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Eddy-Current Inspection for Steam Generator Tubing Program Annual Progress Report for Period Ending December 31, 1983

C. V. Dodd
W. E. Deeds
J. H. Smith
R. W. McClung

Prepared for the
U.S. Nuclear Regulatory Commission
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METALS AND CERAMICS DIVISION

EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1983

C. V. Dodd, W. E. Deeds, J. H. Smith, and R. W. McClung

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1983

C. V. Dodd, W. E. Deeds, J. H. Smith, and R. W. McClung

SUMMARY

Eddy-current inspection is the most suitable method for rapid boreside evaluation of steam generator tubing. However, small flaws can be masked by the effects of harmless variables, such as tube supports. To identify the critical properties accurately and reliably in the presence of extraneous signals caused by variations of unimportant properties, sufficient information is needed to identify harmful variations and reject harmless ones. For this reason we have been developing instrumentation capable of measuring both the amplitude and phase of the eddy-current signal at several different frequencies, as well as computer equipment capable of processing the data quickly and reliably. Our probes and test conditions are also computer-optimized. The most recent probe design embodies an array of small flat "pancake" coils and improves the detection of small flaws and the rejection of tube support signals. We have also experimentally verified the accuracy of our computer programs for calculating the signals produced by defects in tubing and are adapting our new IBM System 9000 computer to take and process the larger amounts of data required by additional variables, such as copper coating and intergranular attack.

INTRODUCTION

This program was established to develop improved eddy-current techniques and equipment for the in-service inspection of steam generator tubing. The purpose is to separate the effects of relatively harmless variables such as denting, probe wobble, tubesheets, tube supports, and conductivity variations from critical ones such as defect size, depth, and wall thickness variations.

PROGRESS DURING YEAR ENDING DECEMBER 31, 1983

The number of combinations of properties that may occur in steam generator tubing may be as high as 3000 or 4000, because many variables must be included. For each combination, at least 16 numbers must be stored in the computer memory, and still more memory is required to perform a least-squares fitting of such large mathematical arrays. The memory capacity of our ModComp IV minicomputer limits it to about 1200 combinations of properties. Our new IBM 9000 microcomputer will be able to handle about 30,000 combinations when we get the programs converted to use it. These larger arrays are needed for including the effects of additional variables, such as iron oxide or copper deposits on the tubing, to "train" the computer to recognize and measure or ignore such variables.

Major emphasis has been on the development and application of the small, flat "pancake" coils. Figure 1 shows one of the pancake coils mounted on a Micarta "sled," which is pushed outward against the tube wall by a flexible cushion on the back. The coil contains 73 turns of No. 42 AWG enameled copper wire wound with an inner diameter of 1.52 mm (0.060 in.), an outer diameter of 5.08 mm (0.200 in.), and an axial length of 0.25 mm (0.010 in.). The self-inductance is approximately 16 μH.

Figure 2 shows a probe with three coils in sleds held in place with retainer rings. The ends of the probe and the ends of the sled are tapered to facilitate both insertion into the tube and moving past uneven spots inside the tube. The ability to maintain contact with the inner surface of the tube reduces the problem of lift-off (coil-to-sample spacing), which is one of the most critical variables in eddy-current testing.

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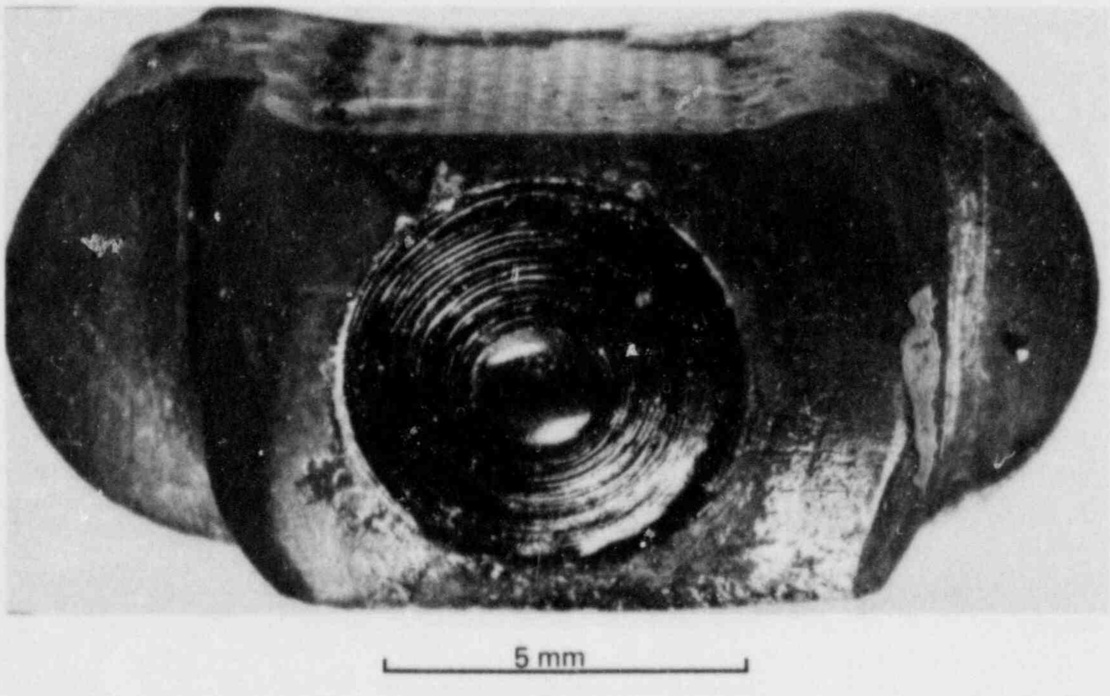

Fig. 1. Pancake coil mounted on a "sled."

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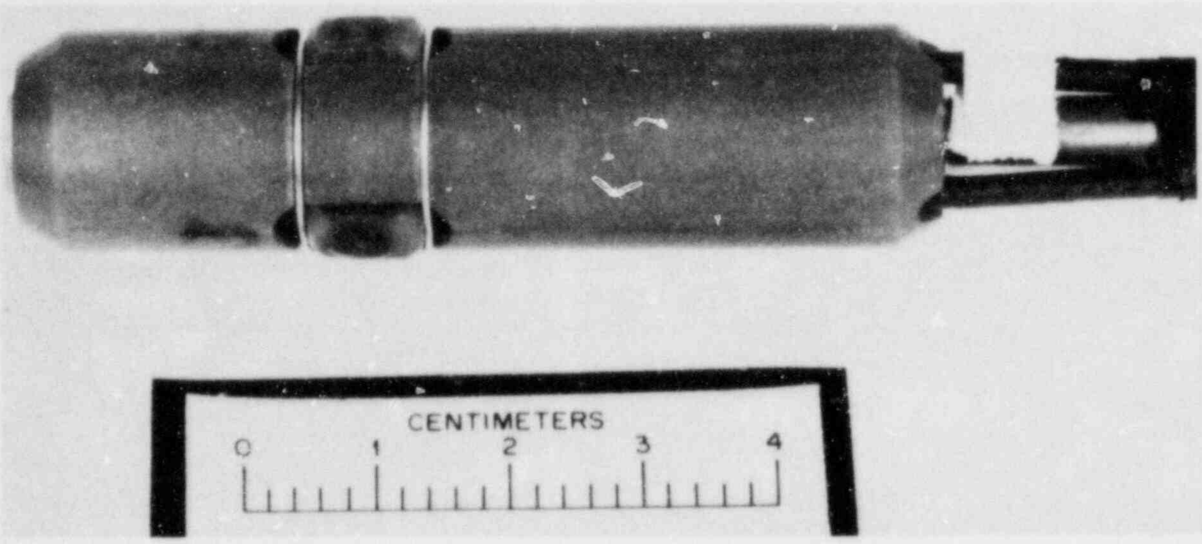

Fig. 2. Probe with array of three pancake coils spaced 120° apart around the axis.

A pancake probe was used to obtain a set of data with two tubing test samples containing notches and holes on the inner and outer surfaces of the samples. The depth of the smallest holes and notches was 10% of the tube wall thickness. Variables examined were defects (type, size, and location), bore holes in tubesheets (diameter and location), tube wall thickness, and probe lift-off. The data were obtained with a pancake coil and the ModComp IV computer. We could distinctly detect 20% holes on the outer surface of the tubes. Signals were obtained from 10% holes on the outer surface but did not significantly exceed the noise level.

We then fabricated three tubing test samples of alloy 600 with nominal wall thicknesses of 0.76, 1.02, and 1.27 mm (0.030, 0.040, and 0.050 in.). Each sample contained four flat-bottom holes and four electrodischarge-machined (EDM) notches. The depths of the discontinuities are 25 and 50% of the sample wall thickness, and two of each type are located on the inner and outer surfaces of each sample.

We modified the data-reading computer programs and reallocated memory space in the laboratory minicomputer to allow us to store the 3240 data lines required to test the three samples described above by multifrequency eddy-current techniques. A data set was then produced by scanning the three tubing test samples at three different lift-off values with two simulated tube supports. The eddy-current probe used to produce these data contained a single pancake coil. The resulting raw data were stored in computer memory.

Using this data set, we could examine such variables as wall thickness, defect size, defect location, lift-off, tube support location, and the spacing between the coil or sample and tube support. At this time, if we use the existing laboratory computer and the fitting programs, memory space is restricted, and we cannot analyze the entire data set of 3240 property value combinations simultaneously. We are working with subsets of the data, and we can determine characteristic trends. The most critical area, as far as accurate measurements are concerned, is with the coil at the edge of the tube support.

Figure 3 shows a trace of a wall thickness scan of a machined sample with wall thicknesses of 1.25, 1.01, and 0.76 mm (0.049, 0.040, and 0.030 in.). The instrument was "trained" (calibrated) with a different coil to produce the designated thicknesses at the indicated points. The (nonoriginal) coil also reproduces the proper thickness very well. The system was not trained to reject flaws, so they show up, too.

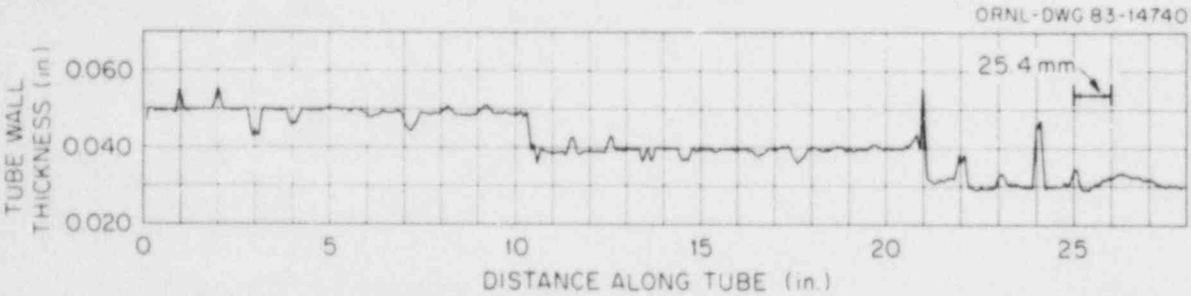

Fig. 3. Reproduction of instrument chart showing scan of wall thickness variations with a pancake probe. Ordinate legends correspond to 0.51, 1.02, and 1.52 mm.

A major effort has been to examine the effects of tube supports (or tubesheets) on the eddy-current response. To do this, we have divided the problem into three separate positions of the tube support with respect to the eddy-current coil and area on the test sample being examined. In these three positions the eddy-current measurement is being conducted (1) completely outside the tube support, (2) completely under or inside the tube support, and (3) at the edge of the tube support (the eddy-current pancake coil either entering or leaving the tube support). We have mathematically fit the data available from our three test samples and have developed independent sets of coefficients for the three positions. We modified existing computer programs to allow us to plot simultaneously three output data curves representing mathematical fits to the data for each of the three positions described. By examining these data, we learned that we can use a single mathematical fit for positions 1 and 2 (i.e., the free tube region and in the tube support or tubesheet). Our test sensitivity is such that we can detect notches with depths equal to 25% of the tube wall in these regions. A separate mathematical fit is required for data obtained from the tubesheet interface region (condition 3), and the test sensitivity is not quite as good. By using three regions, we are barely able to detect a 25% outer surface notch in the free tube region and in the tubesheet region, with the sensitivity decreasing to a 40% notch at the interface region.

We have modified our computer programs to select the appropriate set of coefficients (or proper mathematical fit) for each particular position as the eddy-current probe scans down the tubing past a tube support. This will allow us to produce a single output data curve that has been optimized for maximum sensitivity to defects in the presence of the tube supports for all three positions.

Figure 4 shows scans of a small pancake probe past 50% EDM longitudinal notches on the inner and outer surfaces of nominal alloy 600 tubing, both inside and at the edge of a tubesheet. Notice that the notches are not only readily detected at the edge of the tubesheet but that they also give indications that are essentially the same as when the notch is inside the tubesheet region.

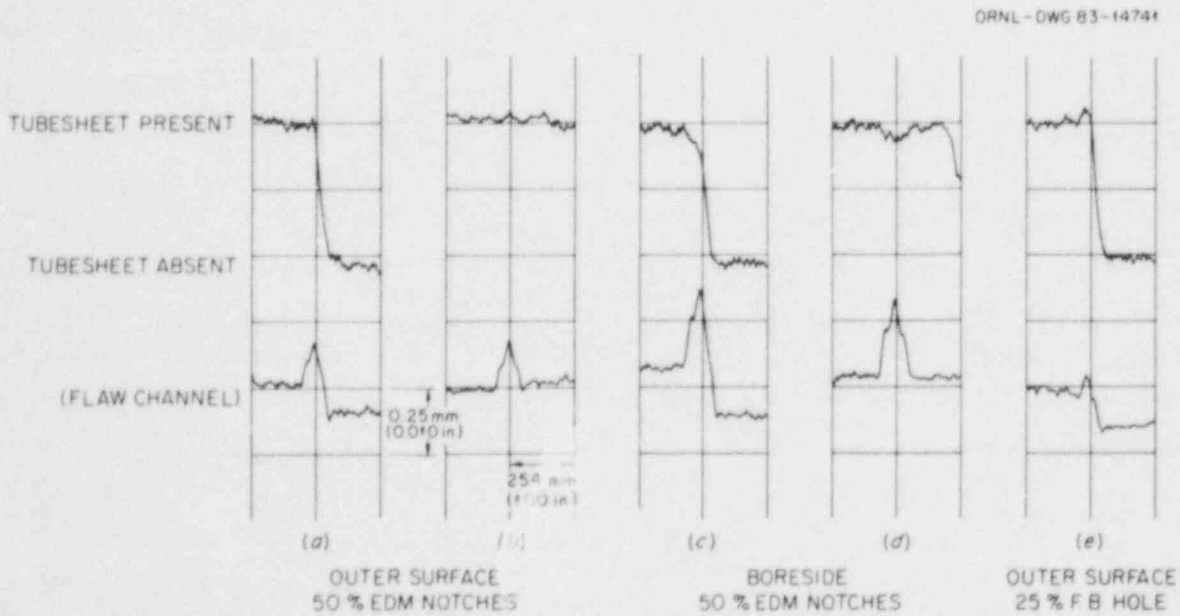

Fig. 4. Scans with a pancake probe of 50% EDM inner and outer surface notches and a flat-bottom hole located inside (*b*) and (*d*) and at the edge (*a*), (*c*), and (*e*) of a tubesheet.

A very important result of these experiments is that the "training" of the instrument was done with one pancake coil and that these traces were run with a similar, but different, pancake coil. In fact, we have run such traces with three different pancake coils in addition to the one used to calibrate the instrument and to obtain the polynomial coefficients; all four coils produced essentially identical results. This shows that the coefficients stored in the instrument are transferable from one coil to another. This is important when we want to multiplex signals from multicoil arrays or to replace a damaged probe. The pancake probes used in the tests were produced without special care to make them identical, although they all have the same number of turns. It is true that the traces made with the later coils show a slight offset of the flaw baseline after emergence from the edge of the tubesheet, which was not present with the original pancake coil, but the flaws are still clearly indicated.

Figure 4(*e*) shows a similar trace of a 25% flat-bottom hole at the edge of a tubesheet, taken with the same coil used in the other traces. The flat-bottom holes are generally easier to detect than are the EDM notches, probably because of the greater defect volume.

Figure 5 shows the computer response when the probe passes the edge of the tubesheets with no defects present. The defect channel remains satisfactorily quiet even though the tubing has a thinner than normal wall and two different tubesheet bore diameters.

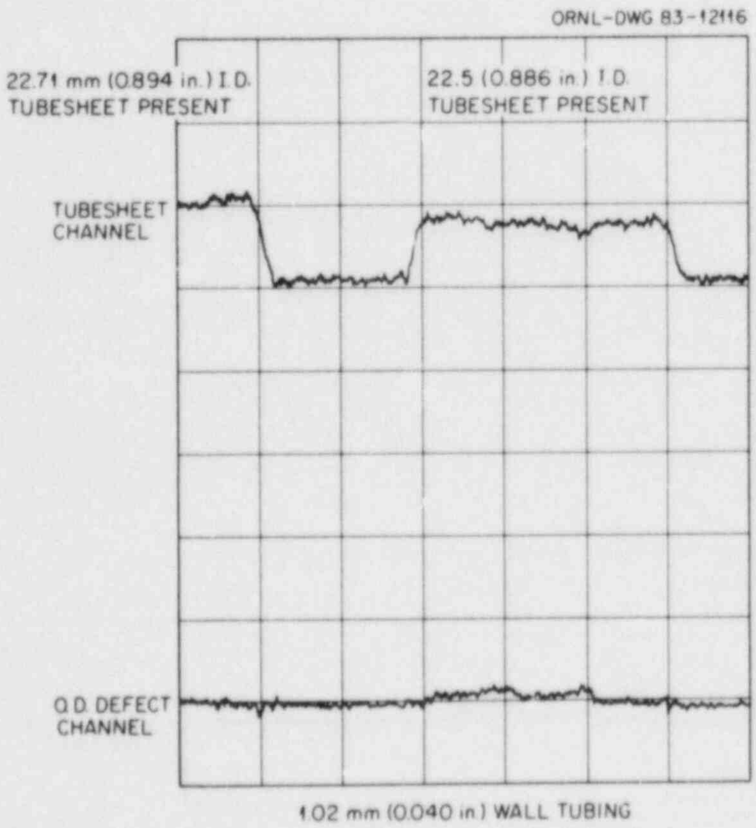

Fig. 5. Thin 1.02-mm-wall tubing with no defects near edge of tubesheets.

A pancake probe has also been used to make a number of measurements on machined defects in alloy 600 tubing and in samples that were brought to ORNL by Kurt Betzold of the Institut für zerstörungsfreie Prüfverfahren, Saarbrücken, Federal Republic of Germany. The test samples from Germany are similar, but not identical, in dimensions and material properties with the alloy 600 tubing samples that we used to develop our mathematical data fits. Because the German samples did not include a complete range of test property combinations, we could not recalibrate or "retrain" our instrument and decided to use our previous calibration on American samples to see how sensitive the calibration might be to somewhat different tubing. The German samples contain several types of manufactured defects such as drilled holes, longitudinal and circumferential notches, simulated striations, and fretting, all located in the free tube region and at the tube support interface region. Copper shims are also located at some tube support interface regions.

We examined the samples by use of a single pancake coil and multifrequency eddy-current techniques developed for this program and were able to detect 59 of the 65 manufactured defects. We did not detect longitudinal notches located on the outer surface with depths of 20% of the wall thickness. We could detect 30%-deep notches located on the outer surface in the free tube area or at the tubesheet interface. We did not detect a 0.8-mm-diam, 40%-deep hole on the outer surface but did detect a 0.5-mm hole drilled through the tube wall. The copper shims at the tubesheet interface were easily detected, even though the set of standards did not include copper as a fitted property.

A quick study was made to examine the effects of ferrite and copper on the outer surface of the tubes. A 0.13-mm-thick (0.005-in.) piece of copper foil and a 0.20-mm-thick (0.008-in.) piece of ferrite tape produced large signals on the multifrequency eddy-current test system. We could detect both ferrite and copper in the free tube area and at the tubesheet interface. Increasing the thickness of the copper shim or the ferrite tape did not significantly increase the magnitude of the output indication; we had not programmed the computer to recognize either copper or ferrite. The indications are similar to defect indications.

Using the American alloy 600 tubing samples, we subsequently obtained a data set that includes copper in the free tube region and copper at the tubesheet interface. We also included a standard tubesheet interface (carbon steel) for reference. In effect, this provides three material interfaces for the eddy-current examination: copper-air, copper-steel, and steel-air. The three interfaces are all located outside and in close proximity [0.1–0.8 mm (0.005–0.030 in.)] to the tubes. We have analyzed and mathematically fit the data to optimize the detection of defects in the presence of the carbon steel tubesheets and copper. We could detect manufactured defects (side-drilled holes and EDM notches in the tubing samples) at any of the three interfaces mentioned above. We can also suppress the signals produced by the copper or steel at any one of the three interfaces, but we have not been able to simultaneously suppress the signals for both copper and carbon steel for all three interfaces for a single data scan. The major problem appears to be computer memory space. Because of insufficient storage space, we can mathematically fit only about one-third of the total points in the data set. We feel that, if we can mathematically fit all the data points, we will be able to suppress the effects of copper and carbon steel and still maintain good defect sensitivity during a tubing inspection. The new IBM 9000 computer system has the storage capacity to analyze all the data. We are interfacing this computer to our scanning system. We also must perform some language conversions for the computer programs that are used to obtain and analyze the data.

We have also assembled and are testing a position controller that interfaces to the new IBM System 9000 computer. When this system is completed, it will allow us to make our readings directly from the IBM computer rather than from the ModComp.

We have assembled a test system (using both single-sided and through-transmission measurements) in a vented area of the laboratory to test the contaminated intergranular attack samples recently obtained from the Ginna reactor.

Figure 6 compares ORNL measurements of the depth of stress corrosion cracks on the outer surface of alloy 600 tubing with depths obtained by metallographic examination. The samples were prepared by Pacific Northwest

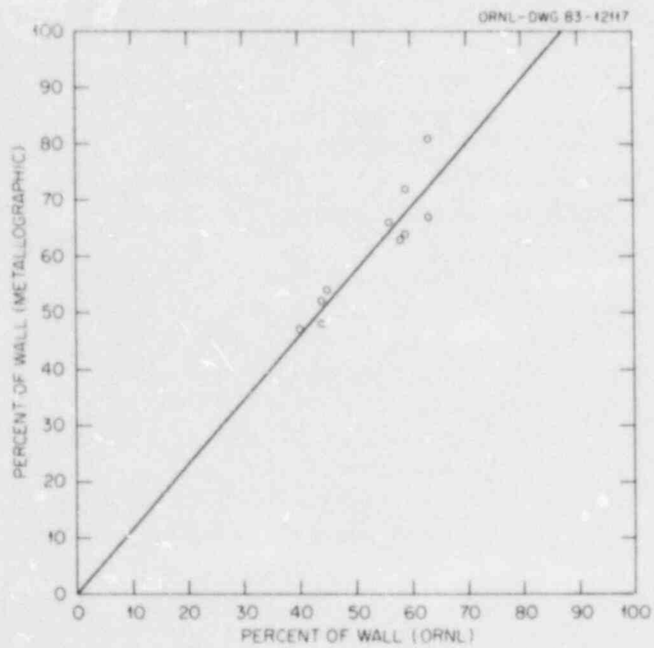

Fig. 6. Comparison of ORNL eddy-current and Pacific Northwest Laboratories metallographic measurements of the depth of stress corrosion cracks in alloy 600 tubing.

Laboratories (PNL), measured by six different laboratories in a round-robin test, and then metallographed by PNL. The ORNL measurements were made with a small pancake coil pressed against the inner wall of the tubing. The solid line in the figure shows where the points should fall if the fit were perfect. It is not at exactly 45° because the ORNL measurements were for *average* depth of cracks, whereas the metallographic data were for *maximum* crack depths. Obviously, the fit is excellent.

A summer student, C. D. Cox, made detailed measurements of coil impedance changes by scanning precise coils past carefully machined flaws in tubing and in flat plates. Figure 7 shows the calculated and measured values of the normalized impedance changes when circumferential coils in a differential arrangement are scanned past a defect on the outer surface of the tube. The agreement is surprisingly good, considering the difficulty of the measurements and the fact that the flaw is hardly infinitestimal, as assumed in the theory.

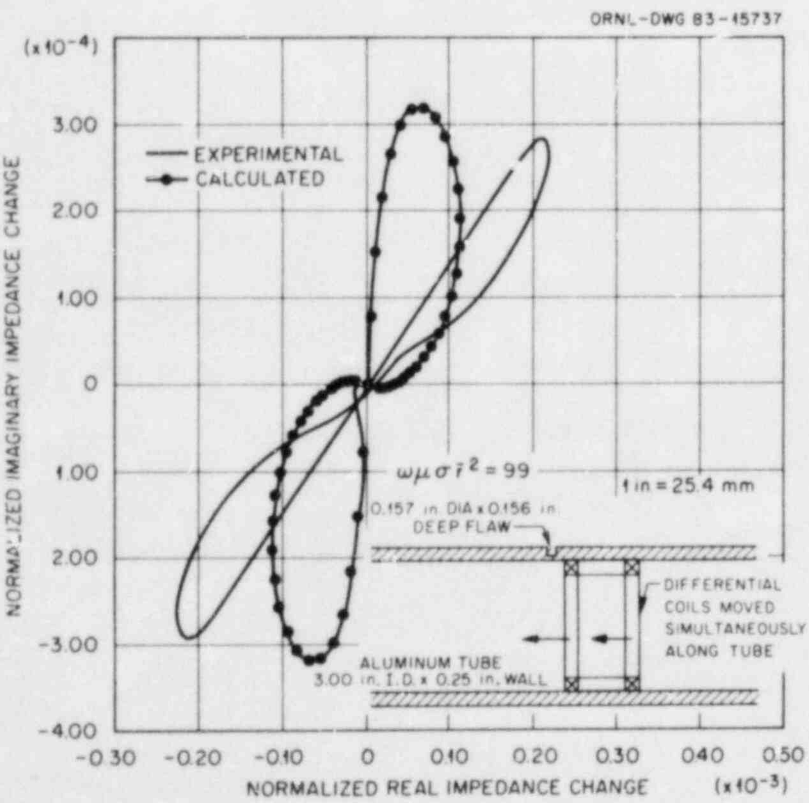

Fig. 7. Impedance changes for a differential coil scanned past an outer-surface flaw in a tube.

Figure 8 shows a similar plot of impedance changes for a single coil scanned past a near-side defect in a flat plate. This simulates the signal from a small pancake coil against the wall of a large-diameter tube. In this particular scan, the flaw is small, and the agreement is better.

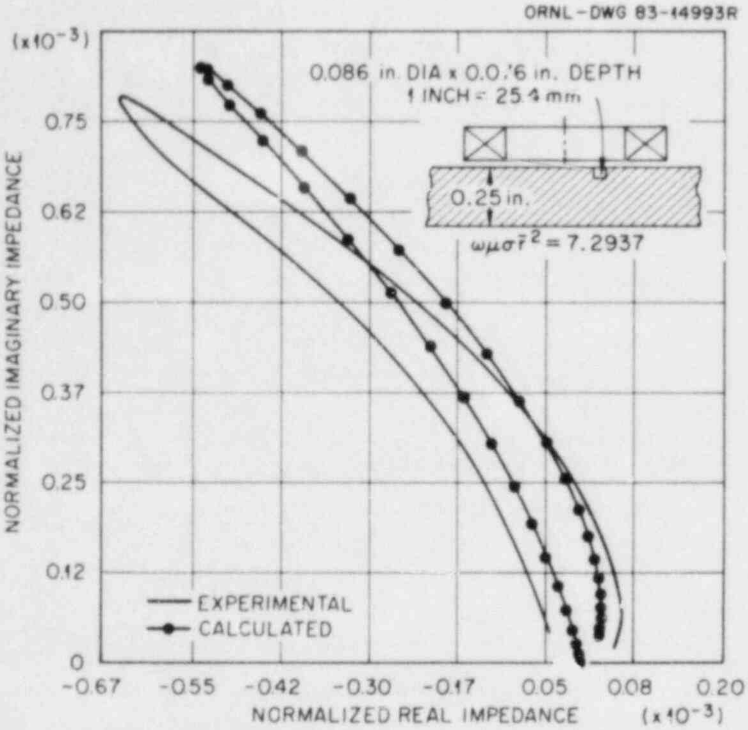

Fig. 8. Impedance changes for a pancake coil scanned past a near-side flaw in a flat plate.

These calculations were made with the "forward" theory of flaw detection, in which, if one knows the size and location of the flaw, one can calculate the effect that it will have on the impedance of the eddy-current coil(s). The integral formulas that we developed for calculating the impedance changes produced in an eddy-current coil by defects of various sizes at various locations are well known, well verified, and widely used. By using the orthogonality of the Bessel functions in the formulas, we can invert the formulas to calculate the size and location of defects from an integral of impedance changes scanned over a range of locations.

Explicitly, the normalized impedance change Z_{n_d} produced in a coil above a semi-infinite plane conductor by a defect of normalized volume Vol_n located at cylindrical coordinates r, z can be written as

$$Z_{n_d}(r,z) = \frac{-3(\omega\mu\sigma\bar{r}^2)}{2I_{\mathrm{air}}}\mathrm{Vol}_n\left[\int_0^\infty \frac{J(r_2,r_1)J_1(\alpha r)(e^{-\alpha l_1} - e^{-\alpha l_2})\alpha e^{\alpha_1 z}}{\alpha^3(\alpha + \alpha_1)}\,d\alpha\right]^2 , \quad (1)$$

where ω is the angular frequency of the eddy currents, and the coil is located at $r_1 < r < r_2$, $l_1 < z < l_2$ with mean radius $\bar{r} = (r_1 + r_2)/2$ and an air integral I_{air}. The conductor is located at $z < 0$ and has permeability μ, conductivity σ, and a complex parameter $\alpha_1 = \sqrt{\alpha^2 + i\omega\mu\sigma r^2}$.

A more complicated system of conductors or coils would require a more complicated formula, but the essential procedure would be the same. If one takes the square root of both sides of Eq. (1), multiplies the result by $rJ_1(r)\,dr$, and integrates with respect to r from 0 to ∞, the orthogonality of the Bessel functions $J_1(r)$ makes it possible to obtain the following formula via the Fourier-Bessel integral formula:

$$\sqrt{\mathrm{Vol}_n}\; e^{\alpha_1 z} = \sqrt{\frac{2\pi I_{\mathrm{air}}}{3(\omega\mu\sigma\bar{r}^2)}}\; \frac{(1+\alpha_1)}{J(r_2,r_1)(e^{-l_1}-e^{-l_2})} \int_0^\infty \sqrt{-Z_{n_d}(r,z)}\, rJ_1(r)\, dr \;. \quad (2)$$

This gives the normalized defect volume Vol_n and depth z in terms of the integral of the square root of the normalized impedance changes Z_{n_d} and other known quantities. Since α_1 and Z_{n_d} are complex variables, Eq. (2) provides two real equations and permits solution for Vol_n and z separately. This would be applicable to a small pancake coil against the inner wall of a thick tube. If we let $\alpha_1 = x + iy$, so that $x = \mathrm{Re}(\alpha_1)$, $y = \mathrm{Im}(\alpha_1)$, and if we let the right side of Eq. (2) equal $CM_0 e^{i\Theta}$, where

$$C = \sqrt{\frac{2\pi I_{\mathrm{air}}}{3(\omega\mu\sigma\bar{r}^2)}}\; \frac{1}{J(r_2,r_1)[\exp(-l_1)-\exp(-l_2)]}$$

$$M_0 = \mathrm{Mag}\left[(1+\alpha_1)\int_0^\infty \sqrt{-Z_{n_d}(r,z)}\; rJ_1(r)\; dr\right]$$

$$\Theta = \mathrm{Pha}\left[(1+\alpha_1)\int_0^\infty \sqrt{-Z_{n_d}(r,z)}\; rJ_1(r)\; dr\right],$$

then the defect depth is

$$z = \Theta/y$$

and the normalized defect volume is

$$\mathrm{Vol}_n = [CM_0\, \exp(-x\Theta/y)]^2 \;.$$

The same procedure can be applied to cylindrical conductors. For a circumferential coil inside a (very thick) cylindrical conductor, the normalized impedance change Z_{n_d} in a coil of length L and mean radius $\bar{r} = (r_1 + r_2)/2$ can be written as an integral involving the modified Bessel functions $I_1(\alpha_1 r)$:

$$Z_{n_d}(r,z) = \frac{-3(\omega\mu\sigma\bar{r}^2)}{2I_{\mathrm{air}}}\, \mathrm{Vol}_n \left[2\int_0^\infty \frac{K(r_2,r_1)}{\pi\alpha^3}\, \frac{I_1(\alpha_1 r)}{F_2(\alpha_1)}\, \sin\!\left(\frac{\alpha L}{2}\right) \cos(\alpha z)\; d\alpha\right]^2 , \quad (3)$$

where $F_2(\alpha_1)$ is a function that depends on the conductor configuration. As before, the orthogonality properties of the cosine functions enable one to invert this formula to obtain the normalized defect volume Vol_n and its radial location [implicitly in the Bessel function $I_1(\alpha_1 r)$]:

$$\sqrt{\mathrm{Vol}_n}\, I_1(\alpha_1 r) = \sqrt{\frac{2\pi I_{\mathrm{air}}}{3(\omega\mu\sigma\bar{r}^2)}}\, \frac{F_2(\alpha_1)}{K(r_2, r_1)\sin(L/2)} \int_0^\infty \sqrt{-Z_{n_d}(r,z)}\, \cos(z)\, dz\ . \qquad (4)$$

As before, this is a complex equation, equivalent to two real equations, so that Vol_n and r can be calculated separately in terms of the integral and known functions on the right-hand side of the equation.

If more complicated configurations of coils and conductors are involved, the same procedures can still be applied; only the functions in the integrals, such as $F_2(\alpha_1)$, become more complicated.

An important motivation for these flaw inversion studies, in addition to the obvious one of obtaining the flaw parameters, is to develop better basic functions for calculating the flaw properties with fewer terms in the polynomial expressions. If a really accurate function could be found for each flaw property, the polynomial could be reduced to a single term, with a dramatic increase in the speed of signal processing and inspection.

MEETINGS AND TRIPS

On February 7, C. V. Dodd traveled to PNL in Richland, Washington, to discuss PNL's eddy-current program and its integration with ours. On February 9, C. V. Dodd made a presentation of the ORNL program at the Electric Power Research Institute and Nuclear Regulatory Commission information exchange meeting in Palo Alto, California.

On Tuesday, April 12, C. V. Dodd presented a paper at Palo Alto, California, entitled "Multifrequency Eddy-Current Development for In-Service Inspection of Steam Generator Tubing," for the Steam Generator Users Group meeting.

On Wednesday, April 13, C. V. Dodd traveled to Issaquah, Washington, to consult with Zetec, Inc., personnel concerning probe construction.

On Friday, April 22, C. V. Dodd presented a midyear review for the Nuclear Regulatory Commission in Washington, D.C.

During the week of June 13, C. V. Dodd consulted at PNL on eddy-current testing involving multifrequency measurements and the inversion problem.

On Tuesday and Wednesday, June 28 and 29, C. V. Dodd attended the Electric Power Research Institute Steam Generator Owner's Group Steam Generator Nondestructive Evaluation Workshop in Charlotte, North Carolina, where he also presented a paper.

C. V. Dodd traveled to Chicago, Illinois, on September 21–23, 1983, to receive one of the *Industrial Research* IR-100 Awards for the development (with L. D. Chitwood and W. E. Deeds) of the three-frequency eddy-current instrument.

C. V. Dodd presented the paper, "Improved Multifrequency Eddy-Current Testing of Steam Generator Tubing," at the Eleventh Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, October 26, 1983.

N. Burrows and M. Russell from the Central Electricity Generating Board, United Kingdom, visited for discussions on eddy-current in-service inspection and detection of intergranular attack in steam generator tubing.

TECHNOLOGY TRANSFER

W. E. Deeds and C. V. Dodd completed a paper on eddy-current inspection of steam generator tubing for a forthcoming handbook on nondestructive testing, which is being compiled by Warren McGonnagle and William Lord.

Three-frequency eddy-current instruments have been constructed for the Bendix Corporation, the Electric Power Research Institute (EPRI), and PNL. The first one has been tested and delivered.

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16. ABSTRACT (200 words or less)

Eddy-current inspection is the most suitable method for rapid boreside evaluation of steam generator tubing. However, small flaws can be masked by the effects of harmless variables, such as tube supports. To identify the critical properties accurately and reliably in the presence of extraneous signals caused by variations of unimportant properties, sufficient information is needed to identify harmful variations and reject harmless ones. For this reason we have been developing instrumentation capable of measuring both the amplitude and phase of the eddy-current signal at several different frequencies, as well as computer equipment capable of processing the data quickly and reliably. Our probes and test conditions are also computer-optimized. The most recent probe design embodies an array of small flat "pancake" coils and improves the detection of small flaws and the rejection of tube support signals. We have also experimentally verified the accuracy of our computer programs for calculating the signals produced by defects in tubing and are adapting our new IBM System 9000 computer to take and process the larger amounts of data required by additional variables, such as copper coating and intergranular attack.

17. KEY WORDS AND DOCUMENT ANALYSIS

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17b. IDENTIFIERS/OPEN-ENDED TERMS

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