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Technical Letter Report
on
PNNL Review of Farley Unit 1 1995 Interim Plugging Criteria 90 Day Report

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Enclosure 1

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 1 steam generators at the end of fuel cycle 13. 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. PNNL's projected EOC voltage distributions, burst pressure probabilities and leak rate agreed closely with those projected in the Farley Unit 1 report and were below the NRC approved thresholds.

This technical letter report reviews the Farley Unit 1 IPC submittal [1] for cycle 13 (EOC) steam generator tube inspections. The cycle 13 inspections were used to predict leak rate and burst probabilities in the steam generators for cycle 14 operation. 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 1 submittal. The three computer programs are documented in [3].

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 [3] for more details.

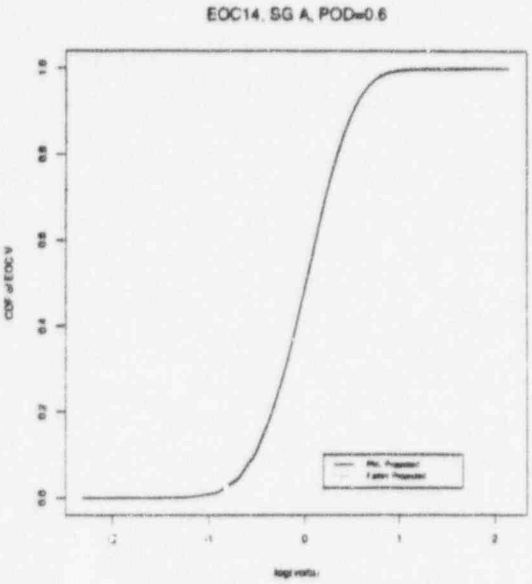
In the Farley Unit 1 report, the input distributions for V_{BOC} were tabulated from EOC 13 results (Table 4-1 in [1]), and the input, V_{GROWTH}, was tabulated for the SGs in Table 4-5 of [1]. The distribution for NDE uncertainties is generated from a normal distribution with mean 0 and relative standard deviation of 12.5% (7% due to probe wear and 10.3% due to analyst variability).

These inputs were used to calculate the projected EOC 14 bobbin voltage distributions given in Table 7-2 in [1]. PNNL's corresponding projections plotted against the Farley Unit 1 projections are presented in Figure 1 and Table 1. As can be seen from the results, Farley Unit 1 calculations agree very closely with PNNL's.

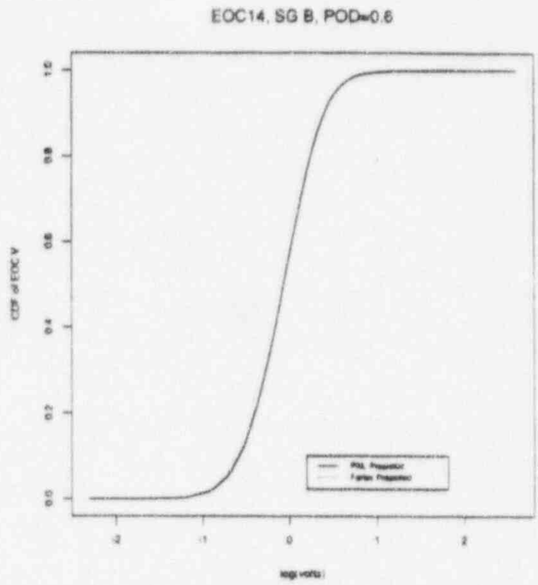
Table 1: Projected Distributions for EOC 14 Voltages

Quant	SG A		SG B		SG C	
-tile	PNNL	Farley	PNNL	Farley	PNNL	Farley
0.000	-2.303	-2.303	-2.303	-2.303	-2.303	-2.303
0.250	-0.259	-0.269	-0.328	-0.339	-0.162	-0.169
0.500	0.019	0.013	-0.061	-0.068	0.108	0.103
0.750	0.285	0.279	0.193	0.185	0.357	0.350
0.900	0.517	0.512	0.406	0.400	0.569	0.562
0.950	0.648	0.642	0.540	0.536	0.689	0.683
0.990	0.898	0.927	0.833	0.851	0.942	0.976
0.995	1.009	1.095	0.981	1.056	1.092	1.204

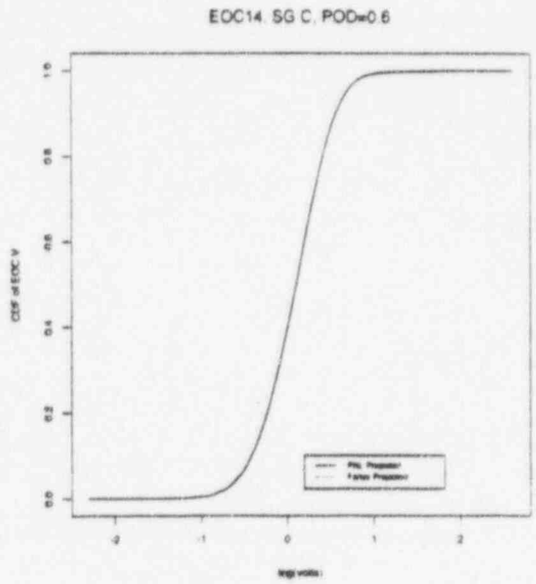
Figure 1: Distributions of projected EOC 14 voltages.



(a) SG A



(b) SG B



(c) SG C

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 [3]. 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 estimates of the regression parameters for burst pressure summarized in Table 3-8 of [1] were used for PNNL's Monte Carlo simulation. Therefore, PNNL's inputs were:

$$(\alpha_1, \alpha_2) = (7.6119, -2.) \quad Cov(\alpha_1, \alpha_2) = \begin{pmatrix} 0.01975 & -0.01080 \\ -0.01080 & 0.02535 \end{pmatrix},$$
$$dof = 77 \qquad \sigma_E = 0.805$$
$$\sigma_m = 3.500$$

It should be noted that these regression parameters have been obtained from a data-base that includes destructive results from Beaver Valley 1, Farley 2, and Sequoyah 1.

Since not all flow stress parameters were available in the Farley Unit 1 report, the flow stress parameters for 7/8-inch tube listed in Table 4-1 of Westinghouse report [7] 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 13 for SGs A, B and C at Farley Unit 1 were estimated to be 1276, 1310, and 1545 respectively (this included the POD=60% adjustment).

PNNL's projections of EOC 14 voltage distributions were obtained as discussed in the previous section. 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. To make comparison easier, the projected EOC 14 probabilities of burst from Table 8-1 of the Farley Unit 1 report [1] were reproduced here in Table 2.

Table 2: Comparison of Projected EOC 14 Burst Probability Results. PNNL's Projections Were Based on 10,000 Simulations. POD=0.6 was used.

	Farley 1 Proj. Burst Prob.		PNNL's Proj. Burst Prob.	
SG	1 Tube Burst	$\geq$ 1 Tube Burst	1 Tube Burst	$\geq$ 1 Tube Burst
A	7.5×10^{-4}	2.5×10^{-5}	0	0
B	7.1×10^{-4}	1.9×10^{-5}	1.0×10^{-4}	0
C	1.4×10^{-4}	1.9×10^{-5}	0	0

As one can see, one burst occurred in the PNNL simulations, so this provides strong evidence that the actual probability of burst is below the NRC-threshold of 1×10^{-2}. The Farley 1 simulations all produced burst probability estimates that were on the order of 10^{-4}, so the PNNL and Farley 1 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 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 [3] for further details). The inputs used for the PNNL simulation are;

$$(\beta_1, \beta_2) = (-6.9901, 8.4470) \quad Cov(\beta_1, \beta_2) = \begin{pmatrix} 3.4522 & -3.8019 \\ -3.8019 & 4.5456 \end{pmatrix}.$$
$$(\beta_3, \beta_4) = (0.5764, 0) \quad Cov(\beta_3, \beta_4) = \begin{pmatrix} 0.0278 & 0 \\ 0 & 0 \end{pmatrix}$$
$$dof = 25 \quad \sigma_E = 0.7982$$

These parameters were obtained from Tables 3-9 and 3-11 of the Farley 1 submittal and were used in PNNL's leak rate 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 [7].

Ten thousand simulations were performed. The result is summarized in Table 3. In order to compare PNNL's projections with those in Farley Unit 1 report, the projected leak rates reported in Table 8-1 of Farley Unit 1 report [1] is reproduced and included in Table 3. The numbers from Farley Unit 1 report [1] are assumed to be the 95% bound values of the SLB leak rates.

The PNNL projections are slightly larger than the Farley 1 leak rate projections, but well within sampling error. It can be seen that these leakage rates (and especial that of Steam Generator C) is quite close to the allowable threshold, which is 11.4 gpm. These results show that the present plugging criteria (2 volt) is not unnecessarily conservative.

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

This submittal also compared the projected EOC distribution with the observed distribution for EOC 13. Figure 2 presents a comparison of the projected with actual EOC 13 Voltage distribution. 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

Table 3: Summary and Comparison of Projected SLB Leak Rates (gpm) at EOC 14. PNNL's Projections Are Based on 10,000 Simulations. POD=0.6 Was Used.

PNNL Projection	SG A (# of ind.=1276)	SG B (# of ind.=1310)	SG C (# of ind.=1545)
Maximum	702.9	359.4	876.9
Minimum	0.00	0.00	0.00
Average	2.03	1.69	2.84
Median	0.29	0.26	0.53
Std Dev.	11.86	8.57	15.69
95% Bound	7.93	6.44	10.78
Farley 1 Proj. (95% Bound)	7.1	6.0	10.2

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 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.

5 Comments on Voltage Dependent POD

This submittal presents an analysis of POPCP that is similar to the analysis presented in [2]. The data presented from both the Farley 1 and Farley 2 inspections produce similar results for POPCP.

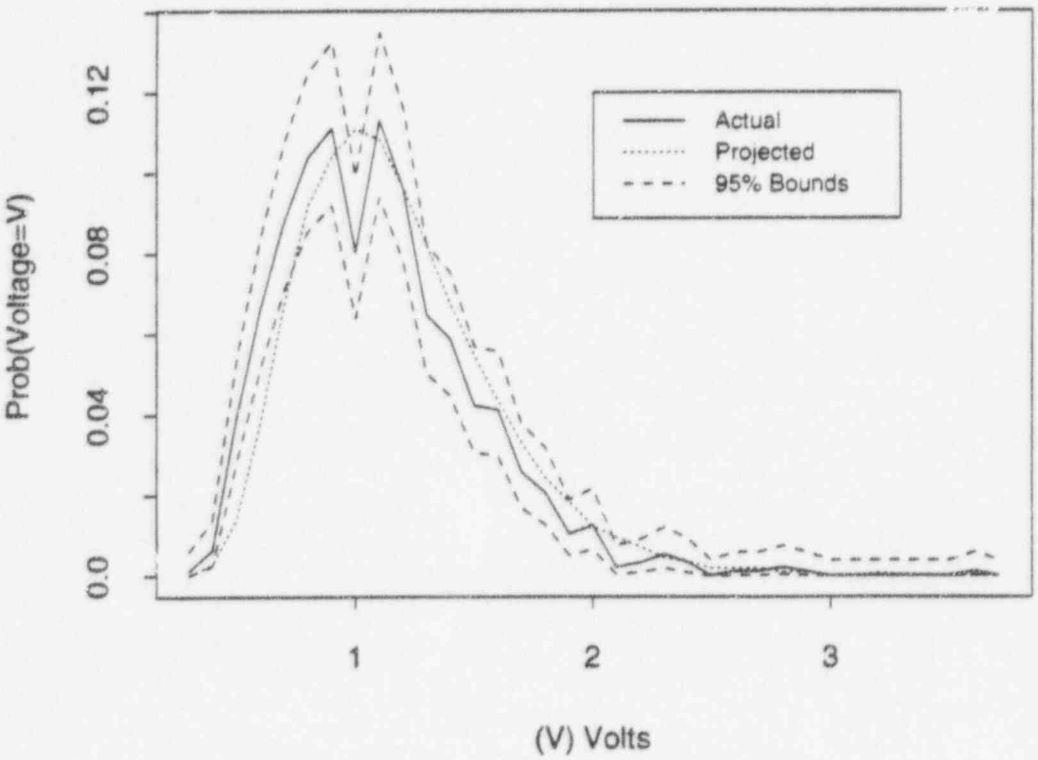
The NRC Interim Plugging Criteria requires the use of a 60% POD in the leak rate and burst probability calculations, unless a different value can be justified. In Section 4.3 of the Farley submittal, evidence is presented to justify a POD that is related to voltage.

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 compares cycle 12 inspection results to those of cycle 13 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. The data shows that POPCD is related to voltage, and for "large" voltages (above 2 volts), POPCD is close to one.

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

Figure 2: Comparison of Projected and Actual EOC 13 Voltage Distributions



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.

6 Tube Pulls and Destructive Examinations

During this outage, one tube was remove from the hot leg side of steam generator B and two tube support plate locations where destructively evaluated. One location (TSP1) had a large 4.03V signal from the field inspection, while the other location (TSP3) was classified as an NDD.

The destructive analysis found cracking at both locations, but the cracking at TSP1 was much more extensive than that at TSP3. Both locations were subject to burst and leak tests. TSP3, which was classified as NDD did not leak during the test and had a burst pressure of 9.243 ksi. TSP1, with a signal of 4.03V, had a burst pressure of 4.666ksi, and leaked at a rate of 2.19 l/hr (0.021 gpm). It should be noted that there was some evidence of tearing at TSP1 during the tube pull, so the results associated with TSP1 may be biased.

This tube pull therefore produced one new datum for the burst and leak rate regressions (See Table 3-7). The new data point is;

Voltage: 4.03

Burst Pressure: 4.666 ksi

Leak Rate: 2.19 l/hr

The submittal presented a very complete evaluation of this data point. The critical evaluations of this data point are visually presented in Figures 3-5 through 3-7. These figures compare the new data point against the present data set, as represented by regression fits. The outlier tests show that the data point is not "significantly" different (at the 5% level) from the old data. This means that it is reasonable to apply the existing regression models (burst pressure, POL, and leak-rate models) to the Farley 1 steam generators.

7 Conclusions

The PNNL review of the Farley 1 submittal included an independent calculation of burst and leak rate estimates, which were compared to the licensees calculations. The following summarizes the conclusions from this review;

1. PNNL's projected EOC 14 voltage distributions for SGs A, B and C at Farley Unit 1 agreed very closely to the licensee's distributions.

2. PNNL's projected burst probabilities during a postulated SLB event at EOC 14 for SGs A, B and C at Farley Unit 1 agreed within sampling error to those projected by the licensee, and were well below the NRC approved threshold of 1×10^{-2}.

3. The 95% bound values of PNNL's projected EOC 14 SLB leak rates and the licensee's leak rates were in close agreement. The projected leak rates were close to the threshold of 11.4 gpm, especially the leak-rate of the limiting steam generator, which was 10.2 gpm.

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

5. The pulled tube data from Farley 1 passes all outlier tests, so the pulled tube data provides evidence that the burst and leak-rate regression models are appropriate for Farley 1 steam generators.

6. Since Farley 1 pulled tube data is consistent with the the leak-rate and burst models, it should be included in the data base.

References

[1] Westinghouse Electric Corporation Nuclear Energy Systems, "Farley Unit 1 1995 Interim Plugging Criteria 90 Day Report," SG-96-01-003, January 1996.

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

[3] 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.

[4] WCAP-14123 (SG-94-07-0C9), "Beaver Valley Unit 1 Steam Generator Tube Plugging Criteria for Indications at Tube Support Plates July 1994".

[5] 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.

[6] 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.

[7] 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.