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

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Technical Report

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

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REPORT SUMMARY

Utilities have made zinc additions to the reactor coolant of PWRs since June 1994 as a means of reducing radiation fields and mitigating primary water stress corrosion cracking (PWSCC) of Alloy 600 components. The majority 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

As of August 2005, 21 PWRs around the world are known to add zinc to the primary coolant at levels ranging from about 5 to 35 ppb, with up to 40 ppb used during some earlier fuel cycles. Plants whose main objective is dose rate reduction use lower concentrations (5 - 10 ppb) while plants whose main objective is mitigation of PWSCC use higher concentrations (15 - 40 ppb). As of August 2005, five units (Farley 1 and 2, Diablo Canyon 1 and 2, and Beaver Valley 1) use zinc addition primarily as a counter against PWSCC. Laboratory studies have shown that zinc addition can double (or more) the time required for an equivalent amount of PWSCC to occur in test specimens, but evaluations of actual plant experience have been fairly limited.

Objective

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 numbers 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). They also performed a comparison of Weibull slopes generated with and without zinc addition.

The project team also analyzed voltage growth rate data, judged the most consistent measure of crack growth generally collected, for operating periods with and without zinc addition. While they focused on Diablo Canyon Units 1 and 2 (DCPP), 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, 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 PWSCC. Individual plant results for TSP and TS PWSCC show that post zinc Weibull slopes are 31-79% less than no zinc Weibull slopes. Industry median analyses show a similar range of reduction in Weibull slopes after the application of zinc injection i.e., 19-79%. These

results appear to confirm that use of zinc significantly decreases the overall rate of PWSCC initiation and growth to 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 47%-60% for TSP PWSCC and 17%-33% for TS PWSCC with the addition of zinc (90^{th} percentile and 50^{th} percentile, respectively).

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. Testing is underway by the MRP to evaluate the effects of zinc on larger, faster growing cracks. The results of this MRP work will help bridge the gap in understanding from the confirmed benefit of zinc in mitigating crack growth rate in relatively small, slow growing cracks, to the uncertain benefit, based on laboratory data showing significant benefit in some cases to no effect in other cases, in larger, faster growing cracks.

Keywords

PWSCC
Alloy 600
Zinc
SG tubing
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. However, the evaluations of the effects of zinc addition have been generally limited to laboratory investigations. The purpose of this report is to help develop a firmer understanding of the beneficial effects of zinc on the mitigation of PWSCC initiation and growth rate.

Because of 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.

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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 the zinc additions. 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. Five units (Farley 1 and 2, Diablo Canyon 1 and 2, and Beaver Valley 1) were known to be using zinc addition primarily as a counter against PWSCC as of August 2005, i.e., adding zinc in the 15-40 ppb range. Experience prior to this report regarding the possible role of zinc on PWSCC at these plants can be summarized as follows [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 is scheduled to be replaced on a preventive basis during the fall 2005 outage, and detailed examination of the removed Farley 2 head could 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 this report is 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. Because of 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 this report were performed using steam generator data (which are much more abundant).

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 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].

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[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: Beaver Valley 2, Diablo Canyon 1 and 2, North Anna 1 (original SGs) and 2 (original SGs), Salem 2, Sequoyah 1 (original SGs) 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, Salem 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 these three units, 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 for these three units 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.

Table 2-1
Zinc Injection History for Beaver Valley 1, Diablo Canyon 1 and 2, and Sequoyah 2

Cycle No.	Zn Addition Days			
	Start	End	Months	Nom. or Ave. Zn Conc., ppb
Beaver Valley 1				
15	12/11/2002	2/22/2003	2	35 target
16	12/3/2003	10/2/2004	11	34.2 (avg)
Diablo Canyon 1				
9	6/24/1998	1/14/1999	7	31
10	12/8/1999	9/22/2000	10	21

Cycle No.	Zn Addition Days			
	Start	End	Months	Nom. or Ave. Zn Conc., ppb
Diablo Canyon 2				
9	3/17/1999	8/25/1999	8	21
10	2/12/2000	3/24/2001	13	16
11	7/3/2001	1/21/2003	8	20
12	4/8/2003	10/14/2004	19	25
Sequoyah 2				

11	2/1/2001	4/10/2002	14	15
12	7/26/2002	3/7/2004	19	20

12	9/24/2002	11/9/2003	13.6	2.75
13	12/16/2003	4/9/2005	15.8	4.89

2.2.2.1 Diablo Canyon 1

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 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 12[3]. The majority of the defects have been axial in orientation.

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
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
TSP	0	31	75	127	67	55	19	15
TS	0	2	3	5	9	4	4	2
Total	0	33	79	131	76	59	23	15

Unit 2 (Axial and Circumferential)								
EFPY	5.74	7.08	8.41	10.03	11.49	12.93	14.53	16.09
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
TSP	17	3	73	33	26	24	31	11
TS	26	13	50	33	19	4	9	3
Total	43	16	123	66	45	28	40	14

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.

[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).

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.

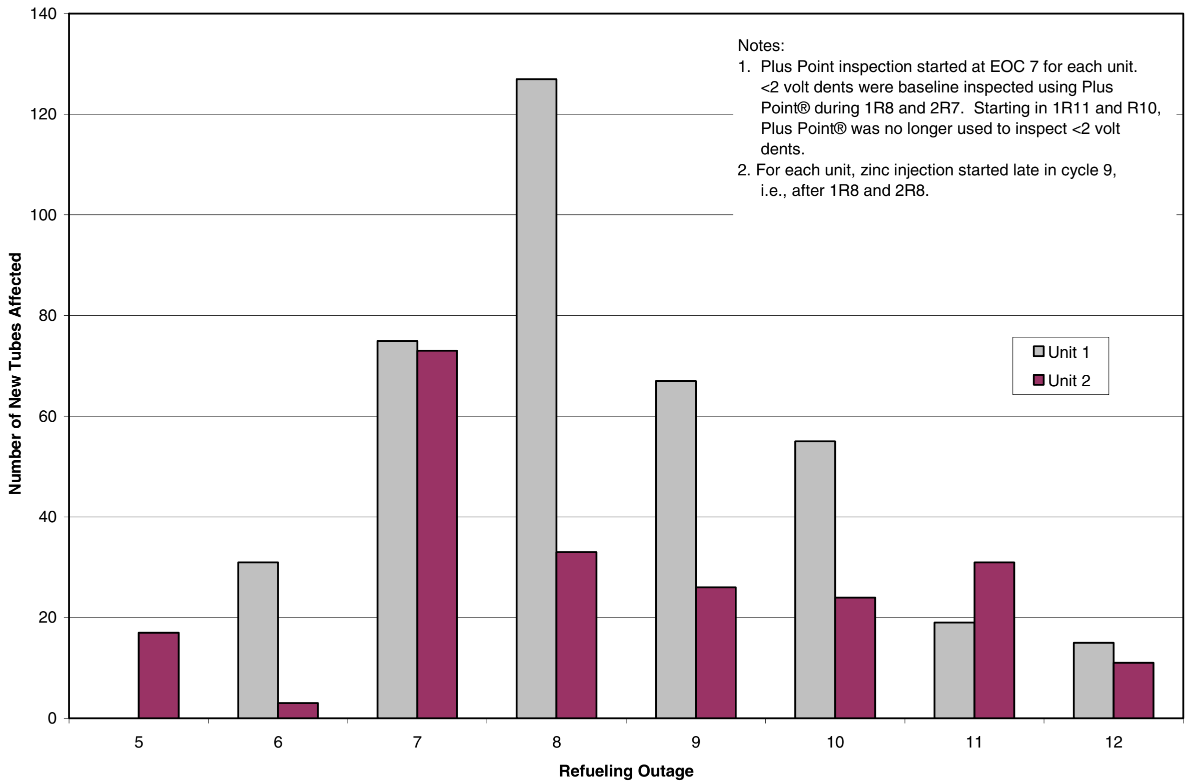

Figure 2-1
Number of New Tubes Affected with TSP PWSCC per Outage at Diablo Canyon

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]).

[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

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:

Table 2-3
Diablo Canyon 1 and 2 Dent Inspection Scope

		Critical Area Inspections (%)			
Outage	**Number of TSP Intersections with Axial PWSCC**	**<2v Dents**	**2 to 5v Dents**	**>5v Dents**	**Notes**
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
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

methodologies described for DCPP. All three voltage categories show the same decreasing trend for the more recent outages.

- 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.

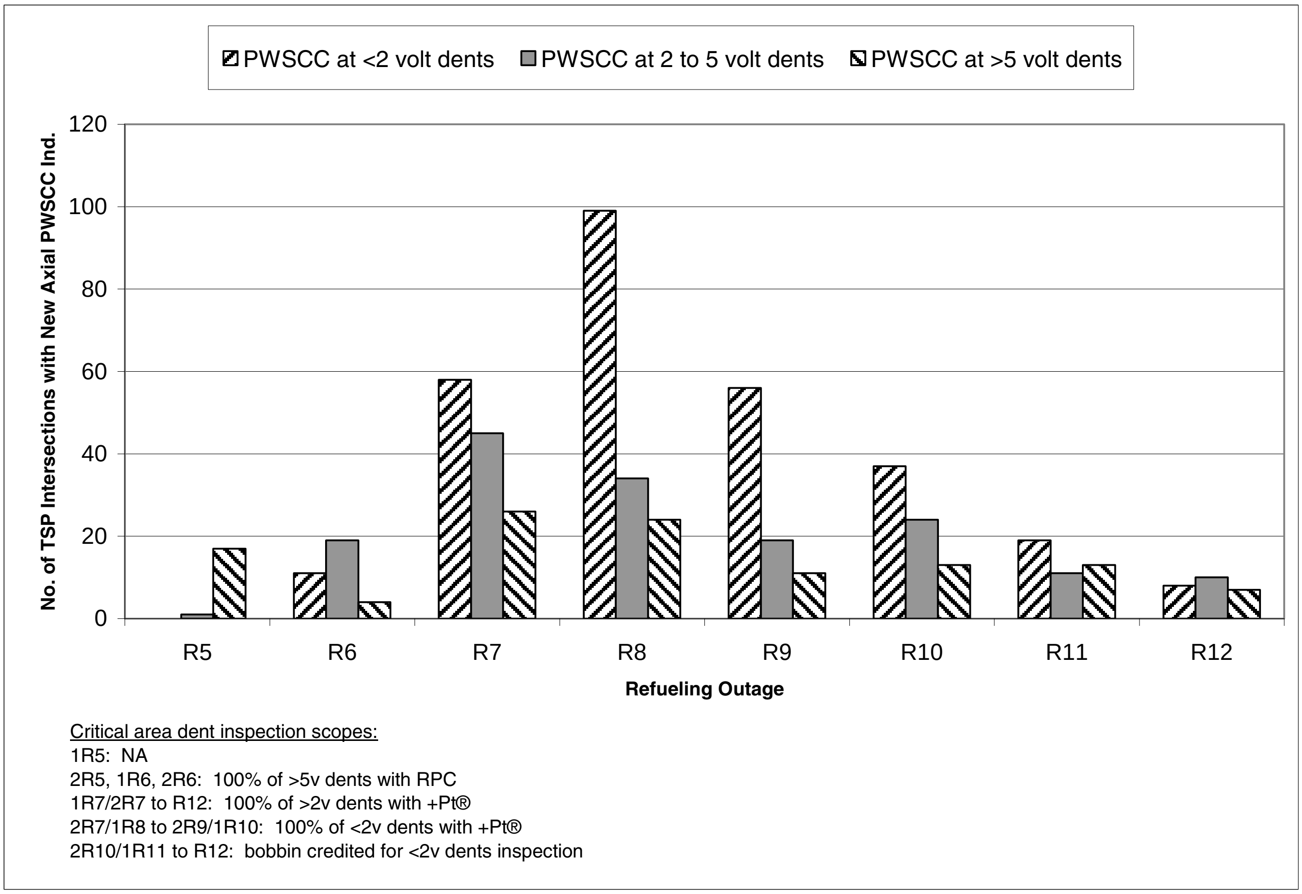

Figure 2-2
Number of TSP Intersections Affected with New Axial PWSCC Indications per Outage at Diablo Canyon 1 and 2 (Combined Data)

- 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.

- 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® 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. 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. 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 the pre-zinc fit is *b* = 2.01.

The post-zinc slope was developed using data for EOC 8 through EOC 12. The EOC 8 through EOC 10 data points were from 100% Plus Point® inspections.[6] The EOC 11 and EOC 12 data

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

[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.

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* = 1.06. Both the pre- and post-zinc fits are shown in Figure 2-3.

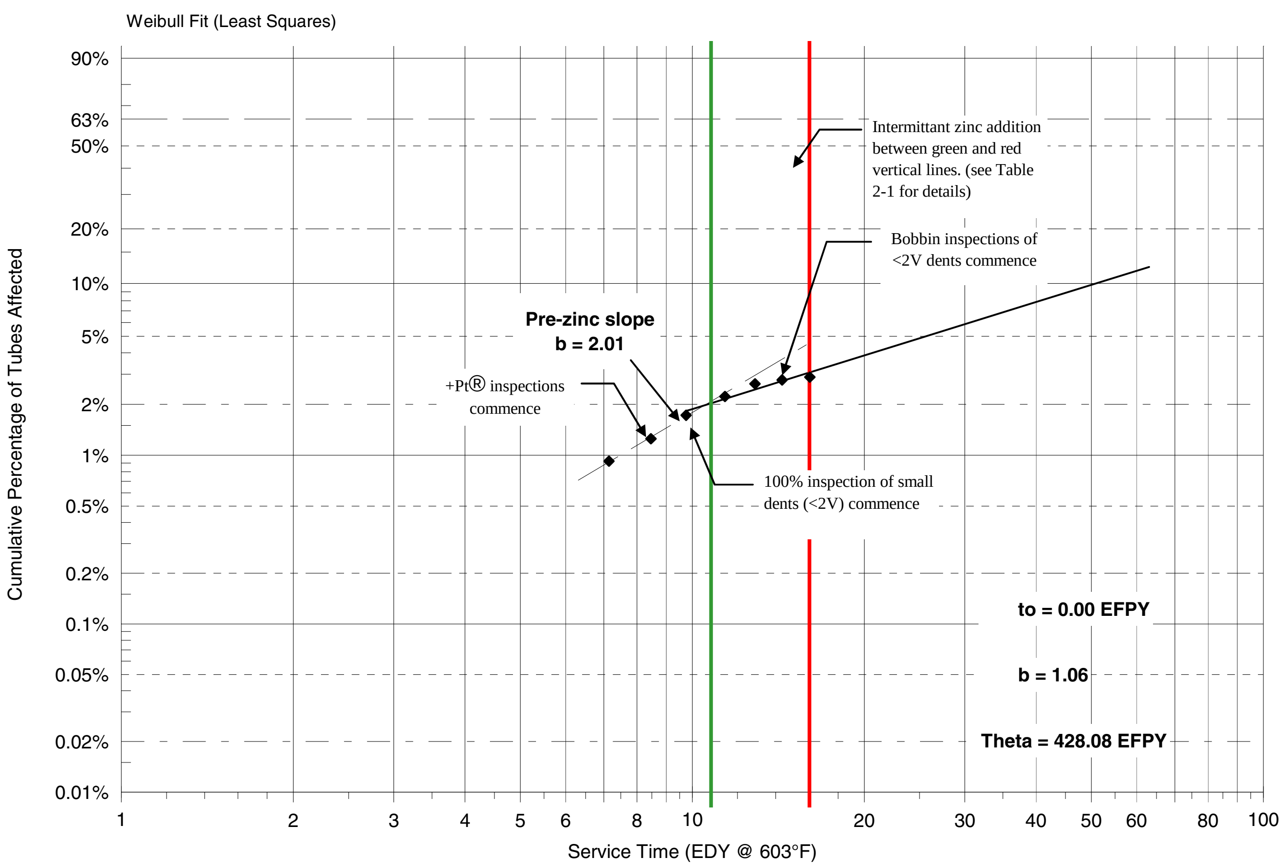

Figure 2-3
Diablo Canyon 1 – All SGs – TSP PWSCC (Axial and Circ.) – Tubes Affected

2.2.2.2 Diablo Canyon 2

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 12. 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 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 has 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 12. The same inspection techniques were used during the EOC 8 and EOC 9 outages. The data from EOC 10 through EOC 12 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 $b = 1.22$. Both the pre- and post-zinc fits are shown in Figure 2-4.

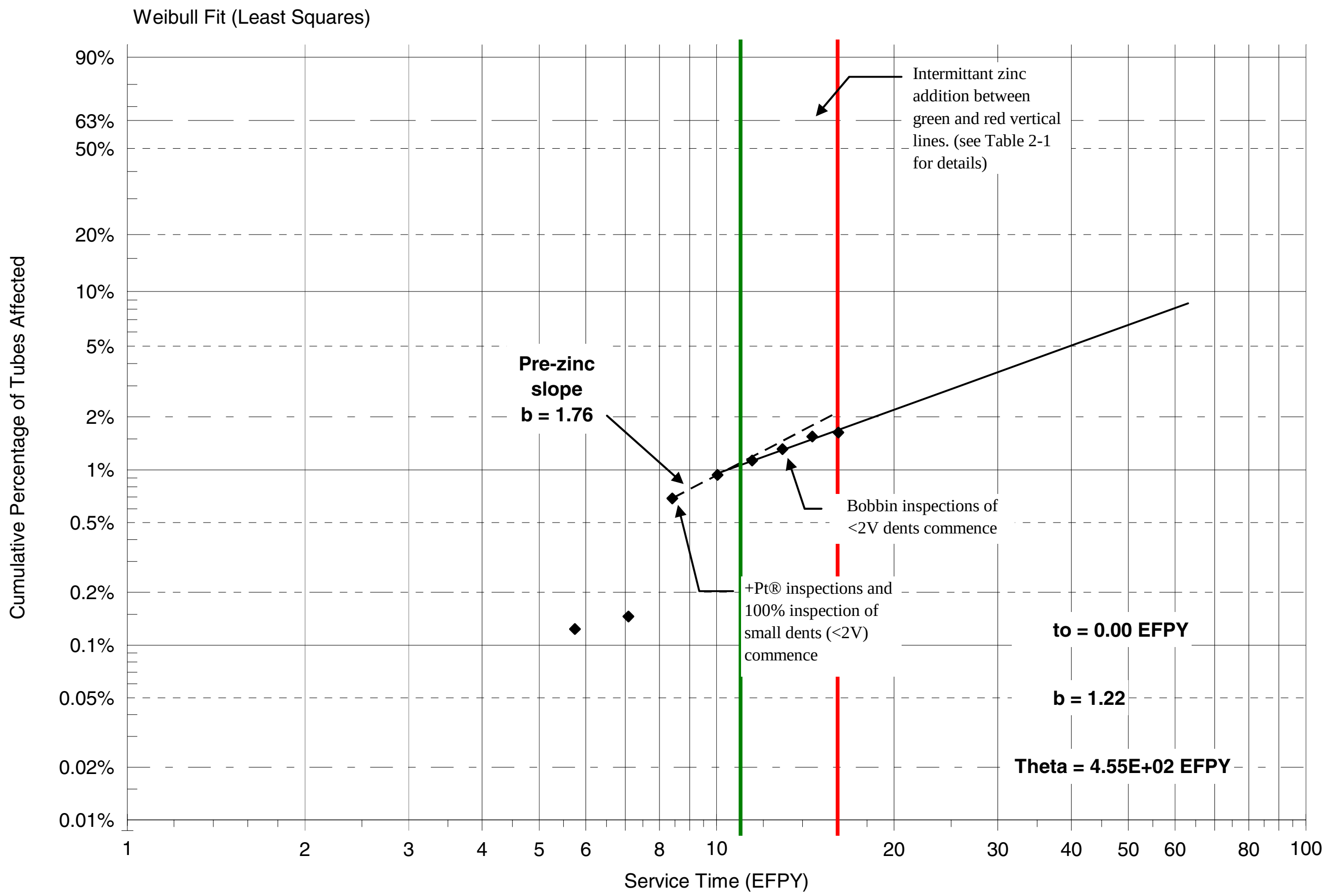

Figure 2-4
Diablo Canyon 2 – All SGs – TSP PWSCC (Axial and Circ.) – Tubes Affected

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 1st TSP (1H) and 2nd TSP (2H), with 90% occurring up to the 3rd TSP (3H). These data support the EPRI Examination Guidelines [12] recommendation to perform Plus Point® inspections of dents up to the highest TSP elevation where PWSCC has been observed in the affected SG.

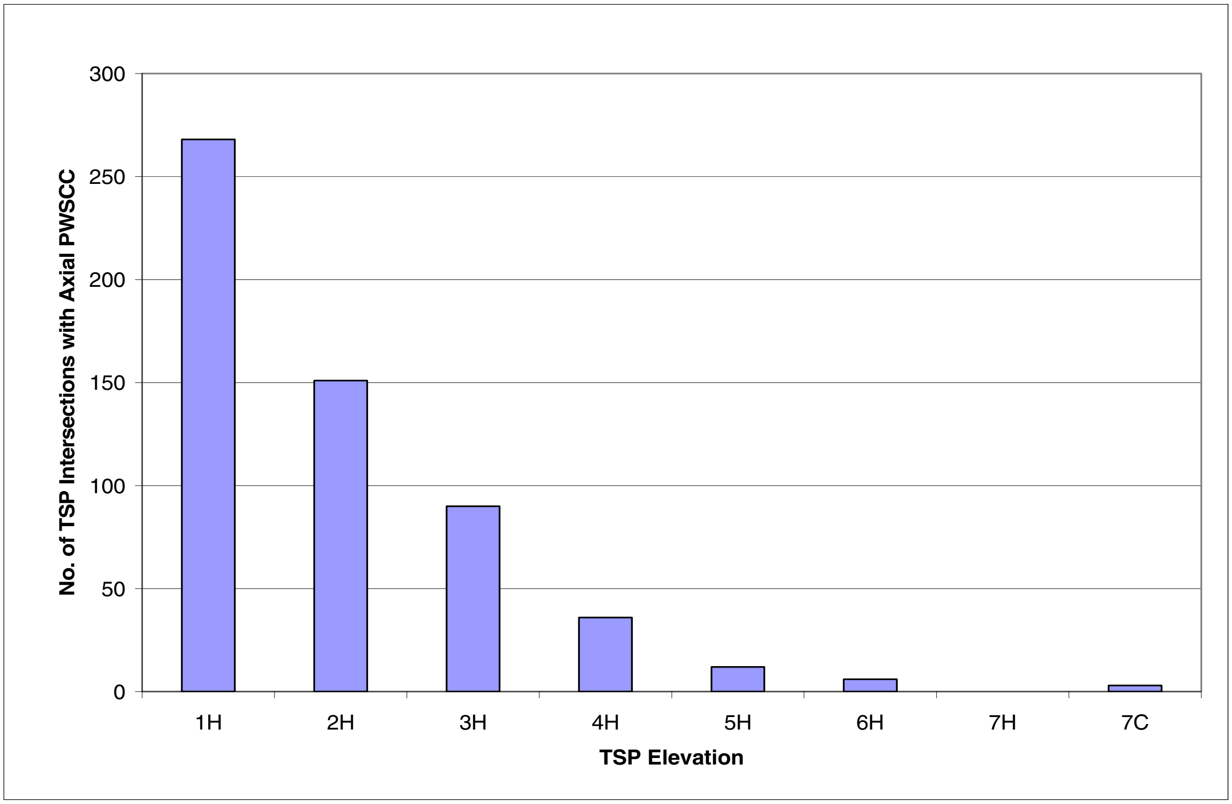

Figure 2-5
Number of TSP Intersections with Axial PWSCC Indications per Elevation at Diablo Canyon 1 and 2 (Combined Data)

2.2.2.3 North Anna 1 (Orig. 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.

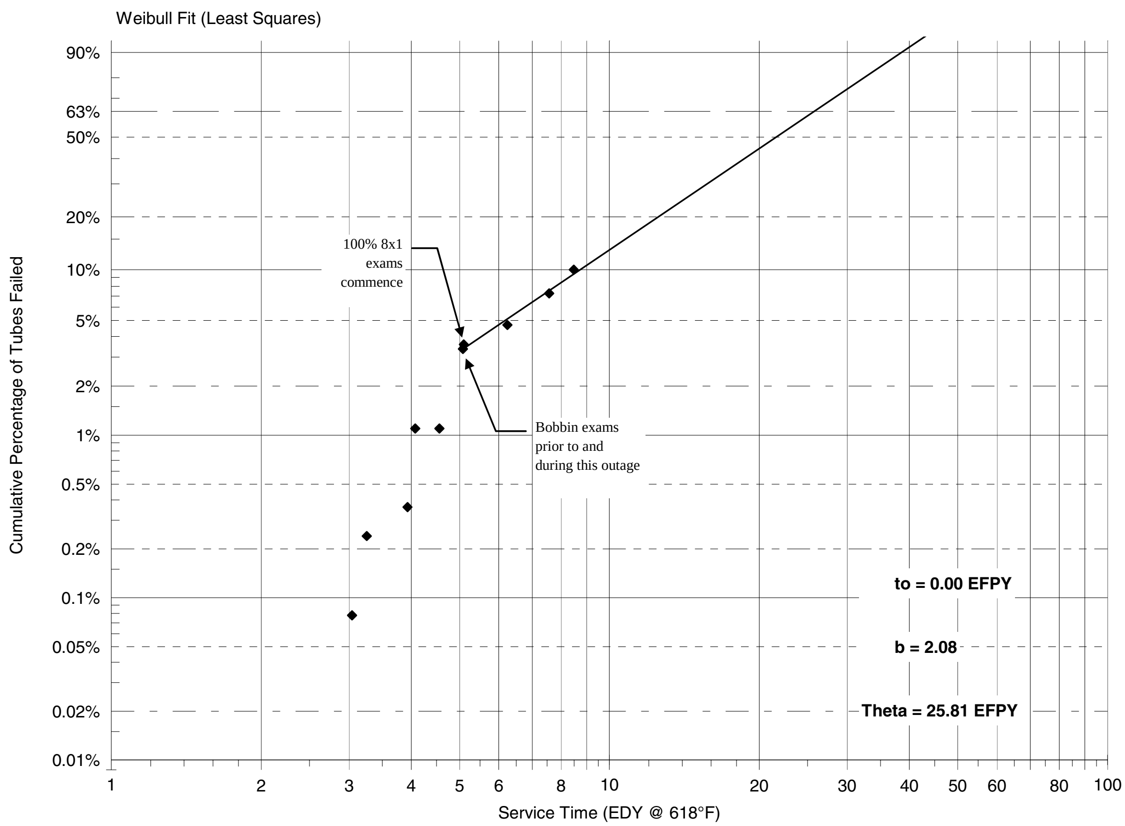

Figure 2-6
North Anna 1 – All Orig. SGs – TSP PWSCC (Axial and Circ.) – Tubes Repaired

2.2.2.4 North Anna 2 (Orig. 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

[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, an RPC probe.

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).

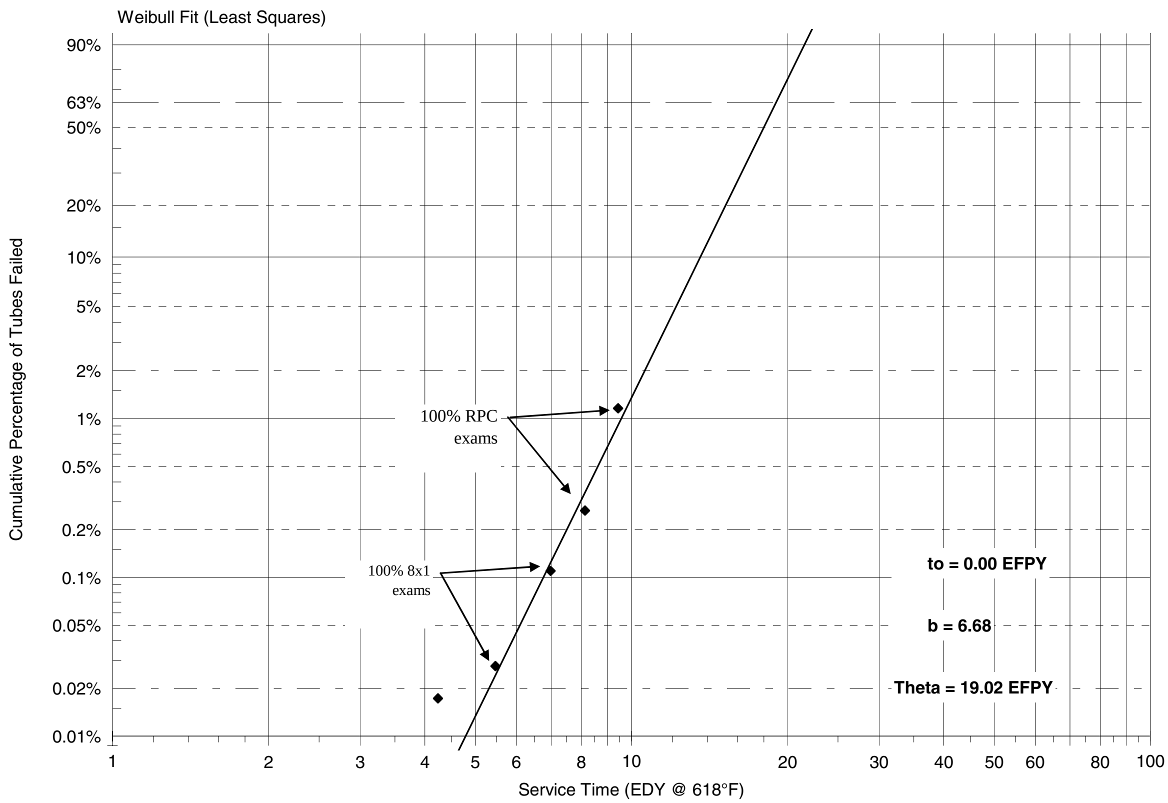

Figure 2-7
North Anna 2 – All Orig. SGs – TSP PWSCC (Axial and Circ.) – Tubes Repaired

2.2.2.5 Sequoyah 1 (Orig. 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 than 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 is 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 2–8.

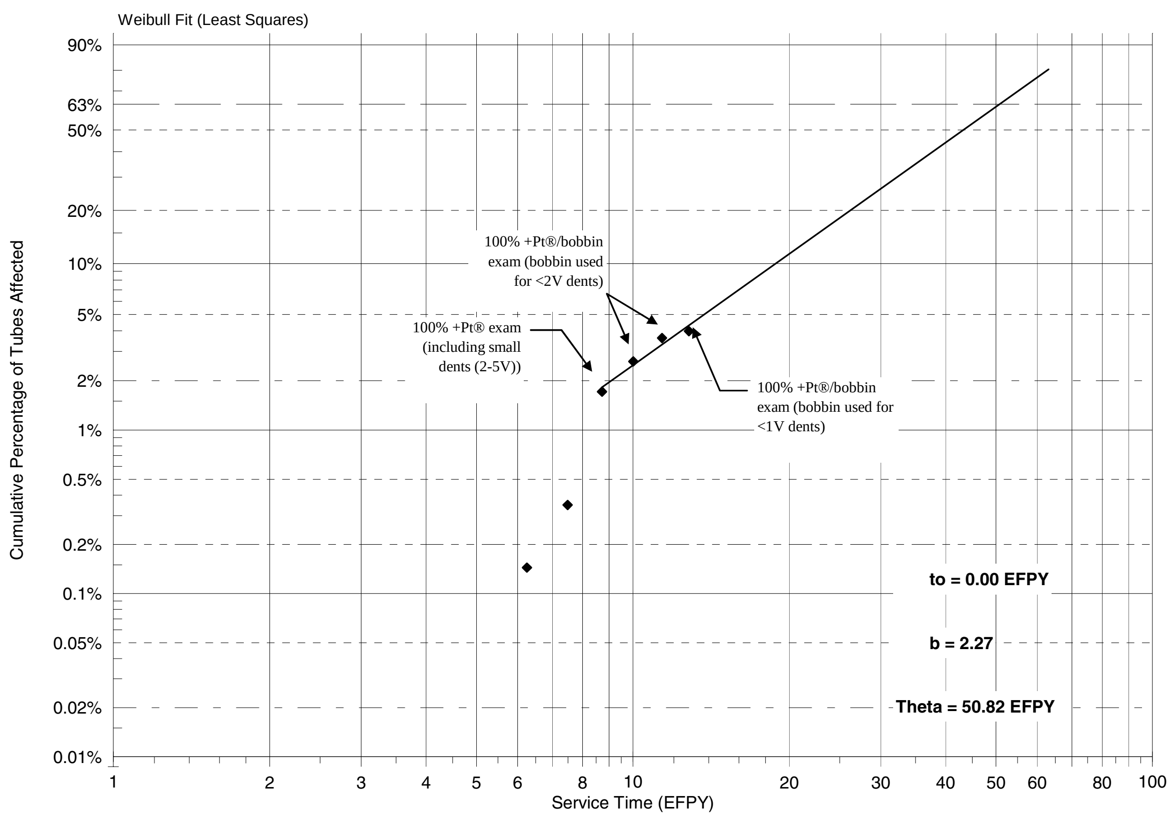

Figure 2-8
Sequoyah 1 – All Orig. SGs – TSP PWSCC (Axial and Circ.) – Tubes Affected

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 have observed significant decreases in their failure rates since zinc addition began. The post-zinc Weibull slopes represent reductions of 47% and 31%

compared to the pre-zinc Weibull slopes for Unit 1 and Unit 2, respectively. Therefore, the average reduction at Diablo Canyon is 39%.

Table 2-4
TSP PWSCC Weibull Slopes

Plant	Pre-/No Zinc Slope	Post-zinc Slope	Reduction
Diablo Canyon 1	2.01	1.06	47%
Diablo Canyon 2	1.76	1.22	31%
North Anna 1 (orig. SGs)	2.08		
North Anna 2 (orig. SGs)	6.68		
Sequoyah 1 (orig. SGs)	2.27		
Median =	2.08	1.14	
Average =	2.96	1.14	

A comparison of the median (50^{th} percentile) result for the five pre-/no zinc units (slope of 2.08) against the median result for the two post-zinc units (slope of 1.14) clearly indicates a decrease in the failure rate (45%). These reductions in Weibull slope result in significant delays in occurrence of PWSCC. For example, the decrease in slope from 2.08 to 1.14 results in an increase in the time required to go from 1% to 10% tubes affected by a factor of 3.3. 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 described above, the Weibull slope parameters for the pre-zinc and post-zinc fits would be b = 2.05 (vs. 2.01) and b = 1.09 (vs. 1.06), respectively.

2.3 Tube Sheet PWSCC

2.3.1 Background of 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 and Beaver Valley 1 have 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 12 units[8]: Beaver Valley 1; Diablo Canyon 1 and 2; Farley 1 (original SGs); Fessenheim 1; North Anna 1 (original SGs) and 2 (original SGs); Salem 1 (original SGs) and 2; Sequoyah 1 (original SGs) and 2; and Trojan. 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.

- 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

[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.

(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 is being 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

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 order to maintain a small Weibull fit error. 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

[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.

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 2–9. 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 and would significantly benefit from additional data as they available.

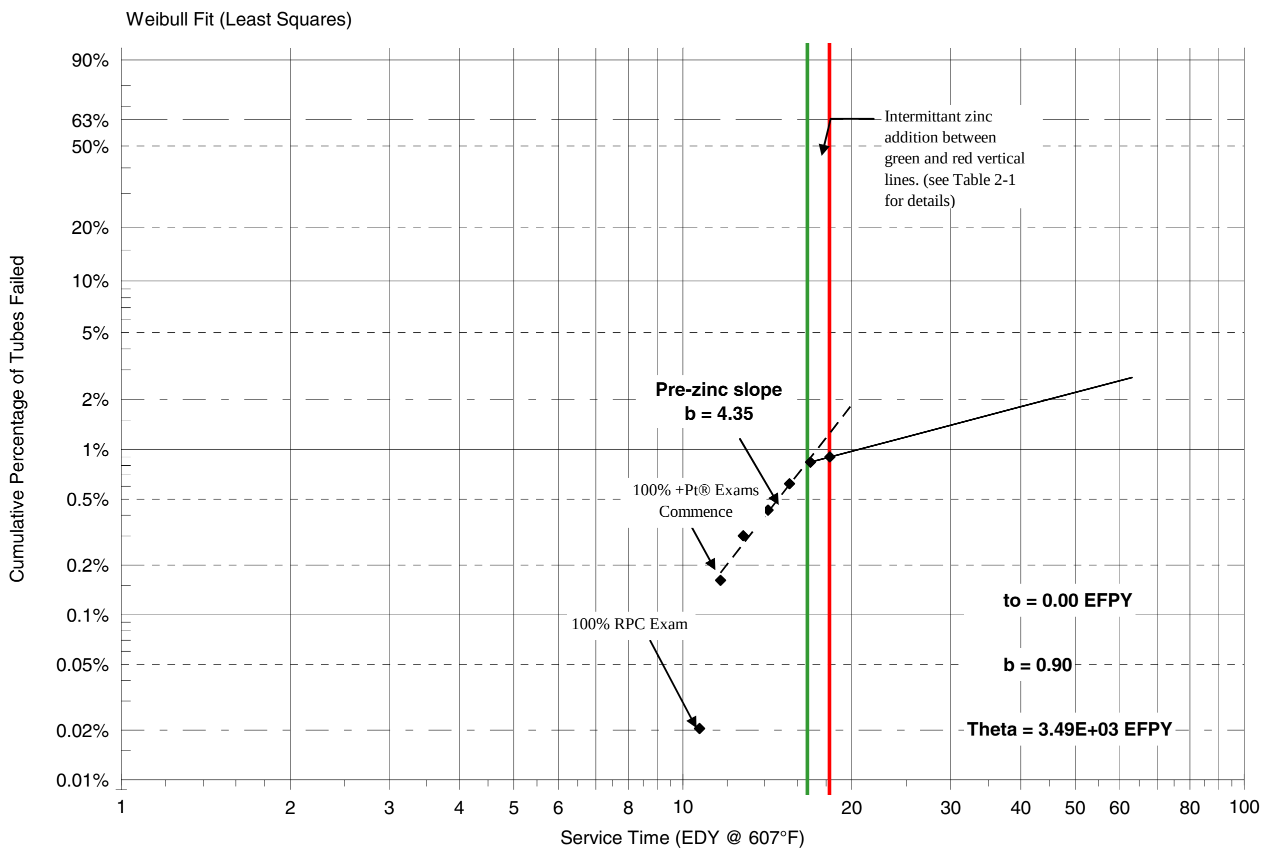

Figure 2-9
Beaver Valley 1 – All SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

2.3.2.2 Diablo Canyon 1

For Diablo Canyon 1, which has been using the W* ARC for the last four 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 2–10 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 29 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 and EOC 12.

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.

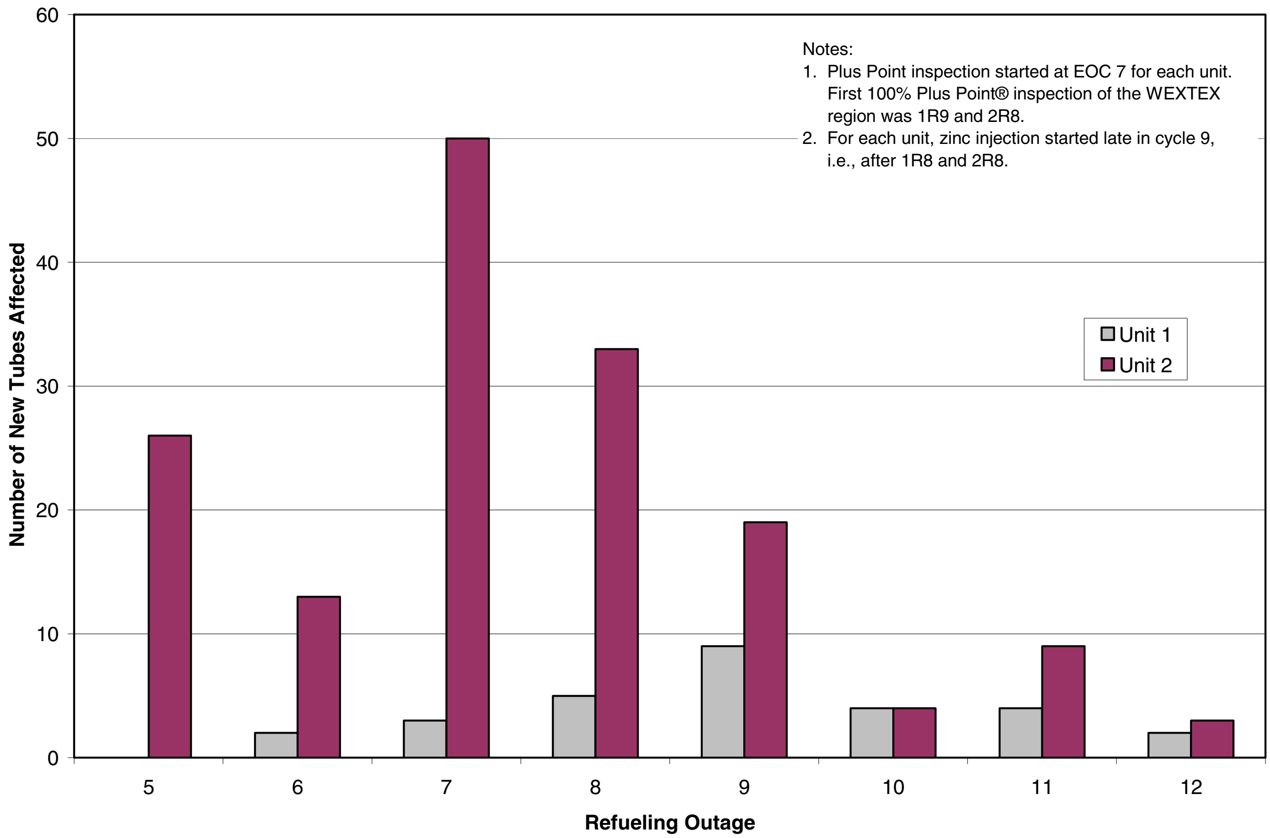

Figure 2-10
Number of New Tubes Affected with TS PWSCC per Outage at Diablo Canyon

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 12. 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 = 1.29. Both the pre- and post-zinc fits are shown in Figure 2–11.

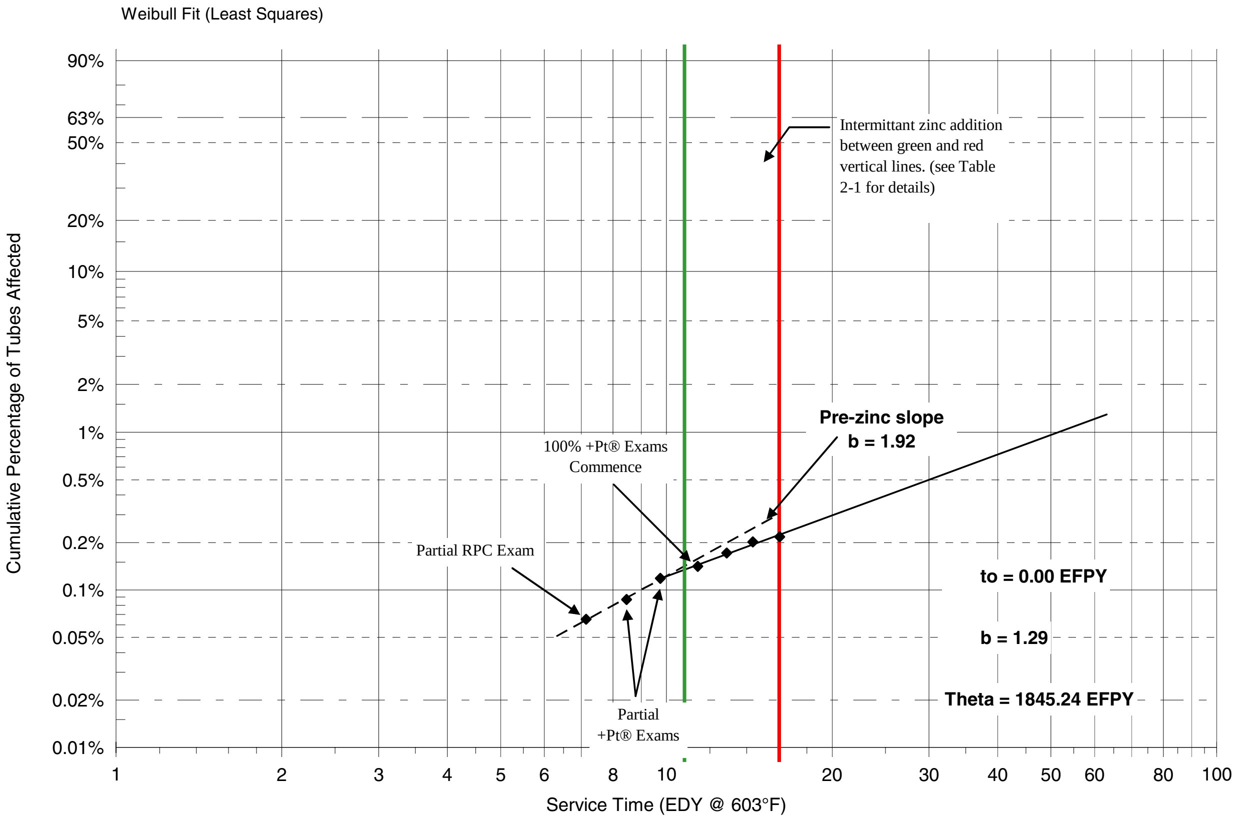

Figure 2-11
Diablo Canyon 1 – All SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Affected

2.3.2.3 Diablo Canyon 2

Like Diablo Canyon 1, Diablo Canyon 2 has been using the W* ARC for the last four 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 2–10 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 12. 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 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, EOC 11, and EOC 12. It is likely that zinc contributed to the decrease in EOC 9, as well as the small numbers of new indications detected in EOC 10, EOC 11, and EOC 12.

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. The post-zinc slope was developed using data for EOC 8 through EOC 12. All five inspections were 100% Plus Point® exams. The Weibull slope parameter for the post-zinc fit is b = 0.52. Both the pre- and post-zinc fits are shown in Figure 2–12. 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.

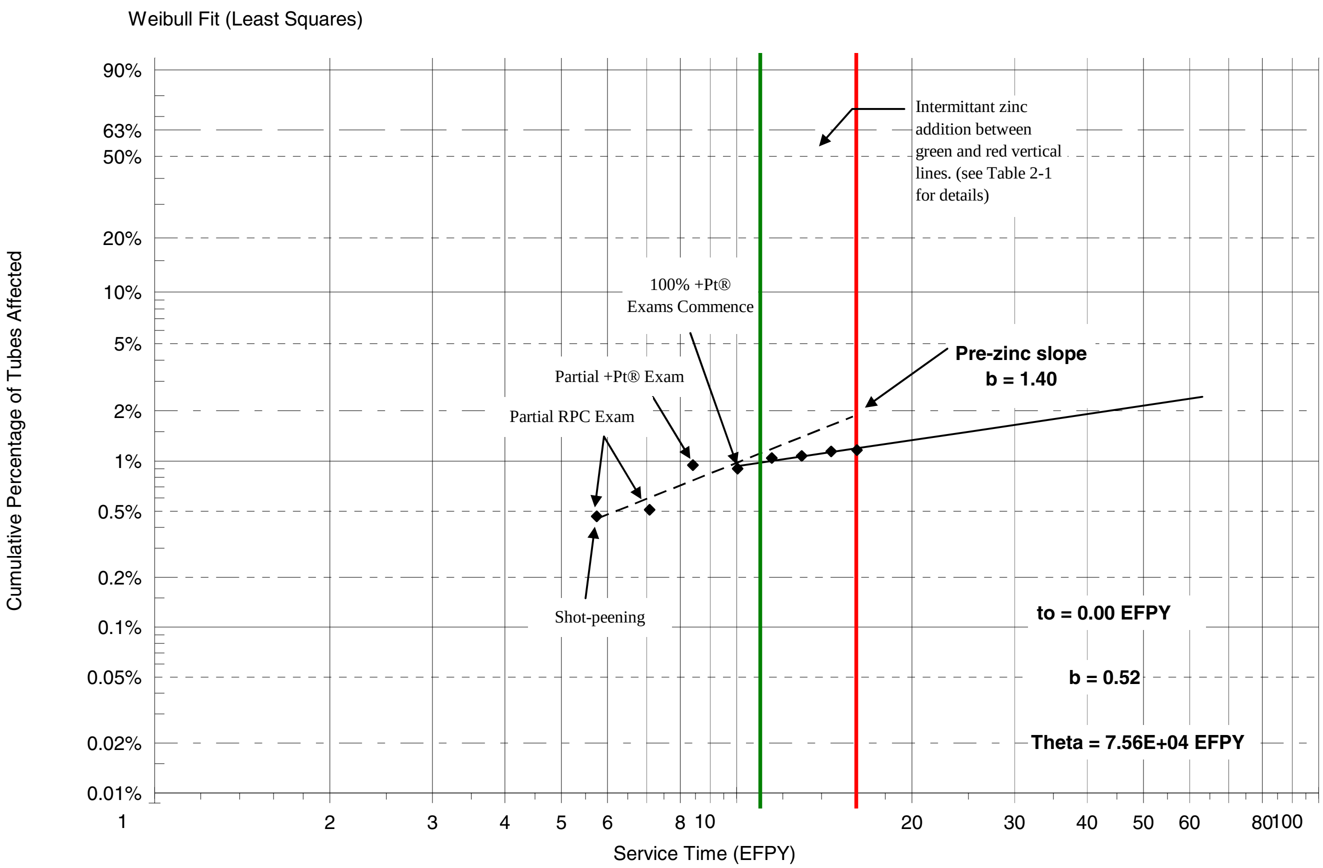

Figure 2-12
Diablo Canyon 2 – All SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Affected

2.3.2.4 Farley 1 (Orig. 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 data are presented in Figure 2–13. The tubes were repaired due to almost equal amounts of circumferentially and axially oriented defects, though slightly more due to axially oriented defects.

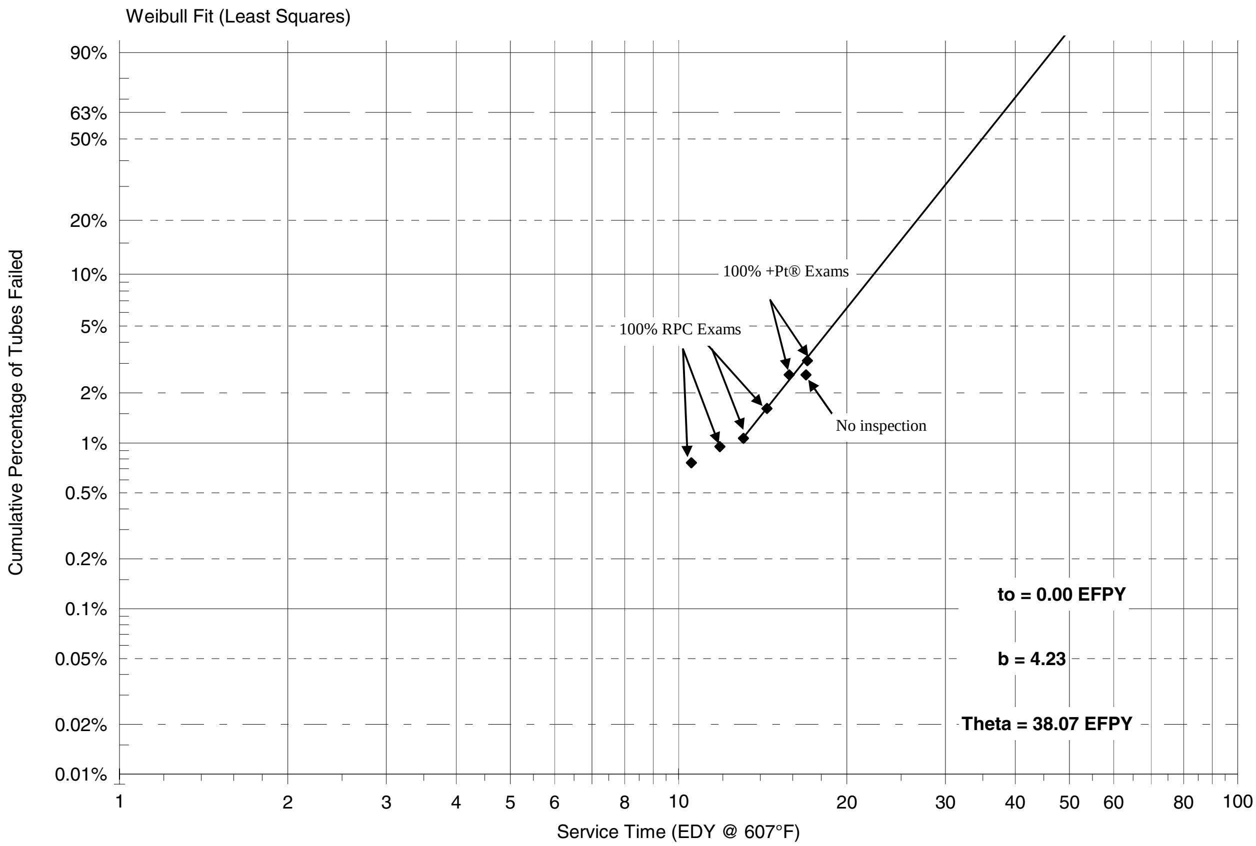

Figure 2-13
Farley 1 – All Orig. SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

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.

2.3.2.5 North Anna 1 (Orig. 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, as shown in Figure 2–14.

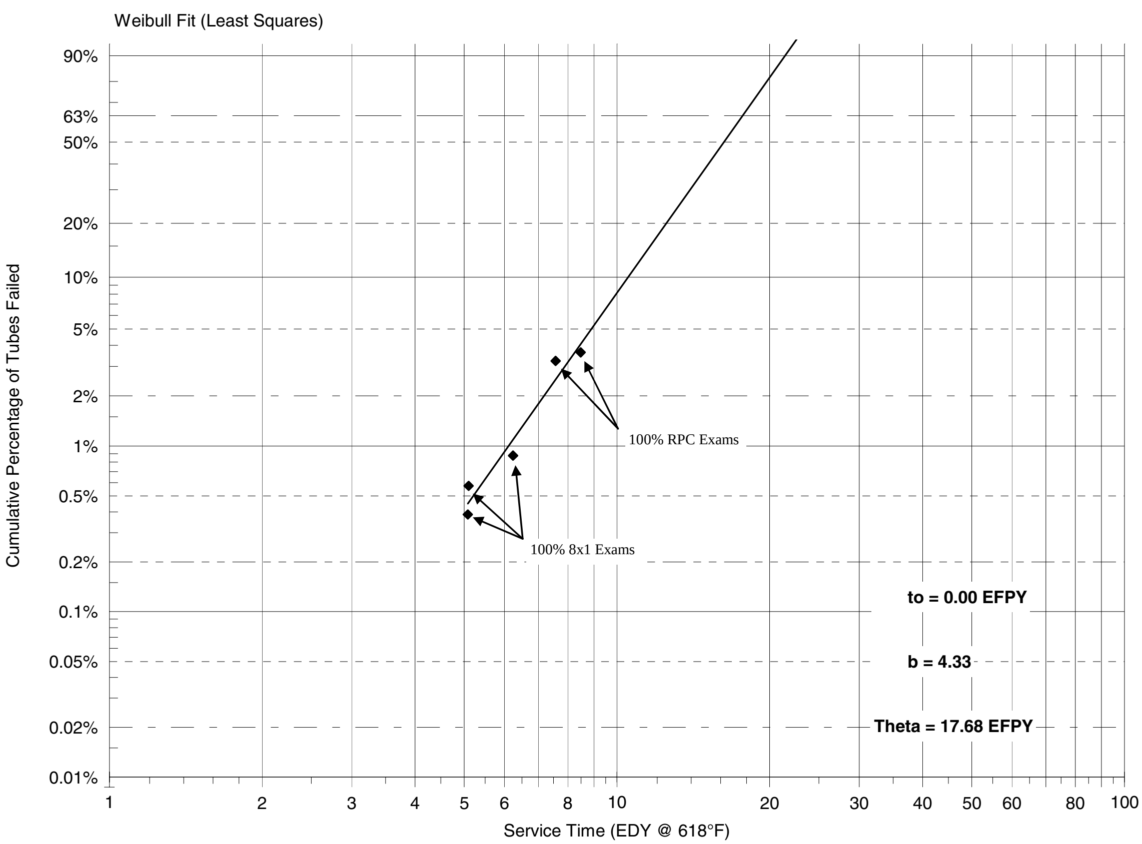

Figure 2-14
North Anna 1 – All Orig. SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

2.3.2.6 North Anna 2 (Orig. SGs)

North Anna 2 first detected TS PWSCC defects during the EOC 5 inspections. 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 2–15).

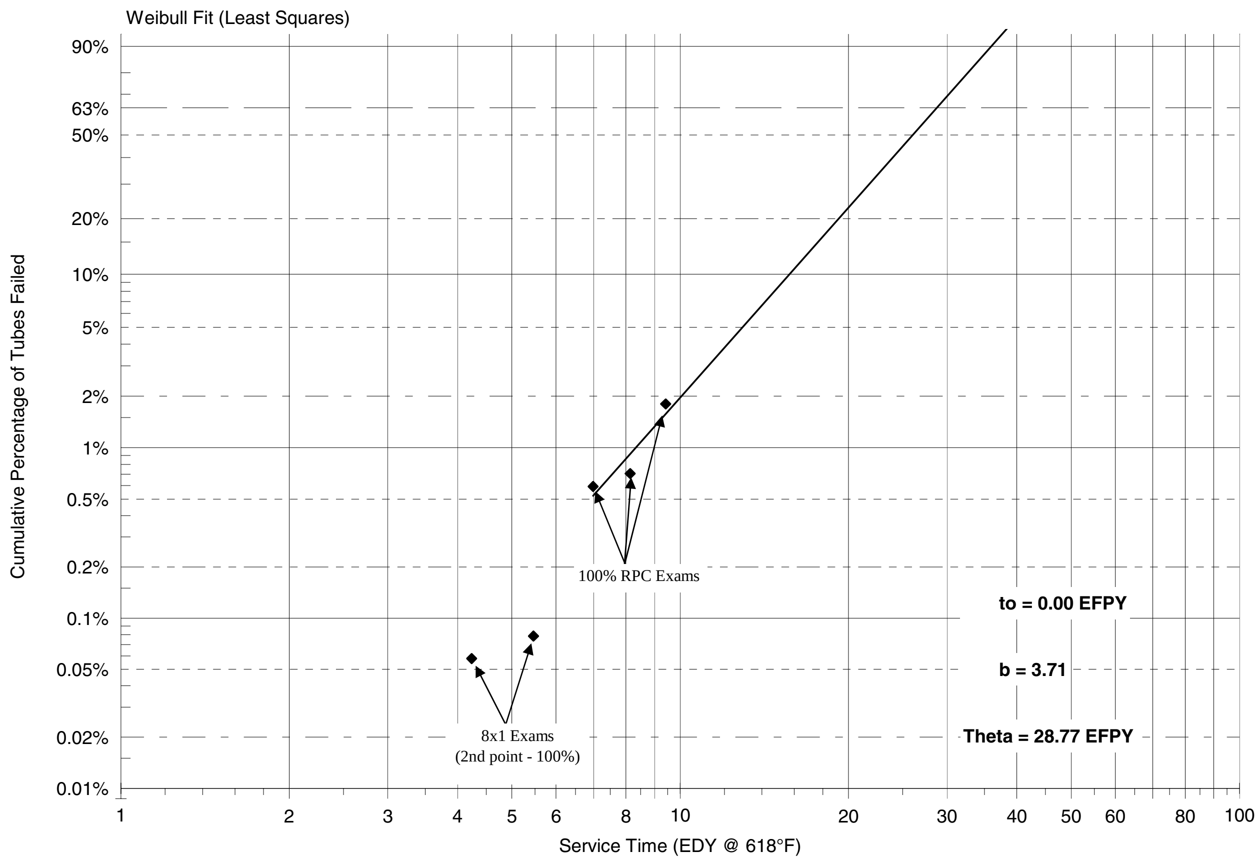

Figure 2-15
North Anna 2 – All Orig. SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

2.3.2.7 Salem 2

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 14 inspections in the spring of 2005, over 2% of the total tube population at Salem 2 has been plugged due to this mechanism. Only six of these repairs were due to circumferentially oriented defects; 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 six outages, i.e., EOC 9 through EOC 14, 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 = 0.80, as shown in Figure 2–16. All the data used for the fit were post-peening.

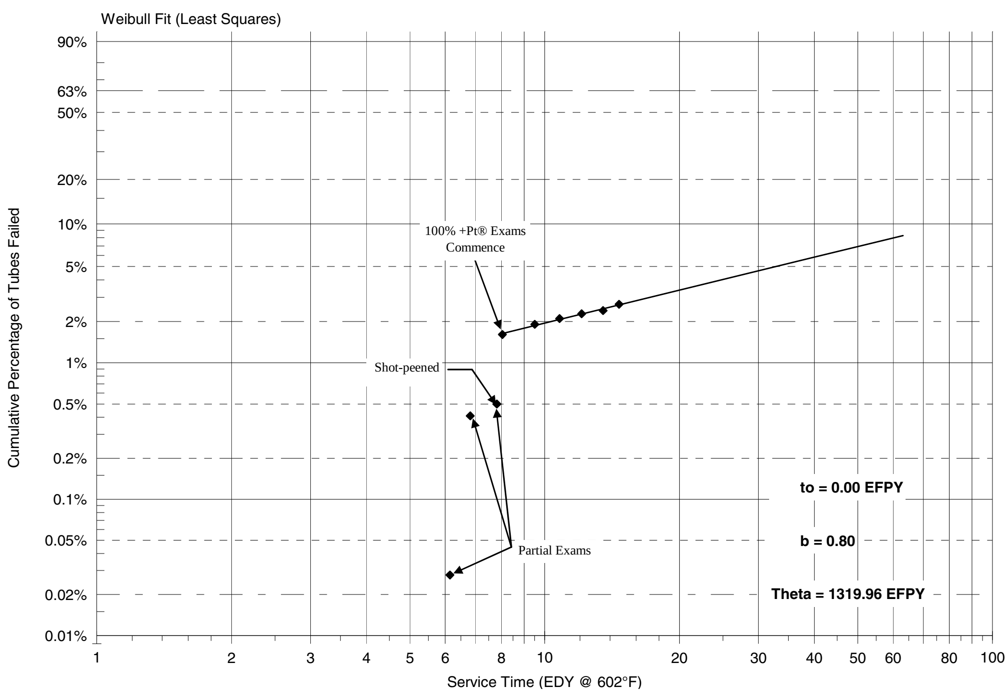

Figure 2-16
Salem 2 – All SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

2.3.2.8 Sequoyah 1 (Orig. 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 than 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 2–17. All the data used for the fit were post-peening.

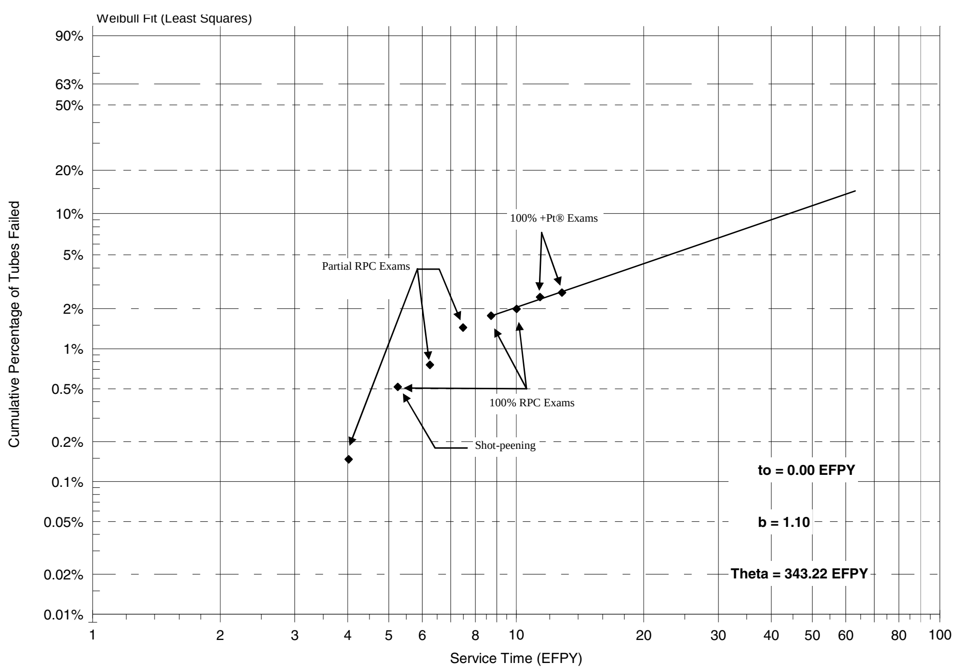

Figure 2-17
Sequoyah 1 – All Orig. SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

2.3.2.9 Sequoyah 2

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 2005 inspection. Over four times as many repairs were due to axially oriented defects than 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 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 = 1.64. The post-zinc slope was developed using data for EOC 11 through EOC 13. All three inspections were 100% Plus Point® exams. The Weibull slope parameter for the post-zinc fit is b = 1.13. Both fits are shown in Figure 2–18. All the data used for the fits were post-peening.

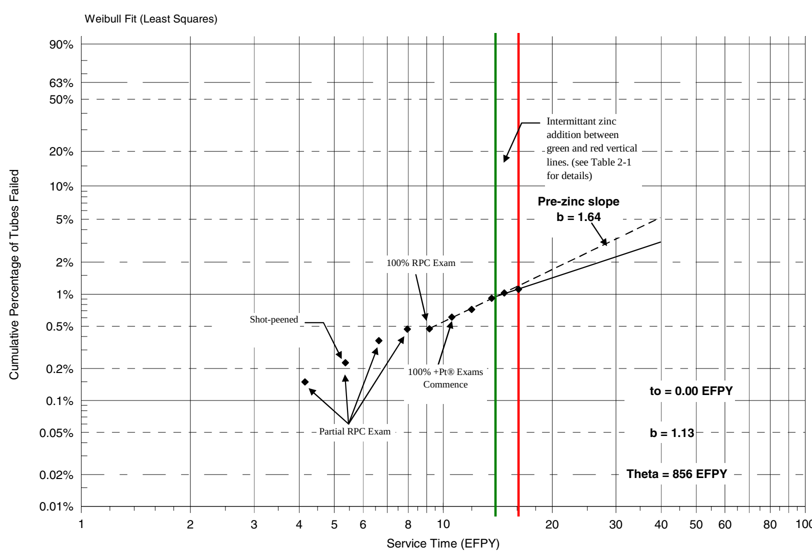

Figure 2-18
Sequoyah 2 – All SGs – WEXTEX PWSCC (Axial and Circ.) – Tubes Repaired

[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.

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 1.02 (a 47% 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 1.13 (a 19% 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 33% reduction at Diablo Canyon 1 and a 63% reduction at Diablo Canyon 2 (for an average reduction of 48% 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 considered necessary to significantly affect ID degradation), the Weibull slopes show a 31% reduction. The average result of all four units with both pre- and post-zinc data shows a 52% decrease in slope with zinc addition.

Table 2-5
TS PWSCC Weibull Slopes

Plant	Pre-/No Zinc		Post-Zinc Slope		Reduction
	Data Description	Slopes	Data Description	Slopes	
Beaver Valley 1	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	1.29	33%
Diablo Canyon 2	Post shot-peening	1.40	Post shot-peening	0.52	63%
Salem 2	Post shot-peening	0.80			

Sequoyah 1 (orig. SGs)	Post shot-peening	1.10			
Sequoyah 2	Post shot-peening	1.64	Post shot-peening	1.13	31%

Post-peening Median =	1.40	1.13
Post-peening Average =	1.37	0.98

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 (625 in Cycles 9 through 12), 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.

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.

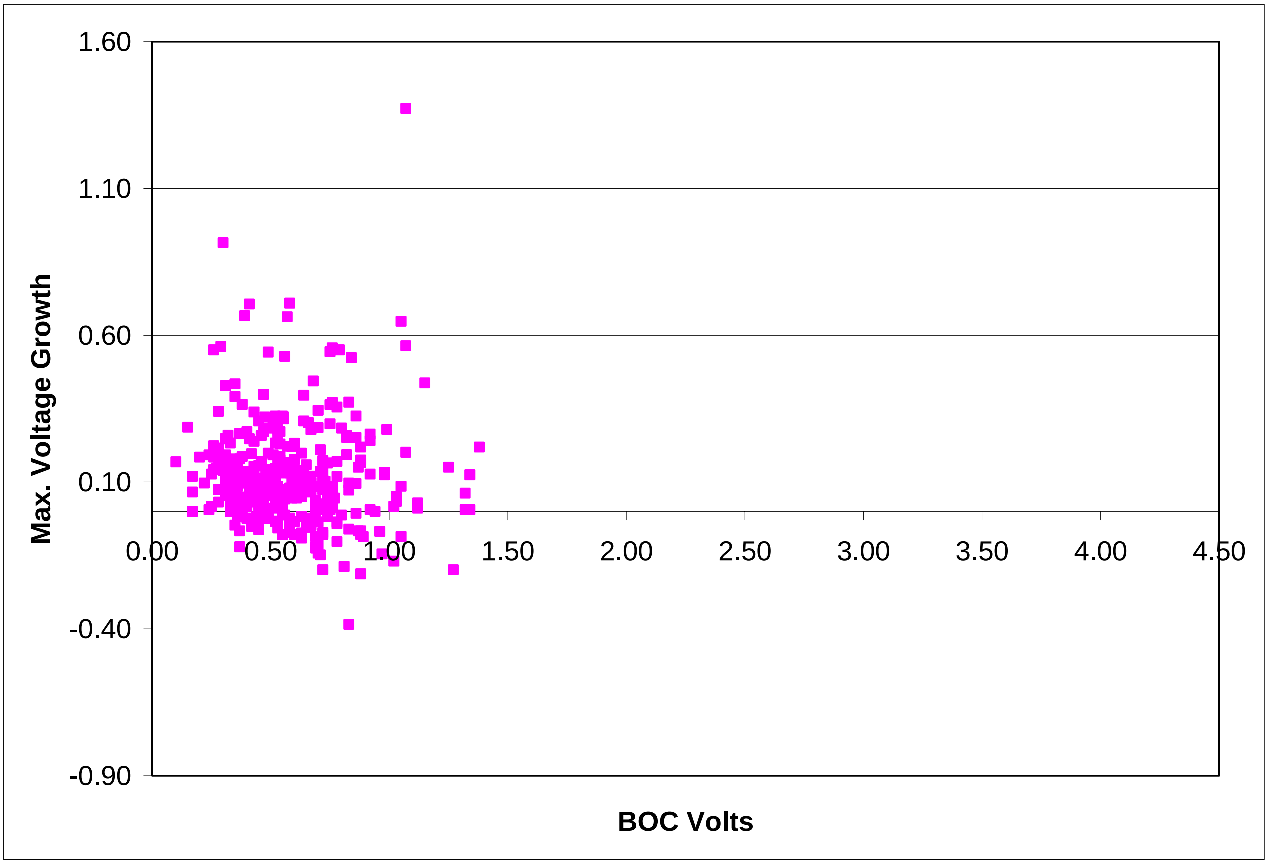

Figure 3-1
BOC Volts vs. Max Voltage Growth at 603°F – No Zinc (DCPP + SQN 1)

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 >1 volt in the prior cycle and <1 volt in the current cycle were excluded in the growth rate assessment. Table 3–1compares 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.

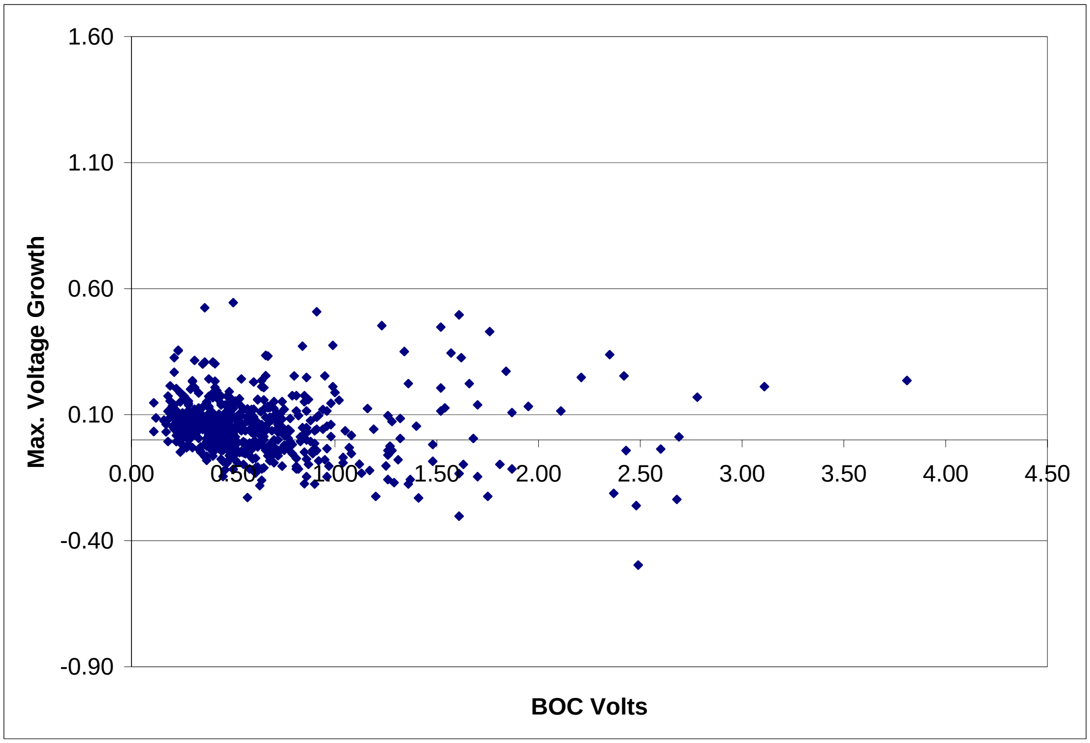

Figure 3-2
BOC Volts vs. Max Voltage Growth at 603°F – Post-Zinc (DCPP)

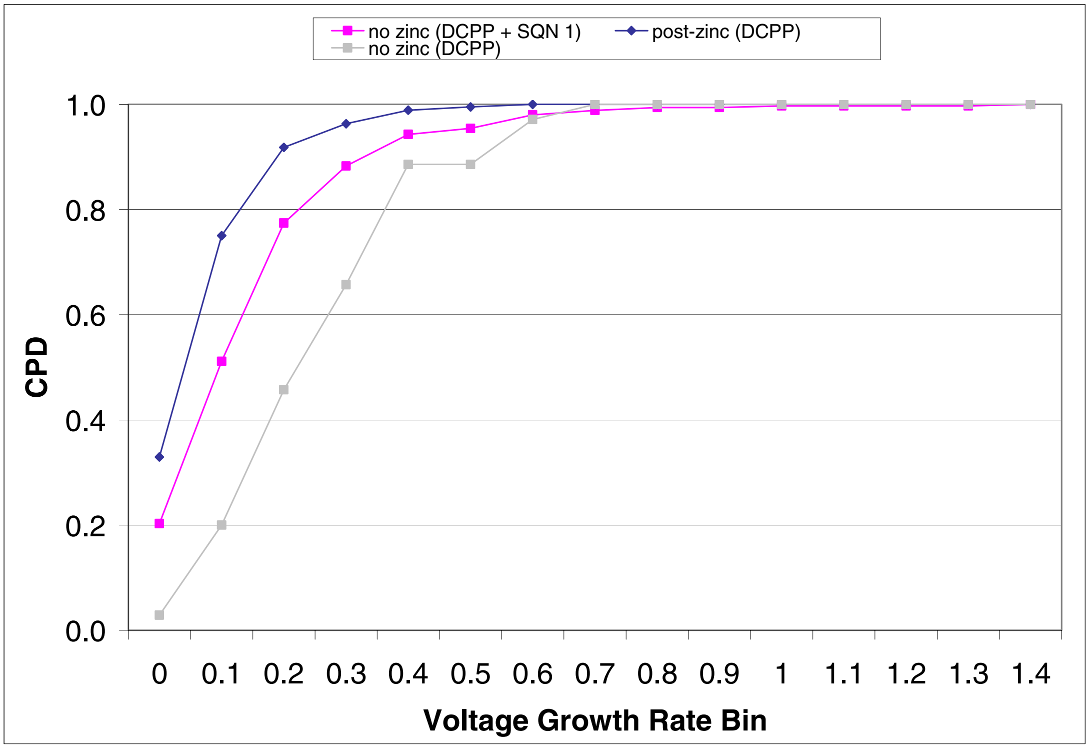

Figure 3-3
TSP PWSCC Maximum Voltage Growth at 603°F

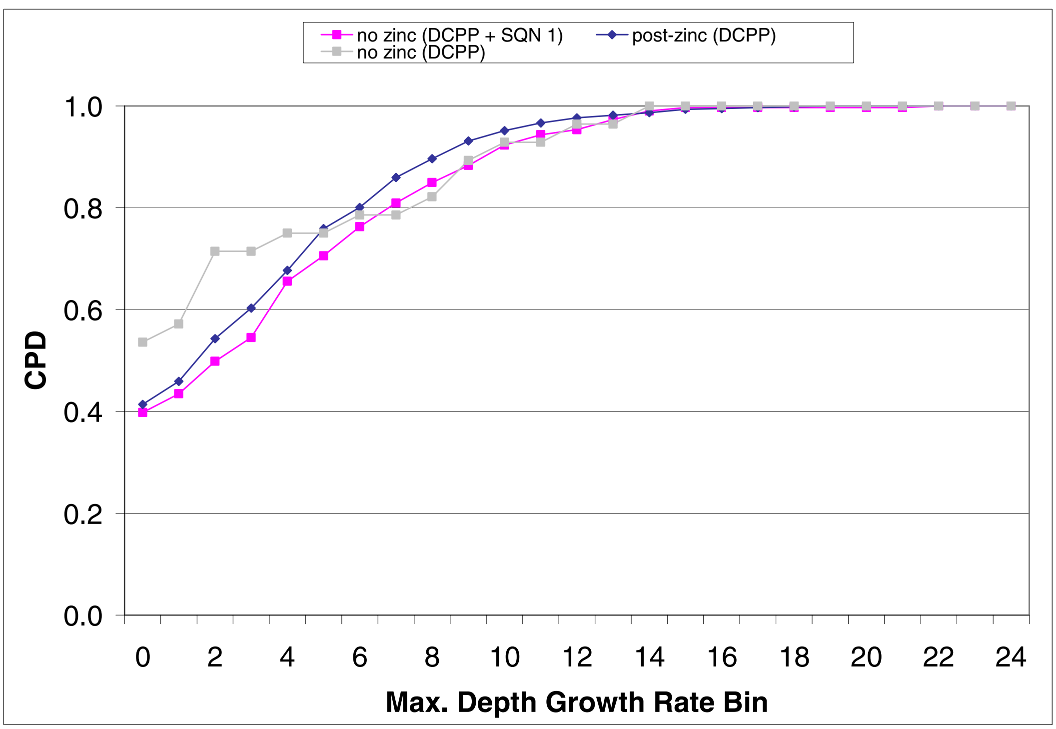

Figure 3-4
TSP PWSCC Maximum Depth Growth at 603°F

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	625	28	599
SQN 1 TSP Axial PWSCC	315		271	
Combined DCPP/SQN1 TSP Axial PWSCC	350	625	299	599
DCPP 1 and 2 TS Axial PWSCC	5	261		
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	278		

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 0.04 volts/EFPY and 1.3%/EFPY, compared to the no zinc values of about 0.10 volts/EFPY and 2.3%/EFPY for the combined data (factor of 60% reduction for voltage growth rates). These numbers reflect the small growth rates for PWSCC, with or without zinc.

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%-ile	90%-tile	50%-ile	90%-tile	50%-ile	90%-tile	50%-ile	90%-tile
DCPP 1 and 2 TSP Axial PWSCC	0.23	0.48	0.04	0.17	0.0	8.8	1.3	8.1
SQN 1 TSP Axial PWSCC	0.09	0.28			2.4	9.3		
Combined DCPP/SQN1 TSP Axial PWSCC	0.10	0.32	0.04	0.17	2.3	9.3	1.3	8.1
DCPP 1 and 2 TS Axial PWSCC	0.08	0.17	0.03	0.32				
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	0.04	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 (261 data points for Cycles 9 through 12), 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 (original SGs), 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.

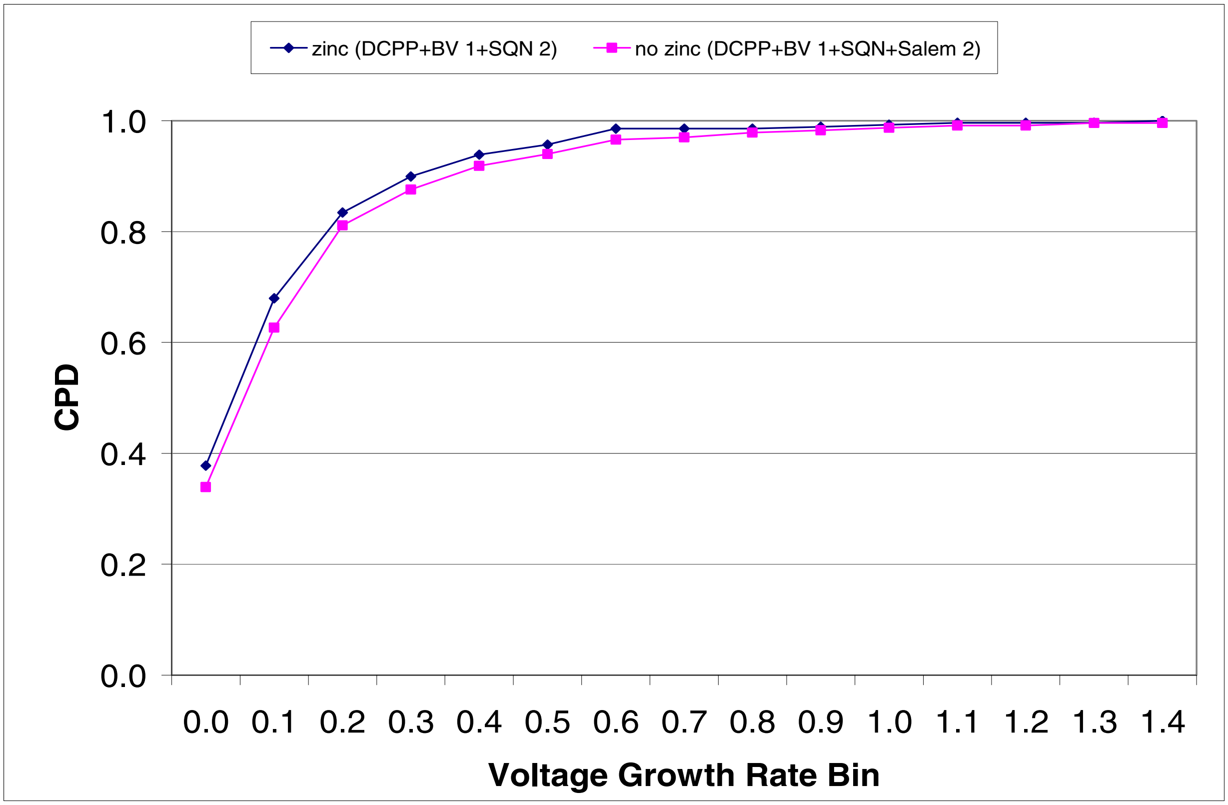

Figure 3-5
TS PWSCC Maximum Voltage Growth at 603°F

3.2.1.1 Beaver Valley 1

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 has 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

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.

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).

Because Sequoyah 2 has 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 0.04 volts/EFPY with zinc and 0.06 volts/EFPY without zinc, indicating a 33% reduction (about a factor of 1.5 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 31-79%[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., 19-79%. 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 0.17 volt/EFPY for the no and post-zinc cases, respectively, i.e., a 47% reduction due to zinc. The median (50th percentile) growth rate with zinc is about 0.04 volts/EFPY compared to about 0.10 volts/EFPY without zinc, indicating a 60% 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

[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 (63%), 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.

growth rates are 0.04 volts/EFPY with zinc and 0.06 volts/EFPY without zinc, indicating a 33% reduction in growth rate due to zinc.

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. Testing is underway by the MRP to evaluate the effects of zinc on larger, faster growing cracks [1].

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
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