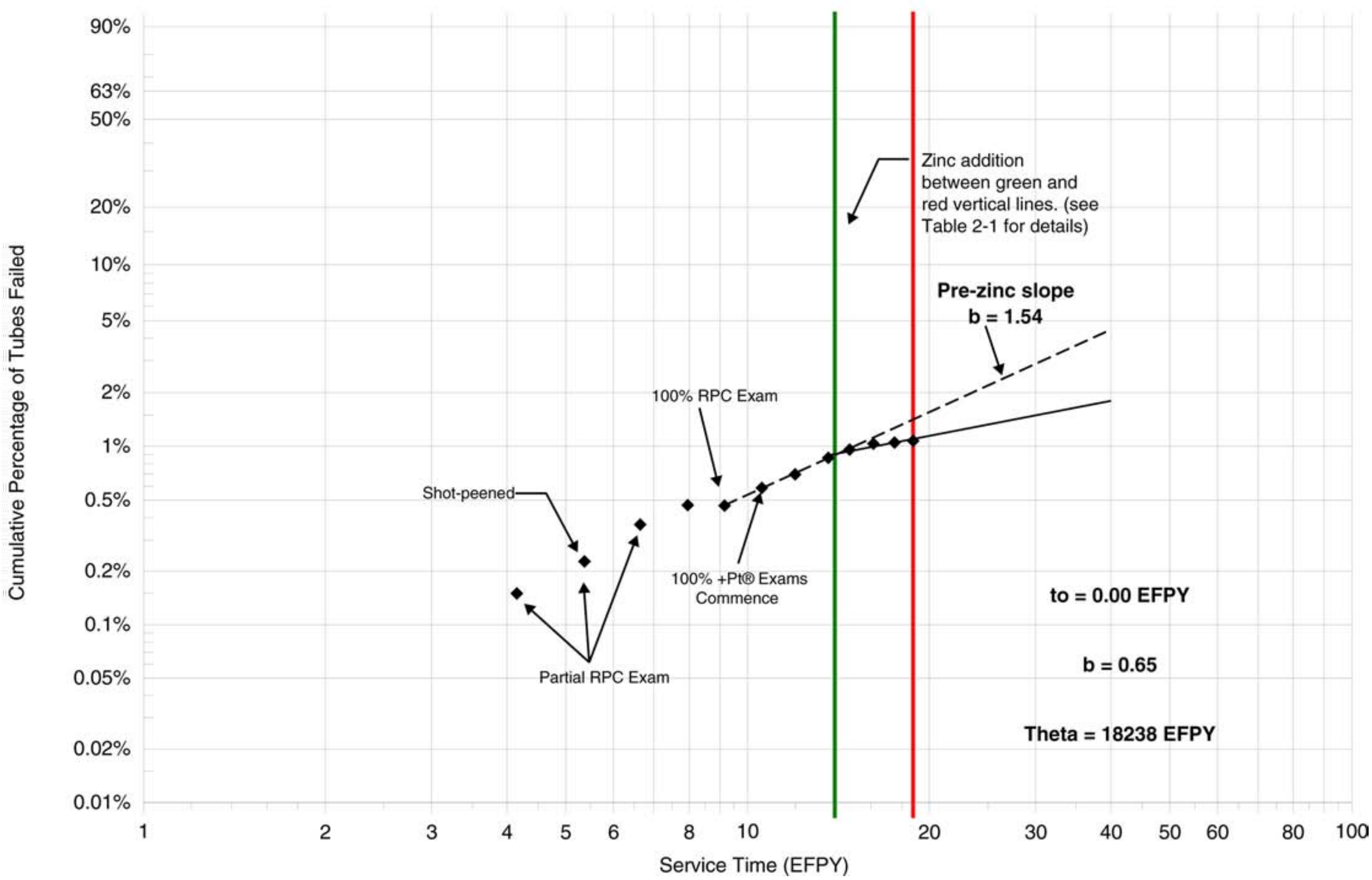
ELECTRIC POWER RESEARCH INSTITUTE

Evaluation of Plant Data to Determine Effects of Zinc on Primary Water Stress Corrosion Cracking

2008 Revision



Evaluation of Plant Data to Determine Effects of Zinc on PWSCC

2008 Revision

1016558

Final Report, December 2008

EPRI Project Manager
K. Fruzzetti

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.

Pacific Gas & Electric Company

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
Reston, VA 20190

Principal Investigators
C. Marks
V. Moroney
J. Gorman

Pacific Gas & Electric Company
Diablo Canyon Power Plant
Avila Beach CA, 93424

Principal Investigator
J. Arhar

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:

Evaluation of Plant Data to Determine Effects of Zinc on PWSCC: 2008 Revision. EPRI, Palo Alto, CA: 2008. 1016558.

REPORT SUMMARY

Zinc additions to the reactor coolant of PWRs have been made since June 1994 as a means of reducing radiation fields and mitigating primary water stress corrosion cracking (PWSCC) of Alloy 600 components. Most of the data regarding the effects of zinc addition on PWSCC are a result of laboratory studies. This report provides a detailed analysis of the effects of zinc on PWSCC using available plant steam generator (SG) data.

Background

In 2006, EPRI issued the *PWR Primary Water Zinc Application Guidelines* (EPRI report 1013420) to assist utilities in the use of zinc to mitigate radiation fields and PWSCC of Alloy 600 components. Laboratory studies have shown that zinc addition can double or more than double the time required to result in the occurrence of an equivalent amount of PWSCC in test specimens. Evaluations based on plant experience with mill annealed Alloy 600 steam generator tubes were documented in the original version of this report (EPRI report 1011775). Additional experience has accumulated since that report was published.

Objectives

To evaluate steam generator tube inspection data to determine the effects of zinc addition on the initiation and growth rate of PWSCC.

Approach

The project team analyzed the number of new PWSCC indications at dented tube support plates (TSPs) and in the explosively expanded (WEXTEX) region in the tube sheet to determine the rates of increase in PWSCC (measured in terms of Weibull slopes) that they exhibit. The team compared the Weibull slopes generated with and without zinc addition and also analyzed the voltage growth rate data, which is judged to be the most consistent measure of crack growth generally collected, for operating periods with and without zinc addition. The team focused on data from Diablo Canyon Units 1 and 2 (DCPP), which have been identified as the units with the most abundant PWSCC growth rate data due to application of alternate repair criteria (ARC) for TSP and WEXTEX axial PWSCC degradation, although they also used other plant data to supplement the DCPP data as required.

Results

The results from the analyses described above indicate that zinc addition is having a beneficial effect on mitigation of PWSCC. Individual plant results for TSP and tube sheet PWSCC show that post zinc Weibull slopes are 38-79% less than no zinc Weibull slopes. Industry median analyses show a similar range of reduction in Weibull slopes after zinc injection has been applied—54-79%. These results appear to confirm that use of zinc significantly decreases the overall rate of PWSCC initiation and growth to barely detectable levels based on plant SG data.

The results from the voltage growth analyses also appear to support this conclusion, specifically for crack growth rate mitigation. The voltage growth rates decrease about 40% for tube support plate PWSCC and about 17% for tube sheet PWSCC with the addition of zinc.

EPRI Perspective

The experience at Diablo Canyon and other units regarding the effects of zinc on PWSCC in SG tubes is encouraging since the rate of PWSCC at these plants is decreasing, rather than increasing as expected in the absence of zinc addition. Assessed in the context of overwhelming laboratory data that show a marked and consistent benefit of zinc on mitigation of PWSCC initiation, Weibull slope assessments of these plant SG data indicate that zinc is having a significant mitigating effect on the initiation of PWSCC and a moderate effect on the growth rate of PWSCC cracks. In this regard, it needs to be understood that cracks in SG tubes are relatively small in depth and grow slowly and thus might respond better to zinc addition than larger, faster growing cracks, such as those found in butt welds and control rod drive mechanisms.

Keywords

PWSCC
Alloy 600
Zinc
SG tubing
Tube support plates (TSPs)
Dents
WEXTEX

ABSTRACT

Primary water stress corrosion cracking (PWSCC) is an increasingly major issue at PWRs because of the high costs involved in inspecting and repairing areas with Alloy 600 type materials. In addition to steam generator tubes, the areas now being affected by PWSCC include control rod drive mechanism (CRDM) and instrument nozzles, nozzle to vessel J-groove welds, and large dissimilar metal butt welds. Several PWR units are currently adding zinc to the reactor coolant in an attempt to mitigate the corrosion. The purpose of this report is to update a previous evaluation (EPRI 1011775) of the beneficial effects of zinc on the mitigation of PWSCC initiation and growth rate.

Due to the lack of measured plant data regarding PWSCC in the reactor vessel head with which to make a robust evaluation of zinc effects, the analyses in this report were performed using steam generator data (which are much more abundant). Comparisons of Weibull slopes, maximum voltage growth rates, maximum depth growth rates, and the number of indications over time were performed for periods of operation with and without zinc. These comparisons were performed for PWSCC at dented tube support locations and PWSCC at explosively expanded areas in the tube sheet. The results from all of these analyses indicate that zinc addition is having a significantly beneficial effect on PWSCC mitigation (in terms of reduced number of new PWSCC indications and reduced PWSCC growth rates). For individual plants that have injected zinc, there are insufficient data to compare PWSCC growth rates before zinc injection and after zinc injection, thus growth rate datasets are combined from different plants to arrive at conclusions.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Primary water stress corrosion cracking (PWSCC) is an increasingly major issue at PWRs because it is now affecting many areas with Alloy 600 type materials in addition to steam generator tubes. These additional areas include control rod drive mechanism (CRDM) and instrument nozzles, nozzle to vessel J-groove welds, and large dissimilar metal butt welds. Because of the high costs involved in inspecting and repairing areas with Alloy 600 type materials, there is a large incentive to reduce the rate of crack initiation and growth due to PWSCC. Partly for this reason, zinc is now being added to the reactor coolant of an increasing number of PWRs. However, there is considerable uncertainty regarding how much benefit will be provided by zinc addition. Developing a firmer understanding of the effects of zinc on PWSCC in plants is important since it can affect planning and scheduling of inspections and application of other mitigating measures, as well as the specific zinc addition strategy.

Laboratory tests have shown that addition of zinc to reactor coolant results in longer times for equivalent amounts of PWSCC to occur in test specimens, e.g., by a factor of two for 20 ppb zinc. Some crack growth rate tests have indicated that zinc also slows down the rate of growth of PWSCC cracks, but other tests have shown no effect.

Evaluations of plant experience with PWSCC have been fairly limited to date. Experience prior to the initial version of this report (2005) regarding the possible role of zinc on PWSCC at these plants can be summarized as follows [1, 2]:

- In 1994, Farley 2 was the first PWR to perform zinc addition to the reactor coolant system. Farley 1 began zinc addition in 1999. Both units experienced SG tube PWSCC in the tube sheet region. However, the steam generators (SGs) at both Farley 1 and 2 were replaced in 2000/2001, and no conclusions regarding the effects of zinc on PWSCC in the steam generators were reached [3]. On the other hand, no PWSCC has been detected in the reactor vessel head at Farley 2 despite it having many nozzles made of a heat of material that has cracked extensively at other plants. This is encouraging since Farley 2 has used zinc for many cycles while it has not been used at the other plants that have experienced cracking in this heat, but other factors such as service temperature and details of fabrication are also involved so this experience is not conclusive. The reactor vessel head at Farley 2 was replaced on a preventive basis during the fall 2005 outage, and detailed examination of nozzles from the removed Farley 2 head, being conducted by the PWR Owners' Group, will provide firmer data regarding the benefits of zinc at mitigating PWSCC.
- Diablo Canyon 1 and 2 started zinc injection in 1998 and 1999. Both units have experienced PWSCC in their steam generators at dented tube support plate (TSP) intersections and in the explosively expanded (WEXTEX) areas of the tubes in the tube sheets. Preliminary evaluations of the Diablo Canyon data showed a decreasing trend in the number of new PWSCC indications following zinc injection, but the results were judged in 2004 as not being conclusive pending more detailed evaluation.

- As of late 2004¸ Beaver Valley 1 had only used zinc injection during two cycles for a combined duration of approximately 13 months. Beaver Valley 1 has experienced SG tube PWSCC in the WEXTEX tube sheet region. No evaluations had been performed of how the addition of zinc has affected the rate of PWSCC at this unit, due to the short operating period with zinc addition.

The purpose of the original issue of this report was to perform evaluations to develop a more definitive understanding of the effects of zinc addition on the initiation and growth rate of PWSCC in operating PWRs. Due to the lack of measured plant data regarding PWSCC in reactor vessel heads with which to make a robust evaluation of zinc effects, the analyses in that report were performed using steam generator data (which are much more abundant). In the three years since the issuance of the original version of this report, additional data have become available, justifying this revision. However, nearly all of the steam generators which provided data for this analysis have been or will soon be replaced. Therefore, no additional updates are anticipated.

2 WEIBULL SLOPE COMPARISON

2.1 Weibull Approach

SG tubes are susceptible to degradation by corrosion and wear at a number of locations. However, due to systematic and statistical variations in material properties, environmental parameters, and stress levels from tube to tube and location to location, all susceptible tubes will not develop defects at the same time; failures[1] instead cover a temporal range. For many types of degradation, the time interval from the first tube failure due to a given mechanism until the last tube would hypothetically fail is quite long (several decades). Experience with the large number of operating SGs in the nuclear industry, worldwide, has shown that tube degradation can be modeled by statistical distribution functions that describe the rate at which a given type of degradation spreads through the population of tubes. As documented, for example, in EPRI Reports NP-7493 [4] and TR-103566 [5], the Weibull statistical distribution has been found to yield good results in predicting the SG tube degradation behavior at numerous plants. Consequently, the Weibull statistical distribution function has often been used for modeling tube degradation and is used here.

In the form used for these analyses, the Weibull probability distribution function is defined by two parameters. The Weibull slope parameter (designated by the symbol b) is related to the rate at which degradation spreads through the tube population after it is first detected.[2] High values of b correspond to degradation which spreads rapidly through the tube population. The other Weibull parameter, the characteristic time (designated as theta or θ), is a measure of the time scale for the degradation; it defines the time at which 63.2% of the tubes are predicted to be degraded.

For a SG that has experienced significant levels of tube degradation over a number of years, the characteristics of the failure time distributions that describe tube degradation can be determined by fitting distribution curves to the plant data. The fitted distributions then provide a mathematical description of the predicted future evolution of tube repairs. Analysis of data for plants that have had significant levels of degradation has confirmed that the Weibull distribution effectively fits the data (albeit with a level of uncertainty), even for large fractions of tubes repaired [5].

---

[1] The term "failure" refers to the detected presence of a structural defect via one of several corrosion or wear mechanisms. This can be distinct from the repair (plug or sleeve) used to remediate the failure (e.g., less than 40% through-wall wear indications can be left in service)—although in most cases the "failure" and "repair" are simultaneous since the defect is repaired upon detection, except for plants that use alternate repair criteria.

[2] Specifically, b is the slope of the line $Y = \ln(-\ln(1-F)) = b \ln(t/\theta)$, where F is the cumulative failure fraction, and t is the time of operation.

The corrosion related steam generator tube degradation mechanisms included in the following analyses are considered to be thermally activated. In the Weibull failure time formulation, the parameter theta is essentially the time constant of the degradation process. Theta is expected to be affected by temperature in accordance with the Arrhenius relationship that describes thermally activated processes. This expectation has been found to hold true in empirical studies of both laboratory and plant data. The Weibull slope parameter is essentially a measure of the proportional breadth of the failure time distribution. If degradation rates for all samples in a population are affected proportionally by a change in temperature, the Weibull slope parameter will not be changed. Although a systematic variation of the Weibull slope parameter with temperature cannot be precluded on a theoretical basis, empirically, both in lab studies and plant analyses, Weibull slope parameters show no systematic variation with temperature.

2.2 Tube Support Plate PWSCC

2.2.1 Background of Tube Support Plate PWSCC

Only eight units are known to have experienced axial tube support plate PWSCC (axial TSP PWSCC) at dents in their original SGs: Beaver Valley 2, Diablo Canyon 1 and 2, North Anna 1 and 2, Salem 2, Sequoyah 1 and 2. Some of these units have also experienced circumferential TSP PWSCC at dents.

The more heavily affected units, i.e., Diablo Canyon 1, Diablo Canyon 2, and Sequoyah 1, have attempted to limit repairs through the use of alternate repair criteria (ARC) for axial TSP PWSCC. Starting in 1999, these units used a 40% through-wall (tw) repair criterion for tubes with axial TSP PWSCC defects. Starting in 2001, an ARC was licensed at each unit, allowing tubes with indications greater than 40% tw to remain in service as long as the axial PWSCC indication meets certain criteria. Use of the ARC requires that each axial PWSCC indication be profiled by eddy current sizing analysts, who assign phase angle, depth, voltage, and axial location (relative to the center of the TSP) to each Plus Point® “hit” of the indication. These length and depth profiles are then adjusted using special processing software based on rules developed for the ARC, documented in WCAP-15128 [6] and WCAP-15573 [7]. Growth rates are developed for maximum depth, average depth, length, and maximum volts, and the length and depth growth rate distributions are used as inputs to the PWSCC ARC Monte Carlo analysis to define the need for tube repair.

2.2.2 Modeling Methodology for Tube Support Plate PWSCC

It was judged reasonable to initially limit the Weibull analysis for this mechanism to the group of eight units known to have axial TSP PWSCC at dents. Beaver Valley 2 and Sequoyah 2 were then excluded due to small numbers of cumulative tube failures (less than 20 tubes). In general, the failure rates were developed using the following guidelines:

- The data presented are primarily based on information available from the EPRI Steam Generator Degradation Database (EPRI SGDD) [8]. Where necessary, the data were supplemented with information supplied directly from the unit or other sources, as was the case for the units that used the axial TSP PWSCC ARC.

- For the plants using ARC, it was necessary to determine the number of new tubes affected during each of the outages involved rather than relying on the number of tubes repaired so that all units could be compared on the same basis. Because the EPRI SGDD provides mostly tubes repaired data, the tubes affected data presented were provided by the utilities and other sources.
- The possible effects of inspection transients (e.g., type of probe, inspection scope) on the Weibull slope were reviewed. Some early data points, often probably representing data obtained prior to an inspection transient, were excluded in order to minimize the error in the fit of the data to the Weibull distribution. The fits presented below were selected to have small Weibull fit errors while including the maximum practical number of reliable data points. In other cases (early DCPP 1 TSP PWSCC data), the inspection data were corrected to account for inspection transients, as discussed in detail later in this section.
- If a unit changed temperature, the effects of any hot leg temperature changes were incorporated into the analyses by defining an equivalent operating time using the Arrhenius equation and a Q value of 50 kcal/mole for crack initiation [4]. The Weibull plots of the affected units have been labeled with the temperature to which the EFPYs have been adjusted. The equivalent operating times are termed effective degradation years (EDYs) referenced to a specific temperature. As noted previously, Weibull slopes have shown no systematic variation with temperature. Therefore, slope parameters are considered to be temperature independent. Plots for the units without temperature changes are simply labeled in EFPY.
- For Diablo Canyon 1 and 2 (DCPP), separate pre- and post-zinc slopes were developed. The zinc addition history for each of these units is shown in Table 2-1. The post-zinc injection slopes include data from the last cycle of no zinc injection as a way of capturing the rate change during the first cycle of operation with zinc.

Each unit is discussed in more detail below.

2.2.2.1 Diablo Canyon 1 (Original SGs)

Because an ARC is used at Diablo Canyon for TSP PWSCC defects, it was necessary to determine the number of new tubes affected during each of the outages involved rather than relying on the number of tubes repaired. The number of tubes affected for both DCPP 1 and 2 is shown in Table 2-2. Figure 2-1 is a graphical representation of the data tabulated for TSP PWSCC. As can be seen in the graph, Diablo Canyon 1 first observed TSP PWSCC defects during EOC 6. The graph also shows that the incremental number of tubes affected appears to have followed a declining trend since zinc addition began during Cycle 9, although the initial decrease from EOC 8 to EOC 9 could also reflect the expected decline in identification of new PWSCC sites due to the enhanced inspection methodology used at EOC 8. The total numbers detected have still been of some significance, with approximately 3% of the tube population affected by this mechanism as of EOC 14[3]. The majority of the defects have been axial in orientation.

---

[3] The nomenclatures "EOC *n*" and "*m*R*n*" are both used interchangeably to refer to the refueling outage at the end of the *n*th cycle at unit *m* (e.g., EOC 12 at Unit 1 or 1R12).

Table 2-1
Zinc injection history for Beaver Valley 1, Diablo Canyon 1 and 2, and Sequoyah 2

Cycle No.	Zn Addition Days				Cycle No.	Zn Addition Days			
	Start	End	Months	Nom. or Ave. Zn Conc., ppb		Start	End	Months	Nom. or Ave. Zn Conc., ppb
Beaver Valley 1					**Diablo Canyon 2**				
15	12/11/2002	2/22/2003	2.4	35 target	9	3/17/1999	8/25/1999	5.4	21
16	12/3/2003	10/2/2004	10.2	33.6 (avg)	10	2/12/2000	3/24/2001	13.4	16
Diablo Canyon 1					11	7/3/2001	1/20/2003	18.9	20
9	6/24/1998	1/14/1999	7	31	12	5/01/2003	9/25/2004	17.1	25
10	12/8/1999	9/22/2000	9.6	21	13	1/01/2005	4/10/2006	15.5	25
11	2/1/2001	4/10/2002	14.4	15					
12	7/26/2002	3/01/2004	19	24	**Sequoyah 2**				
13	6/12/2004	9/25/2005	15.6	25	12	9/24/2002	10/15/2003	12.9	2.6
14	12/20/05	4/30/07	16	25	13	12/17/2003	4/14/2005	15.8	4.8
					14	6/03/2005	11/25/2006	17.5	5
					15	12/30/2006	5/02/2008	16	5

Table 2-2
Number of new PWSCC tubes affected per outage at Diablo Canyon

Unit 1 (axial and circumferential)										
EFPY	5.86	7.14	8.46	9.75	11.37	12.87	14.28	15.88	17.22	18.61
Outage	1R5 / EOC 5	1R6 / EOC 6	1R7 / EOC 7	1R8 / EOC 8	1R9 / EOC 9	1R10 / EOC 10	1R11 / EOC 11	1R12 / EOC 12	1R13 / EOC 13	1R14 / EOC 14
TSP	0	31	75	127	67	55	19	15	17	15
TS	0	2	3	5	9	4	4	2	1	2
Total	0	33	79	131	76	59	23	15	18	17

Unit 2 (axial and circumferential)									
EFPY	5.74	7.08	8.41	10.03	11.49	12.93	14.53	16.09	17.4
Outage	2R5 / EOC 5	2R6 / EOC 6	2R7 / EOC 7	2R8 / EOC 8	2R9 / EOC 9	2R10 / EOC 10	2R11 / EOC 11	2R12 / EOC 12	2R13 / EOC 13
TSP	17	3	73	33	26	24	31	11	5
TS	26	13	50	33	19	4	9	3	4
Total	43	16	123	66	45	28	40	14	9

Notes

1. Plus Point® inspection started at EOC 7 for each unit. First 100% Plus Point® inspection for each unit was EOC 9 for Unit 1 and EOC 8 for Unit 2.
2. For each unit, zinc injection started late in Cycle 9, i.e., after 1R8 and 2R8.

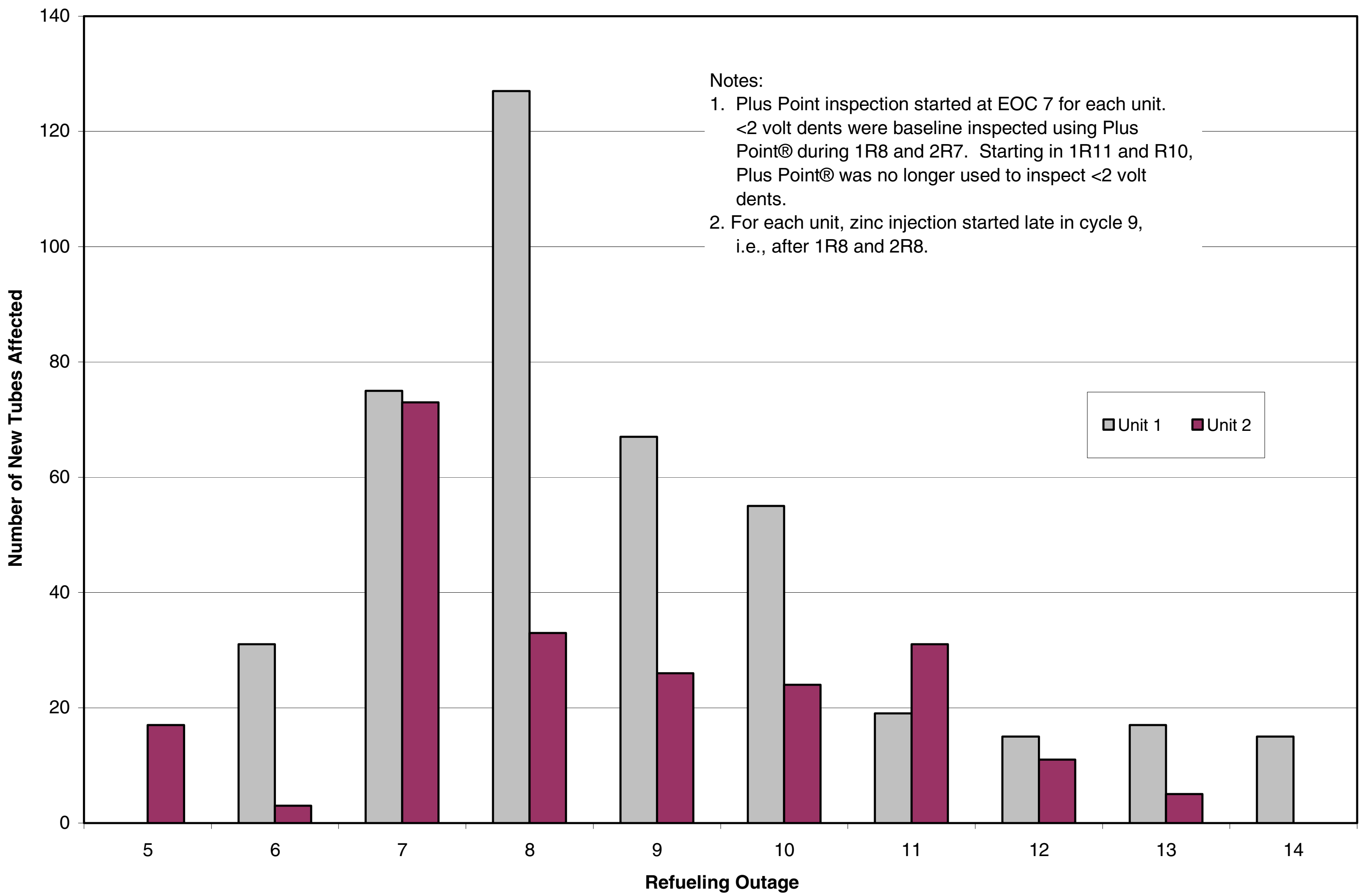


Figure 2-1
Number of new tubes affected with TSP PWSCC per outage at Diablo Canyon

Diablo Canyon 1 was originally operated with a nominal T_{hot} temperature of 603°F. However, the nominal T_{hot} increased to 604°F after EOC 10 due to a power uprate. All EFPY values were adjusted to a temperature of 603°F for this analysis.

Because Diablo Canyon 1 began injecting zinc in 1998, two different failure rates (pre-zinc and post-zinc Weibull slopes) were determined. Three data points were available for the pre-zinc Weibull fit, i.e., EOC 6 through EOC 8. While the error in the Weibull fit to these three points is relatively small (6.6%), it must be noted that each of the three data points is the result of a different inspection methodology. DCPP 1 began performing partial inspections of the TSPs with Plus Point® probes at EOC 7. In addition, the dent inspection scope was increased at EOC 8, as described in Table 2-3; starting at EOC 8, <2 volt dents were baseline inspected using Plus Point® for the first time when it was discovered that the bobbin coil was detecting many PWSCC indications in <2 volt dents that were not originally planned for Plus Point® inspection. This led to a large number of new indications being detected in <2 volt dents (see Figure 2-2[4]). So, for DCPP Unit 1, the large numbers of PWSCC indications detected in EOC 7 and EOC 8 are due to two distinct inspection transients (in EOC 7 due to first time use of Plus Point®, and in EOC 8 due to first time inspection of less than 2 volt dents). Since no two of the pre-zinc data points came from consistent inspection methodologies, confidence in the fit determined by these three points is low. For this reason, it was judged reasonable to attempt to smooth out the inspection transitions by determining as accurately as practical how many tubes would have been detected with PWSCC at the TSPs if the same inspection methodology used at EOC 8 had also been used for EOC 6 and EOC 7. This was performed in the following manner:

- First, DCPP personnel performed a review of the growth rate data set for new axial PWSCC at dented TSPs for EOC 8 through EOC 12 inspections for both units to determine the Plus Point® voltage at and above which indications would probably be called by the analysts. This was determined by identifying which indications had a calculated growth rate based on look-backs to previous inspections. These data represent the first time back to back Plus Point® inspections were conducted. (That is, the first time axial PWSCC was detected represents the second time the Plus Point® probe was used.) The median Plus Point® maximum voltage of these first time detections was 0.5 volts, which represents the median Plus Point® detection threshold for TSP axial PWSCC at DCPP.
- The EOC 7 and EOC 8 TSP axial PWSCC growth rate data for DCPP 1 were then examined in more detail to determine which indications would have been called if the same inspection methodology used at EOC 8 had also been used for all previous inspections.
  - For the indications that had a calculated growth rate, i.e., were inspected by Plus Point® during both EOC 7 and EOC 8, the indication was assumed to have been detected during EOC 8, regardless of the maximum voltage recorded during EOC 8, since no TSP axial PWSCC was detected by the EOC 7 Plus Point® examination.

---

[4] Figure 2-2 shows the combined incremental number of new TSP axial PWSCC indications detected over time at both DCPP units. The numbers of PWSCC indications are categorized as occurring in <2 volt dents, between 2 and 5 volt dents, and >5 volt dents. These dent voltage categories correspond to the categories adopted for rotating coil examinations performed in each outage. The trend in Figure 2-2 is similar to that in Figure 2-1, with the numbers peaking at R7 (for >2 volt dents) and R8 (for <2 volt dents). These outages coincide with the changes in inspection methodologies described for DCPP. All three voltage categories show the same decreasing trend for the more recent outages.

- For the indications that did not have a calculated growth rate, time adjustments were made. It was assumed that these TSPs had never received a prior Plus Point® inspection. This was judged to be a fair assumption, considering that the vast majority of new PWSCC indications are traceable in the prior inspection and would have been identified in the lookback if Plus Point® had been previously used. The data set of indications that had no calculated growth rates was reviewed for potential time adjustments to approximate the number of indications that would have been detected in an earlier outage had Plus Point® been used. If the maximum voltage of the indication was less than 0.5 volts, no time adjustment was made. For indications with a maximum voltage exceeding 0.5 volts, it was assumed that the flaw could possibly have been detected in an earlier outage had Plus Point® been used. To arrive at an approximate earlier outage, the following equation was used:

$$EFPY_{adj} = EFPY_{act} - \frac{(V_{max} - 0.5\text{V})}{0.23\text{V/EFPY}}$$

where

$EFPY_{adj}$ = the adjusted EFPY value
$EFPY_{act}$ = the actual EFPY value
V_{max} = the maximum Plus Point® voltage measured for the tube
0.5V = the median Plus Point® detection threshold for TSP axial PWSCC
and 0.23 v/EFPY[5] = the assumed growth rate.

The indication was assumed to have been detected during the outage with the closest EFPY value after the adjusted EFPY. For example, if the adjusted EFPY was calculated to be 8.75 EFPY, the indication was assumed to have been detected during EOC 8 at 9.75 EFPY.

- This method shows the following:
  - In 1R8, 126 tubes were detected with TSP axial PWSCC (additional circumferential indications were detected but not considered in this trending due to the small number). 64 of these tubes would have been detected in earlier outages had Plus Point® been used, of which 29 would have been detected in 1R7.
  - In 1R7, 71 tubes were detected with TSP axial PWSCC (additional circumferential indications were detected but not considered in this trending due to the small number). 59 of these tubes would have been detected in earlier outages had Plus Point® been used, of which 14 would have been detected in 1R6.

A pre-zinc slope was then developed using the adjusted EOC 6, EOC 7, and EOC 8 data. The Weibull slope parameter for this adjusted pre-zinc fit is $b = 2.01$.

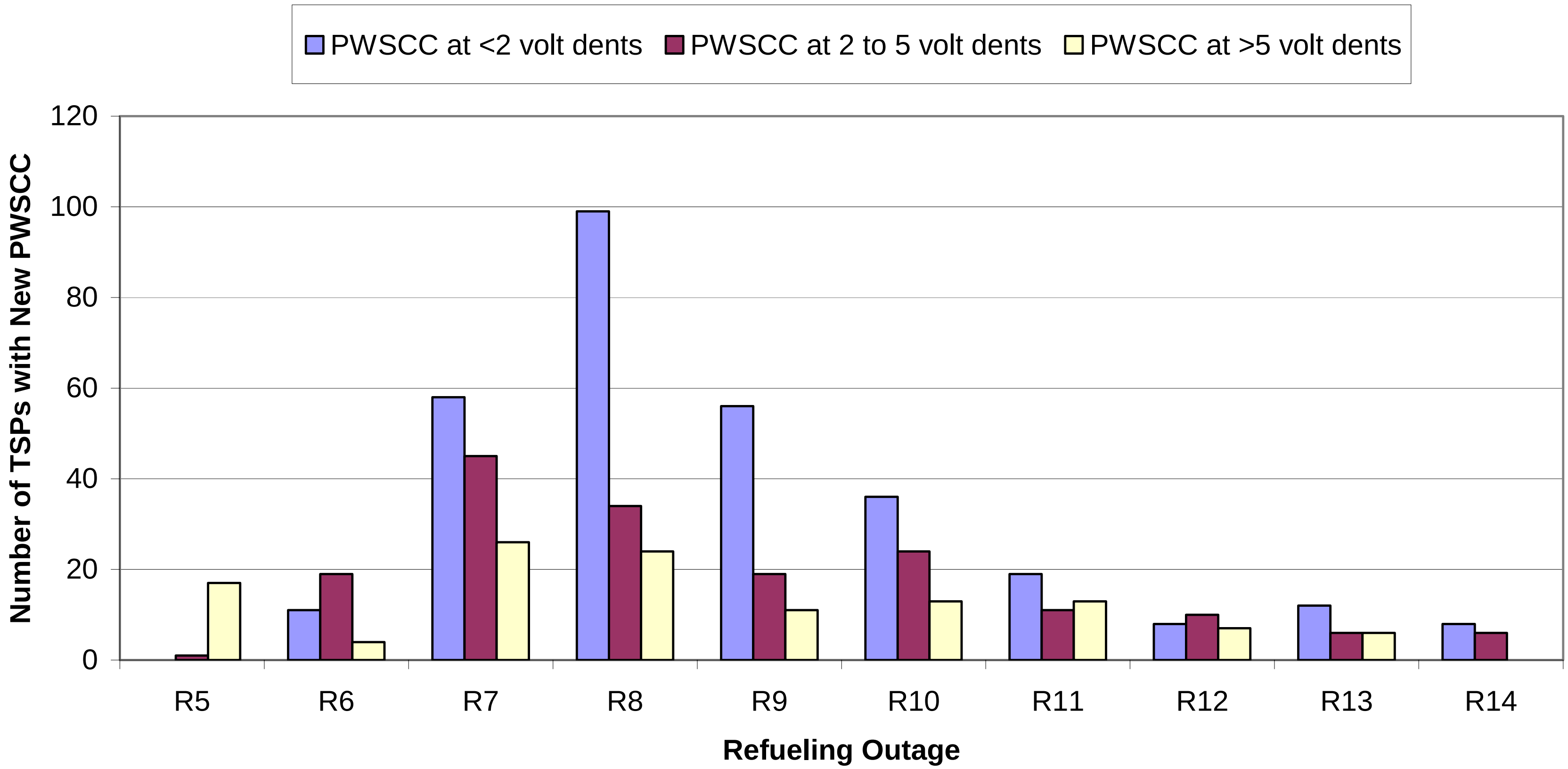
[5] The growth rate is based on the mean growth rate developed in the next chapter for the DCPP Cycle 8 data.

Table 2-3
Diablo Canyon 1 and 2 dent inspection scope

Outage	Number of TSP Intersections with New Axial PWSCC	Critical Area Inspections (%)			Notes
		<2v dents	2 to 5v dents	>5v dents	
1R5	0	0	0	0	
1R6	31	0	0	100	
1R7	73	0	100	100	first time Plus Point
1R8	130	100	100	100	
1R9	65	100	100	100	
1R10	53	100	100	100	
1R11	18	100	100	100	bobbin used for <2V dents
1R12	15	100	100	100	bobbin used for <2V dents
1R13	20	100	100	100	bobbin used for <2V dents
1R14	14	100	100	100	bobbin used for <2V dents
2R5	18	0	0	100	
2R6	3	0	0	100	
2R7	56	100	100	100	first time Plus Point
2R8	27	100	100	100	
2R9	21	100	100	100	
2R10	20	100	100	100	bobbin used for <2 v dents
2R11	25	100	100	100	bobbin used for <2 v dents
2R12	10	100	100	100	bobbin used for <2 v dents
2R13	4	100	100	100	bobbin used for <2 v dents

The post-zinc slope was developed using data for EOC 8 through EOC 14. The EOC 8 through EOC 10 data points were from 100% Plus Point® inspections.[6] The EOC 11 and EOC 14 data points were from 100% combined bobbin/ Plus Point® inspections (Plus Point® was no longer used to inspect <2 volt dents, and bobbin coil was relied upon for detection of PWSCC based on the completion of the bobbin qualification program as part of the PWSCC ARC development). This change in inspection methodology has resulted in less Plus Point® inspections, but is judged not to have had a significant affect on the number of new PWSCC indications detected. The error in the Weibull fit using all five data points is relatively small (5.5%), so using all five data points for the post-zinc fit was judged to be acceptable. The Weibull slope parameter for the post-zinc fit is $b = 0.85$. Both the pre- and post-zinc fits are shown in Figure 2-3.

[6] For TSP PWSCC, the term 100% inspections refers to inspections of all dented TSPs located in the critical areas where PWSCC has been observed, on a SG basis.



<u>Critical area dent inspection scopes:</u>
1R5: NA
2R5, 1R6, 2R6: 100% of >5v dents with RPC
1R7/2R7 to R12: 100% of >2v dents with PP
2R7/1R8 to 2R9/1R10: 100% of <2v dents with PP
2R10/1R11 to R12: bobbin credited for <2v dents inspection

Figure 2-2
Number of TSP intersections affected with new axial PWSCC indications per outage at Diablo Canyon 1 and 2 (combined data)

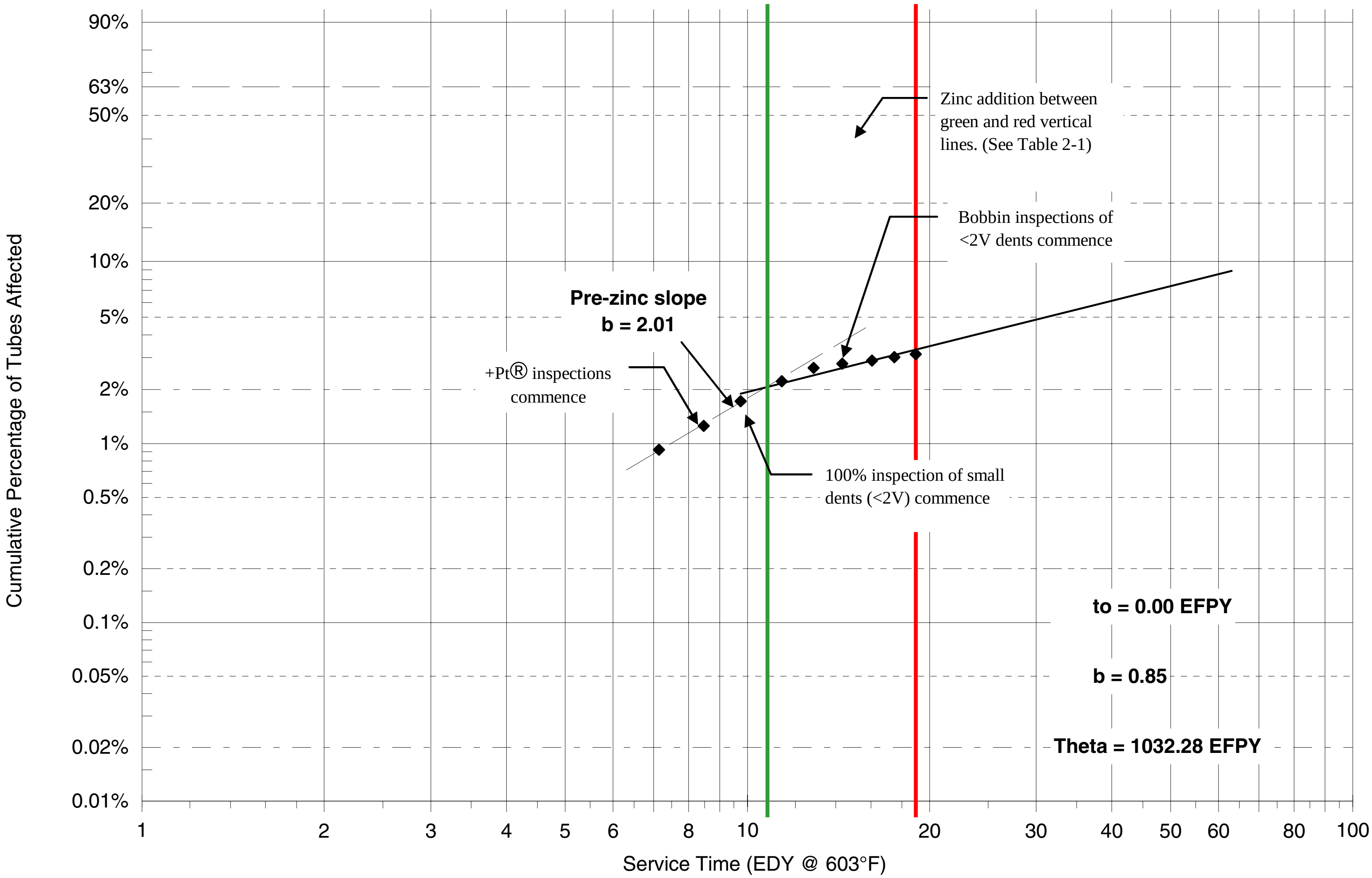


Figure 2-3
Diablo Canyon 1 – all SGs – TSP PWSCC (axial and circ.) – tubes affected

2.2.2.2 Diablo Canyon 2 (Original SGs)

As mentioned above, an ARC for TSP PWSCC is used at Diablo Canyon 2 as well as DCPP 1. The number of tubes affected for DCPP 2 is shown in Table 2-2. Figure 2-1 is a graphical representation of the data tabulated for TSP PWSCC. As can be seen in the graph, TSP PWSCC defects were first detected at Diablo Canyon 2 during EOC 5. The number of tubes affected at Unit 2 is less than at Unit 1, with less than 2% of the total tube population having a defect of this type as of EOC 13. As with Unit 1, the defects have been primarily axial in orientation. Note that the graph shows a decline in the incremental number of tubes affected starting in EOC 8, prior to the injection of zinc. This decrease could reflect the natural decline in identification of new PWSCC sites due to the enhanced inspection methodology used in the prior outage. As described in Table 2-3, DCPP 2 began performing partial inspections of the TSPs with Plus Point® probes at EOC 7. During this same outage, <2 volt dents were baseline inspected using Plus Point® for the first time. So for DCPP 2, the large number of PWSCC indications detected in EOC 7 is due to a single inspection transient (first time use of Plus Point® combined with first time inspection of less than 2 volt dents). A decrease in the incremental number of tubes affected could be expected during the next inspection, EOC 8, since the same inspection methodology was used. The fact that the incremental number of new tubes affected has remained low since then is attributed to zinc.

Diablo Canyon 2 original SGs maintained a T_{hot} operating temperature of 603°F throughout its history.

Because Diablo Canyon 2 began injecting zinc in 1999, two different failure rates were determined. The pre-zinc failure slope was developed using data for the two inspections immediately prior to the addition of zinc, i.e., EOC 7 and EOC 8. Inspections for both outages were performed using similar techniques, i.e., 100% Plus Point® inspections (including <2V dents). Inclusion of the EOC 5 and EOC 6 data, which were collected prior to the use of the Plus Point® probe for inspecting dents at Diablo, would have increased the error in the Weibull fit to 31%. The Weibull slope parameter for the pre-zinc fit is $b = 1.76$. The post-zinc slope was developed using data for EOC 8 through EOC 13. The same inspection techniques were used during the EOC 8 and EOC 9 outages. The data from EOC 10 through EOC 13 are products of 100% combined bobbin/ Plus Point® inspections (bobbin probes were used to inspect <2V dents). As with DCPP 1, this change is judged not to have any transient affect on the number of new PWSCC indications detected. The error in the post-zinc Weibull fit is relatively small (2.4%), so using all five data points for the post-zinc fit was judged to be acceptable. The Weibull slope parameter for the post-zinc fit is $b = 1.09$. Both the pre- and post-zinc fits are shown in Figure 2-4.

Note that Figure 2-5 was prepared as part of the review of the DCPP data. It shows the declining trend of axial PWSCC at DCPP 1 and DCPP 2 as the TSP elevation increases, reflecting the strong dependence of PWSCC on temperature. About 75% of PWSCC indications occur at the hot leg sides of the 1^{st} TSP (1H) and 2^{nd} TSP (2H), with 90% occurring up to the 3^{rd} TSP (3H).

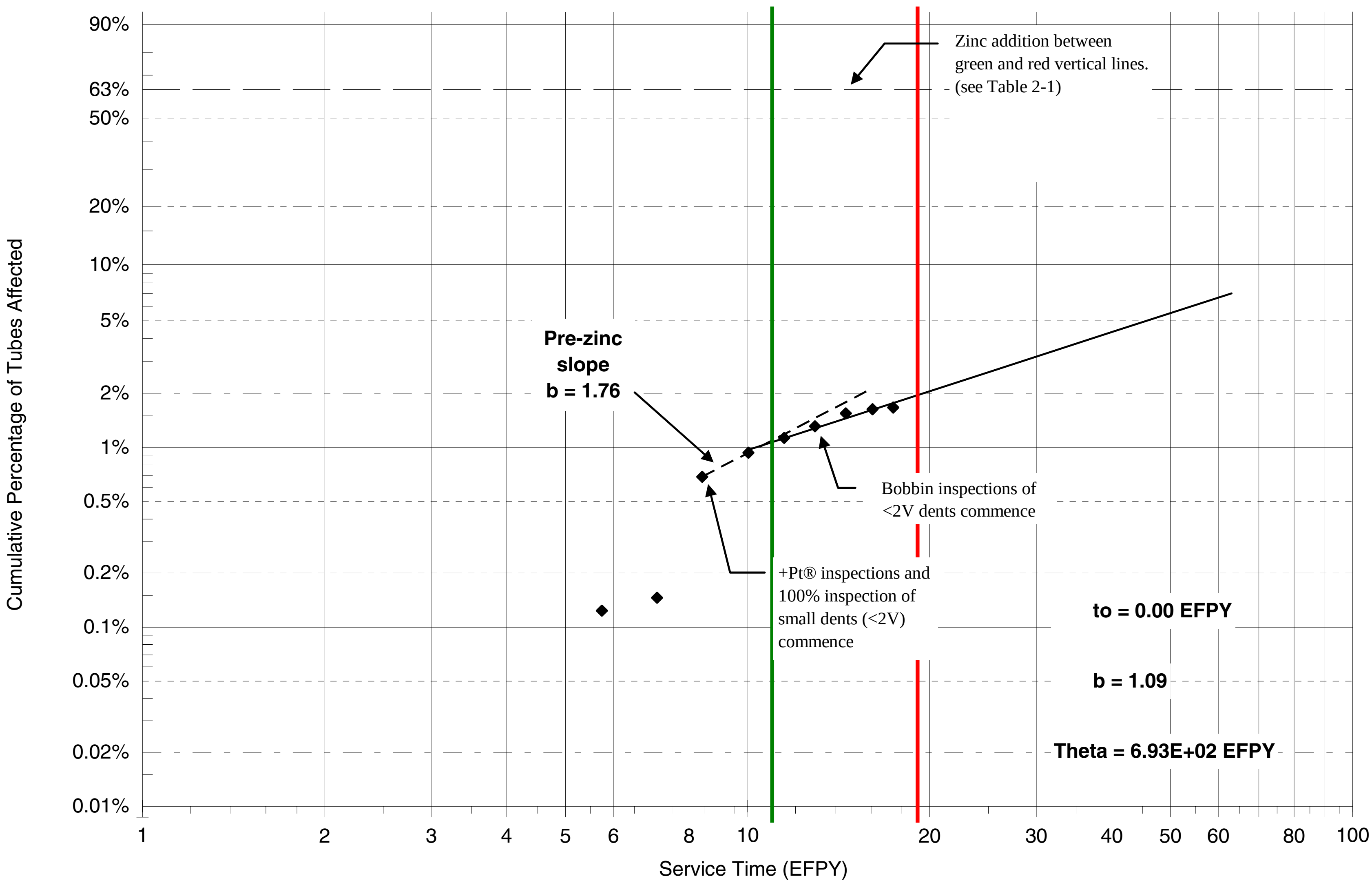


Figure 2-4
Diablo Canyon 2 – all SGs – TSP PWSCC (axial and circ.) – tubes affected

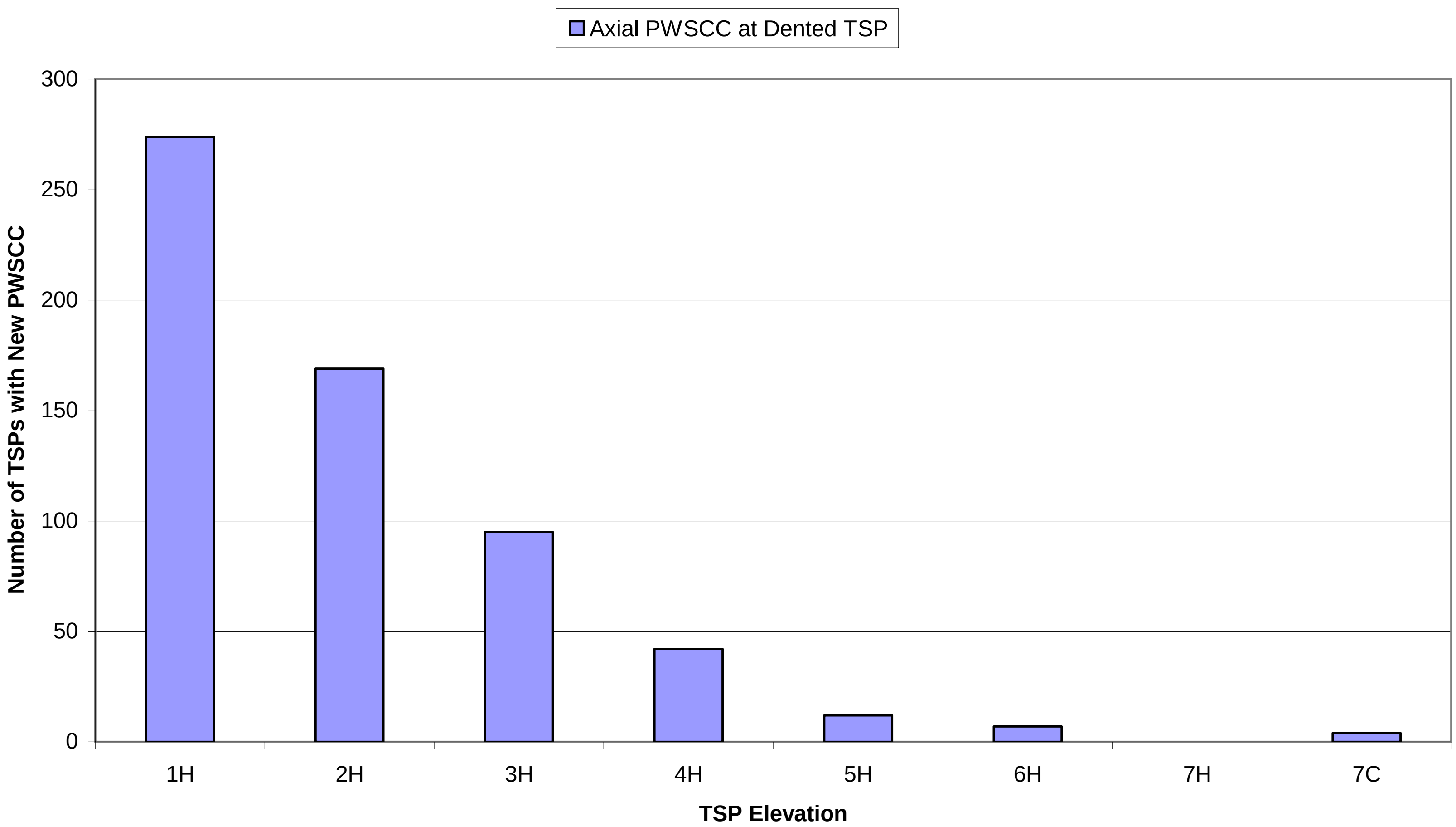


Figure 2-5
Number of TSP intersections with axial PWSCC indications per elevation at Diablo Canyon 1 and 2 (combined data)

2.2.2.3 North Anna 1 (Original SGs)

North Anna 1 first observed TSP PWSCC defects fairly early in life, prior to EOC 4. It continued to detect these defects until the SGs were replaced at EOC 9. As of the last inspection in late 1991, North Anna 1 had over 9% of its tubes repaired due to this mechanism. All of these tubes were repaired due to axially oriented defects.

The hot leg temperature at North Anna 1 was changed more than once during the life of the original SGs. North Anna 1 was originally operated with a T_{hot} temperature of 614°F, but T_{hot} was increased to 618°F during Cycle 6. T_{hot} remained at that temperature until midway through Cycle 9 when T_{hot} was reduced to 612°F. All EFPY values were adjusted to a temperature of 618°F for this analysis.

The failure rate for North Anna 1 was determined using the inspection data for EOC 6 through EOC 8, including the leaker outage during Cycle 7 and the midcycle outage following EOC 8. Despite a change in inspection technology after EOC 6 (from bobbin to 8x1[7] probes), the data from these five inspections were judged to be the most representative of the failure rate late in the life of the SGs, with a Weibull fit error of only 5.5%; inclusion of data prior to EOC 6 would have increased the error of the Weibull fit substantially. The Weibull slope parameter based on the five inspections is b = 2.08, as shown in Figure 2-6.

2.2.2.4 North Anna 2 (Original SGs)

North Anna 2 first detected TSP PWSCC defects during the EOC 4 inspections. Only a few tubes were plugged at each of the next several outages, then a larger number was found during the EOC 9 exam, the last inspection prior to replacement. In total, slightly more than 1% of North Anna 2's tube population was repaired due to this mechanism. As with North Anna 1, all of the defects detected were axial in orientation.

As with North Anna 1, North Anna 2 was originally operated with a T_{hot} temperature of 614°F. T_{hot} was increased to 618°F during Cycle 5 and remained at that temperature until the SGs were replaced. All EFPY values were adjusted to a temperature of 618°F for this analysis.

The failure rate for North Anna 2 was developed using the inspection data for the last four inspections prior to replacement (EOC 6 through EOC 9). The first two data points were the result of 100% 8x1 exams. The other two were the result of 100% rotating pancake coil (RPC) exams. All four data points were used in an attempt to generate a reasonable slope; the Weibull slope calculated using just the two RPC points is fairly high (b = 10.13). Inclusion of the EOC 5 data point would have doubled the error of the Weibull fit, so that data point was excluded. The Weibull slope parameter based on these four inspections is b = 6.68 (see Figure 2-7), with a Weibull fit error of 20.1%.

---

[7] The 8x1 probe, also referred to as a "pancake array," consists of an overlapping array of eight (two sets of four coils at different elevations) independent pancake coils spring-loaded against the inner surface of the tube. This probe is similar to, though not as sensitive as, a rotating pancake coil (RPC) probe.

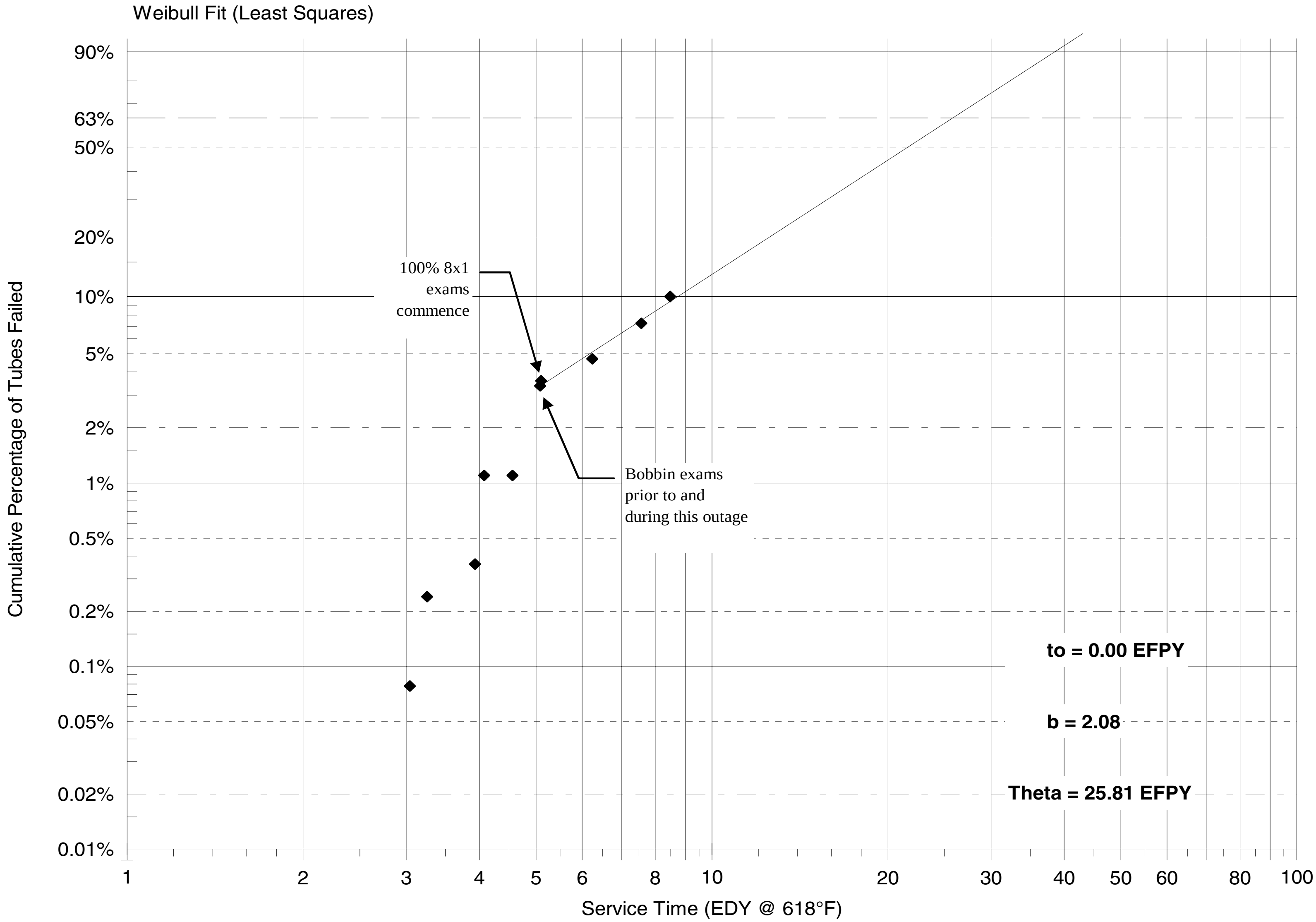


Figure 2-6
North Anna 1 – all original SGs – TSP PWSCC (axial and circ.) – tubes repaired

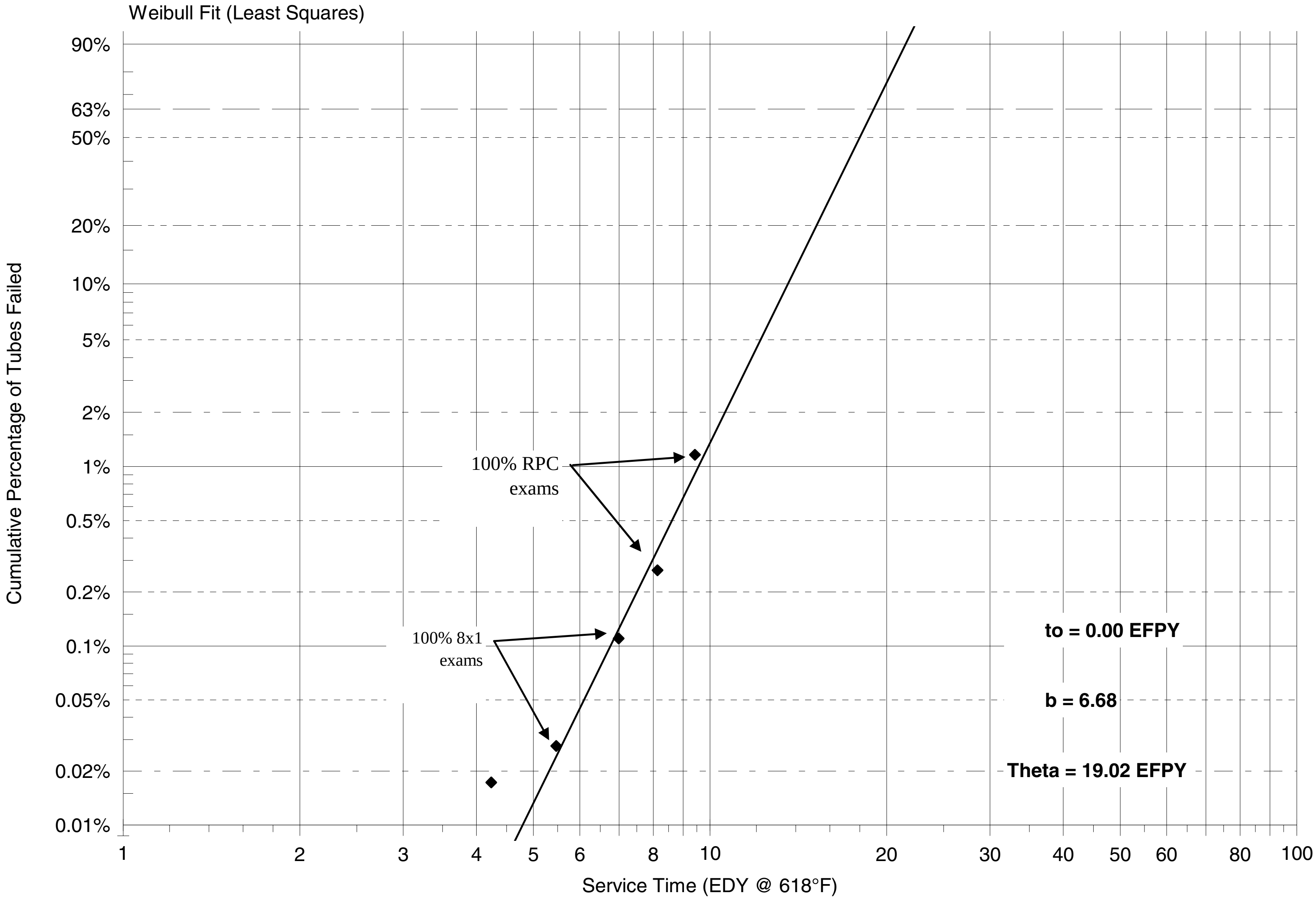


Figure 2-7
North Anna 2 – all original SGs – TSP PWSCC (axial and circ.) – tubes repaired

2.2.2.5 Salem 2 (Original SGs)

Salem 2 first observed TSP PWSCC defects during the EOC 9 exams. At the time of their replacement (during EOC 16), the SGs had only 0.2% of their total tubes affected by TSP PWSCC. Salem 2 began zinc addition during the last few weeks of Cycle 15, so this cycle is treated as no zinc cycle because of the short zinc period. Zinc injection began again in Cycle 16, but the SGs were not subsequently inspected due to their replacement during EOC 16. Therefore, no post zinc data is available.

Salem 2 was originally operated with a T_{hot} operating temperature of 602°F. In March 2004, approximately a quarter of the way through Cycle 14, T_{hot} was increased to 604°F. For the purposes of this analysis, all EFPY values were adjusted to a temperature of 602°F.

The failure rate for Salem 2 was developed using the inspection data for the last seven inspections prior to replacement in spring 2008, assuming each of these inspection points represented a fairly consistent Plus Point dent inspection methodology. Figure 2-8 shows a Weibull fit to the Salem 2 failure data. The Weibull slope parameter based on these data is b = 2.93, with a Weibull fit error of 9.1%.

2.2.2.6 Sequoyah 1 (Original SGs)

Sequoyah 1 first observed TSP PWSCC defects during the EOC 6 exams. At the time of their replacement (during EOC 12), the SGs had almost 4% of their total tubes affected by TSP PWSCC. Almost three times as many tubes were plugged due to axially oriented defects as were plugged due to circumferentially oriented defects. Sequoyah 1 began zinc addition during Cycle 12, but the SGs were not subsequently inspected due to their replacement during EOC 12. Therefore, no post zinc data are available.

Sequoyah 1 maintained a T_{hot} operating temperature of 611°F throughout the history of its original SGs.

The failure rate for Sequoyah 1 was developed using the inspection data for the last four inspections prior to the replacement outage (EOC 8 through EOC 11). Of the four inspections, only the middle two were performed using the same methodology, but the data from all four inspections were judged to be the most representative of the failure rate late in the life of the SGs, with a Weibull fit error of 7.2%. Data prior to EOC 8 were excluded from the Weibull fit because their inclusion would have resulted in a large increase in the Weibull fit error. The Weibull slope parameter based on these inspections is b = 2.27, as shown in Figure 2-9.

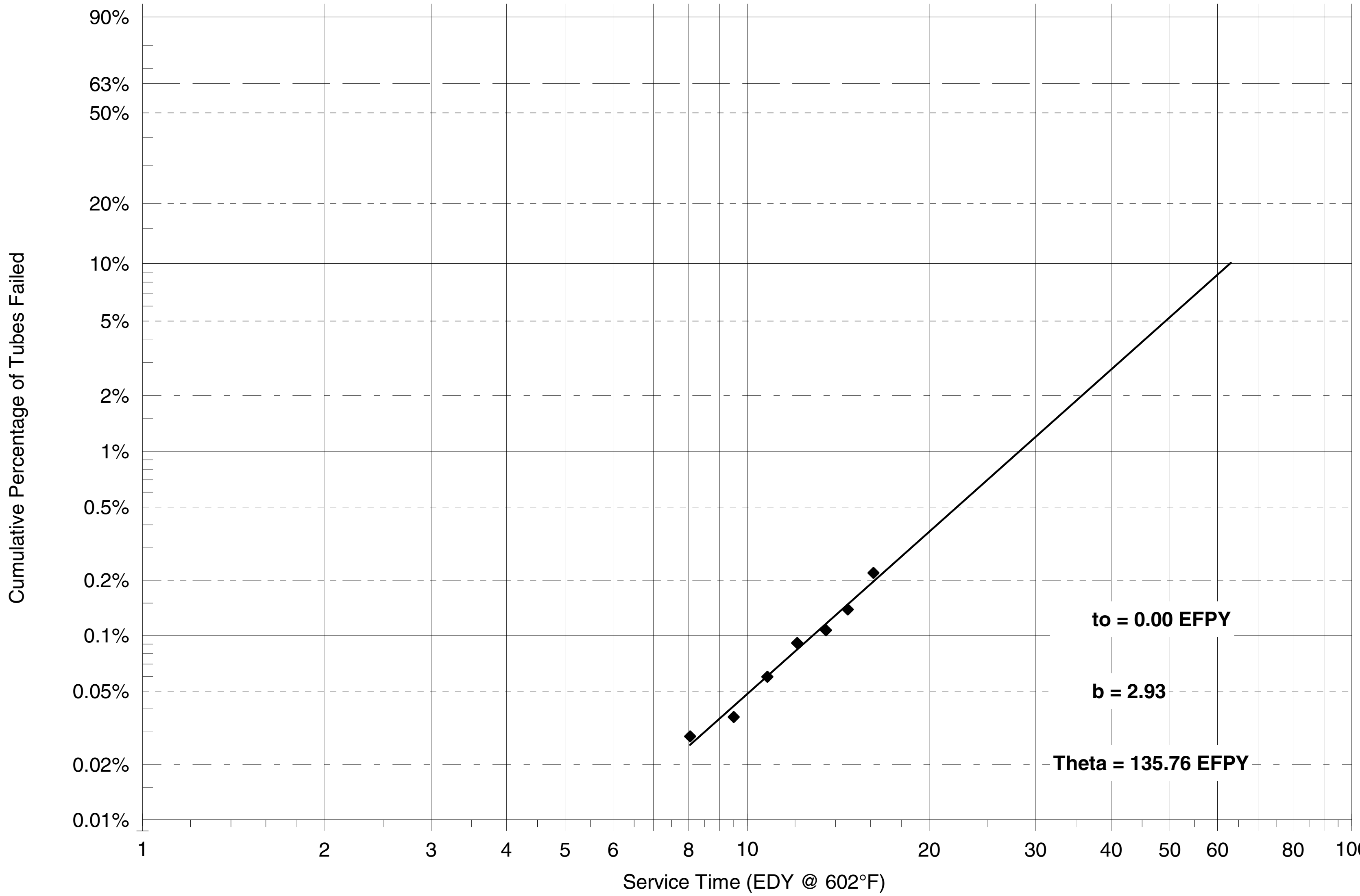


Figure 2-8
Salem 2 – all original SGs – TSP PWSCC (axial and circ.) – tubes affected

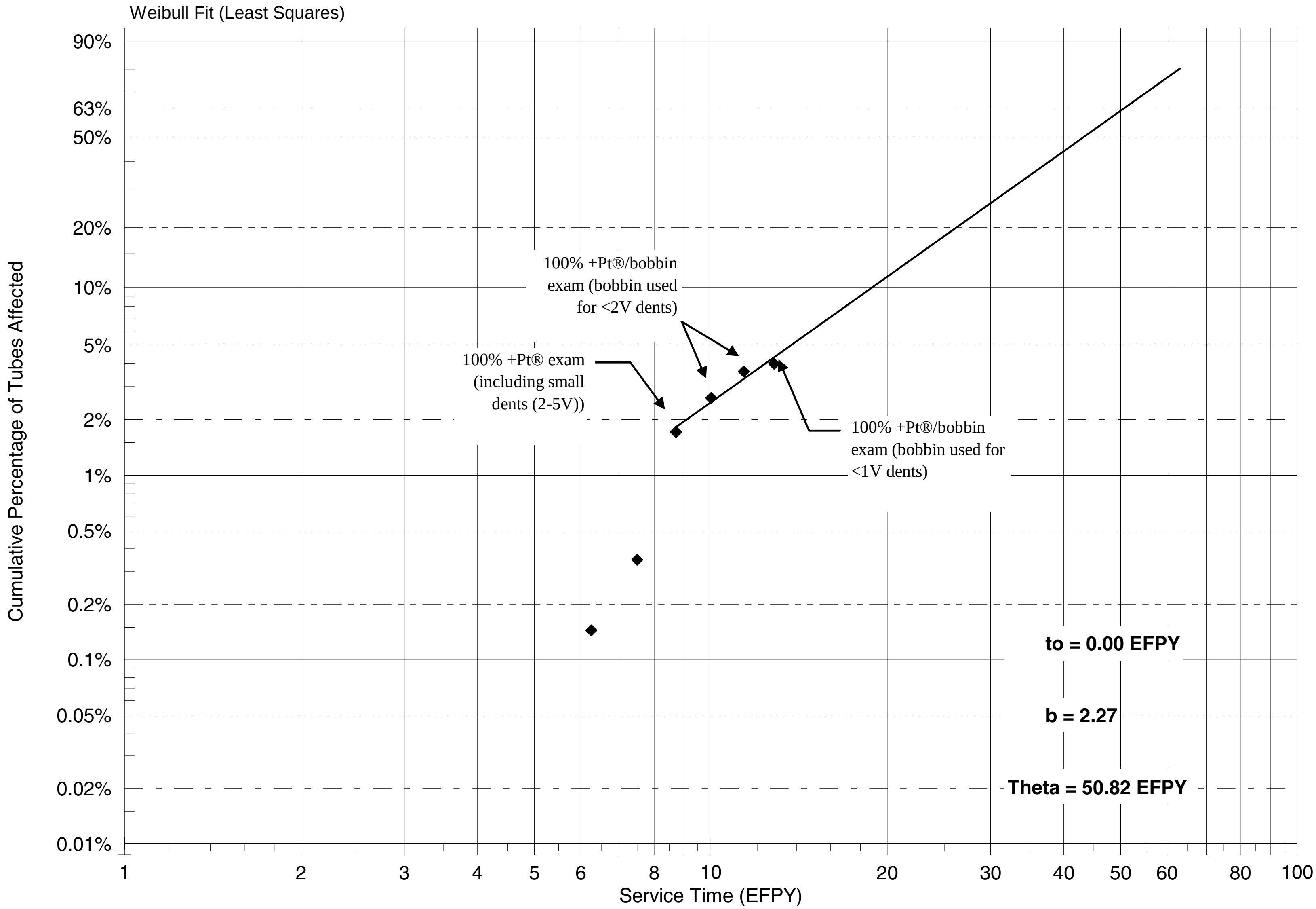


Figure 2-9
Sequoyah 1 – all original SGs – TSP PWSCC (axial and circ.) – tubes affected

2.2.3 Results for Tube Support Plate PWSCC

The Weibull slope values developed using the methodology described above have been listed in Table 2-4. Both Diablo Canyon units observed significant decreases in their failure rates following zinc addition. The post-zinc Weibull slopes represent reductions of 58% and 38% compared to the pre-zinc Weibull slopes for Unit 1 and Unit 2, respectively. Therefore, the average reduction at Diablo Canyon is 48%.

Table 2-4
TSP PWSCC Weibull slopes

Plant	Pre-/No Zinc Slope	Post-Zinc Slope	Reduction
Diablo Canyon 1	2.01	0.85	58%
Diablo Canyon 2	1.76	1.09	38%
North Anna 1 (orig. SGs)	2.08		
North Anna 2 (orig. SGs)	6.68		
Salem 2 (orig. SGs)	2.93		
Sequoyah 1 (orig. SGs)	2.27		
Median =	2.18	0.97	
Average =	2.96	0.97	

A comparison of the median (50^{th} percentile) result for the six pre-/no zinc units (slope of 2.18) against the median result for the two post-zinc units (slope of 0.97) clearly indicates a decrease in the failure rate (56%). These reductions in Weibull slope result in significant delays in occurrence of PWSCC. For example, the decrease in slope from 2.18 to 0.97 results in an increase in the time required to go from 1% to 10% tubes affected by a factor of about 5.2. However, because of the numerous inspection transients for TSPs and the small number of units in the post-zinc dataset, this comparison might not be entirely conclusive. On the other hand, the fact that the Weibull slope after use of zinc is about 1, rather than being in the typical range for PWSCC of 2 to 6 [13] for situations where remedial measures have not been applied, lends confidence to the conclusion that zinc has had a significant benefit.

Note that the Weibull analyses above were performed by assuming that the entire tube population is susceptible to TSP PWSCC. The analyses could have been performed using the assumption that only tubes with dented TSPs were vulnerable. This would have resulted in slightly higher Weibull slopes. For example, Diablo Canyon 1 has 4706 dents located between the first and third TSPs, excluding dents in SGs with no TSP PWSCC. (This value is not the total number of dents, but represents the number of dents where 90% of PWSCC has occurred.) Based on this number, and because many of the tubes can be assumed to have multiple dents, the actual number of susceptible tubes is probably around 4000, or 29.5% of the total tube population. If this factor was applied to the Diablo Canyon analysis 1 described above, the Weibull slope parameters for the pre-zinc and post-zinc fits would be b = 2.05 (vs. 2.01) and b = 0.88 (vs. 0.85), respectively.

2.3 Tube Sheet PWSCC

2.3.1 Background on Tube Sheet PWSCC

Diablo Canyon 1 and 2 are part of a group of Westinghouse design SGs with Alloy 600 mill annealed (MA) tubing and explosively expanded (WEXTEX) tube to tube sheet joints. The WEXTEX process results in residual stresses that lead to either axial or circumferential PWSCC. All of the units with explosively expanded steam generator tubing have experienced tube sheet PWSCC (TS PWSCC) to some degree. Several susceptible units performed shot peening of the hot leg tube sheet regions to mitigate the occurrence of this degradation mechanism. For example, DCPP 1 and 2 and Sequoyah 1 and 2 shot peened at about 5 to 6 EFPY, and Salem 2 shot peened at about 8 EFPY.

The W* ARC have been developed for TS PWSCC at WEXTEX units. The use of W* allows axial PWSCC located within the W* length (about 5 to 7 inches below the top of tube sheet) and cracks of any orientation below the W* length to remain in service. Diablo Canyon 1 and 2 are the only plants to have licensed the W* ARC to return tubes affected by PWSCC to service. Other plants, i.e., Sequoyah 2, Beaver Valley 1, and Salem 2, licensed the W* as a means of limiting the depth into the tube sheet required to be inspected, but still plug tubes affected by PWSCC on detection.

2.3.2 Modeling Methodology for Tube Sheet PWSCC

The group of Westinghouse design SGs with WEXTEX joints is actually comprised of the following 12 units[8]: Beaver Valley 1; Diablo Canyon 1 and 2; Farley 1; Fessenheim 1; North Anna 1 and 2; Salem 1 and 2; Sequoyah 1 and 2; and Trojan. (Note that all of these SGs have been retired or replaced, or planned to replaced – DCPP U1 in Spring 2009, SQN 2 in 2012). It was judged reasonable to initially limit the analysis to this group of units because of their similarity in design. Salem 1 was excluded due to small numbers of failures. Trojan and Fessenheim 1 were excluded later due to difficulties with interpreting the inspection data. In general, the failure rates were developed using the following guidelines:

- The data presented are primarily based on information available from the EPRI Steam Generator Degradation Database (EPRI SGDD) [6]. Where necessary, the data were supplemented with information supplied directly from the unit or other sources.
- For Diablo Canyon 1 and 2, due to the use of the W* ARC, it was necessary to determine the number of new tubes affected during each of the outages involved rather than relying on the number of tubes repaired so that all units could be compared on the same basis. As with the TSP PWSCC Weibull analysis, the tubes affected data presented for these units were provided by the utility since the EPRI SGDD provides mostly tubes repaired data.

[8] Comanche Peak 1, which has WEXTEX expansions in approximately 10% of its SG tubes, was not considered as part of this analysis. Comanche Peak 1 shot peened prior to operation and is therefore not considered to be as susceptible to PWSCC as those units that peened later in life.

- Where possible, only those inspections where 100% of the tube sheet joints were inspected by qualified probes were included in the data analysis. The affects of inspection transients (e.g., probe, inspection scope) on the Weibull slope were assessed to determine if data should be excluded.
- If a unit changed temperature, the effects of any hot leg temperature changes were incorporated into the analyses by defining an equivalent operating time using the Arrhenius equation and a Q value of 50 kcal/mole [4]. The Weibull plots of the affected units have been labeled with the temperature to which the EFPYs have been adjusted. The equivalent operating times are termed effective degradation years (EDYs) referenced to a specific temperature. Plots for the units without temperature changes are simply labeled in EFPY.
- For the four units at which zinc addition was performed (Beaver Valley 1, Diablo Canyon 1 and 2, and Sequoyah 2), separate pre- and post-zinc slopes were developed. The zinc addition history for each of these units is shown in Table 2-1. The post-zinc injection slopes include data from the last cycle of no zinc injection as a way of capturing the rate change during the first cycle of operation with zinc.
- Because peening may be a contributing factor to the decline of tube sheet PWSCC, fits to data from inspections subsequent to shot-peening were considered separately from fits to data prior to/without peening.

Each unit is discussed in more detail below.

2.3.2.1 Beaver Valley 1 (Original SGs)

According to data available through Reference [9],[9] Beaver Valley 1 first detected a TS PWSCC defect during EOC 10. Small numbers of failures have been observed at every inspection since then. As of the EOC 16 exam, almost 1% of the total tube population at Beaver Valley 1 has been plugged due to TS PWSCC. The majority of the defects are axially-oriented.

Beaver Valley 1 was started with a T_{hot} operating temperature of 607°F. T_{hot} was reduced during Cycle 9 to 600°F, but was increased back to the original temperature within a few months. All EFPY values were adjusted to a temperature of 607°F for this analysis.

As of August 2005, Beaver Valley 1 had not peened, so all of its TS PWSCC data included in this report is without peening.

Because Beaver Valley 1 began injecting zinc in late 2002, two different failure rates were determined. The pre-zinc failure slope was developed using data from the four inspections prior to the addition of zinc (EOC 11 through EOC 14) and the first inspection after zinc addition began (EOC 15). The EOC 15 inspection point was included in the pre-zinc analysis, because zinc was injected for only 2 months of the cycle. The EOC 10 inspection point was not used in

[9] The numbers provided in this reference are numbers of indications per outage, not numbers of tubes affected. For the purposes of this report, it was conservatively assumed that each indication equals one tube affected. This is judged to be a reasonable assumption considering the small number of indications observed to date. This same assumption was also used for the Sequoyah 2 TS PWSCC analysis.

order to maintain a small Weibull fit error of 7.6%. The Weibull slope parameter for the pre-zinc fit is b = 4.35. The post-zinc slope was developed using data for EOC 15 and EOC 16. These two inspections were both 100% Plus Point® inspections. The Weibull slope parameter for the post-zinc fit is b = 0.90. Both the pre- and post-zinc fits are shown in Figure 2-10. Note that the number of post-zinc data points is limited to one full cycle of zinc injection, so the Beaver Valley 1 reduction factor based on this analysis is not entirely beyond question. The Beaver Valley 1 SGs were replaced in 2006 without additional inspection.

2.3.2.2 Diablo Canyon 1 (Original SGs)

For Diablo Canyon 1, which used the W* ARC for six end-of-cycle inspections, it was necessary to determine the number of new tubes affected during each of the outages involved rather than relying on the number of tubes repaired. The number of tubes affected is shown in Table 2-2, and Figure 2-11 is a graphical representation of the data. The table and graph show that Diablo Canyon 1 first observed TS PWSCC defects during EOC 6. The numbers detected have been fairly small, with only 32 tubes affected due to this mechanism. The incremental number of tubes affected has followed a declining trend since zinc addition began. However, there is some uncertainty as to exactly when the effect of zinc truly began due to some changes in inspection methodology that occurred immediately prior to zinc addition. DCPP Unit 1 began performing partial tube sheet inspections with Plus Point® probes at EOC 7. One hundred percent inspections of the tube sheet region using Plus Point® were first performed at EOC 9, resulting in a slightly higher number of PWSCC indications being detected at that outage, despite the start of zinc injection during cycle 9. The number of new PWSCC indications declined in the subsequent EOC 10 inspection, which could reflect the natural decline in new PWSCC sites due to the enhanced inspection methodology use in the prior outage. It is also possible that zinc contributed to the decrease in EOC 10, as well as to the small numbers of indications detected in EOC 11 through EOC 14.

As with the TSP PWSCC analysis, all EFPY values were adjusted to a temperature of 603°F for this analysis.

Diablo Canyon 1 shot-peened during EOC 5, prior to the first observation of TS PWSCC, so all of its TS PWSCC data is post-peening.

Because Diablo Canyon 1 began injecting zinc in 1998, two different failure rates were determined. The pre-zinc failure slope was developed using data for the three inspections prior to the addition of zinc, i.e., EOC 6 through EOC 8. The EOC 6 results were from a partial RPC exam, and, as stated above, EOC 7 and EOC 8 results were from partial Plus Point® exams. All three data points represent partial exams, but they are the only pre-zinc data available; the fraction of tubes inspected was considered as part of the analysis, and the estimated cumulative number of tube failures was adjusted accordingly. The Weibull slope parameter for the pre-zinc fit is b = 1.92. The post-zinc slope was developed using data for EOC 8 through EOC 14. With the exception of the EOC 8 exam, all inspections were 100% Plus Point® exams. The Weibull slope parameter for the post-zinc fit is b = 1.13. Both the pre- and post-zinc fits are shown in Figure 2-12.

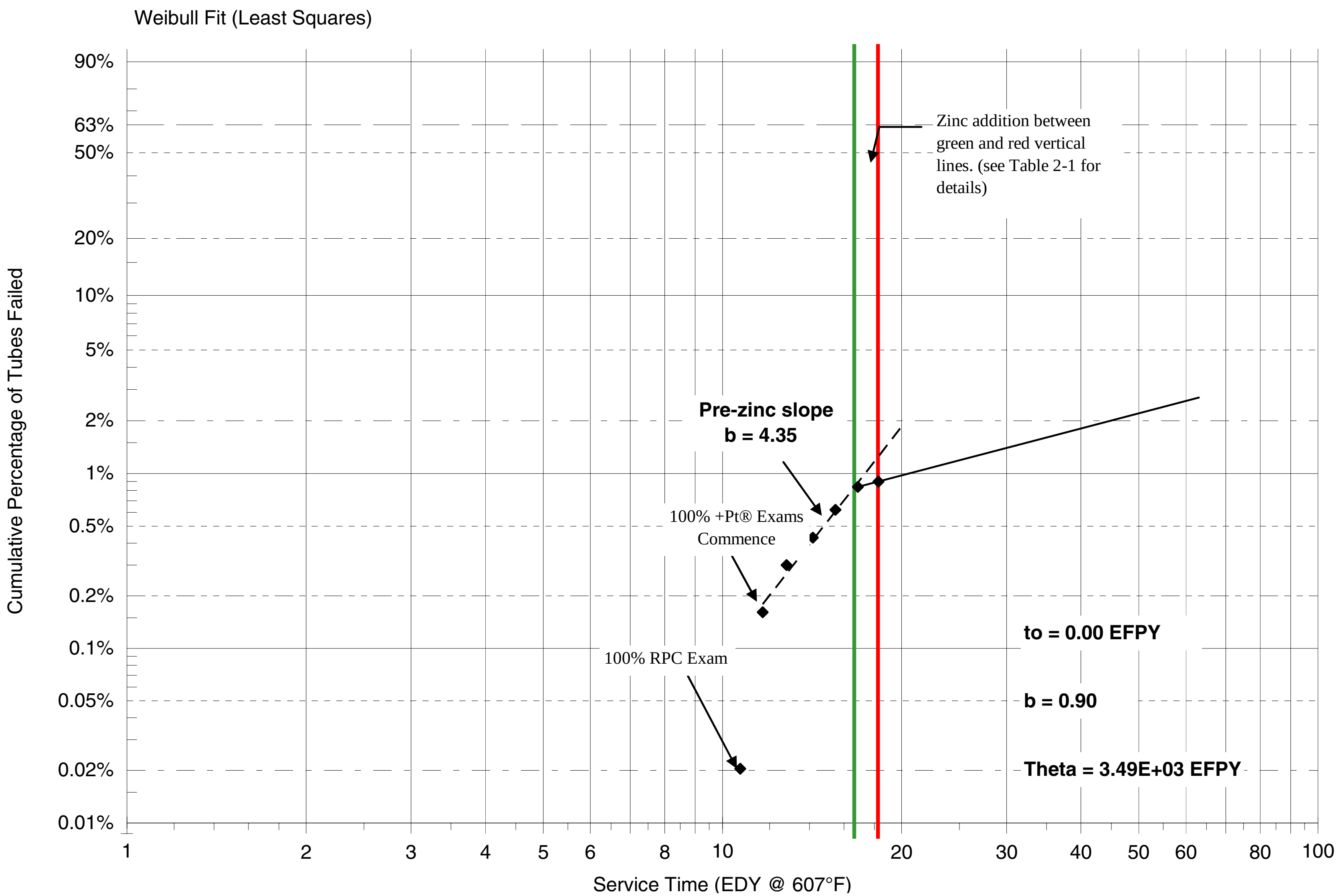


Figure 2-10
Beaver Valley 1 – all original SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

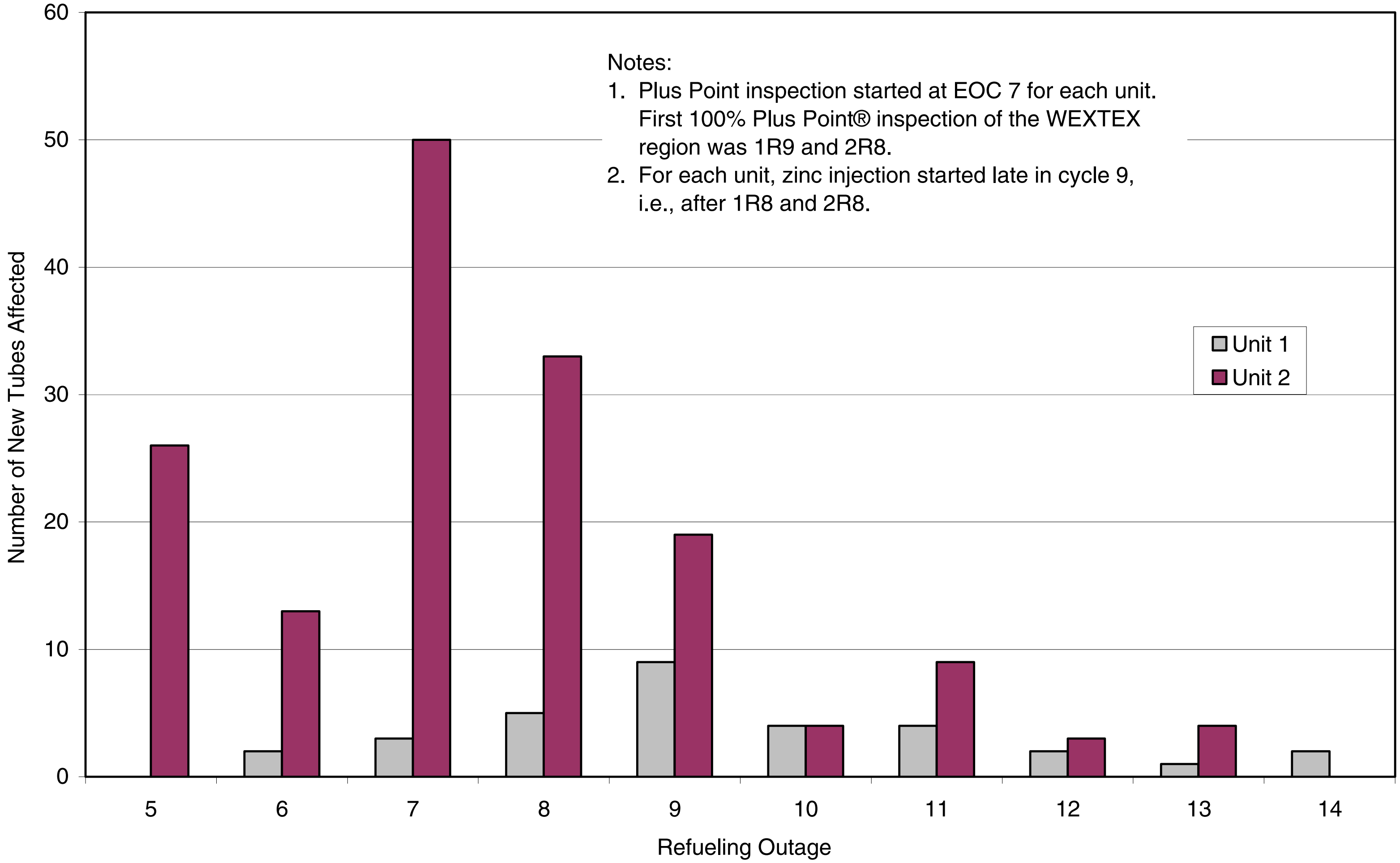


Figure 2-11
Number of new tubes affected with TS PWSCC per outage at Diablo Canyon

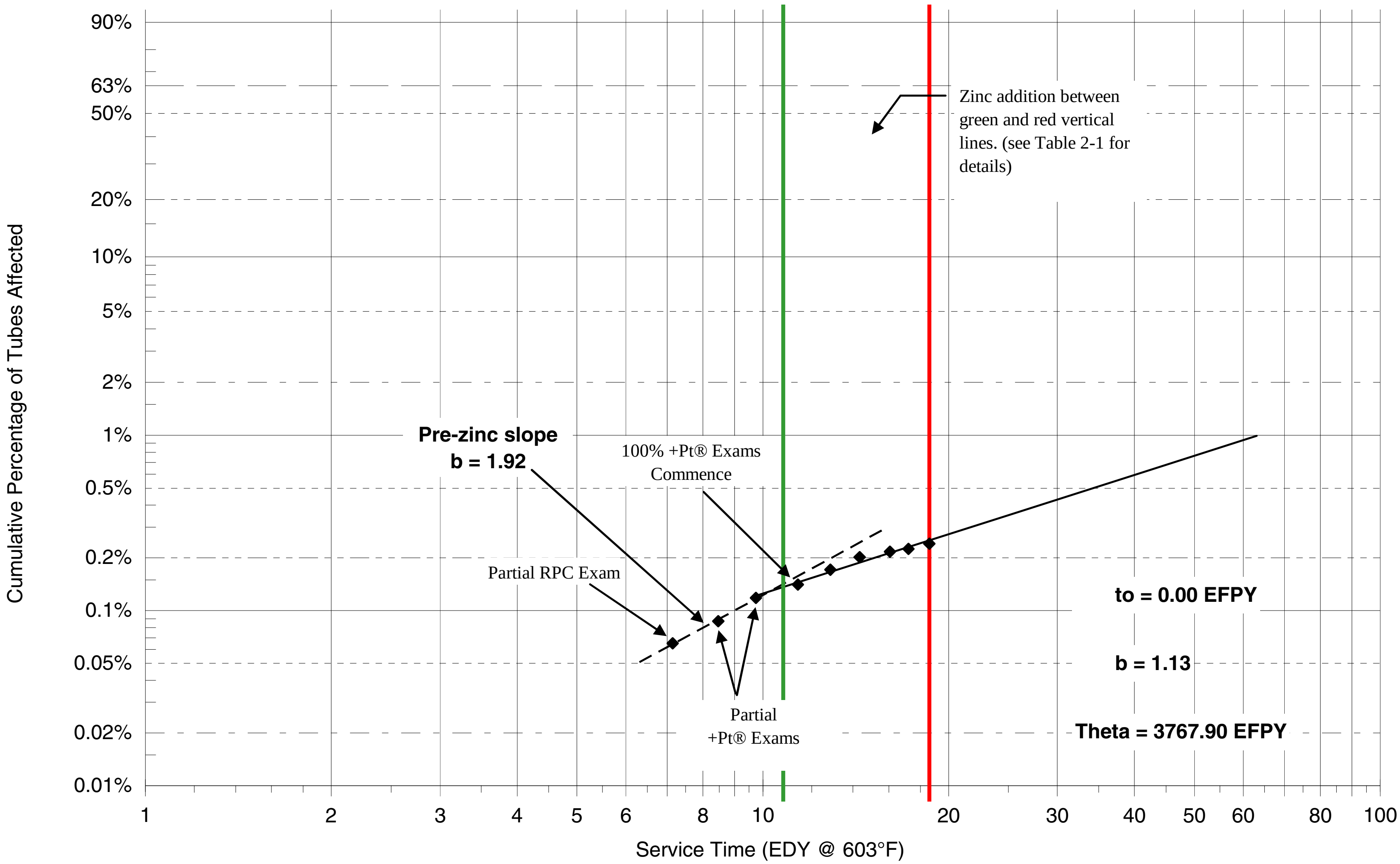


Figure 2-12
Diablo Canyon 1 – all SGs – WEXTEX PWSCC (axial and circ.) – tubes affected

2.3.2.3 Diablo Canyon 2 (Original SGs)

Like Diablo Canyon 1, Diablo Canyon 2 used the W* ARC for the last five end-of-cycle inspections. Therefore, it was necessary to determine the number of new tubes affected during each of the outages involved rather than relying on the number of tubes repaired for Diablo Canyon 2. The number of tubes affected is shown in Table 2-2, and Figure 2-11 is a graphical representation of the data. As shown in both the table and graph, TS PWSCC defects were first detected at Diablo Canyon 2 during EOC 5, prior to peening. The number of tubes affected at Unit 2 is higher than at Unit 1, with slightly more than 1% of the total tube population having a defect of this type as of EOC 13. The defects have been primarily axial in orientation. The incremental number of tubes affected has followed a declining trend since zinc addition began. However, there is some uncertainty, as with the Unit 1 data, as to exactly when the effect of zinc truly began due to some changes in inspection methodology that occurred immediately prior to zinc addition. DCPP Unit 2 performed a 50% top of tube sheet inspection with Plus Point® probes at EOC 7. This first time use of Plus Point® resulted in a large number of new PWSCC indications detected (50 tubes), i.e. an inspection transient. One hundred percent inspections of the top of tube sheet region using Plus Point® were first performed at EOC 8, with 33 new PWSCC indications detected. Although the EOC 8 number is slightly less than EOC 7, it still reflects an inspection transient due to a larger inspection scope. The number of new indications again declined in EOC 9, coincident with the start of zinc injection during Cycle 9, and could reflect the natural decline in identification of new PWSCC sites due to the enhanced inspection methodology used in the prior outages. The number of new PWSCC indications has been very minimal at EOC 10 through EOC 13. It is likely that zinc contributed to the decrease in EOC 9, as well as the smaller numbers of new indications detected in EOC 10 through EOC 13.

Diablo Canyon 2 has maintained a T_{hot} operating temperature of 603°F throughout its history.

Diablo Canyon 2 shot-peened during EOC 5.

Because Diablo Canyon 2 began injecting zinc in 1999, two different failure rates were determined. The pre-zinc failure slope was developed using data for the four inspections prior to the addition of zinc, i.e., EOC 5 through EOC 8. The three earliest data points represent partial exams, the first two by RPC and the last one by Plus Point®; the fraction of tubes inspected was considered as part of the analysis, and the estimated cumulative number of tube failures was adjusted accordingly. The Weibull slope parameter for the pre-zinc fit is b = 1.40, with a Weibull fit error of 14.8%. The post-zinc slope was developed using data for EOC 8 through EOC 13. All five inspections were 100% Plus Point® exams. The Weibull slope parameter for the post-zinc fit is b = 0.48, with a Weibull fit error of 2.7%. Both the pre- and post-zinc fits are shown in Figure 2-13. Note that the pre-zinc slope includes data from the cycle prior to peening as a way of capturing the rate change immediately after peening. All other data used for fits were post-peening.

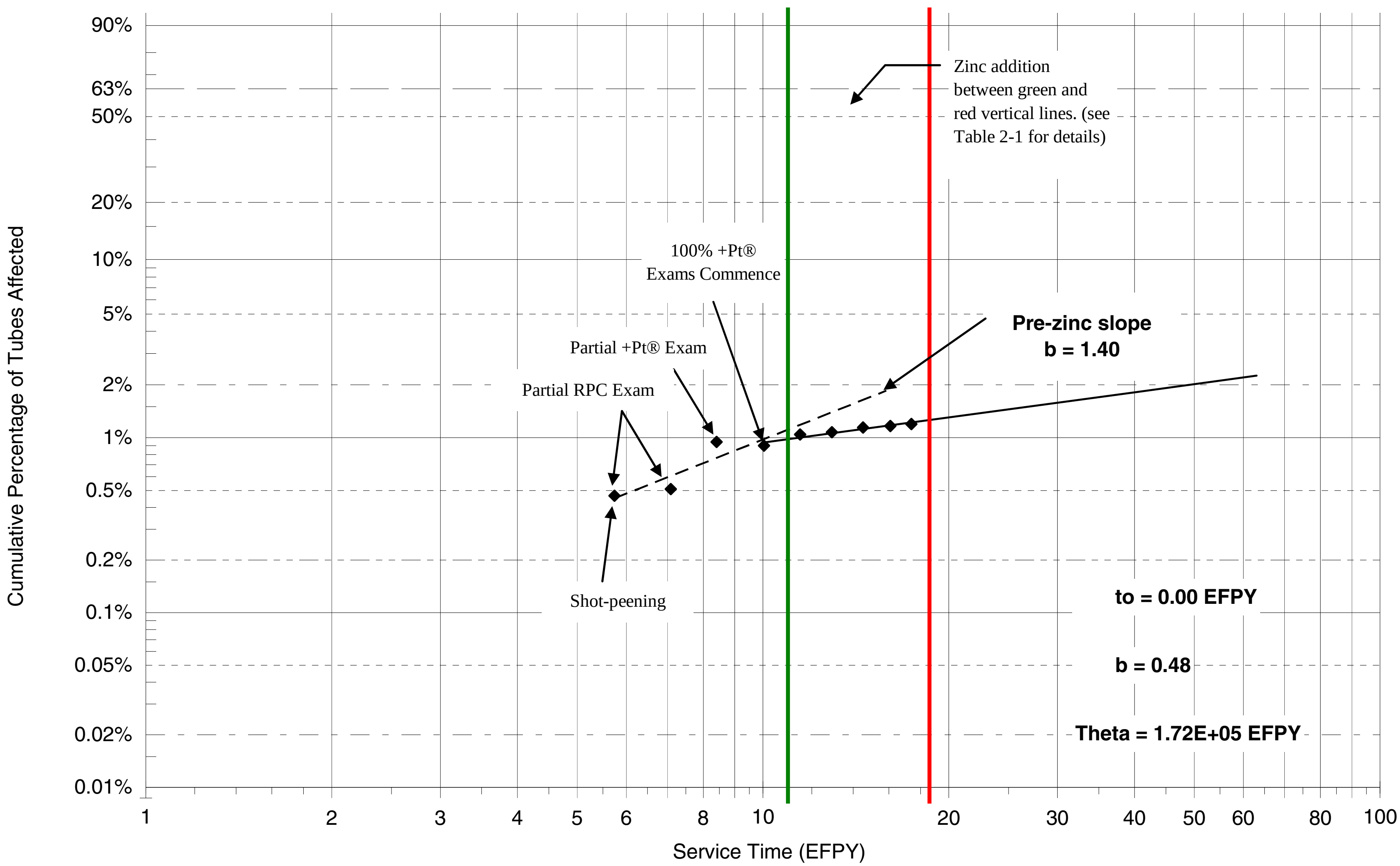


Figure 2-13
Diablo Canyon 2 – all SGs – WEXTEX PWSCC (axial and circ.) – tubes affected

2.3.2.4 Farley 1 (Original SGs)

Farley 1 plugged 75 tubes due to TS PWSCC defects when this mechanism was first detected during the EOC 10 inspection. By the time the SGs were replaced at EOC 16, Farley 1 had repaired a fair number of tubes (~3%) due to this mechanism. The tubes were repaired due to almost equal amounts of circumferentially and axially oriented defects, though slightly more due to axially oriented defects.

Farley 1 was originally operated with a T_{hot} temperature of 610°F, but T_{hot} was reduced to 607°F at EOC 6 and remained at that temperature until the SGs were replaced. All EFPY values were adjusted to a temperature of 607°F for this analysis.

Farley 1 did not peen prior to replacement, so all of its TS PWSCC data is without peening.

The failure rate for Farley 1 was developed using the inspection data for EOC 12 through EOC 15. (The leaker outage during August 1998 was not included since the TS area was not inspected at that time.) The EOC 12 and EOC 13 inspections were 100% RPC exams, and the EOC 14 and EOC 15 inspections were 100% Plus Point® exams, but because there was no noticeable inspection transient caused by the change in inspection technology it was judged reasonable to use all four data points. Despite the fact that EOC 10 and EOC 11 were 100% RPC exams, data prior to EOC 12 were excluded from the fit to avoid doubling the Weibull fit error. The Weibull slope parameter derived from these inspections is b = 4.23 (see Figure 2-14), with a Weibull fit error of 4.4%.

2.3.2.5 North Anna 1 (Original SGs)

North Anna 1 first observed TS PWSCC defects during EOC 6. It continued to detect these defects for the next four inspections, until the SGs were replaced at EOC 9. After the last inspection prior to replacement, North Anna 1 had 3-4% of its tubes repaired due to this mechanism. Only five tubes were repaired due to axially oriented defects, the remaining tubes were plugged due to circumferentially oriented defects.

All EFPY values for the analysis of this mechanism were adjusted to the same temperature of 618°F used for the TSP PWSCC analysis.

North Anna 1 did not peen prior to replacement, so all of its TS PWSCC data is without peening.

The failure rate for North Anna 1 was determined using the inspection data for EOC 6 through EOC 8, including the leaker outage during Cycle 7 and the midcycle outage following EOC 8. The first three inspections were 100% 8x1 exams, and the later two were 100% RPC exams. The extra scatter introduced by using the data from both inspection technologies is considered to be acceptable. The Weibull slope parameter based on the five inspections is b = 4.33 (see Figure 2-15), with a Weibull fit error of 21.0%.

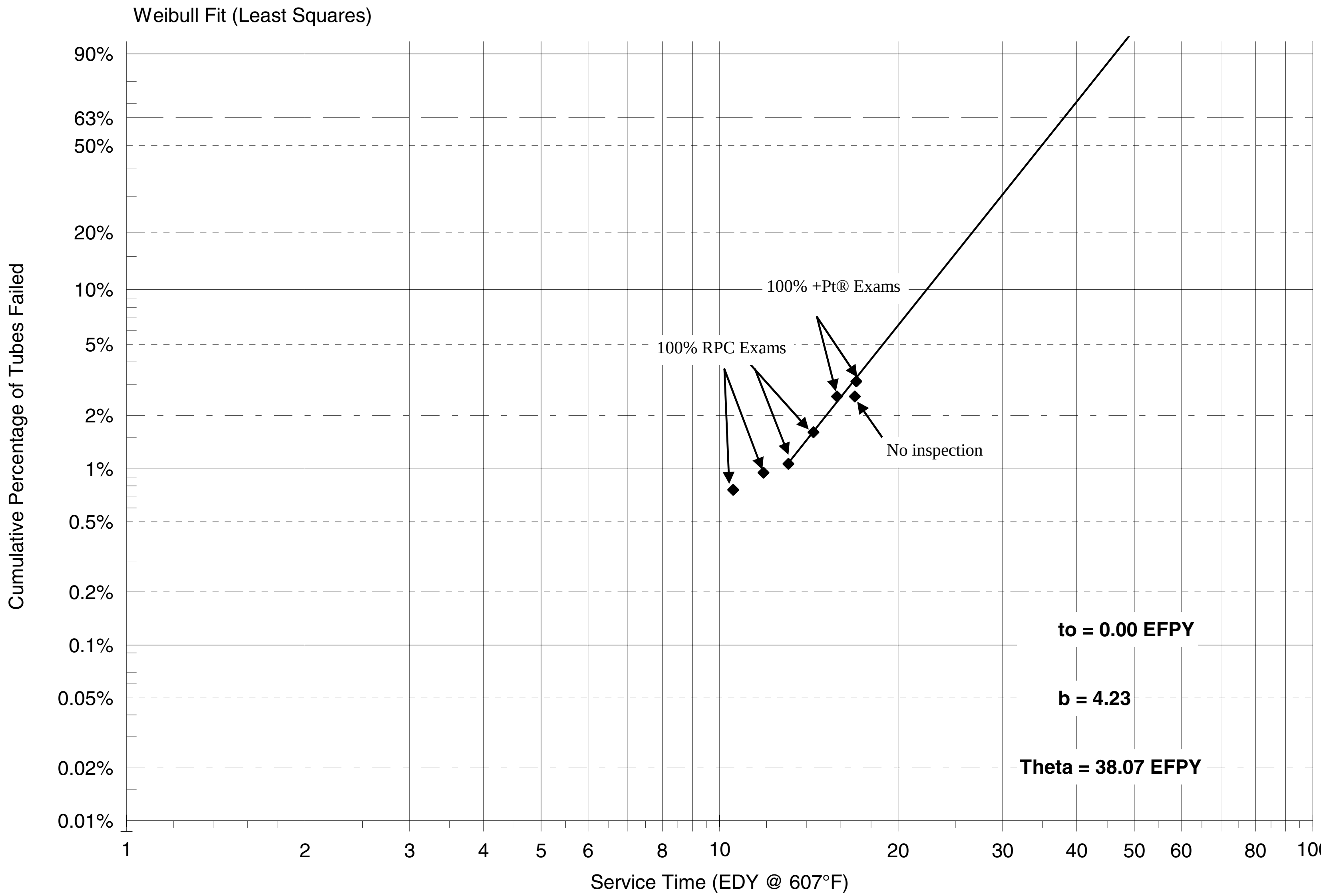


Figure 2-14
Farley 1 – all original SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

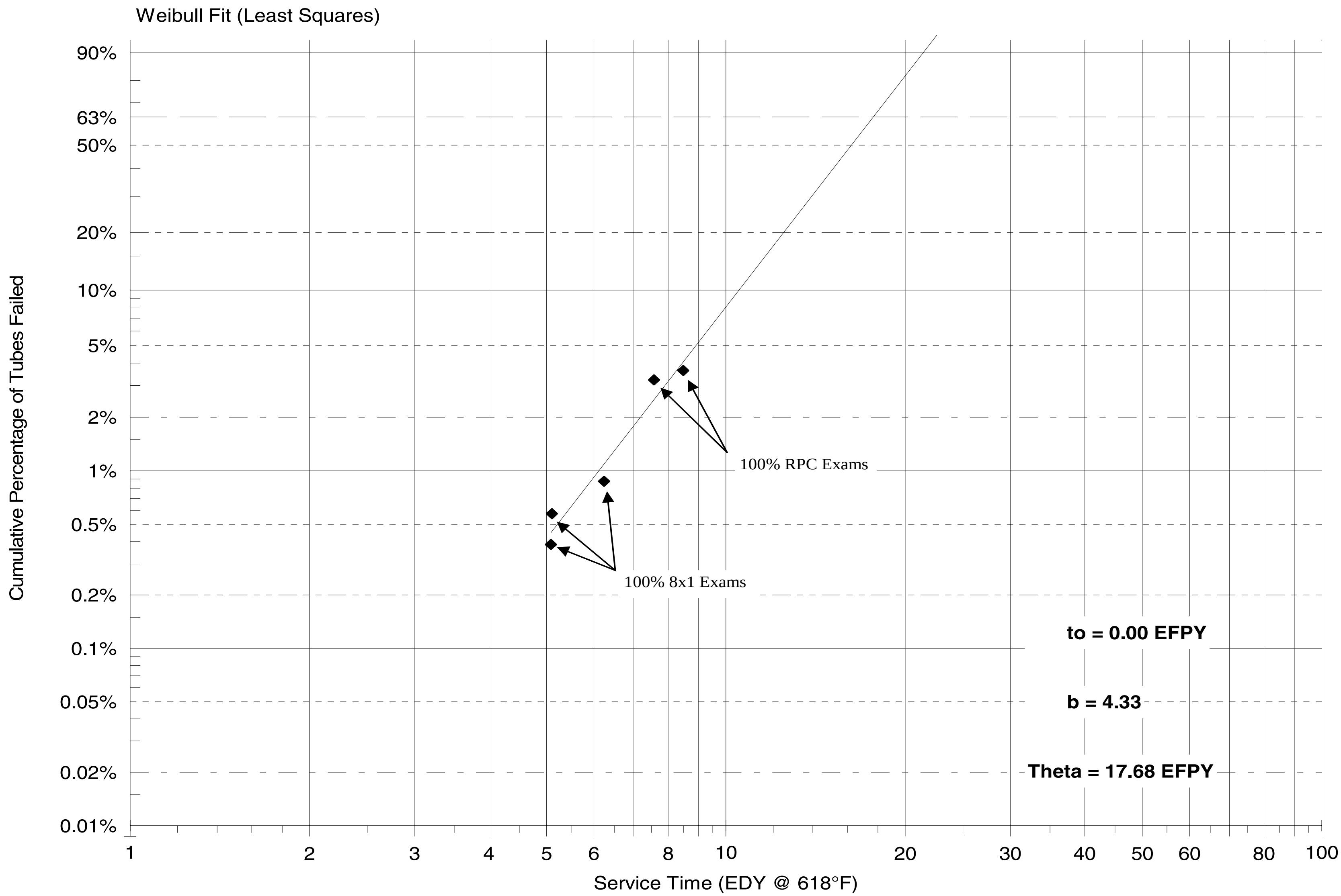


Figure 2-15
North Anna 1 – all original SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

2.3.2.6 North Anna 2 (Original SGs)

North Anna 2 first detected TS PWSCC defects during the EOC 5 inspection. Six tubes were plugged as a result. Two more tubes were plugged due to this mechanism during the next outage, then a large number was found during the EOC 7 exam. By the time the SGs were replaced during EOC 10, almost 2% of North Anna 2's total tube population had been repaired because of TS PWSCC. Over five times as many tubes were plugged due to circumferentially oriented defects than axially oriented.

All EFPY values for the analysis of this mechanism were adjusted to the same temperature of 618°F used for the TSP PWSCC analysis.

North Anna 2 did not peen prior to replacement, so all of its TS PWSCC data is without peening.

The failure rate for North Anna 2 was developed using the inspection data for the last three inspections prior to replacement (EOC 7 through EOC 9). Inclusion of data prior to EOC 7 would have doubled the Weibull fit error. Therefore, only the three 100% RPC inspections were included, and the two inspections using the 8x1 probe were excluded. The Weibull slope parameter based on these three inspections is $b = 3.71$ (see Figure 2-16), with a Weibull fit error of 17.5%.

2.3.2.7 Salem 2 (Original SGs)

Salem 2 first observed TS PWSCC defects during the EOC 6 exams. During the next two inspections, small numbers of defects were detected. A large number of defects was detected during EOC 9. Then Salem 2 was shut down for approximately two years. Following resumption of operation, the incremental number of tubes repaired leveled off, but as of the EOC 15 inspections (last inspection before replacement), over 2% of the total tube population at Salem 2 has been plugged due to this mechanism. The majority of the tubes were plugged due to axially oriented defects.

Salem 2 was originally operated with a T_{hot} operating temperature of 602°F. In March of 2004, approximately a quarter of the way through Cycle 14, T_{hot} was increased to 604°F. For the purposes of this analysis, all EFPY values were adjusted to a temperature of 602°F.

Salem 2 shot-peened during EOC 8.

The failure rate for Salem 2 was determined using the inspection data for the last seven outages, i.e., EOC 9 through EOC 15, all 100% Plus Point® inspections. Inclusion of the three RPC inspections would have increased the error in the Weibull fit substantially (>30%). The Weibull fit to the last six data points is considered to be excellent, with an error of 1.8%. The Weibull slope parameter based on these inspections is $b = 0.77$, as shown in Figure 2-17. All the data used for the fit were post-peening.

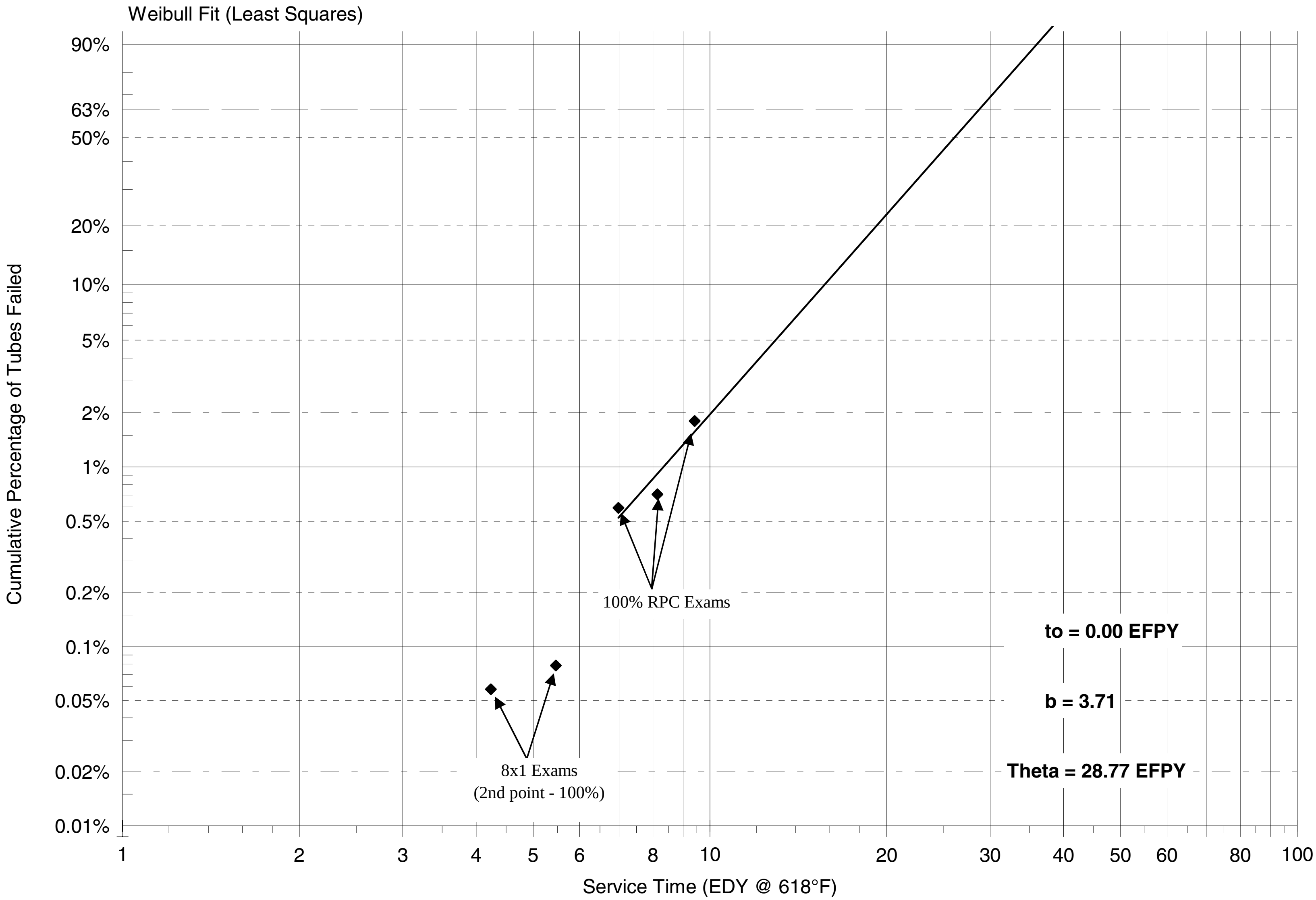


Figure 2-16
North Anna 2 – all original SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

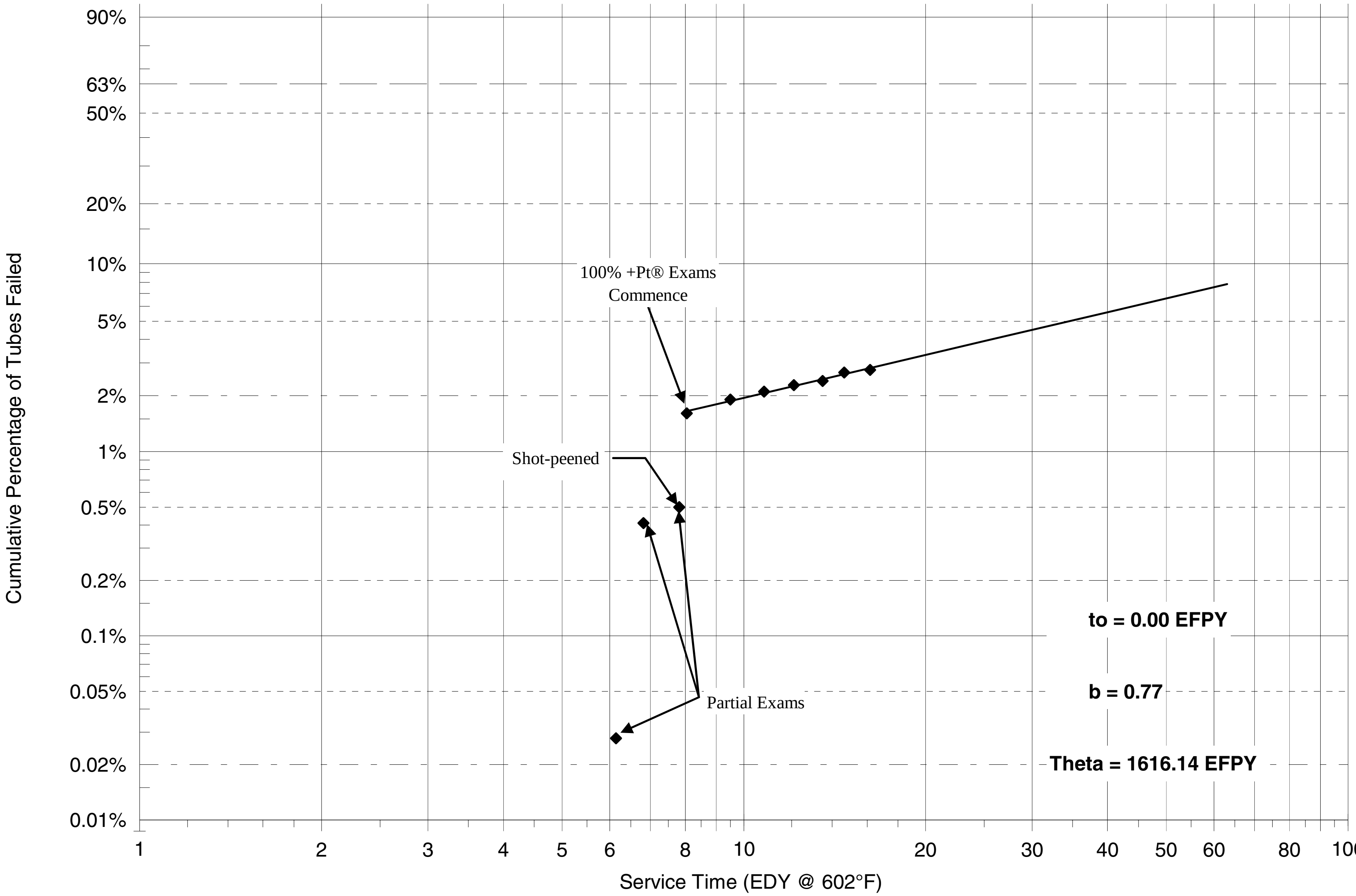


Figure 2-17
Salem 2 – all original SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

2.3.2.8 Sequoyah 1 (Original SGs)

Sequoyah 1 first observed TS PWSCC defects during the EOC 4 exam. During the next outage, all of the SG tubes were shot-peened on the hot leg side. Despite this measure, the number of failures increased steadily until the SGs were replaced at EOC 12. At the time of their replacement, the SGs had almost 3% of their total tubes plugged due to TS PWSCC. Almost three times as many tubes were plugged due to circumferentially oriented defects as axially oriented defects. Sequoyah 1 began zinc addition during Cycle 12, but the SGs were not subsequently inspected due to their replacement in Cycle 13, thus there is no post-zinc data.

Sequoyah 1 maintained a T_{hot} operating temperature of 611°F throughout the history of its original SGs.

The failure rate for Sequoyah 1 was developed using the inspection data for the last four inspections prior to the replacement outage (EOC 8 through EOC 11). The EOC 8 and EOC 9 exams were 100% RPC exams, and the EOC 10 and EOC 11 exams were 100% Plus Point® exams. No obvious inspection transient is apparent, and the Weibull fit to the four data points has an error of only 2.6%. Three of the four earliest inspections were excluded since they were partial inspections and would have increased the uncertainty in the fit. The EOC 5 data point represents a 100% RPC inspection, but it was also the outage during which shot peening was performed; it was excluded in order to maintain a small Weibull fit error. The Weibull slope parameter based on the last four inspections is b = 1.10, as shown in Figure 2-18. All the data used for the fit were post-peening.

2.3.2.9 Sequoyah 2 (Original SGs)

Sequoyah 2 first detected TS PWSCC defects fairly early in life, during the EOC 4 inspections. However, despite the early beginning, according to Reference [10][10] only a small number of tubes have been repaired for the last few outages due to this mechanism, slightly more than 1% of the tube population as of the 2008 inspection. Over four times as many repairs were due to axially oriented defects as circumferentially oriented defects.

Sequoyah 2 has maintained a T_{hot} operating temperature of 611°F throughout its history.

Sequoyah 2 shot-peened during EOC 5.

Because Sequoyah 2 began injecting zinc in the fall of 2002, two different failure rates were determined. The pre-zinc failure slope was developed using data for the four inspections prior to the addition of zinc, i.e., EOC 8 through EOC 11. EOC 8 was a 100% RPC exam, whereas the other three were 100% Plus Point® exams. Despite the change in inspection probes, the pre-zinc Weibull fit is considered to be excellent, with an error of 2.4%. The four earliest inspections were excluded because they were partial inspections and, even though the fraction of tubes

[10] As with the Beaver Valley 1 TS PWSCC reference, the numbers provided in this reference are number of indications rather than the number of tubes affected for each outage. Because the number of indications is relatively small, it was conservatively assumed that each indication equals one tube.

inspected is accounted for as part of the analysis, would have increased the uncertainty in the fit. The Weibull slope parameter for the pre-zinc fit is $b = 1.54$. The post-zinc slope was developed using data for EOC 11 through EOC 15. All three inspections were 100% Plus Point® exams. The Weibull slope parameter for the post-zinc fit is $b = 0.65$. Both fits are shown in Figure 2-19. All the data used for the fits were post-peening.

2.3.3 Results for Tube Sheet PWSCC

The Weibull slope values developed using the methodology described above have been listed in Table 2-5. A comparison of the Weibull slope values developed clearly indicate that zinc addition has decreased the rate of initiation and subsequent growth to detection of TS PWSCC defects. The median Weibull slope value for *all of the pre-zinc and no zinc cases* is 1.92, compared with a post-zinc median Weibull slope value of 0.78 (a 60% reduction in slope). The pre-zinc/no zinc median Weibull slope value for *units where shot-peening was not performed* is 4.28, compared with a post-zinc median Weibull slope value of 0.90 (a 79% reduction in slope). However, because the post-zinc data slope is based on only one unit, this comparison might not be entirely conclusive. The pre-zinc/no zinc median Weibull slope value for *units where shot-peening was performed* is 1.40, compared with a post-zinc median Weibull slope value of 0.65 (a 54% reduction in slope).

On a unit by unit basis, each of the four units that are injecting zinc has observed a decrease in its failure rate. At Beaver Valley 1, the rate of TS PWSCC has decreased 79%, but the number of post-zinc data points is limited. Review of pre- and post-zinc Weibull slopes shows a 41% reduction at Diablo Canyon 1 and a 66% reduction at Diablo Canyon 2 (for an average reduction of 54% at Diablo Canyon). Even though Sequoyah 2's primary objective in adding zinc is not to control PWSCC (i.e., the concentration of the zinc is not at the level previously considered necessary to significantly affect ID degradation), the Weibull slopes show a 58% reduction. The average result of all four units with both pre- and post-zinc data shows a 61% decrease in slope with zinc addition.

These reductions in Weibull slope result in significant delays in occurrence of PWSCC. For example, the decrease in slope from 1.92 to 0.78 results in an increase in the time required to go from 1% to 10% tubes affected by a factor of about 8, assuming that it takes approximately 10 years to reach 1%.

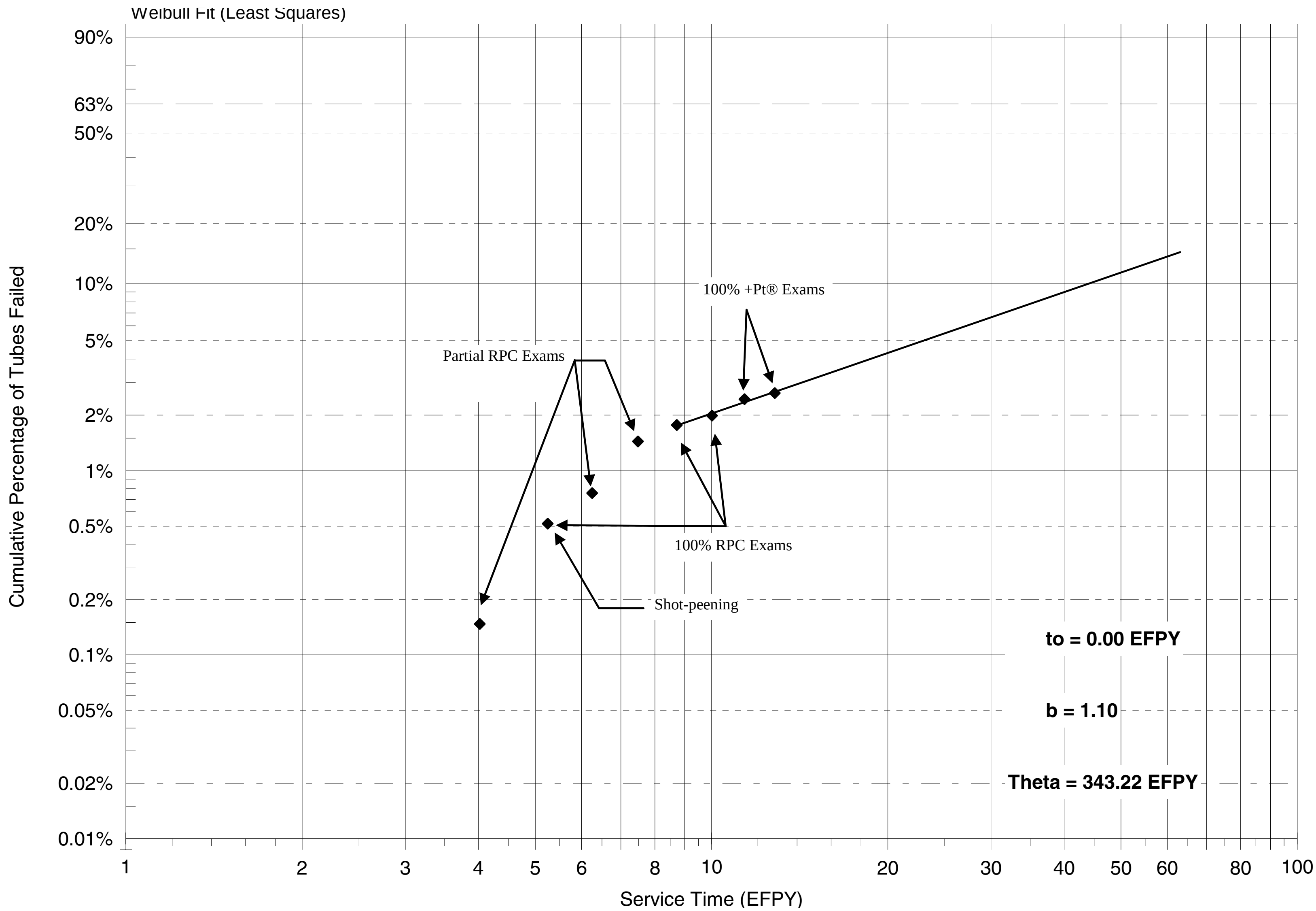


Figure 2-18
Sequoyah 1 – all original SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

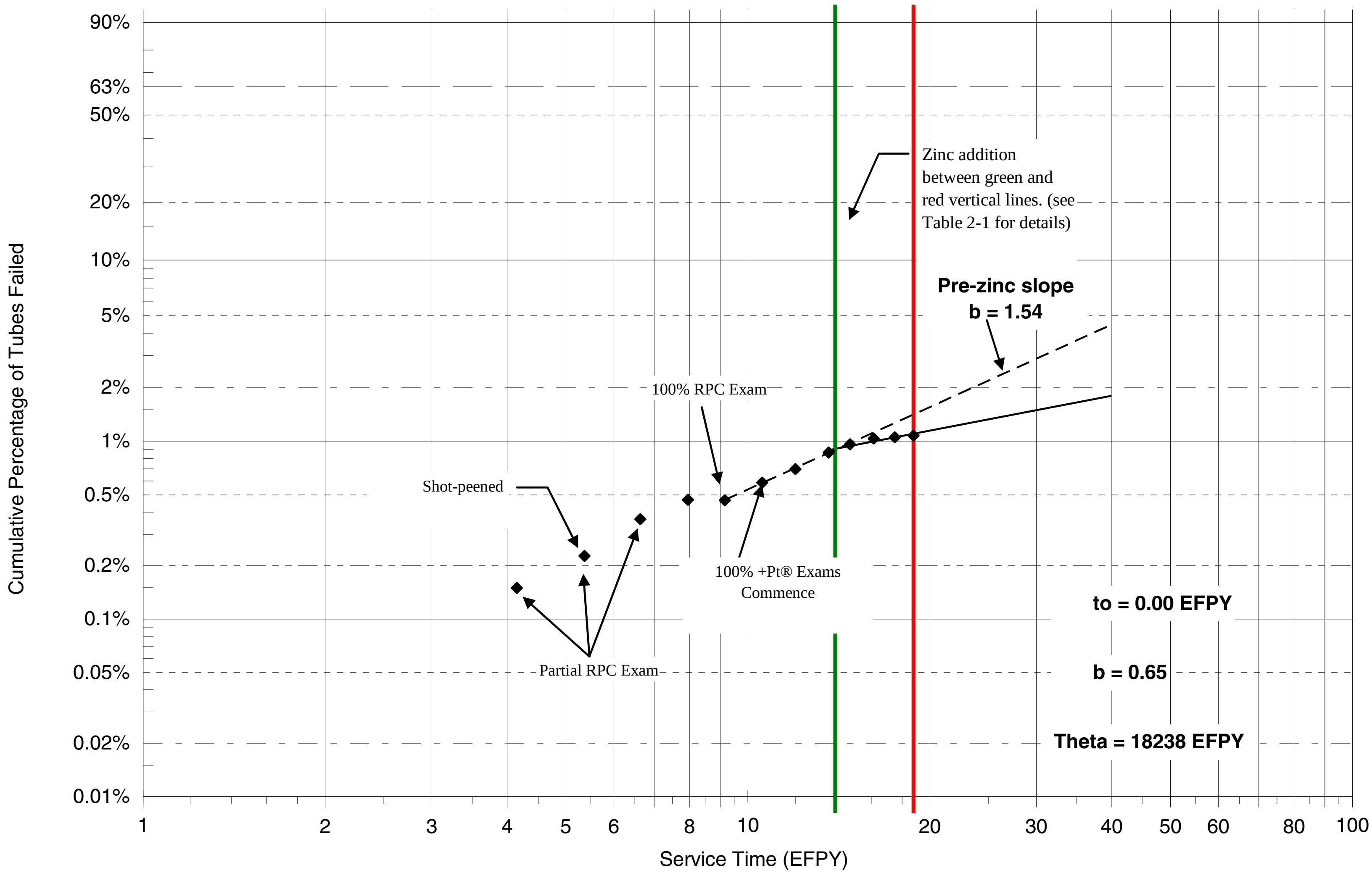


Figure 2-19
Sequoyah 2 – all SGs – WEXTEX PWSCC (axial and circ.) – tubes repaired

Table 2-5
TS PWSCC Weibull slopes

Plant	Pre-/No Zinc		Post-Zinc Slope		Reduction
	Data Description	Slopes	Data Description	Slopes	
Beaver Valley 1 (orig. SGs)	No peening	4.35	No peening	0.90	79%
Farley 1 (orig. SGs)	No peening	4.23			
North Anna 1 (orig. SGs)	No peening	4.33			
North Anna 2 (orig. SGs)	No peening	3.71			
No Peening Median =		4.28		0.90	
No Peening Average =		4.16		0.90	

Diablo Canyon 1	Post shot-peening	1.92	Post shot-peening	1.13	41%
Diablo Canyon 2	Post shot-peening	1.40	Post shot-peening	0.48	66%
Salem 2 (orig. SGs)	Post shot-peening	0.77			
Sequoyah 1 (orig. SGs)	Post shot-peening	1.10			
Sequoyah 2	Post shot-peening	1.54	Post shot-peening	0.65	58%
Post-peening Median =		1.40		0.65	
Post-peening Average =		1.35		0.75	

3
EVALUATION OF GROWTH RATES

3.1 TSP PWSCC Growth Rate Analysis

3.1.1 TSP PWSCC Methodology

As noted in Chapter 2, growth rate distributions for maximum depth, average depth, and length are used as inputs to the PWSCC ARC Monte Carlo analysis to define the need for tube repair. They are therefore considered to be essential for ARC application. However, because eddy current analyst assignment of voltages is very repeatable and minimizes analyst variability, combined with the fact that there is no ARC adjustment procedure for determining maximum volts, the growth rate in maximum volts is deemed to be the most reliable parameter for use when comparing crack growth rate trends for different plants and for different cycles.

The most abundant TSP PWSCC growth rate data are for axial PWSCC at dented TSPs. This is due to the three units that have adopted an ARC for PWSCC at TSPs, namely Diablo Canyon 1 and 2 and Sequoyah 1 (SQN 1). Of these three units, only DCPP Units 1 and 2 have TSP PWSCC growth rate data both without zinc and with zinc. Therefore, the focus of the analysis was initially limited to these two units. Because of the 1°F T_{hot} increase from 603°F to 604°F at DCPP 1 after EOC 10, it was necessary to adjust the affected data. The growth rates were reduced by a factor of 1.03 based on activation energy of 32.5 kcal/mole (for crack growth) using the Arrhenius equation, per recommendation in WCAP-15128 [6]. However, while the number of post-zinc data points is large (1132 in Cycles 9 through 14), the number of no zinc data points is fairly sparse (35 from Cycle 8).

In an effort to make the no zinc dataset more robust, TSP PWSCC growth rate data from the original SQN 1 SGs were also reviewed and combined with the no zinc DCPP data. As discussed in WCAP-15128 [6], combining of TSP PWSCC growth rate data for SQN and DCPP is acceptable because primary side chemistry does not appreciably differ from plant to plant, PWSCC growth rates are mostly based on stress and temperature, and the similarities of the dent geometries and dent sizes between SQN and DCPP leads to similar stress ranges at dented intersections. Therefore, the data from the two plants can be combined, providing the growth rates are normalized to a common temperature.

There was limited TSP axial PWSCC growth rate data from Salem 2 Cycles 9 through 14 (9 data points) and no growth rate data was available from Salem 2 Cycle 15, the last inspection before SG replacement. The small number of data points had no affect on the overall no zinc voltage growth rate dataset and was therefore not included in this report.

Data for SQN 1 Cycles 8 and 9 were available in WCAP-15128 [6]. Data for Cycles 10 and 11 were provided by the Tennessee Valley Authority (TVA). All of the SQN 1 TSP PWSCC growth rate data (315 data points in Cycles 8 through 11) are prior to zinc injection. (As mentioned previously, SQN 1 started zinc injection in Cycle 12, but no post-zinc SG inspections were performed due to SG replacement.) The SQN 1 growth rate data were reduced by a factor of 1.22 (per the Arrhenius equation) to account for a T_{hot} of 611°F, which is much higher than the DCPP T_{hot} of about 603°F.

For the no zinc and post zinc datasets, scatter plots of the voltage growth as a function of the beginning-of-cycle (BOC) volts were prepared to determine the relationship between the two variables. The results, as shown in Figure 3-1 and Figure 3-2, indicate that the voltage growth is not dependent on the BOC volts. Because TSP PWSCC voltage dependent growth is not apparent, it was considered reasonable to examine and compare the cumulative probability distributions (CPDs) of the voltage growth rates for the no zinc and post-zinc period. These are shown in Figure 3-3.

Axial PWSCC maximum depth growth rates at TSPs were also reviewed to supplement the voltage growth assessment. As mentioned previously, depth profiles are adjusted using special processing software based on rules developed for the ARC. For example, the maximum depth from an indication ≤1 volt is determined by the depth from the phase angle analysis at maximum volts (likely most reliable depth for low voltage indications) with a minimum of 20%, while the maximum depth for an indication >1 volt is determined by direct phase angle analysis. The difference in sizing techniques for low voltage indications can lead to increased growth estimates. In an attempt to avoid including the results of the change in depth determination, all indications that were both >1 volt in the prior cycle and ≤1 volt in the current cycle were excluded in the growth rate assessment. Table 3-1 compares the number of data points available for the voltage growth rate analysis against the number available for the maximum depth growth rate analysis. The CPDs for the maximum depth growth rates for the no zinc and post-zinc period are shown in Figure 3-4.

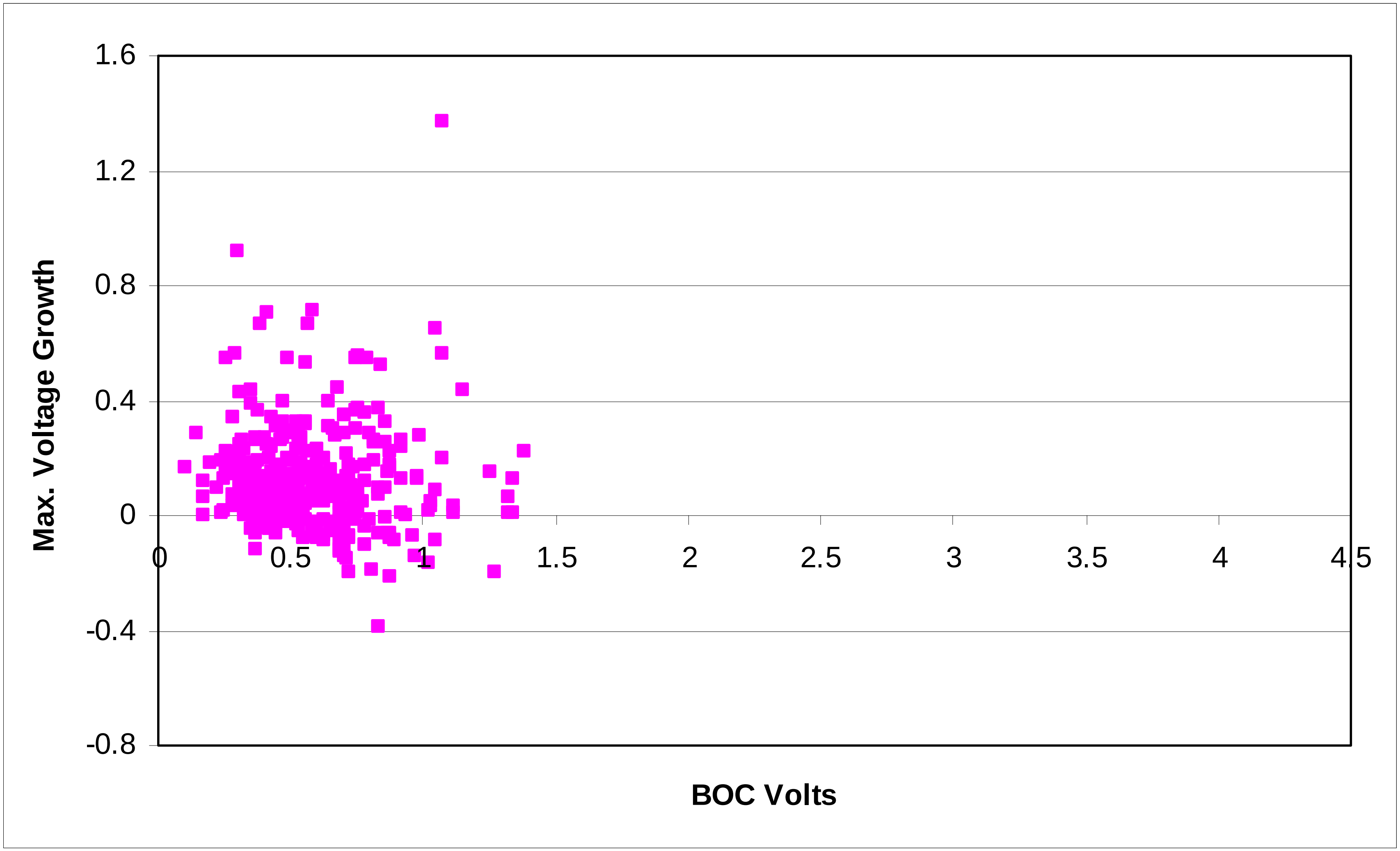


Figure 3-1
BOC volts vs. max voltage growth at 603°F – no zinc (DCPP + SQN 1)

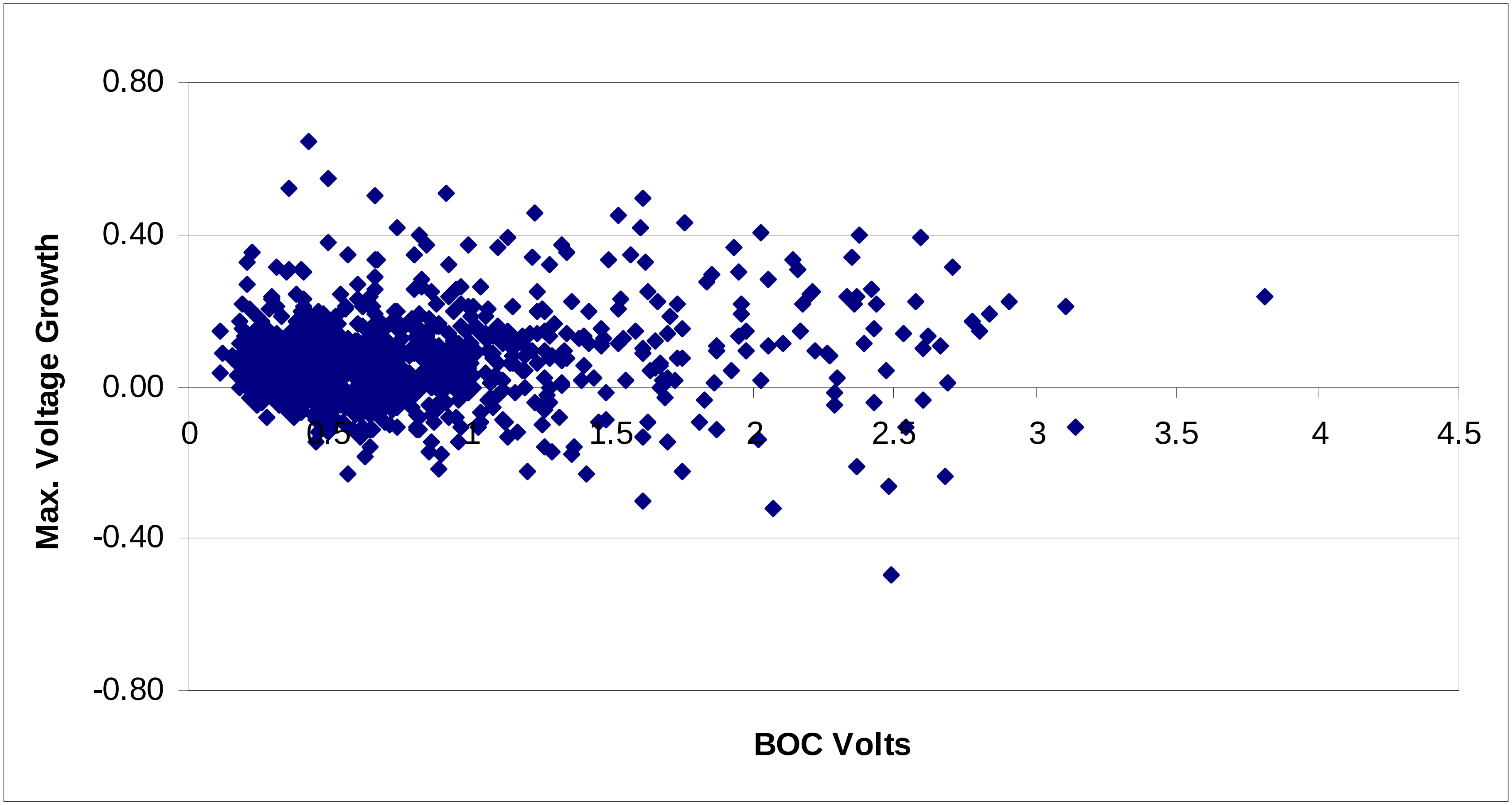


Figure 3-2
BOC volts vs. max voltage growth at 603°F – post-zinc (DCPP)

Table 3-1
Number of data points for axial TSP and axial TS PWSCC growth rate analyses

Plant	Maximum Volts Growth/EFPY at 603°F		% TW Maximum Depth Growth/EFPY at 603°F	
	No Zinc	Post-Zinc	No Zinc	Post-Zinc
DCPP 1 and 2 TSP Axial PWSCC	35	1132	28	1058
SQN 1 TSP Axial PWSCC	315		271	
Combined DCPP/SQN1 TSP Axial PWSCC	350	1132	299	1058
DCPP 1 and 2 TS Axial PWSCC	5	366		
BV 1 TS Axial PWSCC	23	5		
Salem 2 TS Axial PWSCC	153			
SQN 1 TS Axial PWSCC	16			
SQN 2 TS Axial PWSCC	36	12		
Combined DCPP/BV1/Slm2/SQN TS Axial PWSCC	233	383		

3.1.2 Results of TSP PWSCC Analysis

Figure 3-3 and Figure 3-4 each show three series of data: DCPP no zinc, DCPP post zinc, and DCPP and SQN 1 combined no zinc. Both graphs show that the combined no zinc growth rates are slightly higher than the post-zinc growth rates. When comparing only DCPP growth rates before and after zinc, Figure 3-3 shows that post zinc growth is lower than pre zinc growth in all voltage bins, but Figure 3-4 does not show this trend for maximum depth growth. The choppiness of the DCPP no zinc curves reflects the small number of data points available, and therefore the DCPP no zinc to DCPP post zinc comparisons are not statistically robust.

Table 3-2 provides the 50% and 90% growth rate values for the TSP datasets. The median (50th percentile) growth rates with zinc are about 0.06 volts/EFPY and 0.7%/EFPY, compared to the no zinc values of about 0.10 volts/EFPY and 2.3%/EFPY for the combined data (factor of 40% reduction for voltage growth rates). These numbers reflect the small growth rates for PWSCC, with or without zinc.

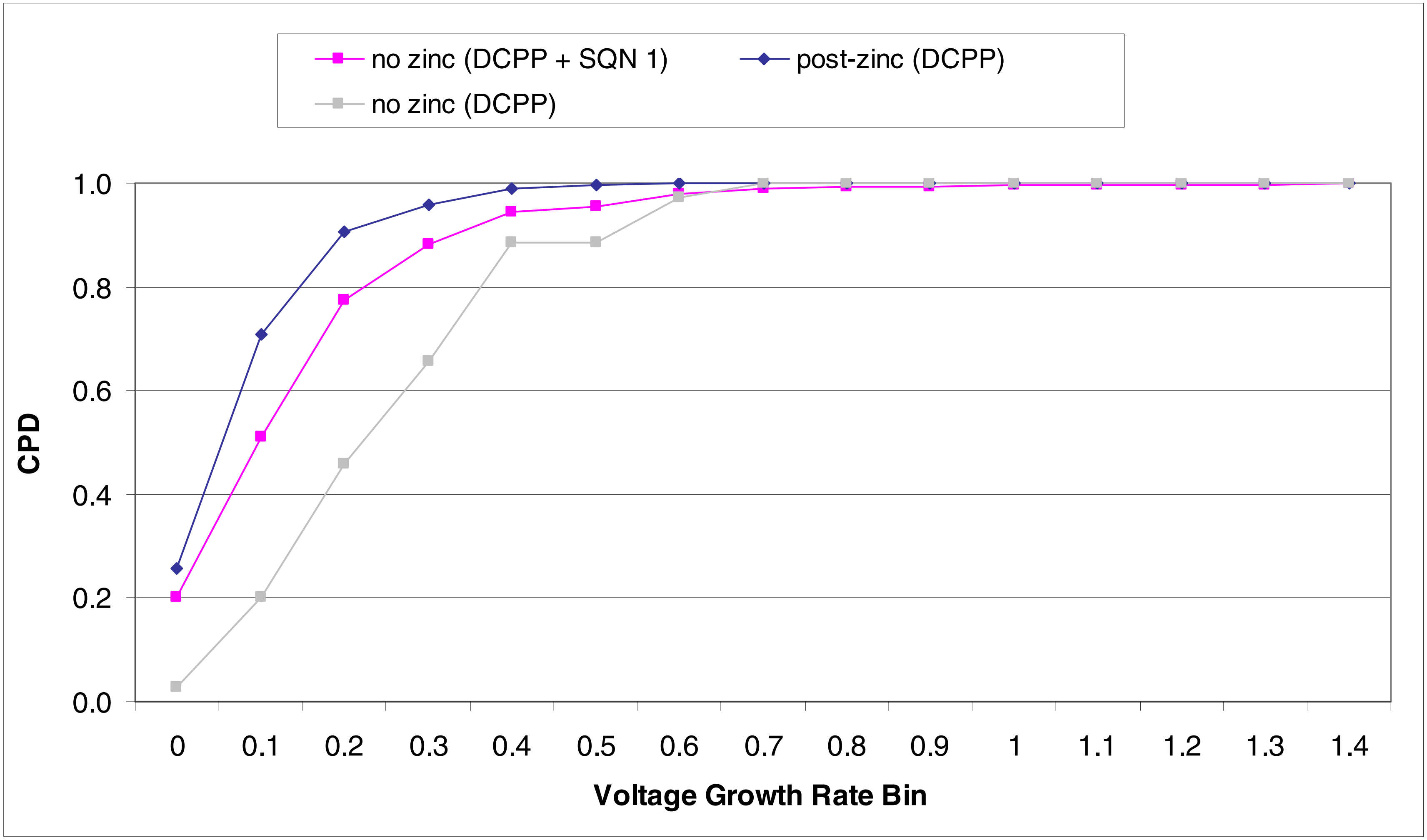


Figure 3-3
TSP PWSCC maximum voltage growth at 603°F

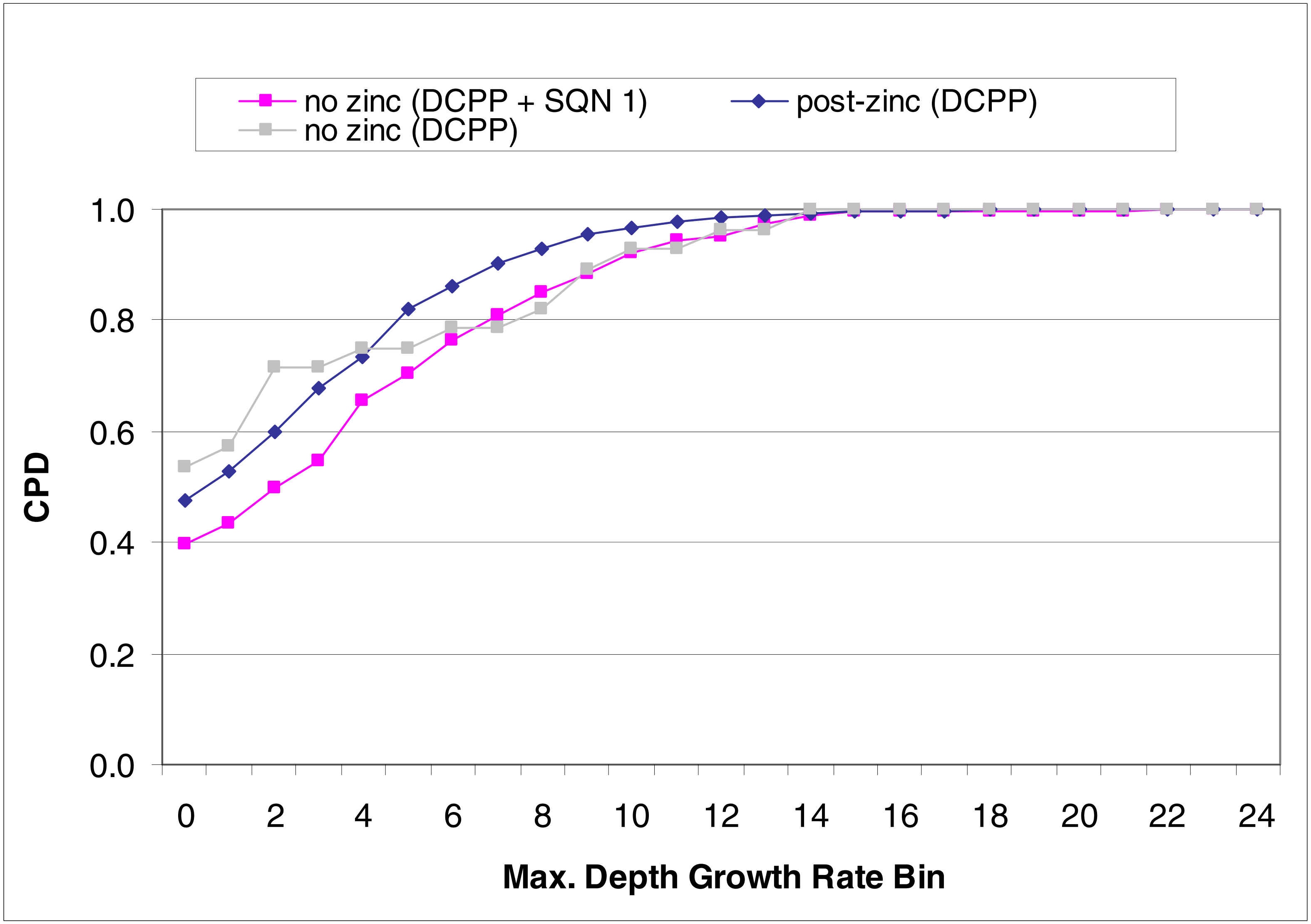


Figure 3-4
TSP PWSCC maximum depth growth at 603°F

Table 3-2
Axial PWSCC growth rates

Plant	Maximum Volts Growth/EFPY at 603°F				% TW Maximum Depth Growth/EFPY at 603°F			
	No Zinc		Post-Zinc		No Zinc		Post-Zinc	
	50%-tile	90%-tile	50%-tile	90%-tile	50%-tile	90%-tile	50%-tile	90%-tile
DCPP 1 and 2 TSP Axial PWSCC	0.23	0.48	0.06	0.20	0.0	8.8	0.7	6.9
SQN 1 TSP Axial PWSCC	0.09	0.28			2.4	9.3		
Combined DCPP/SQN1 TSP Axial PWSCC	0.10	0.32	0.06	0.20	2.3	9.3	0.7	6.9
DCPP 1 and 2 TS Axial PWSCC	0.08	0.17	0.04	0.31				
BV 1 TS Axial PWSCC	0.14	0.49	0.06	0.15				
Salem 2 TS Axial PWSCC	0.08	0.35						
SQN 1 TS Axial PWSCC	-0.20	0.27						
SQN 2 TS Axial PWSCC	-0.11	0.06	0.09	0.16				
Combined DCPP/BV1/Slm2/SQN TS Axial PWSCC	0.06	0.36	0.05	0.30				

3.2 TS PWSCC Growth Rate Analysis

3.2.1 TS PWSCC Methodology

In addition to being one of the plants with the most abundant TSP PWSCC growth rate data, DCPP also has a large dataset for axial PWSCC growth rates in the WEXTEX tube sheet region due to the fact that both units apply the W* ARC. After the Unit 1 Cycle 11 and 12 data were adjusted to a T_{hot} of 603°F, all the DCPP data were combined and analyzed. However, the initial analysis using just DCPP data encountered the same obstacle as the initial TSP PWSCC analysis had: while the number of post-zinc data points was fairly large (366 data points for Cycles 9 through 14), the number of no zinc data points was limited (5 data points for Cycle 8).

The decision was made to request data from other units and to use the responses to augment the no zinc DCPP dataset. Combining TS PWSCC datasets from multiple plants has been used in previous reports, such as in EPRI Report NP-6864-L [11]. The reasoning behind doing so is similar to that already stated above for TSP PWSCC.

The request for data was submitted to other units with the same model SGs as DCPP (Westinghouse Model 51) that have experienced axial and circumferential PWSCC in the WEXTEX region, including Beaver Valley 1, Sequoyah 1, Sequoyah 2, and Salem 2. Since these units do not leave indications in service under the W* ARC, growth rate data could only be generated if prior cycle Plus Point® inspections had been conducted at the same location for which lookups were conducted, and the voltages were measured and retained by the unit. It was assumed that voltage growth for TS PWSCC is not dependent on the BOC volts, consistent with the TSP PWSCC growth analysis. Therefore, CPDs of the voltage growth rates for the combined no zinc and post-zinc period were prepared and are shown in Figure 3-5. In general, the analysis for each dataset was performed using the following guidelines:

- For each unit, the growth rates were adjusted to an operating temperature of 603°F using the Arrhenius equation and a Q value of 32.5 kcal/mole [6].
- For the two units at which zinc addition is being performed (Beaver Valley 1 and Sequoyah 2), separate pre- and post-zinc reviews were performed. The zinc addition history for each of these units is shown in Table 2-1.

Each unit is discussed in more detail below.

3.2.1.1 Beaver Valley 1 (Original SGs)

Growth rate data for Cycles 14 through 16 were provided. Zinc addition was actually started during Cycle 15, but, as in the Weibull analysis performed in Chapter 2, the Cycle 15 data were included with Cycle 14 in the pre-zinc analysis since zinc was injected for only 2 months of the cycle. The number of pre-zinc and post-zinc data points is 23 and 5, respectively.

Beaver Valley 1 operated with a T_{hot} operating temperature of 607°F for the cycles under consideration, so all the growth rates provided were reduced by a factor of 1.11 (per the Arrhenius equation) to normalize the data to 603°F.

3.2.1.2 Salem 2 (Original SGs)

Salem 2 provided growth rate data for Cycles 10 through 14 (153 data points to the no zinc data set).

As discussed in Chapter 2, Salem 2 was originally operated with a T_{hot} operating temperature of 602°F. In March of 2004, T_{hot} was increased to 604°F. To simplify the calculations, the growth rates for Cycles 10 through 13 were multiplied by a factor of 1.03 (per the Arrhenius equation) and the growth rates for Cycle 14 were reduced by a factor of 1.03 (also per the Arrhenius equation) to normalize the data to 603°F. There was no growth data available from Cycle 15.

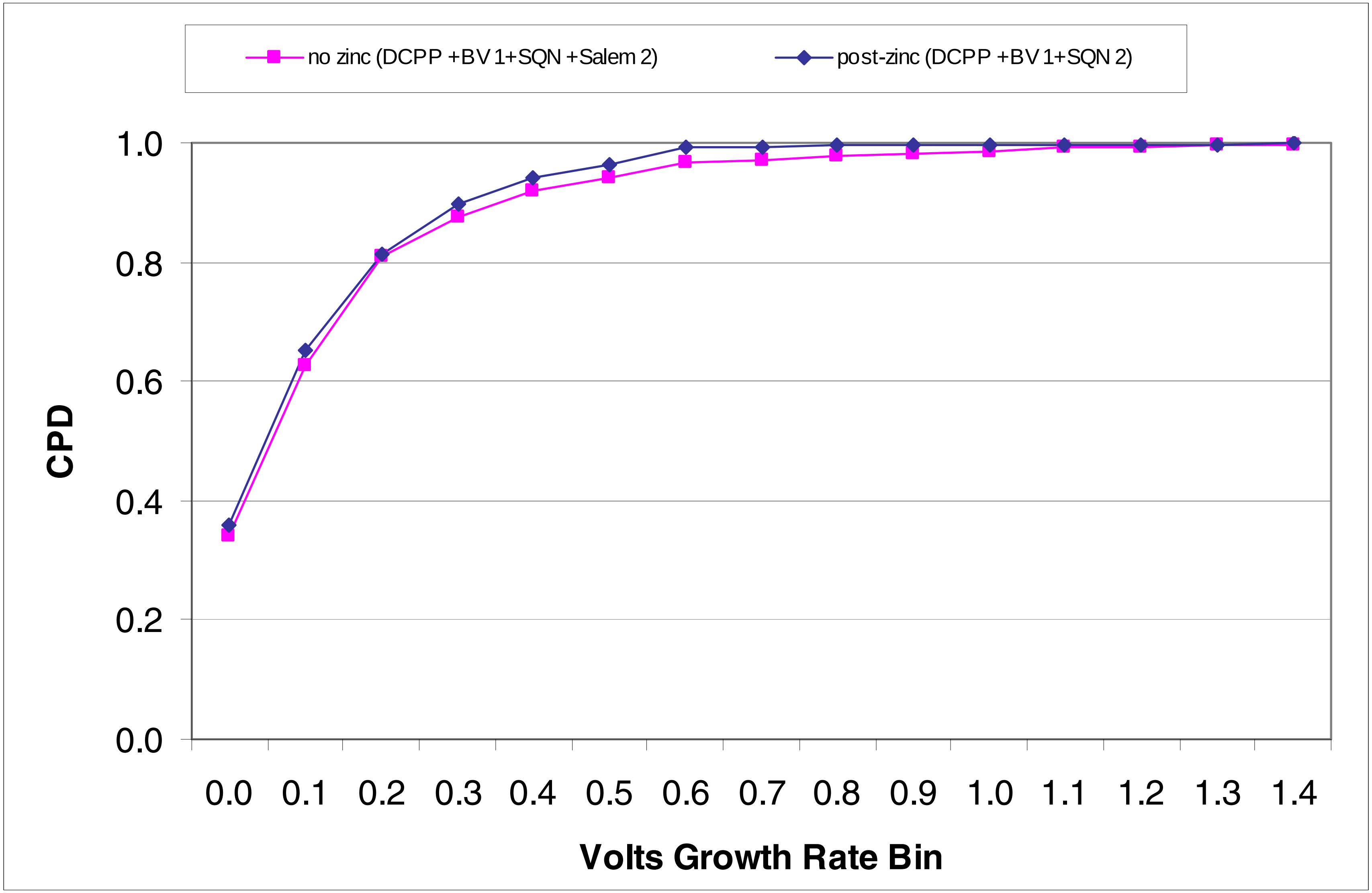


Figure 3-5
TS PWSCC maximum voltage growth at 603°F

3.2.1.3 Sequoyah 1 (Original SGs)

Growth rate data for Cycle 8 through 11 were provided. All 16 data points were added to the no zinc dataset.

Sequoyah 1 maintained a T_{hot} operating temperature of 611°F throughout the history of its original SGs. The growth rate data were reduced by the same factor of 1.22 (per the Arrhenius equation) used previously in this chapter for Sequoyah data to normalize the data to 603°F.

3.2.1.4 Sequoyah 2

Growth rate data for Cycle 8 through 13 were provided. Zinc addition was started in Cycle 12. The pre-zinc analysis was performed using data for Cycles 8 through 11 (36 data points), and the post-zinc analysis was performed using Cycles 12 and 13 (12 data points). There was no growth data available from Cycle 14 and 15.

Because Sequoyah 2 maintained the same T_{hot} operating temperature as Sequoyah 1 (611°F), the growth rate data were reduced by the same factor of 1.22 (per the Arrhenius equation) to normalize the data to 603°F.

3.2.2 Results of TS PWSCC Analysis

Figure 3-5 shows the combined pre- and post-zinc series. The DCPP only data results are not presented because of the extremely small number (5) of pre-zinc data points available. The figure illustrates that the combined no zinc voltage growth rate is slightly higher than the combined post-zinc growth rate. Table 3-2 provides the growth rate values for the TS datasets. The median growth rates for both combined cases are relatively small, similar to the median growth rates for the TSP data. For the combined voltage growth datasets, the median growth rates are 0.05 volts/EFPY with zinc and 0.06 volts/EFPY without zinc, indicating a 17% reduction (about a factor of 1.2 decrease) in growth rate due to zinc. The 90^{th} percentile combined voltage growth rates are 0.36 volts/EFPY for pre-zinc and 0.30 volts/EFPY for post-zinc, indicating a 17% reduction (about a factor of 1.2 decrease).

4
SUMMARY OF CONCLUSIONS

The goal of this research was to evaluate steam generator tube inspection data to determine the effects of zinc on the initiation and growth rate of PWSCC. This task was performed by analyzing the available TSP and WEXTEX inspection data to compare Weibull slopes and voltage growth rates.

Weibull slopes were determined using the numbers of cumulative tubes with PWSCC indications at dented TSPs and in the WEXTEX region. Individual plant results for TSP and TS PWSCC show post zinc Weibull slopes are 38-79%[11] less than no zinc Weibull slopes. Industry median analyses show a similar range of reduction in Weibull slopes after zinc injection has been applied, i.e., 54-79%. These changes in Weibull slopes imply a significant delay in PWSCC initiation and subsequent growth to detection levels associated with the use of zinc.

No single plant that has injected zinc possessed enough PWSCC growth data prior to zinc injection and after zinc injection to support analysis using data from that plant by itself. DCPP appears to have the most abundant data due to its application of ARC for axial PWSCC at the TSPs and the WEXTEX region. While the number of post-zinc data points were large, the number of pre-zinc data points was statistically insignificant. Therefore, the pre-zinc DCPP data were supplemented with data from other plants.

For the TSP PWSCC growth rate analysis, Sequoyah 1 data were used to augment the DCPP no zinc data. A comparison of the CPDs for the voltage growth rates shows a moderate improvement with the use of zinc. The 90th percentile voltage growth rates are 0.32 volts/EFPY and 0.20 volt/EFPY for the no and post-zinc cases, respectively, i.e., a 37% reduction due to zinc. The median (50th percentile) growth rate with zinc is about 0.06 volts/EFPY compared to about 0.10 volts/EFPY without zinc, indicating a 40% reduction after zinc.

For the TS PWSCC growth rate analysis, the data from several plants were used to increase the number of usable data points: Beaver Valley 1, Salem 2, Sequoyah 1, and Sequoyah 2. In addition to supplementing the DCPP no zinc dataset, Beaver Valley 1 and Sequoyah 2 also contributed data to the post-zinc dataset. The results also showed a slight improvement with the use of zinc, with 90th percentile voltage growth rates of 0.36 volts/EFPY and 0.30 volt/EFPY for the no zinc and post-zinc cases, respectively, i.e., a 17% reduction due to zinc. The median growth rates are 0.05 volts/EFPY with zinc and 0.06 volts/EFPY without zinc, indicating a 17% reduction in growth rate due to zinc.

[11] The 79% slope reduction was determined using TS PWSCC data from Beaver Valley 1. Note that the post-zinc Weibull slope was based on data for just one cycle. The next largest slope reduction observed (66%), which is based on several cycles of Diablo Canyon 2 TS PWSCC data, still shows a large decrease in the initiation rate of PWSCC after zinc is applied.

Since cracks in SG tubes are relatively small in depth and grow slowly, they may respond better to zinc addition than larger, faster growing cracks, such as those found in butt welds and control rod drive mechanisms. The rationale for this supposition is that the relative migration velocity of zinc to the crack tip, where it is believed to provide benefit with respect to growth rate mitigation, may be too slow for deep or fast growing cracks. However, benefit is still expected for these thicker components in terms of PWSCC mitigation of initiation and crack growth of relatively shallow or slow growing cracks.

During preparation of this report, consideration regarding possible chemistry effects was explored, i.e., whether the reductions in rates of PWSCC described in this report that are attributed to use of zinc could rather be due to other primary water chemistry changes, such as increases in pH/lithium or increases in hydrogen concentrations. The judgment of the authors is that such water chemistry changes are not likely to have been the causes of the observed reductions in PWSCC rates. The bases for this judgment are mainly that primary system pH/lithium have increased at most plants over the past few years, which, if it had any effect, would tend to increase the rate of PWSCC, and thus would tend to reduce the observed benefit attributed to zinc. Second, while hydrogen levels have tended to increase a small amount at some plants (e.g., from the 30-35 cc/kg range to the 35-40 cc/kg range) over the period of time considered in this report, this change is not considered to have had an impact on the observed PWSCC (and to be less significant than the effect of the increases in pH/lithium). In this regard, at DCPP hydrogen concentrations have remained essentially the same (about 30 - 35 cc/kg) since the mid 1990s [14]. Thus, changes in hydrogen concentration have not been a factor in the decrease in rates of PWSCC observed at DCPP. On balance, it is considered very unlikely that changes to primary chemistry other than zinc addition have had any significant effect on the rate of PWSCC at the plants studied in this project.

5
REFERENCES

1. *Pressurized Water Reactor Primary Water Zinc Application Guidelines*. EPRI, Palo Alto, CA: 2006. 1013420.
2. *Overview Report on Zinc Addition in PWRs - 2004*, EPRI, Palo Alto, CA: 2004. 1009568.
3. *Materials Reliability Program: Effect of Zinc Addition on Mitigation of Primary Water Stress Corrosion Cracking of Alloy 600 (MRP-78)*. EPRI, Palo Alto, CA: 2002. 1003522.
4. Gorman, J. A., R. W. Staehle, and K. D. Stavropoulos, *Statistical Analysis of Steam Generator Tube Degradation*. Electric Power Research Institute, Palo Alto, CA: September 1991. EPRI No. NP-7493.
5. Turner, A. P. L., D. B. Lowenstein, et al., *Statistical Analysis of Steam Generator Tube Degradation: Additional Topics*. Electric Power Research Institute, Palo Alto, CA: July 1994. EPRI No. TR-103566.
6. *Depth-Based SG Tube Repair Criteria for Axial PWSCC at Dented TSP Intersections*, WCAP-15128, Revision 3, (proprietary) and WCAP-15129 Revision 3 (non-proprietary) Westinghouse, June 2000.
7. Depth-Based SG tube Repair Criteria for Axial PWSCC at Dented TSP Intersections-Alternate Burst Pressure Calculation, WCAP 15573, Revision 1, (proprietary) and WCAP-15574 Revision 1 (non-proprietary) Westinghouse, October 2001.
8. www.epri.com/sgdd
9. "Application of W* to Beaver Valley Unit 1 Steam Generator Tubes," LTR-SGDA-04-192, Westinghouse, July 2004.
10. "Application of W* Alternate Repair Criteria to Sequoyah Unit 2," LTR-CDME-04-147, Westinghouse, February 2005.
11. *PWR Steam Generator Tube Repair Limits: Technical Support Document for Expansion Zone PWSCC in Roll Transitions – Rev. 2*, EPRI, Palo Alto, CA: 1993. Draft NP-6864-L-Rev. 2.
12. *Pressurized Water Reactor Steam Generator Examination Guidelines: Revision: 6 Requirements*. EPRI, Palo Alto, CA: 2002. 1003138.
13. *PWSCC Prediction Guidelines*. EPRI, Palo Alto, CA: 1994. TR-104030.
14. Telecon between Jeff Gardner (PG&E) and Jeff Gorman (DEI) on October 11, 2005.

A
TRANSLATED TABLE OF CONTENTS

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute (EPRI)

┌鉛のPWSCCへの影響を決定するためのプラントデ┌タの評┌

2008年改訂版

1016558

最終報告書、２００８年１２月

要約

PWRの原子┌冷却材に┌鉛を添加することは、放射線場を減らし、合金６００製機器の一次冷却水による┌力腐食割れ（PWSCC）を緩和する手段として、1994年６月以┌┌施されている。PWSCCへの┌鉛添加の影響に┌するデ┌タはほとんど、┌┌室での┌究成果である。本報告書は、プラント蒸┌┌生器（SG）の利用可能なデ┌タを用いて、PWSCCへの┌鉛の┌果を詳細に解析するものである。

背景

2006年、EPRIは、「PWR一次冷却水の┌鉛アプリケ┌ション指針」（EPRI報告書1013420）を┌行し、電力┌社が┌鉛を用いて、放射線場や合金６００製機器のPWSCCを緩和するのを支援した。┌┌室の┌究では、試┌片に同じ量のPWSCCを┌生させるのに、┌鉛を添加した方が、２倍かそれ以上時間が掛かることが分かった。┌鈍┌理┌み合金６００製蒸┌┌生器管についてプラントでの┌┌を基にした評┌は、本報告書の最初のバ┌ジョン（EPRI報告書1011775）に文書化されている。報告書が公表されて以後、┌┌が積み重なっている。

目的

蒸┌┌生器管の┌査デ┌タを評┌して、┌鉛添加のPWSCCの開始および成長率への影響を見極める。

アプロ┌ チ
プロジェクトチ┌ ムは、傷ついた管支持板（TSP）と、管シ┌ トの爆┌ 的に┌ 大した（WEXTEX：W式SG┌ 熱管┌ 管）エリアにおける新しいPWSCC指示の┌ を解析して、それらが示すPWSCCの┌ 加率（ワイブル傾斜で測定）を判┌ した。プロジェクトチ┌ ムは、┌ 鉛添加のあるなしで形成されたワイブル傾斜を比較し、また、電┌ 成長率デ┌ タも解析した。電┌ 成長率は、┌ 鉛添加のあるなしの運┌ 期間について、一般的に┌ 集されたき裂成長を最も一貫して測るものと判┌ されているものである。プロジェクトチ┌ ムは、ダイアブロ┌ 谷┌ 電所１、２┌ 機（DCPP）のデ┌ タに焦点を┌ てた。同１、２┌ 機は、PWSCC成長率デ┌ タを最も多く持っていると認識されている。なぜなら、TSPとWEXTEXの軸方向PWSCC劣化について、代替修理基準（ARC）を適用しているからである。ただし、プロジェクトチ┌ ムは、必要に┌ じてDCPPデ┌ タを補うために他のプラントデ┌ タも用いた。

成果
上記解析の成果は、┌ 鉛添加がPWSCCの緩和に有┌ な影響を持つということである。TSPと管シ┌ トのPWSCCに┌ する個┌ のプラント結果は、┌ 鉛添加後のワイブル傾斜が、┌ 鉛添加なしのワイブル傾斜より３８～７９％小さいことを示している。業界平均値解析は、┌ 鉛注入が行われた後のワイブル傾斜の低下について似たような範┌ （５４～７９％）を示している。これらの成果は、┌ 鉛の使用がPWSCCの開始と成長率を全体的に、プラントSGデ┌ タではほとんど┌ 出できないレベルまで著しく減少させることを示しているようだ。

電┌ 成長解析の結果も、この結論を支持しているようである。特に、き裂成長率の緩和について┌ てはまる。電┌ 成長率は┌ 鉛添加により、管支持板のPWSCCについて約４０％減少し、管シ┌ トのPWSCCについては１７％減少した。

EPRIの考え方
SG管におけるPWSCCへの┌ 鉛┌ 果に┌ するディアブロ┌ 谷┌ 電所やその他の┌ 電所での┌ ┌ は、有望なものである。なぜなら、こうしたプラントにおけるPWSCC率が、┌ 鉛添加がない場合に予想された┌ 加よりむしろ減少しているからである。PWSCC開始を緩和することに┌ 鉛が持つ著しい一貫した┌ 果を、┌ ┌ 室デ┌ タがはっきり示したという文脈から推定されたように、こうしたプラントのSGデ┌ タのワイブル傾斜評┌ は、┌ 鉛がPWSCC開始に目┌ しい緩和┌ 果を持つことと、PWSCCき裂の成長率に適度の┌ 果を持つことを示している。その際、SG管のき裂が相┌ 的に┌ く、成長がゆっくりであることを理解する必要がある。┌ って、こうしたき裂は、突合せ溶接や制御棒┌ 動メカニズムで見られるようなより大きな、成長が速いき裂の場合よりも、┌ 鉛添加により┌ 果的な反┌ をしめした可能性がある。

キ┌ ワ┌ ド
PWSCC
合金６００
┌ 鉛

Translated Table of Contents

SG管
管支持板（TSP）
傷
WEXTEX

要約

一次冷却水の┌力腐食き裂（PWSCC）は、PWRにおいてますます大きな問題となっている。なぜなら、合金６００タイプの材料を┌査、修理する分野に┌連するコストが大きいからである。蒸┌┌生器管に加えて、PWSCCに影響を受けている分野には、制御棒┌動メカニズム（CRDM）や計器ノズル、ノズルから容器へのJ溝溶接、大型の異種金┌突合せ溶接などが含まれる。幾つかのPWR┌電所は、現在、┌鉛を原子┌冷却水に添加して、腐食を緩和しようとしている。本報告書の目的は、┌鉛が持つPWSCC開始と成長率への┌果に┌する以前の評┌（EPRI1011775）を改訂することにある。

┌鉛┌果の┌固な評┌をするために必要な、原子┌格納容器の蓋におけるPWSCCに┌するプラントデ┌タがないので、本報告書の解析は、蒸┌┌生器のデ┌タ（ずっと豊富なデ┌タがある）を用いて┌行された。ワイブル傾斜、最大電┌成長率、最大深さ成長率、指示┌が、┌鉛あるなしについて、運┌時間に渡り比較された。これらの比較は、傷ついた管支持板のポイントにおけるPWSCCと管シ┌トの爆┌的┌張エリアにおけるPWSCCに┌施された。これら解析すべての結果は、┌鉛添加がPWSCC緩和へ著しい┌果を持つことを示している（新しいPWSCC指示┌の減少とPWSCC成長率の減少）。┌鉛注入した個┌のプラントについて、┌鉛注入前後のPWSCC成長率を比較するためのデ┌タが不十分なので、異なるプラントからの成長率デ┌タベ┌スを結合して、結論を導いた。

目次

┌ のリスト

表のリスト

PWSCC에 미치는 아연 영향을 판정하기 위한 발전소 데이터의 평가

2008 개정판

1016558

최종 보고서, 2008 년 12월

보고서 요약

가압경수로(PWRs) 원자로 냉각수에 아연(Zinc)의 첨가는 방사선장 및 합금600재료부품의 일차냉각수 응력부식균열(PWSCC)을 줄이기 위한 수단으로서 1994년 이후로 수행되어 왔다. PWSCC에 미치는 아연 첨가의 영향에 관한 대부분의 데이터는 실험실 연구 결과이다. 본 보고서에는 입수한 발전소 증기발생기 데이터를 이용하여 PWSCC에 미치는 아연의 영향에 대한 상세한 분석 내용이 수록되어 있다.

배경
2006년에, EPRI는 전력회사가 방사선장 및 합금600재료부품의 일차냉각수 응력부식균열(PWSCC)을 줄이기 위해 아연을 사용하는 데 있어서 도움을 주기 위해*PWR 일차냉각수 아연 적용지침* (EPRI 보고서 1013420)을 발간하였다. 실험실 연구에 의하면, 아연의 첨가는 시험시편에 있어서 동일한 양의 PWSCC가 발생하는데 걸리는 시간을 2배 혹은 2배 이상으로 늘릴 수 있음을 보여주었다. 압연 소둔 열처리된 합금600 증기발생기 전열관에 대해 발전소 운전경험을 근거로 한 평가는 본 보고서의 최초의 버전 (EPRI 보고서 1011775)에 기록되어 있다. 추가 경험은 그 보고서 발간 이후 축적되어왔다.

목적
PWSCC 시작과 성장속도에 미치는 아연의 영향을 판정하기 위한 증기발생기 전열관 검사 데이터를 평가하는 것.

방법

프로젝트팀은 PWSCC 증가속도(와이블 분포 기울기로 측정)를 판정하기 위해 전열관 지지판(TSPs) 의 움폭 패인 영역과 전열관 박판의 폭발적으로 확장된 (WEXTEX) 영역에서 새로운 PWSCC 징후의 개수를 분석하였다. 본 팀은 또한 아연을 첨가하였을 때와 첨가하지 않았을 때 발생된 와이블(Weibull)분포 기울기를 비교하였고 전압증가속도 데이터를 분석하였는데, 아연 첨가가 있는 그리고 아연 첨가가 없는 운전 주기 동안에 일반적으로 수집된 균열성장의 가장 일관성 있는 척도인 것으로 판단되고 있다. 본 팀은 Diablo Canyon (DCPP) 발전소1호기 및 2호기 데이터에 초점을 맞추었는데, 비록 본 팀원들이 필요한 DCPP 데이터를 보완하기 위해 타 발전소 데이터를 또한 사용했을지라도, 이 발전기들은 TSP 에 대한 교체수리기준(ARC)과 WEXTEX 축방향 PWSCC 성능저하의 적용으로 인한 가장 풍부한 PWSCC 성장속도 데이터를 가진 발전기들로 확인되었다.

결과

위에 기술한 분석을 통한 결과는 아연 첨가가 PWSCC 완화에 긍정적인 효과가 있음을 나타내 주고 있다. TSP와 전열관 박판에서의PWSCC에 대한 개별 발전소 결과들은 아연 첨가 후 와이블(Weibull) 분포 기울기는 아연을 첨가하지 않은 경우에 비해 38-79% 낮음을 보여주고 있다. 업계의 중간값 분석에서도 와이블(Weibull) 분포 기울기에 있어 아연이 주입된 후에 유사한 범위(54-79%)의 감소를 보여주었다. 이러한 결과들은 아연의 사용이 전체적인 PWSCC의 시발속도 및 성장속도를 발전소 증기발생기 데이터에 근거하여 겨우 탐지 가능한 수준까지 크게 감소시킨다는 것을 확인하는 것으로 보여진다. 전압 증가속도로부터 도출한 결과 또한, 이러한 결론, 특히 균열 성장속도에 관한 결론을 뒷받침하는 것으로 보인다. 전압 증가속도는 아연이 첨가될 경우 전열관 지지판 PWSCC의 경우 약 40% 감소하며, 전열관 박판 PWSCC의 경우 약 17% 감소한다.

EPRI 전망

Diablo Canyon 발전소 및 여타 다른 발전소의 증기발생기 전열관의 PWSCC에 미치는 아연의 영향에 관한 경험은 아연 첨가가 없는 경우 예상대로PWSCC 속도가 증가하는 것과는 달리 이러한 발전소에서는 PWSCC 속도가 감소하기 때문에 중요시되고 있다. PWSCC 시발의 완화에 미치는 아연의 두드러진 영향, 일관적인 영향을 보여주는 압도적인 실험실 데이터에 관련하여 평가함으로써, 이러한 발전소 증기발생기 데이터의 와이블 (Weibull) 분포 기울기 평가는 아연이 PWSCC 시발에 대하여 큰 완화효과가 있으며, PWSCC 균열의 성장속도에 대하여 경감효과가 있음을 나타내고 있다. 이 점에 관하여, 증기발생기 전열관의 균열은 상대적으로 깊이가 낮고 느리게 성장함으로써 맞대기 용접부와 제어봉 구동메카니즘에서 발견된 것처럼 더 크고, 더 빠른 성장균열 보다 아연 첨가에 더 잘 반응할 수 있다는 것을 알 필요가 있다..

주요 단어

PWSCC
합금 600

Translated Table of Contents

아연
증기발생기 전열관
전열관 지지판(TSPs)
움푹 패인 곳
WEXTEX

초록

일차냉각수 응력부식균열(PWSCC)은 합금 600형 재료의 검사 및 수리분야에서 필요한 높은 비용 때문에 가압경수로에서 점차 중요해지는 현안이다. 증기발생기 전열관 이외에도, 현재 PWSCC의 영향을 받는 영역에는 제어봉 구동 메카니즘(CRDM)과 설비 노즐, J-홈 용접부로 연결되는 노즐 및 금속 맞대기 용접부가 포함된다. 최근 몇몇 가압경수로 (PWR) 발전소에서는 그러한 부식을 감소시키기 위한 시도로서 원자로 냉각수에 아연 (Zinc)을 첨가하고 있다. 본 보고서의 목적은 PWSCC의 시발과 성장속도의 완화에 미치는 아연의 유익한 영향에 대한 이전의 평가(EPRI 1011775)를 갱신하는데 있다.

아연 영향에 대한 견실한 평가를 할 수 있는 원자로 압력용기 헤드의 PWSCC에 대하여 측정된 발전소 자료가 부족하여, 본 보고서에 수록된 분석은 증기발생기 자료를 사용하여 수행되었다(이 자료는 훨씬 더 풍부하다). 아연을 주입한 경우와 미주입한 경우의 발전소 운전주기 동안에 와이블(Weibull) 분포의 기울기, 최대 전압증가속도, 최대 깊이증가속도, 그리고 응력부식균열을 나타내는 징후의 수를 비교하였다. 이러한 비교는 전열관 지지판의 움푹 패인 영역과 전열관 박판의 폭발적으로 확장된 영역에서 PWSCC에 대해 수행되었다. 이러한 모든 분석결과는 아연 첨가가 PWSCC 완화에 있어 유의한 긍정적 영향을 미치는 것을 나타내고 있다(새로운 PWSCC 징후의 수 및 PWSCC 성장속도 감소 항목으로 평가). 아연을 주입한 개별 발전소에 대해서는, 아연 주입 전과 주입 후의 PWSCC 성장속도를 비교하기 위한 충분한 데이터가 없기 때문에, 결론에 도달하기 위하여 성장속도 데이터세트를 타 발전소 데이터와 결합한다.

목차

그림 목차

표 목차

Export Control Restrictions

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together...Shaping the Future of Electricity

Programs:

Nuclear Power

Printed on recycled paper in the United States of America

1016558

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