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Technical Letter Report

on

PNNL Review of Farley Unit 2 Submittal on EOC Voltage Distributions, Burst Pressure Probabilities and Leak Rate

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Enclosure 2

Abstract

This report evaluates an assessment completed by Southern Nuclear Operating Company, for an interim voltage-based steam generator tube repair criteria applied to the Farley Unit 2 steam generators at the end of fuel cycle 10. The submittal evaluates steam generator integrity in terms of tube leak rates and burst probabilities as specified by NRC's Interim Plugging Criteria (IPC).

The submittal's leak rates, burst probabilities, and EOC voltage distribution were compared to results obtained from three computer programs developed by PNNL for the probabilistic assessment of these quantities. In general, PNNL's projected EOC voltage distributions, burst pressure probabilities and leak rate agreed well with those projected in the Farley Unit 2 report and were all well below the NRC approved thresholds.

This technical letter report reviews the Farley Unit 2 IPC submittal [1] for cycle 11 steam generator tube inspections. The cycle 11 inspections were used to predict leak rate and burst probabilities in the steam generators. Computer programs developed by PNNL for the probabilistic assessment of tube burst and leak rate were used to evaluate the calculations done in the Farley Unit 2 submittal. The three computer programs are documented in [2].

This work was performed under Task Order No. 8 of JCN E-2029.

1 EOC Voltage Distribution

The model for calculating EOC voltage distribution from beginning of cycle (BOC) inspection results is

$$V_{EOC} = (V_{BOC} + V_{GROWTH}) \cdot (1 + U_{NDE}) \tag{1}$$

where V_{BOC} is a random variable representing a BOC voltage at an inspected tube support plate (TSP), V_{GROWTH} a random variable representing the voltage growth experienced at this location, and U_{NDE} a random variable representing the relative uncertainty due to NDE (U_{NDE} is in relative units $\Delta V/V$). The end of cycle voltage distribution is computed by convolving the distributions of the three input variables with each other (see [2] for more details.

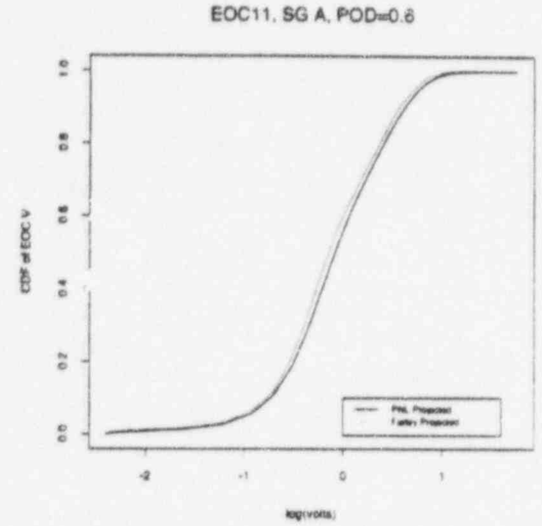
In the Farley Unit 2 report, the input distributions for V_{BOC} were available for cycle 11 for all the SGs (Table 7-2 in [1]). The input V_{GROWTH} was also tabulated for all SGs and for the combination of the 3 SGs for both cycle 9 and cycle 10 (Table 4-6 in [1]). Since the voltage growth distribution for cycle 9 for the combination of the 3 SGs is more limiting, the voltage growth for cycle 9 for the combination of the 3 SGs was used in the projection of EOC 11's voltage distributions.

The distribution for NDE uncertainties is generated from a normal distribution with mean 0 and relative standard deviation of 12.5%. The 12.5% value can be compared to the Cycle 9 and 10 voltage growth curves, which contain information about the actual sizing error experienced during the inspections. The portions of the growth distributions that are negative must be entirely due to sizing error and can be used to estimate the sizing error distribution. These portions of the distribution indicate that the sizing error standard deviation is about 0.1245 Volt, or a relative standard deviation of about 15%, which compares favorably to the postulated relative standard deviation.

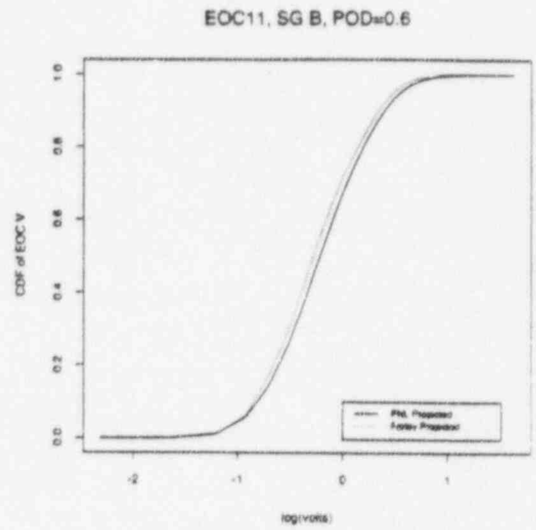
The Farley Unit 2 projected EOC 11 bobbin voltage distributions were given in Tables 7-3 in [1]. PNNL's corresponding projections together with Farley Unit 2 projections are presented in Figure 1 and Table 1. As can be seen from the results, Farley Unit 2 calculations agree well with PNNL's even though all the PNNL distributions are slightly larger than the Farley II distributions.

It should also be noted that the length of cycle 9 is 462 effective full power days (EFPD) while the length of cycle 11 is 479 EFPD. In the calculation of EOC voltage distributions, these cycle lengths were considered to be so close to a full cycle that no cycle length adjustment was made to account for these variations.

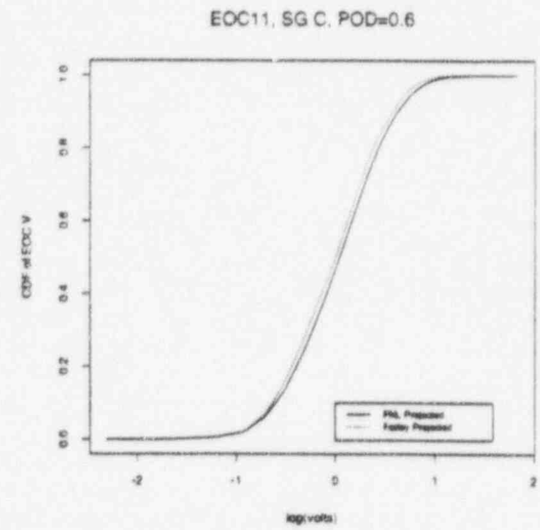
Figure 1: Distributions of projected EOC 11 voltages.



(a) SG A



(b) SG B



(c) SG C

Table 1: Projected Distributions for EOC 11 Voltages

Quant -tile	SG A		SG B		SG C	
	PNNL	Farley	PNNL	Farley	PNNL	Farley
0.00	-2.40	-2.40	-2.30	-2.30	-2.30	-2.30
0.25	-0.42	-0.46	-0.52	-0.58	-0.30	-0.35
0.50	-0.08	-0.15	-0.21	-0.28	0.04	0.00
0.75	0.31	0.27	0.12	0.06	0.36	0.31
0.90	0.62	0.56	0.40	0.34	0.63	0.58
0.95	0.77	0.72	0.56	0.49	0.78	0.71
0.99	1.00	0.92	0.84	0.83	1.02	0.94
.995	1.09	0.98	0.96	0.85	1.11	1.01

2 Burst Probability

The following relationship was used in PNNL's calculation of probability for one or more tube bursts for a SG at the EOC:

$$P_i = \frac{S_i}{S_{ref}}(\alpha_1 + \alpha_2 \log_{10}(V_i) + E_i) \quad (2)$$

where;

1. (α_1, α_2) are regression parameters describing the correlation between voltage and burst pressure data. The regression parameters have an uncertainty described by the covariance matrix $Cov(\alpha_1, \alpha_2)$.

2. V_i is a voltage obtained from the EOC distribution computed in the last section.

3. The error term, E_i has a variance of σ_E^2 with degrees of freedom dof, as determined by the burst pressure regression.

4. S_i is the tube specific flow stress and S_{ref} is the reference flow stress. S_i is assumed to be normally distributed about the value S_m (average flow stress for this steam generator's tubes) with standard deviation σ_m. S_m, σ_m, and S_{ref} are obtained from an industry-developed data-base.

The PNNL model simulates P_i, for each tube using Equation 2 and drawing from appropriate random distributions as described in [2]. The simulation accounts for random variation in S_i, and V_i, as well as uncertainties in the regression that appear in α_1, α_2 and E_i. The value of the burst pressure is then compared to the steam line break (SLB) differential pressure to determine if the tube would be likely to burst during a postulated SLB event.

The EPRI recommended database described in [3] was used to obtain the estimates of the regression parameters for burst pressure in Farley Unit 2 report. The database described in [4] was used to get estimates of the regression parameters for burst pressure in PNNL's Monte Carlo simulation. Therefore, PNNL's inputs were not identical to those used in Farley Unit 2 report. The input parameters used in PNNL's calculation are;

$$(\alpha_1, \alpha_2) = (8.220, -2.515) \quad Cov(\alpha_1, \alpha_2) = \begin{pmatrix} 0.01975 & -0.01080 \\ -0.01080 & 0.02535 \end{pmatrix},$$
$$dof = 64 \qquad \sigma_E = 0.815$$
$$\sigma_m = 3.500$$

Since no flow stress parameters were available in the Farley Unit 2 report, the flow stress parameters for 7/8-inch tube listed in Table 4-1 of Westinghouse report [6] were used in PNNL's simulation. The SLB differential pressure used in PNNL's calculation of probability of burst is 2560 psi.

The numbers of indications at EOC 11 for SGs A, B and C at Farley Unit 2 were estimated to be 73, 114 and 252, respectively, (this included the POD=60% adjustment). PNNL's projections of EOC 11 voltage distributions were obtained as discussed in the previous section. Samples of 73, 114 and 252 voltage values were obtained from the distributions presented in the last section for SGs A, B and C, respectively. Ten thousand simulations were performed on each set of the voltage values for SGs A, B and C to get 10,000 sets of simulated burst pressure values for each voltage value for each SG. Each set was compared to the SLB differential pressure, which was 2560 psi, to determine if any tube in that set would be likely to burst during a postulated SLB event. The results of the simulation are summarized in Table 2 and Table 3. To make comparison easier, the projected EOC 11 probabilities of burst from Table 8-1 of Farley Unit 2 report [1] were reproduced here in Table 2.

Table 2: Comparison of Projected EOC 11 Burst Probability Results. PNNL's Projections Were Based on 10,000 Simulations. POD=0.6 was used.

	Farley 2 Proj. Burst Prob.		PNNL's Proj. Burst Prob.	
SG	0 Tube Burst	≥ 1 Tube Burst	0 Tube Burst	≥ 1 Tube Burst
A	$1 - 2.4 \times 10^{-5}$	2.4×10^{-5}	1	0
B	$1 - 7.3 \times 10^{-6}$	7.3×10^{-6}	1	0
C	$1 - 1.05 \times 10^{-4}$	1.05×10^{-4}	1	0

As one can see, no bursts occured in the 10,000 PNNL simulations, so this provides strong evidence that the actual probability of burst is below the NRC-threshold of 1×10^{-2}. The Farley II simulations all produced burst probability estimates that were on the order of 10^{-4} or lower, so the PNNL and Farley II results agree within sampling error.

3 Leak Rate

The total leak rate, T, is calculated by summing together the leak-rates from individual indications that have a positive voltage at EOC. Assume that L indications have a positive

Table 3: Summary Statistics from PNNL Projected Burst Pressure (ksi) Calculations at EOC 11 Based on 10,000 Simulations and POD=60%.

Statistic	SG A (# of ind.=73)	SG B (# of ind.=114)	SG C (# of ind.=252)
Maximum	15.6642	15.5444	14.9713
Minimum	3.3777	2.8534	3.1335
Average	9.0806	9.2478	8.9795
Median	9.0647	9.2371	8.9615
Std Deviation	1.2103	1.1641	1.1579

eddy current response voltage of V_i, $i = 1, 2, ..., L$. The total leak rate is given by:

$$T = \sum_{i=1}^{L} R_i Q_i, \tag{3}$$

where R_i is a binary variable that describes whether or not indication i is a leaker, and Q_i is the conditional leak rate of the indication. The individual indication leak rates, $R_i Q_i$ are assumed to be independent, and their distributions have been related to inspection results. The relationship between R_i and the inspection voltage V_i is:

$$Pr(R_i = 1) = logit(\beta_1 + \beta_2 \log_{10}(V_i)), \tag{4}$$

and the conditional leak-rate Q_i is determined by:

$$\log_{10}(Q_i) = \beta_3 + \beta_4 \log_{10}(V_i) + E_i \tag{5}$$

where

1. (β_1, β_2) are regression parameters from a logistic regression of leak rate data. The estimated parameters have uncertainty described by the covariance matrix $Cov(\beta_1, \beta_2)$.
2. (β_3, β_4) are regression parameters from a regression of leak-rate on voltage, and their uncertainty is $Cov(\beta_3, \beta_4)$.
3. E_i represents the variations of log-leak-rate about the mean. The regression produces the standard deviation of E_i, σ_E, with degrees of freedom dof.

These results are incorporated into a simulation that produces T according to the above equations. (See [2] for further details). The inputs used for the PNNL simulation are:

$$(\beta_1, \beta_2) = (-6.872, 8.325) \quad Cov(\beta_1, \beta_2) = \begin{pmatrix} 3.505 & -3.849 \\ -3.849 & 4.583 \end{pmatrix},$$

$$(\beta_3, \beta_4) = (0.6555, 0) \quad Cov(\beta_3, \beta_4) = \begin{pmatrix} 0.0265 & 0 \\ 0 & 0 \end{pmatrix}$$

$$dof = 23 \quad \sigma_E = 0.7982$$

The NRC database described in [3] were used to obtain the the regression parameters for both probability of leak and conditional leak rate in Farley Unit 2 report. The database described in [4] were used to get the deterministic estimates of the regression parameters for probability of leak under a SLB differential pressure of 2560 psi, and the database documented in [5] were used to obtain the deterministic estimates of the regression parameters for conditional leak rate in PNNL's simulation.

Since the SLB leak rate data for 7/8-inch tubes do not satisfy the requirement for applying a SLB leak rate/voltage correlation, the SLB leak rate estimate is based on an average of all leak rate data independent of voltage. The analysis method for applying this leak rate model is similar to the method described above, except that the slope β_4 is assumed to be zero and the intercept β_3 is estimated by the average of the common logarithm of the leak rate data. More detail of this method is given in Section 4.6 of WCAP-14277 [6].

Ten thousand simulations were performed. The result is summarized in Table 4. In order to compare PNNL's projections with those in Farley Unit 2 report, the projected leak rates reported in Table 8-1 of Farley Unit 2 report [1] is reproduced and included in Table 4. The numbers from Farley Unit 2 report [1] are assumed to be the 95% bound values of the SLB leak rates.

Table 4: Summary and Comparison of Projected SLB Leak Rates (gpm) at EOC 11. PNNL's Projections Are Based on 10,000 Simulations. POD=0.6 Was Used.

PNNL Projection	SG A (# of ind.=73)	SG B (# of ind.=114)	SG C (# of ind.=252)
Maximum	187.5517	52.6613	109.5373
Minimum	0.0000	0.0000	0.0000
Average	0.2009	0.1381	0.4195
Median	0.0028	0.0000	0.0385
Std Dev.	2.7628	0.9484	1.9793
95% Bound	0.5980	0.5570	1.8667
Farley 2 Proj. (95% Bound)	0.26	0.35	1.23

The PNNL projections are all larger than the Farley II leak rate projections, by about 50%. However, when these results are compared against the plant-specific allowable limit, which is 11.4 gpm, it can be seen that the answers are approximately equal.

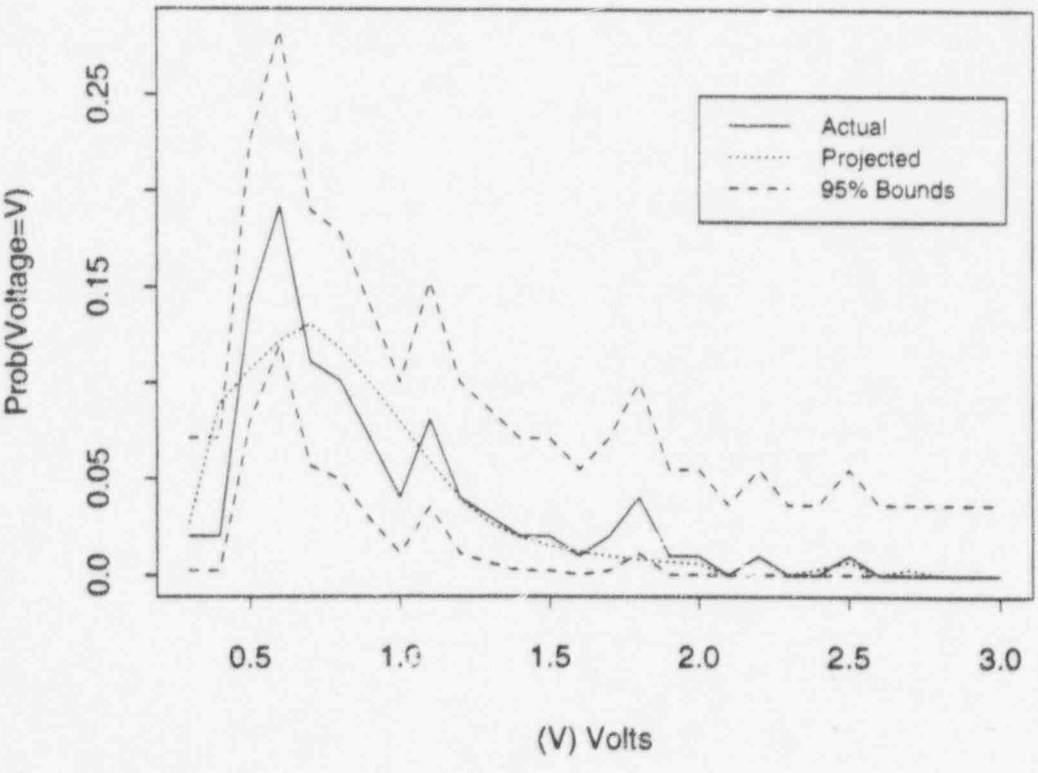
4 Comparison of Projected and Actual EOC Voltage Distribution for SG C

This submittal also compared the projected EOC distribution with the observed distribution. Such a comparison allows one to determine if the components of this inspection model are working correctly. In this report, the projected EOC voltage distribution at EOC 10 can be compared to the actual EOC 10 inspection results for SG C to determine whether the voltage growth modeling is correct.

Figure 2 presents a comparison of the projected with actual EOC 10 Voltage distribution for SG C. These results were extracted from Table 7-1 in [1]. The actual distribution in this plot has been surrounded by 95% confidence bounds, which describe the amount of variability one would expect in an estimate such as this when it is being estimated from a sample of this size. These particular confidence bounds do not describe the sizing and detection inspection errors that might be present within the actual distribution. Nevertheless, the confidence bounds give a gauge that can be used to compare the two distributions.

As one can see from the Figure, the projected distribution generally falls within the 95% bounds, indicating general agreement between the projected and actual distributions. These results show that the strategy of using the voltage growth rates from the previous cycle gives a good prediction for the next cycle.

Figure 2: Comparison of Projected and Actual EOC 10 Voltage Distributions for SG C



5 Comments on Voltage Dependent POD

The NRC Interim Plugging Criteria requires the use of a 60% POD in the leak rate and burst probability calculations, unless a different value can be justified. In Section 4.3 of the Farley submittal, evidence is presented to justify a POD that is related to voltage.

POD is usually considered to be a function of flaw size (as flaws get bigger, they are easier to detect), and experiments have been conducted to determine this relationship. However, in the case of the IPC inspections, no flaw size is produced, so historical POD curves cannot be applied to IPC results.

The submittal presents two sets of data that are relevant to POD; One set of data originates from cycle 9/10 inspections of Farley 2, and the other from cycle 8/9. The data is used to estimate a quantity called *probability of prior cycle detection* (POPCD). The POPCD statistic originates from EPRI, and EPRI has produce a POPCD curve using data from several plants. Both data sets show that POPCD is related to voltage, and for "large" voltages (above 2 volts), POPCD is close to one. Specifically, the submittal comes to the conclusion;

> "In summary, the Farley Unit 2 EOC-8 and EOC-9 POPCD's support a voltage dependent POD higher than the NRC POD=0.6 and approaching unity above 1.8 volts. It is concluded that the POD applied for IPC leak and burst projections needs to be upgraded from the POD=0.6 to a voltage dependent POD."

Based on a review of the POD assessment in reference [1], the these conclusions are not fully supported by the data. The data does indeed show that POPCD is voltage dependent, and that POPCD is close to unity above 1.8 volts. But the submittal treats POD and POPCD as if they were equivalent, and they are not. An examination of the definition of the two statistics should clearly illustrate the differences. POD is defined as;

$$\text{POD} = \frac{\#\text{ of defects detected in inspection}}{\text{Total }\#\text{ of defects in inspected tubes}} \tag{6}$$

while the definition of POPCD (ignoring plugged tubes) is given by;

$$\text{POPCD} = \frac{\#\text{ of defects detected in first \& second inspections}}{\#\text{ of defects detected in second inspection}} \tag{7}$$

POPCD can be best thought of as a POD calculated under the assumption that the second inspection produces a "true-state" description of the tubes. If the second inspection had a very high POD, so that it found almost all the flaws, then POPCD would provide a good estimate for POD. However, no evidence is presented to show that the second inspection POD's are near 100%. In fact, if evidence existed to show that the second inspection POD was high, this evidence would be sufficient to replace the current POD=60% value and there would be no need to calculate POPCD.

Another assumption that could be used to relate POPCD to POD would be the assumption of independence. If the two inspection results were independent, then POPCD would produce a conservative estimate for POD. Unfortunately, there is much evidence to indicate inspection results are not independent, so evaluating the POPCD data from this perspective would require further justification.

6 Tube Pulls and Destructive Examinations

During this outage, one tube (R27C54) was pulled, nondestructively evaluated and then subjected to leak and burst tests. Three locations from this tube (TSP 1, 2, and 3) were subjected to testing, which resulted in the data points listed in Table 3-6 of reference [1].

These data points were evaluated against the EPRI exclusion criteria, and one data point was excluded (TSP3), because of its crack morphology. Also, TSP2 was classified as a NDD during field and lab inspections, so no voltage is associated with this flaw and it cannot be directly included in the burst or leak-rate regressions. However, the flaw at TSP2 is indirectly relevant to these regressions because it is an example of a "missed" flaw that the POD=60% correction is meant to account for.

Only one flaw (at TSP1) provides burst and leak rate information from these destructive tests. The burst pressure and leak-rate information (the flaw did not leak) from TSP1 conform very well with burst and POL regression results (see Figure 3-4 and 3-5 of the submittal). Since the data fits the regression models well, it causes a very small change when included in the regression fits (see tables 3-8 and 3-9). This data point is not significantly different than the other regression data and one can conclude that the Farley 2 cracking fits the burst and leak rate correlations derived from the EPRI data set.

7 Conclusions

In this review, PNNL has produced independent calculations, which have been compared to the licensee's EOC 11 burst and leakage calculations. The following summarizes the findings of this review:

1. PNNL's projected EOC 11 voltage distributions for SGs A, B and C at Farley Unit 2 agreed with those projected by the licensee.

2. PNNL's projected burst probabilities during a postulated SLB event at EOC 11 for SGs A, B and C at Farley Unit 2 were consistent with those projected by the licensee, and were below the NRC approved threshold of 1×10^{-2}.

3. The 95% bound values of PNNL's projected EOC 11 SLB leak rates and the Farley Unit 2 projected EOC 11 SLB leak rates were all well below the plant-specific allowable SLB leakage limit, which is 11.4 gpm. The difference between the two projections is likely caused by small differences in the inputs.

4. The projected and actual EOC 10 voltage distributions agreed quite well.

5. The data presented shows that POPCD is strongly related to voltage. However, it is not clear that POPCD is a good estimate of POD.

6. Farley II data from pulled tubes supports the EPRI leak-rate and burst models.

References

[1] Westinghouse Electric Corporation Nuclear Services Division, "Farley Unit 2 1995 Interim Plugging Criteria 90 Day Report," July 1995.

[2] Gao, F. and Heasler, P. G., "PNL Documentation of Computer Programs to Calculate EOC Voltage Distribution, Burst Pressure Probabilities and Leak-Rate," Pacific Northwest Laboratories, December 1995.

[3] WCAP-14123 (SG-94-07-009), "Beaver Valley Unit 1 Steam Generator Tube Plugging Criteria for Indications at Tube Support Plates July 1994".

[4] Committee for Alternate Repair Limits for OCSCC at TSPs, "PWR Steam Generator Tube Repair Limits - Technical Support Document for Outside Diameter Stress Corrosion Cracking at Tube Support Plates," TR-100407, Revision 2A, EPRI, January 1995.

[5] EPRI Project S404-29, "Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Database for Alternate Repair Limits. Volume 1: 7/8 Inch Diameter Tubing," NP-7480-L, Volume 1, Revision 1, September 1993.

[6] Westinghouse Electric Corporation Nuclear Services Division, "SLB Leak Rate and Tube Burst Probability Analysis Methods for ODSCC at TSP Intersections," Westinghouse, WCAP-14277, January 1995.