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WCAP-13716 SG-93-04-030

NRC-Requested Catawba-1 S/G Leakage Evaluation

April 1993

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1.0 Introduction

This report responds to the NRC request at the Catawba-1 meeting of April 1, 1993 and subsequent written/telecon guidance to provide SLB leak rate analyses based on assuming an average leak rate for the measured data independent of voltage. Leak rate analyses are provided to satisfy the specific NRC analysis method. Sensitivity analyses are provided for alternate analysis methods. Averages of the measured leak rates are provided for the lower voltage (< 9.2 volts) half of the measured population and for the entire population. Uncertainties at 1.645 standard deviations are also defined to account for uncertainties on the distribution of leak rates. If a constant average leak rate is to be applied, it is appropriate that the probability of leakage used in conjunction with the leak rate be associated with a probability of significant leakage rather than zero leakage as used in APC methodology with voltage dependent leak rates. For the present analysis, a probability of leakage >1.0 liter/hr is recommended for applications of a constant leak rate per leaking indication.

It is shown in Section 3.0 by statistical assessments that the significance level of a correlation between SLB leakage and bobbin voltages is >99.9%. Thus a leak rate correlation rather than an average leak rate should be applied. It is inappropriate to average all leak rate data independent of voltage and, as a minimum, application of a constant leak rate should represent an average over the voltage range of interest. Since only a few leak rates measurements are available in the range of interest (<5 volts), a bounding average leak rate for data up to ~9.2 volts (half of the database) is more meaningful than an average of all data. Average leak rates and standard deviations are developed in Section 4.0. The probability of leakage >1.0 liter/hr versus voltage is developed in Section 5.0.

SLB leak rate analyses for Catawba-1, using constant leak rates, are given in Section 6.0. Leak rate sensitivity to the probability of leakage and the constant leak rate used in the analyses are included in Section 6.0. The combination of probability of leakage > 1.0 liter/hr with the average leak rate for < 9.2 volt indications provides a realistically conservative leak rate. A conservative bounding leak rate can be obtained by combining the probability for leakage > 0.0 liter/hr with the average leak rate for < 9.2 volt indications.

2.0 Summary and Conclusions

The following provides the principal conclusions from this report.

Summary of NRC-Requested Leak Rate Analysis Results

- At the NRC's request, the total SLB leak rate has been calculated as:

$$Q_T = n\, Q_\mu + 1.645 \sqrt{n}\, \sigma$$

  where Q_μ and σ are the average and standard deviation of the leak rate, and *n* is the effective number of leaking tubes, i.e. the projected number of leaking tubes, divided by the probability of detection (PoD). The 1.645 factor provides a +95% confidence bound on the total leak rate. The NRC also specified that the analyses should include the maximum likelihood probability of leakage (PoL) curve, a PoD of 0.6, end of cycle (EOC) projected voltages based on all bobbin indications left in service including bobbin indications not confirmed by RPC, and a SLB ΔP of 2560 psi. The NRC requested in telecon discussions that Q_μ and σ be obtained as an average of all leak rate data and as an average of the lower voltage half of the data base.

- Following the above NRC method, the calculated EOC-7 SLB leak rates for Catawba-1 are 0.60 gpm and 2.73 gpm with the leak rates per leaking indication based on the lower voltage range and on all data, respectively. S/G C was found to be the limiting S/G based on EOC-7 voltage projections for all bobbin indications left in service independent of RPC confirmation.

- Based on statistical analyses given in this report showing a high probability (99.99%) that SLB leakage is correlated to voltage, the above NRC methodology is considered to be excessively conservative. It is recommended that the following be considered for specification of a method for SLB leakage analyses:

- As a minimum, the average and standard deviation for the leak rate should be based on the lower half (< 9 volts) of the voltage range for the data base. This provides a minimal recognition of the correlation between leak rates and voltage. In the near term, technical meetings should be held to develop a mutually satisfactory, continuous correlation of SLB leak rate as a function of voltage.

- If a +95% uncertainty level is to be assigned to the sum of all leaking indications, the probability of leakage correlation used in the analysis should be based on the probability of significant leakage (such as > 1 liter/hr), rather than the probability of any leakage greater than zero.

- Leakage analyses should be based on bobbin indications left in service and confirmed by RPC inspection or not RPC inspected. The conservative bobbin criteria for identifying potential indications, such as Appendix A of WCAP-13494, can lead to false calls without supplemental RPC inspection. Even if it is assumed that the bobbin indications are real flaws but not detected by RPC, the high probability of detection for RPC at >40-50% depth leads to low likelihood that RPC NDD indications would lead to SLB leakage over the one cycle between inspections. It is highly desirable to maintain the bobbin and RPC indication basis for leakage analyses to continue to maintain conservative bobbin calling criteria.

- Further discussions should be held to support use of 2335 psi for SLB analyses, based on acceptable PORV reliability of Catawba-1.

- Further discussions should be held to develop a probability of detection based on field experience, rather than the more arbitrary 0.6 value. In WCAP-13692, Westinghouse has provided the NRC with tabulated data and PoD correlations for pulled tube detectability.

Statistical Findings of SLB Leak Rate Evaluations

- Previous analysis of the 3/4 inch leak rate data indicated a correlation with voltage at a high level of probability. Additional statistical evaluations performed in this report support a 99.99% probability level that leak rate is correlated to voltage.

- Neither the leak rates nor the bobbin amplitudes of the test specimens are distributed normally. The logarithms of the leak rates and of the bobbin amplitudes are distributed normally.

- The regression analyses have shown that the distribution of the residuals is normal with a mean of ~0 and constant variance about the regression line. This means that the assumptions inherent in performing the regression analysis were satisfied, and that statistical inference about the regression line may be performed.

- Overall, it is concluded that a SLB leak rate versus voltage correlation is appropriate and supported by statistical analysis of the data. Some correlation with voltage should be recognized in any SLB leak rate methodology at any level of intended conservatism.

Average SLB Leak Rate

- The high probability level that the leak rate is correlated to the voltage strongly supports the contention that segregation of the leak rate data into two groups, according to ascending bobbin amplitude, should be performed to limit the calculation of the pertinent statistics to the voltage range of interest.

- For a SLB pressure differential of 2560 psi, the average leak rate for the lower voltage half of the data base (< 9 volts) is 7.53 liters/hr, with a standard deviation of 10.25 liters/hr. For all leak rate data independent of voltage, the average is 30.8 liters/hr with a standard deviation of 54.0 liters/hr. At +95% uncertainty (1.645σ), the corresponding leak rates for a single indication would be 24.4 and 119.7 liters/hr. These averages are based on all available data, with no exclusions for outliers.

- For a SLB pressure differential of 2335 psi, the average leak rates and standard deviations are 5.53 liters/hr, σ=8.43 liters/hr and 19.1 liters/hr, σ=27.1 liters/hr for the lower voltage range and all data values, respectively. Additional information on PORV reliability for Catawba-1 to support the use of a 2335 psi SLB pressure differential will be provided for future analyses.

Probability of Leakage

- The maximum likelihood probability of leakage greater than zero versus voltage was developed for Catawba-1 in WCAP-13494, Rev. 1 for applications of the APC leak rate methodology.

- A correlation for the probability of leakage >1.0 liter/hr is developed in this report. At the lower voltage range of interest, the probability for >1.0 liter/hr leakage is about a factor of three less than the probability for >0.0 leakage.

Additional Catawba-1 SLB Leak Rate Analyses

- SLB leak rates are obtained for Catawba-1 utilizing the projected EOC-7 voltage distribution obtained for S/G C as the most limiting S/G. Although S/G D had more bobbin indications left in service, the number of EOC indications contributing to potential leakage is less than for S/G C due to lower voltages and growth rates for S/G D.

- Table 2-1 summarizes SLB leak sensitivity to the assumptions of the NRC method and the above noted alternate recommendations. It is seen that leak rates as low as 0.073 gpm can be obtained for the less conservative assumptions in the leak rate analysis.

Table 2-1

Summary of SLB Leakage Analyses

Ind. Included in Analyses	Probability of Leakage	Leak Rate Data	Prob. of Detection	SLB ΔP-psi	Total SLB Leakage-gpm
NRC Method					
All bobbin ind. left in service	> 0.0	< 9.0 volts	0.60	2560	0.60
All bobbin ind. left in service	> 0.0	All	0.60	2560	2.73
Sensitivity to Assumptions					
All bobbin ind. left in service	> 1.0 l/hr	< 9.0 volts	0.60	2560	0.23
All bobbin ind. left in service	> 0.0	< 9.0 volts	0.60	2335	0.46
Bobbin ind. left in service and confirmed by RPC or not RPC tested	> 0.0	< 9.0 volts	0.60	2560	0.29
Bobbin ind. left in service and confirmed by RPC or not RPC tested	> 1.0 l/hr	< 9.0 volts	0.90	2335	0.073

3.0 Statistical Findings of SLB Leak Rate Evaluations

The purpose of this section is to review the leak rate correlation presented in WCAP-13494, Revision 1, for Catawba Unit 1. Prior to discussing the results of the correlation analysis, new information is presented on the underlying distributions of the data to further support the selection of the scales used for the correlation.

Goodness-of-fit analyses were performed to determine if the bobbin amplitude and leak rate data could be satisfactorily represented by a known statistical distribution. In essence, a distribution is postulated and the observed frequency of occurrence of the variable is compared to the theoretical frequency of the variable, based on the sample mean and standard deviation, using a Chi-Square distribution. For the analysis of these data, the inclusion or exclusion of the few outliers will have no significant effect on the conclusions. The frequency of occurrence of the bobbin amplitudes and leak rates is plotted on Figures 3-1 and 3-2. The frequency of occurrence of the logarithms of the bobbin amplitudes and leak rates is plotted on Figures 3-3 and 3-4. Inspection of the figures indicates that the logarithm of the bobbin amplitudes appears to be slightly better correlated than the untransformed amplitudes. The figures also show that the logarithm transformation of the leak rates results in a much better correlation to a normal distribution. For the goodness-of-fit analyses the data were consolidated into bins of no less than (approximately) five observations per bin. Based on the assumed distribution, the theoretical number of observations expected per bin was calculated. The ;^{2} statistic was then found as:

$$\chi^2 = \sum_{i=1}^{i=N_b} \frac{n_i - e_i}{e_i}, \qquad (3.1)$$

where N_b is the number of bins, and n_i and e_i are the actual and expected number of observations of the variable in bin i. The degrees of freedom for the χ^2 statistic is N_b-1.

The segregated data for the goodness-of-fit analyses are provided in Tables 3-1 and 3-2 for the bobbin amplitudes and leak rates respectively. The respective analyses results are provided in Tables 3-3 and 3-4. The specific findings of the analyses are:

(1) The bobbin amplitudes are not distributed normally. There is a 98.5% probability that random samples taken from the theoretical distribution of bobbin amplitudes (based on the sample mean and standard deviation) would yield distributions better than the observed distribution of the sample data. This means that there is only a 1.5% probability that random data from the distribution would correlate to a normal distribution as poorly as the observed data.

(2) The leak rates are not distributed normally. There is essentially a 100% probability that random samples taken from the theoretical distribution of leak rates would yield distributions better than the observed distribution of the sample data. Thus, the probability that random normal data would correlate as poorly as the observed data is approximately zero.

(3) The logarithm, common or natural, of the bobbin amplitudes is distributed normally. The probability that additional (random) data sets from the same parent distribution would be better correlated to a lognormal distribution is only 16.3%. This means that the probability that random data taken from a lognormal distribution would provide a worse correlation than the observed data 83.7% of the time.

(4) The logarithm, common or natural, of the leak rates is distributed normally. The probability that additional data sets would yield distributions better correlated than the observed data set to a lognormal distribution is only 26.7%. Thus, random data from a lognormal distribution with the same parameters as the sample data would provide a worse correlation than the observed data 73.3% of the time.

It is to be noted that the assumption of normality would generally be accepted if the calculated probability of obtaining a worse correlation was on the order of 10%. Thus, the data strongly imply that both the bobbin amplitudes and the leak rates are lognormally distributed. This finding supports the use of logarithmic scales for fitting a regression line (curve) between the two variables.

For a 1st order regression, the significance of the correlation coefficient, r, can be determined from the following t-statistic:

$$t_{1-\alpha/2,n-2} = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}}, \tag{3.2}$$

where n is the number of data pairs used to determine the correlation coefficient, and (1-α) is the probability that the correlation is significant. For the 3/4" tubes leak and bobbin amplitude data, r^2 was found to be 52.6% for a SLB pressure of 2335 psi (the index for 2650 psi is 57.6%). It is readily apparent that a correlation exists simply by considering that 52.6% of the variance of the logarithm of the leak rates can be explained by a linear regression equation. Equation (3.2) yields a t-variate of 6.049, hence $\alpha/2$ is $4.18 \cdot 10^{-7}$, and the significance level of the correlation is $100 \cdot (1-\alpha)=99.9999\%$. This means that a correlation as significant as that observed between the logarithm of the leak rate and the logarithm of the bobbin amplitude would be expected to occur only 0.0001% of the time for repeated tests involving the same sample size.

For a linear first order fit with a relatively large number of data points, the square of the correlation coefficient does not have to be very close to one to reject the null hypothesis that the data are uncorrelated, and thereby accept the alternate hypothesis that a correlation does exist. For example, the critical level of r^2 for significance at a level of 99.9% would be on the order of 28%, and that value is significantly exceeded by the observed r^2. Again, this strongly supports the existence of a correlation between the leak rate and the bobbin amplitude.

An alternate, and approximate, estimate of the level of confidence for the existence of a correlation between the logarithm of the leak rate and logarithm of the bobbin amplitude was also calculated by segregating the data into two groups according to ascending bobbin amplitude. A t-test was then performed to determine if the two groups represented samples from the same population. The test was performed twice, first by assuming the populations from which the samples were drawn had the same variance, and again under the assumption that the variances were not the same. When the variances were assumed to be the same, the test statistic was calculated using a pooled estimate of the variance of the total population. When the variances were not assumed to be equal, the test statistic utilized the appropriate function to determine the degrees of freedom, DoF, to be used. For both evaluations the equations are contained in elementary texts on statistics.

The 3/4" tubes leak rate data were segregated into two groups (including outliers) based on the median voltage. For ΔP_{SLB} = 2560 psi including outliers, the data in each group are listed in Table 3-5, and the results of the analyses are listed in Table 3-6. Similarly, the results for ΔP_{SLB} = 2335 psi are given in Tables 3-7 and 3-8. The results of performing a t-test on the means of the two data sets indicates probabilities 0.5% for ΔP = 2560 psi and 0.1% for ΔP = 2335 psi that they are from the same underlying population. For the logarithm transformed data, the probabilities are 0.008% for ΔP = 2560 psi and 0.01% for ΔP = 2335 psi that they are from the same population. Since the leak rates have been shown to follow a lognormal distribution, the probability value associated with the transformed data is more likely. The conclusion is that it is likely at a 99.99% probability level that the leak rate is correlated to the voltage. This is the same conclusion obtained from analysis of the correlation coefficient.

The regression results presented in WCAP-13494, Revision 1, are repeated on Figure 3-5. Examination of the data presented indicates that the results of the regression analysis would not be significantly different if the single data point at ~1.1 volt and 0.02 l/hr was to be omitted. The correlation would still be significant at a >99.99%

level, and the conclusions relative to the existence of a correlation between leak rate and bobbin amplitude would be unchanged.

Although the analysis was performed specifically for 3/4" diameter tube specimens the general conclusion relative to a correlation between leak rate and bobbin amplitude should also apply to 7/8" tubes. It has been noted that the correlation demonstrated for 7/8" diameter tubes is not as strong as for 3/4" tubes.

Evaluation of the results of the regression analyses for both tube sizes have shown that the residuals are normally distributed with a mean of ~0, and with a constant variance about the regression line. This means that the assumptions inherent in performing the regression analyses were satisfied, and that statistical inference about the regression line is justified.

Table 3 - 1

Data Segregation for Performance of Chi^2 Frequency Analysis
3/4" x 0.043" Alloy 600 SG Tubes (Outliers Excluded), SLB = 2335 psi.

Voltage Data Bins & Frequencies

Min	Max	Frequency	Cumulative %
0	1	0	0.00%
1	2	1	2.86%
2	3	0	2.86%
3	4	1	5.71%
4	5	3	14.29%
5	6	3	22.86%
6	7	3	31.43%
7	8	1	34.29%
8	9	5	48.57%
9	10	4	60.00%
10	11	2	65.71%
11	12	3	74.29%
12	13	0	74.29%
13	14	0	74.29%
14	15	2	80.00%
15	16	2	85.71%
16	17	2	91.43%
17	18	1	94.29%
18	19	1	97.14%
19	20	1	100.00%
		35	

LOG Voltage Data Bins & Frequencies

Min	Max	Frequency	Cumulative %
0.0	0.2	1	2.86%
0.2	0.4	0	2.86%
0.4	0.6	1	5.71%
0.6	0.8	7	25.71%
0.8	1.0	12	60.00%
1.0	1.2	8	82.86%
1.2	1.4	6	100.00%
		35	

Table 3 - 2

Data Segregation for Performance of Chi^2 Frequency Analysis
3/4" x 0.043" Alloy 600 SG Tubes (Outliers Included), SLB = 2335 psi.

Leak Rate Data Bins & Frequencies			
Min	Max	Frequency	Cumulative %
0	5	15	40.54%
5	10	6	56.76%
10	15	1	59.46%
15	20	1	62.16%
20	25	5	75.68%
25	30	1	78.38%
30	35	1	81.08%
35	40	0	81.08%
40	45	3	89.19%
45	50	0	89.19%
50	55	2	94.59%
55	60	0	94.59%
60	55	0	94.59%
65	70	0	94.59%
70	75	0	94.59%
75	80	0	94.59%
80	85	1	97.30%
85	90	0	97.30%
90	95	0	97.30%
95	100	0	97.30%
100	105	0	97.30%
105	110	0	97.30%
110	115	0	97.30%
115	120	0	97.30%
120	125	0	97.30%
125	130	0	97.30%
130	135	1	100.00%
		37	

LOG Leak Rate Data Bins & Frequencies			
Min	Max	Frequency	Cumulative %
-2.00	-1.50	2	5.41%
-1.50	-1.00	1	8.11%
-1.00	-0.50	1	10.81%
-0.50	0.00	3	18.92%
0.00	0.50	5	32.43%
0.50	1.00	9	56.76%
1.00	1.50	9	81.08%
1.50	2.00	6	97.30%
2.00	2.50	1	100.00%
		37	

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Table 3 - 3

Chi^2 Test for Normal Distribution of Bobbin Amplitude
Outliers Excluded from the Analysis

Lower End of Bin	Upper End of Bin	Center of Bin	Observed Frequency w/Outliers	Cumulative Percent	Cumulative to Lower End of Bin	Cumulative to Upper End of Bin	Theoretical Frequency	Chi^2 Term
0	5	2.5	5	14.3%	13.0%	26.4%	4.7	0.021
5	7	6	6	31.4%	26.4%	33.3%	2.4	5.433
7	9	8	6	48.6%	33.3%	40.7%	2.6	4.417
9	11	10	6	65.7%	40.7%	48.5%	2.7	3.915
11	15	13	5	80.0%	48.5%	64.0%	5.4	0.032
15	20	17.5	7	100.0%	64.0%	80.3%	5.7	0.291
		Total:	35			Total	23.5	14.11
						DoF		5
		Chi-Test Check:	**1.49%**			**Prob.**		**1.49%**

Chi^2 Test for Normal Distribution of LOG(Bobbin Amplitude)
Outliers Excluded from the Analysis

Lower End of Bin	Upper End of Bin	Center of Bin	Observed Frequency w/Outliers	Cumulative Percent	Cumulative to Lower End of Bin	Cumulative to Upper End of Bin	Theoretical Frequency	Chi^2 Term
0.0	0.8	0.40	9	25.71%	0.03%	28.08%	10.4	0.183
0.8	1.0	0.90	12	60.00%	28.08%	55.19%	10.0	0.387
1.0	1.2	1.10	8	82.86%	55.19%	79.99%	9.2	0.151
1.2	1.4	1.30	6	100.00%	79.99%	93.97%	5.2	0.133
		Total:		35		Total	34.8	0.854
						DoF		3
		Chi-Test Check:	**83.66%**			**Prob.**		**83.66%**

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Table 3 - 4

Chi^2 Test for Normal Distribution of Leak Rate With Outliers Included in the Analysis								
Lower End of Bin	Upper End of Bin	Center of Bin	Observed Frequency w/Outliers	Cumulative Percent	Cumulative to Lower End of Bin	Cumulative to Upper End of Bin	Theoretical Frequency	Chi^2 Term
0	5	2.5	15	40.54%	2.40E-01	3.01E-01	2.26	72.015
5	10	7.5	6	16.22%	3.01E-01	3.68E-01	2.48	4.980
10	25	17.5	7	59.46%	3.68E-01	5.86E-01	8.06	0.140
25	45	35	5	72.97%	5.86E-01	8.30E-01	9.05	1.814
45	135	90	4	83.78%	8.30E-01	1.00E+00	6.28	0.826
		Total:	37			Total	28.13	79.774
						DoF		4
		Chi-Test Check:	1.94E-16			**Prob.**		**0.00%**

Chi^2 Test for Normal Distribution of LOG(Leak Rate) With Outliers Included in the Analysis								
Lower End of Bin	Upper End of Bin	Center of Bin	Observed Frequency w/Outliers	Cumulative Percent	Cumulative to Lower End of Bin	Cumulative to Upper End of Bin	Theoretical Frequency	Chi^2 Term
-2.0	0.0	-1.00	7	18.92%	0.27%	23.14%	8.46	0.253
0.0	0.5	0.25	5	32.43%	23.14%	41.26%	6.70	0.433
0.5	1.0	0.75	9	56.76%	41.26%	61.50%	7.49	0.305
1.0	1.5	1.25	9	81.08%	61.50%	78.98%	6.47	0.992
1.5	2.5	2.00	7	100.00%	78.98%	96.65%	6.54	0.032
		Total:	37			Total	35.66	2.015
						DoF		4
		Chi-Test Check:	73.30%			**Prob.**		**73.30%**

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Table 3-5. Comparison of Segregated Leak Rates - 2560 psi

Lower Range of Volts			Upper Range of Volts		
Bobbin Amplitude (V)	SLB Leak Rate @ 2560 psi (l/hr)	LOG Leak Rate @ 2560 psi	Bobbin Amplitude (V)	SLB Leak Rate @ 2560 psi (l/hr)	LOG Leak Rate @ 2560 psi
	18	18		19	19
Means:	7.53	0.2866		52.87	1.4758
Vars:	104.992	1.018		4684.17	0.257
StDevs:	10.2465	1.0088		68.4410	0.5071
StErrs:	2.4151	0.2378		15.7014	0.1163
	One Tailed	Two Tailed			
T-test:	2.85E-05	5.71E-05	Homoscedastic		
T-test:	7.10E-05	1.42E-04	Heteroscedastic		

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Table 3-6. Statistical Tests of Segregated Leak Rates - ΔP_{SLS} = 2560 psi

Statistical Tests on the LOG Transformed Variates

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	Variable 2
Mean	0.2866	1.4758
Variance	1.0176	0.2572
Observations	18	19
Pooled Variance	0.6265	
Hypothesized Mean Difference	0	
df	35	
t	-4.5676	
P(T<=t) one-tail	**2.94E-05**	
t Critical one-tail	1.6896	
P(T<=t) two-tail	0.0059%	
t Critical two-tail	2.0301	

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	Variable 2
Mean	0.2866	1.4758
Variance	1.0176	0.2572
Observations	18	19
Pearson Correlation	#N/A	
Pooled Variance	2459.998797	
df	24.77344605	
t	-4.4925	
P(T<=t) one-tail	**7.55E-05**	
t Critical one-tail	1.7109	
P(T<=t) two-tail	0.0151%	
t Critical two-tail	2.0639	

Statistical Tests on the Un - Transformed Variates

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	Variable 2
Mean	7.5339	52.8747
Variance	104.9916	4684.1723
Observations	18	19
Pooled Variance	2459.9988	
Hypothesized Mean Difference	0	
df	35	
t	-2.7793	
P(T<=t) one-tail	**4.35E-03**	
t Critical one-tail	1.6896	
P(T<=t) two-tail	0.8704%	
t Critical two-tail	2.0301	

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	Variable 2
Mean	7.5339	52.8747
Variance	104.9916	4684.1723
Observations	18	19
Pearson Correlation	#N/A	
Pooled Variance	2459.998797	
df	18.85063953	
t	-2.8541	
P(T<=t) one-tail	**5.27E-03**	
t Critical one-tail	1.7341	
P(T<=t) two-tail	1.0538%	
t Critical two-tail	2.1009	

Table 3-7.

Comparison of Lower & Upper Voltage Samples - 2335					
Lower Range of Volts			Upper Range of Volts		
Bobbin Amplitude (V)	SLB Leak Rate @ 2335 psi (l/hr)	LOG Leak Rate @ 2335 psi	Bobbin Amplitude (V)	SLB Leak Rate @ 2335 psi (l/hr)	LOG Leak Rate @ 2335 psi
					e
	18	18		19	19
Means:	5.529	0.123		32.04	1.28
Vars:	70.986	0.989		1036.95	0.28
StDevs:	8.4253	0.9945		32.2017	0.5307
StErrs:	1.9859	0.2344		5.9633	0.4385
	One Tailed	Two Tailed			
T-test:	2.85E-05	5.71E-05	Homoscedastic		
T-test:	7.10E-05	1.42E-04	Heteroscedastic		

Table 3-8.

Comparison of Lower & Upper Voltage Samples, for 2335 psi, With Outliers

Statistical Tests on the LOG Transformed Variates

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	Variable 2
Mean	0.1234	1.2759
Variance	0.9890	0.2816
Observations	18	19
Pooled Variance	0.6252	
Hypothesized Mean Difference	0	
df	35	
t	-4.4314	
P(T<=t) one-tail	**4.41E-05**	
t Critical one-tail	1.6896	
P(T<=t) two-tail	0.0088%	
t Critical two-tail	2.0301	

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	Variable 2
Mean	0.1234	1.2759
Variance	**0.9890**	**0.2816**
Observations	18	19
Pearson Correlation	#N/A	
Pooled Variance	0.6252	
df	25.6471	
t	-4.3633	
P(T<=t) one-tail	**9.70E-05**	
t Critical one-tail	1.7081	
P(T<=t) two-tail	0.0194%	
t Critical two-tail	2.0595	

Statistical Tests on the Un - Transformed Variates

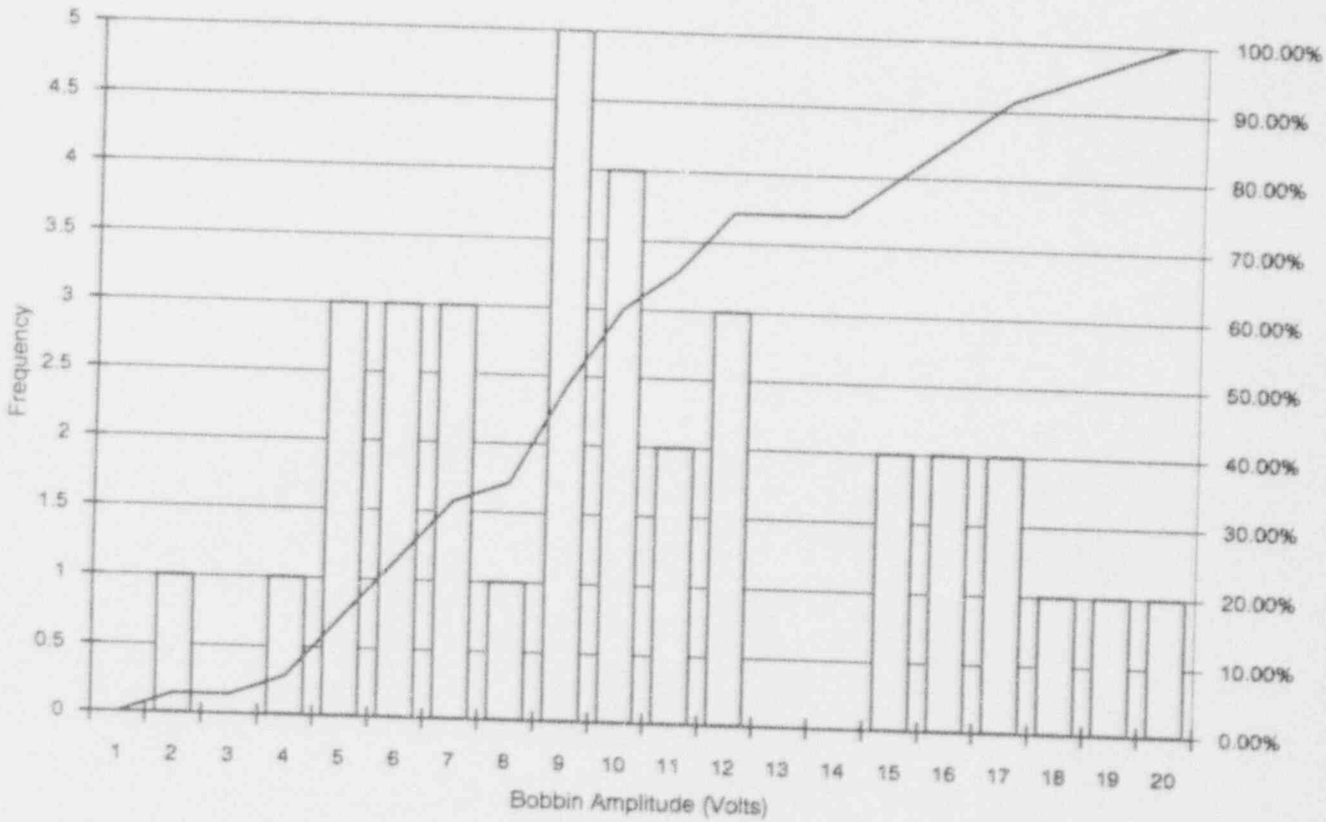
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	Variable 2
Mean	5.5289	32.0353
Variance	70.9859	1036.9511
Observations	18	19
Pooled Variance	567.7680	
Hypothesized Mean Difference	0	
df	35	
t	-3.3820	
P(T<=t) one-tail	**8.92E-04**	
t Critical one-tail	1.6896	
P(T<=t) two-tail	0.1784%	
t Critical two-tail	2.0301	

t-Test: Two-Sample Assuming Unequal Variances

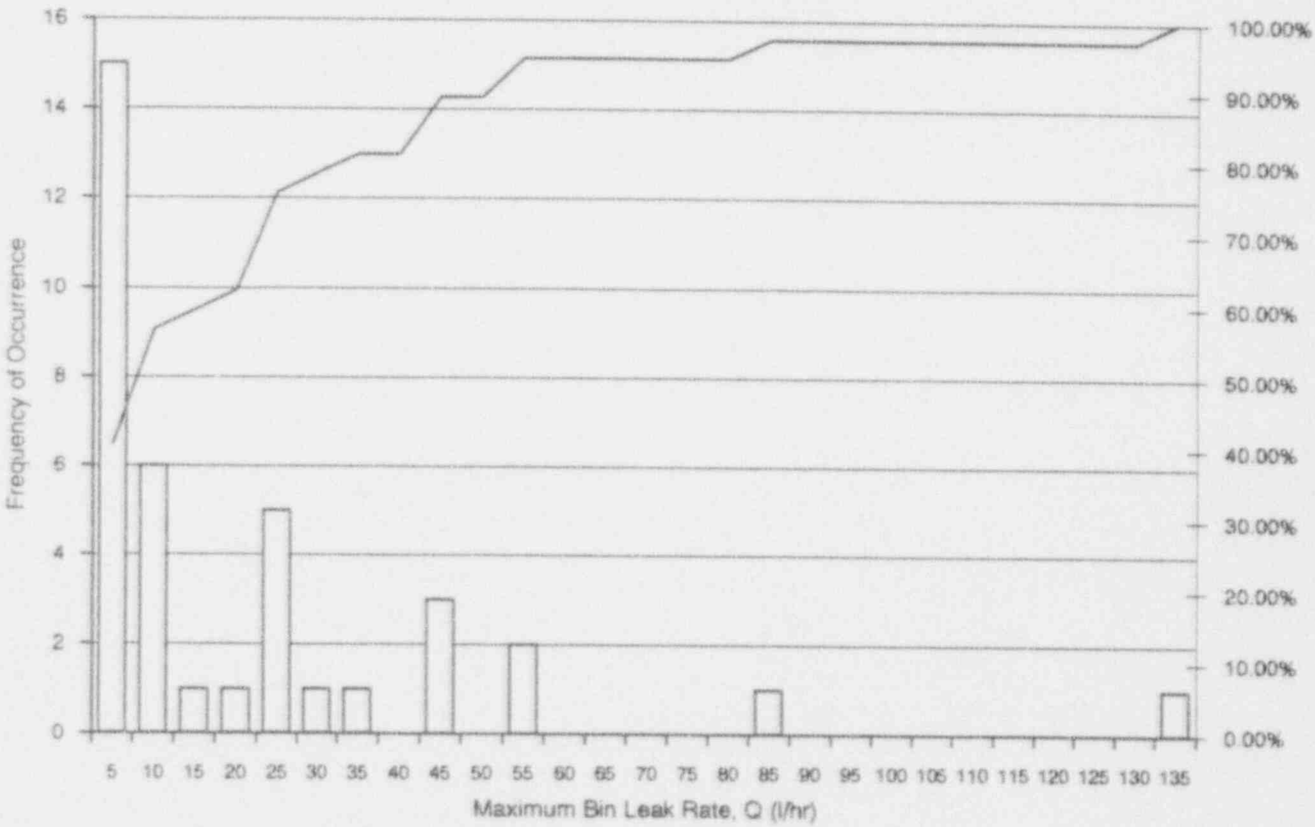
	Variable 1	Variable 2
Mean	5.5289	32.0353
Variance	**70.9859**	**1036.9511**
Observations	18	19
Pearson Correlation	#N/A	
Pooled Variance	567.7680	
df	20.5815	
t	-3.4650	
P(T<=t) one-tail	**1.22E-03**	
t Critical one-tail	1.7247	
P(T<=t) two-tail	0.2446%	
t Critical two-tail	2.0860	

Figure 3-1: Distribution of Bobbin Amplitudes
for 3/4" Tubes Leak Rate Specimens



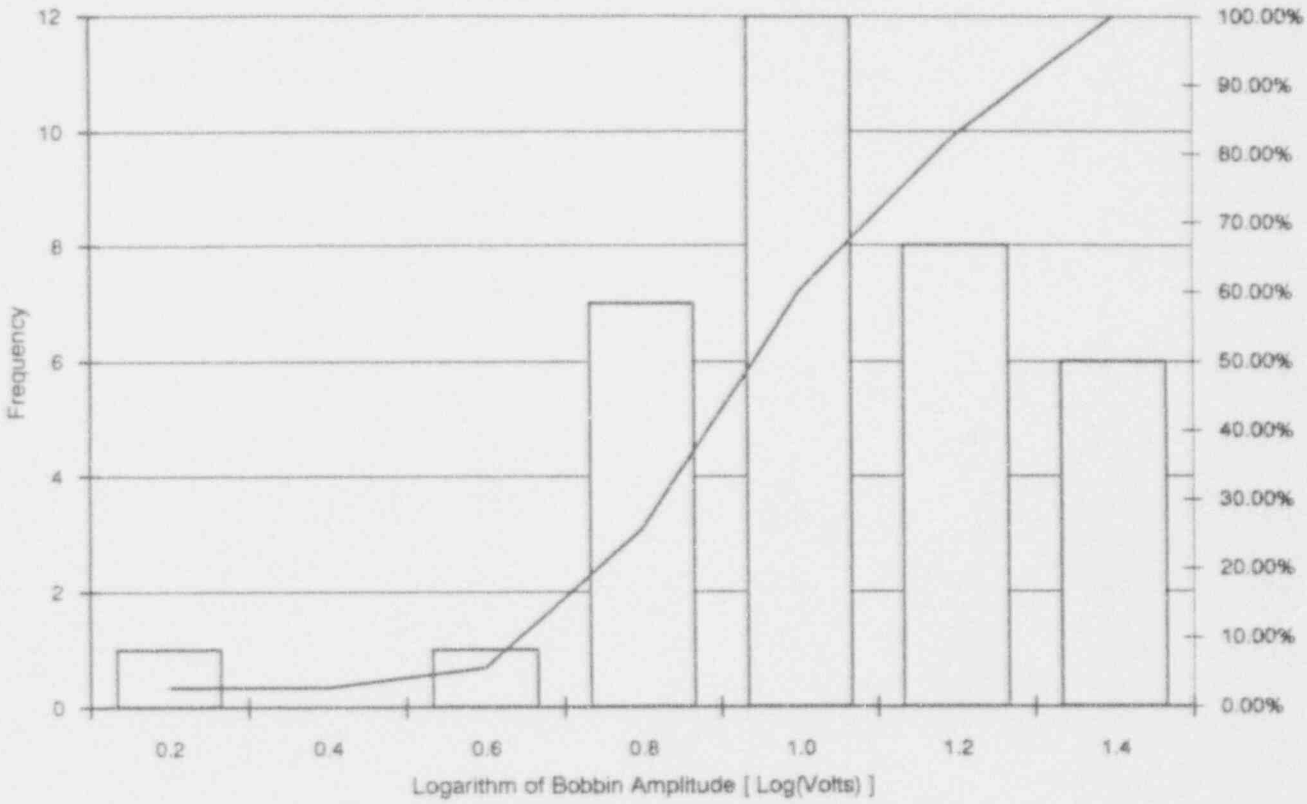
[34LKVLTA.XLW]Volts Histogram

Figure 3-2: Distribution of Leak Rate
3/4" OD x 0.043" Thick Alloy 600 SG Tubes



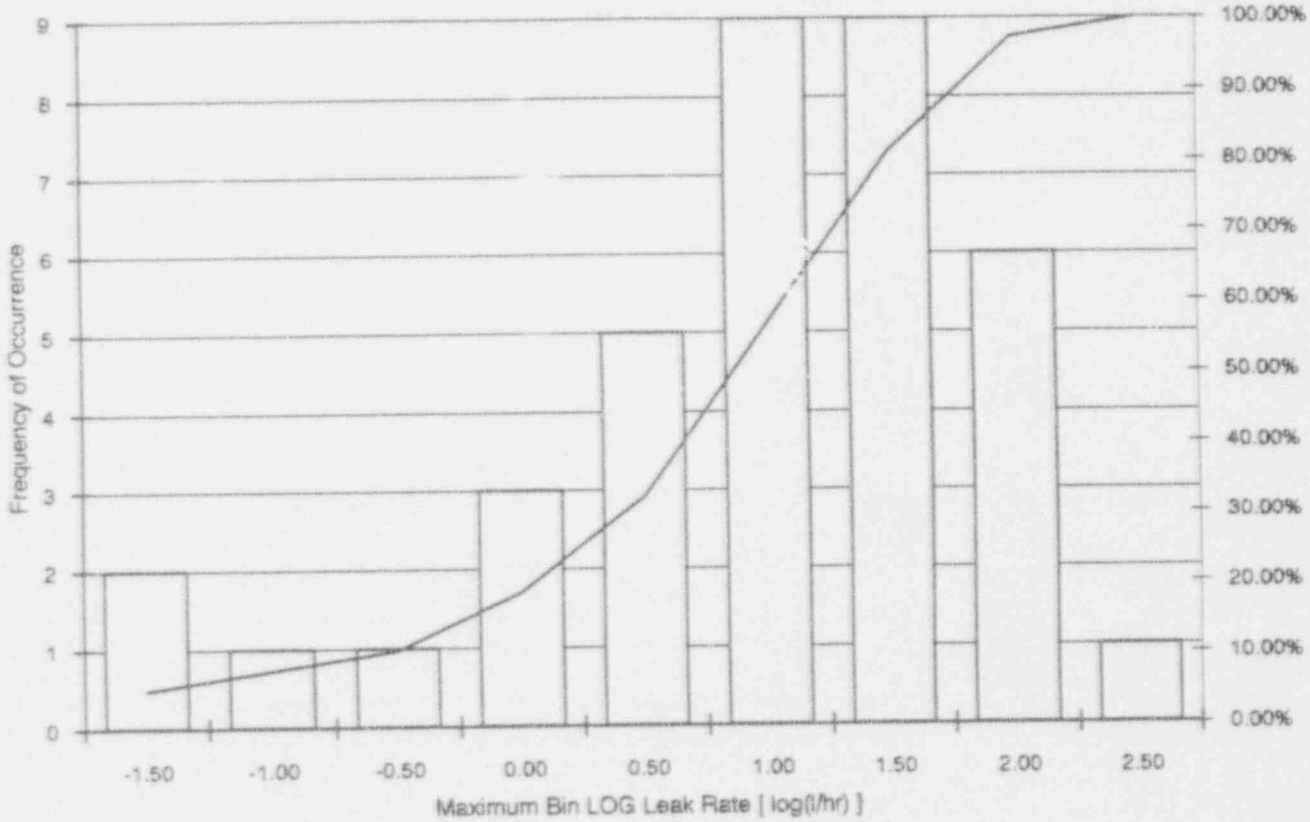
[34LKVLTA.XLW]Leak Distribution Histogram

Figure 3-3: Distribution of Log(Bobbin Amplitude) for 3/4" Tubes Leak Rate Specimens



[34LKVLTA.XLW]Log(Volts) Histogram

Figure 3-4: Distribution of LOG(Leak Rate)
3/4" OD x 0.043" Thick Alloy 600 SG Tubes



[34LKVLTA.XLW]LOG(Leak) Distribution Hist

Figure 3 - 5

2335 psi SLB Leak Rate vs. Bobbin Amplitude

3/4" Tubes, Model Boiler & Field Data

a,

4.0 Average SLB Leak Rates

The purpose of this section is to provide an analysis of the leak rate data without consideration of any correlation to the bobbin amplitude. Although an analysis of this type would not normally be performed owing to the evidence of a correlation, this specific evaluation and the results of the evaluation were requested by the NRC.

The leak rate data for nominal 3/4" OD tubes (including outliers) is summarized in Table 4-1 for a SLB differential pressure of 2560 psi @ 616°F. The average leak rate for the entire voltage range (all data) is 30.8 liters/hr and 7.53 liters/hr for voltage <9.24. The standard deviations on the distributions of leak rates are 54.0 and 10.3 liters/hr, respectively.

Average leak rates are also provided for a SLB pressure differential of 2335 psi. These averages are given in Table 4-2. The average leak rates are 19.1 liters/hr for all data and 5.53 liters/hr for voltages < 9.24. The standard deviations on the leak rate distributions are 27.1 and 8.43 liters/hr, respectively.

Table 4-1: Leak Rate Characteristics for 3/4" Tubes

Total Crack Leak Rate Information 3/4" OD SG Tubes ΔP_{SLB}=2560 psi @ 616°F		
	All Data	V < 9.24 Volts (Median)
Number	37	18
Mean, μ_{est}	30.82 l/hr	7.53 l/hr
Standard Deviation, σ	54.03 l/hr	10.25 l/hr
Standard Error, σ_{err}	8.88 l/hr	2.42 l/hr

Table 4-2: Leak Rate Characteristics for 3/4" Tubes

Crack Leak Rate Information 3/4" OD SG Tubes ΔP_{SLB}=2335 psi @ 616°F		
	All Data	V < 9.24 Volts (Median)
Number	37	18
Mean, μ_{est}	19.140 l/hr	5.529 l/hr
Standard Deviation	27.063 l/hr	8.425 l/hr
Standard Error, σ_{err}	4.449 l/hr	1.986 l/hr

5.0 Probability of Leakage

The probability of leak (P.O.L.) may be defined to be the probability of exceeding a specified leak rate. For APC methodology with leak rates dependent on voltage, the P.O.L. is defined as the probability of any leakage >0.0. This definition was applied in WCAP-13494, Rev. 1, and the P.O.L. versus volts is shown on Figure 5-1.

For application of a constant leak rate per leaking indication, the P.O.L. can be defined as the probability of leakage greater than a significant level compared to the constant leak rate. In Section 4, the leak rate at ΔP_{SLB} = 2335 psi for bobbin amplitudes <9.2 volts (the lower voltage half of the data) was obtained at a mean of 5.53 l/hr with a standard deviation of 8.43 or a leak rate of 19.4 l/hr at the +95% uncertainty level requested by the NRC. Defining a significant leak for P.O.L. determination as 1.0 l/hr (0.0044 GPM) then leads to a factor of 19 conservatism between defining a leaker and assigning a leak rate. This leads to significant conservatism in the leak rate analyses. Use of P.O.L. for any leakage greater than zero together with an assigned leakage of 9 l/hr would be excessively conservative. The probability of leakage >1.0 l/hr is shown on Figure 5-2. This threshold shifts the P.O.L. curve by about one volt toward higher voltages for the same probability. Correspondingly, the 1.0 l/hr threshold lowers the leakage probability by about a factor of three in the 1-4 volt range of interest.

The P.O.L.'s were determined by fitting a logistic equation to the experimental data. The probability of leak, Pr(Q), is a function of the logarithm of the bobbin amplitude, log(V),

$$Pr(Q) = \frac{1}{1 + e^{-[a_0 + a_1 \log(V)]}}.$$

where the coefficients a_0 and a_1 were found based on the principle of maximum likelihood. For the first case, i.e., the probability of the leak rate, Q, being > 0 as a function of volts, the coefficients were found to be -5.276 and 9.185. For the probability of Q being ≥1 l/hr the coefficients were determined to be -6.539 and 8.781. These results do not change for a ΔP of 2560 psi.

Figure 5-1

Probability of Leak > 0 l/hr vs. Bobbin Amplitude

3/4" Tubes, Model Boiler & Field Data

a,e

Figure 5-2

Probability of Leak > 1 l/hr vs. Bobbin Amplitude

3/4" Tubes, Model Boiler & Field Data

a,

6.0 Catawba-1 SLB Leak Rate Analyses

The purpose of this section is to respond to a NRC request to evaluate the Catawba Unit 1 potential steam generator (SG) tube leak rates during a postulated steam line break (SLB) based on the following conditions:

1) Maximum likelihood probability of leak curve.

2) Inclusion of bobbin indications not confirmed by RPC inspection.

3) A probability of detection (PoD) of 0.6.

4) SLB ΔP of 2560 psi.

5) Evaluation of total leak rate, Q_T, per the following equation:

$$Q_T = n\,Q_\mu + 2\sqrt{n}\,\sigma\,, \qquad (6.1)$$

where n is the expected number of potentially leaking tubes at the EOC divided by the probability of detection, σ is the estimated standard deviation of the population leak rate from the specimen measurements, and Q_μ is the average leak rate from the specimen measurements.

The intent of the calculation specified is to "provide a reasonable estimate of the total leak rate (i.e., upper 95% confidence value) where the number of expected leakers is equal to or greater than 5 tubes."

Subsequent discussions with the NRC staff resulted in the agreement that Equation (6.1) be modified to

$$Q_T = n\,Q_\mu + 1.645\sqrt{n}\,\sigma\,. \qquad (6.2)$$

The rationale for the change is that the use of a factor of "2" corresponds to two-sided confidence band with 2.3% in each tail of the distribution, and would result in a 97.7% one sided confidence bound instead of the desired 95% confidence bound. The use of a coefficient of 1.645 corresponds to a 95% one-sided confidence bound based on the sampling distribution of the sum of the leak rates being approximately normally distributed. It was agreed that the leak rate statistics would be calculated without excluding the outliers identified and discussed in WCAP-13494, Revision 1. It was also agreed that SLB leak rate analyses would be performed using the average leak rate and standard deviation for all leak rate data and for the lower voltage half of the leak rate data.

6.1 SLB Leak Rate Analysis Results

This section utilizes the average and standard deviation for SLB leak rates developed in Section 4 and the probability of leakage (P.O.L.) correlations given in Section 5 to obtain very conservative Catawba-1 EOC-7 SLB leak rates. Analyses are performed for ΔP_{SLB} = 2560 psi and 2335 psi, and for voltage distributions based on all bobbin indications left in service independent of RPC confirmation as well as based on bobbin indications less than the 1.0 volt IPC repair limit that were confirmed by RPC or not RPC inspected. These analyses are performed for the following four cases:

Case	Probability of Leakage	Constant SLB Leak Rate
1	P.O.L. for Leakage >0.0	Leak rate for all measured leak rates.
2	P.O.L. for Leakage >0.0	Leak rate for measured leak rates having voltages < 9.2 volts.
3	P.O.L. for Leakage >1.0 ℓ/hr	Same as Case 1.
4	P.O.L. for Leakage >1.0 ℓ/hr	Same as Case 2.

Assuming that a constant leak rate is to be applied, rather than the APC leak rate correlation, Case 4 is the most realistic combination of assumptions while continuing to apply a conservative constant leak rate. Case 4 applies leak rates for the bounding voltage range up to 9.2 volts, which encompasses the lower voltage half of the leak rate measurements. The probability of leakage for Case 4 is developed as the P.O.L. that the leak rate is greater than 1.0 liter/hour, or less than one-tenth of the leak rate applied for Case 4. Applying a P.O.L. for any leakage greater than zero with a conservative constant leak rate is considered excessively conservative.

Although the postulated leak rates are independent of voltage, the P.O.L. is voltage dependent so that EOC voltage distributions are required for the analysis. Catawba-1 EOC ` oltage distributions used for the analyses are described in Section 6.2. Section 6. ` summarizes the results of the SLB leak rate analyses.

6.2 EOC-7 Voltage Distributions

The NRC requested that the SLB leak rates be based on all bobbin indications left in service, including indications not confirmed by RPC inspection. Figure 6-1 shows the S/G C BOC voltage distribution (1933 indications) for these indications. It was shown in WCAP-13494, Rev. 1 that the voltage growth for S/G C is higher than that obtained for all S/G indications. Thus, the S/G C growth distribution, as shown in Figure 6-1, is used for S/G C analyses. The EOC-7 S/G C voltage distribution was obtained by Monte Carlo analysis including allowances for growth and NDE uncertainties. The resulting EOC-7 S/G C voltage distribution of Figure 6-1 is used for the SLB leak rate analyses. The EOC-7 distribution for S/G D was also evaluated to confirm that S/G C is the most limiting S/G for leakage analyses. The S/G D BOC distribution (3410 indications) is shown in Figure 6-2, together with the growth rate distribution for all S/Gs. The all S/G growth distribution is more conservative than the S/G D growth rates. The projected S/G D EOC-7 distribution is also shown in Figure 6-2. By comparison with Figure 6-1, it is seen that S/G C is more limiting than S/G D in that the S/G C EOC distribution has more indications above 0.7 volt than S/G D. Thus, S/G C is appropriate for SLB leakage analyses as the more limiting S/G.

The BOC distribution based on bobbin indications less than 1.0 volt that were confirmed by RPC inspections plus potential indications not inspected by the RPC probe is more appropriate than all bobbin indications for SLB leakage analyses. Based on the high RPC detectability, bobbin indications not confirmed by RPC are expected to be false calls or small indications not a concern for SLB leakage over one operating cycle. Figure 6-3 shows the S/G C BOC 7 voltage distribution (1307 indications). Also shown in Figure 6-3 is the S/G C voltage growth rate. As shown in WCAP-13494, Rev. 1, S/G C growth rates are larger than growth rates found for S/G D or by combining growth for all S/Gs. The EOC-7 S/G C voltage distribution, as shown in Figure 6-3, was obtained by Monte Carlo analyses and is used for the alternate SLB leak rate analyses.

Although S/G D had more bobbin indications than S/G C, the rate of RPC confirmation was much lower than found in S/G C. The S/G D BOC 7 voltage distribution (2218 indications) for RPC confirmed and not RPC tested is shown in Figure 6-4. The voltage growth rate for S/G D is shown in Figure 6-5 and is significantly smaller than the all S/G growth rate of Figure 6-2 or the S/G C growth rate of Figure 6-1. For conservatism, the S/G C voltage growth was applied to the S/G D BOC distribution to obtain the S/G D EOC 7 distribution of Figure 6-4. Due to the fewer number of indications above 1.0 volt for S/G D, the S/G leakage was found to be essentially the same as obtained for S/G C. Only the S/G C leakage analyses are described in this report.

6.3 EOC 7 SLB Leak Rate Analyses

The effective number of indications having potential leakage at EOC-7 can be obtained by multiplying the number of indications in a narrow voltage bin by the probability of leakage at the mean voltage for the bin and summing over all voltage bins. The EOC-7 voltage distributions for S/G C of Figures 6-1 and 6-3 are used for the analyses. Analyses are performed using the P.O.L. correlation for any leakage >0.0 and the P.O.L. correlation for leakage >1.0 liter/hr. These correlations are shown in Figures 5-1 and 5-2. Due to the large number of indications, the probability of leakage is expected to result in the maximum likelihood value and the regression line is used for the leakage analyses as requested by the NRC.

The S/G C SLB leakage analyses for Cases 1 to 4, as described above, are summarized in Table 6-1 for all bobbin indications left in service. Cases 1 and at ΔP_{SLB} = 2560 psi are the cases requested by the NRC. For P.O.L. >0.0, the number of indications times the P.O.L. sums to 6.41 leaking indications due to the low probability of leakage below about two volts. For P.O.L. >1.0 liter/hr, the effective number of leaking indications is only 1.78. The SLB leak rates for Cases 1 to 4 are given at the bottom of Table 6-1 for ΔP_{SLB} = 2560 and 2335 psi. Case 1 for the NRC-requested leak rates at 2560 psid (all data used for leak rates) yields 2.73 gpm, and Case 2 (data < 9.2 volts for leak rates) yields 0.60 gpm. It can be noted that a constant leak rate assumption for the 1.0 volt IPC repair limit leads to the largest leakage contributions between about 0.7 and 1.9 volts, which is inconsistent with realistic expectations. As previously discussed, Case 4 provides the most realistic leak rate estimate for a constant leak rate assumption. Case 4 yields 0.23 gpm at EOC-7 for 2560 psi. At 2335 psi, the corresponding SLB leak rates are reduced by 25-40%.

Table 6-2 provides the SLB leak rate analyses for all bobbin indications < 1.0 volt confirmed by RPC or not RPC tested. By comparison with Table 6-1, the effective number of leaking tubes is reduced from 6.41 to 2.51 when confirmed RPC indications are applied in the analyses. The Case 1 and Case 2 leak rates are reduced from 2.73 to 1.15 gpm and from 0.60 to 0.29 gpm, respectively. The most realistic SLB leak rate estimate is Case 5 at 2335 psi. Case 5 includes P.O.L. > 1.0 l/hr, PoD = 0.9 and leak rates for voltages < 9.2 volts. The resulting leak rate is 0.073 gpm, which compares to 0.006 gpm in WCAP-13494, Rev. 1 for the comparable Monte Carlo EOC-7 voltage distribution and application of the APC leak rate correlations.

Based on the above, Cases 4 and 5, the most realistic for a constant leak rate assumption, lead to a range of 0.07 to 0.23 gpm leakage or well below the 1.0 gpm allowable limit. Case 2, which is equivalent to assuming EOC voltages in the 5-10 volt range, represents a conservative estimate of the upper bound SLB leak rate (0.60 gpm). Cases 1 and 3 have no relation to IPC or APC repair limits, since these cases apply leak rates typical of the 10-20 volt range. Thus, 0.60 gpm at 2560 psi from Case 2 of Table 6-1 provides a bounding SLB leak rate consistent with the NRC request for applying a constant leak rate at the +95% level of the measured data.

Table 6-1

Catawba-1 SLB Leakage for S/G C With Constant Leak Rate: All Indications Left in Service Independent of RPC Confirmation

E.O.C. Volts	Number of Indications	P.O.L. for Leakage > 0.0 l/hr: Probability of Leakage	P.O.L. for Leakage > 0.0 l/hr: No. of Leaking Indications	P.O.L. for Leakage > 1.0 l/hr: Probability of Leakage	P.O.L. for Leakage > 1.0 l/hr: No. of Leaking Indications
0.55	229				
0.65	207				
0.75	176				
0.85	143				
0.95	110				
1.05	83				
1.15	60				
1.25	42				
1.35	29				
1.45	20				
1.55	13				
1.65	10				
1.75	6				
1.85	5				
1.95	3				
2.05	2				
2.15	2				
2.3	1				
2.4	1				
2.6	1				
2.65	1				
			6.41		1.78

a,e

Case	Leak Rate per Leaking Indication: Qu	Leak Rate per Leaking Indication: σ	No. of Leaking Indications ÷ PoD = 0.6	Leak Rate (l/hr)	Leak Rate (gpm)	
ΔP = 2560 psi						
1	30.8	54.0	10.7	620.1	2.73	P.O.L. > 0
2	7.53	10.3	10.7	136.0	0.60	P.O.L. > 0
3	30.8	54.0	2.97	244.6	1.08	P.O.L. > 1.0 l/hr
4	7.53	10.3	2.97	51.6	0.23	P.O.L. > 1.0 l/hr
ΔP = 2335 psi						
1	19.1	27.1	10.7	350.2	1.54	P.O.L. > 0
2	5.53	8.43	10.7	104.5	0.46	P.O.L. > 0
3	19.1	27.1	2.97	133.6	0.59	P.O.L. > 1.0 l/hr
4	5.53	8.43	2.97	40.3	0.18	P.O.L. > 1.0 l/hr
5	5.53	8.43	1.98*	30.5	0.13	P.O.L. > 1.0 l/hr

* Case 5 has PoD = 0.90.

Table 6-2

Catawba-1 SLB Leakage for S/G C With Constant Leak Rate: Bobbin Indications Confirmed by RPC or Not RPC Tested

		P.O.L. for Leakage > 0.0 l/hr		P.O.L. for Leakage > 1.0 l/hr	
E.O.C. Volts	Number of Indications	Probability of Leakage	No. of Leaking Indications	Probability of Leakage	No. of Leaking Indications
0.55	170				
0.65	141				
0.75	111				
0.85	84				
0.95	60				
1.05	42				
1.15	28				
1.25	17				
1.35	10				
1.45	6				
1.55	4				
1.65	2				
1.75	2				
1.85	1				
1.95	1				
2.2	1				
2.3	1				
			2.51		0.71

a,e

Case	Leak Rate per Leaking Indication Qu		No. of Leaking Indications ÷ PoD = 0.6	Leak Rate (l/hr)	Leak Rate (gpm)	
ΔP = 2560 psi						
1	30.8	54.0	4.18	261.5	1.15	P.O.L. > 0
2	7.53	10.3	4.18	66.1	0.29	P.O.L. > 0
3	30.8	54.0	1.18	132.8	0.58	P.O.L. > 1.0 l/hr
4	7.53	10.3	1.18	27.3	0.12	P.O.L. > 1.0 l/hr
ΔP = 2335 psi						
1	19.1	27.1	4.18	171.0	0.75	P.O.L. > 0
2	5.53	8.43	4.18	51.5	0.23	P.O.L. > 0
3	19.1	27.1	1.18	71.0	0.31	P.O.L. > 1.0 l/hr
4	5.53	8.43	1.18	21.6	0.10	P.O.L. > 1.0 l/hr
5	5.53	8.43	0.79*	16.6	0.073	P.O.L. > 1.0 l/hr

* Case 5 has PoD = 0.90.

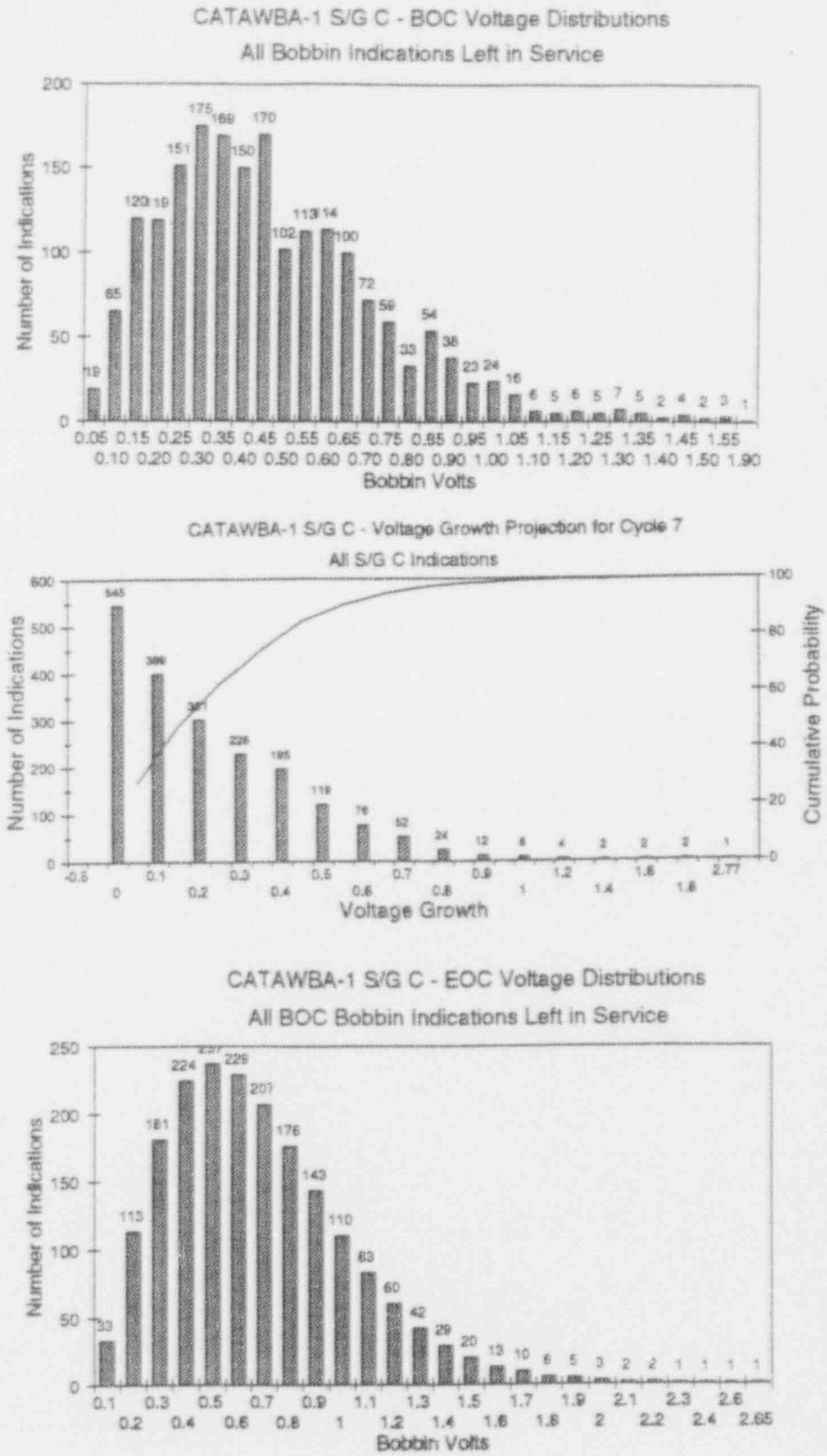


Figure 6-1. Steam Generator C BOC and EOC Voltage Distributions for All BOC Bobbin Indications Left in Service

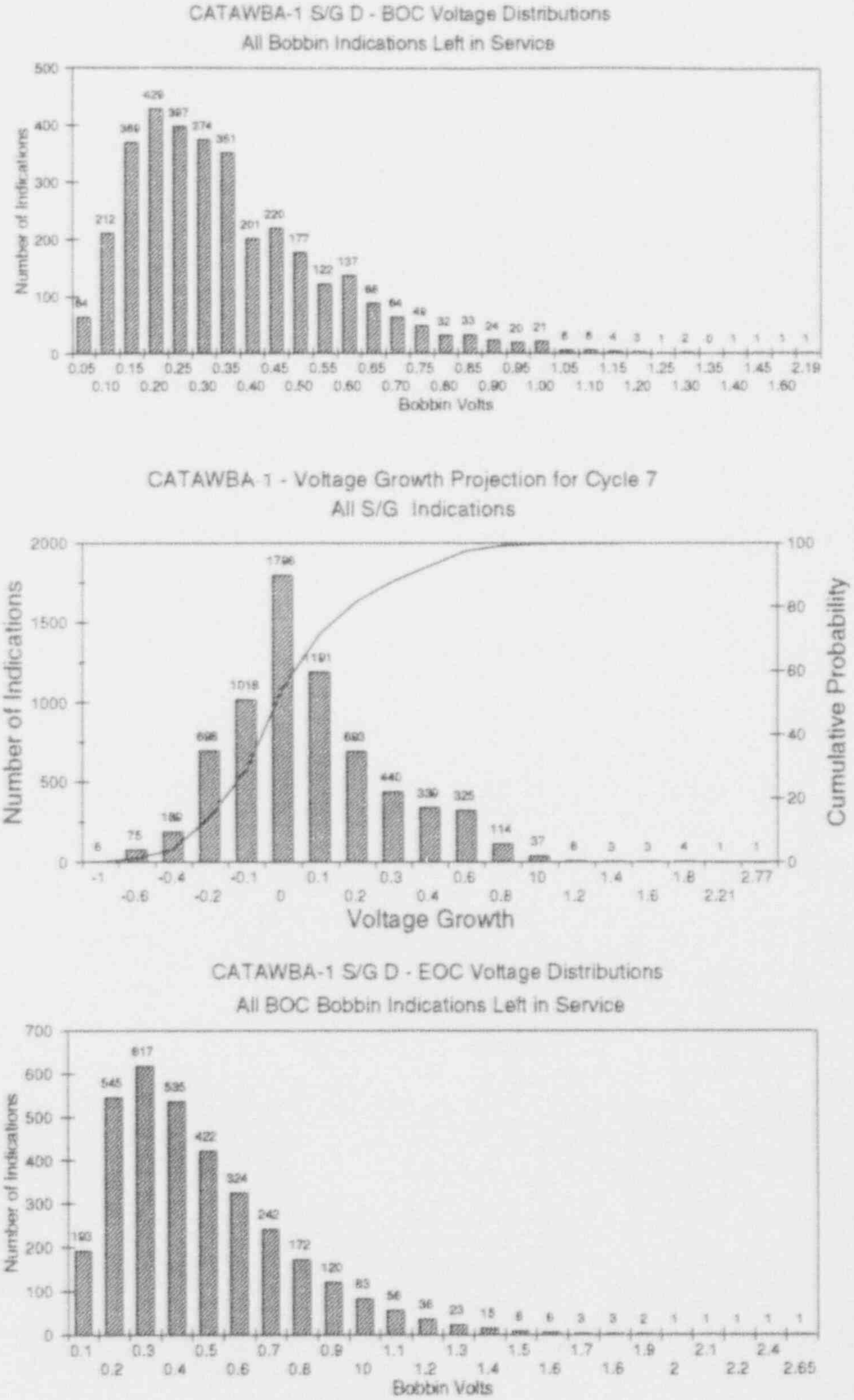


Figure 6-2. Steam Generator D BOC and EOC Voltage Distributions for All BOC Bobbin Indications Left in Service

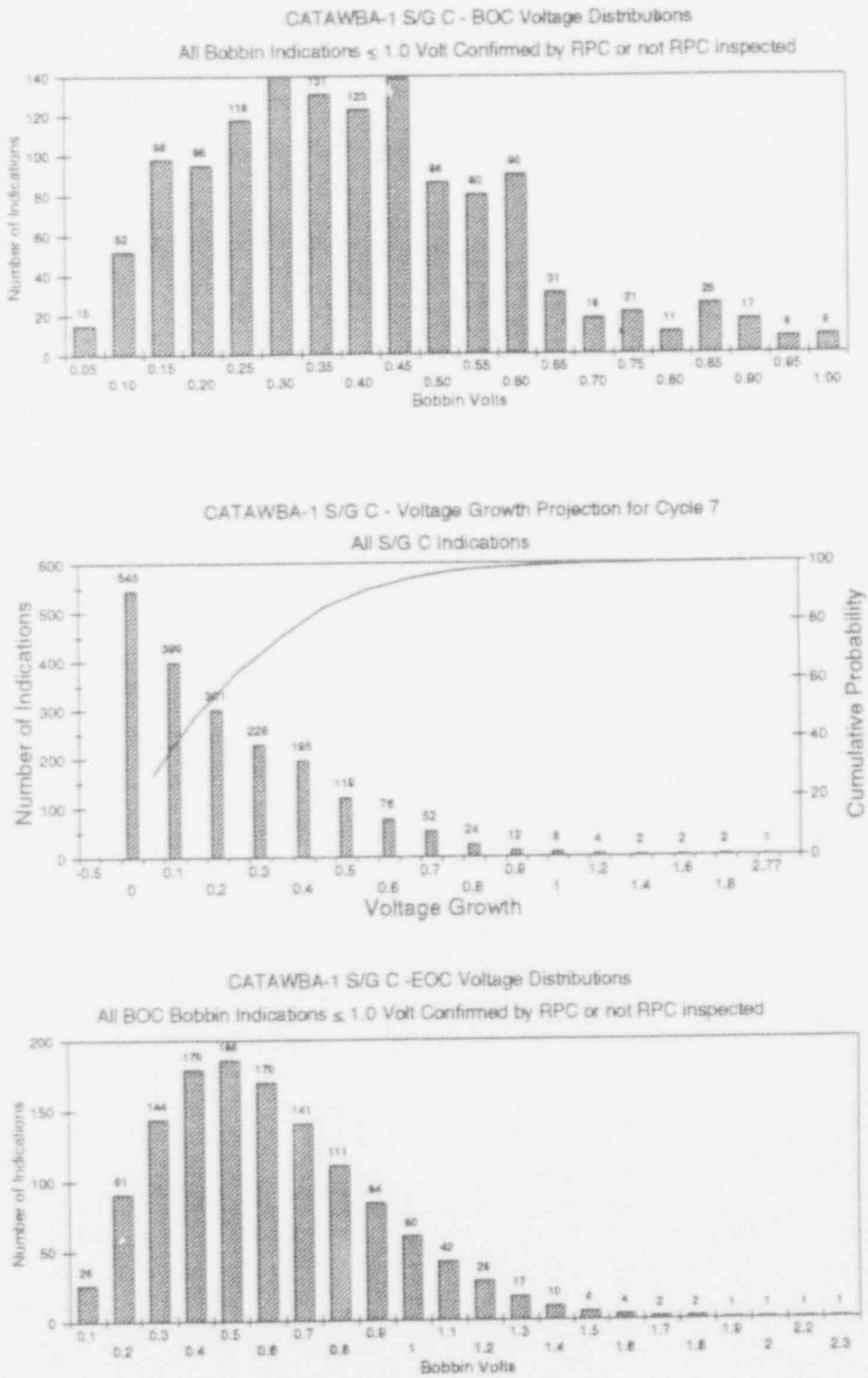


Figure 6-3. Steam Generator C BOC and EOC Voltage Distributions for BOC Bobbin Indications ≤1.0 Volt Confirmed by RPC or Not RPC Inspected

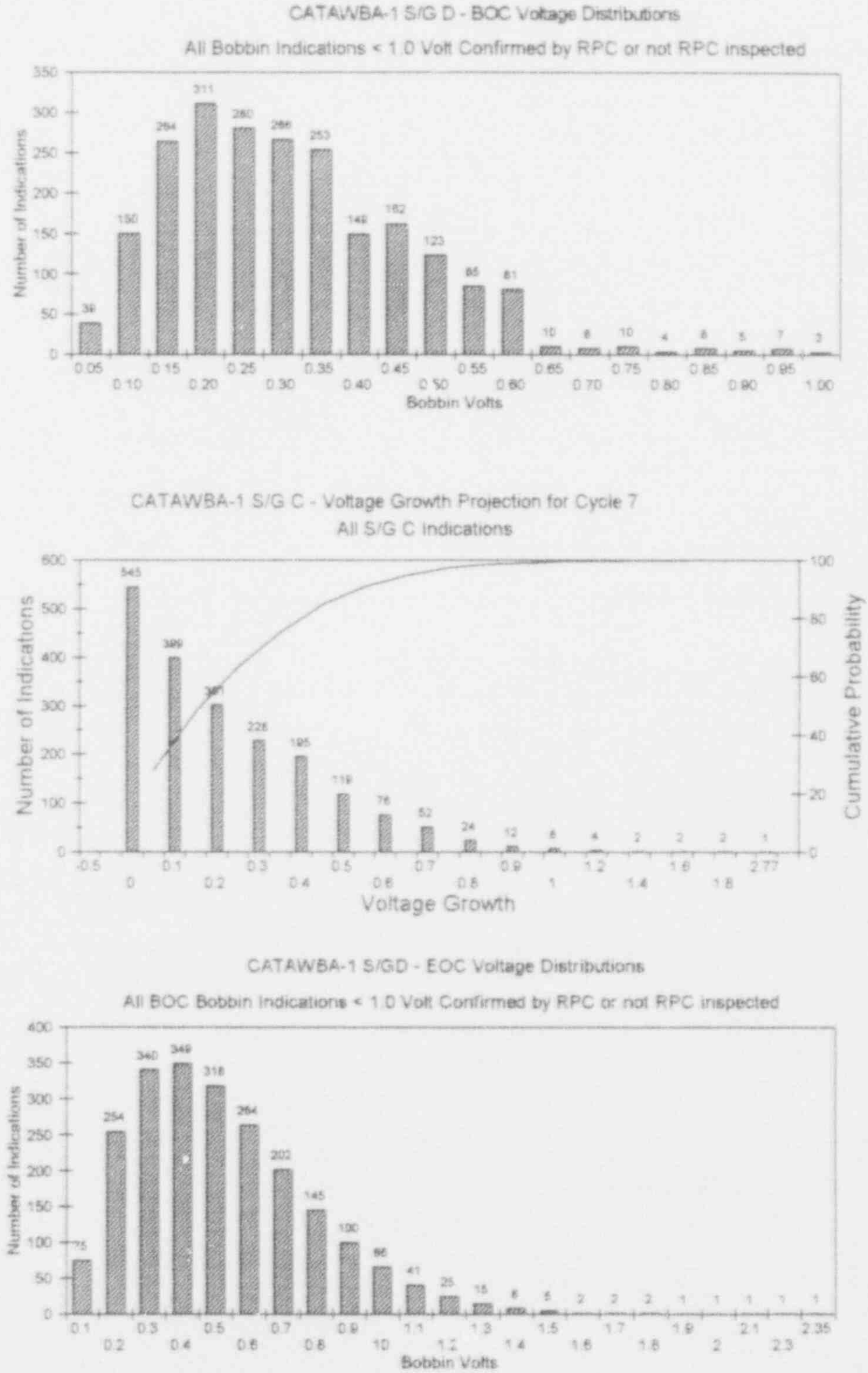


Figure 6-4. Steam Generator D BOC and EOC Voltage Distributions fo BOC Bobbin Indications < 1.0 Volt Confirmed by RPC or Not RPC Inspected

Figure 6-5.

CATAWBA-1 S/G D - Voltage Growth Projection for Cycle 7

RPC Confirmed and Bobbin not RPC Inspected