THE EFFECTS OF ID MAGNETITE DEPOSITS ON STEAM GENERATOR TUBE EDDY CURRENT SIGNALS

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Abstract

The presence of primary-side magnetite deposits in CANDU® steam generator tubes poses a significant challenge to the analysis of eddy current inspection data. In principle, magnetite shields the tubing from the eddy current probe, diminishing its sensitivity to flaws. Since a probe's flaw detection and sizing performance is typically assessed with the use of clean laboratory samples, the shielding effect can become significant enough to affect both the probability of detection (POD) and sizing accuracy of the probe. Hence, there is a need to understand the relationship between inside diameter (ID) magnetite fouling and the actual flaw signals from typical flaws, such as pitting corrosion and fretting wear.

The studies presented in this paper were performed with bobbin and X-probe data in both Inconel 600 and Incoloy 800 tubing. In comparison with clean tubes, ID deposits have a definite impact on both the detection and sizing capabilities of each probe. In all cases, the flaw signal amplitudes tend to decrease with increasing amounts of ID magnetite fouling. This also causes the probes to undersize the flaws in the fouled tubes. The resulting effect can be expressed in terms of a reduction factor versus a measured quantity with the bobbin probe, called V_{shield}, which can be used to determine the correction factor for sizing flaws.

Given the difficulty in controlling the error sources in laboratory experiments on field-pulled tubes with deposits, the resulting scatter in the data makes the extraction of useful relationships between fouling and flaw signals difficult. This paper, therefore, presents an approach that consists of a combination of computer modelling, laboratory experiments on pulled tube samples, and field-data analysis to allow trends and relationships to be developed for a range of ID magnetite loading and thickness beyond that available in pulled tubes. A 3D electromagnetic finite element model was developed for studying the effects of ID magnetite fouling on eddy current signals from a variety of flaw types. A means for expressing the shielding effect was developed, along with a method for implementing correction factors to improve flaw-sizing accuracy.

KEYWORDS: ID magnetite, eddy current inspection, flaw sizing, POD, flaw detection

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1. INTRODUCTION

The presence of inside diameter (ID) magnetite deposits has posed a challenge to inspectors of steam generators (SGs) in CANDU nuclear generating stations (NGSs). Past work [1] has shown that ID magnetite creates a shielding effect on eddy current probes, reducing their potential for detecting flaws. Given the limited ability to produce artificial ID magnetite in the laboratory representative of that found in the field, flaw detection and sizing performance are typically assessed with the use of clean laboratory samples. To account for the effects of ID magnetite, therefore, it is necessary to establish a relationship between ID magnetite fouling and the actual flaw signals. Another important goal is to account for sizing changes measured between outages. Magnetite deposition or cleaning between two inspections can affect flaw responses significantly, thereby affecting growth-rate estimates.

Electromagnetic finite element (FE) modelling is necessary to overcome the effects of noise sources and to allow trends and relationships to be developed for a range of ID magnetite loading and thickness beyond that available in pulled tubes from the field. This paper presents the results of the FE models, which predict a decrease in flaw signal amplitudes with increasing amounts of ID magnetite thickness and/or permeability in either Inconel 600 or Incoloy 800 tubing. The simulations are based on various flaws of interest in these types of tubes. Bruce NGS SG field data, taken both before and after ID cleaning, are analysed to assess the influence of ID magnetite on real flaws, and to compare with the relationships obtained from the model. The results are used ultimately to develop correction factors to compensate for the effects of ID magnetite on flaw signals and sizing estimates.

2. SIMULATING FLAW RESPONSES IN CLEAN TUBES

The FE models for Inconel 600 and Incoloy 800 tubing were developed with Infolytica Corporation's MagNet 6 software. The modelled flaw types were based on typical flaws found in the field. Three flaw types were selected for 12.9-mm diameter Inconel 600 tubing: scallop-bar fretting wear, round-bottom pits, and circumferential flaws, each with four different percent through-wall (%TW) depths. Note that support plates were not modelled in any of these cases.

To obtain results comparable with laboratory data, the modelled signals were calibrated in a manner similar to that performed during an actual tube inspection. For the bobbin probe, the amplitude of the signal from a 10% deep through-wall (TW) concentric groove was set to 5 volts at 240 kHz (simulating Ch 4). The differential signal was set to 10 volts on the same groove at 240 and 480 kHz (simulating Ch 3 and Ch 1). The phase angle from an ID groove was then set with a horizontal-left response. For the X-probe, the 250 kHz axial-channel amplitude from a 30% OD groove was set to 5 volts, with the expansion-transition signal set horizontal-left.

Very good agreement was obtained between modelled and laboratory signals for both probes. Flaw depth response curves are useful for validating modelled results against laboratory data. Figure 1 provides comparisons between modelled and laboratory fretting wear and pitting vertical amplitude (V_{mx}) response curves in clean tubes for the bobbin probe. Similar comparisons were made for the X-probe, including circumferential flaws. In all cases, the models agree very well with laboratory data. In addition, the bobbin probe Ch 1 (480 kHz) phase response curve for frets is plotted in Figure 2, along with laboratory measurements. Considering that phase measurements have inherently higher levels of variance, caused by the influence of horizontal noise, the small discrepancies between the model and laboratory data are minor. Consequently, the FE model is considered valid for predicting ET responses to flaws in clean tubes.

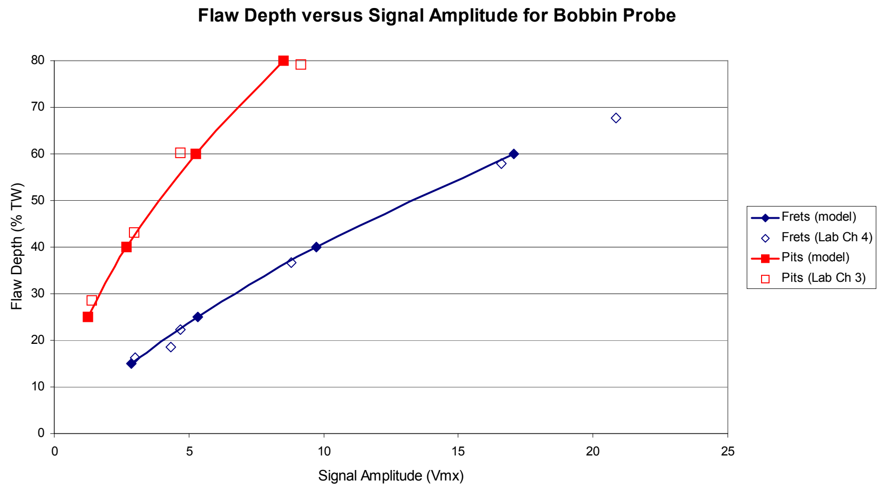

Figure 1 Comparison of model with laboratory data of bobbin-probe V_{mx} responses to scallop-bar frets and pitting in clean Inconel 600 tubing; support plates absent.

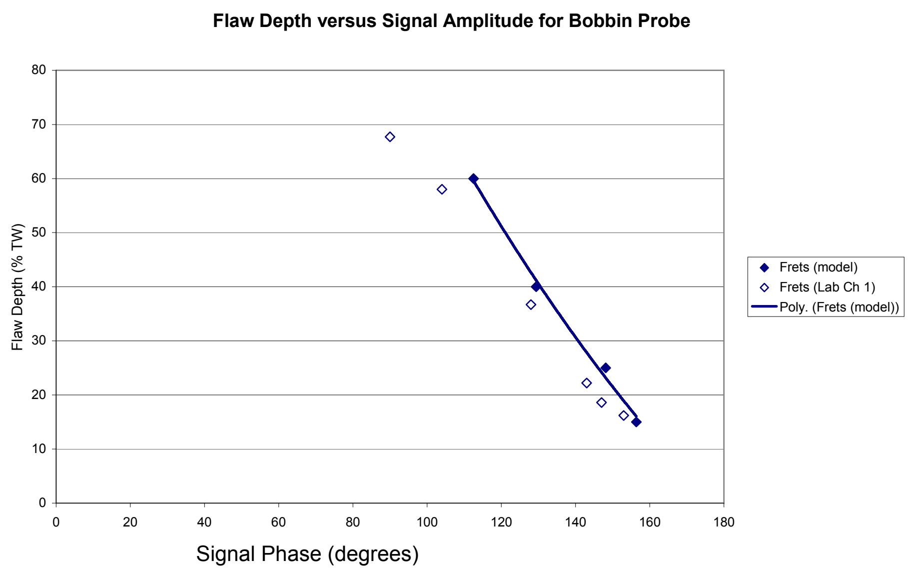

Figure 2 Comparison of model with laboratory data of bobbin-probe phase responses to scallop-bar frets in clean Inconel 600 tubing; support plates absent.

3. SIMULATING THE EFFECTS OF ID MAGNETITE

The FE model was used to simulate thin magnetite layers with linear, isotropic and real values for relative magnetic permeability (μ_r). For this study, four cases were run comprising 16 problems with the ID magnetite parameters given in Table 1 for each flaw type and depth. Each case used a different thickness of magnetite layer.

Table 1
List of ID Magnetite Parameters Simulated in Inconel 600 Tubing

Case #	1	2	3	4
Relative Permeability (μ_r)	4	6	8	10
Thickness (μm)	15, 30, 70, 140	15, 30, 70, 140	15, 30, 70, 140	15, 30, 70, 140

Figure 3 shows the results for Case #4 with the bobbin probe. The presence of ID magnetite is predicted to reduce signal amplitude. Here, only the simulated examples of ID magnetite and clean tubes are plotted since direct comparisons to laboratory data are not possible without knowing the actual μ_r values [1]. Although not presented here, the signal phase changes by a small but noticeable amount with increasing amounts of ID magnetite because a magnetic field undergoes a phase delay as it penetrates the ferromagnetic layer.

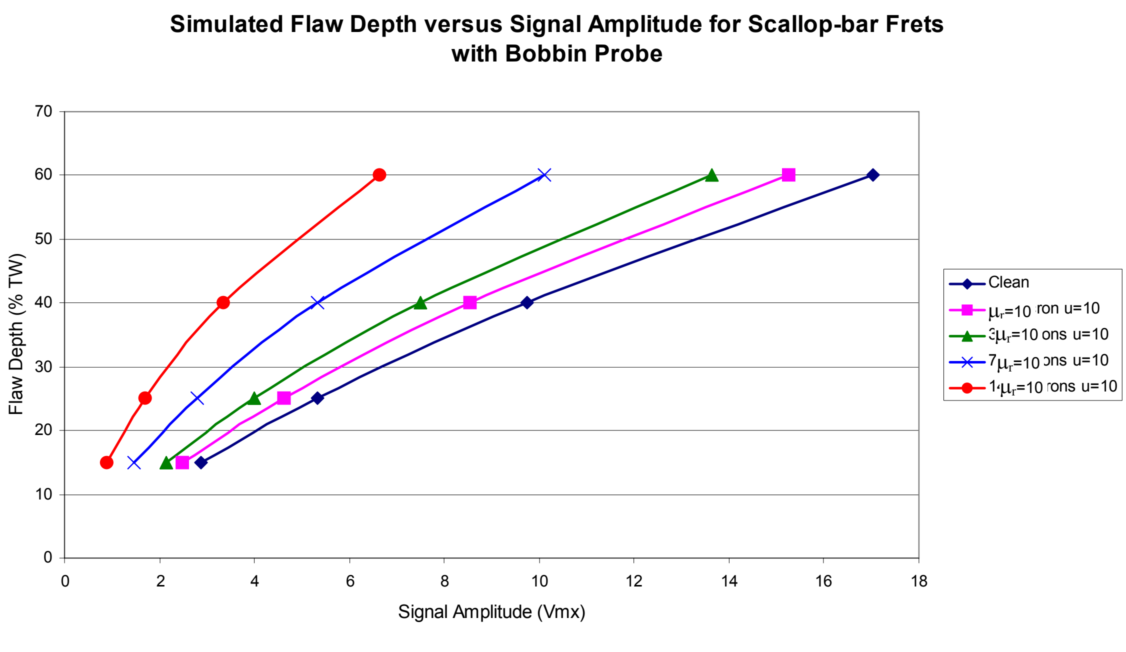

Figure 3 FE model predictions of the ID magnetite effects on bobbin-probe responses to scallop-bar fretting wear at 240 kHz; support plates absent.

The combination of permeability and thickness of a magnetite layer can be called the effective permeability to describe the extent of the shielding effect. This is measured directly as the horizontal voltage drift in the ET signal at 480 kHz with the absolute channel of the bobbin probe. Any practical relationship between ID magnetite loading and flaw detection or sizing can be expressed as a function of the effective permeability (in terms of V_H drift), denoted as V_{shield}. A technique that is currently available to the utilities for estimating the thickness of ID magnetite deposits in the field effectively measures V_{shield}. Hence, this is not an entirely new concept. The ID magnetite shielding effect is based on the relationship between any probe's signal amplitude reduction factor and the bobbin probe's V_{shield}.

4. RELATIONSHIPS DESCRIBING THE EFFECTS OF ID MAGNETITE

The decrease in amplitude due to ID deposits can be expressed as a reduction factor that is less than or equal to one. This factor is calculated as the ratio of the flaw amplitude in the fouled tube to that in the clean tube, for either probe-type. The effect of ID magnetite on the eddy current responses to flaws is then expressed in terms of the reduction factor versus the bobbin V_{shield}. These results are plotted in Figures 4 and 5 for scallop-bar fretting wear for both probes. These types of plots were also obtained for the other flaw types, as well as for flat-bar fretting wear and pitting in 15.9-mm diameter Incoloy 800 tubing. In all cases, a linear fit to the data establishes an equation for the reduction factor given on each plot, and can be used to infer the shielding effect. These equations differ between each probe type, but only slightly for each flaw type. In comparison, the reduction factors measured from field data, discussed in the next section, are also plotted in Figures 4 and 5 with very good agreement.

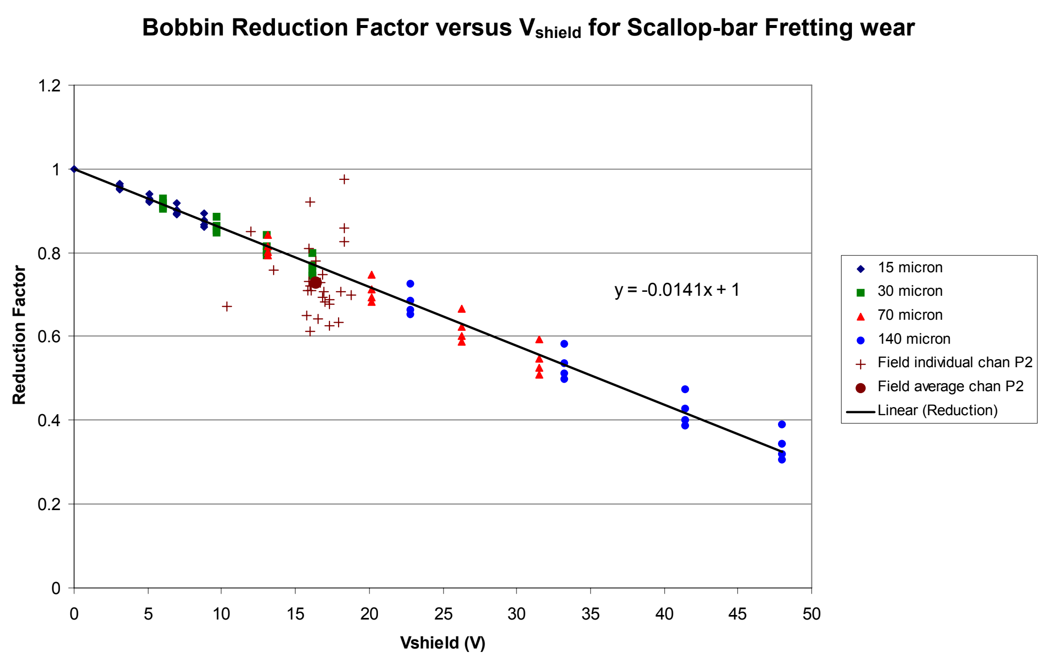

Figure 4 The shielding-effect relation for bobbin-probe responses to scallop-bar fretting wear.

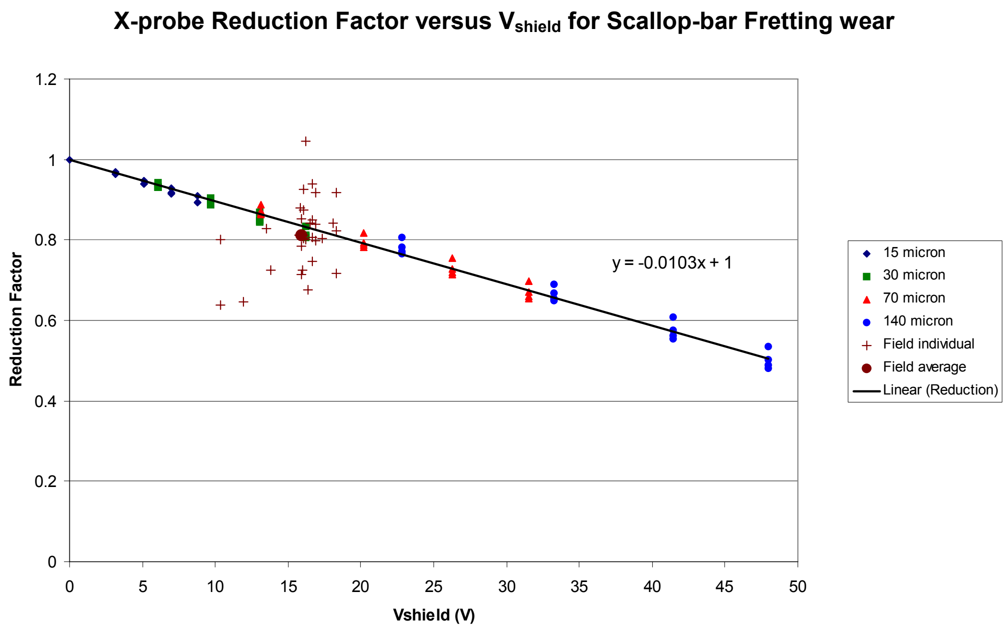

Figure 5 The shielding-effect relation for X-probe responses to scallop-bar fretting wear (using 250 kHz axial channel).

The FE model has shown that the reduction factors for the bobbin probe are identical with both differential and absolute channels.

There is a slight slope increase in the reduction factor relationships for Inconel 600 in comparison to Incoloy 800. In the smaller tube diameter, for a constant ID magnetite thickness, the proportionately smaller probe causes the magnetite to have more of an effect on its OD flaw signals.

The reciprocal of the reduction factors are considered amplitude correction factors, which can be used to adjust the signal amplitudes before applying them to sizing curves. However, an alternative approach would be to adjust the flaw size directly with the use of sizing correction factors. Sizing correction factors can be derived from the plot of modelled ET estimations of flaw depth measured in clean tubes versus those measured in fouled tubes. The line that fits through the data can be considered as the sizing correction line, with its slope as the sizing correction factor. This factor, when multiplied by the “fouled” depth measurement, can be used to correct the size of the flaw to compensate for the undersizing effects of ID magnetite in a given fouling condition.

Figure 6 shows example sizing correction lines for the X-probe, derived from the FE models for scallop-bar fretting wear at several V_{shield} values. The data in these plots are derived by using the reduction factor equation of Figure 5 to calculate the corrected voltage for a given V_{shield} with the use of a lookup table populated with the sizing curve values for V_{mx} and % depth currently used in field inspections. This is accomplished using an Excel spreadsheet, where V_{shield} is entered as the only input variable. The y=x line represents the “clean” condition. The slope of the trend lines through the data points increase with higher values of V_{shield}. This approach assumes that the reduction factor equation for freespan flaws also applies to flaws under supports. The results presented in the next section support this assumption.

Sizing correction lines can also be calculated for pitting and circumferential flaws in Inconel 600 tubing with the X-probe, frets with the bobbin probe, and frets in Incoloy 800 tubing with both probes. Sizing correction lines can only be calculated for a probe having an amplitude-based sizing curve.

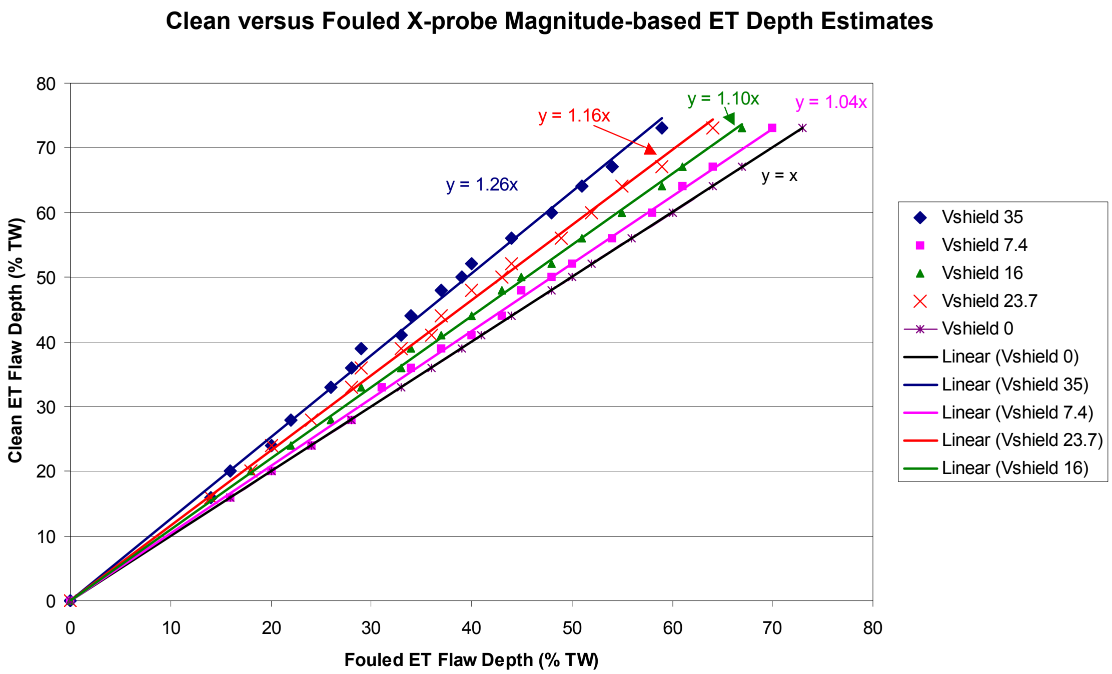

Figure 6 X-probe magnitude-based sizing correction lines derived from modelled data for fretting wear.

5. BRUCE PRE- AND POST-CLEAN FIELD-DATA COMPARISONS

In an effort to compare the models with actual data, laboratory samples were developed from a set of eight Inconel 600 pre-heater pulled tube sections, originally obtained from Bruce Power. A series of OD flaws were machined into these fouled tubes and three clean tubes. Using conventional signal analysis techniques for the bobbin and X-probe, signal comparisons were made with plots of flaw depth versus signal amplitude. From this, ID magnetite was shown to generally reduce the flaw responses; however, the amount of scatter and relatively poor data trends made detailed observations from the laboratory data impossible. A variety of factors had a negative influence on the eddy current signals, such as signal drift, probe wobble, tube variations, localized magnetite variations, and inaccuracies in actual flaw depth measurements. Basically, any effort to compare signals from flaws in clean tubes to similar flaws in fouled tubes for the purpose of evaluating the effect of ID magnetite had inherent disadvantages, mainly due to the uncontrollable variations in the tubes and flaws themselves. On the other hand, comparisons between modelled and actual field data can be more reliable since neither the flaws nor the tubes change, only the ID magnetite properties.

Pre-clean and post-clean data comparisons are ideal for this type of study. B&W Canada provided bobbin probe and X-probe field data from Bruce NGS 2007 pre- and post-clean inspections with U-bend scallop-bar fret indications. The average V_{shield} measured in this field data is 23.7 V before ID cleaning, and 7.4 V after. This results in a "differential" V_{shield} of 16.3 V, assuming a relatively constant and even distribution of magnetite in the U-bend regions of interest. The standard deviation for V_{shield} is 1.9 V; hence, the magnetite loading within these regions is relatively consistent. The reduction factor for each indication with the bobbin probe, calculated by dividing the pre-clean voltage by the post-clean voltage, is plotted against V_{shield} in Figure 4 along with the modelled data. The field data compare very well with the predictions given by the 3D FE model. The average reduction factor in the field data is 0.73, with a standard deviation of 0.09. This indicates that voltage reduction is also relatively consistent within these regions of the SG, and that the values lie well below unity. Similar agreement with the FE model is shown in Figure 5 for the X-probe. These results support the validity of the modelling approach, and indicate that amplitude-related corrections are warranted.

Similar to the sizing correction lines shown in Figure 6, plots of the field pre-clean versus post-clean ET depth estimates can be used to determine correction factors, as was shown in a study presented by B&W [2]. Their work clearly illustrated how the apparent fretting-wear depth increases after ID cleaning. As previously described, the slope of the line that fits the data is the factor that relates the depth estimate increase from a pre-clean (i.e., fouled) tube to a post-cleaned tube (which, however, may not be completely "clean"). Using the V_{shield} values of 23.7 and 7.4 measured in the pre- and post-clean field data, the predicted correction factors are found to be 1.11 for the X-probe and 1.14 for the bobbin probe, which agree very well with B&W's results [2]. This agreement comes despite the absence of support structures in the model, and suggests that support plates are not required in the models for the purpose of establishing and correcting for the effects of ID magnetite in Inconel 600 (or Incoloy 800) tubing.

Note that a similar sizing correction approach can also be applied to phase-based sizing methods. However, the relatively large variations in phase measurements, due to their susceptibility to horizontal noise, diminish the value of correcting signal phase.

6. POD ADJUSTMENT AND SIZING COMPENSATION METHODS

To date, the approach used to determine the POD is based on EPRI guidelines [3] and AECL recommended practices [4]. A flaw is considered detectable if the ET indication signal-to-noise ratio (S/N) at the area of interest is equal to or greater than 2. This criterion ensures that a flaw signal is unambiguously distinguished from noise. However, the POD for flaw detection in "clean" tubes can be adjusted to account for the voltage reduction due to ID magnetite by recalculating S/N. After the V_{shield} is measured during an inspection outage, the signal amplitudes (typically V_{mx}) of the original POD data set can be scaled in accordance with the reduction factor. With this "adjusted" data set of S/N ratios, current POD values can be recalculated to reflect the effect that ID magnetite has on the flaw signals. In addition, future POD studies can take ID magnetite effects into account by assuming a typical value for V_{shield} from sample measurements of field data.

The added value of the reduction factor lies with the ability to determine the maximum fouling condition for which POD reaches the lower bound limit of 0.80. The process is essentially the reverse of that described above. The signal amplitudes from the original POD study are iteratively reduced to the smallest scaling factor while retaining a POD value of at least 0.80. Therefore, with a known maximum value for V_{shield} measured during an inspection, the SG would be identified as a candidate for ID cleaning during the next scheduled inspection to ensure continued detectability. Note that this V_{shield} value will differ from one probe type to another. Hence, the decision on when to clean the tubes should be based on the performance of the primary detection probe.

There are two possible methods for correcting sizing estimates: one based on voltage adjustments and the other based on % TW depth adjustments for a probe and flaw type of interest. The first method requires that measurements of V_{shield} be made in a few tubes to get an average value for the region of interest in the SG. A new process channel is set up by the analyst in EddyNet with normalization performed on the regular calibration flaw (such as a 10% OD groove for the bobbin) to X volts, adjusted by the voltage correction factor. Thus, a corrected normalization voltage would be used throughout the analysis process, while using the same sizing curve as usual. This method assumes that the ID magnetite, and hence V_{shield}, is consistent throughout the region of interest in the SG.

The second method uses the sizing correction factor to adjust all the measured depth sizes, which are found with the regular sizing curve as usual. A spreadsheet is used to calculate the factor, with only V_{shield} as the input variable, to produce a plot and the slope of the sizing correction line similar to one of those shown in Figure 6.

Both adjustment methods assume that the original POD or sizing curves are based on clean tubes. If they were based on field data, an extra step is required to compare the baseline V_{shield} to the one measured in the current inspection. Regardless of the method used, for those cases where flaws are near plugging criteria, it is advisable to measure V_{shield} in those few tubes, and adjust the corrected normalization voltage for each tube individually, which means re-normalizing each time for those tubes.

7. CONCLUSIONS

The shielding effect of ID magnetite reduces the eddy current amplitude response from flaws such as fretting wear. However, it is possible to compensate for the reduced responses with the use of model-predicted correction factors based on the response relationships with magnetite loading, measured with the bobbin probe as V_{shield}. Current and future POD values or curves can now take ID magnetite effects into account. Lastly, sizing correction factors can be used to adjust flaw depths directly by an analyst with a re-normalized process channel, or after the depths have been measured in the usual manner with a sizing correction line.

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