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Improved Eddy-Current Inspection for Steam Generator Tubing*

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ABSTRACT

Oak Ridge National Laboratory has been engaged in the research and development of eddy-current tests for a wide range of different problems. Recent advances have been made on our multiple-property techniques. This technique generates a set of coefficients that correlate the readings from an eddy-current instrument to the properties of the test that produce the readings. While this technique will work with reflection probes, pancake probes, or bobbin probes, we have concentrated on the latter since this type of test is the most widely used in the commercial inspection of steam generators. The test properties varied include tube supports, tube sheets, copper deposits, magnetite deposits, denting, wastage, pitting, cracking and IGA.

While our multiple-property technique has given good results for several years, recent advances in personal computers have considerably improved the results. Fits have been run for the differential bobbin probe that have included over 95,000 different sets of property values and their corresponding readings. Multiple-property fits of these readings have given defect size fits with root-mean-square errors under 5% of the wall thickness for ASME Section XI standards. Although the actual measurement of the defect depths is not that good (without corrections), the signal-to-noise ratio is very good, even at copper and magnetite interfaces. Different types of function fits have been tested for the various types of probes and defects, and optimum functions have been determined for each.

INTRODUCTION

One of the main problems with eddy-current testing is the large number of different properties that can affect an eddy-current test. This allows many physical properties to be measured with eddy currents but can also cause severe problems with the interpretation of the test results. When a significant number

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of these properties vary during an eddy-current test, the resulting signals can be very confusing. The inspection of steam generator tubing with eddy currents is a classic example of a multiple-property problem. In Figure 1, we show an example of the properties that can vary for steam generator inspection.

Figure 1 shows the inspection of a degraded steam generator tube from the bore with a differential bobbin probe. The property variations that cause changes in the eddy-current signals are the probe wobble, wastage, fretting, the presence of tube supports, copper deposits on the tube, pitting, magnetite, denting, intergranular-stress-corrosion-cracking, and intergranular attack. The solution of multiple-property eddy-current problems is quite complex but has been successfully accomplished a number of times.

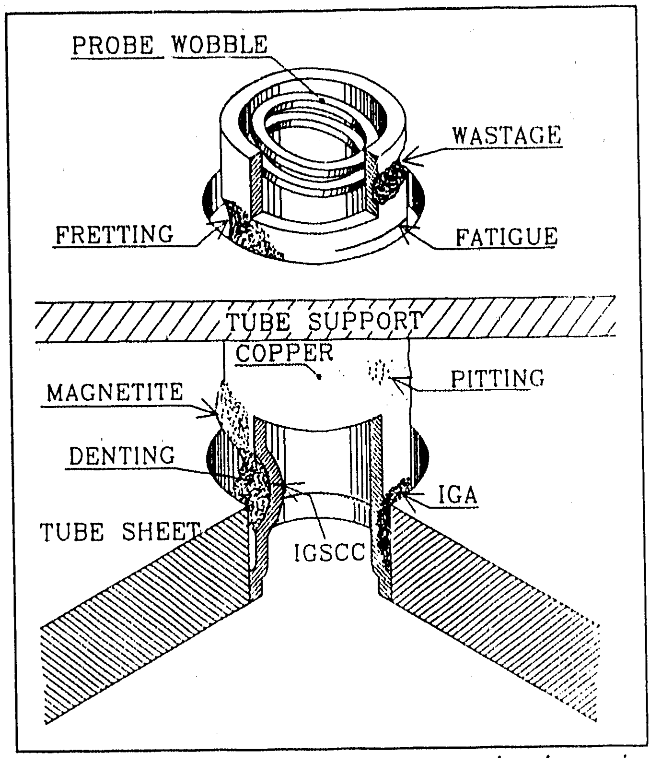

Figure 1 Multiple property variations in a degraded steam generator

The requirements are to have as many measurements as there are unknowns and for the measurements to vary in a unique (different) manner as the properties vary. For eddy-current measurements, we can get unique readings from either multiple-frequency or pulsed eddy-current tests. The multiple-frequency method is the most common and traditional method for eddy-current tests,[1] although pulsed eddy-current inspections have been successfully performed.[2] We then need a way to correlate the experimental measurements to the property variations. If we use a set of standards, we can measure the instrument readings for the known property variations. We can then use least-squares statistical techniques to relate the readings to the properties. We can determine a set of coefficients that can be multiplied by the readings to give the properties. However, eddy currents are inherently nonlinear, and we can get better results if we use a nonlinear function of the readings rather than the readings directly. The best results are obtained if a "natural eddy-current" function is used. Our analytical computation techniques have helped us to discover these natural functions.[3] The resultant set of coefficients, when multiplied by the readings, will give the value of the fitted property variation and suppress the variation of all of the other properties.

Both the properties and the instrument readings that are produced by them must be known in order to determine these coefficients. These may be determined by either experimental measurements on a standard or analytical calculations using a mathematical model. In practice, both experimental measurements and analytical calculations are usually used. The analytical studies are usually done initially so that we can determine the optimum coil design and operating conditions for a given inspection problem. This study may involve a large amount of computer time but no hardware cost. Then, the standards are constructed, the measurements repeated for the standards, and the fitting repeated for the experimental measurements. This is generally necessary since small inadvertent changes in the coil dimensions can produce significant changes in the results, and frequently the electrical and magnetic properties of the materials are not adequately known.

In order to get a set of coefficients that will accommodate property variations over their entire range of values, the set of samples that are used for calibration must vary over this entire range. For instance, if we take 3 wall thicknesses and 3 tube support values, that would give 9 different possible combinations of property values. In Table I, we show the different property values that should be considered for the degraded steam generator shown in Figure 1. Since all of the property combinations are not possible at the same time, we are left with 540,000,000 combinations. Some of the geometrical variations require more values to describe than others. For instance, with the tube sheet, which produces a large, nonlinear signal as the probe moves past its edge, readings must be taken at close intervals in order to characterize and suppress this variable. For other property variations, we can have magnetite occur both under the tube support and on the free span of the tube. Copper, on the other hand, is usually not deposited under the tube supports but only in the free span of the tube.

Table I Property values needed for steam generator test and possible combinations

PROPERTIES VARIED	VALUES
1. TUBE SUPPORTS/TUBE SHEETS	30
2. MAGNETITE	60
3. COPPER	60
4. DENTING	10
5. WASTAGE/THINNING	10
6. PITTING	60
7. CRACKING	60
8. INTERGRANULAR ATTACK	10
POSSIBLE COMBINATIONS	540,000,000

EXPERIMENTAL WORK

While the total combination of property values is too large for most computers today, it is not beyond the capabilities of future computers. We have performed a training run on a smaller set of samples, based on the ASME Section XI eddy-current steam generator standard. A drawing of this standard is shown in Figure 2. The standard consists of drilled holes that run from 100% deep to 20% deep in 20% increments. We have placed a sheath over the standard that consists of copper, ferrite to simulate magnetite, and a tube support/tube sheet ring. The outer sheath can slide over the tube so that we can simulate the defects with any combination of outer artifacts. The outer artifacts are separated by a nonconducting, nonferromagnetic material used as a spacer. The outer artifacts were positioned every 0.10 in. with relation to the defect, and we moved the probe over the defect in 0.01 in. increments. This scan produced a total of 95,000 sets of properties and instrument readings. The readings were taken at frequencies of 20khz, 50khz and 100khz with a Zetec MIZ-17. The tube was scanned with a differential bobbin probe, and the readings were digitized and stored in the computer. Since this particular instrument is a single frequency instrument, we had to make three separate runs and manually set the frequency between each run. The computer-controlled mechanical scanner has a resolution of 0.00025 in. and an accuracy of 0.002 in.

The properties that were fitted were defect size and the type of the outer sheath material. We have used three different techniques for fitting defect size. The most simple is either a defect or no defect. This is adequate for absolute coils if a very coarse scan of the tube is being made but not if we are making a fine scan or if a differential bobbin probe is being used. In Figure 3 we show the type of signals produced for these probes. The absolute probe approximately produces a gaussian response, and the differential bobbin produces approximately the derivative of the absolute probe, or the derivative of a gaussian. For a fine scan, these types of "property values" are much more natural, easier to fit and produce much better results. Since we were using a differential bobbin probe, we fitted the instrument readings to the derivative of the gaussian. The constants A and B were chosen to give the best fit while x represents distance along the tube.

The best fits gave an rms error of less than 4.5%. This percentage error is in terms of total wall thickness. A least-squares fit of this type (with many zero defect values) maximizes the signal-to-noise error at the expense of an increased error in the measurement of the actual defect size. This considerably lessens the probability of false calls in the presence of the artifacts. Other fits were run where the rms error was increased to 6.5%, but the measurements of the defect size were more accurate. The signal-to-noise ratio for these fits was poorer. In

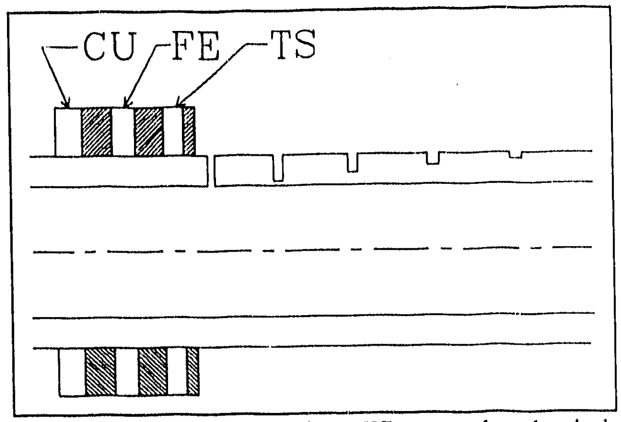

Figure 2 ASME Section XI standard with movable outer artifact sheath

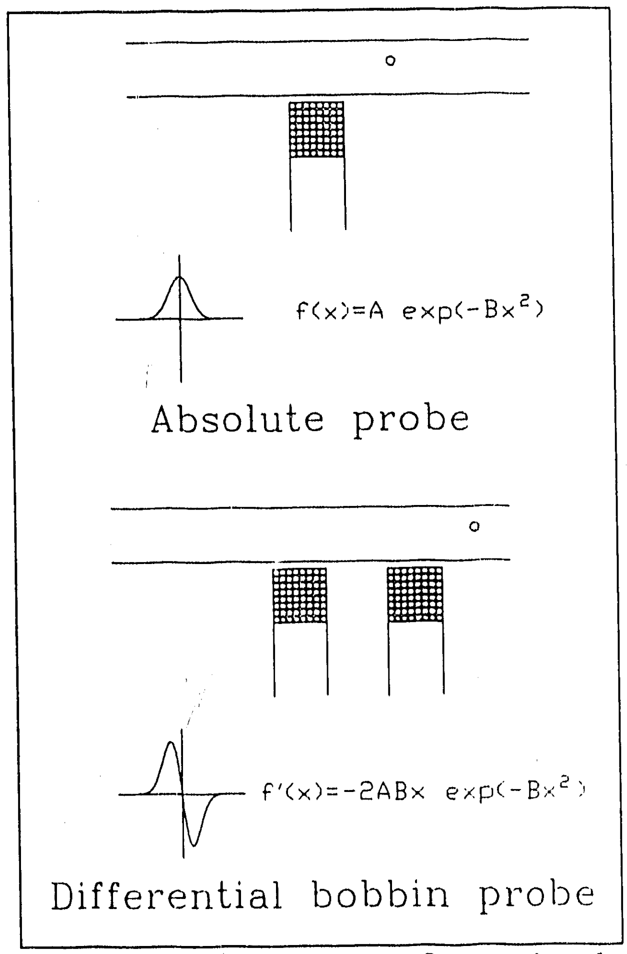

Figure 3 Approximate defect signals for absolute and differential bobbin probes

Figure 4 we show a plot of the error in defect size as a function of the distance between the defect and the tube

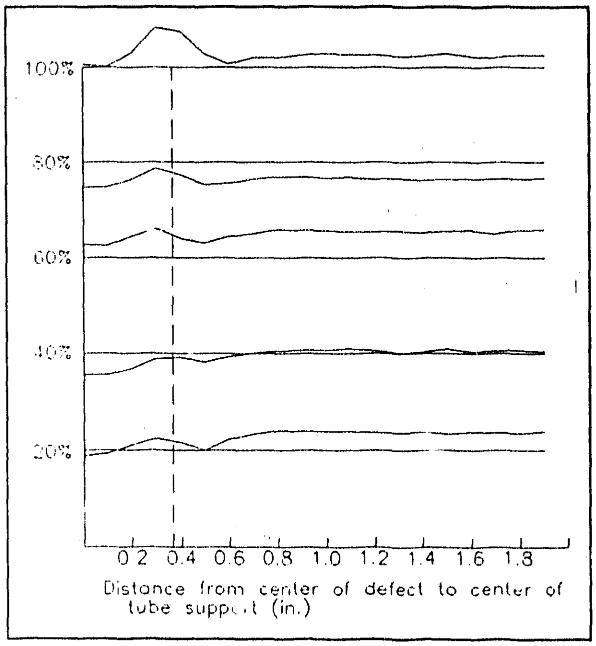

Figure 4 Error in defect depth measurement plotted against distance of the defect from a tube support

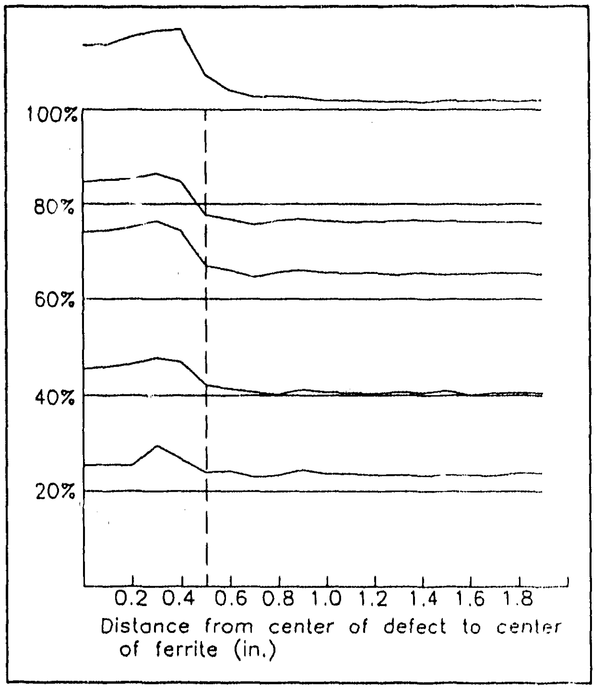

Figure 5 Error in defect depth measurement plotted against distance of the defect from magnetite

support. The dashed line represents the edge of the tube support while the region to the right is the free tube region. The defect size of each of the ASME Section XI defects is plotted against the distance from the center of the tube support. As expected, the maximum error is at the edge of the tube support. However, for the tube support, this error is quite small and well within acceptable limits.A similar plot is also given for magnetite, as shown in Figure 5. The error has increased, particularly in the region under the magnetite. However, the error is in overcalling the defect size and is not significant. For the case of copper, as shown if Figure 6, the error does become significant. Copper shielding tends to cause the defects to be undercalled. However, for a slight increase in complexity, this problem can be corrected. The type of od artifact, such as tube sheet, magnetite, copper or

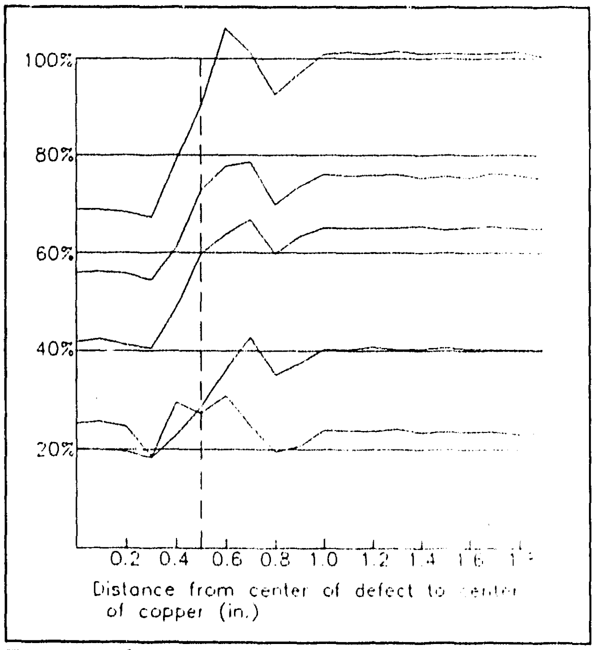

Figure 6 Error in defect depth plotted against distance from copper

free standing, can be computed. If the probe is in one of the first three regions, a correction to the defect size can be applied. This technique has been applied successfully in some instances but requires another level of computations.

In Figure 7 we show the computed value of the defect depth and the "actual" value of the defect depth as a function of distance along the tube. This figure is actually three scans pieced together. The first scan is with the copper centered over the defect, the second with the edge of the copper at the defect and the last with the defect outside the copper. The lower curve is the "actual value" of the defect, which as previously stated is the derivative of the gaussian. The next curve is the defect signal computed from the instrument readings. The peak-to-peak value of the signal is taken as the defect depth. The next three channels are to show the presence of tube supports, magnetite or copper on the outer surface of the tube. A high value represents the presence of a particular artifact; a low value represents its absence. We can look at the copper channel and tell where it is in relation to the defect. Note that while the defect signals in the computed curve are not as large as those in the actual curve, they are clearly visible and well above the noise level. The computed defects are located and sized automatically using a computer reduction of the plot. The location of the copper artifact is shown in the upper curve, and the residual from its edges is small and well below that of the 20% defect.

FUTURE WORK

This study demonstrates the results that can be produced with multiple-property eddy-current tests, but the number of properties is considerably below those outlined in Table I as needed to accurately represent real-world steam generators. We currently are making improvements in the data acquisition, the data analysis and standards needed to accurately represent the degraded generator.

We have acquired a Zetec MIZ-18A, which is a widely used instrument for eddy-current testing of steam generators. This instrument performs highly accurate (16 bit) four-frequency measurements at a high rate of speed (1000 readings per second). The instrument is set up and the measurements are taken over the IEEE-488 bus. We have interfaced the instrument to our IBM PC-AT clone computers, and will use it to gather the large data sets needed for the steam generator problem.

While the ASME Section XI standard is widely used for the calibration of eddy-current instrumentation for steam generators, it is not the best standard for determining the coefficients. It has a limited number of defects, and not enough property variations are present, particularly those for denting. The construction and certification of standards for multiple-property eddy-current

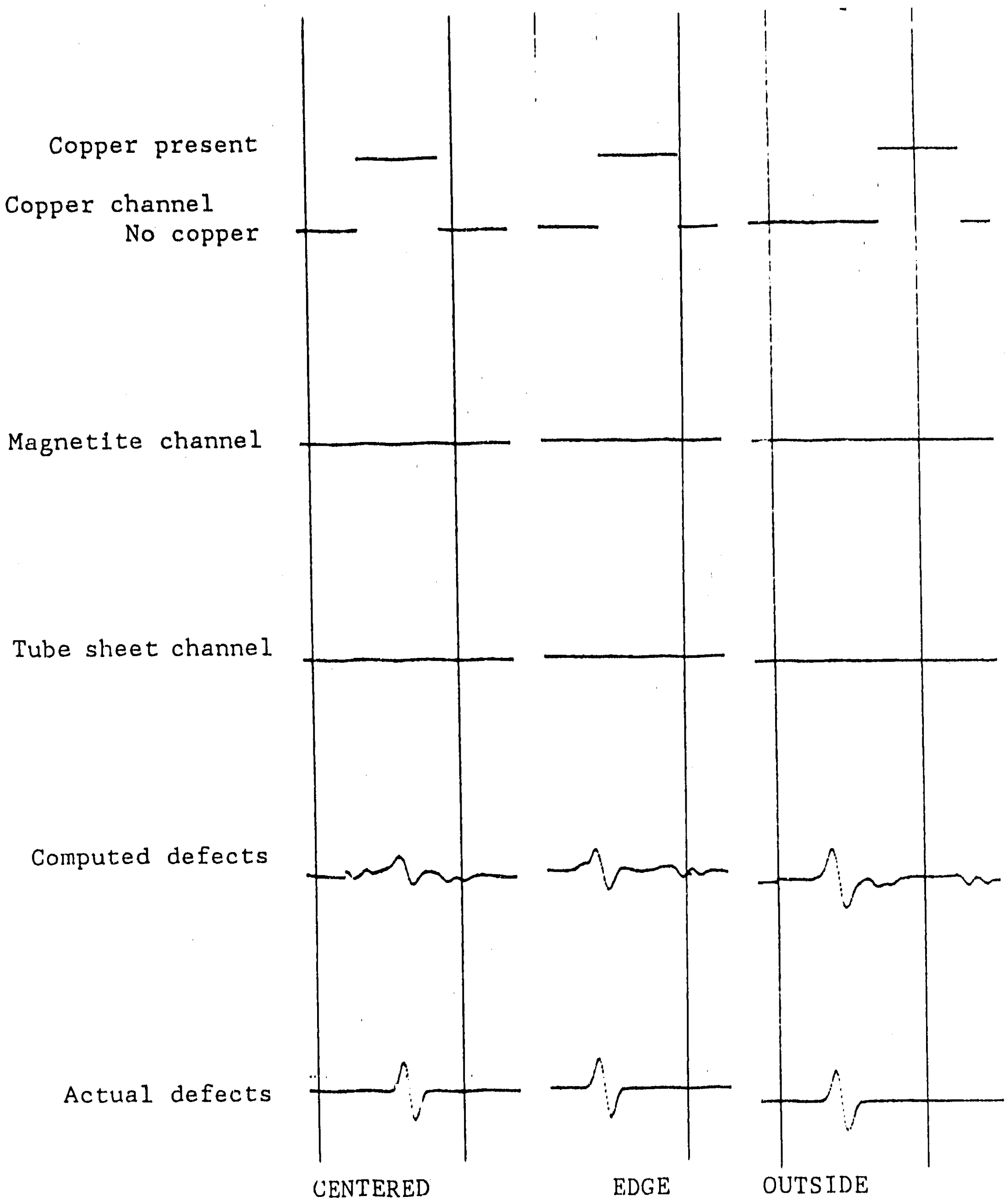

Figure 7 Computed scans and actual defect depth for a 40% defect with the presence of a copper deposit on the tube

tests is the most difficult and expensive part of the process. In Figure 8, we show part of the standard that is used for eddy-current steam generator tests.

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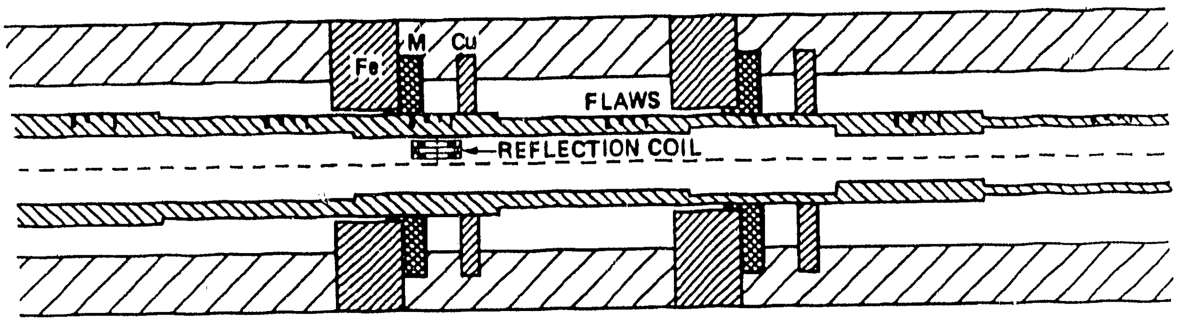

Figure 8 Section of a training standard used for steam generator inspection. Thousands of different property variations are possible with this standard.

This standard consists of two movable parts. The tube is machined in sections with each section having a set of defects, a given tube inner diameter, and wall thickness. The outer sheath consists of a tube sheet/tube support, a magnetite section, and a copper section. The tube sheet section has the nominal inner diameter while the magnetite and copper sections have a inner diameter that is only 0.001 in. greater than the outer diameter of the tube. The magnetite and copper sections are to simulate these deposits growing on the tube. The standard is arranged with increasing tube outer diameters and sheath inner diameters so that the sheath will slide over the tube. In this manner, we can simulate an unlimited combination of defects in relation to the outer artifacts and most of the conditions shown in Figure 1. There are actually two tubes that fit inside the outer sheath. One is for bobbin types of probes and has one set of defects at each location along the tube. The other is for pancake and reflection types of probes and has three defects at each axial location. The tube can be rotated so that the probe looks at each of the three defects, one at a time. Shims of nonconductive tape are placed at the different circumferential locations so that the tube can be rotated to the different defects to simulate lift-off. The standard is mounted in a mechanical scanner which is in turn controlled by a computer over the IEEE-488 bus so that the entire data set can be acquired automatically without human intervention. This is extremely important and allows the data to be taken 24 hours a day. If different property variations are discovered at a later date, measurements from these can be added to the original data set as long as the same instrument calibration is maintained.

The means to process this amount of data is also significant. A two-dimensional array that has one dimension equal to the number of property sets and the other equal to the number of coefficients must be stored in the program. This array is very large and contains all of the readings and returns the coefficients and the least-squares error. However, the cost of computers and memory is decreasing rapidly, and economical systems with large amounts of fast memory are now coming on the market. The property set with 95,000 different values required about 1.)

megabytes of memory. We now have a computer with 32 megabytes of memory and anticipate that it will allow the fitting of about 300,000 different property values and their associated readings.

SUMMARY AND CONCLUSIONS

The steam generator inspection problem is a complex, changing problem that requires our best innovative efforts to solve. The use of multiple-property eddy-current techniques has been demonstrated to be able to solve this problem for a limited set of property variations. We are now in the process of applying this technique to the larger set of property variations that are required for our nation's aging steam generators.

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