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ENGINEERING EVALUATION OF BURST/ PLUGGED TUBE(S) AT CONNECTICUT YANKEE

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ABSTRACT

During the current Connecticut Yankee (CY) outage, inspection in the tube lane portion of the first span of the secondary side of Steam Generator Number 4, cold leg, showed a tube which had been burst. The burst was of the "fishmouth" type and was located at tube location Row 1/Column 35 on the cold leg. The elevation of the fishmouth burst was approximately 16 inches above the top of the tubesheet. The burst was azimuthally oriented approximately toward the cold leg of tube R1/C34. The tube was bowed into the tube lane, i.e., toward the hot leg portion of the same tube.

Investigations and evaluations have been performed which strongly indicate that the source of the bowing of the R1C35 tube at CY was the result of the expulsion of the water in the tube concurrent with the formation of the burst opening in the tube. In addition, dynamic analysis of other plugged tubes in the CY SGs indicates that they would not be subject to fluidelastic excitation if they experienced the burst phenomenon. An evaluation of wear of adjacent tubes was also performed which indicates that either wear would not take place, or that turbulence induced fretting wear could take place at very low wear rates. Although wear due to an impact/sliding mechanism is not predicted, the circumstances of such turbulence induced wear would lead to limited depths which would not challenge the structural integrity of an active tube relative to the requirements of Regulatory Guide 1.121.

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1.0 BACKGROUND

During an inspection of the secondary side of Steam Generator Number 4 (SG #4) at the Connecticut Yankee Atomic Power Co. Haddam Neck Nuclear Plant (CY or CYW), a "fishmouth" opening in the plugged tube located at Row 1/Column 35 (R1C35) was observed at an elevation of approximately 16 inches above the top face of the tubesheet on the cold leg (CL) side of the SG. The opening in the tube was reported to be directed towards the tube located at R1C34 CL. The tube had been plugged in 1986, using Westinghouse (W) mechanical plugs fabricated from Alloy 600 material from heat NX3513, due to the non-destructive testing indication of PWSCC of the tube within the confines of the tubesheet. Owing to the potential for PWSCC of the installed plugs, the plug in the hot leg end of the tube had a Babcock & Wilcox Company "plug-a-plug" (PAP) installed in 1989. The PAP was fabricated from Alloy 600 material. A PAP fabricated from Alloy 690 material was installed in the plug at the cold leg end of the tube in 1993. In addition, the tube was reported by CY to be bowed toward the tube lane by about 0.5 inch to 0.75 inch. Westinghouse review of the video tape of the tube lane inspection has led to the judgement that the bow is about 2/3 of a tube diameter, i.e., 0.5 inch.

The four SGs at CY are W Series 27s with Alloy 600 tubes that are nominally [

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The appearance of a fishmouth opening, signifying the rupture of the tube, in a plugged tube is believed to have been first observed in 1984 at a foreign plant (Ringhals 2). The tubes had been plugged using W explosive plugs fabricated from Alloy 600 material. Two additional plugged tubes were found with burst openings at the Salem 1 nuclear plant in 1991. These tubes had also been removed from service using W explosive plugs. The phenomenon of burst of plugged tubes has been observed at some other foreign plants. The details of the occurrences are still under investigation, however, reported information indicates that the phenomenon has occurred in tubes removed from service by installing explosively welded plugs, welded plugs, rolled plugs, and mechanical plugs similar in design to the W plug where the plug has been subsequently plugged, e.g., repaired, using a device developed by Framatome (FRA). The FRA device is somewhat similar to the PAP in that it consists of a *bolt* that is threaded into the plug *expander* and secured by a locking cup that has been threaded into the mechanical plug skirt. No occurrences of the phenomena have been reported involving non-modified W mechanical plugs, or in W mechanical plugs which have been repaired using the W welded repair device known as the plug-in-plug (PIP). It is to be noted that detection would only be likely in the event of the burst opening occurring between the tubesheet and TSP1 in Row 1 tubes and with the burst opening oriented in a direction visible from the tubelane. No bowing of the affected tubes was observed at Ringhals or Salem. Information has not been received to determine conclusively if tube bowing was observed at the other plants, although bowing was not specifically mentioned.

The mechanism that leads to the burst of a plugged tube has been generally attributed to cracking of the plug in such a way that the cracks function as a *flow diode* or one-way valve. [ ]^{a,c,e}

[

]^{a,c,e}

2.0 PLUGGED TUBE BURST TEST

A tube burst test was performed to ascertain whether or not the bowing of tube R1C35 in SG 4 at CY was due to the reaction force developed during the actual burst of the tube.

2.1 Test Objective

There were numerous reported complexities of this specific structural configuration. Included were the lack of denting, per eddy current test (ECT), of this tube on the CL at (TSP1) and at the TTS, a dent and possible eddy current indication (ECI) at the burst location (1984 ECT data) when the tube was plugged in 1986 and the denting of approximately one-half of the adjacent tubes at TSP1. A review of plugging-year ECT data during the outage showed that six of eight tubes with leaking plugs were bulged. In five of the six cases, the bulges were essentially at locations where dents, pluggable ECIs, or nonpluggable ECIs were determined prior to plugging. (In the sixth case, no ECT data were available for the year of plugging.) It was assumed that the adjacent, dented tubes determined the local movement of TSP1. Due to these complexities, it was concluded that a test would be the best means of gaining an insight into the failure mechanism. The large deflection of the plant tube, in the as-observed condition inferred that the plugged-and-PAPed tubes in this SG which exhibit the same or similar features as listed above, may also deflect in this manner and potentially contact adjacent active tubes.

2.2 Test Mockup

The test was performed at [

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The mockup used in this test is shown in Figure 1. The mockup consisted of four one-inch diameter threaded rods which provided vertical support of the carbon steel plates which simulated the top of the tubesheet and TSP1. The distance between [

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]^{a,c,e}

2.3 Test Major Steps

1. Install the threaded rods in the two plates, with the plates spaced as shown in Figure 1 The nuts should be loose.

2. Install the four strain gages at the designed locations.

3. Measure the tube ID and OD.

4. Weld the tube to the plates. Verify that the plates are perpendicular to the tube.

5. Attach the pressurization system.

6. Make baseline strain gage readings.

7. Tighten rig nuts.

8. "Zero out" strain gages after tightening nuts.

9. Install dial indicator, in the vicinity of the midspan of the tube, to measure deflection.

10. Burst test. Apply pressure until burst.

11. Measure tube enlargement, burst opening and the tube general bending deflection after the test.

12. Determine [

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[

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The significant differences between the test conditions and those existing in the SG were the result of tube geometry and material properties. These are delineated as follows:

1) The volume of water in the R1C35 tube would be [

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2) The material properties of the plugged tube would be [

]^{a,c,e}

3) The water outside of the plant tube would [

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It is judged that the effect [

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In summary, the potential for impact and wear of a neighboring tube must be evaluated. Additionally, it was appropriate to consider the effect of Steam Line Break (SLB) on the burst plugged tubes.

3.0 DYNAMICS ANALYSIS OF BULGED AND BURST TUBES

3.1 Flow Induced Vibration

An analysis was performed to determine the response of a bulged and burst tube assuming that the bulge occurred [

]^{a,c,e} form observed in the CY steam generator, and also reproduced in laboratory experiments. Specifically it has been assumed that a hole with a width of approximately [

]^{a,c,e}

Thermal and hydraulic conditions used in the analysis were generated using the ATHOS computer code. CFD Research Corporation supplied a file that contained all of the relevant information necessary to perform a FIV evaluation of any tube in the CY tube bundle. This information was used in the FLOVIB and FASTVIB computer codes in support of the FIV evaluation. These programs were used to predict the individual response of steam generator tubing exposed to a location dependent fluid velocity and density profile. The programs calculate tube natural frequencies and mode shapes using a linear finite element model of the tube. The fluidelastic stability ratio Ue/Uc (the ratio of the effective velocity to the critical velocity) and the vibration amplitudes caused by turbulence are calculated for a given velocity/density/void fraction profile and tube support condition. The WECAN-generated mass and stiffness matrices used to represent the tube are also input to the code. (WECAN is also a Westinghouse proprietary computer code.)

Each of the spans between the tube support plates (TSPs) for both the hot leg and cold leg were considered in the evaluation. [

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The model used in the analysis includes a burst in each of the spans. The location within the span where the burst was located was defined using locations of known bursts or bulges that were obtained from the recent inspection at CY. For example, the R1C35 burst, located approximately 16 inches from the top of the tubesheet, was assumed to occur in all tubes in the bundle. For this case a degraded zone was placed 16 inches from the top of the tubesheet for each of the tubes in the steam generator. Another degraded zone was placed 32 inches from TSP 1 since a bulge (no burst) was observed at this area for tube R30C84. For spans where no bulges or bursts were observed, a bulge was assumed to be located at mid span between the support locations.

3.2 Fluidelastic Response

The FASTVIB computer code was used to evaluate each of the spans on both the hot and cold leg of the steam generator. The fluidelastic stability ratio was calculated for each of the spans, for a large number of rows and included each column in the given row. Figure 4 contains a summary of the maximum stability ratios observed assuming that the degraded section was located in any hot leg span. For comparison these same tubes were evaluated assuming that no degradation occurred (Figure 5). As can be observed in the figures, the stability ratio changes only slightly when the degraded zones are included. This indicates that the degradation zone, although representative of actual burst tube geometries, is not large enough to significantly affect the response of the tube. In addition, studies were performed to determine the effect of incorporating a bow into the tube model. [

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Figures 6 through 9 contain the stability ratios of the hot leg tubes assuming the degradation occurs in hot leg spans 1, 2, 3 and 4, respectively. As can be observed in the figures, [

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The response of tubes located on the cold leg side of the steam generator follow similar trends as those found in the hot leg. [

]a,c,e Figure 10 contains the maximum fluidelastic stability ratios for the condition where a burst occurs within any span on the cold leg side. Figure 11 contains the response assuming that no degradation occurs.

From the results presented above, it can be concluded that should a plugged tube rupture and produce a burst geometry similar to that found in R1C35 and in laboratory tests, there would be a small increase in the potential for the tube to experience fluidelastic excitation. However, the increase is less than [ ]a,c,e and not large enough to produce a tube susceptible to fluidelastic excitation.

3.3 Turbulent Response and Crack Propagation

The response of both the nominal and the degraded tubes due to turbulence was also considered in the analysis. In this evaluation it was determined that the maximum turbulent amplitudes did not change significantly as a result of a burst condition. The potential for crack propagation due to turbulence was also evaluated. [

]a,c Since these stress levels are below those required to propagate any expected circumferential crack, it can be concluded that crack propagation as a result of turbulence is not projected to occur.

3.4 Bowed Tube Wear Potential

An analysis was performed to determine the potential for a bowed tube to wear into a neighboring tube. In this scenario it is assumed that a plugged tube at the limiting location would burst, bow, and contact a neighboring tube. An estimate of the maximum bow was made through visual inspection of the R1C35 tube. In this inspection it was determined that a bow of approximately 2/3 to 3/4 of a tube diameter (0.56 inch) could be observed. If the tube would have moved into the direction of a neighbor instead of into the tube lane, a residual normal contact force of approximately [ ]^{a,c,e} would have developed at the point of contact. This represents an interference of 0.56-(1.0312-0.75), or 0.28 inch. The turbulent amplitude of the degraded tube at the contact point, assuming that relative motion could occur, was found to be approximately [ ]^{a,c,e} This displacement was calculated assuming that turbulence excitation occurred and that the neighboring tube remained in contact with the degraded tube. Wear calculations were performed assuming that fretting wear occurred between the two Alloy 600 tubes. [

]^{a,b,c}

The calculations indicate that it would take approximately 24 years for a bowed tube to wear a neighboring tube down to a 40 percent wear depth (60 percent remaining tube wall) assuming that the bowed tube is located in the limiting location and that contact occurs. The fretting wear assumption was validated by [

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It has also been considered that it may be possible for a tube to burst and bow, but not result in a contact force of the magnitude calculated above. With reduced contact force the time required to wear a tube down to 40 percent wear depth would increase. This result assumes that fretting wear continues to occur. A parametric evaluation was performed to determine the effects of various bows, the resulting interferences and contact forces, and determine if fretting wear would continue to occur with reduced interference. [

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The potential for a burst tube to contribute to wear of an active neighbor must also be considered. Two potential situations may be postulated for qualitative evaluation since the turbulence root mean square (RMS) forces acting on the tube are low. In the first case the contact force is assumed to be relatively low and relative motion between the tubes takes place. [ ]^{a,ce}

[

]^{a,c,e} Hence, the wear rate in the second case would either not be expected to take place or would be expected to occur at a very slow rate.

4.0 DYNAMICS ANALYSIS OF BULGED AND BURST TUBES AT STEAM LINE BREAK CONDITIONS

4.1 Flow Induced Vibration

An analysis has been performed to evaluate the effects of SLB loads on tubes with bulged or degraded conditions resulting from a burst condition. The analysis was performed using thermal/hydraulic conditions generated with the TRANFLO computer code. Although the analysis was not performed specifically for steam generators at Connecticut Yankee (CY), the results were obtained using a similar Series 27 steam generator. [

]^{a,c,e} The following discussion is based upon results obtained in the previous analysis and are representative of the load magnitude and duration that would be expected if the analysis was specifically performed for CY.

Figure 13 illustrates the predicted fluid velocities near the U-bend portion of the SG during a SLB event. The SLB is defined as a "full break," occurring over approximately 0.001 sec. This case was judged to be the most severe possible. [

]^{a,c,e} At about [ ]^{a,c,e} seconds in the transient, the largest of the fluid velocities in this region are very close to those that would be expected during normal operation.

Figure 14 illustrates the predicted fluid velocities at the top of the tubesheet. As can be observed in this figure, the fluid velocities at the tubesheet elevation are largest at about [

]^{a,c,e} Data are not available after [ ]^{a,c,e} seconds since the computer analysis was stopped at this point. However, a trend can be observed that indicates that the conditions are rapidly decreasing to below levels that would occur during normal operation.

As demonstrated by the TRANFLO analysis results discussed above, the SLB event is a relatively short duration transient. Although the flow rates can [

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For a burst plugged tube to produce a leaking damaged tube as a result of flow induced vibrations (FIV), the tube has to become [

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4.2 Acoustic Wave Effects

The effect of an acoustic wave generated during a SLB event has also been considered. Previously completed analysis have determined that acoustic waves could generate significant loads on some primary side components of a PWR plant, which are filled with subcooled water. Analysis performed for Model D4 S/Gs have recently been completed to determine if these acoustic waves can contribute to loading the S/G internals under steam or steam/water mixture. Results of the Multiflex analysis indicate that the effect of an acoustic wave on S/G internals is insignificant. It was determined that [

]^{a,c,e} The intensity of the acoustic wave upon reaching the tube bundle is now so small as to now be considered insignificant. This type of response would also be expected for the CYW S/G. [

]^{a,c,e} Therefore, it can be concluded that acoustic waves will not significantly contribute to loading tubes in the CYW steam generators.

5.0 TUBE STRESS CORROSION CONSIDERATIONS

The effects of expansion and fishmouth on stress corrosion cracking of a plugged steam generator tube have been evaluated from materials considerations. The primary effects considered are the [

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C. The same conditions exist as for "B" except [

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The consequences of this condition are two-fold. First, the temperature of the tube [

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[$]^{a,c,e}$

This long predicted time to initiate cracking assumes that [

$]^{a,c,e}$

The results of this evaluation indicate that although axially oriented stresses [

$]^{a,c,e}$

6.0 CONCLUSIONS

A postulated mechanism to explain the bowing of the tube has been developed based on the simulated burst test, i.e., the deformation is [

$]^{a,c,e}$ a plugged tube (depending on the axial location of the burst opening).

Bounding cases of dynamic interaction of the burst tube with a neighboring active tube have been performed which indicate that [

$]^{a,c,e}$ for many years of operation.

7.0 RECOMMENDATIONS

No action is recommended for the burst tube. It is recommended that leaking plugs, including repaired W mechanical plugs, be replaced if leaking is observed during future outages. It is also recommended that all active tubes which are adjacent to plugged tubes be inspected for signs of wear at all future outages until such time as remedial action has been taken to obviate the potential for the plugged tubes to be pressurized to burst.

Table 1: Test Specimen Burst Characterization

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Table 2: Test Specimen Post-Burst Diametral Dimensions

Axial Elevation (in.)	Tube Diameter		Diameter Increase (in.)
	0°	90°	

a,c,e

Table 3: Test Specimen Permanent Lateral Deformation

Axial Elevation	Bow Magnitude		Effective 0° Bow
	0°	90°	

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a,c,e

Figure 1. Mockup for Burst Testing of 3/4" Tube Under Fixed - Fixed Conditions with CYW Steam Generator Tube Span.

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Figure 2. Set Up for Determination of Spring Constant of Burst Tube for CYW Steam Generator.

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Figure 3. Measured Bow of a Burst Specimen Similar to the R1C35 CY Tube.

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Figure 4. Maximum Stability Ratio - Hot Leg - With Degradation.

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Figure 5. Maximum Stability Ratio - Hot Leg - No Degradation.

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Figure 6. Stability Ratio - Hot Leg Span 1.

a,c,e

Figure 7. Stability Ratio - Hot Leg Span 2.

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Figure 8. Stability Ratio - Hot Leg Span 3.

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Figure 9. Stability Ratio - Hot Leg Span 4.

a,c,e

Figure 10. Maximum Stability Ratio - Cold Leg - With Degradation.

a,c,e

Figure 11. Maximum Stability Ratio - Cold Leg - No Degradation.

a,c,e

Figure 12. Bowed Tube Contact Force with a Neighboring Tube as a Function of Geometrical Interference.

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Figure 13. Steam Line Break - Full Break - U-bend Velocities

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Figure 14. Steam Line Break - Full Break - Top Of Tubesheet Velocities

a,c,e

Figure 15. Steam Line Break - Fluid Density Versus Time - Full Break.