Generic Tube Degradation Predictions: US Recirculating Steam Generators with Alloy 600TT and Alloy 690TT Tubing, EPRI, Palo Alto, CA: 2003. 1003589.
2. Alloy 690 Improvement Factor Update: Application of Improvement Factor Data to the Analysis of a Secondary System Chemistry Upset at Ginna. EPRI, Palo Alto, CA and Constellation Energy Group, Inc., Baltimore, MD: 2006. 1013640.
3. K. Norring, K. Stiller, and J.O. Nilsson, “Grain Boundary Microstructure, Chemistry, and IGSCC in Alloy 600 and Alloy 690,” Proceedings of the Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors, ANS, 1992.
4. DEI M-5553-00-08, “Laboratory and Plant Experienced Based Improvement Factors for Alloy 600TT versus Alloy 600MA, Guidelines Revision Committee Meeting #2 Action Item # 34,” Revision 0, December 2007.
5. Predicted Tube Degradation for Westinghouse Models D5 and F Type Steam Generators, EPRI, Palo Alto, CA: 1997. TR-108501.
6. Susceptibility of Alloys Alloy 600 and Alloy 690 to Acidified Sulfate and Chloride Environments, EPRI, Palo Alto, CA: 1994. TR-104045.
7. DEI Letter L-8906-04-01, “Alloy 800 Experience and Basis for 5-year Inspection Interval in U.S,” November 22, 2006. Rev. 0.
8. “International Conference on Water Chemistry of Nuclear Reactor Systems,” October 23-26, 2006, Jeju Island, Korea.
9. P. Berge and J.R. Donati, “Materials Requirements for Pressurized Water Reactor Steam Generator tubing,” *Nuclear Technology 55:10*, p88-104104, 1981.
10. Yonezawa, et al., International Symposium Fontevraud I, Contribution of Materials Investigation to the Resolution of Problems Encountered in PWR Plants, p289-296, SFEN 2-6 Sept. 1985.
11. Y. Rouillon, et al., "PWSCC Behavior of Thermally Treated Alloy 600," Proceedings: 1987 EPRI Workshop' on Mechanisms of Primary Water Intergranular Stress Corrosion Cracking", Alexandria, VA, April 29- May 1, 1987, EPRI NP-5987 SP, Sep. 1988.
12. N. Ogawa, et al., "Materials Integrity under Elevated pH Control of RCS Water for the Reduction of Radiation Source," to be presented at ASME Fourth International Conference on Nuclear Engineering, New Orleans, March 1996.

13. N. Pessal, G.P. Airey, and B.P. Lingerfelter, "The Influence of Thermal Treatment on the SCC Behavior of Inconel Alloy 600 at Controlled Potentials in 10% Caustic Soda Solutions at 315°C," *Corrosion 35:3*, 100, 1979.

14. G. Airey, "The Effect of Carbon Content and Thermal Treatment on the SCC Behavior of Inconel Alloy 600 Steam Generator Tubing," *Corrosion 35:3*, 129, 1979.

15. K. Smith, A. Klein, P. Saint-Paul, and J. Blanchet, "Inconel Alloy 690: A Material with Improved Corrosion Resistance for PWR Steam Generator Tubes," *Proceedings of the Second International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, ANS, 1986.

16. T. Yonezawa, K. Onimura, N. Sasaguri, T. Kusakabe, H. Nagano, K. Yamanaka, T. Minami, and M. Inoue, "Effect of Heat Treatment on Corrosion Resistance of Alloy 690," *Proceedings of the Second International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, ANS, 1986.

17. R. J. Jacko, et al., "An Overview of Laboratory Tests Conducted by Westinghouse to Qualify Alloy 690 Steam Generator Tubing," and R. J. Jacko, "Stress Corrosion Testing of Candidate Steam Generator Tube Materials," *Proceedings: Workshop on Thermally Treated Alloy 690 Tubes for Nuclear Steam Generators*, Papers 9A and 15, EPRI, 1986. EPRI NP-4665S-SR.

18. Stress Corrosion of Alloys Alloy 600 and Alloy 690 in Acidic Sulfate Solutions at Elevated Temperatures, EPRI, Palo Alto, CA: 1983. NP-3043.

19. Investigation of Lead as a Cause of Stress Corrosion Cracking at Support Plate Intersections, EPRI, Palo Alto, CA: 1991. NP-7367-S.

20. T. Sakai, T. Senjuh, K. Aoki, T. Shigemitsu, and Y. Kishi, "Study on Corrosion Resistance of Alloy 600 and Alloy 690 in High Temperature Water Containing Lead," *Corrosion 92*, Paper #83, NACE, 1992.

21. J. Sedriks, et al., "Inconel Alloy 690 - A New Corrosion Resistant Material," Boshoku Gijutsu, v28, n2, p82-95, 1979.

22. J. M. Sarver, et al., "Carbide Precipitation and the Effect of Thermal Treatments on the SCC Behavior of Inconel Alloy 690;' *Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, TMS, 1988.

23. B. P. Miglin and G. J. Theus, Stress Corrosion Cracking of Alloys Alloy 600 and Alloy 690 in All Volatile-Treated Water at Elevated Temperatures, EPRI NP5761SP, May 1988.

24. R. J. Jacko, Corrosion Evaluation of Thermally Treated Alloy 600 Tubing in Primary and Faulted Secondary Environments, EPRI NP-6721, June 1990.

25. G. P. Airey, Optimization of Metallurgical Variables to Improve Corrosion Resistance of Inconel Alloy 600, EPRI Report NP-3051, July 1983.

26. O. de Bouvier et al., " Stress Corrosion Cracking of Nickel Alloys in "Complex" (Liquid and Vapor) Environments", Proceedings of 12th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, TMS, 2005, pp.1255 to 1266.

27. *Evaluation of Alternative Alloys for PWR Steam Generator Tubing*, EPRI, Palo Alto, CA: 1984. NP-3703.

28. W. H. Cullen and M. J. Partridge, Susceptibility of Alloys Alloy 600 and Alloy 690 to Acidified Sulfate and Chloride Environments, EPRI TR-I04045, June 1994.

29. H. Takamatsu, "Study of Pb Induced Attack," p30-42 of H. Takamatsu, "Japanese SG Related R&D Program," presented at June 1994 EPRI TAG meeting, Denver, Colorado, June 1994.

30. A. Rocher, et al., "Effect of Lead on the OD Degradation of Steam Generator Tubes," *Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors: Proceedings of the International Symposium Fontevraud III, September 12-16, 1994*, SFEN, 1994.

31. Lumsden, J., Factors Affecting PbSCC in Alloy 600/Alloy 690 Steam Generator Tubing, EPRI, Palo Alto, CA: 2007. 1014990.

32. G.P. Airey, et al., "A Stress Corrosion Cracking Evaluation of Inconel Alloy 690 for Steam Generator Tubing Applications," Nuclear Technology, v55, Nov. 1981, p436-448.

33. Y. Rouillon, "Essais de corrosion sous contrainte en eau pure et en mileau primaire de reactors a eau pressurisee sur tubes de generateurs de vapeur en alliages Alloy 600 et Alloy 690," EDF report HT/PV D 588 MAT/T 42, May 10, 1985.

34. C. Gimond, "The Corrosion Performance of Alloy 690, "Proceedings: Workshop on Thermally Treated Alloy 690 Tubes for Nuclear Steam Generators, Paper 14, EPRI NP-4665S-SP, July 1986.

35. R. J. Jacko, et al., "Effect of Heat Treatment on Corrosion Resistance of Alloy 690," Proceedings of the Second International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p593-Alloy 600, ANS, 1986.

36. B. P. Miglin and C. E. Shoemaker, "A Comparison of the Stress Corrosion Cracking Behavior of Alloys Alloy 600 and Alloy 690 in AVT Water," NACE Corrosion 86, Paper 255, march 17-21, 1986.

37. T. Nakayama, et al., "IGC/IGSCC and General Corrosion Behavior of Alloy 800 as a PWR S/G Tube Material," *Corrosion 87*, Paper No. 82, NACE, 1987.

38. G. P. Airey, et al., "Inconel Alloy 690 Steam Generator Tubing: Material Specification and Corrosion Resistance," Proceedings of the International Symposium Fontevraud II, Contribution of Materials Investigation to the Resolution of Problems Encountered in PWR Plants, p408-417, SFEN 10-14 Sept. 1990.

39. K. Norring, K. Stiller, and J. O. Nilsson, "Grain Boundary Microstructure, Chemistry and IGSCC in Alloy 600 and Alloy 690," Proceedings of the Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p482-487, ANS, 1992.

40. K. Norring et al., "Intergranular Stress Corrosion Cracking of Steam Generator Tubing, 25000 Hours Testing of Alloy 600 and Alloy 690," Proceedings of the Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p12-1 - 12-11, NACE, 1990.

41. G. Sui, et al., "Stress Corrosion Cracking of Alloy 600 and Alloy 690 in Hydrogen/Steam and PWR Primary Water," Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p274-281, ANS, 1997.

42. N. Ogawa, T. Tsurata, et al., "PWSCC Susceptibility Tests for Improving Primary Water Chemistry Control," Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p395-401, ANS, 1997.

43. K. Smith, A. Klein, P. Saint-Paul, and J. Blanchet, "Inconel Alloy 690 A Material with Improved Corrosion Resistance for PWR Steam Generator Tubes," *Proceedings of the Second International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, Monterey, California, September 9-12, 1985.

44. M.G. Angell, S.J. Allan, and G.P. Airey, "The Effect of Primary Coolant Zinc Additions on the SCC Behaviour of Alloy 600 and Alloy 690," *Proceedings of the Ninth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, Newport Beach, California, Aug 1-5, 1999.

45. J.M. Boursier, F. Vaillant, P. Saulay, Y. Brechet, and G. Zacharie, "Effect of the Strain Rate on the Stress Corrosion Cracking in High Temperature Primary Water: Comparison between the Alloys Alloy 690 and Alloy 600," *Proceedings of the Eleventh International Conference on the Environmental Degradation of Materials in Nuclear Systems—Water Reactors*, Stevenson, Washington, August 10-14, 2003.

46. Materials Reliability Program (MRP), Resistance to Primary Water Stress Corrosion Cracking of Alloys Alloy 690, 52, and 152 in Pressurized Water Reactors (MRP-111), EPRI, Palo Alto, CA: 2004. 1009801.

47. L. Wilson and R. G. Aspden, "Caustic Stress Corrosion Cracking of Iron-Nickel-Chromium Alloys, Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, Conference held at Unieux-Firminy, France, June 12-16, 1973, NACE, 1977.

48. J. Sedriks, et al., "The Effect of Nickel Content on the Stress Corrosion Resistance of Fe-Cr-Ni Alloys in an Elevated Temperature Caustic Environment," *Corrosion 32:4*, 157, 1976.

49. R. McIlree and H. T. Michels, "Stress Corrosion Behavior of Fe-Cr-Ni and Other Alloys in High Temperature Caustic Solutions," Corrosion, v33, n2, p60-67, February 1977.

50. W. Pement, et al., "Stress Corrosion Cracking Studies of High Nickel Austenitic Alloys in Several High Temperature Aqueous Solutions," Materials Performance, v19, n4 p43-49, April 1980.

51. Ph. Berge and J. R. Donati, "Materials Requirements for Pressurized Water Reactor Steam Generator Tubing," Nuclear Technology, v55, Oct. 1981, p88-104.

52. Crum, J. R., and R. C. Scarberry, "Corrosion Testing of Alloy 690 for PWR Steam Generators," J. Materials for Energy Systems, v4, n3, p125-130, Dec. 1982.

53. J. R. Crum, "IGA/SCC of Inconel Alloys Alloy 600 and Alloy 690 in Caustic Solutions," Proceedings: 1983 Workshop on Secondary-Side Stress Corrosion Cracking and Intergranular Corrosion of PWR Steam Generator Tubing, EPRI NP-4458, Appendix 16, March 1986.

54. J. E. Harris, et al., Predicted Tube Degradation for Westinghouse Models D5 and F Type Steam Generators, pA-10, EPRI TR-108501, Sept. 1997.

55. J. L. Nelson and S. Floreen, "Evaluation of Alternate Alloys for PWR Steam Generator Tubing," Proceedings of the Second International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p632-639, ANS, 1986.

56. R. Pascali, et al., "SCC of Alloy 600 in PWR Steam Generator Tubes," Corrosion 86, Paper No. 239, NACE, March 1986.

57. *Production of Intergranular Attack of Alloy 600, Alloy 690, and Alloy 800 Tubing in Tubesheet Crevices*, EPRI, Palo Alto, CA: 1987. NP-5263.

58. J. M. Sarver, et al., "Carbide Precipitation and the Effect of Thermal Treatments on the SCC Behavior of Inconel Alloy 690," Corrosion 87, Paper No. 95, March 1987.

59. J. B. Lumsden, Mechanisms for Formation and Disruption of Surface Oxides, EPRI report NP-5368, August 1987.

60. Sarver, J.M., J.V. Monter, and M.P. Miglin, "The Effect of Thermal Treatment on the Microstructure and SCC Behavior of Alloy 600," Proceedings of the 4th International Symposium on the Environmental Degradation of materials in Nuclear Power Systems – Water Reactors, Jekyll Island, GA, 1989. Pp. 5-47 to 5-63.

61. N. Sumitani, et al., "IGA/SCC Behavior of Thermally Treated Alloy 690," Proceedings: 1989 EPRI Alloy 690 Workshop, Appendix B8, EPRI NP-6750-SD, April 1990.

62. R. E. Gold, et al., Alloy 690 for Steam Generator Tubing Applications, EPRI NP-6997-SD, October 1990.

63. P. Miglin and J. M. Sarver, Investigation of Lead as a Cause of Stress Corrosion Cracking at Support Plate Intersections, EPRI NP-7367-S, June 1991.

64. Ma. L. Castaño Marín, et al., "Steam Generator Replacement: Inconel Alloy 690TT and Incoloy Alloy 800 Mod. as an Alternative to Inconel Alloy 600," *Progress in the Understanding and Prevention of Corrosion, Vol. 1, Barcelona, Spain, July 1993*, The Institute of Materials, London, 1993.

65. Gómez Briceño, et al., "Stress Corrosion Cracking Susceptibility of Steam Generator Tube Materials in AVT Chemistry Contaminated with Lead," *Chemistry in Water Reactors, Operating Experience & New Developments*, SFEN, April 24-27, 1994.

66. F. Vaillant, et al., "Comparative Behavior of Alloys Alloy 600, Alloy 690, and Alloy 800 in Caustic Environments," *Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, NACE, 1995.

67. Gómez Briceño, et al., "Stress Corrosion Cracking Susceptibility of Steam Generator Tube Materials in AVT (all volatile treatment) Chemistry Contaminated with Lead," *Nuclear Engineering and Design 165:1-2*, 161, 1996.

68. H. Kajimura, et al., "Corrosion Resistance of TT Alloy 690 Manufactured by Various Melting Processes in High Temperature NaOH Solution," Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p149-156, ANS, 1997.

69. H. Kawamura, H. Hirano, S. Shirai, H. Takamatsu, T. Matsunaga, K. Yamaoka, K. Oshinden, and H. Takiguchi, "Role of Grain Boundary Characteristics in Caustic IGA/SCC Resistance of Thermally-Treated Alloy 690 and Shot-Peened Alloy 800," *Proceedings if the Ninth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, Newport Beach, California, Aug 1-5, 1999.

70. U.C. Kim, K.M. Kim, and E.H. Lee, "Effects of Chemical Compounds on the Stress Corrosion Cracking of Steam Generator Tubing Materials in a Caustic Solution," *Proceedings of the International Conference Water Chemistry of Nuclear Reactor Systems*, San Francisco, California, October 11-14, 2004, pp. 1098-1104.

71. K.M. Kim, E.H. Lee, and U.C. Kim, "Lead Induced Stress Corrosion Cracking of SG Tubing Materials in Caustic Environments," *Pb+S SG Workshop*, EPRI/ANL/NRC, May 24-27, 2005, Argonne National Laboratory.

72. H. Hirano, H. Kawamura, H. Takamatsu, and H. Takiguchi, "Interrelation between Grain Boundary Characteristic and IGSCC of Alloy 600, Alloy 690, and Alloy 800 in High Temperature Acidic and Alkaline Solution," *Pb+S SG Workshop*, EPRI/ANL/NRC, May 24-27, 2005, Argonne National Laboratory.

73. R. Hermer, "SCC Testing of Alloy 600 and Alloy 690 Tubing in 10% NaOH and in 10% NaOH + PbO," *Pb+S SG Workshop*, EPRI/ANL/NRC, May 24-27, 2005, Argonne National Laboratory.

74. R. M. Rentler, "Laboratory Corrosion Test Results for Alloys Alloy 600 and Alloy 690 Steam Generator Tubing Exposed to Faulted Secondary Chemistry Conditions," *Proceedings: Workshop on Thermally Treated Alloy 690 Tubes for Nuclear Steam Generators*, EPRI, Palo Alto, CA: 1986. EPRI NP-4665-SR, Paper 11.

75. W. H. Cullen and M. J. Partridge, Susceptibility of Alloys Alloy 600 and Alloy 690 to Acidified Sulfate and Chloride Environments, EPRI TR-104045, June 1994.

76. J. J. Krupowicz, et al., Corrosion Performance of Alternative Steam Generator Materials and Designs, Volume 3: Posttest Examination of a Freshwater-Faulted Alternative Materials Model Steam Generator, EPRI NP-3044, Volume 3, July 1983.

77. J. F. Newman, Stress Corrosion of Alloys Alloy 600 and Alloy 690 in Acidic Sulfate Solutions at Elevated Temperatures, EPRI NP-3043, Oct. 1983.

78. J. Daret, "IGA/IGSCC in Non-Caustic Waters - CEA Experience," CEA report LETC/770/89, CEA, July 1989.

79. Pierson and C. Laire, “The Influence of Copper on the SCC of Alloy 600 and Alloy 690 Steam Generator Tubes,” Proceedings of the International Symposium Fontevraud IV, Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, p381-390, SFEN 14-18 Sept. 1998., and L. sur Nedden, et al., “Effect of Simulated Outage Conditions in Acid Environment Containing Copper on Corrosion of Steam Generator Tubes,” Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p91-99, ANS, 1997.

80. O. de Bouvier and B. Prieux, “Corrosion sous contraintes en milieux “Sulfate” a divers pH de tubes en alliages Alloy 600, Alloy 690 et Alloy 800 pour generateurs de vapour de centrales REP,” EDF Report HT-44/98/018/A, Dec. 1, 1998.

81. O. de Bouvier, et al., “Nickel Alloy Stress Corrosion Cracking in Neutral and Lightly Alkaline Sulfate Environments,” presented at EPRI/EDF meeting, Les Renardières, Sept. 19, 2000.

82. O. de Bouvier, et al., “Effect of Copper Species on IGA/SCC of Alloy 600 in Neutral Sulfate Environments,” *Tenth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, NACE, 2001.

83. J. Daret, T. Cassagne, Y. Lefevre, T.Q. Tran, R. Benoit, and R. Erre, “Evidence for the Reduction of Sulfates Under Representative SG Secondary Side Conditions, and for the Role of Reduced Sulfates on Alloy 600 Tubing Degradation,” *Proceedings of the Ninth International Symposium on Environmental Nuclear Power Systems - Water Reactors*, Newport Beach, California, Aug 1-5, 1999.

84. T. Sakai et al., “Study on Corrosion Resistance of Alloy 600 and Alloy 690 in High Temperature Water Containing Lead,” presented at NACE Corrosion 92, Paper No. 83.

85. N. Lewis, S.A. Shei, P.N. Pica, B.W. Bussert, and R.E Hermer, "AEM Analysis of SCC in Alloy 690 Tested in 10% Caustic and 10% Caustic + PbO," *Pb+S SG Workshop*, EPRI/ANL/NRC, May 24-27, 2005, Argonne National Laboratory.

86. Kim, K., et al., “Experiments on a Lead Induced Stress Corrosion Cracking of SG Tubing Materials at High Temperature”, International Conference on Water Chemistry of Nuclear Reactor Systems, Jeju Island, Korea, October 2006.

87. Yamamoto, Y, et al., “Development of the Crack Growth Rate Curves for Stress Corrosion Cracking of Nickel Based Alloys in a Simulated Primary Water Environment,” Proceedings of the International Symposium, Fontevraud VI, v1 p369-382, JNESO:MHI, September 2006.

88. Lumsden, J, and A. McIlree, “Factors Affecting PbSCC in Alloy 600 and Alloy 690 Steam Generator Tubing”, Proceedings of the International Symposium, Fontevraud VI, v2, A085-T06, p1237-1246, September 2006.

89. Resistance of Alloy 600 and Alloy 690 Tubing to Stress Corrosion Cracking in Environments With and Without Lead, EPRI, Palo Alto, CA: 2004. 1009532.

90. W. DeBray and L. Steiding, “Materials in the Primary Circuit of Water-cooled Power Reactors,” *Proceedings from the International Nickel Power Conference*, Lausanne, Switzerland, Paper No. 3, p1-24, May 1972.

91. P. K. De and S. K. Ghosal, " A Comparative Study of Stress Corrosion Cracking of Steam Generator Tube Materials in Water at 315°C," *Corrosion 37:6*, 341, 1981.

92. I. L. Wilson and R. G. Aspden, "The Influence of Specimen Type and Heat Treatment on the Caustic Stress Corrosion Cracking of Some Stainless Alloys," *Corrosion 32:5*, 193, 1976.

93. Bo J. E. Johansson, *SVF Project 30: Material Tests in Deaerated 20% NaOH and 20% NaOH + 5% NaCl Solutions at 325°C: Final Report*, 1976. SVF report AE-MS-20.

94. Ph. Berge, et al., "Caustic Stress Corrosion of Fe-Cr-Ni Austenitic Alloys," *Corrosion 33:12*, 425, 1977.

95. J. B. Lumsden and P. J. Stocker, "Inhibition of IGA in Nickel Base Alloys in Caustic Solutions," *Corrosion 88,* Paper Number 252, NACE, March 1988.

96. R. Kilian, "Effect of Caustic Plus Impurities on Alloy 690 and Alloy 800 mod.," *Proceedings: 1992 EPRI Workshop on Secondary Side IGA/SCC San Antonio, Texas December 8-10, 1992*, EPRI, Palo Alto, CA: 1998. TR-106546 Appendix B.

97. R. L. Tapping, et al., "The susceptibility of CANDU steam generator tubing alloys to IGA/IGSCC in acid sulphate environments," *Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors: Proceedings of the International Symposium - FONTEVRAUD III - Sept. 12-16, 1994,* SFEN, 1994.

98. H. Takamatsu, "Study of Pb Induced Attack," p30-42 of H. Takamatsu, "Japanese SG Related R&D Program," presented at June 1994 EPRI TAG meeting, Denver, Colorado, June 1994.

99. R. Kilian, "Influence of Lead on the SCC - Behaviour of SG Tubing," *Proceedings of the Specialists Meeting on Steam Generator Problems and Replacements, Madrid, Spain, 13-16 December 1993,* Session B, No. 5, IAEA, 1994.

100. E. Pierson, et al., " Résistance en milieu acide des matériaux alternatifs pour tubes de GV (alliages Alloy 690 et Alloy 800)," *Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors: Proceedings of the International Symposium - FONTEVRAUD III - Sept. 12-16, 1994,* SFEN, 1994.

101. Daret, J. and D. Feron, "Secondary Side Chemistry and Corrosion, CEA Model Boiler Tests," CEA Technical Note CEA/LETC/292/92, December 1992.

102. Daret, J., "Synthese de L'Essai AJAX 14-10 Realise avec une Pollution Par De L'Oxyde De Plomb, CEA Technical Note CEA/LETC/368/93, June 1993.

103. Hwang, S. S., et al. "Stress Corrosion Cracking Aspects of Nuclear Steam Generator Tubing Materials in the Water Containing Lead at High Temperatures, "Proceedings of the Eighth International Symposium on Environmental Degradation of materials in Nuclear Power Systems – Water Reactors, p200-207, ANS, 1997.

104. M. Helie, "Lead Assisted Stress Corrosion Cracking of Alloys Alloy 600, Alloy 690, and Alloy 800," Proceedings of the Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors, San Diego, California, August 1-5, 1993.

105. Materials Reliability Program: Resistance of Alloys Alloy 690, 52 and 152 to Primary Water Stress Corrosion Cracking (MRP-237, Rev. 1): Summary of Findings From Completed and Ongoing Test Programs Since 2004. EPRI, Palo Alto, CA: 2008. 1018130.

106. Hermer, R., "SCC Testing of Alloy 600 and Alloy 690 Tubing in 10% NaOH and in 10% NaOH + PbO,", Pb+S SG Workshop, EPRI/ANL/NRC, May 24-27, 2005, Argonne National Laboratory.

107. F. Vaillant, "Influence of Lead on the Secondary Side Corrosion of Nickel Base Alloys," presented at Eurocorr'96, Nice, Sept. 1996.

108. PWR Molar Ratio Control Application Guidelines: Volume 2: Secondary Chemistry Control, EPRI, Palo Alto, CA: 1995. TR-104811-V2.

109. F. Nordmann (Acentis), email to C. Marks (DEI), June 26, 2007. (with attachments)

110. MULTEQ: Equilibrium of an Electrolytic Solution with Vapor-Liquid Partitioning and Precipitation—The Database, Version 5.0, EPRI, Palo Alto, CA: 2007. 1014602.

111. B. Sala, P. Combrade, R. Erre, and A. Gelpi, "Local Chemistry and Formation of Deposits on the Secondary Side of Steam Generators a Laboratory Study," *Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, The Minerals, Metals, and Materials Society, 1993.

112. Pressurized Water Reactor Secondary Water Chemistry Guidelines – Revision 6, EPRI, Palo Alto, CA:2004.1008224.

113. T. Nakayama, H. Tomair, K. Fujiwara, and K. Shimogori, "IGC/IGSCC and General Corrosion Behavior of Alloy 800 as a PWR S/G/ Tube Material," Corrosion 87, NACE, Houston, TX, 1987.

114. J. A. Gorman and K. D. Stavropoulos, "Correlation of Temperature with Rate of Steam Generator Tube Corrosion," Draft Dominion Engineering, Inc. Report for EPRI, February 1993.

115. Dr. R. B. Abernethy, The New Weibull Handbook, Second Edition, Dr. Robert B. Abernethy, July 1996.

116. "Seabrook Steam Generator Tube Assessment Program," FPL Energy Seabrook presentation to the NRC, November 14, 2002.

117. Karwoski, K., L. Miller, and N. Morgan (US NRC), "Regulatory Perspective on Steam Generator Tube Operating Experience," presented at The Nuclear Pressure Expertise and Regulation 2005 Symposium, June 22–24, 2005.

118. Lagally, H. O., R. E. Gold, A. R. Vaia, and W. A. Byers, et al., *Seabrook Tube Cracking Root Cause Evaluation Report*, No. SG-SGDA-02-37, Revision 1. Madison, PA: Westinghouse Electric Company LLC, September 2002.

119. E-mail from D. Mayes (Duke Power) to J. Gorman (consultant to DEI), dated February 27, 2008, including the electronic file "Catawba Unit 2.ppt."

120. E-mail from D. Mayes (Duke Power) to V. Moroney (DEI), dated August 27, 2008, including the electronic file "Spring 08 IARC Data Sumary.doc."

121. Indications in Thermally Treated Alloy 600 Steam Generator Tubes and Tube-to-Tubesheet Welds, NRC, Washington, DC, 2005. NRC IN-2005-09.

122. US NRC Information Notice 2008-07, "Cracking Indications in Thermally Treated Alloy 600 Steam Generator Tubes," April 24, 2008.

123. G. Gratton (NRC), letter to D.E. Grissette (SNC), June 3, 2005. ML051400035.

124. "Almaraz-1 Restarts after Steam Generator Fix-Up," *Nucleonics Week*, August 25, 1988.

125. Alloy 690 Qualification: Corrosion Under Prototypic Heat Flux and Temperature Conditions, EPRI, Palo Alto, CA: 1995. TR-104064.

126. Steam Generator Reference Book, EPRI, Palo Alto, CA: 1985.

127. Steam Generator Reference Book Revision 1, EPRI, Palo Alto, CA: 1994. TR-103824.

128. PWR Secondary Water Chemistry Guidelines – Revision 5, EPRI, Palo Alto, CA: 2000. TR-102134-R5.

129. PWR Molar Ratio Control Application Guidelines Vol. 1 Summary, EPRI, Palo Alto, CA: 1995. TR-104811.

130. J. Gorman, "Chloride Limits to Avoid Denting," Attachment H to *Detailed Minutes of the Meeting of the PWR Secondary Water Chemistry Guidelines Committee*, St. Pete Beach, February 17-18, 2000.

131. Correlation of Tube Support Corrosion Studies, Final Report, EPRI, Palo Alto, CA: 1986. NP-4818.

132. Corrosion Performance of Alternative Steam Generator Materials and Designs, EPRI, Palo Alto, CA: 1983. NP-3044.

133. Detailed Minutes of the Meeting of the PWR Secondary Water Chemistry Guidelines Committee, St. Pete Beach, February 17- 18, 2000.

134. J. Daret, T. Cassagne, Y. Lefevre, T.Q. Tran, R. Benoit, and R. Erre, "Evidence for the Reduction of Sulfates Under Representative SG Secondary Side Conditions, and for the Role of Reduced Sulfates on Alloy 600 Tubing Degradation," *Proceedings of the Ninth International Symposium on Environmental Nuclear Power Systems - Water Reactors*, Newport Beach, California, Aug 1-5, 1999.

135. O. de Bouvier, E.M. Pavageau, F. Vaillant, and D. Vermeeren, "Influence of High Reducing Conditions on IGA/SCC of Alloy 600 in Neutral Sulfate Solutions," *Proceedings of the Eleventh International Conference on the Environmental Degradation of Materials in Nuclear Systems—Water Reactors*, Stevenson, Washington, August 10-14, 2003.

136. N.L. Dickinson, D.N. Felgar, and E.A. Pirsh, "An Experimental Investigation of Hydrazine-Oxygen Reaction Rates in Boiler Feedwater," *Proceedings of the American Power Conference*, March 27-29, 1957.

137. S.B. Dalgaard and M.D. Sanford, "Review of the Hydrazine/Oxygen Reaction Kinetics," *Corrosion 81*, Paper 15, NACE, 1981.

138. Electrochemical Potential Monitoring in the PWR Secondary Cycle of St. Lucie 2, EPRI, Palo Alto, CA: 1995. TR-104951.

139. Electrochemical Measurements in the Secondary System of Ringhals Unit 3, Studsvik Material, Nykoping, Sweden, 1992. Studsvik M/92-4.

140. Prairie Island-2 Steam Generator Hideout, EPRI, Palo Alto, CA: 1991. NP-7236.

141. *Diffusion and Hideout in Crevices*, EPRI, Palo Alto, CA: 1983. NP-2979.

142. Hideout and Return of Chloride Salts in heated Crevices Prototypic of Support Plates in Steam Generators, EPRI, Palo Alto, CA: 1987. NP-5015.

143. R. Eaker, "Calculation of Crevice Boiling Conditions for McGuire Unit 2 10/31/88 Shutdown," Duke Power memo attached to letter from R. Eaker to B. H. Hamilton (McGuire Nuclear Station) dated December 12, 1988.

144. J. Gorman, "Comments on Technical Bases of Action Levels for Recirculating Steam Generators For Consideration by the REV 7 Secondary Water Chemistry Guidelines Committee," dated 8-28-07, distributed to Secondary Water Chemistry Guidelines Revision 7 Committee by K. Fruzzetti email, "PWR Secondary Water Chemistry Guidelines Revision 7 Committee: Meeting #2 Reading Material," dated Sept. 6, 2007.

145. J. R. Balavage, "Modular Model Boiler Alternate Materials Test," Appendix B in *Alloy 690 for Steam Generator Tubing Applications*, EPRI, Palo Alto, CA: 1990. NP-6997-SD.

146. J. R. Balavage and S. J. Gardner, "Material Test Results on Thermally-Treated Alloy 690 and Shot Peened Alloy 800 Steam Generator Tubing," Appendix C in *Alloy 690 for Steam Generator Tubing Applications*, EPRI, Palo Alto, CA: 1990. NP-6997-SD.

147. Intergranular Attack of Alloy 600: Simulation Tests, EPRI, Palo Alto, CA: 1985. NP-4053.

148. R. M. Rentler, "Laboratory Corrosion Test Results for Alloys Alloy 600 and Alloy 690 Steam Generator Tubing Exposed to Faulted Secondary Chemistry Environments," *Proceedings: Workshop on Thermally Treated Alloy 690 Tubes for Nuclear Steam Generators*, EPRI, Palo Alto, CA: 1986. NP-4665S-SR.

149. Production of Intergranular Attack of Alloy 600, Alloy 690, and Alloy 800 Tubing in Tubesheet Crevices, EPRI, Palo Alto, CA: 1987. NP-5263.

150. Intergranular Attack of Alloy 600 Tubing: Simulation Tests, EPRI, Palo Alto, CA: 1987. NP-5377.

151. T. Cassagne, et al., "Les essai en boucle sous flux thermique: etude des causes de degradation des tubes et des remèdes envisageables," *Corrosion côté secondaire des faisceaux tubulaires des générateurs de vapeur de REP: bilan et consequences*, SFEN, 1995.

152. S. Tsujikawa, et al., "Study on the IGA/SCC Behavior of Alloy 600 and Alloy 690 SG Tubing Materials in High Temperature Solutions," *Proceedings of the ASME/JSME 4th International Conference on Nuclear Engineering (ICONE-4)," New Orleans, LA, March 10-14,1996*, ASME, 1996.

153. Inhibition of IGA/SCC on Alloy 600 Surfaces Exposed to PWR Secondary Water, EPRI, Palo Alto, CA: 1997. TR-106212-V1.

154. DEI M-5557-00-03, "Sub-Committee Recommendations to the Full Committee," Revision 2, July 2008.

155. Sodium Chloride Hideout in a Simulated Steam Generator Tube and Tube Support Plate Crevice, EPRI, Palo Alto, CA: 1998. TR-110803. (San Jose State University)

156. *Salt Concentration in Heated Crevices and Simulated Scale*, EPRI, Palo Alto, CA: 1983. NP-3050. (Central Electricity Research Laboratories)

157. *Diffusion and Hideout in Crevices*, EPRI, Palo Alto, CA: 1983. NP-2979. (Westinghouse)

158. *Prairie Island-2 Steam Generator Hideout*, EPRI, Palo Alto, CA: 1991. NP-7236. (NWT)

159. S. Odar (FANP) email to K. Fruzzetti (EPRI), December 14, 2001. (with attachments)

160. R. Kilian, "Operating Experience with Alloy 800 SG Tubing in Europe," 13th International Conference on Environmental Degradation of Materials in Nuclear Power Systems, CNS, 2007.

161. EPRI Steam Generator Degradation Database (SGDD Version 6.0), EPRI, Palo Alto, CA: 2009.

162. Steam Generator Tube Plug Integrity Summary Report, Revision 1, Westinghouse, Pittsburgh, PA: 1989. WCAP-12245.

163. Steam Generator Tube Plug Integrity Summary Report, Revision 2, Westinghouse, Pittsburgh, PA: 1989. WCAP-12245.

164. Steam Generator Tube Plug Integrity Summary Report, Revision 3, Westinghouse, Pittsburgh, PA: 1989. WCAP-12245.

165. Steam Generator Tube Plug Integrity Summary Report, Revision 1, Westinghouse, Pittsburgh, PA: 1989. WCAP-12245.

166. Steam Generator Reference Book Volume 1, Revision 1, Chapter 7, EPRI, Palo Alto, CA: 1994. TR-103824-V1R1.

167. Susceptibility and Mitigation of PWSCC in Thermally Treated Alloy 600 Steam Generator Tubes: Tubesheet Bulges and Overexpansions, EPRI, Palo Alto, CA: 2009. 1018887.

168. ANSYS Engineering Analysis System, Revision 11.0, ANSYS, Inc.

169. A. Chaaban, H. Ma, and A. Bazergui, "Tube-Tubesheet Joint: A Proposed Equation for the Equivalent Sleeve Diameter Used in the Single-Tube Model," *Journal of Pressure Vessel Technology 114*, 19-22, 1992.

170. ASME Boiler and Pressure Vessel Code, Section II, Part D, Properties, 2007 Edition.

171. Alloy 690 for Steam Generator Applications, EPRI, Palo Alto, CA: 1990. NP-6997-SD.

172. H.E. Boyer, ed., *Atlas of Stress-Strain Curves*, ASM International, Metals Park, OH, 1987.

173. PWR Steam Generator Tube Plug Assessment Document, EPRI, Palo Alto, CA: 1997. TR-109495.

174. NRC Bulletin 89-01. (with supplements)

175. NRC Information Notice 89-65.

176. NRC Information Notice 94-87.

177. United States Patent 4,513,786.

178. United States Patent 4,722,122.

179. I600 SG Tube Plugs Report (McG1 and Sum) Accession #: 8902170125.

180. A. Redpath (Progress Energy), email to M. Dumouchel (DEI), June 2, 2009.

181. K. Wallin, V. Rainer, J. Schmidbauer, H. Ostermeyer, and G. Nagel, "Statistical Assessment Method for the Optimization of the Inspection Need for Nuclear Steam Generators Based on Existing Inspection Data," *20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)*,Espoo, Finland: August 9-14, 2009. Paper 1731.

182. T. Magee and T. O'Brien, "Laboratory Characterization of Vogtle-1 Tubes with ODSCC," *28th Steam Generator NDE Workshop, August 3-5, 2009, National Harbor, MD*, EPRI, Palo Alto, CA: 2009.

183. J.R. Fernandez and J.J. Jimenez, "Almarez 2 NPP Incoloy 800 Update," *28th Steam Generator NDE Workshop, August 3-5, 2009, National Harbor, MD*, EPRI, Palo Alto, CA: 2009.

184. C. Cueto-Felguerso, "International Report – Spain," *Working Group on Implementation of Risk Based Examination*, May 11, 2009.

185. P. Berge, D. Noel, J.-M. Gras, and B. Prieux, "Chloride Stress Corrosion Cracking of Alloy 600 in Boric Acid Solutions," *Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, Amelia Island, Florida, August 10-14, 1997.

186. G.I. Ogundele, O. Lepik, A.V. Manolescu, M. Wright, S. Pagan, M. Mirzai, and C. Maruska, *The Cracking of Alloy 600 in Simulated BNGS "A" Crevice Environment*, Ontario Hydro Technologies, Toronto, 1988. OHT 3167-010-1997-RA-0001-R00. COG-98-123.

187. G. Ogundele, *Stress Corrosion Cracking of Alloy 800 Tubing*, CANDU Owners Group, Toronto, 2002. COG-00-167.

188. G. Goszczynski and G. Ogundele, *Stress Corrosion Cracking (SCC) of Alloy 800 Steam Generator Tubing*, CANDU Owners Group, Toronto, 2003. COG-02-4041.

189. G. Ogundele and G. Goszczynski, *Stress Corrosion Cracking (SCC) of Alloy 800 Steam Generator Tubing*, CANDU Owners Group, Toronto, 2004. COG-03-4035.

190. Y.C. Lu and G. Ogundele, *Lead-Induced Stress Corrosion Cracking (PBSCC) of Steam Generator Tubing Materials – A Summary Report*, CANDU Owners Group, Toronto, 2005. COG-05-4066.

191. J.M. Smith, *Steam Generator Tubing Corrosion Driven by the Interactive Combination of Impurities – The Effect of Lead and Various Anionic Species*, CANDU Owners Group, Toronto, 2008. TN-08-4068.

A
WEIBULL SLOPE SENSITIVITY ANALYSIS FOR ALLOY 690TT

The purpose of this appendix is to present an alternate approach, with respect to the methodology used in Section 3, for the calculation of a plant-based Alloy 690TT improvement factor using steam generator tubing data. This approach is demonstrated in this appendix for Alloy 690TT tubing as there have been no failures observed in operating steam generators resulting from the mechanisms discussed in Section 3. It could also be applied to other material populations, such as Alloys 600TT and 800NG, in which no failures of interest (i.e., axial and circumferential PWSCC, axial and volumetric OD TTS IGA/SCC, circumferential ODSCC, and TSP IGA/SCC) have been observed.

The Weibayes analyses presented in Section 3 are based on the assumption that an entire unit has reached the failure criterion for a given mechanism. This assumption leads to the calculation of highly conservative improvement factors as it implies that many tubes have failed at a given unit, when in reality, there have been few or no observed failures (resulting from the mechanisms of interest) in tubing fabricated from Alloys 600TT, 690TT, and 800NG in operating steam generators.

A.1 Methodology

Field performance was again quantified by comparing the times to reach a mechanism-specific degradation threshold known as the failure criterion, and the improvement factor for the performance of two alloys was defined as the ratio of the median times to failure for each material.

Due to the absence of any observed cracking in Alloy 690TT steam generator tubing, the Weibayes method was again used to determine the times required to reach various different degradation thresholds for each failure mechanism. However, instead of addressing the Alloy 690TT tubing on a unit-by-unit basis alone (the analyses performed in Section 3), all of the installed Alloy 690TT tubing was first treated as a single population. Weibayes analyses for the overall Alloy 690TT population were performed for each degradation mode using the 25th, 50th, and 75th percentile Weibull slopes derived from the appropriate Alloy 600MA populations. These analyses were used to determine the times required for the first tube failure and the times required to reach the individual plant failure criterion at the unit with the fewest installed tubes, the Mihama 1 replacement steam generators having 5,836 installed tubes, for each degradation mode and Weibull slope. For example, for axially-oriented PWSCC the times of the first tube failure and the times required for 5.836 tubes (0.1% of 5,836 tubes) to crack were determined using the Weibayes method and the 25th, 50th, and 75th percentile axial PWSCC Weibull slopes from plants with WEXTEX-expanded Alloy 600MA tubing. The unit with the fewest installed tubes was selected to yield the shortest times and, therefore, the most conservative improvement factor values. Distributions of the Weibull slopes relevant to Alloy 690TT tubing are presented in Section A.2. Note that for simplicity, and due to an apparent lack of inspection data up to the final ISI, tubes that failed due to degradation modes not quantitatively examined in this report after the completion of the pre-service inspection were ignored, and it was assumed that all tubes at a given unit reached the final ISI. This assumption is not expected to have had a significant impact on the results of the analysis as the number of plugged Alloy 690TT tubes is miniscule relative to the overall installed tube population. The results of the overall tube population analysis are presented in Section A.2.2.

The times discussed above for each Weibull slope and degradation mode, a total of 15 pairs, were then used to shift the suspension times of each unit with Alloy 690TT tubing beyond the time of the of the last ISI at each unit. The shifted time at a given unit is defined in Equation A-1:

$$t_{shift,i,j,k} = t_{ISI,i} + t_{FC,j,k} - t_{FT,j,k} \qquad \textbf{Eq. A-1}$$

where:

$t_{shift,i,j,k}$ = shifted suspension time at unit *i*, for degradation mode *j*, using Weibull slope *k* (EFPY)

$t_{ISI,i}$ = time of the last ISI at unit *i* (EFPY)

$t_{FC,j,k}$ = failure criterion time for degradation mode *j* predicted with Weibull slope *k* (EFPY)

$t_{FT,j,k}$ = first failure time for degradation mode *j* predicted with Weibull slope *k* (EFPY)

Note that the values of $t_{FT,j,k}$ and $t_{FC,j,k}$ are determined from the overall Alloy 690TT tube population analysis, not from the unit-by-unit analysis. The time by which each suspension time will be shifted, the difference between $t_{FT,j,k}$ and $t_{FC,j,k}$, will henceforth be referred to as the *time shift factor*.

Following the determination of the shifted suspension time for each unit, degradation mode, and Weibull slope, a sensitivity analysis was performed in which the median times to failure were calculated using the shifted suspension times and the methodology discussed in Section 3.1.3. Note that the time shift factors were determined using the 25th, 50th, and 75th percentile Weibull slopes observed at individual units (i.e., for the progression of degradation at individual units), but for consistency, the trends for groups and median ranking were evaluated using the Weibull slopes calculated in the unit-by-unit analyses presented for Alloy 600MA in Section 3.3.1 (i.e., for the progression of degradation among plant populations).

A.2 Sensitivity Analysis

The main results of the sensitivity analysis performed for this appendix for Alloy 690TT tubing versus Alloy 600MA tubing are presented in Table A-1.

Table A-1
Estimated Improvement Factors for Alloy 690TT Based on Plant Experience

Mechanism	600MA		690TT				
	Design Group*	Median Time to Failure (EFPY)	Design Group	Median Time to Failure (EFPY)	IF_R	Shifted Median Time to Failure (EFPY)	Shifted IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	West. (All)	102.9	>12.6	196.6	>24.2
	West. (HE)**	10.9			*>9.5*		*>18.1*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	West. (All)	102.8	>10.4	191.4	>19.4
	West. (HE)**	10.9			*>9.5*		*>17.6*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	West. (All)	48.9	>5.4	77.4	>8.6
	West. Preheater (KR)**	14.9			*>3.3*		*>5.2*
	West. Feedring (KR)	8.4			>5.8		>9.2
	West. Feedring (HE)**	15.9			*>3.1*		*>4.9*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	West. (All)	29.4	>5.3	35.8	>6.4
	West. Preheater (KR)**	5.8			*>5.1*		*>6.2*
	West. Feedring (KR)	13.9			>2.1		>2.6
	West. Feedring (HE)**	15.7			*>1.9*		*>2.3*
TSP IGA/SCC	West. Preheater (DH)	8.2	West. (All)	106.0	>13.0	126.3	>15.5
	West. Feedring (DH)	8.3			>12.8		>15.3
	West. Feedring (BH)**	25.7			*>4.1*		*>4.9*

**Labels in parenthesis indicate the tube-in-tubesheet expansion method or TSP geometry:*

WEXTEX = Explosive Expansion   FDR = Full-Depth Roll   DH = Drilled Hole (TSP)   DH = Drilled Hole (TSP)

HE = Hydraulic Expansion   KR = Kiss Roll   BH = Broached Hole (TSP)   BH = Broached Hole (TSP)

***This population includes three (3) or fewer plants. Thus, IF_R estimates cannot be made with confidence. Calculated IF_R values are italicized to indicate low confidence.*

Note that the values presented in this table for Alloy 690TT are based on the 75th percentile Weibull slope for degradation of Alloy 600MA tubing. This selection yields the most conservative estimates of the level of improvement associated with Alloy 690TT relative to Alloy 600MA as the level of improvement associated with a given material for a given mechanism is inversely proportional to the value of the assumed Weibull slope. Comparison of the results presented in this table with those derived in Section 3.3.3 (these results are included here for convenience) shows that this approach leads to significantly higher improvement factor values for Alloy 690TT versus Alloy 600MA. The magnitude of this impact decreases as the Weibull slopes used in the sensitivity analyses increase.

A.2.1 Alloy 600MA Weibull Slope Distributions

The distribution of Weibull slopes for each plant population and degradation mode was determined for the relevant Alloy 600MA populations. These distributions are presented in Figure A-1 throughFigure A-5. The 25th, 50th, and 75th percentile Weibull slopes for each degradation mode were calculated for use as inputs in the analyses discussed in Section A.1 and presented in Sections A.2.2 and 1.1.1.1.1A.1.1, and are presented in Table A-2.

Table A-2
Degradation-Mode-Specific Weibull Slope Quantiles

Mechanism	Design Group	Weibull Slope		
		25th Percentile	50th Percentile	75th Percentile
Axial EZ PWSCC	West. (WEXTEX)	1.92	2.47	3.56
Circ. EZ PWSCC	West. (WEXTEX)	2.33	2.86	3.21
A&V TTS OD IGA/SCC	West. Feedring (KR)	3.00*	3.00*	4.29
Circ. TTS OD IGA/SCC	West. Feedring (KR)	2.50	4.26	6.03
TSP IGA/SCC	West. Feedring (DH)	3.23	5.17	8.04

*An assumed slope of 3.00 was used to calculate median failure times for a number of French units.

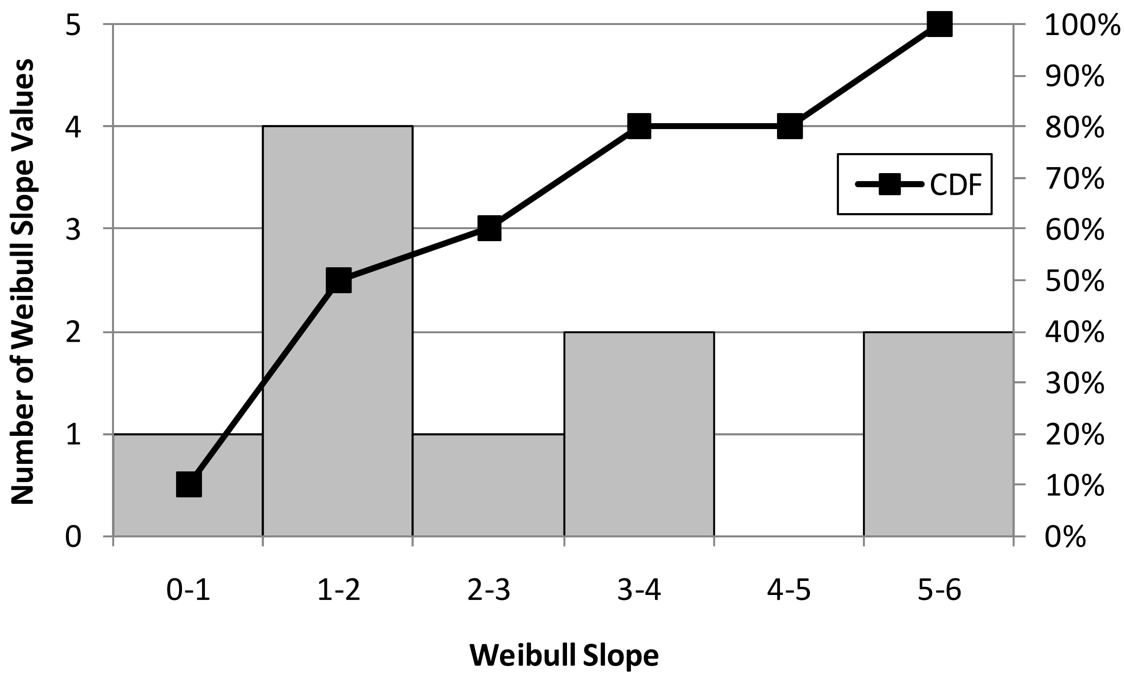

Figure A-1
Weibull Slope Distribution for HL Axial EZ PWSCC – All Westinghouse Design Alloy 600MA WEXTEX Plants

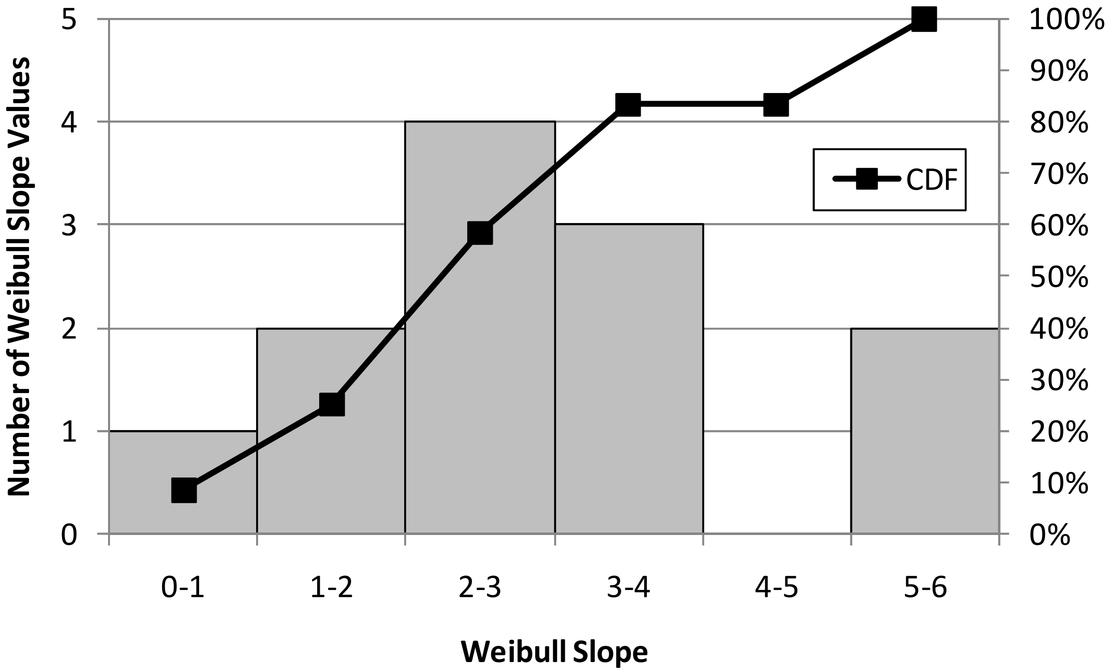

Figure A-2
Weibull Slope Distribution for HL Circumferential EZ PWSCC – All Westinghouse Alloy 600MA WEXTEX Plants

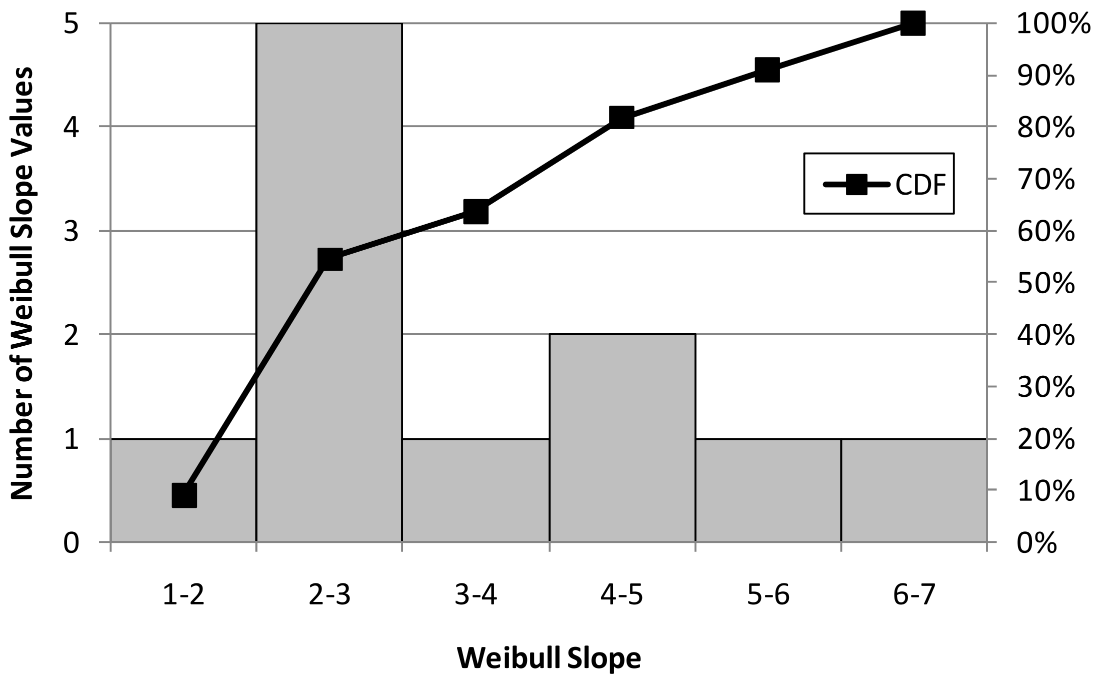

Figure A-3
Weibull Slope Distribution for HL OD TTS A&V IGA/SCC – French Alloy 600MA Plants with Kiss Rolls and FDBs

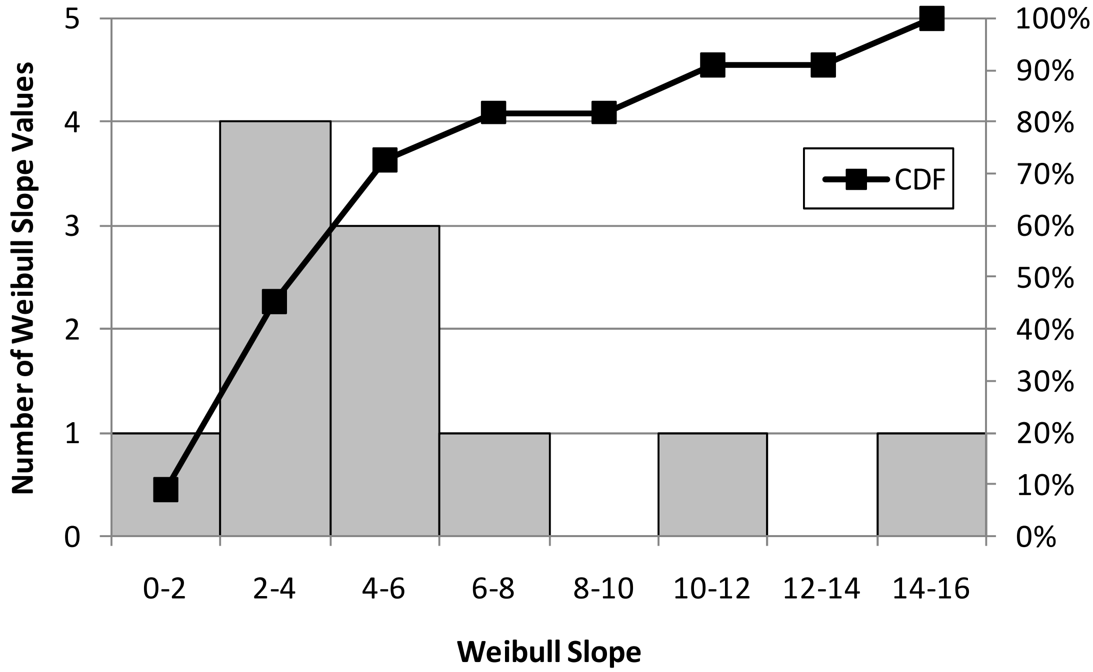

Figure A-4
Weibull Slope Distribution for HL OD TTS Circumferential SCC – All French Alloy 600MA Feedring Plants with Kiss Rolls and FDBs

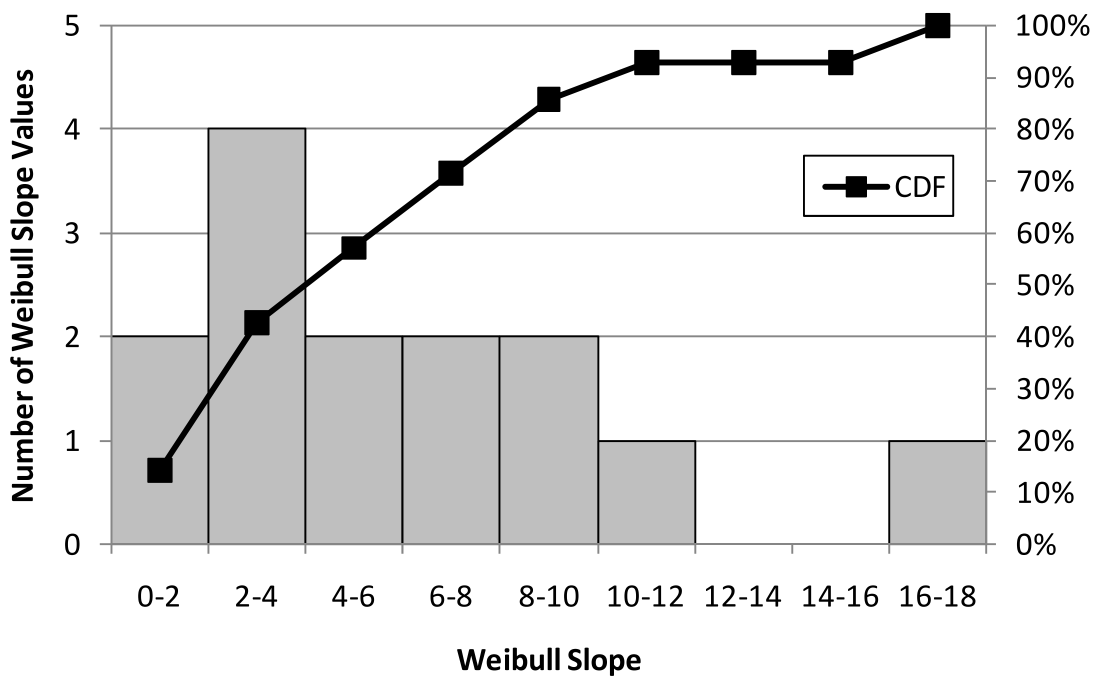

Figure A-5
Weibull Slope Distribution for Hot Leg TSP IGA/SCC – U.S. Westinghouse Alloy 600MA Drilled Hole Feedring Plants

A.2.2 Alloy 690TT Overall Population Analysis

As discussed in Section 3.3.3, there have been no instances of stress corrosion cracking or intergranular attack observed in steam generators tubed with Alloy 690TT, and it was appropriate to use the Weibayes method to model potential future degradation of Alloy 690TT tubing. The times required to reach degradation thresholds discussed in Section A.1 were determined for each degradation mode and Weibull slope for use as inputs in the analyses described in Section 1.1.1.1.1A.1.1. The main results of this effort are presented in Table A-3. For reference the Weibull slopes from which the threshold times were generated are also included in Table A-3.

Table A-3
Degradation Threshold Times and Time Shift Factors by Mechanism and Weibull Slope for Alloy 690TT Tubing

Mechanism	25th Percentile				50th Percentile				75th Percentile			
	Weibull Slope, b	Time to First Crack (EFPY)	Time to Failure Criterion (EFPY)	Time Shift Factor (EFPY)	Weibull Slope, b	Time to First Crack (EFPY)	Time to Failure Criterion (EFPY)	Time Shift Factor (EFPY)	Weibull Slope, b	Time to First Crack (EFPY)	Time to Failure Criterion (EFPY)	Time Shift Factor (EFPY)
Axial EZ PWSCC	1.92	9.51	27.97	18.45	2.47	10.14	23.45	13.31	3.56	11.02	19.72	8.70
Circ. EZ PWSCC	2.33	10.00	24.27	14.27	2.86	10.49	21.64	11.15	3.21	10.78	20.51	9.74
A&V TTS OD IGA/SCC	3.00	9.16	18.25	9.09	3.00	9.16	18.25	9.09	4.29	9.93	16.08	6.15
Circ. TTS OD IGA/SCC	2.50	8.77	14.87	6.10	4.26	9.94	13.55	3.61	6.03	10.71	13.33	2.62
TSP IGA/SCC	3.23	13.13	19.75	6.62	5.17	14.58	18.82	4.24	8.04	16.05	18.92	2.86

The data used to determine these values are presented in Figure A-6 through Figure A-10. The figures are filled-in forms used for median ranks analyses of the occurrence of degradation, and provide the input data for the Weibayes analyses for each degradation mode. Since there have been no occurrences of degradation of Alloy 690TT tubes for the modes covered by the figures, the data in the figures are essentially lists of the EDYs of the Alloy 690TT plants at the reference temperatures used for the analyses. Note that the Weibull plots corresponding to Figure A-6 through Figure A-10 are not included as they do not include any information that is used in the next step of the analysis and is not captured in Table A-7-3.

A.2.2.1 Axial primary-side IGA/SCC at the expansion transition (Axial EZ PWSCC)

The time shift factor is currently estimated to range from about 8.70 to 18.45 EFPY for axial PWSCC for the 75th and 25th percentile Weibull slopes, respectively. The field data for all Westinghouse design Alloy 690TT plants used to determine these values are presented in Figure A-6.

A.2.2.2 Circumferential primary-side IGA/SCC at the expansion transition (Circ. EZ PWSCC)

The time shift factor for circumferential PWSCC is estimated to range from about 9.74 to 14.27 EFPY for the 75th and 25th percentile Weibull slopes, respectively. The field data for all

Westinghouse design Alloy 690TT plants used to determine these values are presented in Figure A-7.

A.2.2.3 Axial and volumetric secondary-side IGA/SCC at the top of tubesheet (OD TTS A&V IGA/SCC)

The time shift factor is currently estimated to range from about 6.15 to 9.09 EFPY for OD TTS A&V IGA/SCC for the 75th and 25th percentile Weibull slopes, respectively. The field data for all Westinghouse design Alloy 690TT plants used to determine these values are presented in Figure A-8.

A.2.2.4 Circumferential secondary-side IGA/SCC at the top of tubesheet (OD TTS Circ. SCC)

The time shift factor for Alloy 690TT tubed SGs is estimated to range from 2.62 to 6.10 EFPY with respect to circumferential secondary-side IGA/SCC at the top of the tubesheet. The field data analyzed for this degradation mode are presented in Figure A-9.

A.2.2.5 IGA/SCC at the tube support plate intersection (HL TSP IGA/SCC)

For IGA/SCC at the tube support plate intersection, the time shift factor for Alloy 690TT tubed SGs is estimated to range from 2.86 to 6.62 EFPY for the 75th and 25th percentile Weibull slopes, respectively. The field data analyzed for this degradation mode are given in Figure A-10.

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	Number Tubes	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	17776	0.00		599	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	6476	4.40		594	2.41		2.41	2	0		0.00	
Ginna (repl.)	6/96	12.26	9528	11.0 (est.)		589	4.90		4.90	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	6476	9.90		594	5.41		5.41	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	6998	9.05		597	5.59		5.59	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	17038	8.60		599	5.76		5.76	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	9988	4.95		613	5.80		5.80	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	13528	4.4 (est.)		617	6.03		6.03	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	10776	6.80		607	6.28		6.28	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12856	12.50		593	6.56		6.56	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	17037	9.80		601	7.12		7.12	11	0		0.00	
Kori 1 (repl.)	7/98	10.18	9868	7.78		607	7.19		7.19	12	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	9990	6.14		613	7.19		7.19	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	5836	9.7 (est.)		603	7.63		7.63	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	6772	7.5 (est.)		613	8.78		8.78	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	26529	8.49		610	8.83		8.83	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	10776	9.2 (est.)		608	8.84		8.84	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	15390	10.00		606	8.87		8.87	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	9990	7.64		613	8.95		8.95	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	14368	8.2 (est.)		613	9.60		9.60	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	9988	8.25		613	9.66		9.66	21	0		0.00	
Civaux 2	1/00	8.67	22236	5.23		625	9.78		9.78	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	6764	10.60		607	9.79		9.79	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	26531	9.50		610	9.88		9.88	24	0		0.00	
Sizewell B	2/95	13.59	22499	7.30		617	10.00		10.00	25	0		0.00	
Civaux 1	1/00	8.67	22236	5.37		625	10.04		10.04	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	9987	8.60		613	10.07		10.07	27	0		0.00	
Penly 2	11/92	15.84	21364	7.81		616	10.29		10.29	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10164	10.30		609	10.30		10.30	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	14367	12.20		606	10.83		10.83	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	10146	9.3 (est.)		613	10.89		10.89	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	30340	7.20		620	11.09		11.09	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	10164	9.65		613	11.30		11.30	33	0		0.00	
Chooz B2	4/97	11.43	22234	6.29		625	11.76		11.76	34	0		0.00	
McGuire 2 (repl.)	12/97	10.76	18694	8.20		619	12.15		12.15	36	0		0.00	
Catawba 1 (repl.)	10/96	11.92	26513	10.57		613	12.38		12.38	35	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10776	10.60		613	12.42		12.42	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	9990	10.60		613	12.42		12.42	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10146	10.70		613	12.53		12.53	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	6764	10.80		613	12.65		12.65	40	0		0.00	
Genkai 4	7/97	11.11	13528	9.30		617	12.74		12.74	41	0		0.00	
Chooz B1	8/96	12.09	22234	6.98		625	13.05		13.05	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	18686	9.00		619	13.33		13.33	43	0		0.00	
Ikata 3	12/94	13.72	10146	11.5 (est.)		613	13.52		13.52	44	0		0.00	
Golfech 2	3/94	14.52	21366	10.63		616	14.01		14.01	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	18053	8.38		623	14.50		14.50	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	10164	14.20		610	14.77		14.77	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	10164	12.78		613	14.97		14.97	48	0		0.00	
Genkai 3	3/94	14.47	13528	11.30		617	15.49		15.49	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	10776	13.30		613	15.58		15.58	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	14592	10.50		621	16.81		16.81	51	0		0.00	
Ohi 4	2/93	15.59	13528	12.6 (est.)		617	17.27		17.27	52	0		0.00	
Summer (repl.)	12/94	13.76	18918	12.00		619	17.78		17.78	53	0		0.00	
Ohi 3	12/91	16.72	13528	13.8 (est.)		617	18.91		18.91	54	0		0.00	

Ave. Thot= 612

Reference Temperature

609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-6
Median Ranks Input Data for Weibayes Analysis of HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	Number Tubes	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	17776	0.00		599	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	6476	4.40		594	2.41		2.41	2	0		0.00	
Ginna (repl.)	6/96	12.26	9528	11.0 (est.)		589	4.90		4.90	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	6476	9.90		594	5.41		5.41	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	6998	9.05		597	5.59		5.59	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	17038	8.60		599	5.76		5.76	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	9988	4.95		613	5.80		5.80	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	13528	4.4 (est.)		617	6.03		6.03	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	10776	6.80		607	6.28		6.28	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12856	12.50		593	6.56		6.56	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	17037	9.80		601	7.12		7.12	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	9990	6.11		613	7.16		7.16	12	0		0.00	
Kori 1 (repl.)	7/98	10.18	9868	7.78		607	7.19		7.19	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	5836	9.7 (est.)		603	7.63		7.63	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	6772	7.5 (est.)		613	8.78		8.78	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	26529	8.49		610	8.83		8.83	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	10776	9.2 (est.)		608	8.84		8.84	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	15390	10.00		606	8.87		8.87	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	9990	7.64		613	8.95		8.95	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	14368	8.2 (est.)		613	9.60		9.60	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	9988	8.25		613	9.66		9.66	21	0		0.00	
Civaux 2	1/00	8.67	22236	5.23		625	9.78		9.78	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	6764	10.60		607	9.79		9.79	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	26531	9.50		610	9.88		9.88	24	0		0.00	
Sizewell B	2/95	13.59	22499	7.30		617	10.00		10.00	25	0		0.00	
Civaux 1	1/00	8.67	22236	5.37		625	10.04		10.04	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	9987	8.60		613	10.07		10.07	27	0		0.00	
Penly 2	11/92	15.84	21364	7.81		616	10.29		10.29	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10164	10.30		609	10.30		10.30	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	14367	12.20		606	10.83		10.83	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	10146	9.3 (est.)		613	10.89		10.89	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	30340	7.20		620	11.09		11.09	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	10164	9.65		613	11.30		11.30	33	0		0.00	
Chooz B2	4/97	11.43	22234	6.29		625	11.76		11.76	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	26513	10.57		613	12.38		12.38	35	0		0.00	
McGuire 2 (repl.)	12/97	10.76	18694	8.20		619	12.15		12.15	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10776	10.60		613	12.42		12.42	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	9990	10.60		613	12.42		12.42	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10146	10.70		613	12.53		12.53	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	6764	10.80		613	12.65		12.65	40	0		0.00	
Genkai 4	7/97	11.11	13528	9.30		617	12.74		12.74	41	0		0.00	
Chooz B1	8/96	12.09	22234	6.98		625	13.05		13.05	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	18686	9.00		619	13.33		13.33	43	0		0.00	
Ikata 3	12/94	13.72	10146	11.5 (est.)		613	13.52		13.52	44	0		0.00	
Golfech 2	3/94	14.52	21366	10.63		616	14.01		14.01	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	18053	8.38		623	14.50		14.50	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	10164	14.20		610	14.77		14.77	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	10164	12.78		613	14.97		14.97	48	0		0.00	
Genkai 3	3/94	14.47	13528	11.30		617	15.49		15.49	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	10776	13.30		613	15.58		15.58	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	14592	10.50		621	16.81		16.81	51	0		0.00	
Ohi 4	2/93	15.59	13528	12.6 (est.)		617	17.27		17.27	52	0		0.00	
Summer (repl.)	12/94	13.76	18918	12.00		619	17.78		17.78	53	0		0.00	
Ohi 3	12/91	16.72	13528	13.8 (est.)		617	18.91		18.91	54	0		0.00	

Ave. Thot= 612

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-7
Median Ranks Input Data for Weibayes Analysis of HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	Number Tubes	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	6476	4.40		594	1.93		1.93	1	0		0.00	
Ginna (repl.)	6/96	12.26	9528	11.0 (est.)		589	3.87		3.87	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	6476	9.90		594	4.35		4.35	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	6998	9.05		597	4.54		4.54	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	17038	8.60		599	4.70		4.70	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	9988	4.95		613	4.95		4.95	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	13528	4.4 (est.)		617	5.21		5.21	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12856	12.50		593	5.25		5.25	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	10776	6.80		607	5.26		5.26	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	17037	9.80		601	5.85		5.85	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	9868	7.78		607	6.02		6.02	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	9990	6.14		613	6.14		6.14	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	5836	9.7 (est.)		603	6.31		6.31	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	15390	10.00		606	7.41		7.41	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	10776	9.2 (est.)		608	7.43		7.43	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	26529	8.49		610	7.47		7.47	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	6772	7.5 (est.)		613	7.50		7.50	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	9990	7.64		613	7.64		7.64	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	14368	8.2 (est.)		613	8.20		8.20	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	6764	10.60		607	8.20		8.20	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	9988	8.25		613	8.25		8.25	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	26531	9.50		610	8.36		8.36	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	9987	8.60		613	8.60		8.60	23	0		0.00	
Sizewell B	2/95	13.59	22499	7.30		617	8.65		8.65	24	0		0.00	
Civaux 2	1/00	8.67	22236	5.23		625	8.66		8.66	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10164	10.30		609	8.68		8.68	26	0		0.00	
Penly 2	11/92	15.84	21364	7.81		616	8.87		8.87	27	0		0.00	
Civaux 1	1/00	8.67	22236	5.37		625	8.90		8.90	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	14367	12.20		606	9.04		9.04	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	10146	9.3 (est.)		613	9.30		9.30	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	10164	9.65		613	9.65		9.65	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	30340	7.20		620	9.68		9.68	32	0		0.00	
Chooz B2	4/97	11.43	22234	6.29		625	10.42		10.42	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	18694	8.20		619	10.57		10.57	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	26513	10.57		613	10.57		10.57	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	9990	10.60		613	10.60		10.60	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10776	10.60		613	10.60		10.60	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10146	10.70		613	10.70		10.70	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	6764	10.80		613	10.80		10.80	39	0		0.00	
Genkai 4	7/97	11.11	13528	9.30		617	11.02		11.02	40	0		0.00	
Ikata 3	12/94	13.72	10146	11.5 (est.)		613	11.54		11.54	41	0		0.00	
Chooz B1	8/96	12.09	22234	6.98		625	11.56		11.56	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	18686	9.00		619	11.60		11.60	43	0		0.00	
Golfech 2	3/94	14.52	21366	10.63		616	12.07		12.07	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	10164	14.20		610	12.49		12.49	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	18053	8.38		623	12.77		12.77	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	10164	12.78		613	12.78		12.78	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	10776	13.30		613	13.30		13.30	48	0		0.00	
Genkai 3	3/94	14.47	13528	11.30		617	13.39		13.39	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	14592	10.50		621	14.72		14.72	50	0		0.00	
Ohi 4	2/93	15.59	13528	12.6 (est.)		617	14.93		14.93	51	0		0.00	
Summer (repl.)	12/94	13.76	18918	12.00		619	15.47		15.47	52	0		0.00	
Ohi 3	12/91	16.72	13528	13.8 (est.)		617	16.35		16.35	53	0		0.00	
					Ave. Thot=	612								

Reference Temperature

613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-8
Median Ranks Input Data for Weibayes Analysis of HL OD TTS A&V IGA/SCC – All Westinghouse Alloy 690TT Plants

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	Number Tubes	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	6476	4.40		594	1.93		1.93	1	0		0.00	
Ginna (repl.)	6/96	12.26	9528	11.0 (est.)		589	3.87		3.87	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	6476	9.90		594	4.35		4.35	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	6998	9.05		597	4.54		4.54	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	17038	8.60		599	4.70		4.70	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	9988	4.95		613	4.95		4.95	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	13528	4.4 (est.)		617	5.21		5.21	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12856	12.50		593	5.25		5.25	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	10776	6.80		607	5.26		5.26	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	17037	9.80		601	5.85		5.85	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	9868	7.78		607	6.02		6.02	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	9990	6.14		613	6.14		6.14	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	5836	9.7 (est.)		603	6.31		6.31	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	15390	10.00		606	7.41		7.41	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	10776	9.2 (est.)		608	7.43		7.43	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	26529	8.49		610	7.47		7.47	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	6772	7.5 (est.)		613	7.50		7.50	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	9990	7.64		613	7.64		7.64	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	14368	8.2 (est.)		613	8.20		8.20	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	6764	10.60		607	8.20		8.20	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	9988	8.25		613	8.25		8.25	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	26531	9.50		610	8.36		8.36	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	9987	8.60		613	8.60		8.60	23	0		0.00	
Sizewell B	2/95	13.59	22499	7.30		617	8.65		8.65	24	0		0.00	
Civaux 2	1/00	8.67	22236	5.23		625	8.66		8.66	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10164	10.30		609	8.68		8.68	26	0		0.00	
Penly 2	11/92	15.84	21364	7.81		616	8.87		8.87	27	0		0.00	
Civaux 1	1/00	8.67	22236	5.37		625	8.90		8.90	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	14367	12.20		606	9.04		9.04	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	10146	9.3 (est.)		613	9.30		9.30	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	10164	9.65		613	9.65		9.65	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	30340	7.20		620	9.68		9.68	32	0		0.00	
Chooz B2	4/97	11.43	22234	6.29		625	10.42		10.42	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	18694	8.20		619	10.57		10.57	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	26513	10.57		613	10.57		10.57	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	9990	10.60		613	10.60		10.60	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10776	10.60		613	10.60		10.60	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10146	10.70		613	10.70		10.70	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	6764	10.80		613	10.80		10.80	39	0		0.00	
Genkai 4	7/97	11.11	13528	9.30		617	11.02		11.02	40	0		0.00	
Ikata 3	12/94	13.72	10146	11.5 (est.)		613	11.54		11.54	41	0		0.00	
Chooz B1	8/96	12.09	22234	6.98		625	11.56		11.56	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	18686	9.00		619	11.60		11.60	43	0		0.00	
Golfech 2	3/94	14.52	21366	10.63		616	12.07		12.07	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	10164	14.20		610	12.49		12.49	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	18053	8.38		623	12.77		12.77	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	10164	12.78		613	12.78		12.78	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	10776	13.30		613	13.30		13.30	48	0		0.00	
Genkai 3	3/94	14.47	13528	11.30		617	13.39		13.39	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	14592	10.50		621	14.72		14.72	50	0		0.00	
Ohi 4	2/93	15.59	13528	12.6 (est.)		617	14.93		14.93	51	0		0.00	
Summer (repl.)	12/94	13.76	18918	12.00		619	15.47		15.47	52	0		0.00	
Ohi 3	12/91	16.72	13528	13.8 (est.)		617	16.35		16.35	53	0		0.00	
					Ave. Thot=	612								

Reference Temperature
613.0 °F = 595.94 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-9
Median Ranks Input Data for Weibayes Analysis of HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	Number Tubes	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	6476	4.40		594	2.72		2.72	1	0		0.00	
Ginna (repl.)	6/96	12.26	9528	11.0 (est.)		589	5.46		5.46	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	6476	9.90		594	6.13		6.13	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	6998	9.05		597	6.39		6.39	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	17038	8.60		599	6.63		6.63	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	9988	4.95		613	6.97		6.97	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	13528	4.4 (est.)		617	7.34		7.34	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12856	12.50		593	7.40		7.40	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	10776	6.80		607	7.41		7.41	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	17037	9.80		601	8.24		8.24	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	9868	7.78		607	8.48		8.48	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	9990	6.14		613	8.65		8.65	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	5836	9.7 (est.)		603	8.90		8.90	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	15390	10.00		606	10.44		10.44	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	10776	9.2 (est.)		608	10.47		10.47	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	26529	8.49		610	10.53		10.53	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	6772	7.5 (est.)		613	10.57		10.57	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	9990	7.64		613	10.76		10.76	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	14368	8.2 (est.)		613	11.55		11.55	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	6764	10.60		607	11.55		11.55	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	9988	8.25		613	11.62		11.62	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	26531	9.50		610	11.78		11.78	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	9987	8.60		613	12.12		12.12	23	0		0.00	
Sizewell B	2/95	13.59	22499	7.30		617	12.19		12.19	24	0		0.00	
Civaux 2	1/00	8.67	22236	5.23		625	12.21		12.21	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10164	10.30		609	12.23		12.23	26	0		0.00	
Penly 2	11/92	15.84	21364	7.81		616	12.50		12.50	27	0		0.00	
Civaux 1	1/00	8.67	22236	5.37		625	12.53		12.53	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	14367	12.20		606	12.74		12.74	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	10146	9.3 (est.)		613	13.10		13.10	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	10164	9.65		613	13.60		13.60	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	30340	7.20		620	13.64		13.64	32	0		0.00	
Chooz B2	4/97	11.43	22234	6.29		625	14.68		14.68	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	18694	8.20		619	14.89		14.89	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	26513	10.57		613	14.89		14.89	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	9990	10.60		613	14.93		14.93	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10776	10.60		613	14.93		14.93	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10146	10.70		613	15.08		15.08	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	6764	10.80		613	15.22		15.22	39	0		0.00	
Genkai 4	7/97	11.11	13528	9.30		617	15.52		15.52	40	0		0.00	
Ikata 3	12/94	13.72	10146	11.5 (est.)		613	16.26		16.26	41	0		0.00	
Chooz B1	8/96	12.09	22234	6.98		625	16.29		16.29	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	18686	9.00		619	16.34		16.34	43	0		0.00	
Golfech 2	3/94	14.52	21366	10.63		616	17.01		17.01	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	10164	14.20		610	17.60		17.60	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	18053	8.38		623	18.00		18.00	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	10164	12.78		613	18.01		18.01	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	10776	13.30		613	18.74		18.74	48	0		0.00	
Genkai 3	3/94	14.47	13528	11.30		617	18.86		18.86	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	14592	10.50		621	20.74		20.74	50	0		0.00	
Ohi 4	2/93	15.59	13528	12.6 (est.)		617	21.03		21.03	51	0		0.00	
Summer (repl.)	12/94	13.76	18918	12.00		619	21.79		21.79	52	0		0.00	
Ohi 3	12/91	16.72	13528	13.8 (est.)		617	23.03		23.03	53	0		0.00	
					Ave. Thot=	612								

Reference Temperature

605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-10
Median Ranks Input Data for Weibayes Analysis of HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants

A.2.3 Alloy 690TT versus Alloy 600MA

As discussed earlier in this report, in the absence of observed failures, field performance based improvement factors are calculated from the current length of operating experience. In these situations, the first incidence of failure is assumed to be imminent. Because Alloy 690TT has been in use for a relatively short period of time, the improvement factors derived from plant experience are generally lower than those for Alloy 800NG and Alloy 600TT at this time.

Based on the evaluations related to plug and laboratory data presented earlier in this report, it is expected that the improvement factors for Alloy 690TT will be much greater than the current estimates as failure-free operation continues. Improvement factor estimates were calculated using the same approach discussed in Section 3.1.3, but rather than using the final ISI at a given unit as the suspension time, the suspensions times were shifted as described in Section A.1. The data collected for Alloy 690TT experience to date in all Westinghouse design plants, the shifted suspension times, and their respective Weibull plots for each degradation mechanism and Weibull slope are given at the end of this section. Note that the time shift factors were determined using the 25th, 50th, and 75th percentile Weibull slopes observed at individual units, but the trends for groups and median ranking were evaluated using the Weibull slopes calculated in the unit-by-unit analyses presented for Alloy 600MA in Section 3.3.1.

A.2.3.1 Axial primary-side IGA/SCC at the expansion transition (Axial EZ PWSCC)

The shifted median time to failure is estimated to range from 196.6 to 273.1 EFPY for axial PWSCC for the 75th and 25th percentile Weibull slopes, respectively. The field data and Weibull plots for all Westinghouse design plants with respect to axial PWSCC are shown in Figure A-11 though Figure A-16.

A.2.3.2 Circumferential primary-side IGA/SCC at the expansion transition (Circ. EZ PWSCC)

The shifted median time to failure for circumferential PWSCC is estimated to range from 191.4 to 233.2 EFPY for circumferential PWSCC for the 75th and 25th percentile Weibull slopes, respectively. The field data and corresponding Weibull plots for all Westinghouse design Alloy 690TT plants with respect to circumferential PWSCC are shown in Figure A-17 through Figure A-22.

A.2.3.3 Axial and volumetric secondary-side IGA/SCC at the top of tubesheet (OD TTS A&V IGA/SCC)

The shifted median time to failure is estimated to range from 77.4 to 91.6 EFPY for A&V secondary-side IGA/SCC at the top of the tubesheet. The field data and Weibull plots for all Westinghouse design Alloy 690TT plants analyzed for OD TTS A&V IGA/SCC are presented in Figure A-23 though Figure A-28.

A.2.3.4 Circumferential secondary-side IGA/SCC at the top of tubesheet (OD TTS Circ. SCC)

The shifted median time to failure for Alloy 690TT tubed SGs is estimated to range from 35.8 to 45.0 EFPY with respect to circumferential secondary-side IGA/SCC at the top of the tubesheet. The field data analyzed for this degradation mode and the corresponding Weibull plots are presented in Figure A-29 through Figure A-34.

A.2.3.5 IGA/SCC at the tube support plate intersection (HL TSP IGA/SCC)

For IGA/SCC at the tube support plate intersection, the shifted median time to failure for Alloy 690TT tubed SGs is estimated to range from 126.3 to 154.9 EFPY. The data analyzed and the plots generated are given in Figure A-35 though Figure A-40.

A.2.3.6 Conclusions

The shifted material improvement factors for Alloy 690TT versus Alloy 600MA for each degradation mode and Weibull slope are given in Table A-4 through Table A-6. For comparison, the median times to failure presented in Section 3.3.1 are included in these tables.

Table A-4
Estimated Shifted Material Improvement Factors for Alloy 690TT vs. Alloy 600MA Using 25th Percentile Weibull Slopes

Mechanism	600MA		690TT				
	Design Group*	Median Time to Failure (EFPY)	Design Group	Median Time to Failure (EFPY)	IF_R	Shifted Median Time to Failure (EFPY)	Shifted IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	West. (All)	102.9	>12.6	273.1	>33.5
	West. (HE)**	10.9			*>9.5*		*>25.2*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	West. (All)	102.8	>10.4	233.2	>23.6
	West. (HE)**	10.9			*>9.5*		*>21.5*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	West. (All)	48.9	>5.4	91.6	>10.1
	West. Preheater (KR)**	14.9			*>3.3*		*>6.1*
	West. Feedring (KR)	8.4			>5.8		>10.9
	West. Feedring (HE)**	15.9			*>3.1*		*>5.8*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	West. (All)	29.4	>5.3	45.0	>8.1
	West. Preheater (KR)**	5.8			*>5.1*		*>7.8*
	West. Feedring (KR)	13.9			>2.1		>3.2
	West. Feedring (HE)**	15.7			*>1.9*		*>2.9*
TSP IGA/SCC	West. Preheater (DH)	8.2	West. (All)	106.0	>13.0	154.9	>19.0
	West. Feedring (DH)	8.3			>12.8		>18.8
	West. Feedring (BH)**	25.7			*>4.1*		*>6.0*

**Labels in parenthesis indicate the tube-in-tubesheet expansion method or TSP geometry:*

WEXTEX = Explosive Expansion FDR = Full-Depth Roll DH = Drilled Hole (TSP) DH = Drilled Hole (TSP)

HE = Hydraulic Expansion KR = Kiss Roll BH = Broached Hole (TSP) BH = Broached Hole (TSP)

***This population includes three (3) or fewer plants. Thus, IF_R estimates cannot be made with confidence. Calculated IF_R values are italicized to indicate low confidence.*

Table A-5
Estimated Shifted Material Improvement Factors for Alloy 690TT vs. Alloy 600MA Using 50th Percentile Weibull Slopes

Mechanism	600MA		690TT				
	Design Group*	Median Time to Failure (EFPY)	Design Group	Median Time to Failure (EFPY)	IF_R	Shifted Median Time to Failure (EFPY)	Shifted IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	West. (All)	102.9	>12.6	231.2	>28.4
	West. (HE)**	10.9			*>9.5*		*>21.3*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	West. (All)	102.8	>10.4	204.4	>20.7
	West. (HE)**	10.9			*>9.5*		*>18.8*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	West. (All)	48.9	>5.4	91.6	>10.1
	West. Preheater (KR)**	14.9			*>3.3*		*>6.1*
	West. Feedring (KR)	8.4			>5.8		>10.9
	West. Feedring (HE)**	15.9			*>3.1*		*>5.8*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	West. (All)	29.4	>5.3	38.4	>6.9
	West. Preheater (KR)**	5.8			*>5.1*		*>6.6*
	West. Feedring (KR)	13.9			>2.1		>2.8
	West. Feedring (HE)**	15.7			*>1.9*		*>2.4*
TSP IGA/SCC	West. Preheater (DH)	8.2	West. (All)	106.0	>13.0	136.7	>16.8
	West. Feedring (DH)	8.3			>12.8		>16.6
	West. Feedring (BH)**	25.7			*>4.1*		*>5.3*

**Labels in parenthesis indicate the tube-in-tubesheet expansion method or TSP geometry:*

WEXTEX = Explosive Expansion   FDR = Full-Depth Roll   DH = Drilled Hole (TSP)   DH = Drilled Hole (TSP)

HE = Hydraulic Expansion   KR = Kiss Roll   BH = Broached Hole (TSP)   BH = Broached Hole (TSP)

***This population includes three (3) or fewer plants. Thus, IF_R estimates cannot be made with confidence. Calculated IF_R values are italicized to indicate low confidence.*

Table A-6
Estimated Shifted Material Improvement Factors for Alloy 690TT vs. Alloy 600MA Using 75th Percentile Weibull Slopes

Mechanism	600MA		690TT				
	Design Group*	Median Time to Failure (EFPY)	Design Group	Median Time to Failure (EFPY)	IF_R	Shifted Median Time to Failure (EFPY)	Shifted IF_R
Axial EZ PWSCC	West. (WEXTEX)	8.1	West. (All)	102.9	>12.6	196.6	>24.2
	West. (HE)**	10.9			*>9.5*		*>18.1*
Circ. EZ PWSCC	West. (WEXTEX)	9.9	West. (All)	102.8	>10.4	191.4	>19.4
	West. (HE)**	10.9			*>9.5*		*>17.6*
A&V TTS OD IGA/SCC	West. Preheater (FDR)	9.1	West. (All)	48.9	>5.4	77.4	>8.6
	West. Preheater (KR)**	14.9			*>3.3*		*>5.2*
	West. Feedring (KR)	8.4			>5.8		>9.2
	West. Feedring (HE)**	15.9			*>3.1*		*>4.9*
Circ. TTS OD IGA/SCC	West. Preheater (FDR)	5.6	West. (All)	29.4	>5.3	35.8	>6.4
	West. Preheater (KR)**	5.8			*>5.1*		*>6.2*
	West. Feedring (KR)	13.9			>2.1		>2.6
	West. Feedring (HE)**	15.7			*>1.9*		*>2.3*
TSP IGA/SCC	West. Preheater (DH)	8.2	West. (All)	106.0	>13.0	126.3	>15.5
	West. Feedring (DH)	8.3			>12.8		>15.3
	West. Feedring (BH)**	25.7			*>4.1*		*>4.9*

**Labels in parenthesis indicate the tube-in-tubesheet expansion method or TSP geometry:*

WEXTEX = Explosive Expansion   FDR = Full-Depth Roll   DH = Drilled Hole (TSP)   DH = Drilled Hole (TSP)

HE = Hydraulic Expansion   KR = Kiss Roll   BH = Broached Hole (TSP)   BH = Broached Hole (TSP)

***This population includes three (3) or fewer plants. Thus, IF_R estimates cannot be made with confidence. Calculated IF_R values are italicized to indicate low confidence.*

Using the approach presented in this appendix, plant experience to date indicates a lower bound on the improvement factor of about 2.3, limited by the predictions for circumferential OD SCC at the top of the tubesheet. The material improvement factors for OD IGA/SCC have the potential to be overly conservative as the slopes used for the Weibayes analyses were assumed to be the same as those derived from French kiss roll plant data.

The sensitivity analyses presented in this appendix show that this method can be used to reduce some of the conservatism present in the recommended improvement factor values presented in Section 3. The improvement factor values developed using the 75th percentile Weibull slopes from individual plant data are the most conservative results of this analysis and are considered to be a conservative compromise between the values developed using the 25th percentile Weibull slopes and those developed in Section 3.

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 54	SCC=1 No SCC =0	No. of Items Following
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00	0.00		0.00	1	0	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41	20.86		20.86	2	0	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90	23.35		23.35	3	0	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41	23.87		23.87	4	0	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59	24.05		24.05	5	0	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76	24.22		24.22	6	0	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80	24.25		24.25	7	0	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03	24.48		24.48	8	0	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28	24.74		24.74	9	0	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56	25.02		25.02	10	0	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12	25.57		25.57	11	0	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19	25.64		25.64	12	0	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	7.19	25.65		25.65	13	0	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63	26.09		26.09	14	0	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78	27.24		27.24	15	0	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83	27.29		27.29	16	0	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84	27.30		27.30	17	0	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87	27.33		27.33	18	0	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95	27.40		27.40	19	0	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60	28.06		28.06	20	0	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66	28.12		28.12	21	0	
Civaux 2	1/00	8.67	5.23		625	9.78	28.23		28.23	22	0	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79	28.24		28.24	23	0	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88	28.34		28.34	24	0	
Sizewell B	2/95	13.59	7.30		617	10.00	28.46		28.46	25	0	
Civaux 1	1/00	8.67	5.37		625	10.04	28.49		28.49	26	0	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07	28.53		28.53	27	0	
Penly 2	11/92	15.84	7.81		616	10.29	28.75		28.75	28	0	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30	28.75		28.75	29	0	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83	29.28		29.28	30	0	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89	29.35		29.35	31	0	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09	29.55		29.55	32	0	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30	29.76		29.76	33	0	
Chooz B2	4/97	11.43	6.29		625	11.76	30.21		30.21	34	0	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15	30.60		30.60	35	0	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38	30.84		30.84	36	0	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42	30.87		30.87	37	0	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42	30.87		30.87	38	0	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53	30.99		30.99	39	0	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65	31.11		31.11	40	0	
Genkai 4	7/97	11.11	9.30		617	12.74	31.20		31.20	41	0	
Chooz B1	8/96	12.09	6.98		625	13.05	31.50		31.50	42	0	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33	31.79		31.79	43	0	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52	31.97		31.97	44	0	
Golfech 2	3/94	14.52	10.63		616	14.01	32.46		32.46	45	0	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50	32.96		32.96	46	0	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77	33.23		33.23	47	0	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97	33.42		33.42	48	0	
Genkai 3	3/94	14.47	11.30		617	15.49	33.94		33.94	49	0	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58	34.03		34.03	50	0	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81	35.27		35.27	51	0	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27	35.72		35.72	52	0	
Summer (repl.)	12/94	13.76	12.00		619	17.78	36.23		36.23	53	0	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91	37.37		37.37	54	0	
				Ave. Thot=	612							

Reference Temperature
609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-11
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shif

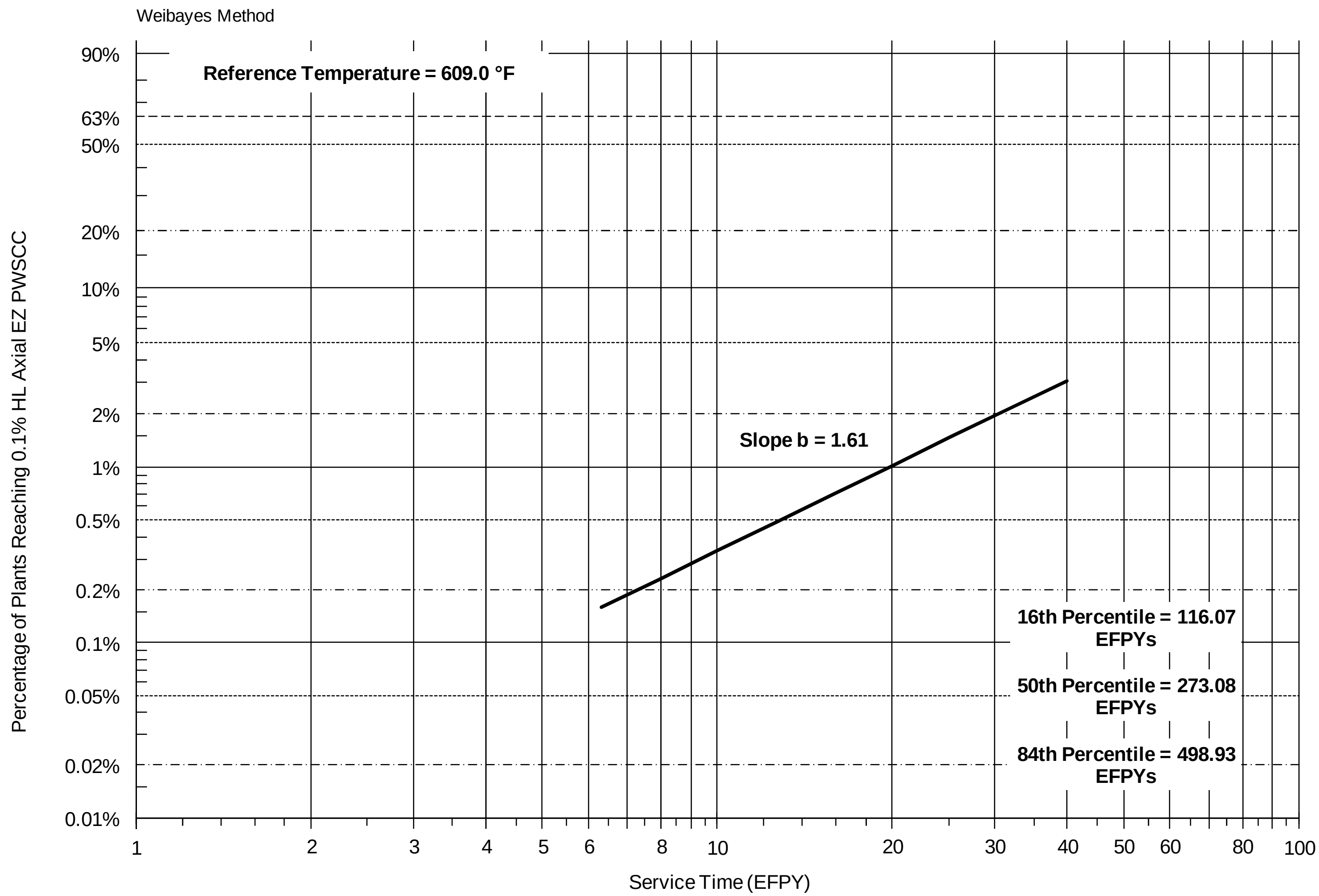

Figure A-12
Time to 0.1% HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41	16.35		16.35	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90	18.84		18.84	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41	19.35		19.35	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59	19.53		19.53	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76	19.70		19.70	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80	19.74		19.74	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03	19.97		19.97	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28	20.22		20.22	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56	20.50		20.50	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12	21.06		21.06	11	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19	21.13		21.13	12	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	7.19	21.13		21.13	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63	21.58		21.58	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78	22.73		22.73	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83	22.77		22.77	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84	22.78		22.78	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87	22.82		22.82	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95	22.89		22.89	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60	23.55		23.55	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66	23.60		23.60	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78	23.72		23.72	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79	23.73		23.73	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88	23.82		23.82	24	0		0.00	
Sizewell B	2/95	13.59	7.30		617	10.00	23.94		23.94	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04	23.98		23.98	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07	24.01		24.01	27	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29	24.23		24.23	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30	24.24		24.24	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83	24.77		24.77	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89	24.83		24.83	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09	25.03		25.03	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30	25.24		25.24	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76	25.70		25.70	34	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15	26.09		26.09	36	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38	26.32		26.32	35	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42	26.36		26.36	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42	26.36		26.36	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53	26.47		26.47	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65	26.59		26.59	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74	26.68		26.68	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05	26.99		26.99	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33	27.27		27.27	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52	27.46		27.46	44	0		0.00	
Golfech 2	3/94	14.52	10.63		616	14.01	27.95		27.95	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50	28.44		28.44	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77	28.71		28.71	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97	28.91		28.91	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49	29.43		29.43	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58	29.52		29.52	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81	30.75		30.75	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27	31.21		31.21	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78	31.72		31.72	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91	32.85		32.85	54	0		0.00	

Ave. Thot= 612

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-13
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift

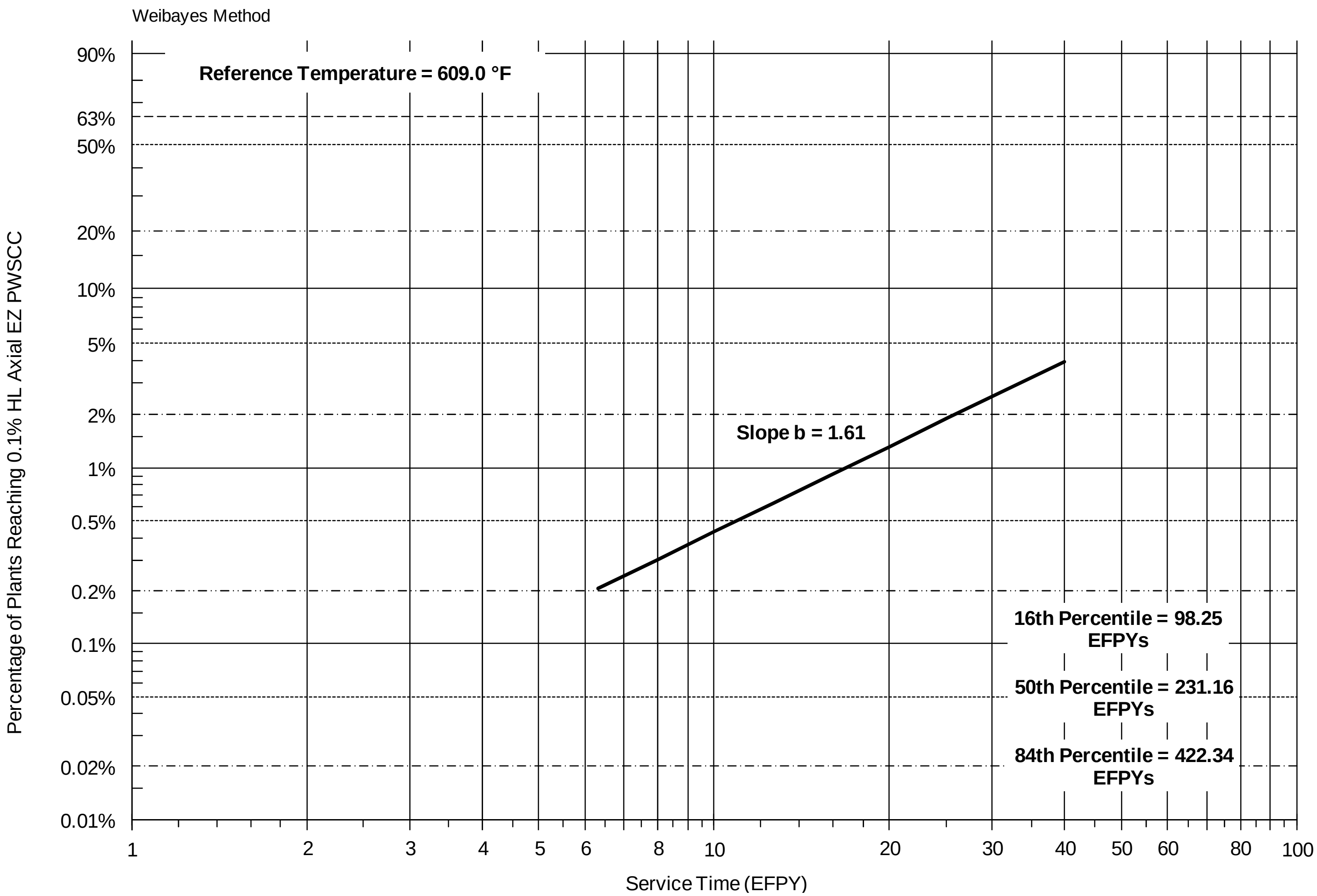

Figure A-14
Time to 0.1% HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Last ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41	12.62		12.62	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90	15.11		15.11	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41	15.62		15.62	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59	15.80		15.80	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76	15.97		15.97	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80	16.01		16.01	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03	16.24		16.24	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28	16.49		16.49	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56	16.77		16.77	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12	17.33		17.33	11	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19	17.39		17.39	12	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	7.19	17.40		17.40	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63	17.84		17.84	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78	18.99		18.99	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83	19.04		19.04	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84	19.05		19.05	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87	19.08		19.08	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95	19.16		19.16	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60	19.81		19.81	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66	19.87		19.87	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78	19.99		19.99	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79	20.00		20.00	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88	20.09		20.09	24	0		0.00	
Sizewell B	2/95	13.59	7.30		617	10.00	20.21		20.21	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04	20.25		20.25	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07	20.28		20.28	27	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29	20.50		20.50	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30	20.51		20.51	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83	21.04		21.04	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89	21.10		21.10	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09	21.30		21.30	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30	21.51		21.51	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76	21.97		21.97	34	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15	22.36		22.36	36	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38	22.59		22.59	35	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42	22.63		22.63	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42	22.63		22.63	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53	22.74		22.74	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65	22.86		22.86	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74	22.95		22.95	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05	23.26		23.26	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33	23.54		23.54	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52	23.73		23.73	44	0		0.00	
Golfech 2	3/94	14.52	10.63		616	14.01	24.22		24.22	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50	24.71		24.71	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77	24.98		24.98	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97	25.18		25.18	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49	25.69		25.69	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58	25.79		25.79	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81	27.02		27.02	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27	27.48		27.48	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78	27.99		27.99	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91	29.12		29.12	54	0		0.00	

Ave. Thot= 612

Reference Temperature
609.0 °F = 593.72 K   Q= 50.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-15
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift

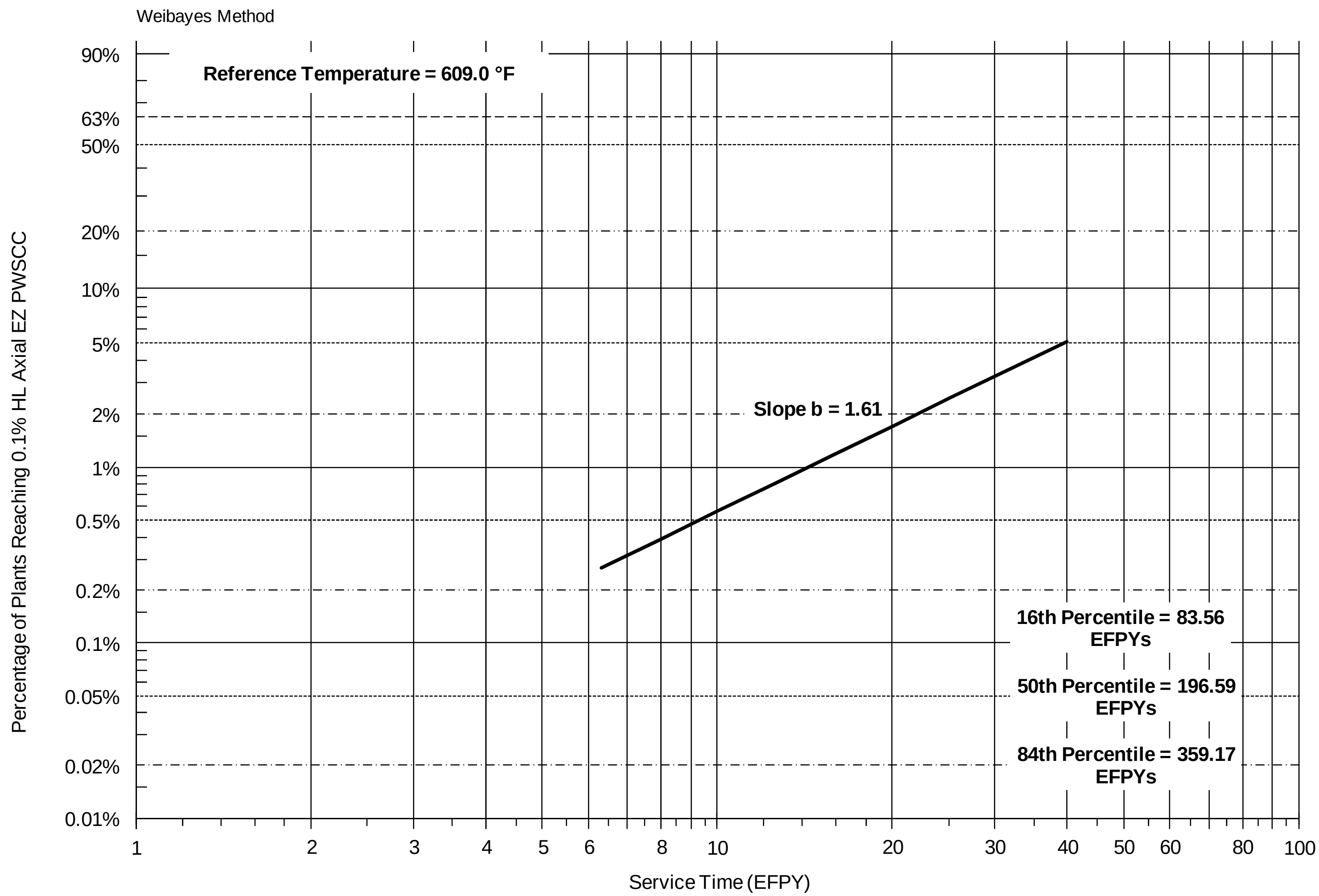

Figure A-16
Time to 0.1% HL Axial EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41	16.68		16.68	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90	19.17		19.17	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41	19.68		19.68	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59	19.86		19.86	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76	20.03		20.03	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80	20.07		20.07	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03	20.30		20.30	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28	20.55		20.55	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56	20.83		20.83	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12	21.39		21.39	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.11		613	7.16	21.43		21.43	12	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19	21.46		21.46	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63	21.90		21.90	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78	23.06		23.06	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83	23.10		23.10	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84	23.11		23.11	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87	23.15		23.15	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95	23.22		23.22	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60	23.88		23.88	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66	23.93		23.93	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78	24.05		24.05	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79	24.06		24.06	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88	24.15		24.15	24	0		0.00	
Sizewell B	2/95	13.59	7.30		617	10.00	24.27		24.27	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04	24.31		24.31	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07	24.34		24.34	27	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29	24.56		24.56	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30	24.57		24.57	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83	25.10		25.10	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89	25.16		25.16	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09	25.36		25.36	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30	25.57		25.57	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76	26.03		26.03	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38	26.65		26.65	35	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15	26.42		26.42	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42	26.69		26.69	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42	26.69		26.69	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53	26.80		26.80	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65	26.92		26.92	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74	27.01		27.01	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05	27.32		27.32	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33	27.60		27.60	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52	27.79		27.79	44	0		0.00	
Golfech 2	3/94	14.52	10.63		616	14.01	28.28		28.28	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50	28.77		28.77	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77	29.04		29.04	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97	29.24		29.24	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49	29.76		29.76	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58	29.85		29.85	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81	31.08		31.08	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27	31.54		31.54	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78	32.05		32.05	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91	33.18		33.18	54	0		0.00	
				Ave. Thot=	612									

Reference Temperature

609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-17
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift

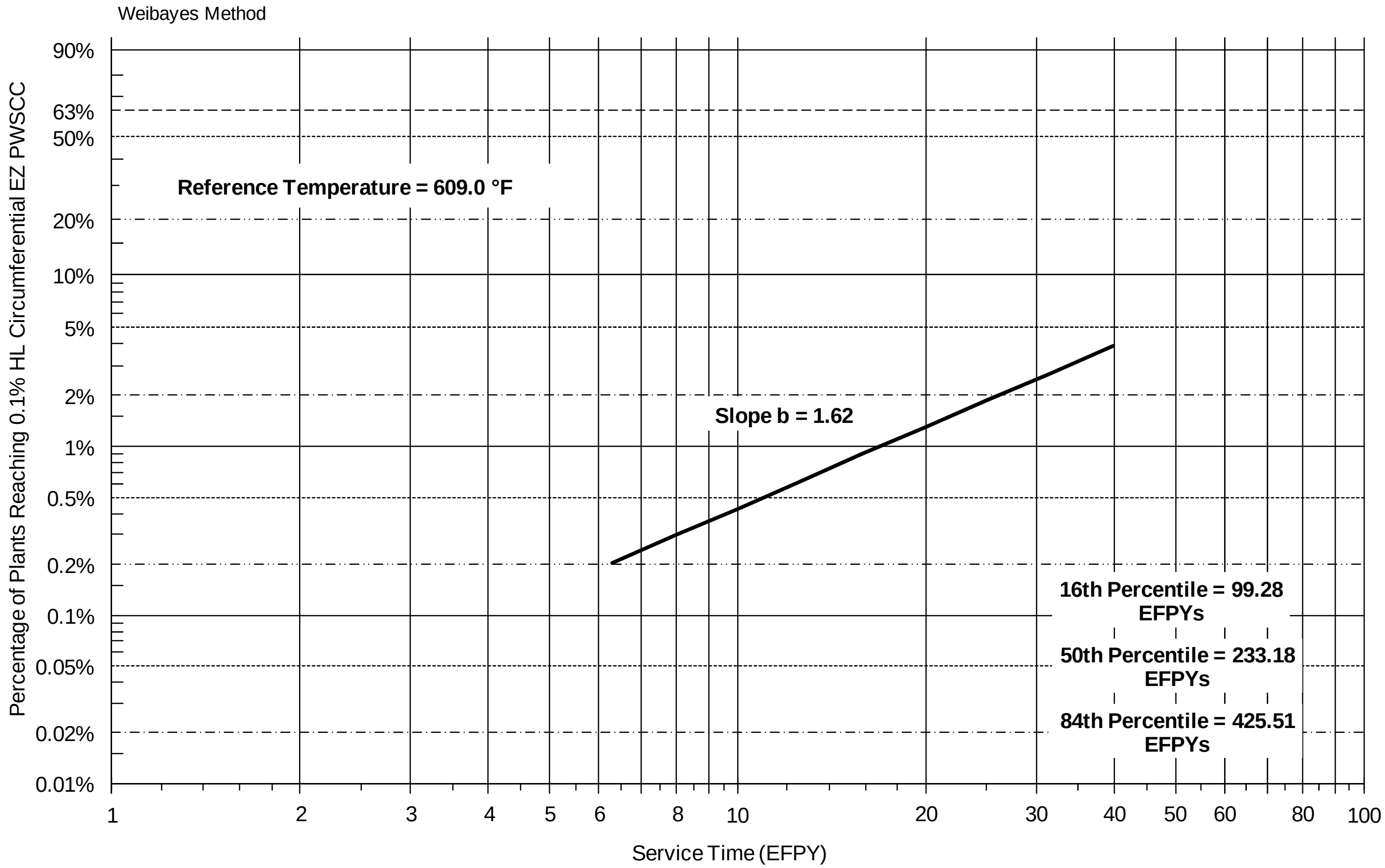

Figure A-18
Time to 0.1% HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41	13.55		13.55	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90	16.05		16.05	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41	16.56		16.56	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59	16.74		16.74	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76	16.91		16.91	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80	16.95		16.95	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03	17.18		17.18	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28	17.43		17.43	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56	17.71		17.71	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12	18.27		18.27	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.11		613	7.16	18.31		18.31	12	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19	18.33		18.33	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63	18.78		18.78	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78	19.93		19.93	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83	19.98		19.98	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84	19.99		19.99	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87	20.02		20.02	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95	20.10		20.10	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60	20.75		20.75	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66	20.81		20.81	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78	20.92		20.92	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79	20.94		20.94	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88	21.03		21.03	24	0		0.00	
Sizewell B	2/95	13.59	7.30		617	10.00	21.15		21.15	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04	21.19		21.19	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07	21.22		21.22	27	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29	21.44		21.44	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30	21.45		21.45	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83	21.98		21.98	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89	22.04		22.04	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09	22.24		22.24	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30	22.45		22.45	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76	22.91		22.91	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38	23.53		23.53	35	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15	23.30		23.30	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42	23.56		23.56	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42	23.56		23.56	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53	23.68		23.68	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65	23.80		23.80	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74	23.89		23.89	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05	24.20		24.20	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33	24.48		24.48	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52	24.67		24.67	44	0		0.00	
Golfech 2	3/94	14.52	10.63		616	14.01	25.16		25.16	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50	25.65		25.65	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77	25.92		25.92	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97	26.12		26.12	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49	26.63		26.63	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58	26.73		26.73	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81	27.96		27.96	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27	28.42		28.42	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78	28.93		28.93	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91	30.06		30.06	54	0		0.00	
				Ave. Thot=	612									

Reference Temperature
609.0 °F = 593.72 K　　Q= 50.0 Kcal/mole　　R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-19
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift

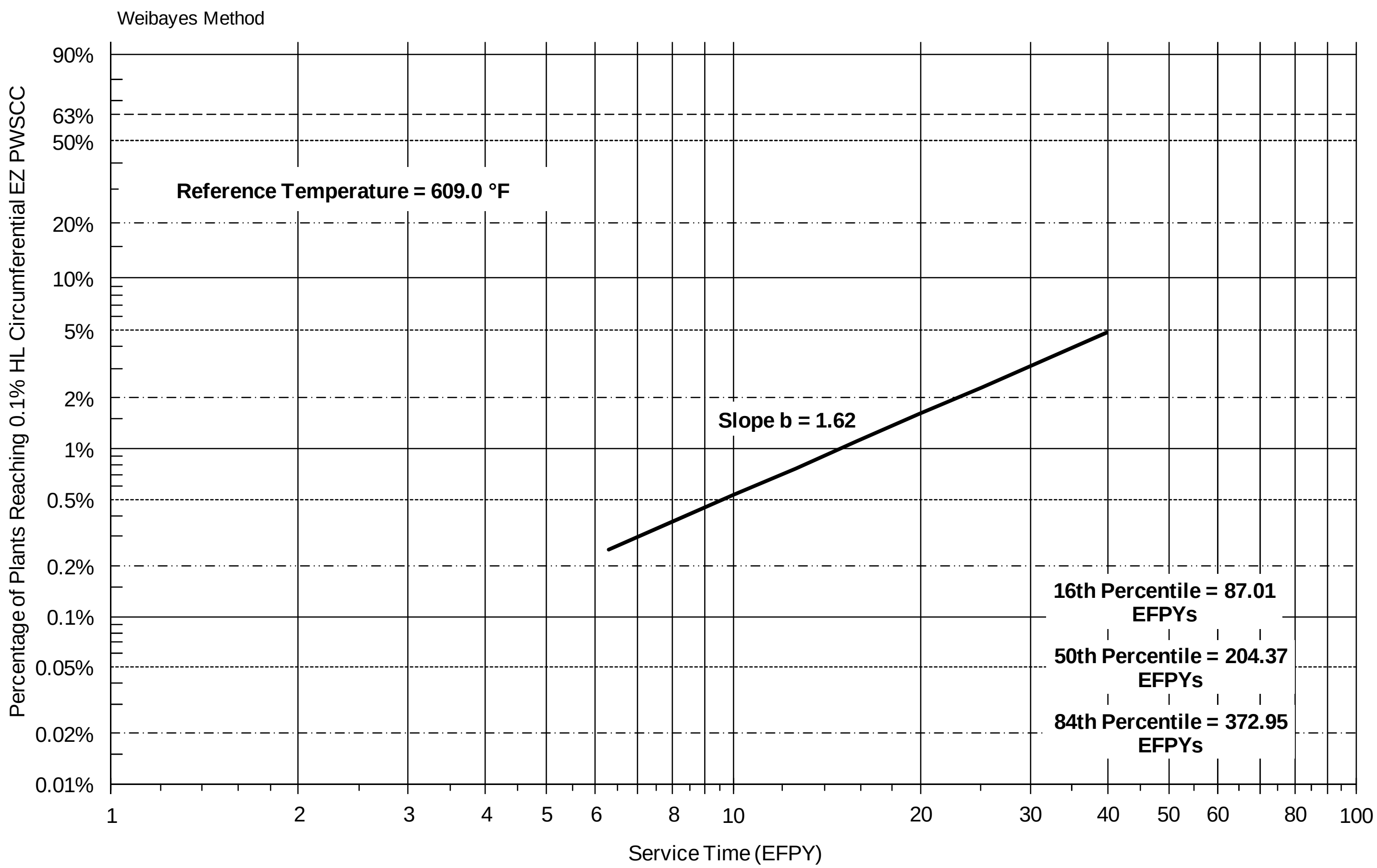

Figure A-20
Time to 0.1% HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift – Weibayes Analysis

No. Plants = 54 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% PWSCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% PWSCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 54	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Diablo Canyon 2 (repl	2/08	0.58	0.00		599	0.00	0.00		0.00	1	0		0.00	
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.41	12.14		12.14	2	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	4.90	14.64		14.64	3	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	5.41	15.15		15.15	4	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	5.59	15.33		15.33	5	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	5.76	15.50		15.50	6	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	5.80	15.54		15.54	7	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	6.03	15.77		15.77	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	6.28	16.02		16.02	9	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	6.56	16.30		16.30	10	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	7.12	16.86		16.86	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.11		613	7.16	16.89		16.89	12	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	7.19	16.92		16.92	13	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	7.63	17.37		17.37	14	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	8.78	18.52		18.52	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	8.83	18.57		18.57	16	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	8.84	18.58		18.58	17	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	8.87	18.61		18.61	18	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	8.95	18.69		18.69	19	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	9.60	19.34		19.34	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	9.66	19.40		19.40	21	0		0.00	
Civaux 2	1/00	8.67	5.23		625	9.78	19.51		19.51	22	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	9.79	19.53		19.53	23	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	9.88	19.62		19.62	24	0		0.00	
Sizewell B	2/95	13.59	7.30		617	10.00	19.74		19.74	25	0		0.00	
Civaux 1	1/00	8.67	5.37		625	10.04	19.78		19.78	26	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	10.07	19.81		19.81	27	0		0.00	
Penly 2	11/92	15.84	7.81		616	10.29	20.03		20.03	28	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	10.30	20.04		20.04	29	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	10.83	20.57		20.57	30	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	10.89	20.63		20.63	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	11.09	20.83		20.83	32	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	11.30	21.04		21.04	33	0		0.00	
Chooz B2	4/97	11.43	6.29		625	11.76	21.50		21.50	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	12.38	22.12		22.12	35	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	12.15	21.89		21.89	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	12.42	22.15		22.15	37	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	12.42	22.15		22.15	38	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	12.53	22.27		22.27	39	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	12.65	22.39		22.39	40	0		0.00	
Genkai 4	7/97	11.11	9.30		617	12.74	22.48		22.48	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	13.05	22.78		22.78	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	13.33	23.07		23.07	43	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	13.52	23.25		23.25	44	0		0.00	
Golfech 2	3/94	14.52	10.63		616	14.01	23.75		23.75	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	14.50	24.24		24.24	46	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	14.77	24.51		24.51	47	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	14.97	24.71		24.71	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	15.49	25.22		25.22	49	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	15.58	25.32		25.32	50	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	16.81	26.55		26.55	51	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	17.27	27.00		27.00	52	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	17.78	27.52		27.52	53	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	18.91	28.65		28.65	54	0		0.00	
				Ave. Thot=	612									

Reference Temperature
609.0 °F = 593.72 K Q= 50.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-21
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift

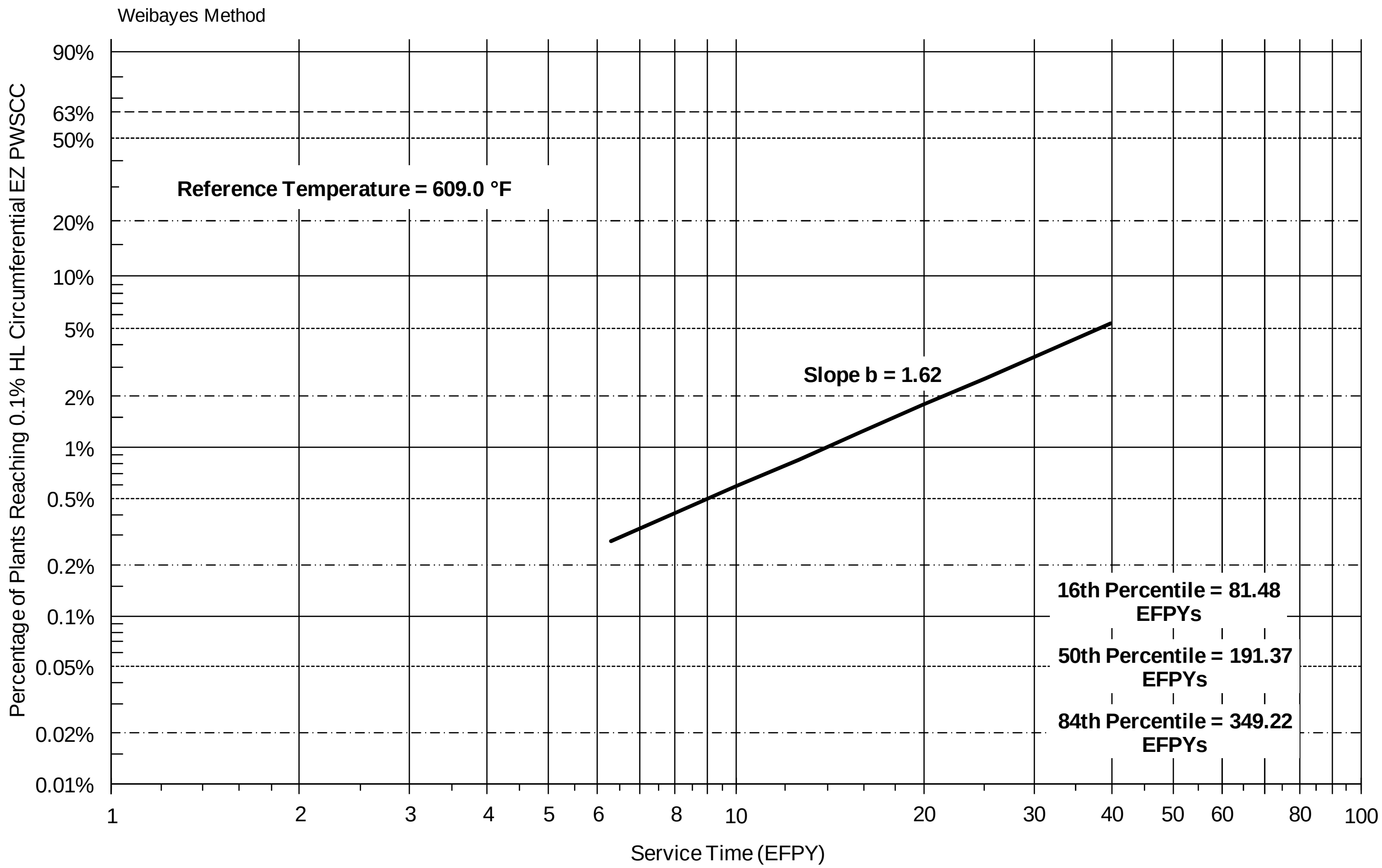

Figure A-22
Time to 0.1% HL Circumferential EZ PWSCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93	11.02		11.02	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	3.87	12.96		12.96	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35	13.44		13.44	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54	13.63		13.63	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70	13.80		13.80	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95	14.04		14.04	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21	14.30		14.30	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25	14.35		14.35	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26	14.35		14.35	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85	14.94		14.94	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02	15.11		15.11	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14	15.23		15.23	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	6.31	15.41		15.41	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41	16.50		16.50	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43	16.52		16.52	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47	16.56		16.56	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	7.50	16.59		16.59	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64	16.73		16.73	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	8.20	17.29		17.29	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20	17.29		17.29	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25	17.34		17.34	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36	17.45		17.45	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60	17.69		17.69	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	8.65	17.74		17.74	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66	17.76		17.76	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68	17.77		17.77	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	8.87	17.96		17.96	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90	17.99		17.99	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04	18.13		18.13	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30	18.39		18.39	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65	18.74		18.74	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68	18.77		18.77	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42	19.51		19.51	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57	19.66		19.66	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57	19.66		19.66	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60	19.69		19.69	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60	19.69		19.69	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	10.70	19.79		19.79	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80	19.89		19.89	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02	20.11		20.11	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	11.54	20.63		20.63	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56	20.65		20.65	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60	20.69		20.69	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	12.07	21.16		21.16	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49	21.59		21.59	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77	21.86		21.86	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78	21.87		21.87	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30	22.39		22.39	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39	22.48		22.48	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72	23.81		23.81	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	14.93	24.02		24.02	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47	24.56		24.56	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	16.35	25.44		25.44	53	0		0.00	
				Ave. Thot=	612									

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-23
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL OD TTS A&V IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift

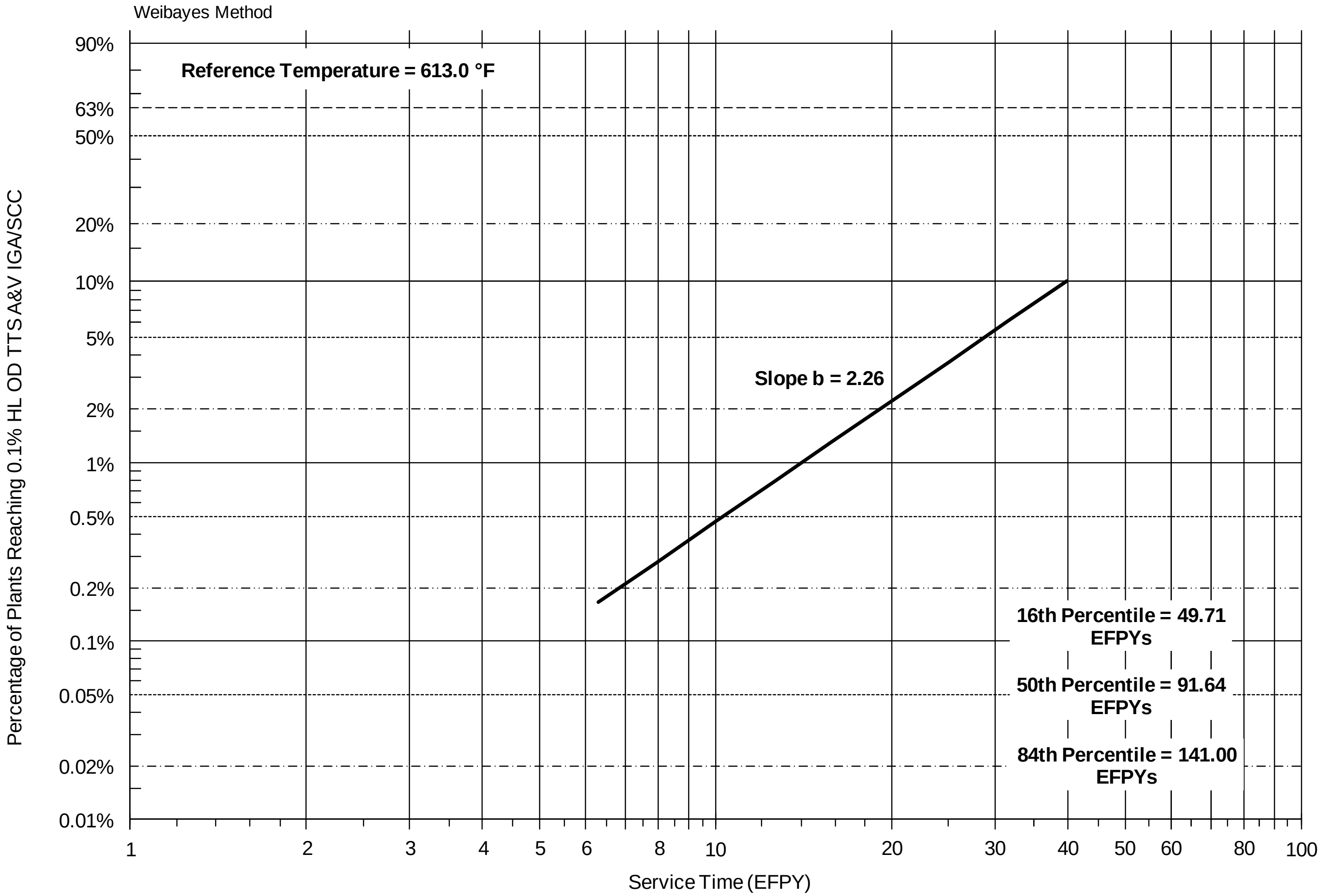

Figure A-24
Time to 0.1% HL OD TTS A&V IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93	11.02		11.02	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	3.87	12.96		12.96	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35	13.44		13.44	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54	13.63		13.63	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70	13.80		13.80	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95	14.04		14.04	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21	14.30		14.30	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25	14.35		14.35	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26	14.35		14.35	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85	14.94		14.94	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02	15.11		15.11	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14	15.23		15.23	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	6.31	15.41		15.41	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41	16.50		16.50	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43	16.52		16.52	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47	16.56		16.56	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	7.50	16.59		16.59	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64	16.73		16.73	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	8.20	17.29		17.29	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20	17.29		17.29	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25	17.34		17.34	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36	17.45		17.45	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60	17.69		17.69	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	8.65	17.74		17.74	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66	17.76		17.76	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68	17.77		17.77	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	8.87	17.96		17.96	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90	17.99		17.99	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04	18.13		18.13	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30	18.39		18.39	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65	18.74		18.74	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68	18.77		18.77	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42	19.51		19.51	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57	19.66		19.66	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57	19.66		19.66	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60	19.69		19.69	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60	19.69		19.69	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	10.70	19.79		19.79	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80	19.89		19.89	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02	20.11		20.11	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	11.54	20.63		20.63	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56	20.65		20.65	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60	20.69		20.69	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	12.07	21.16		21.16	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49	21.59		21.59	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77	21.86		21.86	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78	21.87		21.87	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30	22.39		22.39	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39	22.48		22.48	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72	23.81		23.81	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	14.93	24.02		24.02	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47	24.56		24.56	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	16.35	25.44		25.44	53	0		0.00	
				Ave. Thot=	612									

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-25
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL OD TTS A&V IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift

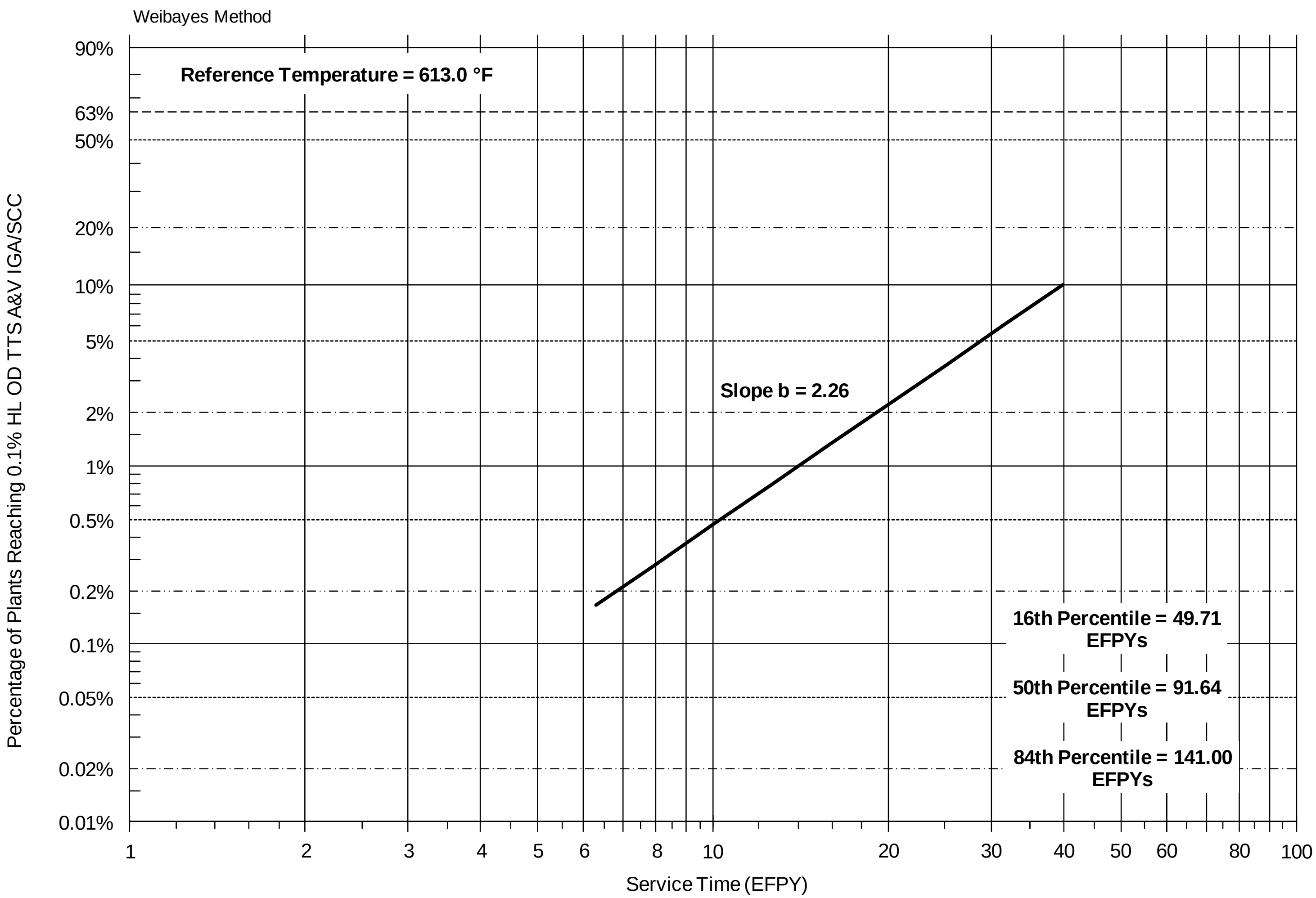

Figure A-26
Time to 0.1% HL OD TTS A&V IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.1% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.1% IGA/SCC	Adjusted EDYs to 0.1% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93	8.08		8.08	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	3.87	10.02		10.02	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35	10.50		10.50	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54	10.68		10.68	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70	10.85		10.85	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95	11.10		11.10	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21	11.36		11.36	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25	11.40		11.40	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26	11.41		11.41	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85	12.00		12.00	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02	12.17		12.17	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14	12.29		12.29	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	6.31	12.46		12.46	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41	13.56		13.56	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43	13.58		13.58	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47	13.62		13.62	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	7.50	13.65		13.65	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64	13.79		13.79	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	8.20	14.35		14.35	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20	14.35		14.35	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25	14.40		14.40	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36	14.51		14.51	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60	14.75		14.75	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	8.65	14.80		14.80	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66	14.81		14.81	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68	14.83		14.83	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	8.87	15.02		15.02	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90	15.04		15.04	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04	15.19		15.19	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30	15.45		15.45	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65	15.80		15.80	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68	15.83		15.83	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42	16.57		16.57	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57	16.72		16.72	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57	16.72		16.72	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60	16.75		16.75	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60	16.75		16.75	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	10.70	16.85		16.85	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80	16.95		16.95	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02	17.17		17.17	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	11.54	17.69		17.69	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56	17.71		17.71	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60	17.75		17.75	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	12.07	18.22		18.22	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49	18.64		18.64	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77	18.92		18.92	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78	18.93		18.93	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30	19.45		19.45	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39	19.54		19.54	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72	20.87		20.87	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	14.93	21.08		21.08	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47	21.61		21.61	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	16.35	22.50		22.50	53	0		0.00	
				Ave. Thot=	612									

Reference Temperature
613.0 °F = 595.94 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-27
Median Ranks Input Data for Weibayes Analysis of Time to 0.1% HL OD TTS A&V IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift

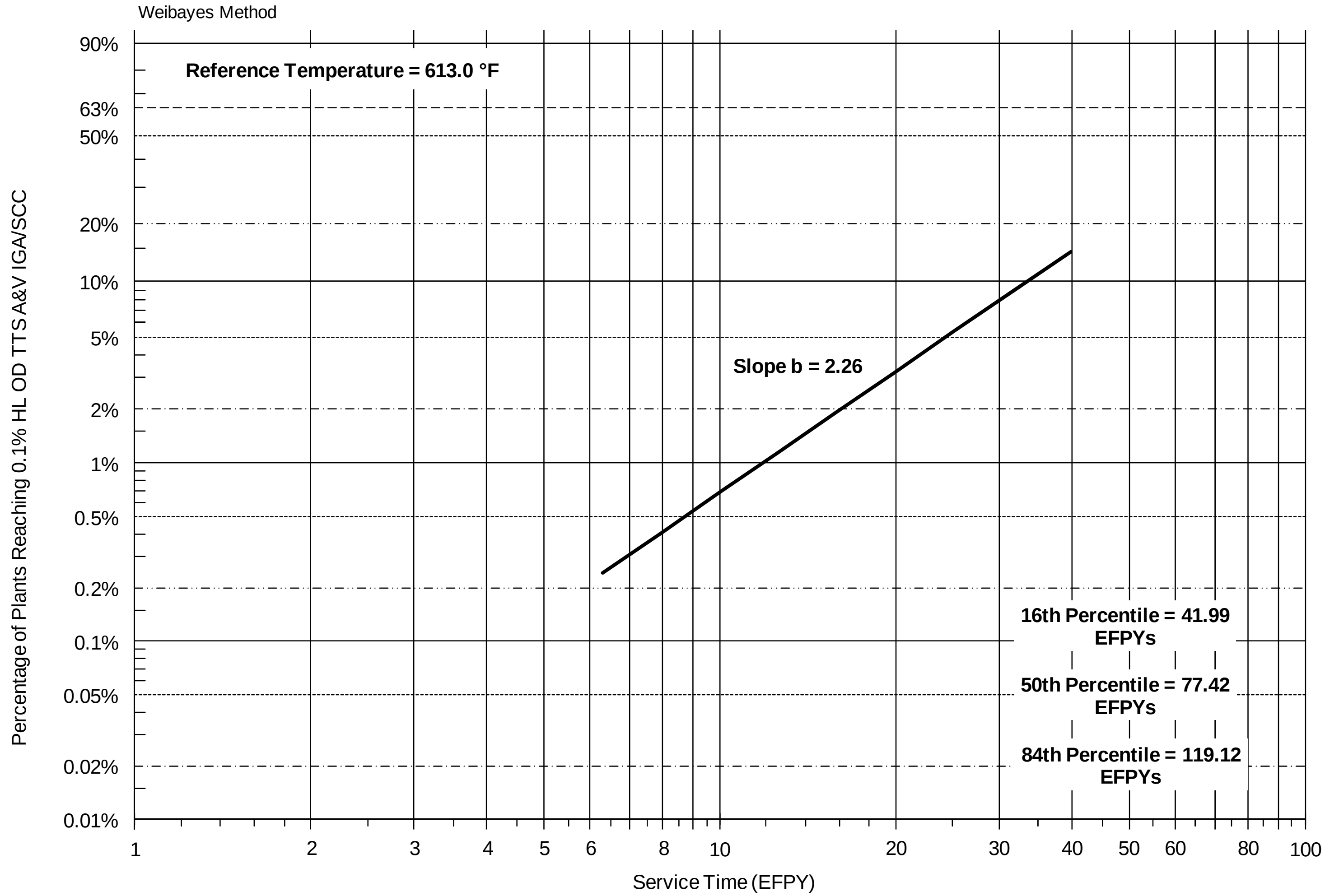

Figure A-28
Time to 0.1% HL OD TTS A&V IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift – Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.1% PWSCC or to Shifted ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93	8.04		8.04	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	3.87	9.97		9.97	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35	10.45		10.45	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54	10.64		10.64	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70	10.81		10.81	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95	11.05		11.05	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21	11.32		11.32	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25	11.36		11.36	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26	11.36		11.36	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85	11.95		11.95	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02	12.12		12.12	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14	12.24		12.24	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	6.31	12.42		12.42	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41	13.51		13.51	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43	13.53		13.53	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47	13.57		13.57	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	7.50	13.60		13.60	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64	13.74		13.74	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	8.20	14.30		14.30	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20	14.30		14.30	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25	14.35		14.35	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36	14.46		14.46	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60	14.70		14.70	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	8.65	14.75		14.75	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66	14.77		14.77	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68	14.79		14.79	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	8.87	14.97		14.97	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90	15.00		15.00	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04	15.14		15.14	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30	15.40		15.40	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65	15.75		15.75	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68	15.78		15.78	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42	16.52		16.52	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57	16.67		16.67	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57	16.67		16.67	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60	16.70		16.70	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60	16.70		16.70	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	10.70	16.80		16.80	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80	16.90		16.90	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02	17.12		17.12	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	11.54	17.64		17.64	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56	17.67		17.67	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60	17.70		17.70	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	12.07	18.18		18.18	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49	18.60		18.60	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77	18.88		18.88	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78	18.88		18.88	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30	19.40		19.40	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39	19.49		19.49	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72	20.82		20.82	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	14.93	21.03		21.03	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47	21.57		21.57	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	16.35	22.45		22.45	53	0		0.00	
				Ave. Thot=	612									

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-29
Median Ranks Input Data for Weibayes Analysis of Time to 0.05% HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift

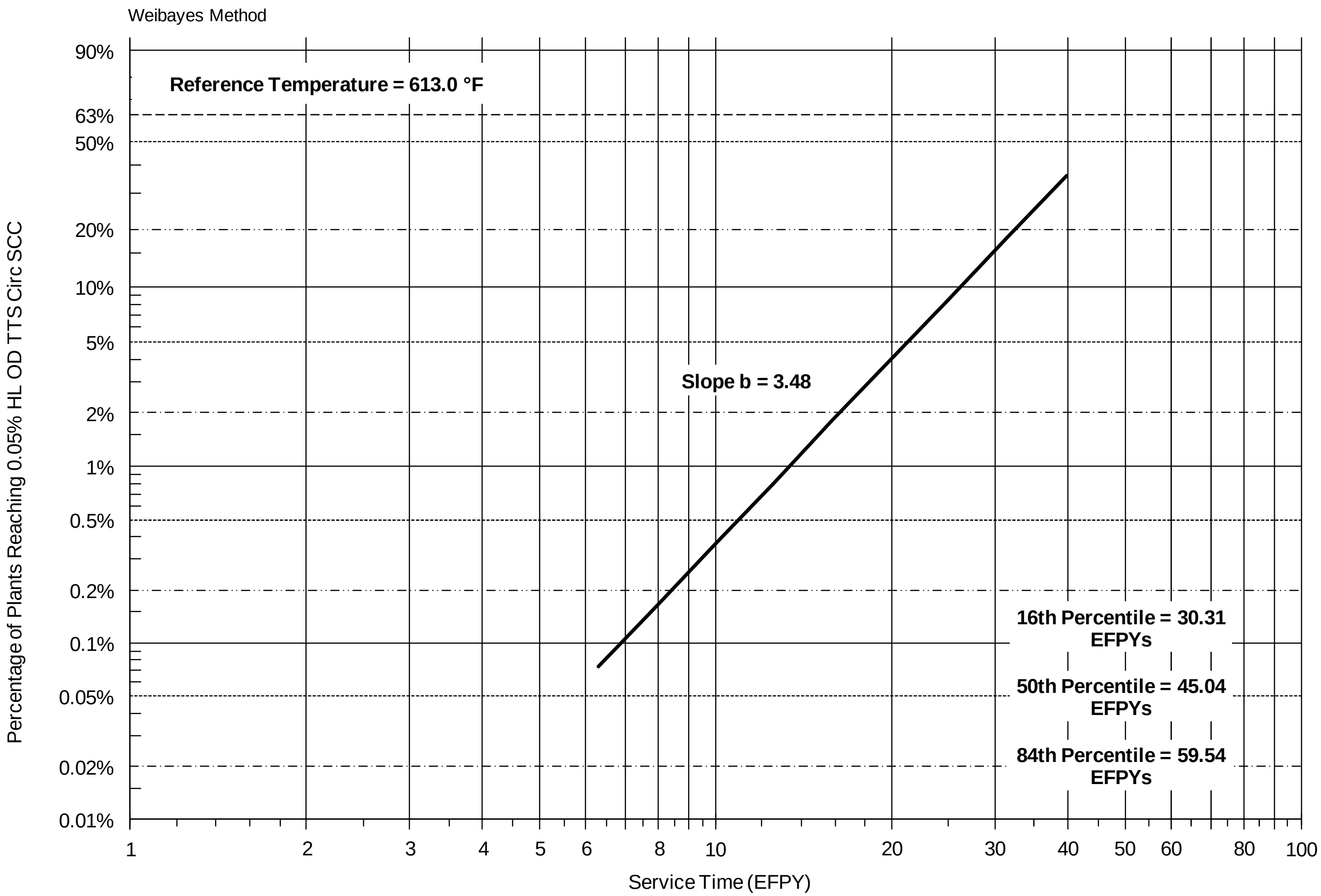

Figure A-30
Time to 0.05% HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93	5.54		5.54	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	3.87	7.48		7.48	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35	7.96		7.96	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54	8.14		8.14	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70	8.31		8.31	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95	8.56		8.56	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21	8.82		8.82	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25	8.86		8.86	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26	8.87		8.87	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85	9.46		9.46	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02	9.63		9.63	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14	9.75		9.75	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	6.31	9.92		9.92	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41	11.02		11.02	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43	11.04		11.04	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47	11.08		11.08	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	7.50	11.11		11.11	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64	11.25		11.25	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	8.20	11.81		11.81	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20	11.81		11.81	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25	11.86		11.86	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36	11.97		11.97	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60	12.21		12.21	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	8.65	12.26		12.26	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66	12.27		12.27	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68	12.29		12.29	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	8.87	12.48		12.48	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90	12.51		12.51	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04	12.65		12.65	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30	12.91		12.91	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65	13.26		13.26	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68	13.29		13.29	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42	14.03		14.03	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57	14.18		14.18	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57	14.18		14.18	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60	14.21		14.21	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60	14.21		14.21	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	10.70	14.31		14.31	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80	14.41		14.41	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02	14.63		14.63	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	11.54	15.15		15.15	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56	15.17		15.17	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60	15.21		15.21	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	12.07	15.68		15.68	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49	16.10		16.10	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77	16.38		16.38	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78	16.39		16.39	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30	16.91		16.91	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39	17.00		17.00	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72	18.33		18.33	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	14.93	18.54		18.54	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47	19.08		19.08	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	16.35	19.96		19.96	53	0		0.00	
				Ave. Thot=	612									

Reference Temperature
613.0 °F = 595.94 K   Q= 54.0 Kcal/mole   R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-31
Median Ranks Input Data for Weibayes Analysis of Time to 0.05% HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift

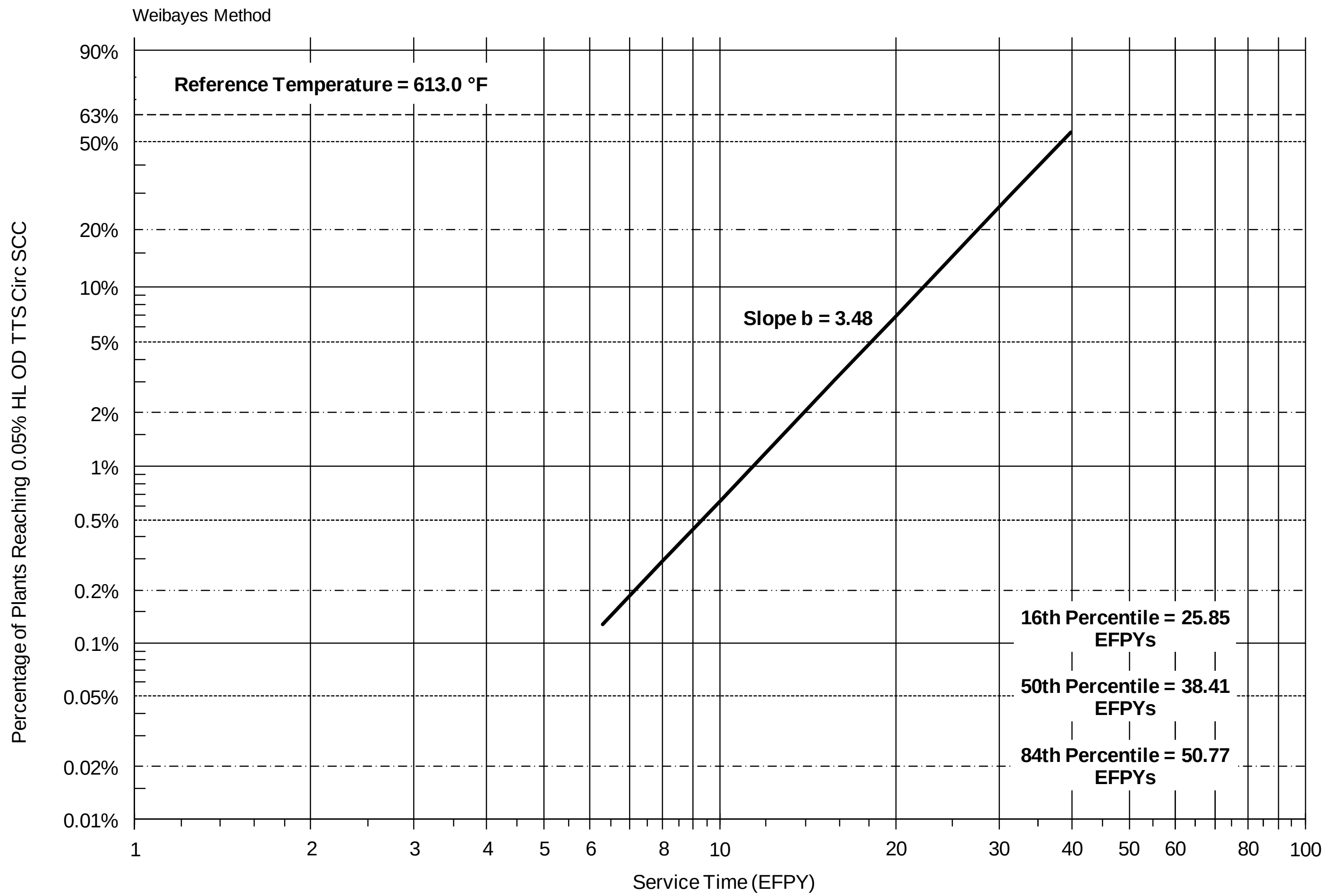

Figure A-32
Time to 0.05% HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift – Weibayes Analysis

Weibull Slope Sensitivity Analysis for Alloy 690TT

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% TTS SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.05% TTS SCC	Adjusted EDYs to 0.05% TTS SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	1.93	4.55		4.55	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	3.87	6.49		6.49	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	4.35	6.97		6.97	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	4.54	7.15		7.15	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	4.70	7.32		7.32	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	4.95	7.57		7.57	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	5.21	7.83		7.83	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	5.25	7.87		7.87	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	5.26	7.88		7.88	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	5.85	8.47		8.47	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	6.02	8.64		8.64	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	6.14	8.76		8.76	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	6.31	8.93		8.93	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	7.41	10.03		10.03	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	7.43	10.05		10.05	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	7.47	10.09		10.09	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	7.50	10.12		10.12	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	7.64	10.26		10.26	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	8.20	10.82		10.82	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	8.20	10.82		10.82	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	8.25	10.87		10.87	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	8.36	10.98		10.98	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	8.60	11.22		11.22	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	8.65	11.27		11.27	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	8.66	11.28		11.28	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	8.68	11.30		11.30	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	8.87	11.49		11.49	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	8.90	11.51		11.51	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	9.04	11.66		11.66	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	9.30	11.92		11.92	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	9.65	12.27		12.27	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	9.68	12.30		12.30	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	10.42	13.04		13.04	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	10.57	13.19		13.19	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	10.57	13.19		13.19	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	10.60	13.22		13.22	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	10.60	13.22		13.22	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	10.70	13.32		13.32	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	10.80	13.42		13.42	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	11.02	13.64		13.64	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	11.54	14.16		14.16	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	11.56	14.18		14.18	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	11.60	14.22		14.22	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	12.07	14.69		14.69	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	12.49	15.11		15.11	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	12.77	15.39		15.39	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	12.78	15.40		15.40	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	13.30	15.92		15.92	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	13.39	16.01		16.01	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	14.72	17.34		17.34	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	14.93	17.55		17.55	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	15.47	18.09		18.09	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	16.35	18.97		18.97	53	0		0.00	

Ave. Thot= 612

Reference Temperature

613.0 °F = 595.94 K Q= 54.0 Kcal/mole R= R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-33
Median Ranks Input Data for Weibayes Analysis of Time to 0.05% HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift

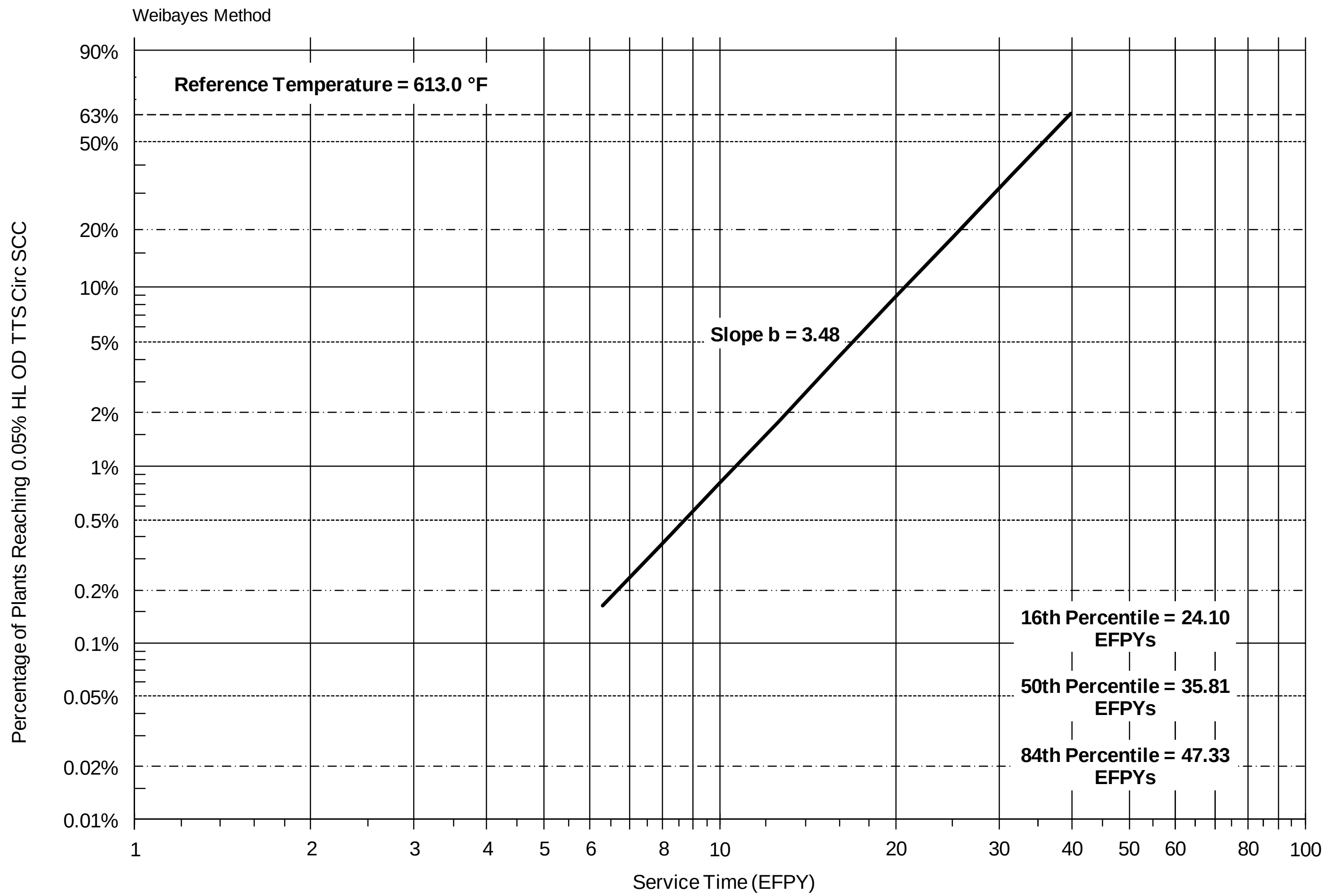

Figure A-34
Time to 0.05% HL OD TTS Circumferential SCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift – Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.72	9.34		9.34	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	5.46	12.08		12.08	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	6.13	12.75		12.75	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	6.39	13.01		13.01	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	6.63	13.25		13.25	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	6.97	13.59		13.59	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	7.34	13.96		13.96	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	7.40	14.02		14.02	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	7.41	14.03		14.03	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	8.24	14.86		14.86	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	8.48	15.10		15.10	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	8.65	15.27		15.27	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	8.90	15.52		15.52	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	10.44	17.06		17.06	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	10.47	17.09		17.09	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	10.53	17.15		17.15	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	10.57	17.19		17.19	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	10.76	17.38		17.38	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	11.55	18.17		18.17	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	11.55	18.17		18.17	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	11.62	18.24		18.24	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	11.78	18.40		18.40	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	12.12	18.74		18.74	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	12.19	18.81		18.81	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	12.21	18.83		18.83	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	12.23	18.85		18.85	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	12.50	19.12		19.12	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	12.53	19.15		19.15	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	12.74	19.36		19.36	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	13.10	19.72		19.72	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	13.60	20.22		20.22	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	13.64	20.26		20.26	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	14.68	21.30		21.30	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	14.89	21.51		21.51	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	14.89	21.51		21.51	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	14.93	21.55		21.55	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	14.93	21.55		21.55	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	15.08	21.70		21.70	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	15.22	21.84		21.84	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	15.52	22.14		22.14	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	16.26	22.88		22.88	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	16.29	22.91		22.91	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	16.34	22.96		22.96	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	17.01	23.63		23.63	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	17.60	24.22		24.22	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	18.00	24.62		24.62	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	18.01	24.63		24.63	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	18.74	25.36		25.36	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	18.86	25.48		25.48	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	20.74	27.36		27.36	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	21.03	27.65		27.65	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	21.79	28.41		28.41	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	23.03	29.65		29.65	53	0		0.00	

Ave. Thot= 612

Reference Temperature
605.0 °F = 591.49 K Q= 54.0 Kcal/mole R= 0.001986 Kcal/mole K

NOTES:
1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-35
Median Ranks Input Data for Weibayes Analysis of Time to 0.05% HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift

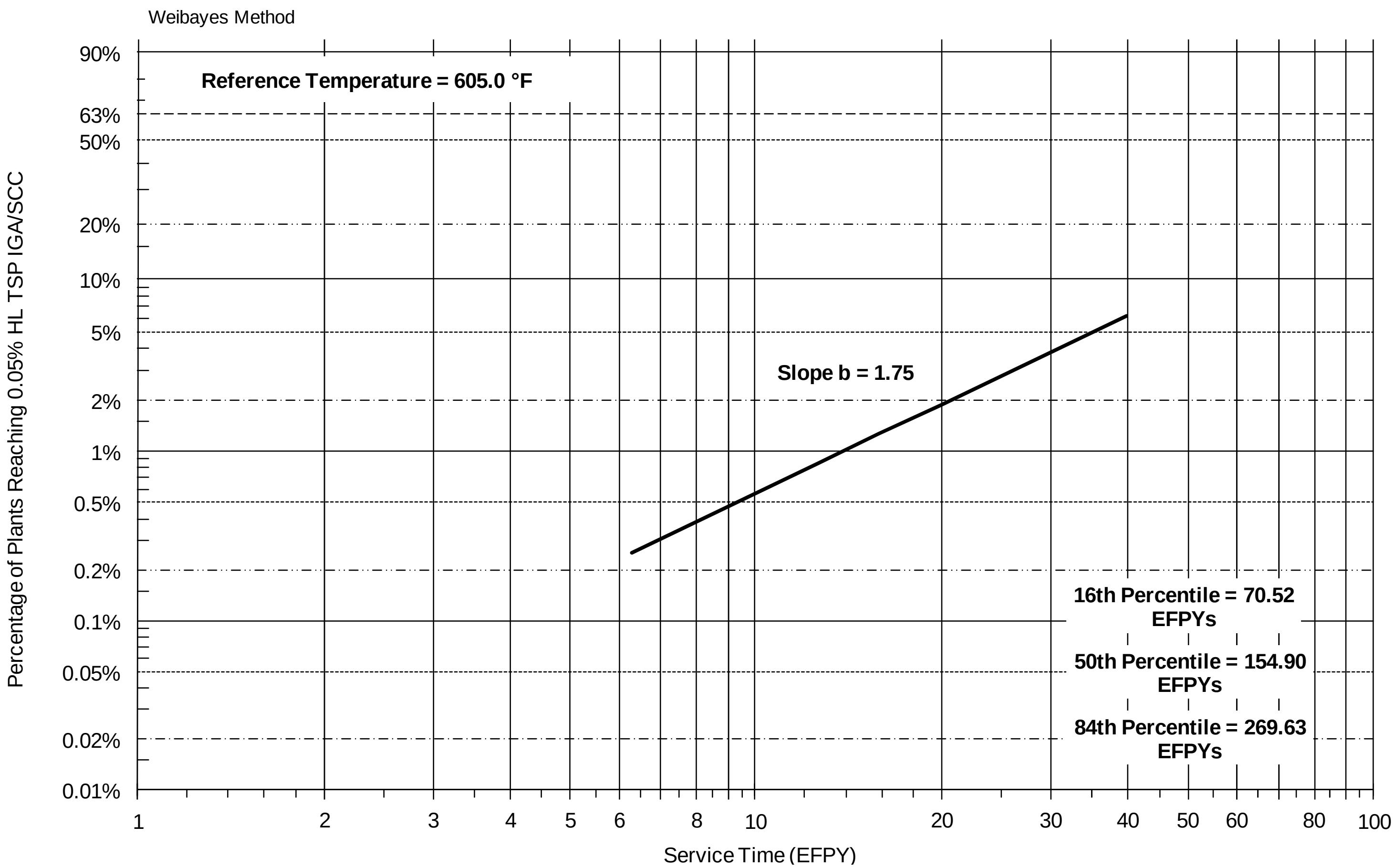

Figure A-36
Time to 0.05% HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 25th Percentile Slope Time Shift – Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.72	6.96		6.96	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	5.46	9.69		9.69	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	6.13	10.37		10.37	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	6.39	10.63		10.63	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	6.63	10.87		10.87	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	6.97	11.21		11.21	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	7.34	11.58		11.58	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	7.40	11.64		11.64	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	7.41	11.65		11.65	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	8.24	12.48		12.48	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	8.48	12.72		12.72	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	8.65	12.89		12.89	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	8.90	13.14		13.14	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	10.44	14.68		14.68	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	10.47	14.71		14.71	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	10.53	14.76		14.76	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	10.57	14.81		14.81	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	10.76	15.00		15.00	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	11.55	15.79		15.79	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	11.55	15.79		15.79	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	11.62	15.86		15.86	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	11.78	16.02		16.02	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	12.12	16.36		16.36	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	12.19	16.42		16.42	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	12.21	16.45		16.45	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	12.23	16.47		16.47	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	12.50	16.74		16.74	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	12.53	16.77		16.77	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	12.74	16.98		16.98	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	13.10	17.34		17.34	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	13.60	17.84		17.84	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	13.64	17.88		17.88	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	14.68	18.92		18.92	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	14.89	19.13		19.13	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	14.89	19.13		19.13	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	14.93	19.17		19.17	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	14.93	19.17		19.17	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	15.08	19.31		19.31	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	15.22	19.46		19.46	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	15.52	19.76		19.76	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	16.26	20.50		20.50	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	16.29	20.53		20.53	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	16.34	20.58		20.58	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	17.01	21.25		21.25	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	17.60	21.84		21.84	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	18.00	22.23		22.23	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	18.01	22.25		22.25	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	18.74	22.98		22.98	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	18.86	23.10		23.10	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	20.74	24.98		24.98	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	21.03	25.27		25.27	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	21.79	26.03		26.03	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	23.03	27.27		27.27	53	0		0.00	

Ave. Thot= 612

Reference Temperature

605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R=   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-37
Median Ranks Input Data for Weibayes Analysis of Time to 0.05% HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift

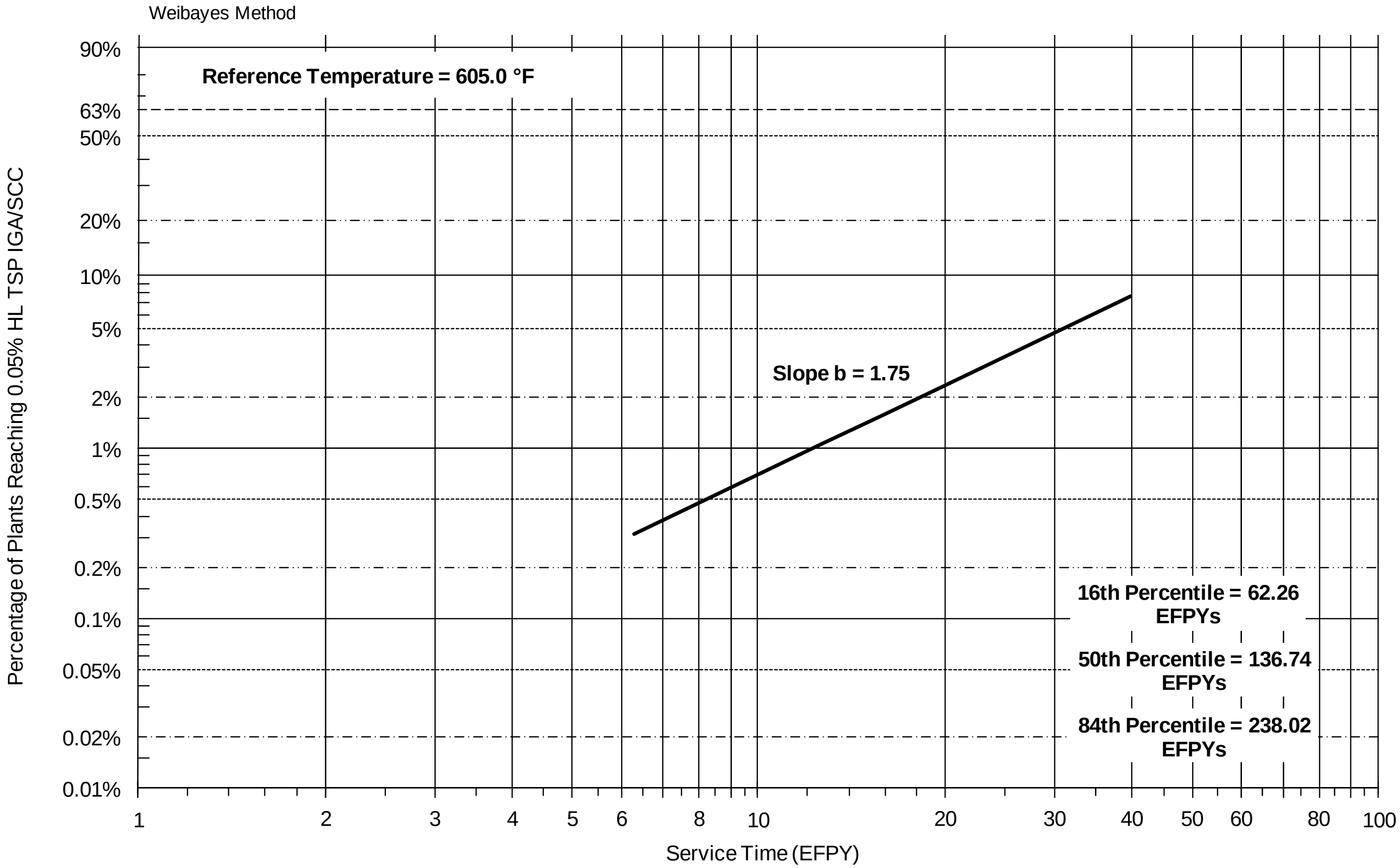

Figure A-38
Time to 0.05% HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 50th Percentile Slope Time Shift –Weibayes Analysis

No. Plants = 53 Plant	Date Commercial Operation	Operating Years to 9/2008 (5)	EFPYs at Last ISI (4)	EFPYs to 0.05% IGA/SCC	Thot (°F)	Adjusted EDYs at Last ISI	Shifted EDYs at Last ISI	Adjusted EDYs to 0.05% IGA/SCC	Adjusted EDYs to 0.05% IGA/SCC or to Last ISI	N= 53	SCC=1 No SCC =0	No. of Items Following	Order of Failure	Median Rank 1
Beznau 2 (repl.)	6/99	9.26	4.40		594	2.72	5.59		5.59	1	0		0.00	
Ginna (repl.)	6/96	12.26	11.0 (est.)		589	5.46	8.32		8.32	2	0		0.00	
Beznau 1 (repl.)	7/93	15.18	9.90		594	6.13	8.99		8.99	3	0		0.00	
Point Beach 2 (repl.)	3/97	11.51	9.05		597	6.39	9.25		9.25	4	0		0.00	
St. Lucie 1 (repl.)	1/98	10.67	8.60		599	6.63	9.49		9.49	5	0		0.00	
Gravelines 4 (repl.)	7/00	8.16	4.95		613	6.97	9.84		9.84	6	0		0.00	
Ohi 1 (repl.)	5/95	13.28	4.4 (est.)		617	7.34	10.21		10.21	7	0		0.00	
Indian Point 3 (repl.)	6/89	19.27	12.50		593	7.40	10.26		10.26	8	0		0.00	
Farley 1 (repl.)	5/00	8.28	6.80		607	7.41	10.28		10.28	9	0		0.00	
Millstone 2 (repl.)	1/93	15.68	9.80		601	8.24	11.10		11.10	10	0		0.00	
Kori 1 (repl.)	7/98	10.18	7.78		607	8.48	11.34		11.34	11	0		0.00	
Tricastin 1 (repl.)	11/98	9.77	6.14		613	8.65	11.51		11.51	12	0		0.00	
Mihama 1 (repl.)	4/96	12.42	9.7 (est.)		603	8.90	11.76		11.76	13	0		0.00	
Ringhals 3 (repl.)	8/95	13.10	10.00		606	10.44	13.30		13.30	14	0		0.00	
Mihama 3 (repl.)	2/97	11.54	9.2 (est.)		608	10.47	13.33		13.33	15	0		0.00	
Braidwood 1 (repl.)	9/98	9.98	8.49		610	10.53	13.39		13.39	16	0		0.00	
Ikata 1 (repl.)	6/98	10.25	7.5 (est.)		613	10.57	13.43		13.43	17	0		0.00	
Tricastin 2 (repl.)	5/97	11.34	7.64		613	10.76	13.63		13.63	18	0		0.00	
Ohi 2 (repl.)	8/97	11.06	8.2 (est.)		613	11.55	14.42		14.42	19	0		0.00	
Mihama 2 (repl.)	10/94	13.90	10.60		607	11.55	14.42		14.42	20	0		0.00	
Gravelines 2 (repl.)	8/96	12.01	8.25		613	11.62	14.49		14.49	21	0		0.00	
Byron 1 (repl.)	2/98	10.59	9.50		610	11.78	14.64		14.64	22	0		0.00	
St-Laurent B1 (repl.)	8/95	13.03	8.60		613	12.12	14.98		14.98	23	0		0.00	
Sizewell B	2/95	13.59	7.30		617	12.19	15.05		15.05	24	0		0.00	
Civaux 2	1/00	8.67	5.23		625	12.21	15.07		15.07	25	0		0.00	
Tihange 1 (repl.)	6/95	13.26	10.30		609	12.23	15.10		15.10	26	0		0.00	
Penly 2	11/92	15.84	7.81		616	12.50	15.36		15.36	27	0		0.00	
Civaux 1	1/00	8.67	5.37		625	12.53	15.40		15.40	28	0		0.00	
Cook 2 (repl.)	3/89	19.52	12.20		606	12.74	15.60		15.60	29	0		0.00	
Takahama 1 (repl.)	8/96	12.09	9.3 (est.)		613	13.10	15.97		15.97	30	0		0.00	
Dampierre 3 (repl.)	11/95	12.84	9.65		613	13.60	16.46		16.46	31	0		0.00	
South Texas 1 (repl.)	5/00	8.34	7.20		620	13.64	16.50		16.50	32	0		0.00	
Chooz B2	4/97	11.43	6.29		625	14.68	17.54		17.54	33	0		0.00	
McGuire 2 (repl.)	12/97	10.76	8.20		619	14.89	17.75		17.75	34	0		0.00	
Catawba 1 (repl.)	10/96	11.92	10.57		613	14.89	17.76		17.76	35	0		0.00	
Gravelines 1 (repl.)	2/94	14.58	10.60		613	14.93	17.80		17.80	36	0		0.00	
North Anna 2 (repl.)	6/95	13.26	10.60		613	14.93	17.80		17.80	37	0		0.00	
Takahama 2 (repl.)	8/94	14.09	10.70		613	15.08	17.94		17.94	38	0		0.00	
Genkai 1 (repl.)	10/94	13.85	10.80		613	15.22	18.08		18.08	39	0		0.00	
Genkai 4	7/97	11.11	9.30		617	15.52	18.39		18.39	40	0		0.00	
Ikata 3	12/94	13.72	11.5 (est.)		613	16.26	19.12		19.12	41	0		0.00	
Chooz B1	8/96	12.09	6.98		625	16.29	19.15		19.15	42	0		0.00	
McGuire 1 (repl.)	5/97	11.35	9.00		619	16.34	19.21		19.21	43	0		0.00	
Golfech 2	3/94	14.52	10.63		616	17.01	19.87		19.87	44	0		0.00	
Ringhals 2 (repl.)	8/89	19.10	14.20		610	17.60	20.47		20.47	45	0		0.00	
Tihange 3 (repl.)	8/98	10.09	8.38		623	18.00	20.86		20.86	46	0		0.00	
Dampierre 1 (repl.)	2/90	18.55	12.78		613	18.01	20.87		20.87	47	0		0.00	
North Anna 1 (repl.)	4/93	15.43	13.30		613	18.74	21.60		21.60	48	0		0.00	
Genkai 3	3/94	14.47	11.30		617	18.86	21.72		21.72	49	0		0.00	
Doel 4 (repl.)	7/96	12.18	10.50		621	20.74	23.60		23.60	50	0		0.00	
Ohi 4	2/93	15.59	12.6 (est.)		617	21.03	23.89		23.89	51	0		0.00	
Summer (repl.)	12/94	13.76	12.00		619	21.79	24.65		24.65	52	0		0.00	
Ohi 3	12/91	16.72	13.8 (est.)		617	23.03	25.90		25.90	53	0		0.00	
				Ave. Thot=	612									

Reference Temperature

605.0 °F = 591.49 K   Q= 54.0 Kcal/mole   R=   R= 0.001986 Kcal/mole K

NOTES:

1. List limited to plants with Westinghouse design SGs with Alloy 690TT tubing.
2. Activation energy (input value) is used to correct EDY to that for a Thot equal to reference.
3. EDYs are actual or calculated from operating years using effective capacity factors.
4. Last ISI for which DEI has data. EDYs adjusted as required to account for temperature and/or power changes at EDY Thot, using the reference value of Q.
5. "R" indicates steam generators replaced at indicated calendar years of operation. "S" indicates plant was shut down after indicated years of operation.

Figure A-39
Median Ranks Input Data for Weibayes Analysis of Time to 0.05% HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift

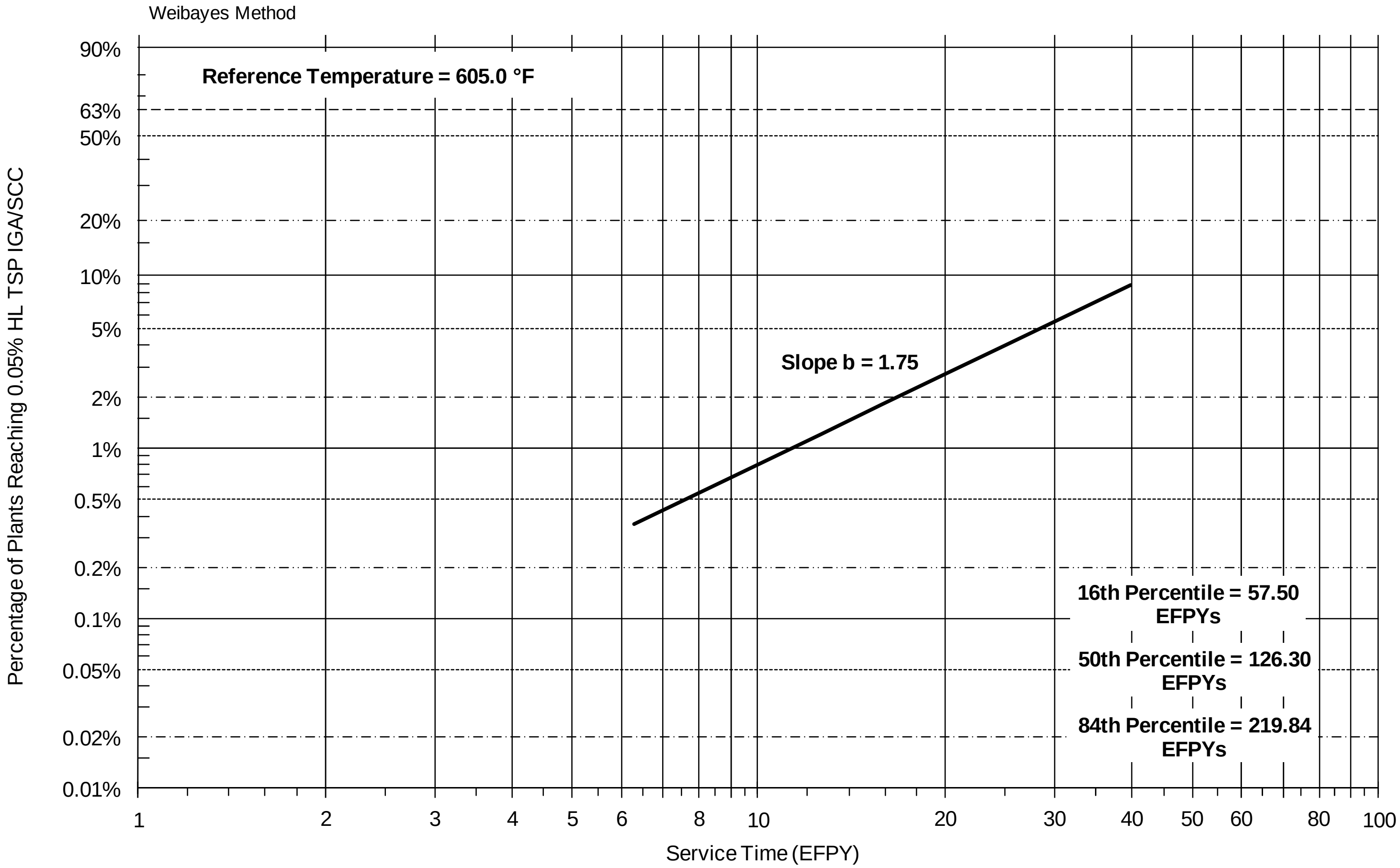

Figure A-40
Time to 0.05% HL TSP IGA/SCC – All Westinghouse Design Alloy 690TT Plants; 75th Percentile Slope Time Shift – Weibayes Analysis

B
TRANSLATED TABLE OF CONTENTS

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute (EPRI)

蒸気発生器の管理プログラム:加圧水型原子炉の蒸気発生器管材料

1019044

最終報告 2009年12月

報告書の要約

この報告書には、以前に作成された、PWR蒸気発生管の材料向けの先進的な合金の使用に関する、改善要因の最新情報が含まれています。この中では、圧延機アニールAlloy 600（Alloy 600MA）蒸気発生器管に関する熱処理Alloy 600（Alloy 600TT）、熱処理Alloy 690（Alloy 690TT）、およびAlloy 800原子炉級（Alloy 800NG）向けの改善要因について説明しています。

背景

先進的な合金の使用に関する性能向上の予測は、これまでは改善要因を使用して行われてきました。EPRI報告書1003589により、Alloy 600TTおよびAlloy 690TTの改善要因が作成および提示されました。ただし、予想される故障寿命に関する実地経験が短いため、実地経験に基づいたこれらの改善要因の予測は過度に控えめである可能性があります。

目的

- さまざまなグレードの管を使用することで得られた、腐食耐性における現時点での改善の知識を要約すること
- 劣化抵抗における合金特有の改善を示すために、現在の水質化学のガイドライン対する適切な変更を評価する基盤を与えること

方法

この報告書を準備するにあたって、プロジェクトチームでは次のことを実施しました。

- Alloy 600TT、Alloy 690TT、およびAlloy 800NG管に関して、経験に基づく改善要因を更新し、最新の腐食イベントおよび特質すべき障害数のない追加の運転時間を反映しました。
- Alloy 600TTおよびAlloy 690TTで構成される蒸気発生器管のプラグの相対的性能を考慮することでこのプラントの経験の分析を補いました。
- Alloy 600MAに対するAlloy 600TT、Alloy 690TT、およびAlloy 800NGの実験室ベースの改善要因を更新し、文献の検証による最新の研究結果を含めました。
- ナトリウム汚染のあるモデルボイラーで実施されたこれまでの実験の要約を編集しました。モデルボイラーの試験プログラムは、応力、材料、および熱流力の条件が実際のプラントに極めて近いものになるに従って、その実際のプラント性能が適度に模倣されますが、これらの試験で得られる化学反応は、実稼働時にみられる可能性の高い反応よりも強い可能性があります。

結果

この報告書で説明される評価によって、Alloy 600MAと比較したAlloy 600TT、Alloy 690TT、およびAlloy 800NGの控えめな改善要因が導かれました。これらの改善要因をAlloy 600MAで得られる経験と併用して使用することで、PWR蒸気発生器の将来的な管劣化を控えめに予測することができます。これらの予測は控えめな内容なので、予測結果が最善なものになるわけではありません。つまり、実際の管劣化を過剰に予測しがちであ

ると考えられます。データセットごとに控えめの度合いが異なるので、これらの改善要因は3つの合金の相対的な性能の比較に使用するのには適当ではありません。ただし、これらの改善要因は、控えめであるというその性質から、たとえば、より厳しくない化学ガイドラインを使用したり、点検の間隔を増やしたりするなど、電力会社がこれらの合金の耐腐食性の性質を信頼できる限度を定めるのに役立ちます。

EPRIの観点

この報告書は、電力会社が蒸気発生器の将来的な劣化の可能性を評価するのを支援するためのEPRIによる継続的な取り組みの内容を示しています。これは、EPRI報告書1003589『Pressurized Water Reactor Generic Tube Degradation Predictions (2003)』および1013640『Alloy 690 Improvement Factor Update: Application of an Improvement Factor to the Evaluation of a Chemistry Upset at Ginna NPP (2006)』を含む、以前の報告書を更新するものです。EPRI報告書1009801（MRP-111）『Resistance to Primary Water Stress Corrosion Cracking of Alloys 690, 52, and 152 in Pressurized Water Reactors』とその改訂版であるEPRI報告書1018130（MRP-237）を補足します。ここで展開されるモデルは、経済計算、および併用期間中の適切な検査間隔と適切な合金特有の化学仕様を決定する技術的な基礎の作成の両方において役立ちます。

キーワード

蒸気発生器
材料劣化
Alloy 600MA
Alloy 600TT
Alloy 690TT
Alloy 800NG
改善要因
SG配管
蒸気発生器管理プログラム
化学ガイドラインの基盤

蒸気発生器の劣化

PWR

目次

図リスト

表リスト

증기 발생기 관리 프로그램: 가압수형 원자로 증기발생기 튜브 소재의 개선 요인

1019044

최종 보고서, 2009년 12월

보고서 요약

이 보고서는 이전에 개발된 PWR 증기발생기 튜브 소재용 첨단 합금의 사용과 관련된 개선 요인들을 갱신한다. 이 보고서에서는 제철소에서 소둔된 Alloy 600(Alloy 600MA) 증기발생기 튜브와 관련하여 열처리 Alloy 600(Alloy 600TT), 열처리 Alloy 690(Alloy 690TT), 그리고 Alloy 800 원자력 등급(Alloy 800NG)에 대한 개선 요인들에 대해 설명한다.

배경
과거에는 '개선 요인’ 의 사용을 통해 첨단 합금의 사용과 관련된 성능 증가를 예측하였다. EPRI 보고서 1003589는 Alloy 600TT와 Alloy 690TT에 대한 개선 요인들을

개발하여 제시했다. 그러나, 예상 고장 시간에 관한 현장 경험이 아직 짧아서 현장 경험에 기반한 이러한 개선 요인들의 예측은 지나치게 보수적일 수도 있다.

목적

- 다양한 등급의 튜브의 사용으로부터 얻은 내식성 개선에 대한 현재의 지식을 요약한다.
- 합금별 열화 내성 개선을 반영하여 현재의 수화학 지침에 대한 적절한 수정을 평가하기 위한 기반을 제공한다.

접근방법

이 보고서 작성 중 프로젝트 팀은

- 최근의 부식 사건과 고장이 많지 않은 추가 운전 시간을 반영하여 Alloy 600TT, Alloy 690TT, Alloy 800NG 튜브에 대한 경험 기반 개선 요인들을 갱신하였다.
- Alloy 600TT와 Alloy 690TT로 만들어진 증기발생기 튜브 플러그의 상대적인 성능을 고려하여 발전소 경험 분석을 보완하였다.
- Alloy 600MA에 대비한 Alloy 600TT, Alloy 690TT 및 Alloy 800NG의 실험실 기반 개선 요인들을 갱신하여 문헌 검토에 따라 최근 연구 결과를 포함시켰다.
- 나트륨 오염이 있는 모형 보일러에서 현재까지 수행된 실험들을 요약하였다. 모형 보일러 시험 프로그램은 발전소에서 일어나는 응력, 소재 및 열수력 조건과 매우 비슷하기 때문에 실제 발전소 성능의 합리적인 모사로 믿어진다. 그러나 이들 시험에서 얻은 화학조건은 정상 운전 중에 경험하는 것보다 더 공세적일 수도 있다.

결과

이 보고서에서 설명한 평가를 통해 Alloy 600MA에 대비한 Alloy 600TT, Alloy 690TT 및 Alloy 800NG의 보수적인 개선 요인들을 끌어냈다. 이러한 개선 요인들을 Alloy 600MA에서 얻은 경험과 함께 이용하여 PWR 증기발생기에서 미래의 튜브 열화 속도에 대한 보수적인 추정치를 구할 수 있다. 이 추정값은 보수적이므로 최선의 추정 예측값을 제공하지 않는다. 즉, 실제 튜브 열화를 과도하게 예측할 가능성이 높은 것으로 생각된다. 보수성의 수준은 데이터 집합 별로 다르기 때문에 이러한 개선 요인들은 3가지 합금의 상대적 성능을 비교하기에 적절하지 않다. 그러나 그 보수성으로 인해 이 개선 요인들은

전력회사들이 예를 들어 덜 엄격한 화학 지침을 사용하거나 검사 간격을 증가시켜서 이들 합금의 내식성에 의존할 수 있는 정도를 확립하는데 유용할 것으로 예상된다.

EPRI의 관점

이 보고서는 미래의 증기발생기 열화 가능성을 평가하는 전력회사들을 지원하기 위한 EPRI의 지속적인 노력의 일환이다. 이 보고서는 EPRI 보고서 1003589, "*가압수형 원자로 일반 튜브 열화 예측*" (2003)과 1013640, "*합금 690 개선 요인 업데이트: Ginna NPP에서 화학 업셋 평가에 대한 개선 요인의 적용*" (2006)을 포함한 이전 보고서들을 갱신한다. 이 보고서는 EPRI 보고서 1009801(MRP-111), "*가압수형 원자로에서 Alloy 690, 52 및 152의 일차 냉각수 응력부식균열에 대한 내성*" 과 그 개정판인 EPRI 보고서 1018130(MRP-237)에 대한 보충 정보를 제공한다. 여기에서 개발된 모형이 경제성 계산과 적절한 사용 중 검사 간격과 적절한 합금별 화학 규격을 결정하기 위한 기술 기반 개발에 도움을 줄 것으로 예상된다.

키워드

증기발생기
소재 열화
Alloy 600MA
Alloy 600TT
Alloy 6900TT
Alloy 800NG
개선 요인
SG 튜브
증기발생기 관리 프로그램
화학 지침 근거
증기발생기 열화
PWR

목차

그림 목록

표 목록

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

Programs:

Nuclear Power

Steam Generator Management Program

1019044

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com