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U-bend Support Structure Verification and Mapping

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ABSTRACT

Support of the steam generator tube bundle in the U-bend or square bend by antivibration bars (AVB) or other structures is important for safe and efficient operation of the steam generators. Several industry events where the inadequate tube support was identified resulted in unplanned plant shutdowns and extensive tube repairs. Not controlling tube-to-AVB clearance is known as one of the most important contributors to the tube wear resulting from the fretting between the tube and the AVB.

Depending on the steam generator design, there may be several tens of thousands of tube-to-AVB intersections so any verification and evaluation of AVB signals require automated screening tool. Automated software normally used for the data analysis can be very efficiently used as the screening tool to determine exact position of each AVB within the U-bend thus providing the most important information which is the depth of insertion. Data obtained by the bobbin probe during regular eddy current examination of tubing can also be used to identify possible axial misalignment between two AVBs supporting the tube at the same designed location and to a lesser level to provide the qualitative information about the tube-to-AVB clearance.

Rotating probe can provide more information as it is the surface riding technique that has the spatial resolution so it is capable to quantify individual AVB signal unlike the bobbin probe that integrates impact of both AVBs into one signal. The highest precision particularly when measuring the tube-to-AVB clearance is obtained by the ultrasonic testing.

This paper deals with the development and application of eddy current and ultrasonic techniques intended to verify the locations of U-bend support structures, to identify and quantify possible anomalies and discrepancies between the designed and “as built” conditions. It focuses on the application of AREVA’s automated data analysis tool (AIDA) and delineates possible benefits to the utilities when having the full information of the U-bend supports.

1. BACKGROUND

The structures that support steam generator tube bundle in the U-bend or square bend region above the uppermost drilled, broached, lattice or eggcrate tube support have a significant role in contributing to the overall structural integrity of the steam generator. Whether these structures are in the form of the antivibration bars[1], fan bars, connector bars, diagonal or vertical straps, their role is to maintain the tube bundle in such conditions to minimize the tube vibration that could otherwise lead to the development of the fatigue related degradation or to tube-to-tube wear. Adequate and uniform depth of insertion of AVBs and adequately controlled clearance between the tube and the AVBs should not only minimize the vibration but also minimize the fretting that would result in the tube wall wear at the AVB intersection.

[1] The term *antivibration bar* or *AVB* is used throughout the paper to designate all types of support structures. Similarly, the term U-bend is used for both U-bend and square bend tube bundle geometries.

2. AVB MAPPING

The first step in verifying the depth of insertion of the U-bend structures and comparing the as-designed with as-built locations consists in the AVB mapping. Using the appropriate techniques during the regular inspection of the steam generator, the goal is to:

- detect and identify the signals that correspond to the AVBs
- identify and measure the characteristics of the signal that are relevant, such as signal amplitude, phase angle, duration (width, length), signal shape
- determine the location of the signals axially along the tube length relative to the easily detectable reference location

This information enables to determine the depth of insertion of the AVBs. One way to present the depth of insertion of the particular AVB, as found during the SG examination, is to plot the tubes that exhibit that AVB signal in the tubesheet map as shown in Figure 1. Comparing these as-found conditions with the as-designed conditions, the adequacy of the depth of insertion can be verified. The example in Figure 1 shows AV3 inserted deeper in the low column area where it starts in row 28. Same AV3 starts above row 30 in the high column area.

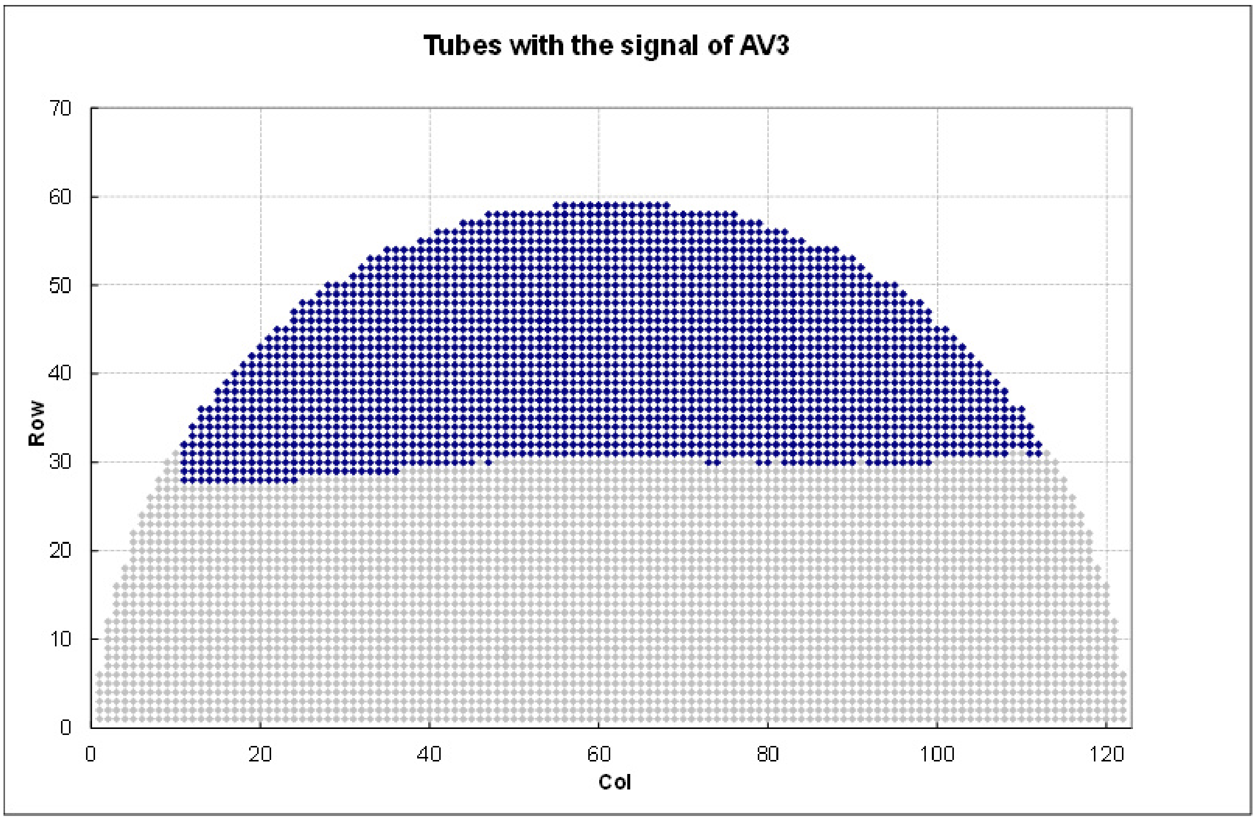

Figure 1. Example of the depth of insertion.

Situation like this was relatively common in earlier days of the nuclear industry. As the result of the improved assembling procedures and processes, it is not expected in the case of replacement steam generators and new builts.

AVB tube supports are identified through the presence of the low frequency signals of sufficient amplitude at or near the expected axial locations. All identified signals attributable to the AVBs are reported and shown on the tubesheet map for each of the AVB-to-tube intersections so the interpretation and the comparison between as-found and as-designed conditions can be made.

Particular attention needs to be paid when the AVB-like signals are identified further away from the expected locations, when signals are of smaller or significantly larger amplitude than expected or when their duration and/or shape is different from expected.

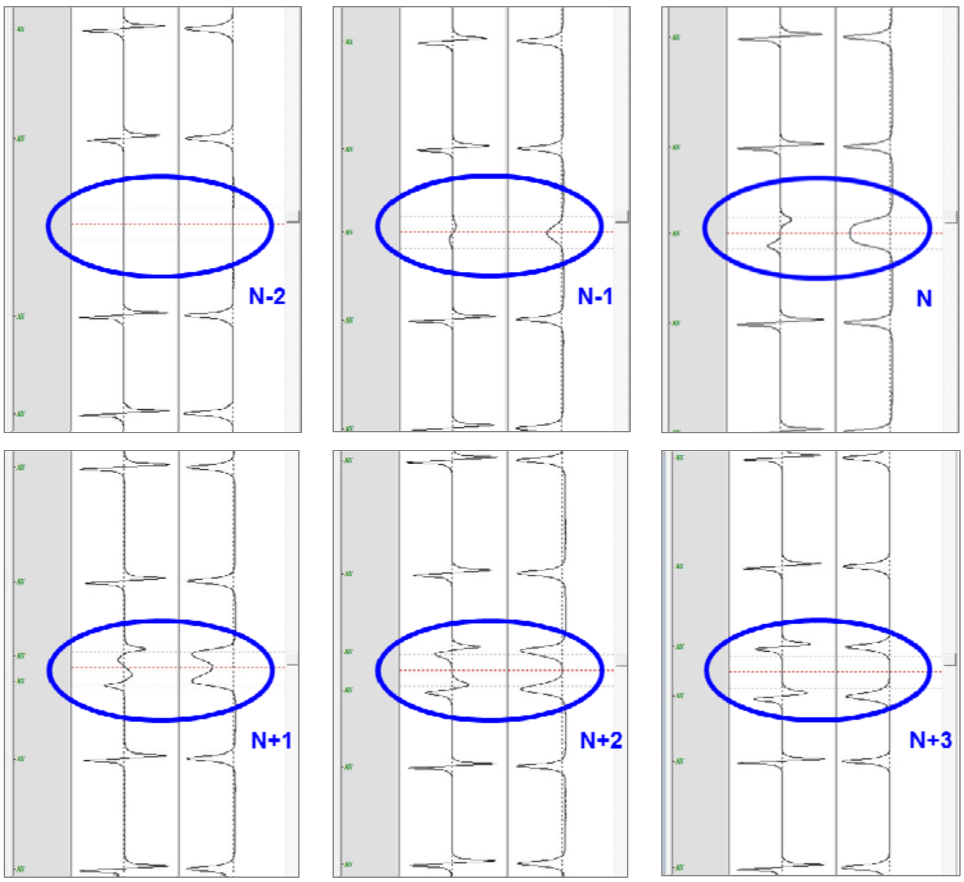

Figure 2. Example of the mid-AVB signal change.

Figure 2 illustrates the evolution of the signal of one AVB assembly in the zone marked with the blue ellipse. Signal of the same AVB assembly is shown throughout six adjacent rows labeled as N-2 through N+3. There is no AVB signal detectable in row N-2. Row N-1 shows a single low amplitude signal that is a proximity signal where the probe “sees” the AVB that supports the tube in the row above so no support of the row N-1 can be claimed. The single wide AVB signal in row N corresponds to the intersection of the bottom of the AVB assembly and the apex of the tube. Tubes exhibiting this type of signal are usually described as crossover tubes and they are supported by the AVB. Tubes in rows N+1 through N+3 show increasing separation between signals of the two legs of the same AVB assembly.

3. AVB MISALIGNMENT AND TUBE-TO-AVB GAP

3.1 AVB misalignment

The most of replacement steam generators and large number of older steam generators exhibit AVB signals of large amplitude and predictable shape so they are easily detectable. Example on the left-hand side in Figure 3 illustrates aligned AVB signal where the two AVBs, one on each flank of the same tube, are perfectly aligned. Bobbin probe signal is sharp and has a single continuous transition between two peaks if observed at the low frequency differential channel.

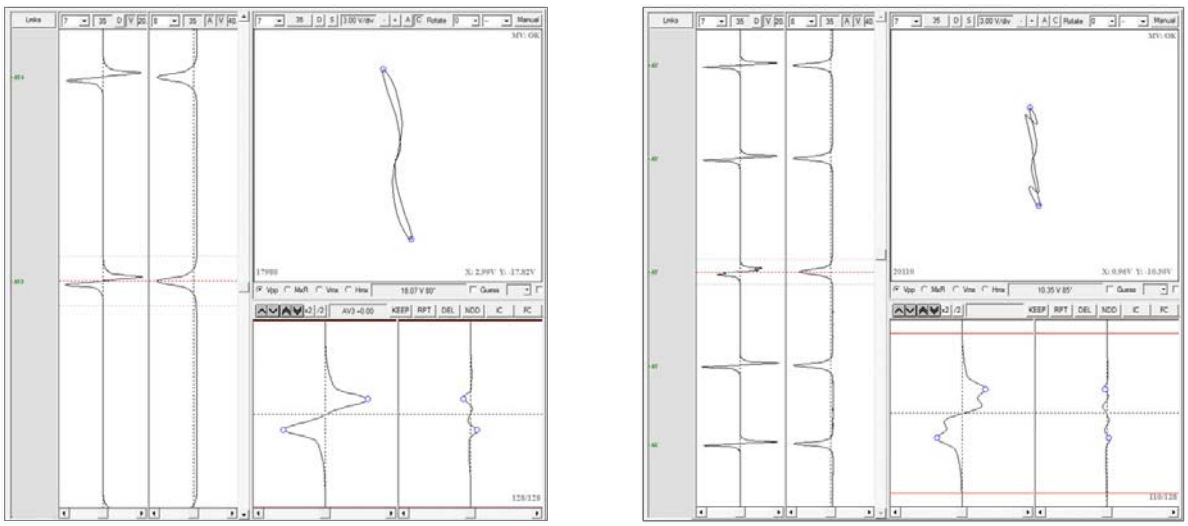

Figure 3. Example of aligned and misaligned AVBs.

Example on right-hand side in Figure 3 illustrates the case where two AVBs are not perfectly aligned exhibiting the particular signal shape that has a broken transition. This type of signal results in longer effective length (duration) between the two peak measuring points and in lower signal amplitude.

AVB misalignment is common in both older and new replacement steam generators and it is not known to have any negative impact on the tube integrity and steam generator operation. Nevertheless, the fact that the NDE techniques can identify the misalignment through measuring the signal amplitude and the length, can be used to deduce on possible gap variations between the tube and the AVB which is of much more importance than the misalignment itself.

Signal on the left-hand side in Figure 4 exhibits significant voltage drop compared to the regular AVB response. Differential signal is not sharp and it is characteristic for the misalignment. Simple automated peak-to-peak amplitude measurement will not indicate the misalignment based on the increased length as the signal length does not differ from the nominal. Additional measurement techniques and evaluators are needed in the cases like this one to characterize the signal appropriately.

Signal shown on the right-hand side in Figure 4 also exhibits significant voltage drop compared to the regular AVB response. Automated peak-to-peak measurement does not indicate any misalignment and manual review cannot identify the misalignment neither. Exclusion of the misalignment combined with the voltage drop indicates increased gap between the tube and the AVB.

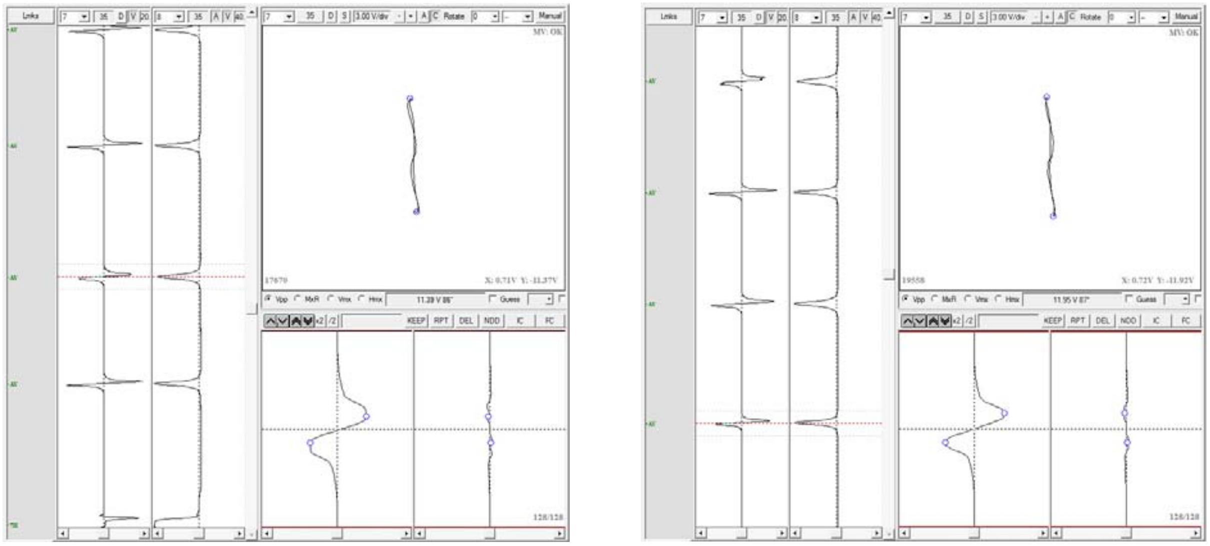

Figure 4. Example of possible misalignment and increased gap.

Discussion so far has been limited to the utilization of the bobbin probe results. The advantage of the bobbin probe is that it is commonly used during the regular inspection of the steam generator tubes with usually a large inspection scope covering frequently 100% of the tube bundle. Data is collected rapidly without adding any time and equipment to the planned inspection of the tubes. The data is analyzed automatically so the main results can be provided promptly.

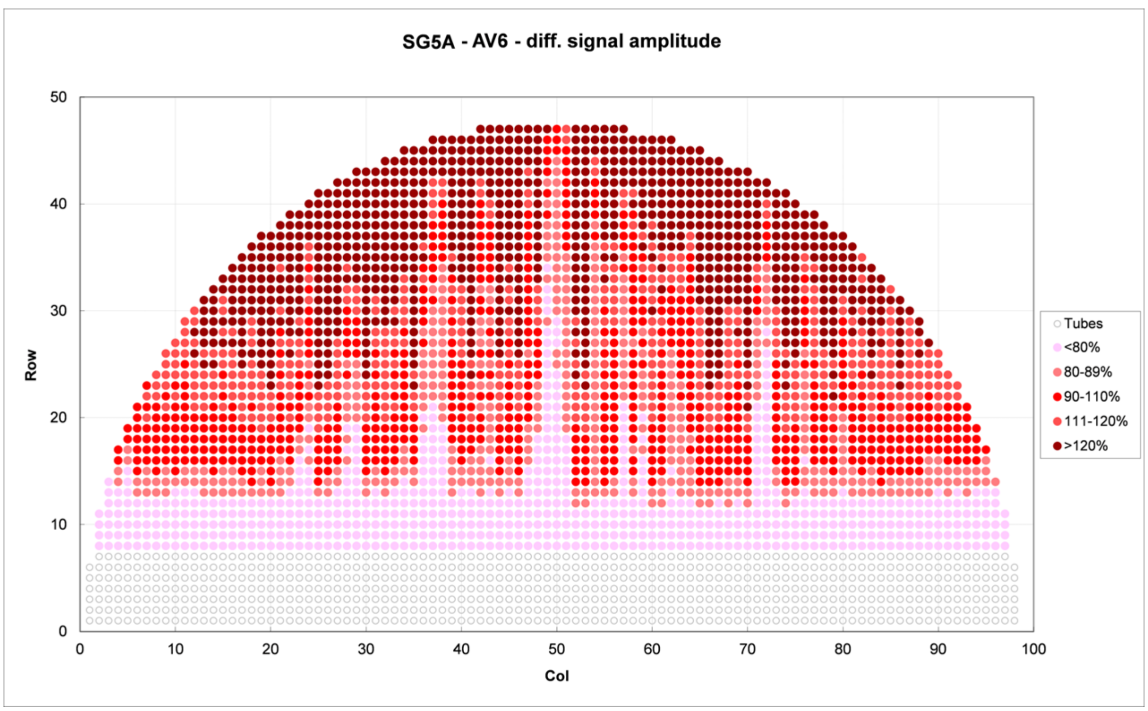

Figure 5. AVB signal voltage distribution.

Figure 5 shows the distribution of the AV6 signal voltage as measured on low frequency differential channel and shown in the tubesheet map. All AVB signals are shown as the percentage of the average signal and split in five groups. Lower amplitude signals are represented by the lighter colors and signals of low amplitudes are usually observed in lower rows. Vertical stripes of the lighter colors indicate misalignment or increased gap or both whereas the vertical stripes of darker color indicate reduced gap.

Bobbin probe is not a surface riding technique so it already includes a gap between the probe coil and the tube ID wall. Both AVBs are situated at the flanks bur probe can still have less than perfect centering relative to flanks especially in lower rows. All these points make bobbin probe the least favorable technique for quantifying the gap. Nevertheless, it can be used to identify and quantify the misalignment while some global qualitative conclusions can be made relative to the gap.

3.2 Tube-to-AVB gap

Tubes in the replacement steam generators are packed tightly usually in the triangular pattern with a small pitch resulting in a very small nominal gap between the tube and the AVB. Increased gap results in the drop of the AVB signal amplitude whether it is measured by bobbin, array or rotating probe.

3.2.1 Bobbin technique

Gap vs. voltage function is weak for the bobbin probe and the function is not linear. With bobbin integrating the impact of two AVBs within one signal, using bobbin probe for the gap assessment is very limited and can only be a global qualitative evaluation.

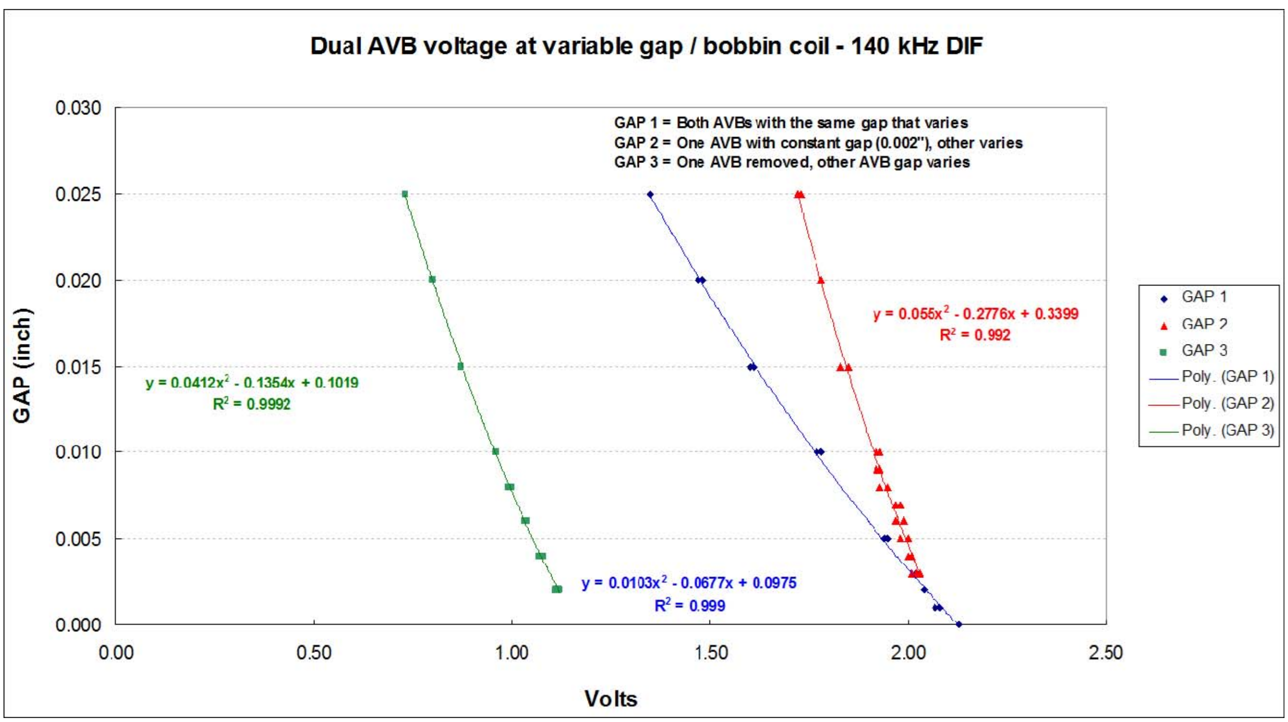

Figure 6. Bobbin probe gap measurement performance.

Figure 6 shows gap vs. voltage functions for the bobbin probe at 140 kHz differential frequency. Even with two AVBs where the gap varies by the same amount (GAP1, blue curve in the middle), the function is weak. It is much weaker for the most realistic case of one AVB with the constant gap of 0.002” and the other AVB that varies (GAP2, red curve on the right-hand side).

3.2.2 Array technique

Array probe is equivalent to the bobbin probe regarding the time needed to perform the inspection and, same as bobbin, introduces a variable gap between the coils and the tube inside surface due to its non-surface riding nature.

Unlike bobbin, array probe uses individual coils at the same axial intersection so it has a circumferential resolution needed to measure each AVB individually. Gap vs. voltage function on the right-hand side in Figure 7 represents the X-Probe® gap measurement performance of 50 kHz Axial channel. It shows roughly twice better performance compared to the bobbin probe.

Only one trial has been performed using array probe with limited number of data points.

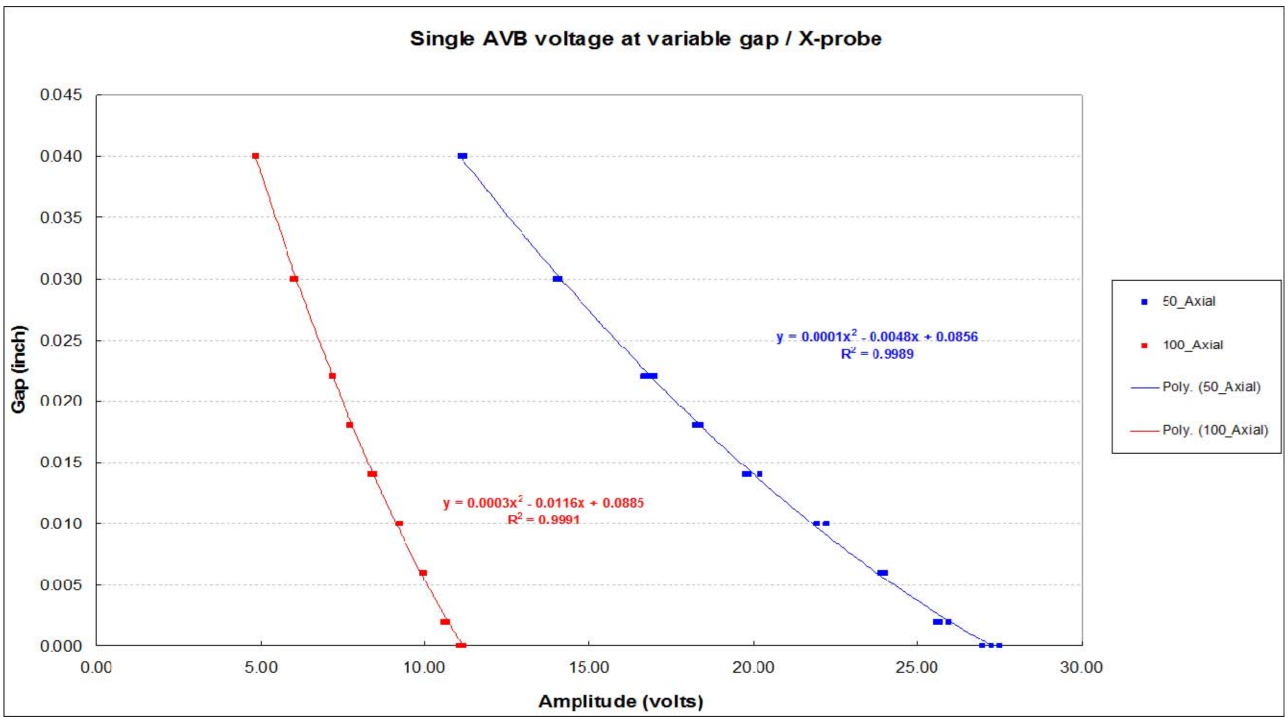

Figure 7. Array probe gap measurement performance.

3.2.3 Rotating probe technique

Rotating pancake probe showed performance superior to the array probe. Several trials were performed using different equipment and material and they all demonstrated the equivalent level of accuracy between the trials. Figure 8 shows the gap vs. voltage function for the rotating pancake coil at 35 kHz.

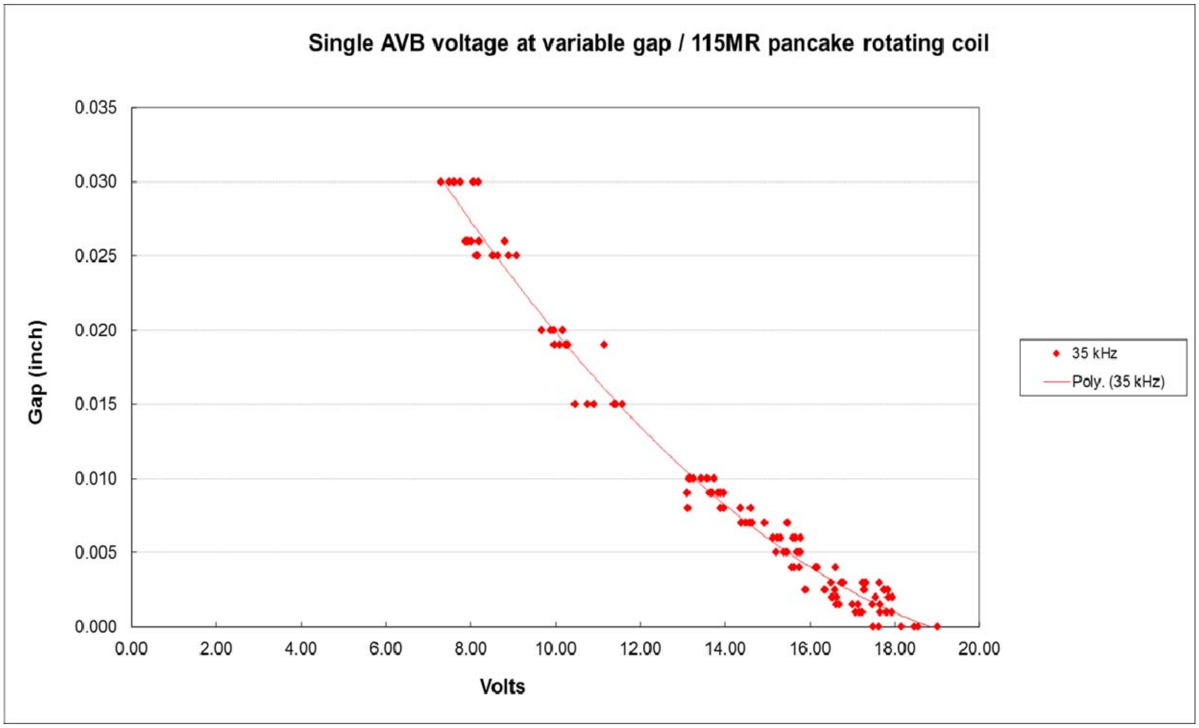

Figure 8. Rotating pancake probe gap measurement performance.

114 measurements were taken obtaining the RMSE of 0.0011”. Trials showed the accuracy 50% better than the array probe and demonstrated high confidence of the results when repeating the tests even when altering the essential variables.

3.2.4 Ultrasonic technique

Gap measurement applying the eddy current method whether it is bobbin, array or rotating probe technique is negatively impacted by the presence of wear or dings, by the deposit on the tube surface and by the additional gap introduced in the case of non-surface riding probes. Even without any of these factors present, the most accurate results are achieved by the ultrasonic technique.

The UT-360 equipment normally used for the examination of the steam generator tubes and the accompanying software have been adapted to provide an in-tube rotating U-bend UT technique to measure the tube OD-to-AVB gap distance but also to measure the tube OD wear and tube-to-tube gap distance.

Immersion technique uses a longitudinal wave with 0° incident angle and it demonstrated to work from inside the steam generator tube in U-bends down to 20 inch radius.

Figure 9 shows the rotating ultrasonic probe next to the U-bend steam generator tube. Low frequency (7.5 MHz) is used to put sufficient sound into the water to yield acceptable signal-to-noise results for the reflections from the AVB structures as well as from the adjacent tubes.

Figure 9. Rotating ultrasonic probe.

The gap reflections can be revealed by subtracting wall thickness waveforms that do not have reflections from the AVB gap (or adjacent tube) from the thickness waveform that contains AVB gap reflections in addition to the expected reflections generated by the tube wall thickness.

The data analysis results indicate that the technique is capable of sizing AVB gaps to an accuracy of 0.0005” (0.0127 mm) with a confidence of 94% using a two tailed confidence bind.

	Analyst 1			Analyst 2		
	Cal. Std.	750UB-4 u-bend	750UB-2 u-bend	Cal. Std.	750UB-4 u-bend	750UB-2 u-bend
max:	0.0005	0.0007	0.0006	0.0006	0.0009	0.0008
min:	-0.0006	-0.0004	-0.0004	-0.0006	-0.0005	-0.0004
ave:	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001
stdev:	0.0002	0.0003	0.0002	0.0003	0.0003	0.0003

Table 1. Data analysis results.

4. IMPLEMENTATION

Automated data screening tool is needed for AVB mapping providing it performs precise landmarking and/or detects signals attributable to AVBs, employs additional analysis methods capable of separating the AVB signals from other signals (MBM, deposit), writes AVB mapping results in a separate report and carries out automated verification of the results alerting if any unusual condition is identified. That tool can be successful if it uses the data acquired during the regular examination process and if it does not need any special or additional equipment. Significant challenge in AVB mapping is verification and post-processing of the results due to the large number of measurements.

Automated data analysis platform (AIDA) is used to screen AVBs and to generate the AVB mapping report. It is done in parallel to the regular automated analysis of the bobbin data without any involvement of the data analyst.

When discussing the gap measurement, the most important factor that will determine the applicability of the technique is the required accuracy. Bobbin probe is on one side of the scale providing the global qualitative information quickly for the large number of tubes. Ultrasonic technique is on the other side of the scale providing very precise information for much smaller number of tubes. The accuracy of the technique is inversely proportional to its execution speed.

CONCLUSIONS

U-bend support structure mapping and verification is beneficial to the utility as it provides the as-found conditions of the support structures in the upper part of the tube bundle. Adequate tube support is important for the safe and reliable operation of the steam generators. Controlling tube-to-AVB gap is important factor in preventing the tube-to-AVB wear so measuring the gap is needed when evaluating the existing wear and predicating its possible evolution.

Several eddy current techniques and immersion ultrasonic technique have been tested and implemented to perform either the AVB mapping and/or tube-to-AVB gap measurement. They confirmed the feasibility of the techniques where the choice of the technique depends of the level of accuracy that is required. AVB mapping is performed during the regular steam generator eddy current examination and the report generation is fully automated.