DEVELOPMENT OF EDDY-CURRENT PROBES FOR THE EVALUATION OF MAGNETITE IN THE SUPPORT-PLATE CREVICES OF NUCLEAR STEAM GENERATORS

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ABSTRACT

Eddy current technique has played an important role in the understanding of the corrosion behavior of steam generator components. Until recently, its role has been primarily in the evaluation of the condition of the heat exchanger tubes. Recent developments have led to the use of this technique for detecting corrosion of the carbon steel plates supporting the tubes. The detection and quantification of possible accumulation of corrosion products such as magnetite in the crevices between tubes and supports may often be a desired objective of such inspections since the presence of such deposits is of interest with respect to tube denting and other corrosion phenomena. This paper discusses the difficulty of an unambiguous determination of the presence of magnetite in the tube support crevices and points to the difficulty of obtaining a quantitative estimate for the amount of magnetite which may be present. This paper further discusses the development of new probes which provide improved discrimination between magnetite and a steel support thus providing for a better estimate of the amount of magnetite in tube support crevices.

INTRODUCTION

Eddy current technique has been extensively used for the inservice inspection of nuclear steam generators. The inspections have usually involved the evaluation of the heat exchanger tubes. Recent developments regarding the tube denting phenomena in steam generators have led to an increased interest in the evaluation of the carbon steel support plates and the crevices between tubes and the supports. Although the detection of corrosion of the support plate could be accomplished at some stage by an evaluation of the distortions of the support plate signals, a quantitative estimate of the corrosion of the I.D. of the supports using the standard eddy current inspection data has not been possible. The multi-frequency technique and the use of linear combinations of the multi-frequency data have reduced the ambiguities in the data interpretation and have improved our ability to quantify the depth of tube wall discontinuities in the presence of interfering signals from such sources as support plates, metallic and magnetic deposits on the O.D. of the tubes, etc. However, this technique has not been useful for quantifying the corrosion of the steel supports. An estimate of the I.D. of the support plate holes could be accomplished from the standard eddy current data if one could assume that there are no magnetic or electrically conducting deposits in the crevices. Such an assumption is generally not valid, however, due to the presence of magnetite (one of the products of steel plate corrosion) in the crevices. The verification of its presence can be accomplished by a careful examination of standard eddy current inspection data but the quantification of the amount of magnetite deposits has not been possible from this data.

The detection of magnetic oxides such as magnetite in the absence of other interfering signals such as signals from carbon steel is quite straightforward and has been routinely carried out for years in terms of sludge height determination using the standard eddy current data since the sludge is known to contain magnetic materials. The difficulty of a quantitative evaluation of magnetite build up in the crevices of tube support plates arises because of the interference from the steel support signals which themselves may change upon corrosion of these steel supports. In order to accomplish a quantitative evaluation of magnetite build up and of the I.D. of the tube support, we need sensors which have higher sensitivity for magnetite than for carbon steel (or vice versa).

The conventional probes used for steam generator inspection consist of two circumferentially wound coils within approximately 0.060 inches (1.6 mm) of each other (Fig. 1). The inspection is performed from the I.D. side of the tubes. The test frequencies used range from about 3 kHz to 500 kHz depending on the objective of the test and the

Fig. 1 The conventional eddy current probe used for Steam Generator Inspection consisting of two circumferentially wound coils within 0.060 inches (1.5 mm) of each other.
thickness of heat exchanger tube wall. For the evaluation of the tube support plates and the crevices, the test is performed in the low frequency range (below 10 kHz) in order to minimize the interference from the signals representing discontinuities in the tube wall. The probes can be used in differential or in absolute mode.

This paper discusses the relative sensitivities of the conventional probe (used in normal steam generator inspections) for the magnetite and for the steel supports surrounding the Inconel-600 tubes. It is shown that this probe is quite sensitive to both magnetite and the carbon steel support plate. This results in complicated signals when the two are present simultaneously and makes the job of obtaining a reliable estimate of the I.D. of the steel support or the thickness of the magnetite in the crevice near impossible. It is further shown that the new probes described in this paper have preferential sensitivity for one (e.g. magnetite) relative to the other (e.g. steel support) for our sample geometry. The work reported here is directed towards designing probes which have large differences in the sensitivities for the two components (magnetite and steel supports) and have $90^\circ$ phase discrimination between the signals from the two at low enough operating frequencies such that the signals from the tube wall discontinuities would not interfere with the evaluation of the steel support and of the magnetite in the crevice.

**EXPERIMENTAL**

The geometry of the test specimens used in this work is shown in Fig. 2. The tube alloy was Inconel-600. The O.D. of the tube was 0.875 inches (22.2 mm) and the nominal thickness of the tube wall was 0.050 inches (1.27 mm). The carbon steel support plate sample was 0.75 inches (19 mm) thick and the hole diameter was 1.00 inch (25.4 mm). The magnetite cylinder used was 0.050 inches (1.27 mm) thick and 0.75 inches (19 mm) long. The density of magnetite was about 93% of the theoretical density. An organic binder was mixed in magnetite powder to fabricate the magnetite samples.

The eddy current instrument used was Model EM3300 (Automation Industries, Inc.). The conventional probe used here was similar to the ones used for standard inspections of steam generators (Fig. 1).

**RESULTS**

Figure 3a shows the eddy current signals using the conventional probe of Fig. 1 in the absolute mode at different test frequencies from (1) magnetite cylinder, (2) steel support sample and (3) steel support with magnetite cylinder in the crevice surrounding the Inconel-600 tube. The data shows that the sensitivity of this probe for steel support relative to its sensitivity for magnetite increases slightly with the test frequency. However, the probe sensitivities for our magnetite sample and the steel support sample remain about the same (within 30%) in the frequency range of our work. Because of this somewhat similar sensitivity for the two, the signals marked (3) obtained when the magnetite cylinder is present in the tube support crevice are quite complicated and do not lend themselves to any quantitative evaluation of either the steel support or the magnetite thickness. The addition of magnetite in the crevice results in a counter-clockwise rotation of the steel support signal in addition to the change in its shape. This is most obvious in the low frequency data. The counterclockwise rotation of the signal signifies the presence of high magnetic permeability material in the crevice. It may be noted that at 7 kHz test frequency, there is $90^\circ$ phase angle separation between the steel support signal and the magnetite signal.

![Fig. 2](image)

Fig. 2 The crevices between the Inconel-600 tubes and the carbon steel support plates may contain corrosion products such as magnetite.

![Fig. 3a](image)

Fig. 3a The eddy current signals using the conventional probe in the absolute mode showing similar sensitivities for magnetite and steel support samples surrounding Inconel-600 tube.
Figure 3b shows the data when the conventional probe is used in the differential mode. Here again, the data shows that the probe has about the same sensitivity for our magnetite as for the steel support sample surrounding the Inconel tube. The meaning of the slope of the signal is not quite so simple here since the separation between the two coils is much smaller than the length of the steel support sample (0.75 inches, 19 mm). If we define the slope of the signal as the slope of the straight line joining the points of maximum amplitude, we note that the angle between the two signals increases with frequency. The counter-clockwise rotation of the steel support signal on the addition of magnetite in the crevice is also apparent in these data. Of course, the 90° phase separation between signals 1 and 2 at 7 kHz noted in the absolute mode data is not obvious here because of the lack of precise definition of signal phase for the differential mode case.

Figure 4a shows the lift-off traces at different test frequencies from magnetite and from carbon steel for a pancake coil of diameter 0.245 ±0.055 inches (6.2 ±1.4 mm). Figure 4b shows similar data for the pancake coil of diameter 0.420±0.035 inches (10.7±0.9mm). The phase angle separation between the magnetite and the carbon steel signals increases with test frequency for both coils as expected(1). For the larger coil, the 90° phase angle separation between the two signals occurs at 150 KHz whereas it occurs at 260 KHz for smaller coil. Of course, the amplitude discrimination between the two signals when they have 90° separation is slightly higher for the smaller coil. At 1 kHz and 10 kHz test frequencies, the magnetite signal is smaller than the carbon steel signal. This is perhaps an indication of lower effective magnetic permeability value for our magnetite sample than for carbon steel.

Figure 5a shows the signals obtained from the same magnetite and steel support samples surrounding an Inconel-600 tube as in Figs. 3a and 3b but using a different probe (also shown in the figure). This probe consists of two circumferential coils wound in opposition and connected in series. It has higher sensitivity for the magnetite sample than for the steel support. This probe has optimum performance near 100 kHz. At this frequency, the phase separation between the two signals is 90° and the ratio of the amplitudes of the signals from magnetite and from steel support is about three. Furthermore, the signal from the combination of magnetite and steel support is about the same as from the magnetite sample alone. The best frequency for 90° phase separation for signals 1 and 2 can be changed by simply changing the spacing between the two coils (Fig. 5b). It may be noted from Fig. 5b that by increasing the coil spacing, the test frequency for the 90° phase separation is lowered from 100 kHz (Fig. 5a) to 16 kHz. However, it may be observed that this results in somewhat similar sensitivities for the two samples (magnetite and steel support) and is therefore not of practical value for a quantitative evaluation of the steel support or of the magnetite in the crevice. Decreasing the spacing between the two coils improves the sensitivity for magnetite as compared to its sensitivity for steel support but it also increases the test frequency for 90° phase discrimination between the two signals.
The eddy current signals using the new probe consisting of two circumferential coils wound in opposition and connected in series, show that the new probe has higher sensitivity for magnetite sample surrounding Inconel-600 tube than for steel support sample surrounding Inconel-600 tube.

Figure 6 shows the signals obtained from the samples using a probe consisting of eight pancake coils in series. The coils were wound on a ferrite piece about 0.25 inch (6.35 mm) thick. The probe has optimum characteristics near 200 kHz. At this frequency there is 90° phase separation between signals 1 and 2 and the ratio of the amplitudes of magnetite signal to steel support signal is about 4. Also the magnetite signal is almost unchanged by the presence of the steel support.

Figure 6 The eddy current signals from magnetite and steel support surrounding Inconel-600 tube using a probe with eight pancake coils in series. It has optimum performance at 200 kHz.

It may be noted that this probe has somewhat similar characteristics to the probe in Fig. 5a (notice similar shapes of the steel support signals). This is not surprising since the circumferential component of the current resulting from the currents in the pancake coils of this probe has similar features to the current for the circumferential coils of Fig. 5a.

Figure 7 shows the signals using a somewhat similar probe as in Fig. 6 except that the sense of the windings of the alternate pancake coils has been reversed. This probe can be visualized as having eight poles while the probe of Fig. 6 may be considered as having sixteen poles. The test frequency for optimum characteristics of this probe is near 400 kHz. At this frequency, the ratio of the magnetite signal to the steel support signal is about three and the two signals have 90° phase separation. It may be noted that this probe has a large axial component of current which would make it sensitive to the circumferential discontinuities as compared to the performance of the conventional probes with circumferentially wound coils such as Fig. 1 which have poor sensitivity to circumferentially oriented discontinuities. This coil configuration with a radial D.C. magnetic field can also be used for generating higher order tortional mode elastic waves in the tube.
Fig. 7 The eddy current signals from magnetite and steel support surrounding Inconel-600 tubes using eight pancake coils in series but with alternate coils wound in reverse. It has optimum performance at 400 kHz.

Figure 8a shows the results obtained from a long unevenly wound circumferential coil (also shown in the figure). The turn density is gradually increased as we move from the center of the coil to the ends. The coil has higher sensitivity for steel support than for the magnetite sample surrounding the Inconel-600 tube. The sensitivity of the coil to the steel support sample compared to its sensitivity for the magnetite sample increases as the test frequency is increased. This advantage seems to level off around 100 kHz. The ratio of the signal from the steel support sample to the signal from the magnetite sample at 100 kHz is about eight. However, the phase separation between the two signals at this frequency is about 180° instead of 90° which is more the preferred separation. Decreasing the test frequency reduces this phase separation but it also reduces the ratio of the amplitudes of the two signals. At 1 kHz, the phase separation is about 105° but the ratio of the amplitudes of the two signals is only three. This coil has the important characteristic that it produces an unambiguous indication from a steel support with one or more ligaments containing 100% through-the-wall axial slots in its entire 0.75 inch (19 mm) length (Fig. 8b).

Fig. 8b Eddy current signals from as manufactured steel support surrounding Inconel-600 tube and from a support sample with 100% through the wall slotted ligament surrounding Inconel-600 tube using the long coil of Fig. 8a. The coil produces unambiguous indication from a steel support with a slotted ligament.

It may be observed that this coil has a straight line response to the steel support surrounding the Inconel-600 tube at 10 kHz test frequency. This was achieved empirically by manipulating the turn density profile along the length of the coil. In fact, one can obtain a straight line response to the steel support at a different frequency by making a judicious choice of coil length and by manipulating the turn density profile along the coil length. The straight line response of this coil to the steel support surrounding the Inconel-600 tube may be compared to the complicated signals obtained by using the conventional coil in absolute mode (Fig. 3a).
DISCUSSION OF RESULTS

The quantitative evaluation of multiple parameters simultaneously present in a specimen can be achieved through multiple tests. The minimum number of tests needed is equal to the number of parameters to be evaluated. In eddy current technique, one of the test variables is the test frequency used since the signals from different test variables often have different frequency dependence. However, the separation of the information about the various simultaneously present test specimen parameters from the multifrequency data is not easy and is often not possible. For example, it has not yet been possible to obtain quantitative information about the steel supports or magnetite in the crevices from multifrequency eddy current data of the type shown in Figs. 3a and 3b. In this study, we are approaching this problem by using different probes which have very different sensitivities for the steel support and for the magnetite. We find that we have here three sets of probes: (1) The conventional probe which has somewhat similar sensitivities for the steel support and for the magnetite sample. (2) Probes which have larger sensitivity for the magnetite sample than for the steel support sample (Figs. 5, 6 and 7). The probe shown in Fig. 6 has the best characteristics if the objective is the evaluation of the tube support crevice. (3) The probe which has larger sensitivity for steel support than for the magnetite sample (Fig. 8). This probe has the best characteristics if the evaluation of the support plate ligaments is the objective.

A complete understanding of the characteristics of these coils would obviously require computer based solutions of the field problems involved here and is not within the scope of this work. However, an intuitive understanding of the response of coils to magnetite and carbon steel is in order. We will ignore the Inconel tube from this discussion since it is a constant parameter in our tests. The magnetite and carbon steel can be fully defined for this discussion by \( B_m \), \( \sigma_m \) and \( \mu_m \), the magnetic permeability and electrical conductivity of the respective materials. We will not be too far off if we take \( \mu_m \approx \mu_s \) and \( \sigma_m \ll \sigma_s \). We will further assume for this discussion that \( \sigma_m \approx 0 \) so that the response of the coils to the magnetite is a measure of \( B_m \) (i.e. eddy current effects can be ignored). The probes discussed in this paper can be classified into two broad categories, (1) probes with circumferential coils (Figs. 1 and 8) and (2) pancake probes (Figs. 4 to 7). The probe of Fig. 5 has circumferential coils but the field is so arranged that it functions as a pancake probe.

The impedance locus of the test coil caused by the variation in the sample properties is a function of the coil size and geometrical shape (3). For example, the resistance maximum in the conductivity locus of the impedance of cylindrical coils becomes proportionately larger for longer coils which results in the longer coils having proportionately higher sensitivity for higher conductivity samples. Since we can take \( \sigma_m \approx 0 \), we are assuming that the magnetite has hardly any effect on the coil resistance. The magnetite only increases the coil reactance. Thus, the sensitivity of a cylindrical coil for carbon steel relative to its sensitivity for magnetite can be increased by increasing the coil length. Increasing the length of the coil would also result in increasing the phase angle separation between the signals from magnetite and carbon steel. The data of Figs. 3a and 3b for the short coil and of Fig. 8a for the long coil are consistent with the above qualitative arguments.

The impedance loci of the pancake coils extend less in the resistance direction than even those of the short cylindrical coils. Thus, the sensitivity of a pancake coil for carbon steel relative to its sensitivity for magnetite is smaller than that of a short cylindrical coil of similar radius. This is in qualitative agreement with the data of the coil of Figs. 4 a,b when compared to the data on the short cylindrical coil (Fig. 3a). Similarly, a decrease in the diameter of the pancake coil means moving the impedance point for carbon steel to a higher location on the conductivity locus since a smaller coil radius gives a lower effective reference number for the same metal. This results in a higher value for the ratio of the magnetite to the carbon steel signal for smaller pancake coils and is consistent with our data using pancake coils (Figs. 4a and 4b).

The above discussion helps only in an intuitive understanding of the coil characteristics. It does not attempt to explain the characteristics of coils with complicated shapes (e.g. figs. 6 and 7) nor does it help in understanding the complicated signal shapes obtained for carbon steel. A detailed mathematical analysis of the field problem is needed to understand more fully the characteristics of these coils.

The data we have shown here are limited to carbon steel support plate with 1 inch (25.4 mm) diameter hole and a magnetite cylinder of 0.050 inch (1.27 mm) wall in the support plate crevice. We need to obtain data for steel supports of different I.D.'s with the resulting crevices filled with magnetite in order to evaluate these probes more completely. For example, as the support hole I.D. and the thickness of magnetite decreases, the influence of steel support on the coil relative to that of the magnetite would increase which would result in reducing the slope of the signal obtained from the combination of steel support and magnetite for the coils of Fig. 5, 6 and 7. Thus, for a complete characterization of these coils, we need data on signal slope and amplitude as a function of the support plate I.D. and magnetite thickness. However, the data presented here conclusively show that the new probes have much better discrimination between steel supports and magnetite cylinder surrounding the Inconel-600 tubes than the conventional probes.

SUMMARY AND CONCLUSIONS

1. The phase angle separation between signals from steel support and from magnetite surr-
ounding an Inconel-600 tube can be changed by simply changing the coil geometry without changing the test frequency (Figs 5a and 5b).

2. Probes have been designed which have much higher signal phase and amplitude discrimination between steel supports and magnetite cylinders surrounding Inconel-600 tubes than the conventional probes.

3. The long unevenly wound circumferential coil (Fig. 8a) has an unambiguous indication for steel supports with one or more ligaments containing 100% through the wall axial slot.

4. More experimental work towards a complete characterization of these probes needs to be carried out.

5. Theoretical work on the coil design is needed in order to determine if the test frequency for optimum characteristics of the coils can be lowered to near 10 kHz.

REFERENCES


(3) Reference 1, Chapter 2. A very intuitive discussion of coil loci for various coil geometries is given here.
SUMMARY DISCUSSION

Jim Martin, Chairman (Rockwell Science Center): I think we have time for questions. If not, I have a question.

I am not completely familiar with this field. The operation at 10 kilohertz seems to be very important. What is the disadvantage of operating at higher frequencies?

Amrit Sagar (Westinghouse Electric): At high test frequencies, the signals from tube discontinuities such as dents and wall thinning are large and interfere with the evaluation of the support plate condition. At lower test frequencies in the range of 10 KHz, signals from such sources are relatively insignificant and do not interfere with the evaluation of the support plate and crevices.

Bert Auld (Stanford University): I have a question. How do these coils relate to the standard differential and absolute coils in regard to the probe wobble signals? Did you find any differences?

Amrit Sagar: Since we are working at low test frequencies, the probe wobble signals are very small and present no problem. A coil somewhat similar to the long coil was, I guess, tried in the field a couple of years ago. The information I got was that the field people liked its performance since this coil produces very unambiguous signals from the support plates with broken ligaments. In fact, separating the support-plates with broken ligaments from the good support plates becomes a trivial problem. In this presentation, I am not implying that the problem is completely solved. In fact, some of these coils have problems, for example, some of them have optimum performance at high frequencies in which case probe wobble could be a problem.

Thank you.