HIGH-RESOLUTION X-PROBE FOR 12.9 MM (0.51") DIAMETER I600 TUBING

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Abstract

A new high-resolution (HiRes) X-probe™ was designed to improve the performance of the X-probe for detection and characterization of lay-up induced, localized IGA in 12.9-mm diameter I600 tubing at the Bruce Nuclear Generating Station. The new probe contains two rows of twelve coils versus the original X-probe's three rows of eight coils and improves profiling, circumferential resolution and characterization of volumetric flaws. This higher coil density per row leads to better detection of localized volumetric flaws and short circumferentially oriented cracks as well as superior characterization of volumetric flaws, when compared to the original X-probe.

These changes to the probe design had an impact on the qualification of the probe, since they introduced modifications to an essential variable: number of coils, i.e., coil density. In February of 2008, after several prototypes, studies and field trials, the equivalency of the two probes was demonstrated for flaw detection. This paper summarizes these efforts and the improvements made with respect to the original X-probe, and with successive generations of the HiRes X-probe prototypes. The results presented here demonstrate superior resolution and flaw discrimination for the examination of 12.9-mm diameter I600 SG tubing, which should also be applicable to tubing of similar diameters.

Keywords

X-Probe, High-Resolution X-probe, HiRes X-Probe, Inconel 600, I600, 12.9 mm, 0.510", CANDU

1 INTRODUCTION

The development of the X-probe was aimed at obtaining a single-pass probe with similar capabilities to that of rotating probes. For the most part, this objective has been achieved, and the probe is being used routinely for the inspection of CANDU steam generator tubing with excellent results. However, some aspects of the X-probe for 12.9-mm diameter Inconel 600 tubing required improvement.

A new high-resolution (HiRes) X-probe™ has been designed to improve the performance of the X-probe for detection and characterization of lay-up induced, localized intergranular attack (IGA) in 12.9-mm diameter Inconel 600 tubing at the Bruce Nuclear Generating Station (NGS). The new probe contains two rows of twelve coils versus the original X-probe's three rows of eight coils to improve profiling, circumferential resolution and characterization of volumetric flaws. This higher coil density per row leads to better detection of localized volumetric flaws and short circumferentially oriented cracks as well as superior characterization of volumetric flaws, when compared to the original eight-coil X-probe.

Since the new probe design introduced modifications to essential variables such as: number of coils and coil density, the original X-probe qualification no longer applies. In February of 2008, after several prototypes, studies and field trials, the equivalency of the two probes was demonstrated for flaw detection. This paper summarizes these efforts and the improvements made with respect to the original X-probe, and with successive generations of the HiRes X-probe prototypes. The results presented here demonstrate superior resolution and flaw discrimination for the examination of 12.9-mm diameter I600 SG tubing, which should also be applicable to tubing of similar diameters.

This paper will present descriptions of the original and new designs, signal comparisons between the original and new probe, issues encountered during probe development and a brief summary of the demonstration of equivalency between the original and new probe.

2 BACKGROUND

2.1 Original X-Probe Design

The original X-probe, developed in 2000, featured a robust design, was available for full length and tight radius (low row) applications and had been field-tested, qualified and proven over many inspection cycles.

The original design of the X-Probe for 12.9 mm diameter I600 steam generator tubing is shown in Figure 1. It contains three rows of eight coils [1, 2]. The centre-to-centre coil spacing in each transmit-receive (T/R) unit was optimized for the damage mechanisms known to be prevalent at the time the probe was originally designed. The coil spacing of the circumferentially-oriented transmit-receive units was not optimized for the detection and characterization of short volumetric flaws. This became an issue with the introduction of lay-up induced, localized IGA at BNGS. Having eight circumferentially aligned channels can be an important limitation if detection and profiling of short circumferential cracks is an issue. Additionally the axial and circumferential responses to a volumetric flaw are not inherently the same with this coil set, further complicating analysis of IGA and other short length volumetric flaws.

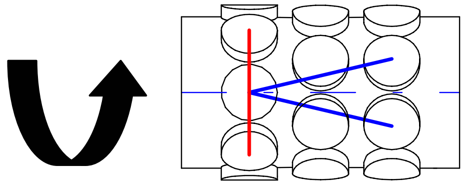


Figure 1 Original X-probe with 3 rows of 8 coils.

2.2 High Resolution X-Probe

The HiRes X-probe was developed in 2004 in an attempt to improve the performance of the probe in the following areas: improved capability in characterizing volumetric flaws, profiling capabilities and circumferential resolution of the circumferential detection mode.

The HiRes X-probe, designed with twelve coils per row, as shown in Figure 2, provides better symmetry between the axial and circumferential responses [3]. Centre-to-centre coil spacing between the circumferentially oriented coils, when projected on the tube wall, is approximately the same as in the axially oriented coils; therefore, the size of the actual detection regions of the circumferential and the axial modes are comparable.

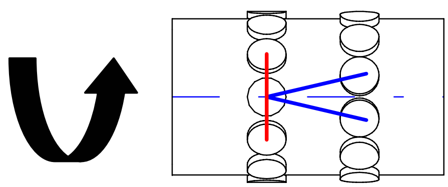


Figure 2 HiRes X-probe with 2 rows of 12 coils.

3 CHARACTERIZATION OF VOLUMETRIC FLAWS

The analysis technique for the original X-probe requires that the amplitude response from a 30% deep, 12.9-mm (0.5-inch) wide concentric groove be normalized to 5 volts for the circumferential mode channels and to 3.5 volts for the axial mode channels. These settings were intended to compensate for the different responses between the circumferential and axial channels that result from the different transmit-receive coil spacing in the axially and circumferentially oriented coil pairs when projected on the tube wall. However, since the distance between coils in the HiRes X-probe is comparable for both modes of detection, there is no need for different settings and the scales are set at 5 volts for both axial and circumferential modes.

Volumetric similitude is defined as the ability of the probe to provide amplitude responses to a volumetric indication from the axial and circumferential channels that are as similar as possible when calibrated to a common reference indication. Figure 3 compares the original X-probe responses and the HiRes X-probe responses to 1-mm diameter holes. In this case, both the circumferential and axial detection channels have been calibrated to the same voltage on the same reference indication (30% OD Groove). The ratio of axial channel response to circumferential channel response is close to unity for the HiRes X-probe whereas it is greater than 2:1 for the original X-probe.

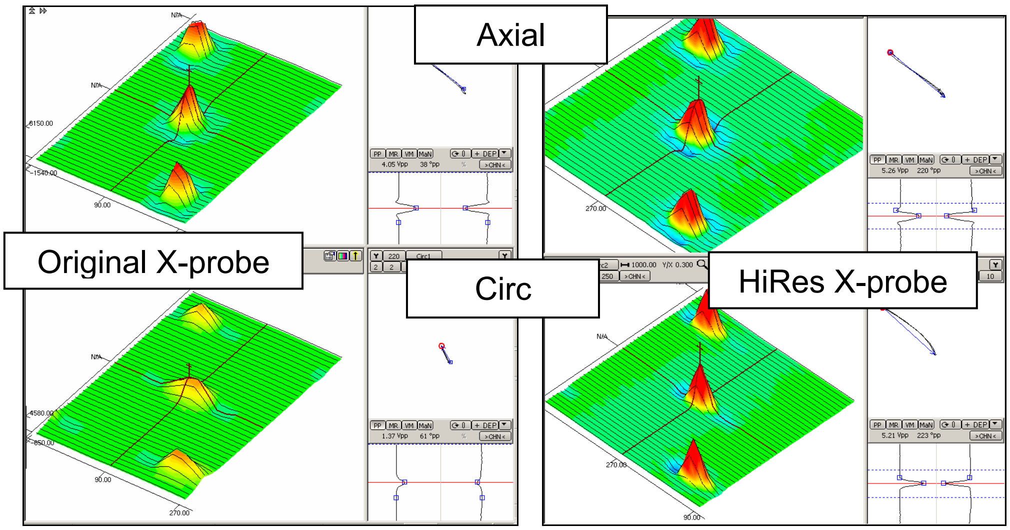


Figure 3 Axial and circ. channel responses of the original X-probe and the HiRes probe to 1-mm diameter through wall holes.

Figure 4 illustrates signals from volumetric flaws attributed to IGA detected above the top-of-tubesheet (TTS) with both probes obtained during the probe's field trial. The axial and circumferential mode responses of the HiRes X-probe to this volumetric flaw are equivalent, thus allowing unambiguous characterization of the flaw type. However, for the original X-probe, the axial mode amplitude is just less than twice that of the circumferential mode, making it more difficult to characterize the flaw type.

The indication shown in Figure 4 was found to be a volumetric pit with a very short circumferential extent. This flaw is difficult to detect on the circumferential channels of the original X-probe but is easily detectable with the HiRes X-probe.

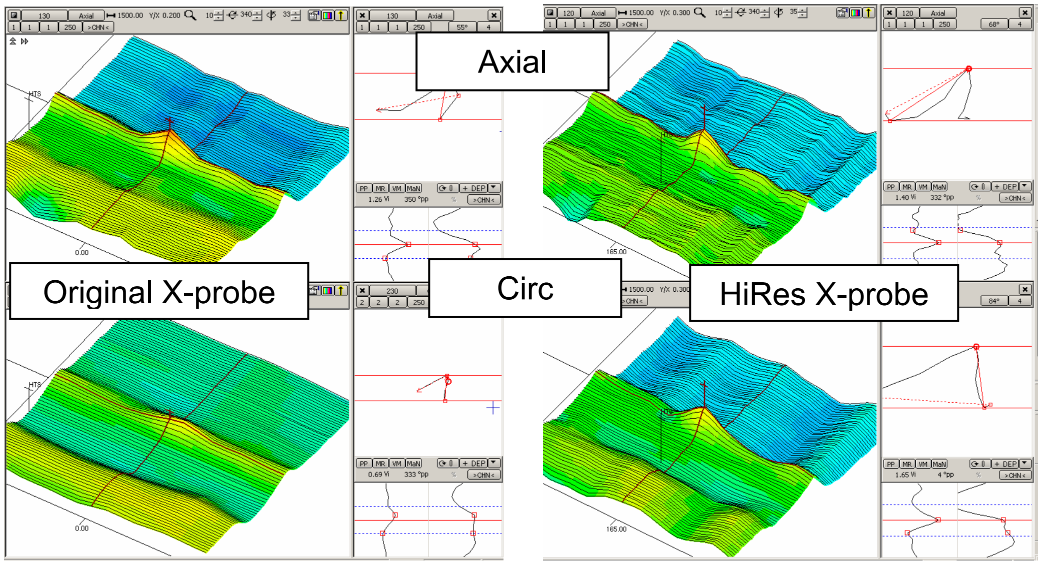
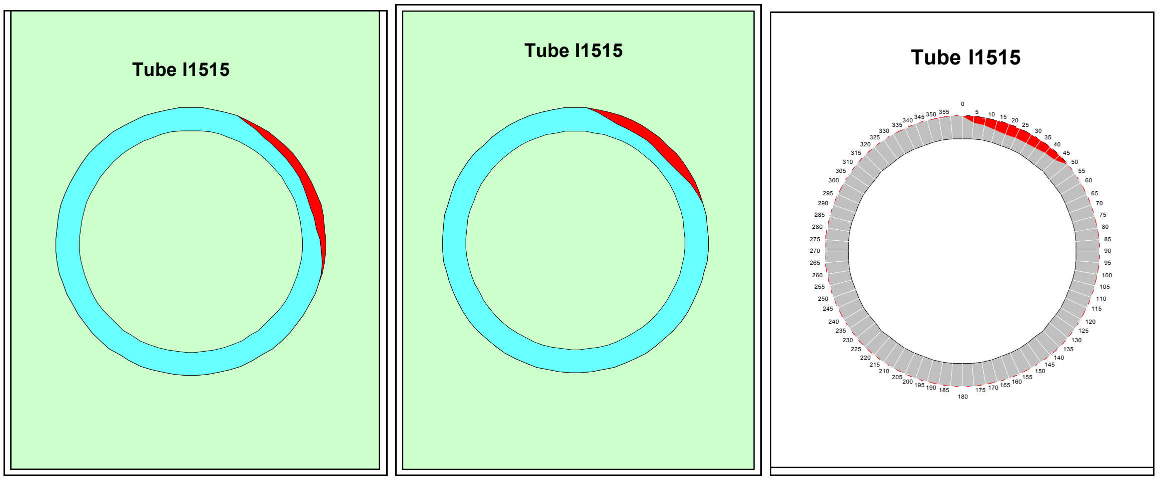


Figure 4 Comparison of the original X-probe and the HiRes X-probe response to a short volumetric indication at the TTS.

4 CRACK PROFILING

Previous studies have shown that array-probe data can be effective for producing two-dimensional profiles of circumferential cracks and estimating crack percent-degraded area (PDA) [4]. An algorithm based on correlations between crack depth and eddy current responses (vertical component) and a polynomial approximation is used for crack profiling. The original X-probe algorithm uses a 16-order polynomial that utilizes the actual response from the eight circumferential channels as well as the circumferential interpolation channels. This method assumes that the circumferential interpolation approximates the true eddy current response from the X-probe. In the HiRes case, the algorithm uses a 24-order polynomial since the probe has 12 circumferential channels.

Figure 5 shows an example of profile estimations of an outside diameter (OD) stress corrosion crack (SCC) with both probes compared to destructive examination results. The original X-probe tends to overestimate the circumferential extent of these types of flaws because of the small number of measurement points around the circumference, whereas the HiRes X-probe permits a more accurate estimate. In this example, the depth and circumferential extent were 44% and 70° with the original probe and 48% and 50° with the HiRes probe, versus 54% and 44° measured by destructive examination.



(a) (b) (c)

Figure 5 Graphic representations of crack profile a) Original X-probe, b) HiRes X-probe, c) Destructive examination.

5 SYSTEM IMPROVEMENTS

Although the design objectives for the probe were met, the initial field-testing results of the probe showed elevated levels of high frequency noise, suggesting that such a probe concept might have been impractical. It was hypothesized that the scale factor required to produce calibrated signals in the HiRes X-probe was greater than that required for the original X-probe. Extensive studies were conducted to determine the root cause of this noise issue, which included using alternative instrument configurations, optimized drive voltages, increased amplifier gain and slight modifications of the coil design to provide higher output. The results were promising and, overall, the studies showed that the poor signal quality seen in the field data could be attributed to a source not necessarily inherent to the intended design of the probe. It is important to note that this noise was not seen in laboratory trials and that the noise found in the field trials was intermittent in nature.

Ultimately, the noise reduction and signal improvement measures were successful, with noise levels on the subsequent field trial of the HiRes X-probe being comparable to those from the original X-probe. The field tests conducted during the 2007 October outage of Bruce NGS produced excellent results and the noise issues that had been identified in previous studies were not present. The main reasons for this improvement are twofold: the probe design had been modified to provide more output and the introduction of the MIZ-80*iD* instrument. This instrument reduces the susceptibility to external noise by eliminating the slip-rings and extension cables. Figure 6 illustrates the levels of noise obtained during the subsequent field trial with the HiRes probe after the system changes to the noise levels observed in field trials prior to the system changes.

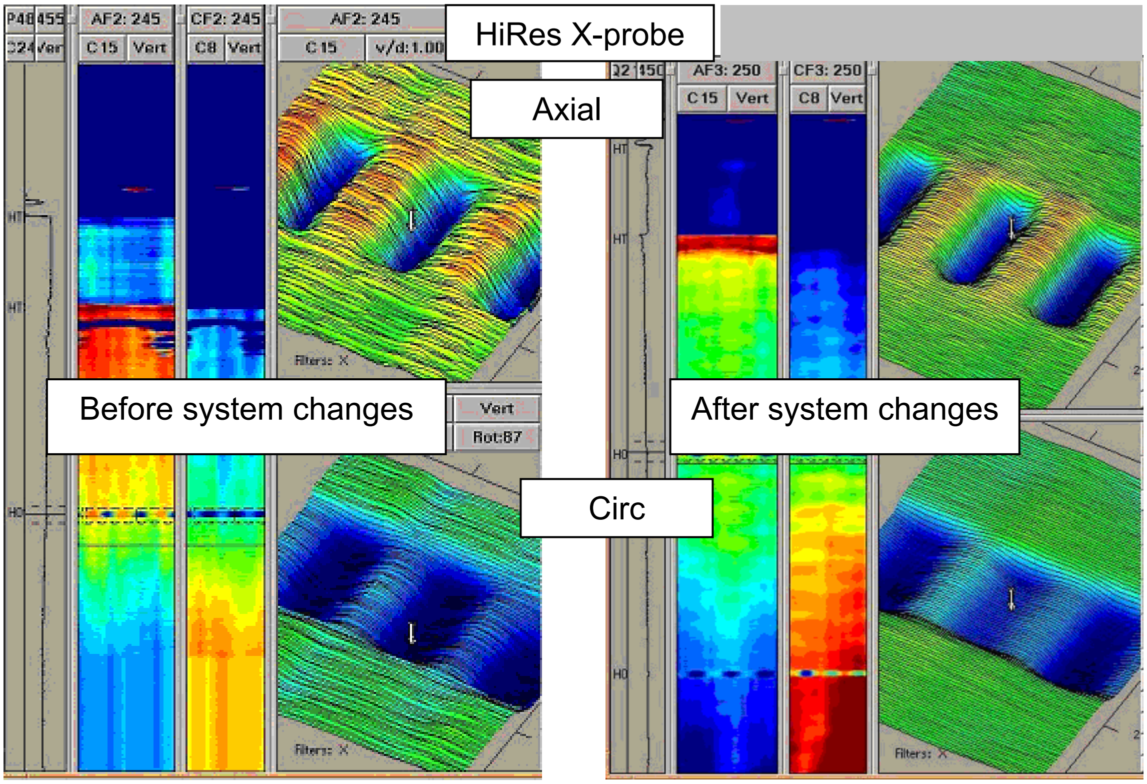


Figure 6 High-resolution X-probe field data showing reduced noise levels before and after system changes.

6 EQUIVALENCY DEMONSTRATION

A demonstration of probe capability was required prior to using the HiRes probe for examinations of record. The approach chosen was to demonstrate the equivalency (or superiority) of the HiRes X-probe to the original X-probe.

The studies reported here used a larger number and a variety of machined specimens for a more systematic comparison of the signal responses from both probes to different flaw geometries and types. The data were collected using acquisition techniques consistent with those used under field conditions.

Table 1 summarizes an amplitude ratio comparison from the HiRes X-probe to the original X-probe with the two main detection frequencies: 250-70 kHz mix and 450 kHz.

Based on the samples tested, the ratio between the circumferential amplitude responses from circumferentially oriented flaws is 1.8 and 2.1 times larger at 250-70 kHz mix and at 450 kHz, respectively.

The amplitude responses of the axial channels from simulated fretting-wear scars, with and without the influence of the support plate respectively, were also compared. As indicated earlier, the calibration value in the axial mode for the HiRes X-probe is 5 volts whereas a value of 3.5 volts was used for the original probe. Hence, the voltages with the HiRes X-probe are expected to be approximately 40% higher than the voltages with the original X-probe. An additional column with the voltages re-normalized to equal values is added to the table to allow an un-biased comparison between the probes without the effect of additional gain caused by calibration. Table 1 lists the ratios between the probe responses before and after the scaling factor has been applied. On average, the HiRes X-probe showed an improved performance at the 250-70 kHz mix of 1.3 times without the support plate and of 1.4 times when the support plate was present. This improvement in probe performance is due to the smaller angle and slightly smaller distance between the coils in the T/R units, as well as a smaller detection area. The combination of these two factors results in better probe response to localized flaws. Furthermore, the results show that the HiRes X-probe is less influenced by the presence of the support plates at the lower frequency. When the scaling gain due to the new calibration method is factored in, the improvement is similar to that of the circumferential oriented channels: that is, about 1.8 times larger amplitude signals.

The responses from localized flat-bottom holes, axially oriented flaws and pit-like IGA produced similar results and are listed in the final line of Table 1.

Table 1
Summary of Average Ratios Between the Responses from the HiRes X-Probe and the Original X-Probe to Different Types of Flaws

	250-70 kHz		450 kHz	
Flaw Type	**Average Ratio**	**Average Ratio Adjusted**	**Average Ratio**	**Average Ratio Adjusted**
Circumferential oriented flaws	1.8	n/a	2.1	n/a
Fretting wear w/o support	1.8	1.3	1.7	1.2
Fretting wear with support	2.0	1.4	1.7	1.2
Volumetric or axial flaws	1.7	1.2	1.6	1.1

The unadjusted voltage comparisons are illustrated in Figure 7. The figure shows the responses from the HiRes X-probe versus the original X-probe voltages for all of the flaws used in this study. The trend lines have a coefficient of 1.8 for the 250-70 kHz mix channels and 1.75 for the 450 kHz channels.

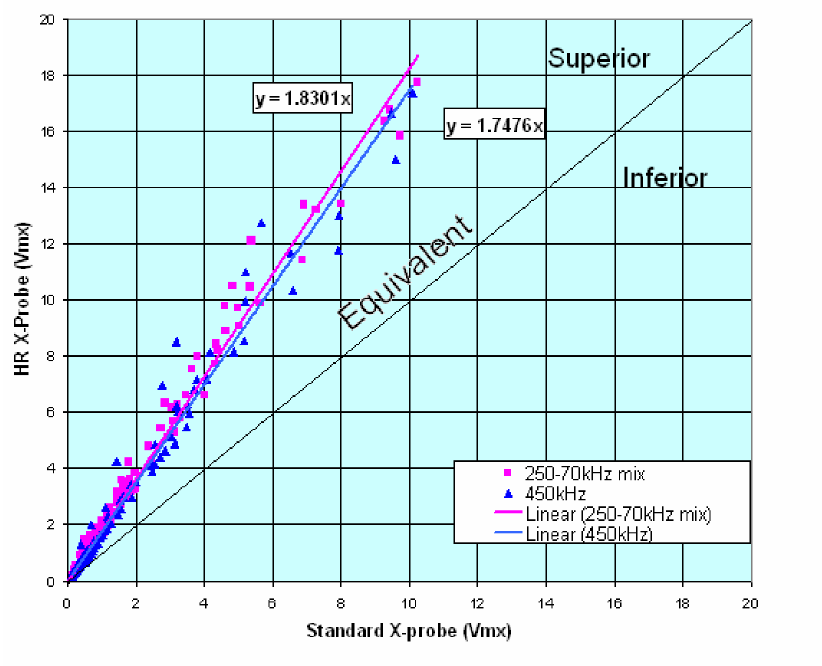


Figure 7 Plot of the responses for all tested flaws obtained with the HiRes X-probe versus the responses from the original X-probe.

7 CONCLUSIONS

The HiRes X-probe has been demonstrated to possess superior design features to the original X-probe: that is, the higher coil density leads to better detection of flaws with short circumferential extent, such as pit-like volumetric flaws, short circumferentially oriented flaws, etc. The HiRes X-probe, therefore, is able to characterize volumetric flaws better than the original probe. It also has better crack profiling ability.

The new probe is a viable and effective tool for the inspection of 12.9-mm-OD I600 tubing and has been demonstrated to have a performance equivalent or superior to its predecessor X-probe.

8 ACKNOWLEDGEMENTS

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