WEC PROPRIETARY CLASS 3

Westinghouse Energy Systems

WESTINGHOUSE CLASS 3

WCAP-13238

SG-92-03-009

Preliminary Data on Voltage/Burst/Leakage of 3/4 Inch Diameter Tubing for ODSCC at TSPs

March, 1992

Approved by: [signature]

M. J. Wootten, Manager
Steam Generator Technology & Engineering

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

This report describes the preliminary results from the testing of 0.75 inch specimens for tube burst strength and leak rate. This experimental work, which is continuing, was performed to support the development of tube repair limits based on bobbin voltage amplitudes of indications for outside diameter stress corrosion cracking (ODSCC) of steam generator tubes at support plate locations. Development of tube repair limits for 0.875 inch diameter tubing has been discussed elsewhere, including Reference 1. Reference 1 also discussed in detail the tests performed for the 7/8 inch tubing. The same test procedures were used in the testing of 3/4 inch specimens described in this report. Therefore, no attempt is made here to repeat the more detailed test descriptions. The emphasis is placed on reporting the preliminary results of 3/4 inch test data.

An attempt is made to assess whether the 3/4 inch data can be scaled to merge with the 7/8 inch data using theoretical considerations as well as an empirical treatment. The reference 3/4 inch voltage normalization is based on scaling considerations between tube diameters. Additional adjustments to the 3/4 inch data are necessary for comparisons with 7/8 inch data. The theoretical or first principle comparison is based on adjusting bobbin amplitudes to obtain approximately equal voltages for equal crack lengths combined with well established non-dimensional correlations of burst pressures. It is found that these first principle adjustments result in differences in the mean fits to the data for the two tube sizes. An additional comparison of the 3/4 and 7/8 inch data is then made based on adjusting the 3/4 inch voltages to obtain approximately the same mean fit as the 7/8 inch data.

The overall trends (burst strength vs. bobbin voltage and leak rate vs. bobbin voltage) of the two sets of data (3/4 inch and 7/8 inch) are substantially similar. However, based on the limited work described herein, the 3/4 inch data may belong to a separate population than the 7/8 inch diameter data; i.e., different correlations may be applicable to the two data sets. Additional data and evaluation are required to finalize a position on separate or combined correlations for the 3/4 inch data.

2. MODEL BOILER SPECIMEN PREPARATION

Cracked tube specimens were produced in the Forest Hills Single Tube Model Boiler test facility. The facility consisted of thirteen pressure vessels in which a forced flow primary system transfers heat to a natural circulation secondary system. Appropriate test specimens were placed around a single heat transfer tube to simulate steam generator tube support plates. The tests were conducted in two boiler configurations, shown schematically in Figures 1 and 2. The majority of the tests were conducted in the vertically oriented boilers shown in Figure 1, in which four support plates were typically mounted on the tube. A few tests were conducted in horizontally mounted boilers, shown in Figure 2. Because there was no steam space in these boilers, seven support plates can be mounted on the heat transfer tube. Since capillary forces, rather than gravity forces, dictate the flow pattern in packed tube support plate crevices, the tube orientation should have little effect on the kinetics of the corrosion processes.

The thermal-hydraulic specifications utilized in the test are presented in Table 1. As indicated, the temperatures are representative of those found in PWR steam generators, and the heat flux is typical of that found on the hot leg side of the steam generator.

The cracks were produced in what is termed the reference cracking chemistry, consisting of either 600 ppb (1X) or 6 ppm (10X) sodium as sodium carbonate in the makeup tank. Typically a test was initiated with the 1X chemistry, and if a through wall leak was not identified after 30 days of operation, the 10X chemistry was applied. The occurrence of primary to secondary leakage was determined by monitoring the boilers for lithium, which would ordinarily only be present in the primary system. Because of hideout in the crevices, the boiler sodium concentration was typically between 50 and 75% of the makeup tank concentration. Hydrazine and ammonia were also added to the makeup tanks for oxygen and pH control, respectively.

The tests utilized 3/4 inch (1.9 cm) O.D. mill annealed Alloy 600 tubing from heat NX7368. The tubing was manufactured by the Plymouth Tubing Co. to Westinghouse specifications.

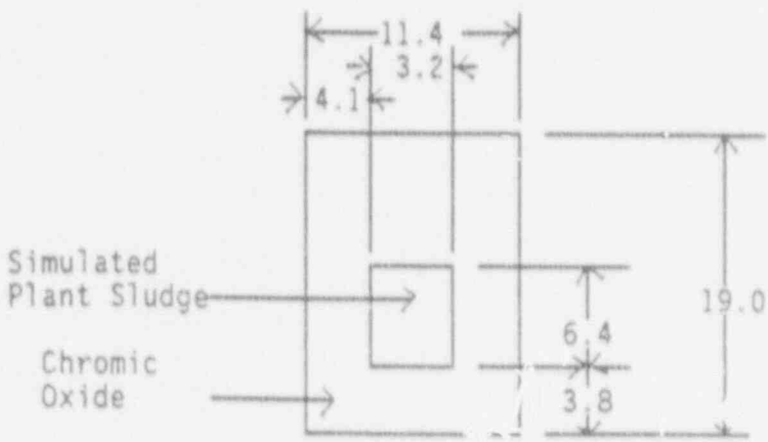
A summary of the test pieces which were subsequently leak and burst tested are presented in Table 2. Two groups of tests are listed; the EPRI test pieces were provided under the auspices of an EPRI program, while the Spanish test pieces were fabricated for a group of Spanish utilities Permission from the utilities has been obtained to use the results of these tests in other applications. The only difference between the two groups of tests is that the crevices were

packed with different sludge formulations. The EPRI tests were performed with what is termed simulated plant sludge, which has been used in most previous model boiler test programs, while the Spanish tests used a formulation more representative of that typically found in Spanish steam generators. As indicated in the following table, the only difference between the two formulations is that magnetite has replaced the metallic copper content in the simulated plant sludge.

	Weight %	
Constituent	Simulated Plant Sludge	Spanish Sludge
Magnetite	59.7	92.2
Copper	32.5	
Cupric Oxide	4.5	4.5
Nickel Oxide	2.1	2.1
Chromic Oxide	1.2	1.2

As outlined in Table 2, three means of packing the tube support plate crevices were utilized. In the fritted configuration, loose sludge was vibratorily packed into the crevice and then held in place with Alloy 600 porous frits placed over both ends of the crevice. In this configuration, cracks were typically produced near the interface between the sludge and the frits. In some cases, multiple cracks were produced at both ends of the crevice.

The dual consolidated configuration consisted of two sludge regions, in which the outer region contained chromic oxide, while the inner region contained either simulated plant or Spanish sludge. The regions had the following design, with the dimensions given in millimeters:



The two-region sludge configuration was specified in order to limit cracking to the small inner region, containing an oxidizing sludge. Chromic oxide is nonoxidizing, and previous testing had found that accelerated corrosion does not occur in its presence. The outer region provided thermal insulation for the inner region, so that the temperature in the inner region was sufficiently high to produce accelerated corrosion. The two sludge regions were baked onto the tube using a mixture consisting of 5% sodium hydroxide, 2.5% sodium sulfate, and 0.8% sodium silicate. The support plates were then mounted on the tube over the sludge and held in place with externally mounted set screws. Since corrosion should be confined to the inner region, this configuration was intended to produce short, individual cracks.

The mechanically consolidated sludge configuration was fabricated by mechanically compacting sludge within a tube support plate simulant, drilling a hole in the sludge for the tube, and then sliding the tube through the hole until positioned properly. This configuration was used because relatively low voltage indications had been produced in previous tests having this configuration.

As indicated in Table 2, there was considerable variation in the time taken for a crack to be produced in a given test piece. In general, cracking was produced in shorter time spans with this heat of material than for the heats used in similar tests performed with 7/8 inch diameter tubes. Cracks were typically produced most rapidly with the fritted configuration and most slowly with the dual consolidated configuration, although a few cracks were produced very quickly with the dual consolidated configuration.

3. NDE MEASUREMENTS

Bobbin coil tests were performed on the specimens prior to leak rate and burst testing. The bobbin probe with a 0.620 inch diameter was used and the results reported in this report is based on the differential mix frequency of 550/130 kHz. Selection of this probe and frequency mix is related to the 0.720 inch probe and 400/100 kHz frequency used for the testing of 7/8 inch diameter tubing and the following considerations.

To a first approximation, bobbin probe voltages for different tubing sizes would be equal for scaled flaw sizes if:

1. The tubes are geometrically similar, that is, all linear dimensions are scaled by the same factor. This applies for the 3/4 inch and 7/8 inch diameter tubes.

2. Respective eddy current dimensions are scaled by the same scale factor. This applies for the 0.720 inch and 0.620 inch probe diameters used in this report.

3. The probe excitation frequency is inversely proportional to the square of the tubing thickness. This applies for the 550/130 kHz and 400/100 kHz frequencies used in this report.

Thus the bobbin coil dimensions and test specifications were intended to yield similar responses for the 3/4 inch diameter tubing as in the 7/8 inch tubing. Bobbin voltages were normalized to 4.0 volts for the four, 20% deep holes in the ASME calibration standard.

In addition to bobbin coil testing, RPC (rotating pancake coil) tests were also performed on the laboratory specimens. The RPC voltages were obtained at 550 kHz based on normalization to 20 volts for a 0.5 inch, through-wall EDM (electric discharge machining) slot.

The results of the NDE measurements for the 3/4 inch diameter model boiler specimens are summarized in Table 3.

4. LEAK RATE AND BURST TESTING

The procedures applied for leak rate measurements and burst testing of 3/4 inch diameter tubing were the same as applied for 7/8 inch diameter tubing. These procedures are described in prior reports dealing with 7/8 inch diameter tubing. Leak rate measurements were performed at normal operating and SLB pressure differentials. The results for the leak rate and burst pressure tests for the 3/4 inch diameter model boiler specimens are given in Table 4.

5. BURST AND LEAK RATE CORRELATIONS FOR 3/4 INCH DATA

5.1 Burst Pressure Correlation

The model boiler and pulled tube burst pressure data available for 3/4 inch diameter tubing is plotted in Figure 3 as a function of bobbin coil voltage. The overall trend of the burst pressure vs bobbin coil data is quite similar to the comparable plot for the 7/8 inch diameter tubing (see Figure 4). It was judged that a linear equation on the semilog plot will adequately fit the available 3/4 inch data. Therefore a linear regression analysis between burst pressure and log of the bobbin voltage was performed. The resulting linear equation for the mean curve is:

[ ]g

where BP is the burst pressure in ksi and v is the bobbin voltage (550/130 kHz differential mix). The coefficient of correlation for this regression fit is 0.73 and the error of the BP estimate is 1.326. The linear fit is plotted in Figure 3 as a straight line.

5.2 SLB Leak Rate Correlation

The leak rate data for the 3/4 inch diameter model boiler specimens under steam line break pressure differential are plotted as a function of bobbin voltage in Figure 5. A similar plot for the 7/8 inch diameter tubing (model boiler and pulled tubes) data is shown in Figure 6. It is observed that the overall trend with voltage is quite similar. Therefore a correlation similar to the 7/8 inch data was developed for the 3/4 inch leak rate results.

Linear regression analysis of the logarithms of the data results in the following mean leakage rate correlation where Q is the SLB leak rate in l/hr and v is the bobbin voltage (550/130 kHz differential mix):

[ ]g

The coefficient of correlation for this regression fit is 0.64 and the error of the estimate is 1.165. The regression fit is also shown in Figure 5.

6. THEORETICAL SCALING OF 3/4 INCH RESULTS FOR COMPARISONS WITH 7/8 INCH DATA

As noted in Section 5, there is considerable similarity between the 3/4 inch and 7/8 inch tube data. Figure 7 shows the 3/4 inch and 7/8 inch burst pressure data on the same plot, without applying any scaling factors to either set. It is clear that, despite the similar trends, the data appear to come from two different populations. The same conclusion is derived from a review of the leak rate data (see Figure 8).

It is desirable to scale one set of data to assess whether or not the two data sets may be combined and the entire data base represented by a given correlation for tube burst and another for leak rate. By having a larger number of "observations," the uncertainty in the correlation will be reduced. However, in order to perform the scaling appropriately, a scaling factor has to be developed. In addition to improving the fit of the correlation to the data, the scaling factor should have a sound (theoretical) basis. An attempt at such scaling is made here. This work is considered quite preliminary and the results indicate that additional development is needed. It is discussed here merely to present the current status of this task, rather than to derive any conclusions.

As discussed in Section 3, selection of the bobbin coil probe and test specifications were intended to provide similar results for comparable cracks in 3/4 inch and 7/8 inch diameter tubes. The principal difficulty in comparing the 3/4 inch and 7/8 inch results is developing the appropriate adjustments to the bobbin voltages, leak rates and burst pressures to permit direct comparisons of the data for the two tubing sizes. The tubing sizes are geometrically similar in that the wall thicknesses (0.050 inch for 7/8 inch tubing, 0.043 inch for 3/4 inch tubing) are proportional to the tube diameters. However, adjustments in addition to appropriate scaling are required to directly compare the two tubing sizes. The approach applied is as follows:

- Eddy current probe diameters (0.720 inch, 0.620 inch) are scaled by the tube diameters. However conventional bobbin coil width and spacing are not scaled.

- Eddy current inspection frequencies (400/100 kHz, 550/130 kHz) are appropriately scaled as inversely proportional to the square of the tubing thickness.

A limitation on theoretical scaling of bobbin coil voltage responses results from the fact that, although probe diameters are scaled, the conventional bobbin probes do not scale coil width and coil spacing. In addition, ASME calibration standards for the 20% depth flaw in 3/4 inch and 7/8 inch tubing have the same 0.187 inch hole diameter. Consequently, conventional eddy current practices would not be expected to yield exact scaling. To obtain the same voltage for equal crack lengths in 3/4 inch and 7/8 inch tubing, the 3/4 inch voltages would be expected to increase by the diameter ratio of 1.17 if voltage is assumed to be linear with crack length over the range of interest of ~0.2 to 0.7 inch long cracks. An empirical factor of 1.25 is found for the model boiler specimens as discussed below.

Using an empirically derived scaling factor for the bobbin voltages of 0.875 inch and 0.750 inch diameter tubes having through wall cracks of the same length, voltage normalization procedures are described in the following paragraphs to permit the scaling of bobbin voltage-leak rate and bobbin voltage-burst pressure data between 0.750 inch and 0.875 inch diameter tubing.

The bobbin voltages of model boiler specimens with ODSCC at simulated tube support plate intersections were determined using standard, well calibrated procedures as described in Section 3. Following leak rate tests at normal operating and steam line break conditions, burst tests were performed at room temperature. After burst testing, the fracture surfaces were examined at a magnification of 20X. The average lengths of the outer diameter stress corrosion cracks were measured. Figure 9 shows a plot of bobbin voltage versus axial crack length. Most, but not all, of the tubes had through wall cracks. At a given crack length of the dominant crack in the tube, very high voltages are measured when multiple axial cracks are distributed around the circumference of the tube. Conversely, when cracking is only partially through the wall or when ligaments exist between coplanar axial cracks, the measured bobbin voltages form the low side of the scatterband at a given crack length.

If only tubes with essentially single, through wall, axial cracks without ligaments are considered, then the relationship between bobbin voltage and crack length can be determined empirically as a function of tube size. Recall that apriori considerations indicate that bobbin voltage versus crack length correlations for 0.875 inch and 0.750 inch diameter tubes should be nearly the same allowing for a scaling factor of about 1.17. Figure 10 shows that the bobbin voltage (volts) of a 0.875 inch diameter tube is 31.9 times the crack length (inches). Figure 11 shows that for a 0.750 inch diameter tube this slope is 25.5. Hence, at a given crack length,

the bobbin voltage of the 0.750 inch diameter tube will be less than that of a 0.875 inch diameter tube as given by:

$$\frac{V_{.875}}{V_{.750}} = \frac{31.9}{25.5} * \frac{L_{.875}}{L_{.750}} = 1.252 * \frac{L_{.875}}{L_{.750}}$$

Thus, if the bobbin voltage of a crack in a 0.750 inch diameter tube measures x, then the voltage of this same crack in a 0.875 inch tube will measure 1.252 times x. With this basis, bobbin voltage-leak rate and bobbin voltage-burst pressure correlations are scaled between tubing sizes as follows.

Experimental leak rate measurements on 0.875 inch and 0.750 inch diameter steam generator tubes containing through wall, sharp fatigue cracks show that leak rate versus crack length curves are similar but not identical. A leak rate calculational model, benchmarked with experimental data, shows that leak rates for 0.750 inch tubing are lower than for 0.875 inch tubing at the same crack length by 10 to 25%. In the range of crack sizes of interest, this effect can be accounted for by adjusting 0.750 inch leak rates by a factor of 0.9. To compare bobbin voltage versus leak rate correlations on the same basis, the bobbin voltages of the 0.750 inch tubes should be multiplied by a factor of 1.252 to match respective crack lengths. Figure 8 shows steam line break leak rates versus bobbin voltage without any normalization factors while Figure 12 shows that normalization to the 0.875 inch diameter size brings the respective scatterbands into reasonable agreement.

Theoretical and experimental studies show that, for ductile tubes with through wall, axial cracks, the normalized hoop stress at burst is a function of the normalized crack length, lamda = $L/(R^*t)^{.5}$, where L is the crack length, R is the mean tube radius and t is the wall thickness. At equal values of lamda, the hoop stress at burst divided by the sum of the yield and ultimate strength will be the same for different sizes of tubing. For both 0.875 inch and 0.750 inch diameter tubes, bobbin voltage is essentially directly proportional to crack length over the range of interest. Hence equal values of lamda for the same burst pressure can be converted to equivalent values of bobbin voltage for the same burst pressure.

For equal lamda,

$$\frac{L_{.875}}{L_{.750}} = \frac{1}{1.25} \cdot \frac{V_{.875}}{V_{.750}} = \frac{(R \cdot t)^{.5}_{.875}}{(R \cdot t)^{.5}_{.750}} = 1.17$$

$$V_{.875} = 1.25 \cdot 1.17 \cdot V_{.750} = 1.46 \cdot V_{.750}$$

Thus, to convert the bobbin voltage of a 0.750 inch tube to an equivalent bobbin voltage of a 0.875 inch diameter tube with the same burst pressure, the conversion factor is 1.46. Figure 7 illustrates a plot of burst pressure versus bobbin voltage for the two tubing sizes without any normalization factors. Figure 13 shows the burst pressure normalized to a yield and ultimate strength total of 147 ksi and the bobbin voltage normalized to a 0.875 inch diameter tube using the 1.46 factor on the 0.750 inch data. The normalization approach can be used to combine data on different tubing sizes and perform appropriate statistical analyses on this larger combined database.

A comment on apparent outliers in burst and leak rate correlations is worthy of consideration. It is clear that single dominant cracks essentially determine leak and burst properties. Multiple cracking can lead to very high voltages compared to a single crack and thus lead to the non conservative edges of the respective scatterbands of leak rates and burst pressures. Ligaments beneath partial through wall cracks and ligaments between coplanar through wall cracks decrease bobbin voltages relative to the no ligament case. The presence of such ligaments is considered to be responsible for the conservative edges of leak rate and burst pressure scatterbands when ligament sizes are in a very narrow range. For example, any substantial ligament will decrease the leak rate and increase the burst pressure while leading to a lower voltage. The net effect in this case leads to another point in the body of the scatterband. Very small ligaments will mechanically fracture due to normal operating pressure differentials. Conservative side outliers are produced by ligaments in a narrow size range which decrease the voltage while not significantly increasing the burst pressure relative to the no ligament case. For leakage, the voltage reducing ligaments must fracture at steam line break conditions but not at normal operating conditions to produce an outlier effect.

The above development provides a procedure based on equal voltates for equal crack lengths to compare the 3/4 inch and 7/8 inch data. An alternate procedure for comparing the data based on adjusting the 3/4 inch data to make the mean fits to the two sets of data approximately equal is given in Section 8. Table 5 provides the 3/4 inch data including the adjusted volts, SLB leak rates and burst pressures. The Table 5 data are used below to perform statistical analyses of the combined data base.

7. CORRELATIONS FOR THE COMBINED 3/4 INCH AND 7/8 INCH DATABASE

7.1 Burst Pressure Correlation

The adjusted 3/4 inch voltages and burst pressures from Table 5 are combined with the 7/8 data (from Figure 4) in Figure 13. A linear regression fit to this entire data base results in the following correlation between burst pressure (BP in ksi) and bobbin voltage (v in volts):

[ ]g

The coefficient of correlation for this regression fit is 0.88 and the error of the BP estimate is 1.083. The linear fit is plotted in Figure 14 as a straight line.

The lower 95% confidence interval adjusted for lower tolerance limit strength properties (LTL) at operating temperature for the combined data leads to 4.55 volts at 3ΔP and 22.1 volts at SLB burst pressure. These values are compared to 6.2 and 28.9 volts, respectively, for the 7/8 inch data only. Thus the 3/4 inch data tend to lower the burst pressure limits compared to the 7/8 inch data only. In part, this is due to the lower mean fit for the 3/4 inch data as discussed in Section 8.

The destructive examinations of the 3/4 inch tubes with the lower burst pressure values tend to indicate small ligaments that could reduce voltages but not contribute significantly to the burst pressure. Even though there are more 7/8 inch model boiler burst tests than obtained for 3/4 inch specimens, the comparable voltage burst pressure data points have not been found in the 7/8 inch data base.

7.2 SLB Leak Rate Correlation

The adjusted 3/4 inch voltages and SLB leak rates from Table 5 are combined with the 7/8 inch data (from Figure 6) in Figure 12. The following correlation between SLB leak rate (Q in l/hr) and bobbin voltage (v in volts) is developed for the combined database:

[ ]g

The coefficient of correlation for this regression fit is 0.72 and the error of the estimate is 1.439. The regression fit is shown in Figure 15 as a straight line.

Thus combining the 3/4 inch and 7/8 inch data tends to increase the SLB leakage at a given bobbin voltage compared to the 7/8 inch data alone. Similarly, the upper 95% confidence band is also increased.

8. CORRELATIONS FOR THE COMBINED 3/4 AND 7/8 INCH DATA BASED ON APPROXIMATELY EQUAL MEAN FIT

The theoretical approach described in Section 6 and the resulting correlations developed in Section 7 do not fully resolve the differences in the fit of the burst pressure and leak rate correlations with bobbin voltage. It may be that the difference cannot be fully resolved. However, a more rudimentary alternate approach is applied in this section to investigate the feasibility of resolving these differences.

The basic premise in this approach is that the voltages (from the 3/4 inch specimens) can be scaled using a multiplicative factor such that the combined data (both 3/4 inch and 7/8 inch) can then be represented by a single correlation with the scaled bobbin voltage as the independent parameter.

8.1 Burst Pressure Correlation

Applying this approach to the burst pressure data, a factor was developed on bobbin voltage to obtain nearly the same values of regression analysis coefficients as obtained for the 7/8 inch data only. The scaling on burst pressure is described in Section 6. The resulting factor of 2.4 was applied to the bobbin amplitudes of 3/4 inch diameter tubes. The combined database after application of the factor is plotted in Figure 16. A linear regression analysis is performed to result in the following correlation:

[ ]g

The coefficient of correlation for this regression fit is 0.88 and the error of the BP estimate is 1.061. The linear fit is plotted in Figure 16 as a straight line.

The lower 95% confidence interval (LTL) for the combined data leads to 5.4 volts at 3 ΔP and 28.0 volts at SLB burst pressure. These values are compared to 6.2 and 28.9 volts, respectively, for the 7/8 inch data only. In this case, the lower confidence limits are lowered for the combined data compared to 7/8 inch only near the 3 ΔP limit with negligible change at the SLB pressure differential.

9. COMPARISON OF CORRELATIONS

9.1 Burst Pressure Correlations

Correlations have been developed for the 3/4 inch and 7/8 inch diameter individually. The correlations express the burst pressure (BP, in ksi) as a function of log of the bobbin amplitude (v in volts). A linear fit was developed for the 3/4 inch data (Section 5) and for the 7/8 inch data (see Figures 3 and 4). The 3/4 inch data was scaled using a theoretical approach and a correlation developed for the resulting combined (3/4 and 7/8 inch) database in Section 7. Further, in Section 8, an empirical approach was used by applying an adjustment factor to the 3/4 inch data to yield an "approximately equal mean fit." The resulting combined, adjusted database yielded another resulting correlation between burst pressure and bobbin voltage.

Table 6 provides the linear regression analysis parameters for the leak rate and burst pressure correlations. It may be observed that the 3/4" data (unscaled) evaluated individually has significantly different linear regression analysis parameters than the 7/8" data. When the 3/4" data is scaled in the manner described in Section 6 and combined with the 7/8" data, however, the linear regression analysis parameters are comparable to the parameters for the 7/8" data, alone. In fact the data spread (reflected in the "Error of BP") is also similar (1.01 vs. 1.08). Thus, the statistical analysis methodology used to develop the prediction intervals for the 7/8" data is confirmed to be consistent with the additional 3/4" scaled data.

An alternate adjustment of the bobbin voltages for the 3/4 inch specimens by a factor 2.4 was made to compare the 3/4 inch and 7/8 inch data as described in Section 8. This adjustment method results in essentially the same mean fit parameters while slightly increasing the data spread ("Error of BP") from 1.01 for 7/8 inch to 1.06 for the combined data. At the lower 95% confidence interval, the voltage at 3ΔP structural limit decreases from 6.2 to 5.4 volts for the combined data while the voltage for the SLB pressure differential is negligibly different for the two cases.

9.2 Leak Rate Correlations

In the case of the SLB leak rate, the empirical approach of obtaining an "approximately equal mean fit" has not yet been applied. The correlation from the combined database is available only

for the methodology applying theoretical scaling as discussed in Section 6.

The linear regression analysis parameters for the leak rate correlations are provided in Table 6. As for the burst pressure correlations, it may be noted that the 3/4" data (unscaled) evaluated individually has significantly different linear regression analysis parameters than the 7/8" data. When the 3/4" data is scaled and combined with the 7/8" data, however, the linear regression analysis parameters are quite comparable to the parameters for the 7/8" data, alone. In fact the data spread (reflected in the "Error of Q") is almost identical. Thus, the statistical analysis methodology used to develop the prediction intervals for the 7/8" data is confirmed to be consistent with the additional 3/4" scaled data.

10. PRELIMINARY CONCLUSIONS

The 3/4 inch and 7/8 inch data show very similar trends for voltage versus burst pressure and SLB leakage correlations. However, voltage normalizations based on current eddy current practice (Section 3) lead to significant differences in the correlation parameters. To provide comparisons of the two data sets, the 3/4 inch voltages were scaled on a theoretical basis (approximately equal voltages for equal crack lengths) and an empirical basis (approximately equal mean fits) as summarized below.

At the present time, there is insufficient 3/4 inch data to fully evaluate the feasibility of merging the 3/4 inch and 7/8 inch data into a combined data base. The theoretical scaling of the 3/4 inch data, as described in Sections 6 and 7, does not adequately merge the means of the 3/4 inch and 7/8 inch data sets. For this reason, the theoretical scaling methods applied do not appear to be an acceptable basis for combining the data for a voltage/burst correlation applicable to either or both tube sizes.

In the case of the burst pressure correlation, the 3/4 inch and 7/8 inch data were also merged by normalizing the 3/4 inch data to obtain approximately equal mean fits for both tube sizes. This approach might be considered to be arbitrary as there is no theoretical basis to support this approach. This approach requires that the 3/4 inch voltages be increased by a factor of 2.4 compared to the factor of 1.46 for theoretical scaling. Pending availability of additional 3/4 inch data and evaluation of associated adjustment factors for the 3/4 inch data, the equal mean fit is judged to be more appropriate than the theoretical basis for comparing the combined data with the 7/8 inch data set.

The equal mean fit approach for the combined data reduces the voltage at a 3ΔP burst pressure of 4380 psi from 6.2 volts for the 7/8 inch data to 5.4 volts for the combined data while the voltage at SLB burst pressure is essentially unchanged (28.0 vs 28.9 volts). The influence of the combined data on tube repair limits requires a reduction of the voltage at 3ΔP for NDE uncertainty and crack growth allowances. These allowances are typically about 16% and 35%, respectively (although values of 20% and 50% have been applied conservatively). Reducing the 3 ΔP voltage limit by a factor of 1.51 for the NDE and growth allowances would lead to a tube repair limit of about 3.6 volts for the combined data compared to about 4.1 volts for the 7/8 inch data only. Applying the conservative 70% allowance and using the burst correlation with

7/8 inch data alone, the 3ΔP voltage of 6.2 volts yields a tube repair limit of 3.6 volts as developed in Reference 1. Thus the conservatism of combining the 3/4 inch and 7/8 inch data has the same effect on tube repair limits as conservatively increasing NDE and growth allowances from 51% to 70%.

At the present time, no firm conclusion can be drawn as to whether the 3/4 inch and 7/8 inch data should be evaluated separately or combined. Further data collection and a more extensive review, such as by the EPRI ad hoc committee for tube repair criteria, is required to establish the basis for 3/4 inch data evaluation.

11 REFERENCES

1. "J. M. Farley Units 1 and 2 SG Tube Plugging Criteria for ODSCC at Tube Support Plates," WCAP-12871, Revision 2, Westinghouse Electric Corporation, Proprietary Class 2, February, 1992.

Table 1

THERMAL AND HYDRAULIC SPECIFICATIONS

Primary loop temperature	327°C (620°F)
Primary loop pressure	13.8 MPa (2000 psi)
Primary boiler inlet temperature	324°C ± 3°C (615°F ± 5°F)
Primary boiler outlet temperature	313°C ± 3°C (595°F ± 5°F)
Secondary T_{sat} at 6.1 MPa (900 psi)	278°C ± 3°C (532°F ± 5°F)
Steam bleed	0.1 - 0.2 l/day
Blowdown	8 cm^3/min (continuous)
Nominal heat flux	16.28 x 10^4 kcal/m^2-hr (60,000 Btu/ft^2-hr)

Table 2

TEST SPECIMEN SUMMARY

SPEC. ID	GROUP	CREVICE CONFIGURATION	DAYS IN TEST
590-1	EPRI	Frit	8
591-1	EPRI	Frit	8
590-2	EPRI	Frit	15
590-3	EPRI	Frit	15
591-2	EPRI	Frit	10
591-4	EPRI	Frit	10
596-3	EPRI	Dual Cons.	5
590-4	EPRI	Frit	19
591-3	EPRI	Frit	21
596-2	EPRI	Dual Cons.	10
595-1	EPRI	Dual Cons.	30
598-1	EPRI	Mech. Cons.	27
598-2	EPRI	Mech. Cons.	27
598-3	EPRI	Mech. Cons.	27
594-1	EPRI	Dual Cons.	85
604-2	EPRI	Frit	7
600-1	SPNSH	Dual Cons.	10
600-2	SPNSH	Dual Cons.	14
600-3	SPNSH	Dual Cons.	38
601-1	SPNSH	Frit	12
601-2	SPNSH	Frit	12
601-3	SPNSH	Frit	17
601-4	SPNSH	Frit	17
601-5	SPNSH	Frit	17
601-6	SPNSH	Frit	17

Table 3

NDE Results for 3/4-Inch Diameter Model Boiler Specimens

No.	Model Boiler Spec. No.	Bobbin Coil Volts	Bobbin Coil % Depth	RPC Volts	RPC No. of Cracks
1	590-1				
2	590-2				
3	590-3				
4	590-4				
5	591-1				
6	591-2				
7	591-3				
8	591-4				
9	594-1				
10	595-1				
11	596-2				
12	596-3				
13	598-1				
14	598-2				
15	598-3				
16	600-1				
17	600-2				
18	600-3				
19	601-1				
20	601-2				
21	601-3				
22	601-4				
23	601-5				
24	601-6				
25	604-2				

g

* RPC data have not yet been analyzed.

Table 4

Burst Pressure and Leak Rate Data for 3/4-Inch Specimens

No.	Model Boiler Spec. No.	Leak Rate (l/hr) N. Op. ΔP	Leak Rate (l/hr) SLB ΔP	Burst Pressure (psi)	Destructive Exam. Length (inch) Max.	Destructive Exam. Length (inch) Thruwall
1	590-1					
2	590-2					
3	590-3					
4	590-4					
5	591-1					
6	591-2					
7	591-3					
8	591-4					
9	594-1					
10	595-1					
11	596-2					
12	596-3					
13	598-1					
14	598-2					
15	598-3					
16	600-1					
17	600-2					
18	600-3					
19	601-1					
20	601-2					
21	601-3					
22	601-4					
23	601-5					
24	601-6					
25	604-2					

g

Table 5. Adjusted 3/4-Inch Diameter Volts, Leakage and Burst Pressures for Comparisons With 7/8-Inch Diameter Data

No.	Model Boiler Specimen	Bobbin Volts	Leakage Adjusted Volts (Note 1)	Burst Pressure Adjusted Volts (Note 2)	SLB Leak Rate (l/hr)	Adjusted SLB Leak Rate (l/hr) (Note 3)	Burst Pressure	Adjusted Burst Pressure (Note 4)
1	590-1							
2	590-2							
3	590-3							
4	590-4							
5	591-1							
6	591-2							
7	591-3							
8	591-4							
9	594-1							
10	595-1							
11	596-2							
12	596-3							
13	598-1							
14	598-2							
15	598-3							
16	600-1							
17	600-2							
18	600-3							
19	601-1							
20	601-2							
21	601-3							
22	601-4							
23	601-5							
24	601-6							
25	604-2							

g

Notes:

1) 0.750" bobbin volts adjusted by a factor of 1.252 to obtain equivalent 0.875" volts at equal crack lengths.
2) 0.750" bobbin volts adjusted by a factor of 1.46 to obtain equivalent 0.875" volts for equal burst pressure.
3) 0.750" leakage rates adjusted by a factor of 0.9 to obtain leak rates comparable to 0.875" tubing.
4) 0.750" burst pressures reduced by a factor of 1.11 to obtain burst pressure at flow strength of 0.875" tubing.

Table 6.

Linear Regression Analysis Parameters for Burst Pressure and Leakage

[ ]g

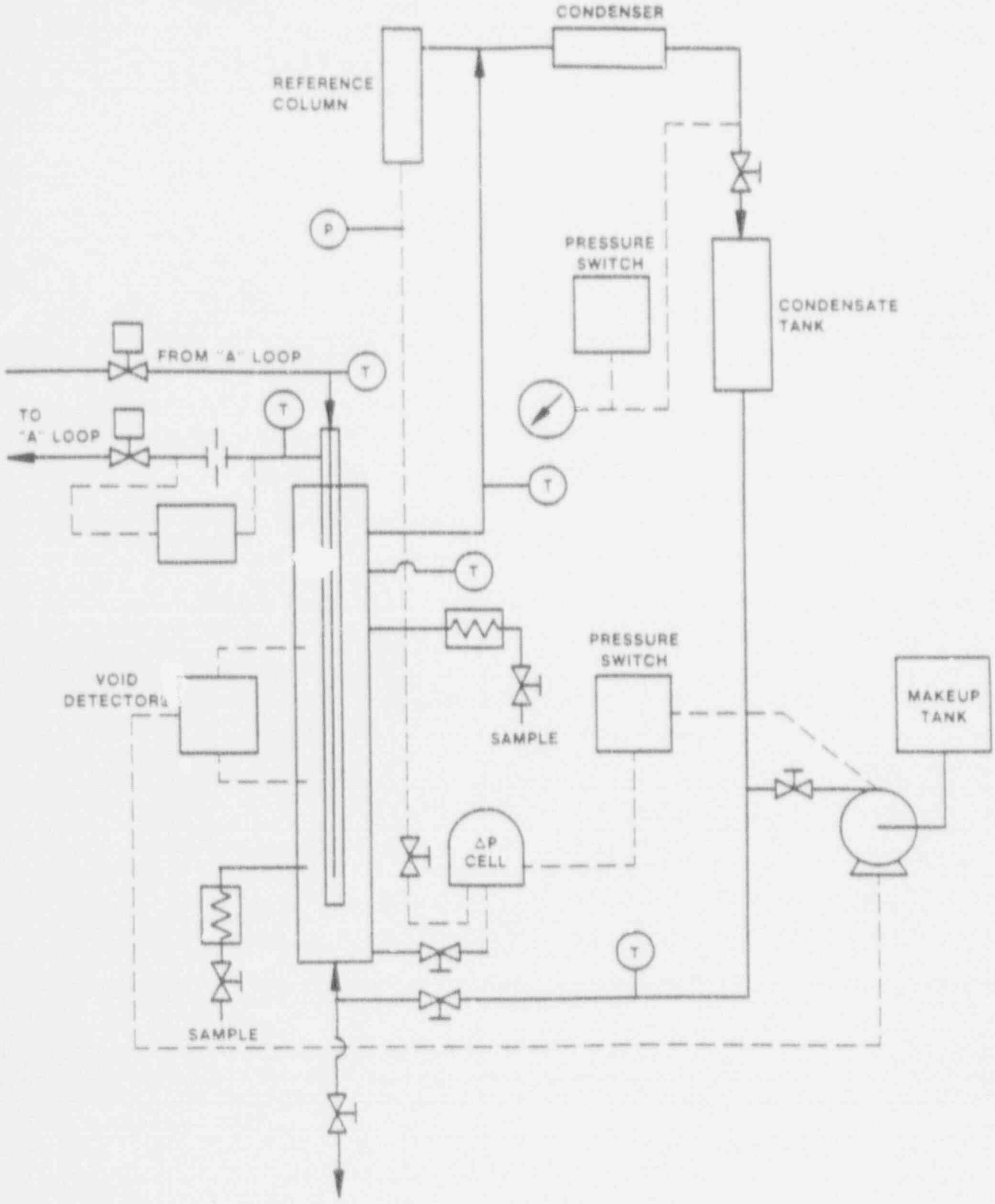


Figure 1. Schematic of Vertically Mounted Single Tube Model Boiler

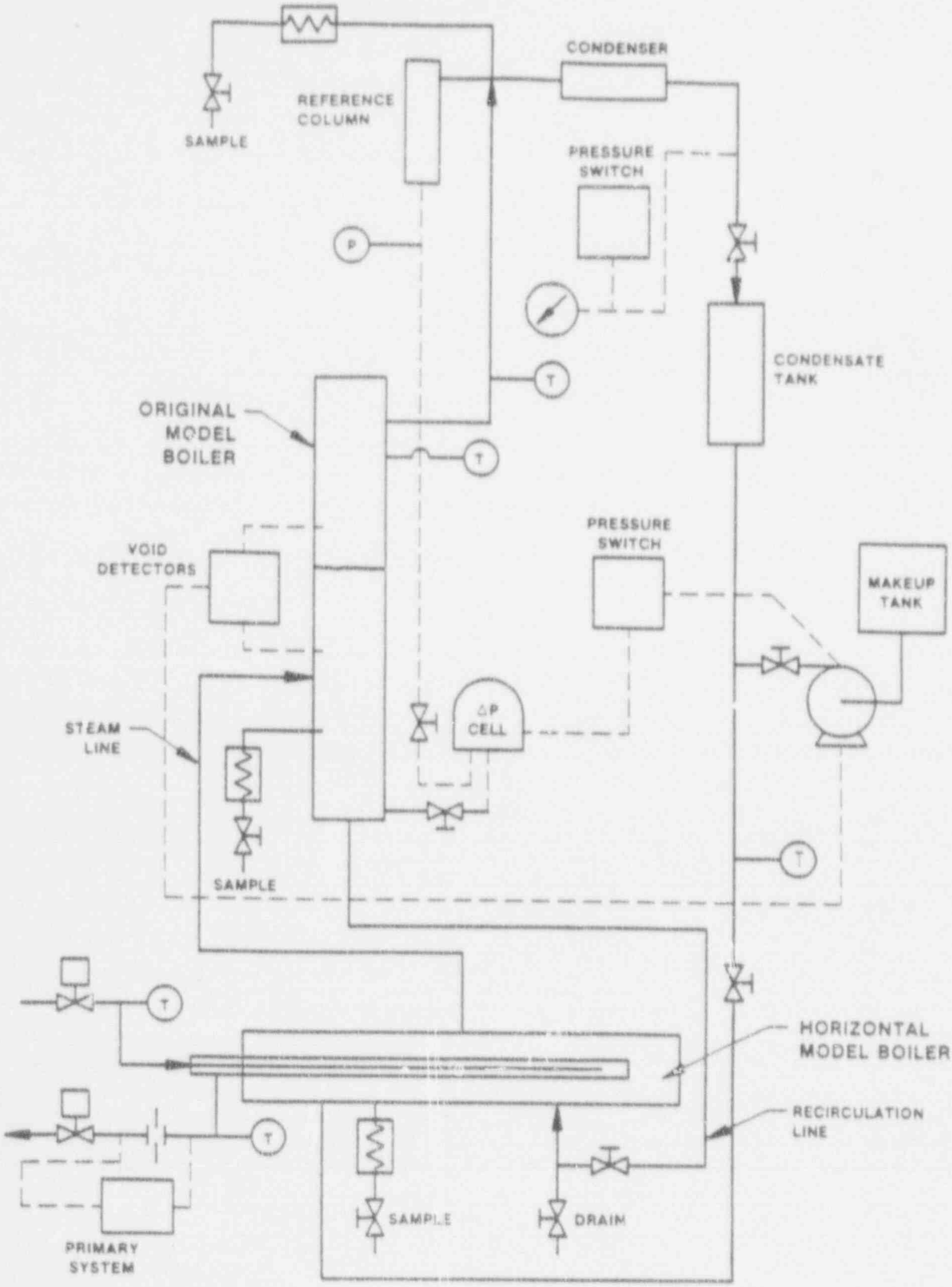


Figure 2. Schematic of Horizontally Mounted Single Tube Model Boiler

Figure 3.

Burst Pressure vs. Bobbin Voltage for 3/4 Inch Tubes

[ ] g

Figure 4.

Burst Pressure vs. Bobbin Voltage for 7/8 Inch Tubes

[ ]^{g}

Figure 5.

SLB Leakage vs. Bobbin Voltage for 3/4 Inch Tubes

[ ] g

Figure 6.

SLB Leakage vs. Bobbin Voltage for 7/8 Inch Tubes

[ ][g]

Figure 7. Burst Pressure vs. Unscaled Bobbin Voltage for 3/4 and 7/8 Inch Tubes

[ ]g

■ 3/4 Inch Model Boiler Specimens

□ 3/4 Inch Pulled Tube - Not Tested to Burst

◆ 7/8 Inch Model Boiler Specimens

◇ 7/8 Inch Model Boiler Specimens - Not Tested to Burst

● 7/8 Inch Pulled Tubes

○ 7/8 Inch Pulled Tube - Not Tested to Burst

Figure 8. SLB Leakage vs. Unscaled Bobbin Voltage for 3/4 and 7/8 Inch Tubes

[ ]g

Figure 9. Bobbin Voltage vs. Crack Length - 3/4" and 7/8" Model Boiler Specimens

[g]

Figure 10. Bobbin Voltage vs. Crack Length, Essentially Single Through Wall Axial Cracks, 7/8" Dia. Tubes

[ ]g

Figure 11. Bobbin Voltage vs. Crack Length, Essentially Single Through Wall Axial Cracks, 3/4" Dia. Tubes

g

Figure 12. Normalized SLB Leak Rate vs. Bobbin Voltage
Normalized to 0.875" Diameter Tubing

g

Figure 13. Normalized Burst Pressure vs. Bobbin Voltage Normalized to 7/8 Inch Diameter Tubing

[ ]g

Figure 14.

Burst Pressure Correlation for the Theoretically Scaled, Combined Database

[ ]g

Figure 15.

SLB Leakage Correlation for the Theoretically Scaled, Combined Database

[ ] g

Figure 16.

Burst Pressure Correlation for the Empirically Scaled, Combined Database

[ ]g