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NORTH ANNA 2 STEAM GENERATOR TUBE FATIGUE EVALUATION AND REMEDIAL ACTIONS REPORT

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1.1 INTRODUCTION

North Anna Unit #1 and Unit #2 are each three-loop plants with Westinghouse Series 51 steam generators and essentially identical design and operating conditions. A tube rupture event occurred at North Anna Unit #1 on July 15, 1987. The tube was located in Row 9 Column 51 in steam generator "C", and the rupture location was at the top support plate on the cold leg side of the tube. Extensive analytical and test investigations were performed to determine the cause of the tube rupture in Unit #1 to be high cycle fatigue (Reference 1).

1.2 SUMMARY

A series of tube fatigue evaluations performed for North Anna Unit #2 are described. The prerequisite conditions for tube high cycle fatigue mechanism, and U-bend tube vibration analytical results are described. Eddy current techniques used to characterize AVB positions, and AVB location maps specific to North Anna Unit #2 are provided. A description is provided of the implemented preventive measures, which include preventive plugging and the installation of a downcomer flow resistance plate. As a result of the modifications, the potential for large leakage occurrences due to tube fatigue is reduced to negligible levels, based on multiple criteria which significantly reduce the probability of occurrence of tube fatigue. This report documents the tube fatigue evaluation conducted for North Anna Unit #2 in October, 1987. The evaluation was conducted using essentially the same criteria and methods as the North Anna Unit #1 evaluation documented in Reference 1.

2.0 EVALUATION CRITERIA

2.1 Tube Fatigue Mechanism

As previously stated, the North Anna Unit #1 tube rupture was determined to be due to high cycle fatigue. The source of the loads is a combination of a mean stress level in the tube and a superimposed alternating stress. The mean stress was produced by denting at the top tube support plate and the alternating stress was due to out-of-plane deflection of the tube above the top tube support caused by flow-induced vibration. The loads were sufficient to produce fatigue and are consistent with a lower bound fatigue curve for the Alloy 600 tube material. The magnitude of the

alternating stress was consistent with a fluidelastic tube vibration mechanism.

The reduction in damping at the tube-to-tube support plate interface caused by denting was a significant contributor to excessive vibration. The absence of antivibration bar (AVB) support was also required for vibration to occur. The presence of AVB support limits tube motion and therefore the deflection amplitude required for fatigue. Also contributing to the level of vibration, and thus the loading, was the local flow field associated with the detailed geometry of AVB insertion depths in the steam generator. The ruptured tube was considered to have a worst case combination of loadings and fatigue properties.

2.2 Prerequisite Conditions

Summarizing the information described above, and described in detail in Reference 1, the following are the prerequisite conditions for the tube fatigue mechanism:

Fatigue Requirements	Prerequisite Conditions
Mean Stress	• Denting
Alternating Stress	• Tube Vibration * Denting at top TSP * High local fluid forces * Absence of AVB support
Material Fatigue Properties	• Lower range of properties

3.0 EDDY CURRENT REVIEW

3.1 Tube Denting

As noted, tube denting was determined to be a prerequisite for the North Anna #1-type tube fatigue mechanism, and therefore of interest in the North Anna #2 tube evaluation. Tube support plate crevice corrosion products and tube dent sizes as small as 1-2 mils (0.001" to 0.002") are detectable by eddy current testing. Although the difference between tube denting and the presence of crevice corrosion products is significant in terms of the tube fatigue mechanism, it was judged

conservative to consider a tube to be dented if either tube denting or top tube support plate crevice corrosion products were detected. Based upon the preliminary eddy current information available at the time, all North Anna Unit #2 tubes were assumed to be dented at the top tube support plate in the October, 1987, tube preventive plugging evaluation.

Subsequent eddy current evaluations of top tube support plate corrosion confirmed that most of the tubes had crevice corrosion product buildups at the top tube support plate, but were not dented. Of the 118 tubes recommended for preventive plugging, 104 tubes were evaluated as having top tube support plate corrosion, 2 showed denting, 6 showed no detectable denting, and 6 were unreadable.

Tube wall indications were also found in two tubes -- R10C22 of Steam Generator B, and R9C3 of Steam Generator C. These tubes were plugged.

3.2 Identification of AVBs from Eddy Current Testing

Since tube supports limit tube vibration potential, an evaluation of the presence or absence of AVB support was needed for each North Anna #2 tube. The minimum depth of AVB insertion in the Series 51 steam generator is to tube Row 11, and in most cases, the actual depth of insertion went to Row 10, 9, 8, and sometimes Row 7. Direct visual or fiberoptic observation of AVB positions would have been difficult and potentially unreliable, therefore, eddy current test information was used to evaluate presence of AVBs. A typical ECT data trace indicating the intersection of an AVB with the tube is shown in Figure 3-1.

The basis for the use of eddy current information to evaluate the presence of AVBs was developed using data from laboratory tests with a standard bobbin coil. Considering a number of factors, including noise levels, lateral and vertical offset of the AVB from the tube, and the effect of tube deposits, the tests showed that under limiting conditions AVBs could be detected at a distance greater than the tube-to-AVB gaps. As discussed later, AVBs provide adequate support for tubes even at the maximum possible Series 51 tube-to-AVB gap distance. Therefore, the presence of a verified AVB eddy current signal that provides support at the tube centerline indicates at least one-sided support.

The term "visible" was used to indicate that a measurable, above-noise level AVB eddy current signal was interpreted for the tube of interest, and conversely, "invisible" was used to indicate that

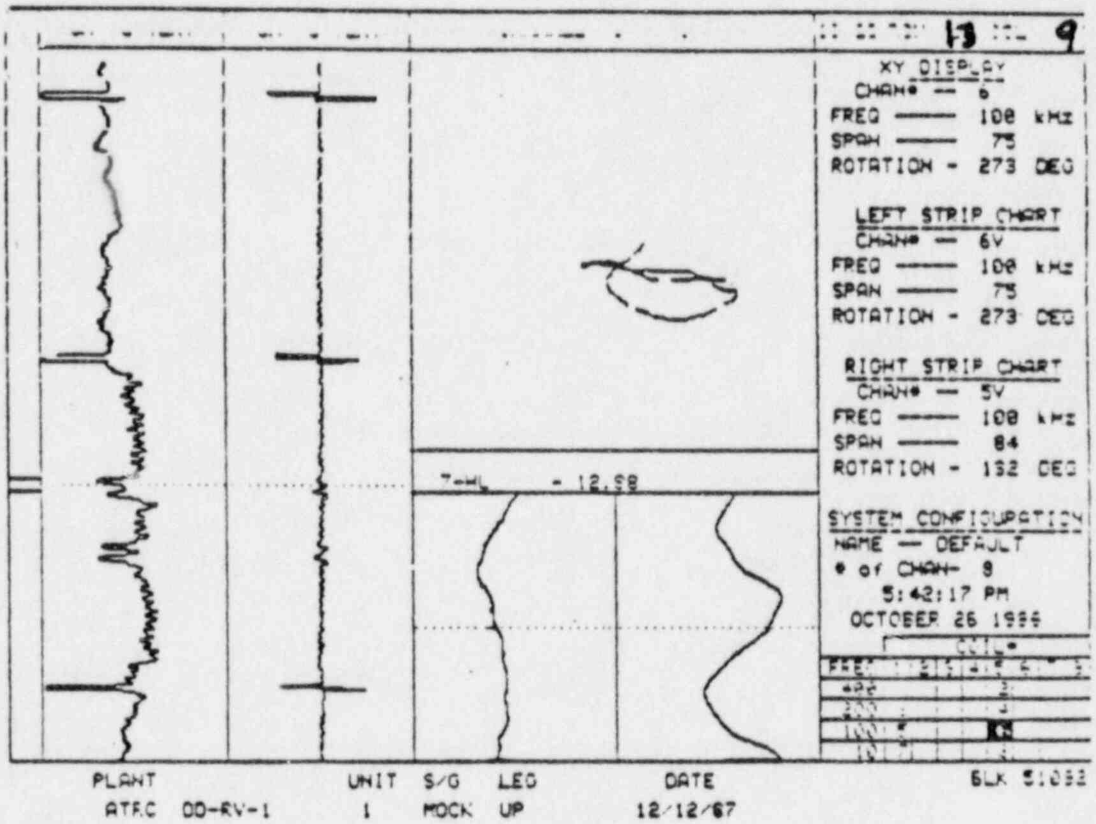

FIGURE 3-1 Typical Eddy Current Signal for AVBs

no AVB eddy current signals were apparent. Initial ECT evaluations of North Anna #2 AVB positions were limited to interpreting whether or not an AVB was "visible" or "invisible". Rows 8 through 12 were examined and "visible" and "invisible" interpretations were made for all tubes. Some anomalies appeared where it is likely that the signals were masked by copper deposits. Figures 3-2 through 3-4 show the "visible" - "invisible" map (without AVBs) in this preliminary stage of data interpretation.

3.3 0, 1 or 2 AVB Present Eddy Current Calls

To obtain additional information for evaluating the AVB positions, eddy current information for selected tubes was also examined to evaluate the number of AVB intersections (including zero) "visible" along the U-bend length. Tubes for the "0, 1, or 2 AVB Present" callout were selected based upon the results of preliminary AVB positioning from the "visible"-"invisible" maps.

Zero indicated that no AVBs were "visible", one (1) indicated that a continuous uninterrupted AVB signal (regardless of length) was observed, and two (2) indicated that two or more distinct, separate AVB leg signals were observed. Single intersections (1's) can be interpreted in a number of ways: a) as a single bar (one-sided support) inserted to a depth such that the AVB centerline is approximately tangent to the tube wall centerline, b) as two bars (two-sided support) both inserted to essentially the same depth, and c) as two bars (two-sided support) with the second bar lower than the first bar, but still close enough to provide a continuous AVB eddy current feedback signal. The identification of one AVB signal does not, by itself, mean that the AVB is located at the tube centerline or below (i.e., supporting the tube on one side), since it is possible for the eddy current probe to identify an AVB that is slightly above the tube centerline. The overlay of the "visible" - "invisible" data and the "0, 1, or 2 AVB Present", as well as top tube support plate denting results, are shown in Figures 3-5 to 3-7 (a description of AVB Insertion Map techniques and Preventive Plugging Criteria follow in Sections 5.0 and 6.0).

4.0 UNIT 2 VIBRATION ANALYSIS

4.1 Similitude with North Anna Unit #1

Since the design and operating parameters of North Anna Unit #1 and Unit #2 are essentially the same, the same vibration analyses are applicable to both. Test results documented in Reference 1 showed that single-sided AVB support limits the vibration amplitude for fluidelastic vibration.

FIGURE 3-2

North Anna #2: S/G -A
AVB Visibility

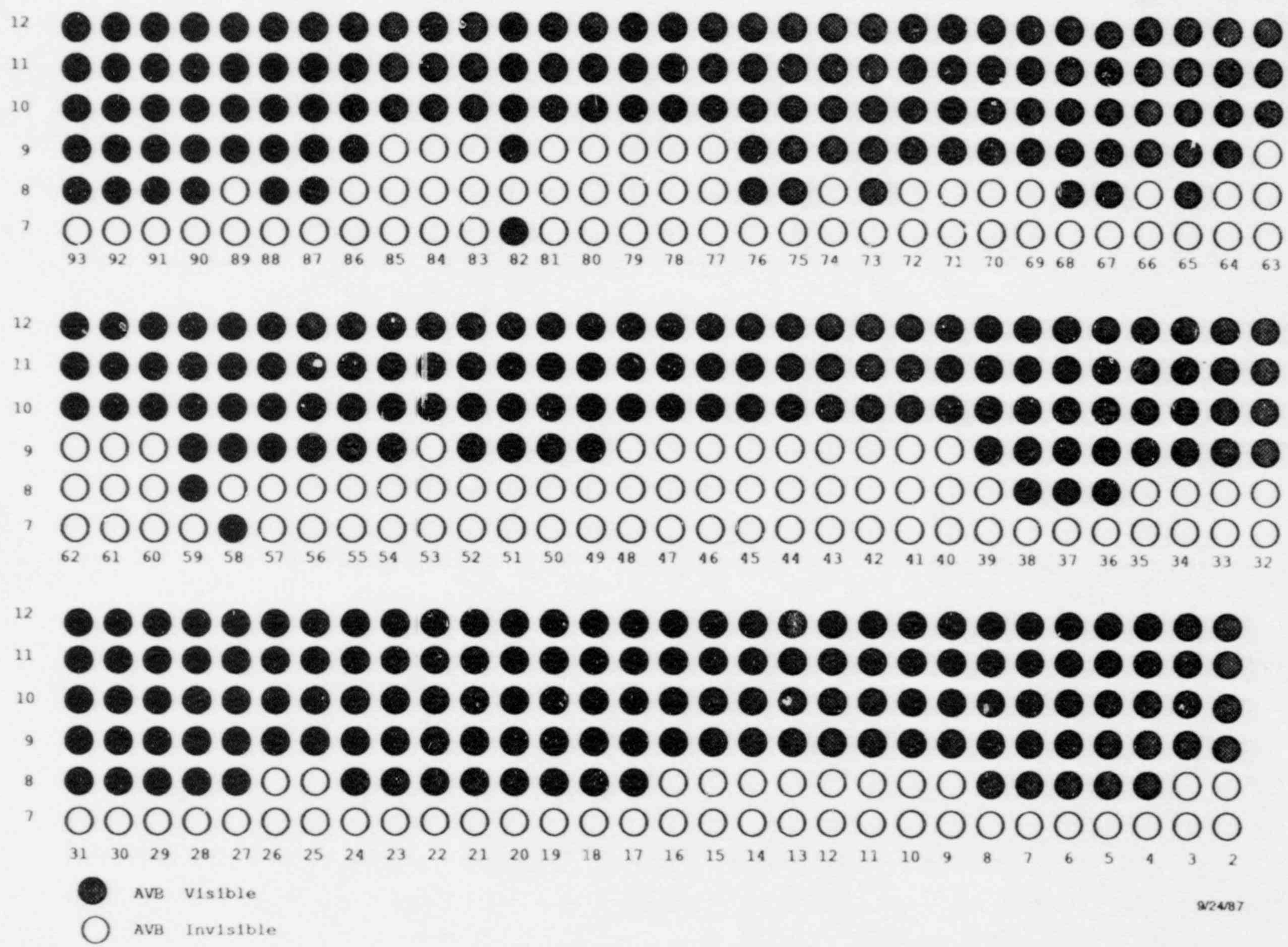

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FIGURE 3-3

North Anna - 2: S/G -B
AVB Visibility

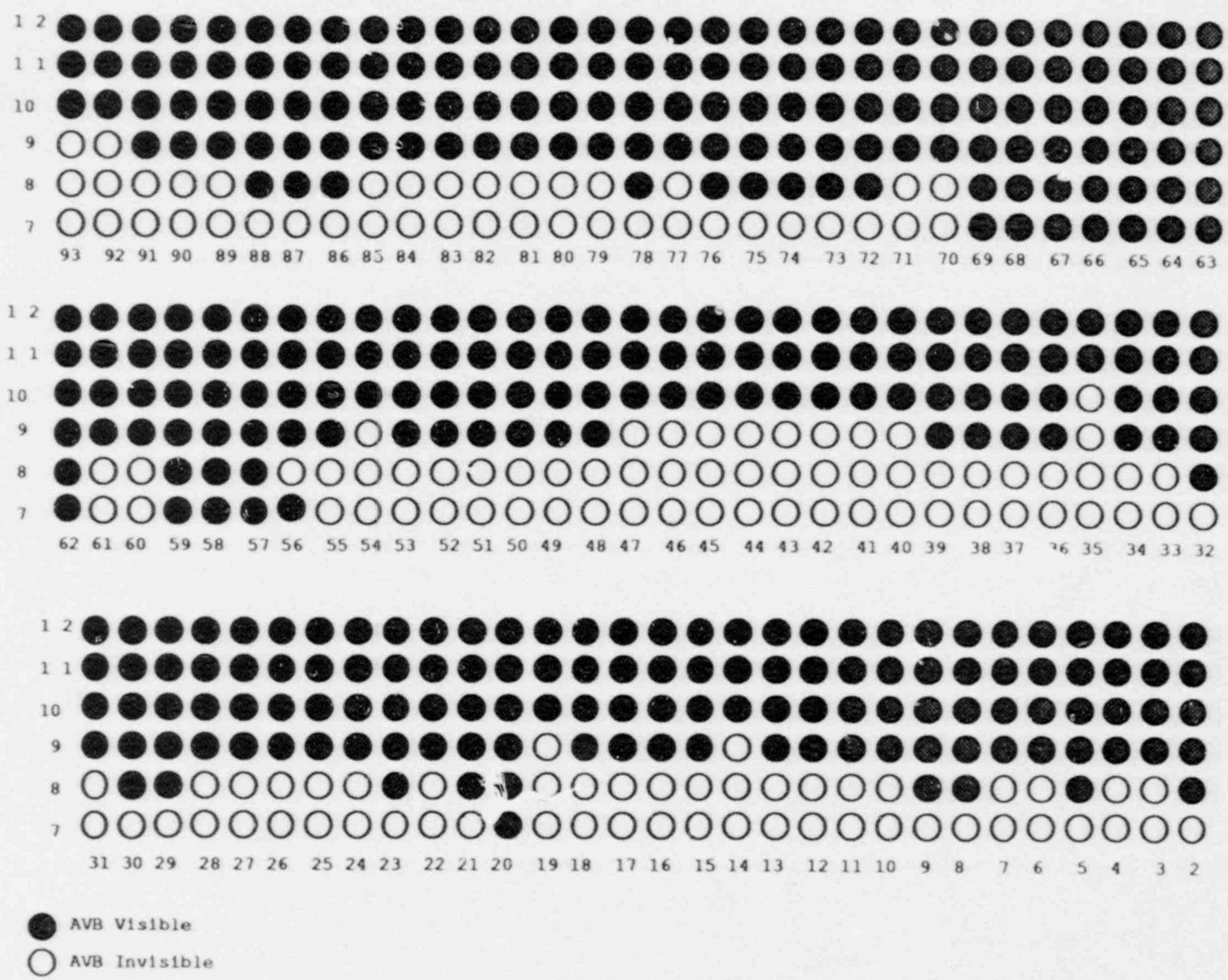

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FIGURE 3-4

North Anna - 2: S/G-C
AVB Visibility

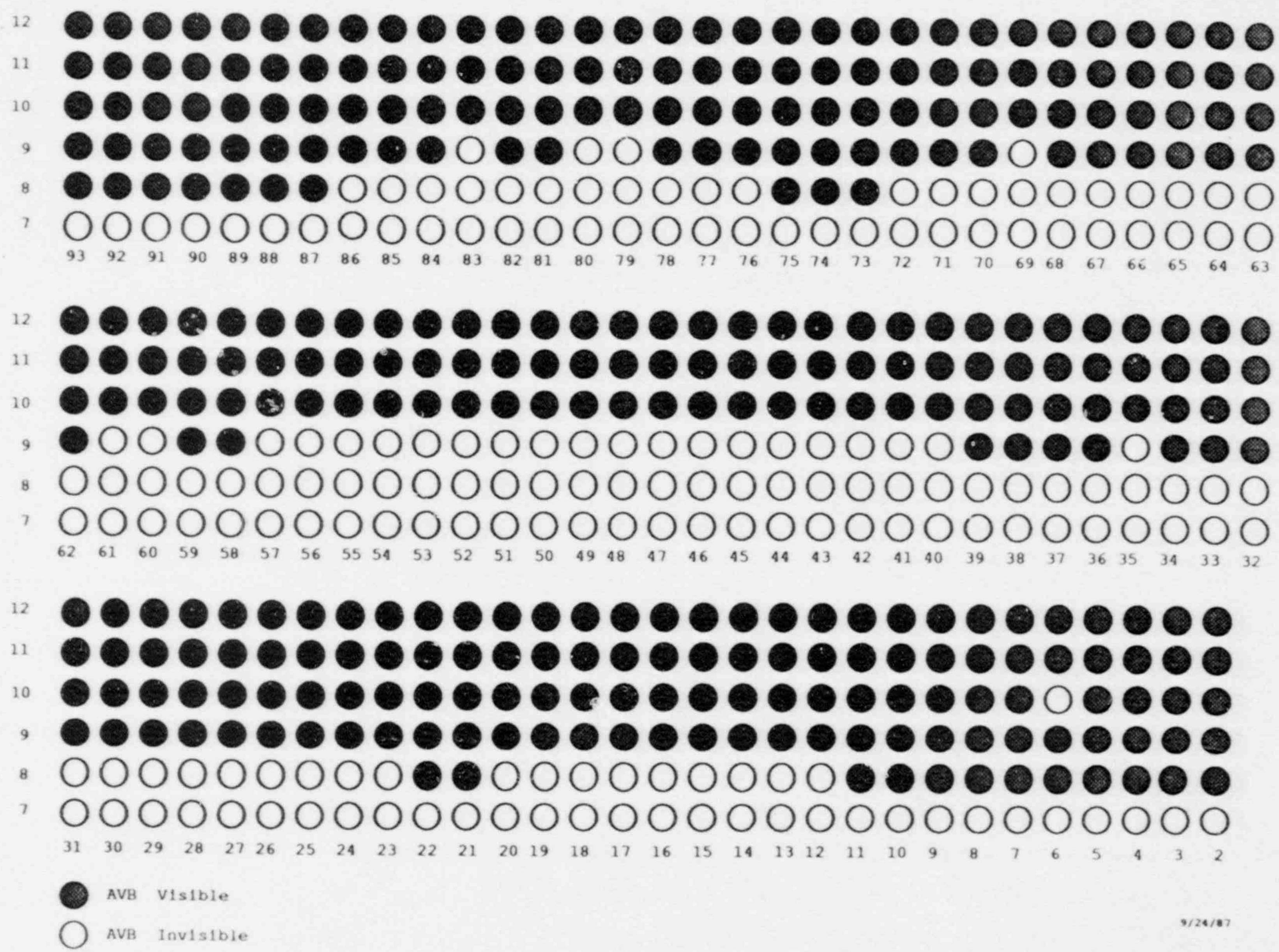
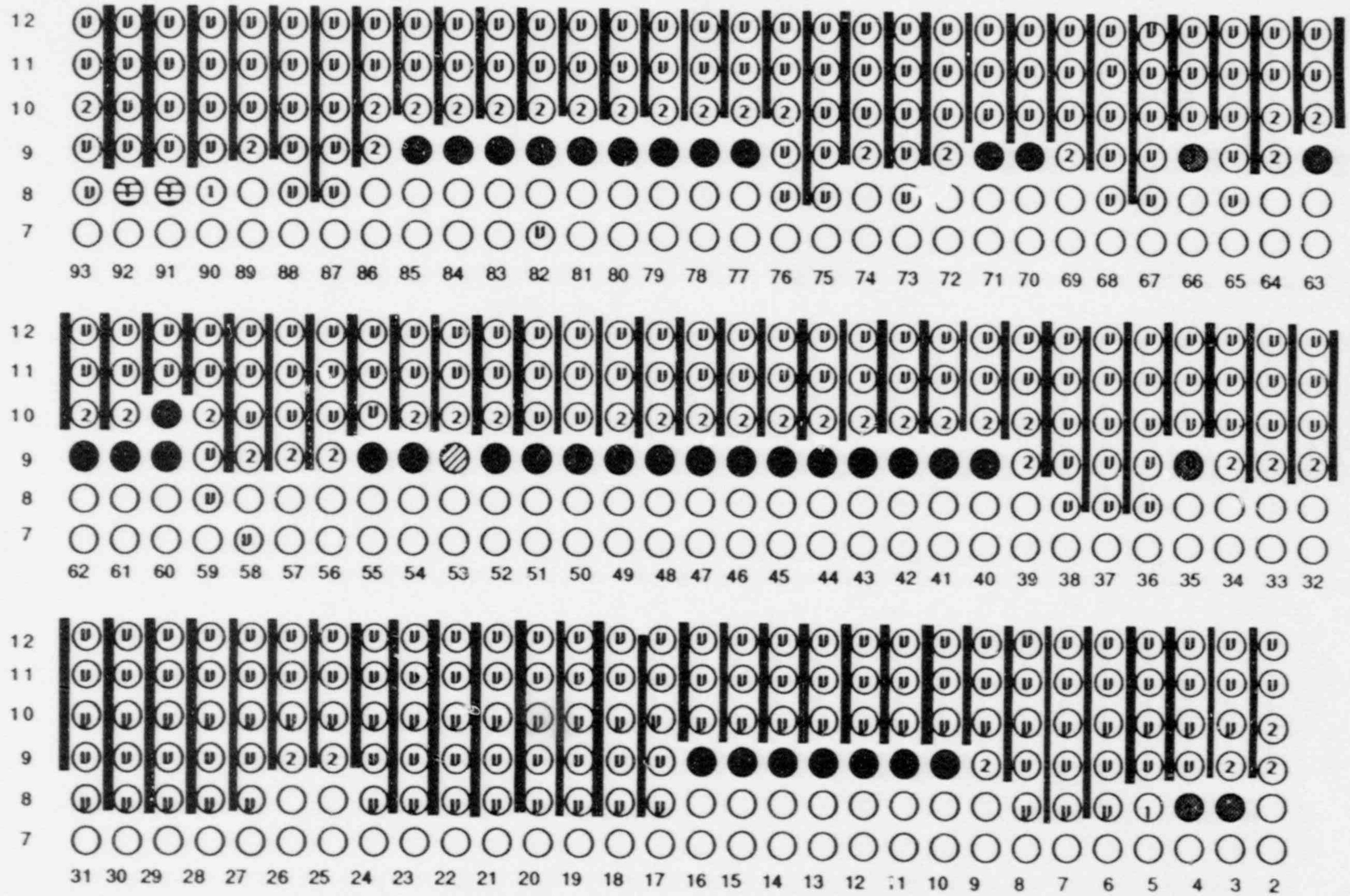


FIGURE 3-5

North Anna #2 (VGB): S/G -A
AVB Insertion and Plugging



• Numbers in circles represent the number of distinct AVB leg segments indicated "visible" from the tube. No entry or zero means no AVBs are "visible".

(U) AVB Visible

Plugged (Wall Indication)

Preventively Plugged; Tube Denting Deformation Detected

Preventively Plugged; Top Support Plate Corrosion Detected

Preventively Plugged; No Detectable Denting

Preventively Plugged; TSP Corrosion Data Unreadable

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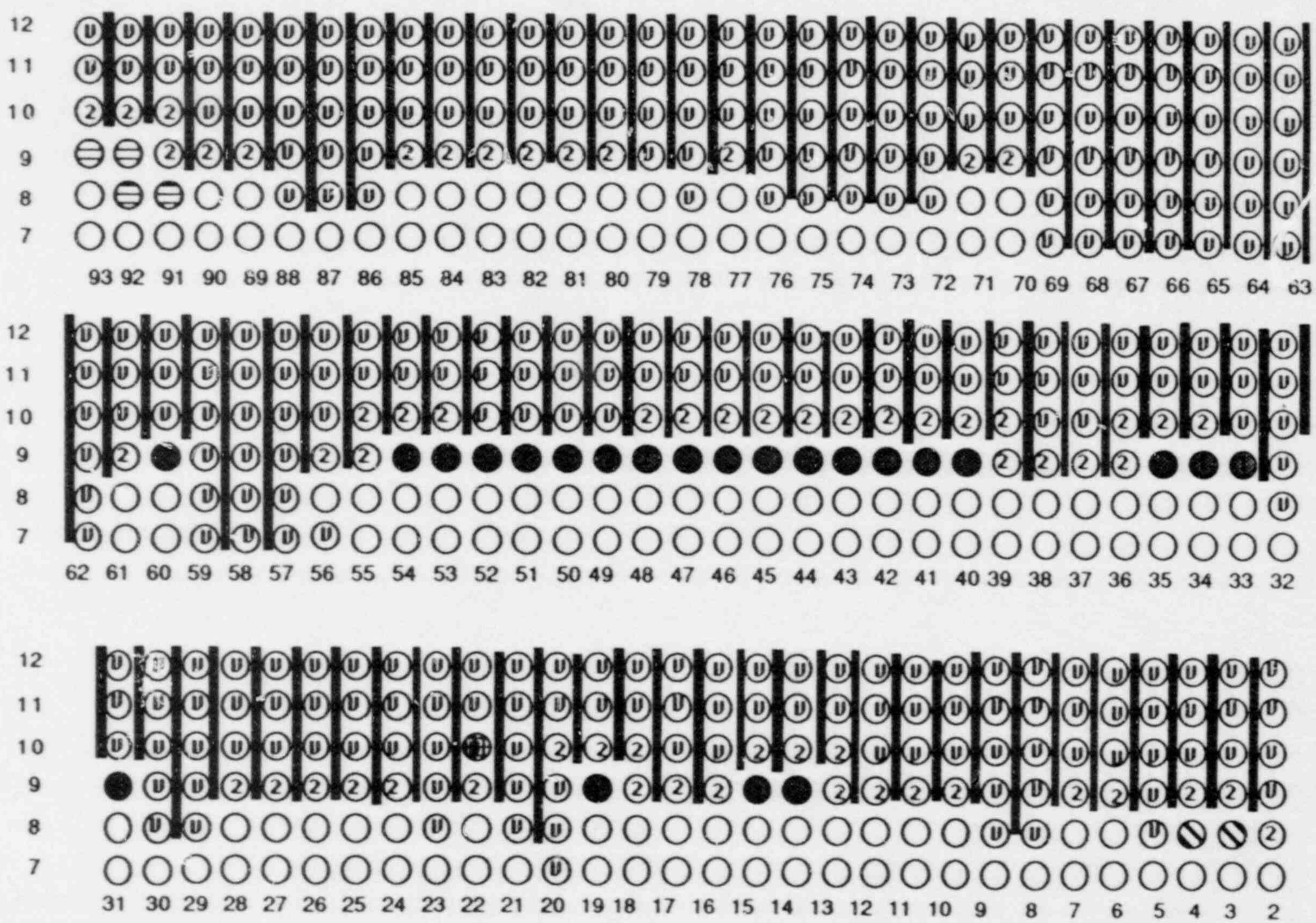
FIGURE 3-6

North Anna #2 (VGB): S/G -B
AVB Insertion and Plugging



- Numbers in circles represent the number of distinct AVB leg segments indicated "visible" from the tube. No entry or zero means no AVBs are "visible".

Ⓤ AVB Visible

⊕ Plugged (Wall Indication)

Preventively Plugged; Tube Denting Deformation Detected

Preventively Plugged; Top Support Plate Corrosion Detected

Preventively Plugged; No Detectable Denting

Preventively Plugged; TSP Corrosion Data Unreadable

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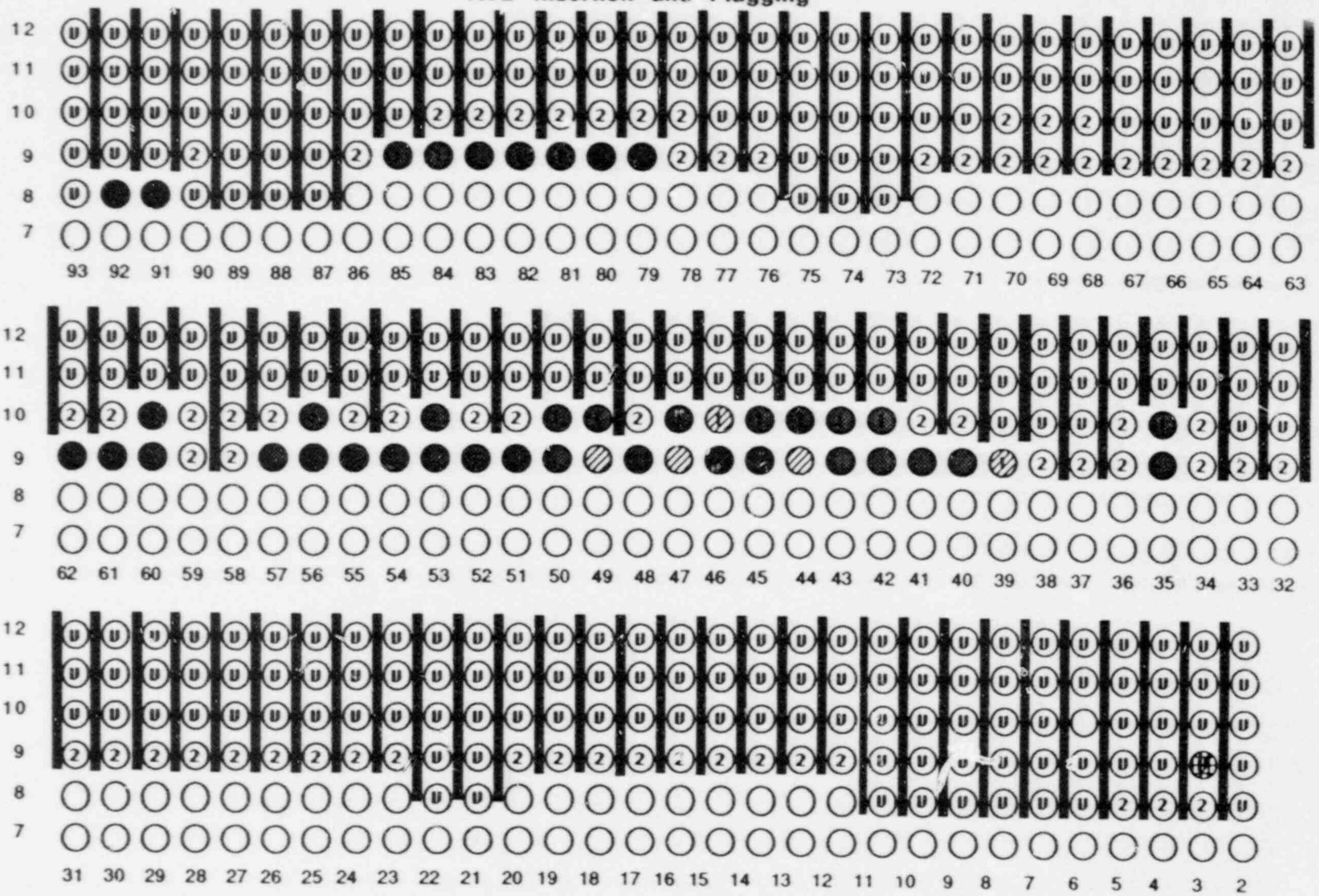
FIGURE 3-7

North Anna #2 (VGB): S/G-C

AVB Insertion and Plugging



- Numbers in circles represent the number of distinct AVB leg segments indicated "visible" from the tube. No entry or zero means no AVBs are "visible".

(U) AVB Visible

Plugged (Wall Indication)

Preventively Plugged; Tube Denting Deformation Detected

Preventively Plugged; Top Support Plate Corrosion Detected

Preventively Plugged; No Detectable Denting

Preventively Plugged; TSP Corrosion Data Unreadable

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Reference 1 (Section 4.2) also describes the method used to determine the tube stability ratios for Unit #1. Figure 4-1 provides calculated results developed from Table 4.2.3.3-1 of Reference 1, and shows the tube stability ratios for tube Rows 8 through 11 pre- and post-modification relative to the pre-modification ratio for R9C51. The modifications (principally the Downcomer Flow Resistance Plate or DFRP) are the same in both North Anna Unit #1 and Unit #2. The pre-modification stability analyses represent the North Anna #1 operating conditions at the time of the R9C51 tube rupture. The expected relative stability ratios are based on the nominal or test-based damping values for clamped tube supports and no local flow effects. Results for a low damping assumption with reduced dependence on void fraction and for constant damping (independent of void fraction) are also included in Figure 4-1. The relative stability ratio results with low and constant damping values are provided to assess the sensitivity of the downcomer modification to the damping dependence on void fraction.

A summary of the stability ratio reductions can be obtained from the Row 9 results of Figure 4-1 as follows:

Reduction in Stability Ratios
Due to Downcomer Flow Resistance Plane (DFRP) Modifications

Tube Damping Assumption	Stability Ratio Reduction
Low tube damping independent of void fraction	24%
Low tube damping with associated linear dependence on void fraction	15%
Nominal tube damping with test based dependence on void fraction	9%

FIGURE 4-1

Pre- and Post-Modification Stability Ratios Relative to R9C51

Tube Row	Stability Ratio Relative to R9C51		
	Nominal Damping	Low Damping	Constant Damping
	Pre-Modification		
Row 8	0.84	0.85	0.86
Row 9	1.0	1.0	1.0
Row 10	1.16	1.15	1.16
Row 11	1.45	1.44	1.45
	Post-Modification		
Row 8	0.76	0.72	0.66
Row 9	0.91	0.85	0.76
Row 10	1.08	1.00	0.90
Row 11	1.34	1.25	1.12

Notes:
1.) Ratios relative to Pre-Modification R9C51
2.) Calculations performed for Columns 51 in all rows
3.) Nominal Damping - Expected tube damping based on test results
Low Damping - Reduced tube damping dependence on void fraction
Constant Damping - Tube damping assumed independent of void fraction

If low tube damping (substantially lower than clamped tube test data) rather than local flow peaking effects were a contributor to the R9C51 tube rupture, the results of Figure 4-1 show that the downcomer modification is more effective in reducing stability ratios with the low damping assumption. Test data available since this evaluation show that local flow peaking effects are the dominant contributor to the R9C51 tube instability and that low tube damping assumptions are not necessary to explain the tube rupture.

From Figure 4-1, it is seen that the Row 9 post-modification (with DFRP) relative stability ratios of 0.91 are close to meeting the Reference 1 criteria for a 10% stability ratio reduction. This is the case for other Row 9 tubes having the same local flow peaking factor as R9C51. For unsupported Row 9 tubes with lower flow peaking than R9C51, as is expected to be the case, the 10% lower stability ratio criteria is satisfied. Unsupported Row 8 tubes with a relative stability ratio of 0.76 compared to R9C51 are acceptable even with peaking factors comparable to R9C51. The Row 8 tubes have negligible potential for flow peaking and thus can be expected to have relative stability ratios much less than 0.76. At North Anna #2, unsupported tubes in Row 9 or higher rows have been preventively plugged. Consequently, the highest relative stability ratio for a remaining active tube relative to R9C51 is less than 0.76.

4.2 Modeling at Tube Bundle Periphery

The use of the ATHOS code to model the U-bend region of North Anna Unit #1 was discussed in Section 4.2 of Reference 1. In addition to this basic information, certain limitations to ATHOS model were examined.

The ATHOS code does not include the capability to adequately model the presence of the AVBs in the U-bend region. However, Westinghouse has modified the code to include the capability to model the AVBs at a uniform depth of insertion via flow cell boundary resistance factors. Practical lower limits of cell size in the ATHOS code, however, prevent a fine grid representation of the AVB V-bar shape which, in turn, limits the accuracy of the AVB representation. ATHOS calculations have been performed with and without AVBs in the model. In addition, calculations show that the relative stability ratios for tubes near the center of the steam generator are essentially the same with or without AVBs in the models. The ATHOS AVB modeling sensitivity studies with uniform insertion show some tendency for the AVB resistance effect to lower tube gap velocities near the central regions and to increase velocities near the peripheral tubes. However, the magnitude of this effect is uncertain due to the limitations in ATHOS for modeling of the

AVBs. Further, the global flow resistance of staggered AVBs would be less than that for uniform insertion. Based on the sensitivity studies using ATHOS with and without uniformly inserted AVBs, the most reliable relative stability ratios (for actual steam generators with non-uniform AVB insertion depths) are expected using ATHOS models excluding AVBs.

Results of ATHOS models available at the time of the North Anna #2 evaluation indicated potential peaks in the flow velocities of a tube row at tube locations 2 and 3 columns from the periphery. These peaks were included in the relative stability ratio calculations for North Anna #2. Later ATHOS modeling results have shown that the peaks at peripheral tubes are a consequence of inadequate mesh in the model. Consequently, the use of the stability ratio peaks at peripheral tubes for the North Anna #2 evaluation provides further conservatism in this assessment.

5.0 AVB MAPPING AND SUPPORTED TUBES

5.1 Consistency Checks in AVB Insertion Mapping

From the AVB eddy current signal callouts, the AVB positions were evaluated. Since ambiguity can occur in the interpretation of the ECT data due to the inability of ECT to differentiate which side of a tube a "visible" AVB is located, and due to possible masking of signals due to copper deposits, other factors were considered to establish the location of the AVBs. These factors include consistency with the design of the AVB assembly, consistency of data for adjacent columns, and consistency of data within a tube column. In each instance, a conservative judgement was made, locating the AVB insertion depth to an evaluated minimum possible insertion depth.

5.2 Use of Eddy Current Data to Determine Supported Tubes

To conservatively accommodate these uncertainties, the following guidelines were adopted for defining tubes with AVB support:

1.) The eddy current data should indicate the presence of 2 AVBs such that the bottom apex of the AVB would be below the tube centerline,

OR

2.) When only AVB "visible" data is available for a tube column, only the larger row tube of two consecutive rows with AVB "visible" data is assumed to be supported by an AVB.

The first guideline was adopted since eddy current can detect AVBs in the vicinity of the tube, even though the AVB may not support the tube, as discussed in Section 3.3.

An example the second condition be seen in SG-B, Column 32 (See Figure 5-1). R8C32 and R9C32 are reported as "visible". By the second guideline, R9C32 is assumed to be supported, and is shown with single-sided AVB support. Although support is reasonably assumed for R9C32, both adjacent tubes, R9C31 and R9C33 were plugged, since it could not be determined on which side support was provided to R9C32.

Figures 3-5 through 3-7 show AVB insertion maps developed according to the above guidelines of the AVB "visible" analysis, "0, 1, or 2 AVB Present" analysis, as well as top tube support plate denting results of preventively plugged tubes.

6.0 CORRECTIVE ACTIONS

6.1 Preventive Plugging

After evaluating the tube support conditions (not supported, one-sided support, two-sided support) from the AVB mapping, the tube vibration analysis results were used to set the criteria for preventive plugging. The criteria for acceptable tubes were as follows:

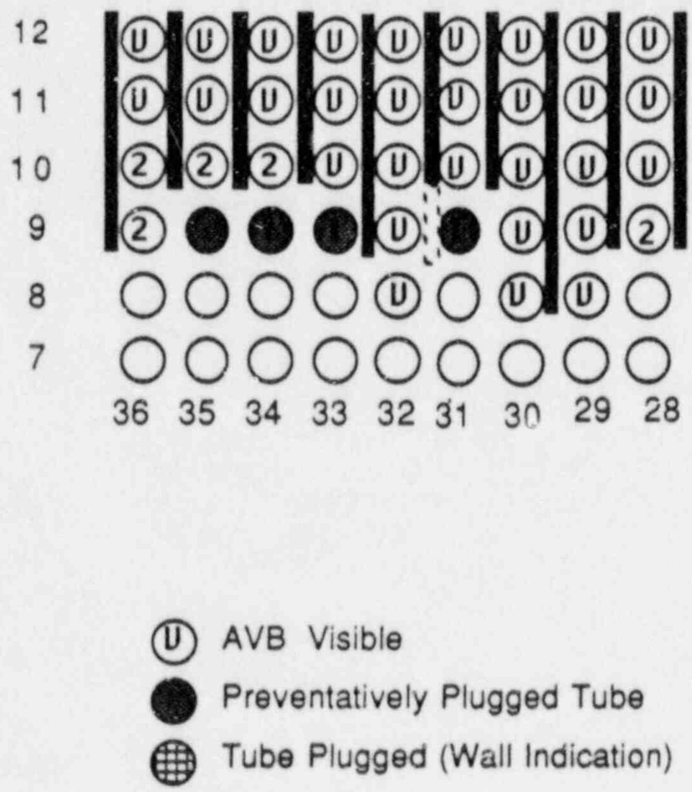
- Tubes with stability ratios less than 90% of North Anna #1 R9C51 are acceptable. This criterion was developed in Reference 1.

- All Row 8 tubes, with the exception of Columns 3, 4, 91, and 92 were judged to be acceptable without AVB support. This conclusion is based on the results of Figure 4-1 which show Row 8 stability ratios, except for the noted peripheral columns, to be less than 90% of North Anna #1 R9C51. Row 8, Columns 3, 4, 91, and 92 were judged to be acceptable provided that single-sided AVB support is assured based on the criteria for AVB support given in Section 5.1.

- All Row 9 or larger row tubes were judged to be acceptable provided that single-sided AVB support is assured based on the criteria for AVB support given in Section 5.1.

Figure 5-1

North Anna #2 (VGB): S/G -B
Isolated View of R9C32



- Numbers in circles represent the number of distinct AVB leg segments indicated "visible" from the tube. No entry or zero means no AVBs are "visible".

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These criteria are essentially identical with the North Anna #1 tube plugging criteria, except that the acceptability of single-sided support was extended from Row 9 to include all rows in the Unit #2 evaluation. The above criteria led to preventive plugging of all tubes without at least single-sided AVB support in Rows 9 or larger, and Columns 3, 4, 91, and 92 in Row 8. The tubes selected for preventive plugging are also shown in Figures 3-5 through 3-7.

6.2 Downcomer Modification

The mechanical, structural, and thermal-hydraulic implications of the Downcomer Flow Resistance Plate modification (DFRP) are identical to those of Unit #1 (See Reference 1). Figure 6-1 shows a typical DFRP.

7.0 CONCLUSIONS

Conservative criteria essentially identical to those of Unit #1 were used in the tube fatigue evaluation for Unit #2. Denting was conservatively assumed to have occurred at the top tube support plate of both the hot leg and cold leg sides of all Row 8 through 12 tubes. The installation of the Downcomer Flow Resistance Plate provided a stability ratio of all unplugged tubes which is at least 10% lower than the stability ratio of the failed R9C51 North Anna #1 tube, the criteria for acceptance. Preventive plugging associated with the tube fatigue mechanism was performed for 45 tubes in SG-A, 29 tubes in SG-B, and 44 tubes in SG-C, for a total of 118 tubes. Two tubes were also plugged for wall indications.

With preventive tube plugging implemented for all unsupported tubes in Rows 9 or larger, the maximum stability ratio of any remaining, unsupported active tubes is less that 0.76 of the North Anna #1 R9C51 tube. This result assumes that the local flow peaking factor for the remaining unsupported tubes is the same as found for R9C51. However, the unsupported Row 8 tubes show negligible potential for local flow peaking. Based on peaking factors determined for the R9C51 tube since this North Anna #2 tube evaluation was completed, the maximum relative stability ratio of 0.76 can be reduced to less than 0.55 of R9C51. Consequently, the acceptance criteria of achieving tube stability ratios relative to R9C51 of 0.90 or less are exceeded by a large margin.

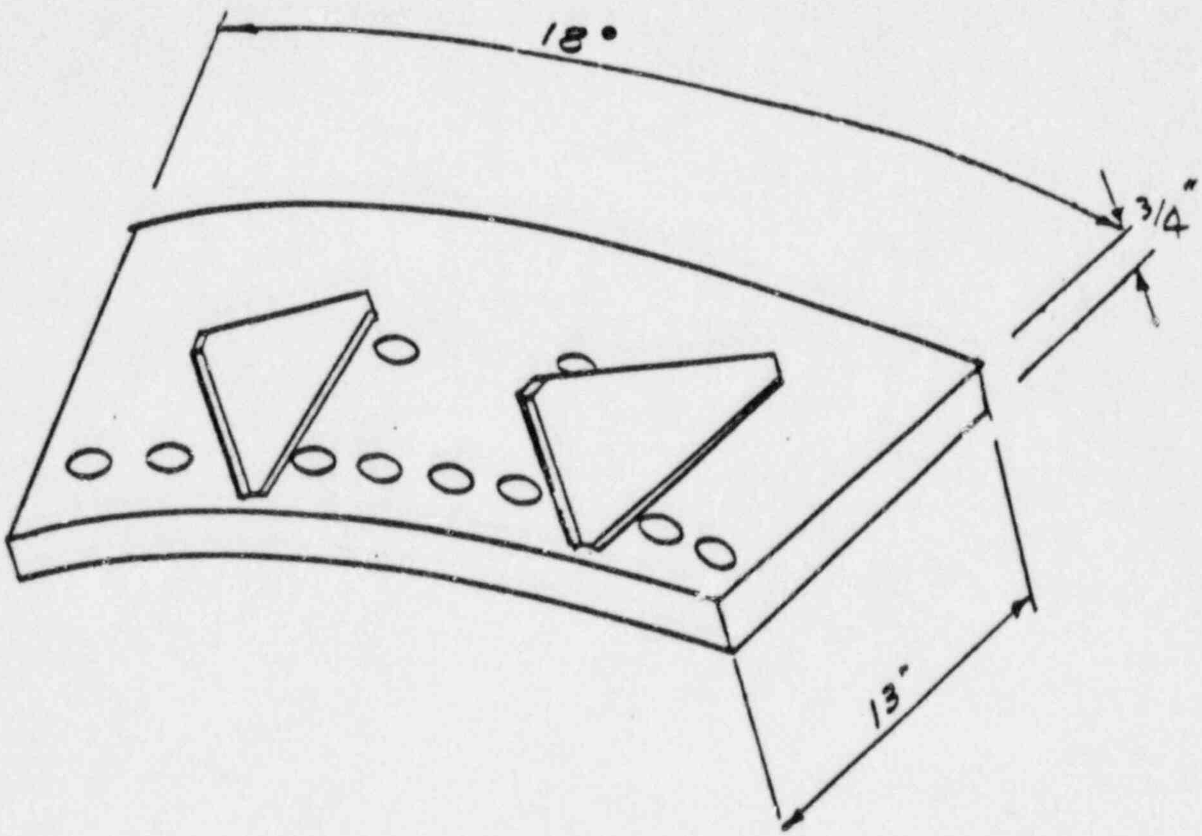

FIGURE 6-1 Typical Downcomer Flow Resistance Plate

8.0 REFERENCES

1.) WCAP-11601, "North Anna Unit 1 Steam Generator Tube Rupture and Remedial Actions Technical Evaluation", Westinghouse Electric Corporation NES, September, 1987.

2.) Bulletin 88-02, "Rapidly Propagating Fatigue Cracks in Steam Generator Tubes", United States Nuclear Regulatory Commission (NRC), Washington, D.C. February 5, 1988.