THE IMPACT OF MAGNETITE DEPOSITS ON STEAM GENERATOR INSPECTIONS

Brian Lepine, Laura Obrutsky,
Atomic Energy of Canada Ltd.

A successful steam generator (SG) health-monitoring program requires flaw detection, depth prediction and efficient analysis tools. It also needs reliable and timely input from advanced inspection, monitoring and diagnostic tools to assess other parameters that can impact the performance of the SG. One of these parameters is tube fouling that can affect heat transfer, flow velocity and distribution, and corrosion susceptibility.

The deposition of primary and secondary side magnetite deposits in SGs of CANDU® nuclear power stations also poses a challenge during SG eddy current testing (ET) inspection campaigns. Inner diameter (ID) magnetite deposits mechanically restrict, and in extreme cases prevent inspection with ET probes. Furthermore, even thin layers of ID deposits can diminish probe sensitivity to flaws since magnetite is a ferromagnetic compound that produces a shielding effect for alternating electromagnetic fields. This can have an impact on both the probability of detection (POD) and the ability to size flaws. Patchy ID magnetite, such as that which can occur after cleaning, can also cause excessive noise of the eddy current signals. This also affects the POD and the inspectability of the tubes. Monitoring and quantification of outer-wall magnetite-loaded sludge deposits is also an inspection requirement, especially at the defect prone top-of-tubesheet and tube support locations.

This paper will detail these issues from an inspection perspective, and present the results of studies evaluating the ability to quantify magnetite deposits and manage its impact on flaw detection and sizing techniques.

KEYWORDS: ID magnetite, eddy current inspection.

CANDU® CANada Deuterium Uranium is a registered trademark of Atomic Energy of Canada Limited (AECL).

INTRODUCTION

In keeping with this year's theme "Management of Real-life Equipment Conditions and Solutions for the Future", it is necessary to consider one of the most troublesome environmental aspects encountered during eddy current inspections of steam generator tubes. The vast majority of inspection technique development and qualification studies are performed in the laboratory under clean, controlled conditions. However, in field conditions, many tubes will be fouled with internal and external magnetite deposits, with CANDU steam generators being especially susceptible to ID magnetite fouling. These deposits can have several effects on both the mechanical and electromagnetic aspects of the inspections, in both cases affecting the signals in several different ways. In most cases, the signals exhibit noise that can mask flaws. The ID magnetite deposited inside the tube, with sufficient thickness, can also act as a shield and reduce signal amplitude from flaws, thus reducing their detectability. The deposits can restrict the tubes, causing added friction for the inspection probes and, in extreme cases, rendering them incapable of negotiating any part of the tubes. For various reasons, measuring magnetite on the primary and secondary sides is considered an important inspection requirement.

This paper presents examples of the various effects of magnetite deposits on the ability to perform inspections, and the inspection requirements that stem from the inevitable presence of deposits.

MECHANICAL ASPECTS

The standard probes used in most SG inspections are conventional bobbin probes of a nominal diameter that maximizes the fill-factor without compromising its ability to negotiate the majority of U-bends and tube dents and dings. For example, a 9.7 mm diameter bobbin probe is used in Bruce Nuclear Generating Station SGs and preheaters, which consist of 12.9 mm Inconel 600 tubes. CANDU 6 and Darlington nuclear generating stations (NGS) have larger 15.9 mm diameter Incoloy 800 tubes that typically require 12.2 mm bobbin probes. These standard probes are capable of negotiating tubes with deposits from 200 to 500 microns thick. Beyond that range, however, it becomes necessary to use smaller diameter probes to overcome the added constrictions and also the friction due to loose magnetite. Probe wear rates also tend to increase with magnetite fouling due to the abrasive nature of the fixed and loose deposits.

Efforts are currently underway to design and test specialty probes for this purpose at AECL for 12.9 mm I600 tubing. The primary issues that arise during such an exercise are the ability to maintain a good signal-to-noise ratio and sensitivity to flaws given the reduced size of the coils and their added distance from the inner tube wall (smaller fill factor). It is also important to maintain continuity with the standard probe in terms of signal response and analysis procedures to reduce training needs and ensure historical relevance.

FLAW DETECTION AND SIZING ASPECTS

If tubes are not cleaned, the signals from either a standard or special small diameter probe can be heavily influenced by the ID magnetite in many ways. First, the shielding effect causes the flaw to have a smaller amplitude than that of a similar sized flaw in a clean tube. This reduces the detectability threshold, but also affects the sizing accuracy since sizing curves typically are based on flaws in clean tubes. A preliminary study has shown that a fundamental relationship exists between magnetite thickness and flaw responses. These studies were conducted on 15.9 mm

I800 tubing, using a small sample of Darlington NGS pulled tubes. They show that, for the bobbin probe, there is a mean decrease in flaw depth estimates by a factor of 0.97 (3% reduction) with a 40 μm deposit. In a similar fashion, the X-probe undergoes a mean sizing decrease of 0.96 (4% reduction).

Given the limited available data from the pulled DNGS tubes, to extract a relationship or a quantifiable trend, a computer model was used to illustrate the trends that would be expected and provide a means for expressing these trends. The bobbin and X-probe were modelled in a clean tube and in tubes with a 13 μm and 40 μm thick ID magnetite layer, each with their respective relative permeability (μ_r) values, to simulate the signals from outer-diameter (OD) wall-loss flaws of various depths. The ET modelling software for the bobbin probe simulates probe responses and wall-loss flaws in a concentric tubular geometry; hence, wall-loss is modelled as infinitely long OD concentric grooves. The resulting 240 kHz (absolute) flaw response curve for the bobbin probe is shown in Figure 1. The trend curves are second order polynomial fits to the data. For illustrative purposes, the 240 kHz laboratory flat wall-loss flaw response is also given in the same plot for a clean tube. The large discrepancy is mainly due to the significant difference in the volume detected with the bobbin between the flat and concentric wall-loss.

The model used for the X-probe configuration simulates a transmit/receive (T/R) unit on a flat-plate geometry; however, for the purpose of this study, we assume the geometry to be tubular, also with concentric wall-loss flaws. The resulting 250 kHz response curves are given in Figure 2. The 250 kHz laboratory data for the clean tube compares relatively well with the model since the smaller interrogation area of a T/R unit results in only a slightly smaller amount of volume detected from the flat relative to the concentric wall-loss.

Figure 3 shows the effects of deposits on the sizing ability of the bobbin probe by comparing the results from the fouled tubes directly to the clean tube. A decrease in the sizing estimation is clearly illustrated, corresponding closely to the aforementioned findings that a probe tends to undersize flaws in fouled tubes compared to a clean tube.

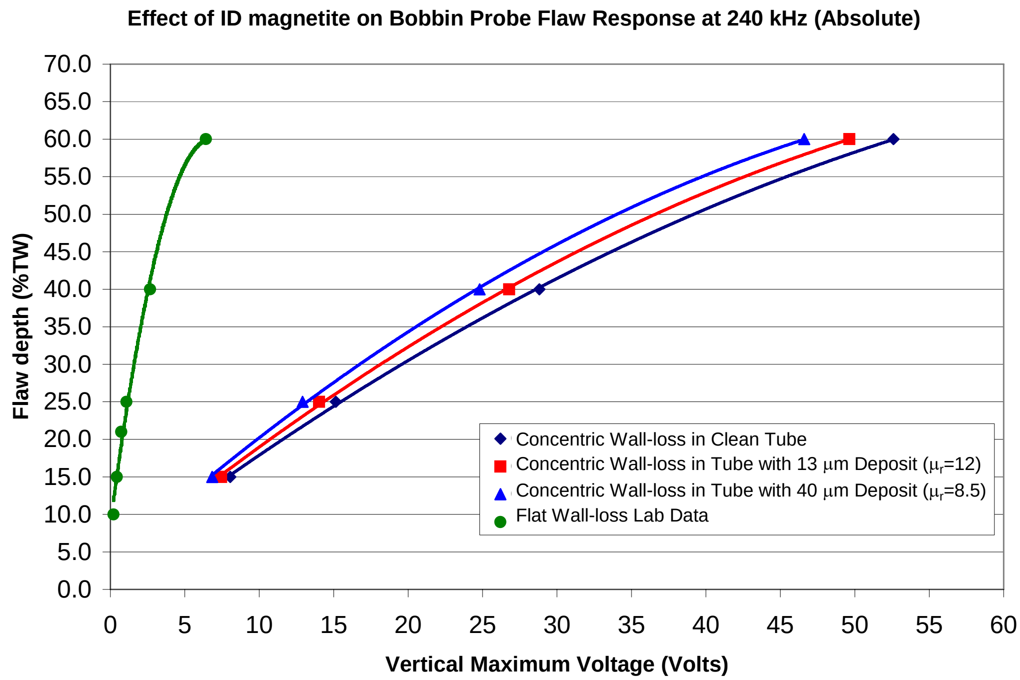

Figure 1: Simulated changes in bobbin responses to fretting-wear due to deposits.

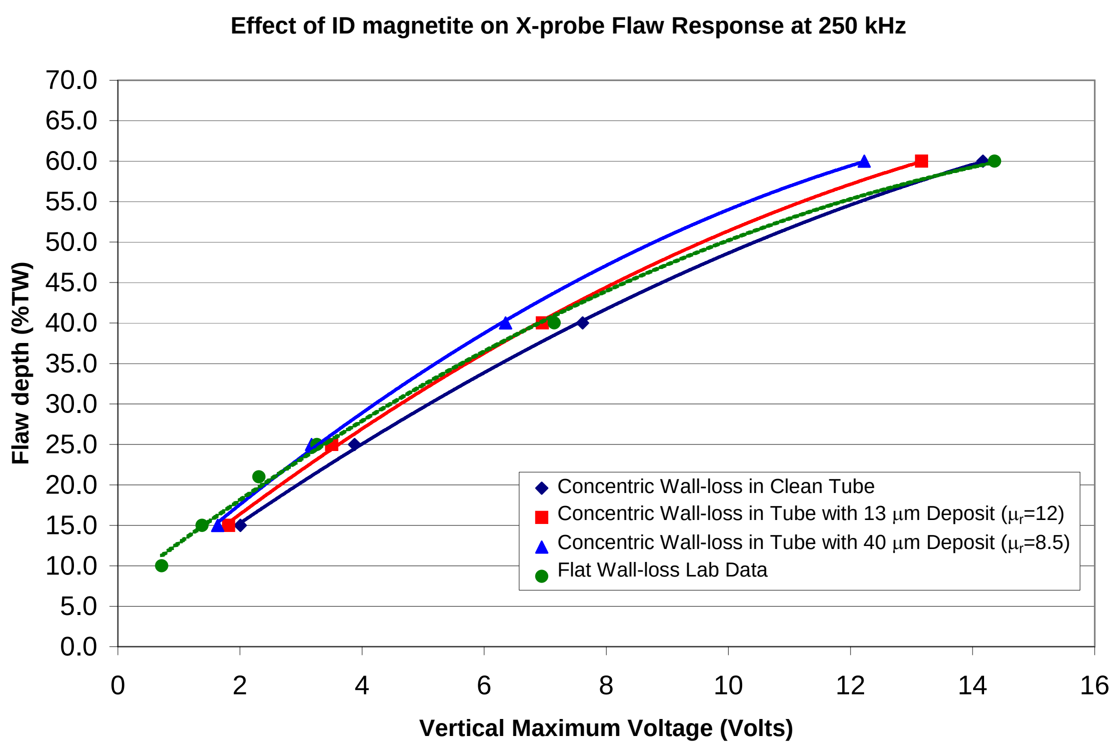

Figure 2: Simulated changes in X-probe responses to fretting-wear due to deposits.

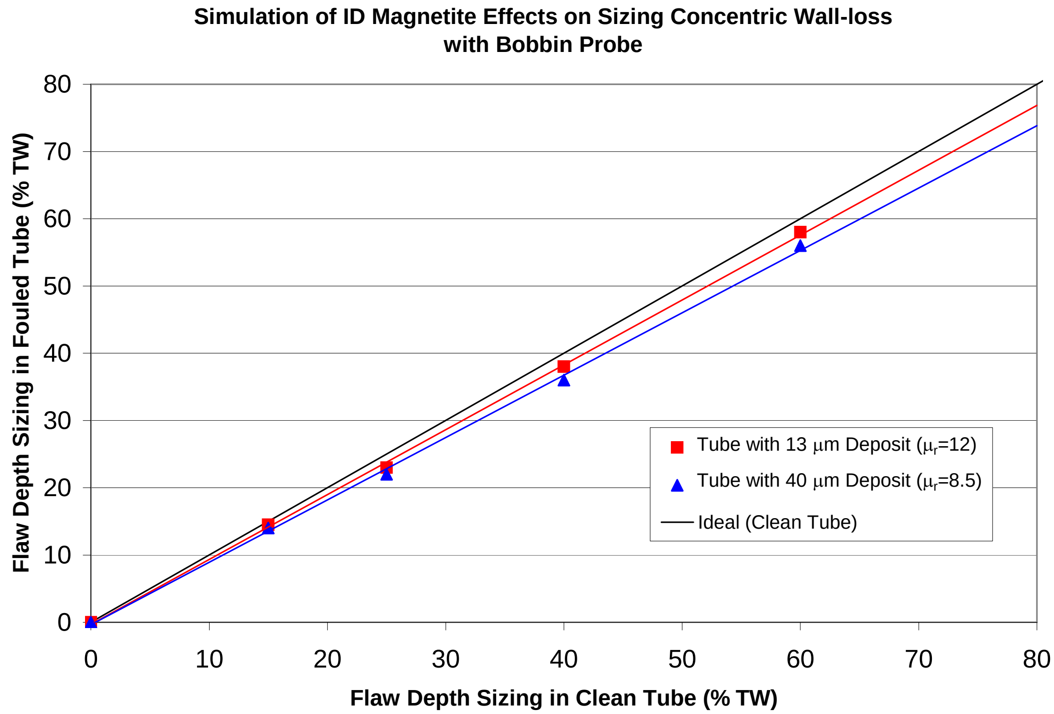

Figure 3: Simulated sizing comparisons for flaws in clean and fouled tubes (bobbin).

From the relationships in Figure 3, it can be shown that the 13 µm (μ_r=12) and 40 µm (μ_r=8.5) deposits reduce the mean sizing estimates by a factor of 0.95 and 0.91, respectively. For the X-probe, the factors are 0.94 and 0.88, respectively. In theory, the reciprocal of these values can be considered correction factors, and implemented to field-analysed data when the magnetite thickness and permeability values are known. These results demonstrate the concept behind an approach to compensate for ID magnetite. For the models to be useful in predicting and extrapolating the trends found in the field, their output must be adapted to accommodate geometries other than concentric grooves to determine whether the effects are equivalent for other flaw types, such as frets and pit-like flaws. These and other discrepancies, such as coil parameters, can be accounted for by normalizing the models to laboratory data. Normalization and validation of these results can be achieved experimentally with a sufficient number of samples from the field with a large range of deposits.

A second issue arises when the ID magnetite becomes noisy, such as that due to irregular patchy distributions or spalled areas. Advanced analysis methods are required for suppressing the noise due to patchy magnetite and enhancing detection under such conditions. A technique was developed with multi-frequency channels that effectively mix-out the noise, allowing the ET analyst to screen the data for flaws in the noisy areas that were difficult to inspect. As an example, bobbin probe data in a particularly noisy area of the tube was selected. At this location, the signal from an artificial flaw obtained in the laboratory has been superimposed into the field data using a process called signal-injection. The signal-injected flaw is shown within the noisy area in the screen capture of Figure 4. The new process channel (P11) is a 240-480 kHz differential frequency mix that can be used as a detection channel for the freespan in place of the standard 480 kHz channel (1) during data screening. Since the ID magnetite noise primarily consists of horizontal excursions, the mixed signals also tend to suppress most of the horizontal components of other signals. Hence, phase analysis cannot be performed with this channel. However, once a flaw is detected with these channels, it can be analysed as per normal procedure with careful application of the cursor and the realization that the noise can affect the phase.

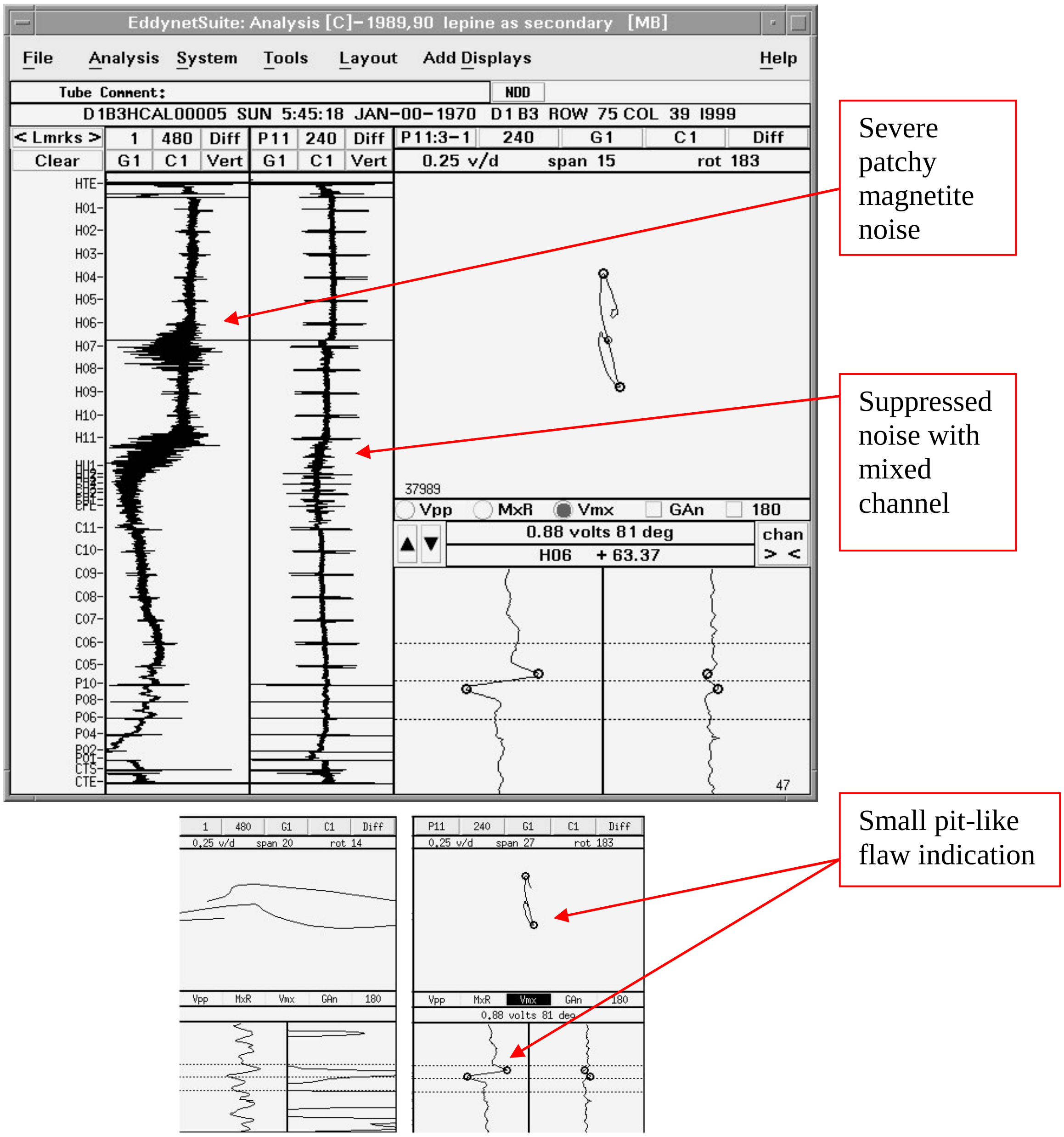

Figure 4: Patchy ID magnetite noise, with a simulated 39% Through-Wall OD Pit.

In addition, there is another multi-frequency mixing method that combines three frequencies with the use of the TURBO mix function in the Zetec EddyNet software, which suppresses both the noise and support plates. This channel retains phase information since the OD, ID and through-wall hole signals are saved before the ID magnetite noise and support plates are suppressed during the mixing routine. Consequently, the resulting process channel can be used to confirm indications and even size fretting-wear flaws at the lattice-bar (LB) support locations.

QUANTIFYING MAGNETITE

There is a need to quantify both ID and OD deposits for the purpose of evaluating the condition of the SG for heat transfer, flow velocity and distribution, and corrosion susceptibility. In addition, it assists SG maintainers optimize SGs cleaning intervals, and in the future, as inputs to correction factors for sizing flaws as described in the previous section. ID magnetite thickness is quantifiable with eddy current data with the use of the high frequency horizontal component response. The ID magnetite is typically not uniform throughout the length of the tube, causing drift in the absolute eddy current channels. Normally, very little magnetite deposits on the lower portions of the hot leg side, and gradually increases in thickness towards the U-bends, and can either increase or decrease through the cold leg region.

Past work has developed conversion factors to relate the voltage response to the actual thickness of the magnetite. With this technique, plots of magnetite thickness and loading could be produced based on eddy current data, as shown in Figure 5. However, this approach has its limitations. Since the ID magnetite permeability and thickness both affect the ET signals, there is no clear method to accurately measure the thickness without the prior knowledge of the permeability. During the development of the method for measuring ID magnetite thickness and loading, it was assumed that the permeability remained relatively constant within each NGS. However, the permeability varies with thickness and has not been shown to be consistent from one SG, or tube, to another. To reduce the resulting error, in-field measurements of permeability are possible with the use of modified bobbin probes or the X-probe, using techniques that have already been demonstrated in the laboratory. Future research efforts will explore this issue in depth with the goal of improving the accuracy with eddy current field data.

Regarding the detection and sizing of flaws in the presence of magnetite, any practical relationship between ID magnetite loading and eddy current flaw responses must be a function of the permeability/thickness combination. Fortunately, the combination of permeability and thickness, which could be called the effective permeability to describe the extent of the shielding effect, is measured directly as the horizontal voltage drift in the ET signal, especially at a high frequency (480 kHz absolute for the bobbin probe). Hence, the next step in the continuing effort to establish the associations between ID magnetite and probe responses or sizing capabilities is to express them as a function of the effective permeability (in terms of V_H, or horizontal voltage drift) rather than thickness. The implementation of correction factors or curves could be easily performed, therefore, without the need for potentially inaccurate thickness estimations. However, both parameters would still need to be determined to model the responses and obtain the relationships. In any case, more field data from both eddy current probes and other independent means, such as with the Oxiprobe, is required to both adjust and improve the confidence level of the relationships developed in the past or the future.

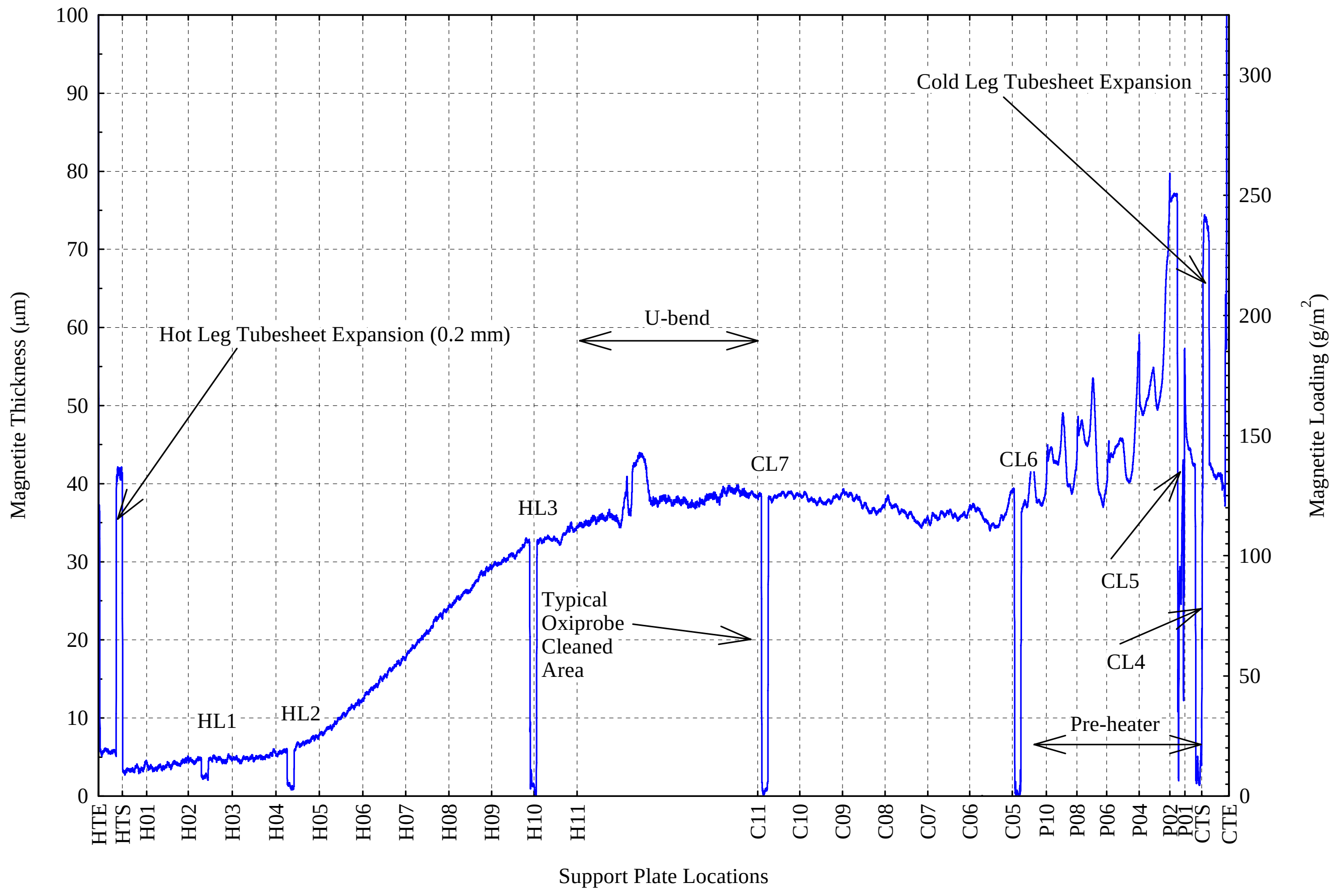

Figure 5: Magnetite thickness and loading values based on absolute bobbin probe data at 480 kHz.

Outer-wall (or OD) magnetite-loaded sludge deposit measurements are also inspection requirements. Some efforts in the past have shown that it is possible to determine the level of the deposits in terms of height from the top-of-tubesheet. However, it is much more difficult to measure the actual thickness of the sludge. There is a voltage value associated with OD sludge, as shown in the bobbin probe screen capture of Figure 6, which implies a relationship exists between the extent of fouling and the eddy current signal. As is the case for ID magnetite, the signal response to OD magnetite deposits is proportional to thickness and permeability. Thus, we must assume one to obtain the other. In the case of sludge it can be assumed that the thickness exceeds 5 mm along the entire sludge pile just below the top of the pile. Hence, it is possible to estimate permeability of the sludge. On the other hand, with the assumption that OD deposits have a permeability of 2, we can estimate thickness. Of course, this assumption is the primary source of error in the estimation and should be confirmed with laboratory tests to increase the confidence level of any future measurements. This approach is useful to determine OD deposit thickness along the length of tube beyond the sludge, which also affects thermal performance of SGs. To do this, a low frequency is used, such as 30 kHz with the bobbin probe, to penetrate through the tube wall and into the sludge itself.

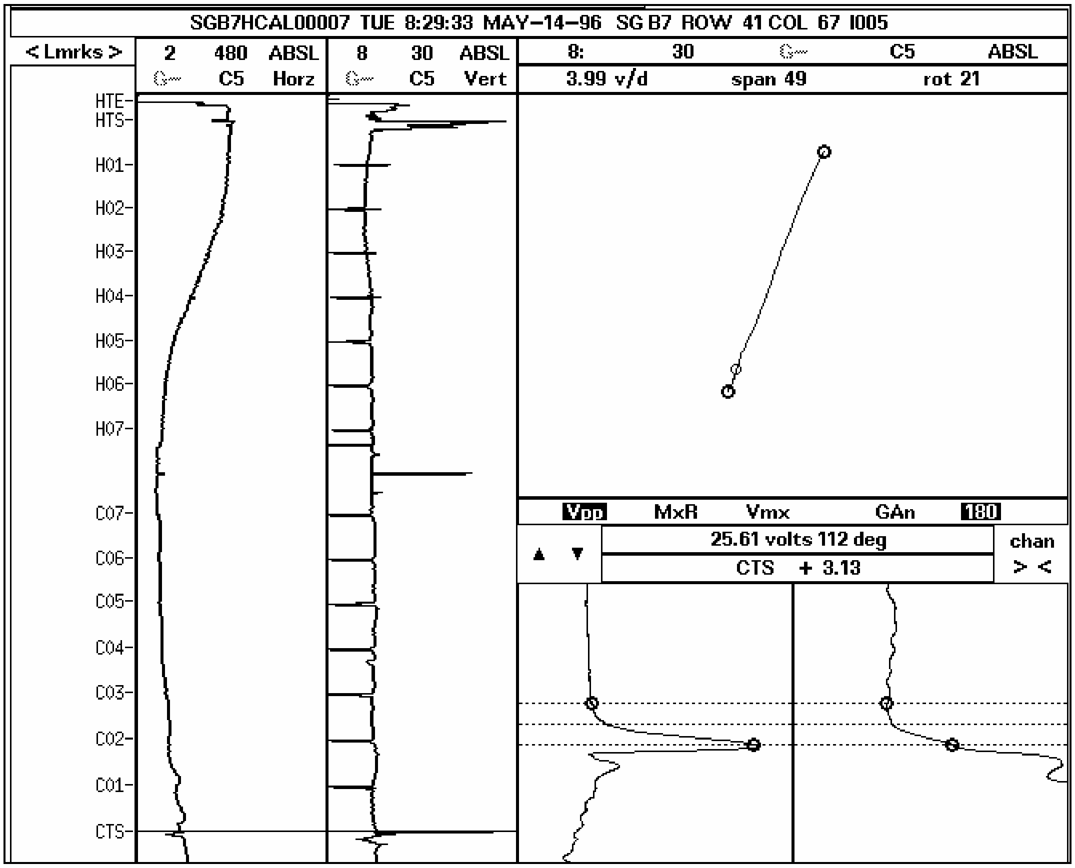

Figure 6: Absolute Bobbin Probe Response to Cold-leg Tubesheet Sludge, in a Bruce A SG Tube, at 30 kHz.

CONCLUSIONS

Several advancements have been made over the past several years on assessing the condition of tubes in terms of ID and OD magnetite. Noise arising from patchy magnetite and/or spalling can be effectively suppressed with the use of special frequency mixing techniques. 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 either model-predicted or laboratory-measured correction factors based on their relationships with magnetite thickness. Both ID and OD magnetite thickness can be measured from eddy current data; however, there remains several outstanding issues on accuracy and the assumptions used during their implementation that should be addressed in future work.

ACKNOWLEDGEMENTS

The authors wish to express thanks to Joe Renaud of AECL's IMD Branch for the valuable information he provided on probe characteristics and capabilities. In addition, we thank John Lu for the valuable computer simulations and signal injection exercises performed for much of this work. Finally, we also thank Dennis Hawley for the data acquisition and analysis performed during the course of the work referenced in this paper.

REFERENCES

1. L. Obrutsky and M. Mirzai, "Overview of Eddy Current Inspection Technology for CANDU SG Tubing", Proceedings of the 6th International Conference on CANDU Maintenance, Toronto, ON, 2003 November.