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EVALUATION OF THE EDDY-CURRENT METHOD FOR THE INSPECTION OF STEAM GENERATOR TUBING —DENTING—

S.D. BROWN AND J.H. FLORA
Battelle Columbus Laboratories

SEPTEMBER 30, 1977

PREPARED FOR THE CORROSION GROUP
DEPARTMENT OF NUCLEAR ENERGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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PROJECT 10-19-02-01

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $4.50; Microfiche $3.00

December 1977 350 copies

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FOREWORD

During the last two years the phenomenon referred to as denting has become widespread in certain PWR steam generators. This denting is caused by a run-away oxidation of the carbon steel tube support plates in the crevices between the Inconel tubes and the support plates. The magnetite produced by this run-away corrosion exerts sufficient force on the Inconel tubing to distort it (dent it) and to distort the carbon steel support plates as well. As a result of both these distortions, stress corrosion cracking has been observed in the Inconel tubing, originating from the primary coolant side.

It is important to determine the capabilities of the commercially used eddy current techniques to detect the following: 1, the presence of magnetite filling the tube-tube support crevices, 2, the degree of denting present, 3, the presence of stress corrosion type defects in the dented area, and 4, the presence of corrosion induced defects on the tubes above the dented area, especially where the denting is too severe to permit passage of a standard eddy current probe.

Detecting the presence of magnetite deposits in the crevices gives the operator of the steam generator an indication that conditions leading to denting may be developing. The accuracy in measuring the size of small dents indicates the ability of the eddy current inspection to determine, by inspections at selected time intervals, the rate of progress of the denting reactions, and, therefore, the rate of straining of the Inconel tubes and the carbon steel support plates. The ability of the technique to detect defects in the presence of dents reflects on its ability to perform its primary function: the detection of wastage or cracks before they progress to the point at which they become a serious hazard to continued safe operation of the steam generator. The ability of the technique to detect defects in areas of the tubing above the dents also affects its continued usefulness in performing its primary function.

Consequently, the experimental program at Battelle-Columbus Laboratories, the first phase of which was reported in BNL-NUREG-50512R[1], was extended to include a study of these capabilities of the standard eddy current inspection equipment. It is apparent that the signals produced by the dents are pronounced so that denting has a substantial, negative influence on the ability of the standard eddy current inspection technique to detect small, corrosion-induced defects in the dented areas. Alternate techniques are being developed to overcome this problem, and are being tested on an experimental basis by the industry; their capabilities were outside the scope of this phase of the program.

Since the tubing is rigidly supported by the magnetite deposits in the dented area, the presence of a short through-wall crack is unlikely to lead to rupture of the tube, and, therefore, to massive leakage during the brief pressure transients anticipated to occur in the event of a design basis accident. Further, the cracks observed in the dented areas of tubes that have been removed to date for examination, have all been primarily longitudinal. The length of such cracks is unlikely to exceed the thickness of the support plate, or 3/4". Consequently, possible safety concerns over the inability of the eddy current technique to detect such cracks are countered by the lesser probability of their causing pipe rupture in these areas.

This report represents the findings by the Battelle workers. The data that it contains should be useful for those evaluating in-service inspection programs and the results of these programs in steam generators in which denting has been observed.

John R. Weeks
Leader, Corrosion Group
Brookhaven National Laboratory

REFERENCE

1. J.H. Flora, S.D. Brown and J.R. Weeks, "Evaluation of the Eddy Current Method of Inspecting Steam Generator Tubing", September 30, 1976.

SUMMMARY REPORT

on

EVALUATION OF THE EDDY-CURRENT METHOD FOR THE INSPECTION OF STEAM GENERATOR TUBING

-DENTING-

to

BROOKHAVEN NATIONAL LABORATORY

September 30, 1977

by

S. D. Brown and J. H. Flora

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505 King Avenue
Columbus, Ohio 43201

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EVALUATION OF THE EDDY-CURRENT METHOD FOR THE INSPECTION OF STEAM GENERATOR TUBING

-DENTING-

S. D. Brown and J. H. Flora

SUMMARY

Continued evaluation of existing eddy-current in-service inspection (ISI) methods for steam generator tubing has emphasized the effects of denting. Denting is a circumferential deformation of the tube in the support region as a result of the formation of a magnetite, Fe_3O_4, corrosion product on the carbon steel tube support plate in the crevice between the support plate and the tube wall. The effects of denting on eddy current inspection are twofold: (1) The detection and measurement of defects in the dented region is hampered by the distortion of the eddy-current response signals caused by the dents and (2) large dents may prevent the passage of high fill factor probes forcing the inspection teams to use a smaller probe in undented regions. Unless appropriate measures are taken, less reliable detection of defects and estimation of their depth can result.

This report presents an experimental evaluation of existing eddy-current ISI methods when used to inspect dented regions. Tubes were mechanically dented to simulate various degrees of service induced denting. These tubes were then inserted in carbon steel tube support plates and the crevice region between the support plate and tube was subsequently packed with powdered magnetite. Diametral dent sizes considered during this program varied between 1 and 10 mils. Eddy-current signal patterns and strip chart recordings were obtained using a variety of test parameters, such as frequency, phase rotation and coil configuration, on tube samples containing various degrees of denting and with several types of defects in the dented region.

Results of laboratory experiments suggest that diametral dents which are 1 mil and greater have an adverse effect on the detection and measurement of small volume defects, i.e., notches and pits, in the dented region. Relatively large dents, 5 mils or greater, prevent reliable small volume defect detection with existing coil configurations in the dented region. Differential probe coils of reduced diameter can be used to inspect undented regions in the steam generator tubes if the probes can be centered and restricted from excessive wobble.

The detection of magnetite prior to dent formation appears feasible and may be best accomplished using an absolute probe coil in which the support signal has been minimized in the vertical channel. The presence of magnetite is determined by a reduction in amplitude and a flattening of the support signal as observed on the strip chart.

Early detection of denting is easily accomplished. Laboratory investigations suggest that an absolute probe coil for which the tube support signal has been minimized in the vertical channel provides more reliable detection and dent size measurement. Measurement of dent size is possible by the establishment of appropriate calibration curves and preliminary studies indicate that errors in diametral dent size estimates using eddy-current techniques are on the order of twenty-five percent.

TECHNICAL BACKGROUND

Denting

As shown in Figure 1, the Series 51 Westinghouse designed PWR steam generator tube/tube support plate intersection consists of a nominally 0.75 inch high circumferential gap with a nominal radial clearance of 0.014 inch. Corrosion of the carbon steel support plate has occurred within this annular space producing a non-protective layer of magnetite, Fe_3O_4, corrosion product. Since the volume of magnetite formed is approximately twice the volume of carbon steel consumed, the

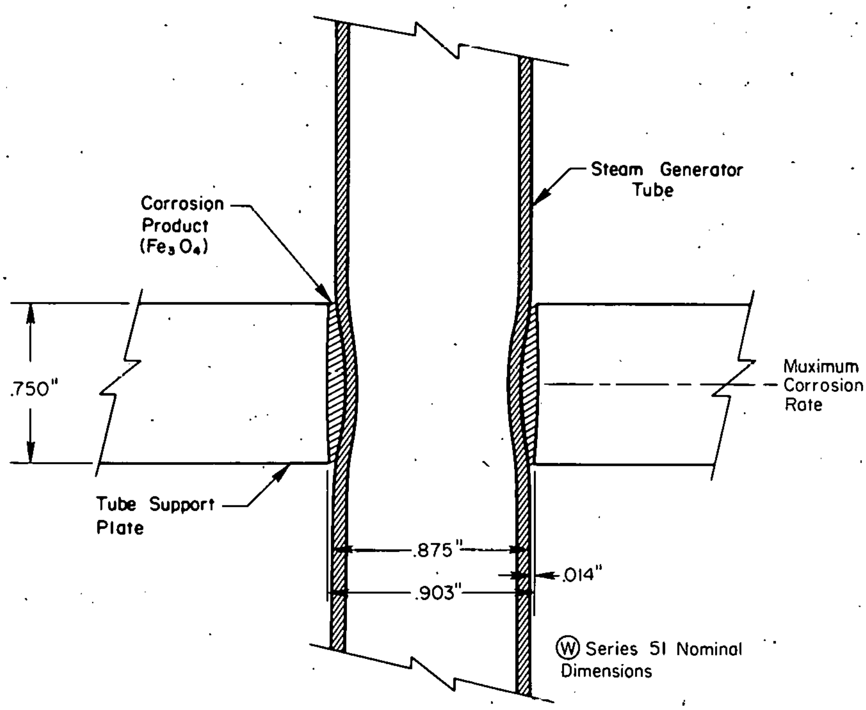

Figure 1. Crossectional view of denting at tube support plates.

gap between the tube and tube support becomes filled with magnetite as the tube supports corrode with the greatest rate of plate corrosion occurring at mid-plane. As magnetite formation continues, sufficient pressure is exerted on the tube to cause yielding. This yielding is generally symmetric about the longitudinal axis of the tube within the confines of the tube support plate and is referred to as denting. The net effect of denting is to reduce the overall diameter of the tube with essentially no reduction in the tube wall thickness, i.e., $\leq$2 percent.

Field data relative to the denting phenomenon suggest that at extensively dented sites, i.e., Surry & Turkey Point, dents are indicated at all tube-to-tube support plate intersections. For units which exhibit moderate denting, i.e., Point Beach & Ginna, the dents are predominantly on the hot leg side. The distribution of dent size appears to be random across the support plate, with different distributions, i.e., mean and standard deviation, on the hot leg and cold leg sides. Mean depth of denting may typically vary between one and sixteen mils diametral. Extreme denting is on the order of 60 mils diametral.

The ISI implications of denting are apparent. Inspection for discontinuities in the dented region is difficult because of the superposition of the eddy-current dent signal and the defect signal. The dent signal in general is of large amplitude and may in fact saturate the instrumentation obscuring any defect signal. Large dents may prevent the passage of the normal 0.720 inch diameter probe. Regions beyond the restricting dent may have to be inspected with smaller fill-factor probes resulting in a lower signal-to-noise ratio, i.e., decreased sensitivity and increased wobble, unless appropriate probe centering devices are utilized.

Since denting can be detrimental to the efficient and safe operation of steam generators, early detection of denting and the accurate measurement of the amount of denting are important considerations. Furthermore, it is desirable to detect the presence of a magnetite filled crevice between the tube and support plates before actual denting has occurred. Therefore, it is of interest to investigate the detrimental effects of denting on existing ISI eddy-current methods. Specifically, it has been the purpose of the experimental investigation described in this report to address the following areas of interest:

- Procedure and capability for detecting early stages of denting;
- Ability to measure the amount of denting;
- Effect of reducing probe diameter required to clear large dents on the measurement of discontinuities in non-dented areas of the tubes;
- Ability to detect discontinuities in dented areas;
- Ability to detect magnetite formation before denting occurs.

Eddy Current Inservice Inspection

Eddy-current testing involves placing a coil of electrically conducting insulated wire in close proximity to the material to be inspected. When the test coil is excited by an alternating current, usually sinusoidal, an alternating magnetic flux penetrates the material and induces eddy currents. In general, these eddy currents flow at right angles to the magnetic flux lines.

The induced currents in turn produce a magnetic flux that opposes the magnetic flux of the test coil. Changes in the magnitude and phase of the eddy currents cause corresponding changes in the electrical impedance seen at the test-coil terminals. For example, if a crack is present at the surface of the material, it will alter the flow of eddy currents when the test coil is near the crack. This will change the magnitude and phase of the magnetic flux and in turn alter the electrical impedance of the test coil. Similarly, changes in electrical resistivity, magnetic permeability, and material thickness will cause changes in the test-coil impedance.

Eddy current instruments translate these changes in test-coil impedance into output voltages which can be monitored at the instrument output terminals. Figure 2 is a block diagram illustrating the components of the basic eddy-current instrumentation used to inspect steam generator tubing.

An internal differential probe coil is used to inspect the steam generator tubing. This incorporates two annular-shaped test coils adjacent to each other in the axial direction so that both coils induce eddy currents in the test material, as illustrated in Figure 3. The differential bridge network subtracts the alternating voltages associated with one test coil from the voltage associated with the other coil. Output signals result only when the test-coil impedances are different. For example, abrupt changes in the tubing such as corrosion pits and short cracks cause impedance differences and, therefore, a condition of bridge unbalance. This produces a signal at the output of the bridge network. Gradual changes such as temperature gradients and some inside diameter variations cause much smaller changes in the output, depending on the design and spacing between the test coils.

The vertical (V) and horizontal (H) outputs are simultaneously recorded on a strip chart recorder and FM (Frequency Modulation) tape recorder so that the signals can be redisplayed for subsequent interpretation. The V and H outputs are also displayed on a storage oscilloscope with V connected to the vertical input and H connected to the horizontal input. This provides real time indication signal interpretation and accommodates balance adjustment of both V and H outputs during tube scans. Balance adjustments compensate for drift and assure that the recorded voltages fall within dynamic range of the instrumentation. The FM tape recordings facilitate display of the V and H output voltages on the storage oscilloscope at a later time, so that data can be carefully analyzed.

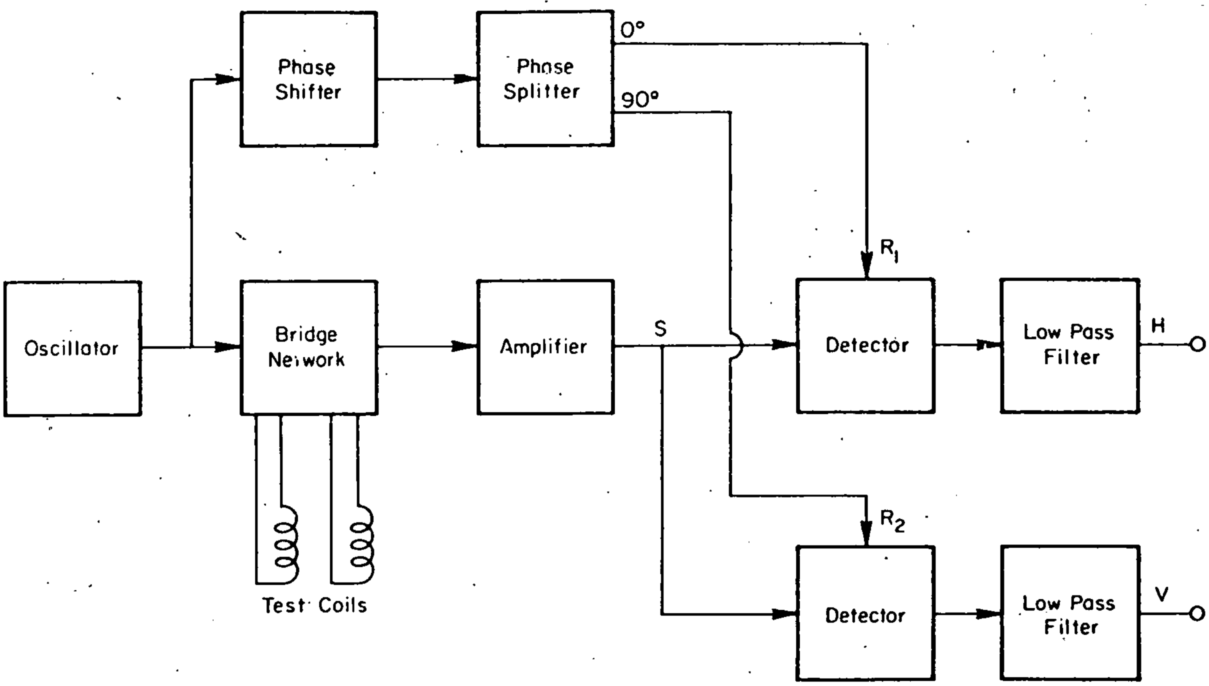

Figure 2. Block diagram of basic eddy-current system.

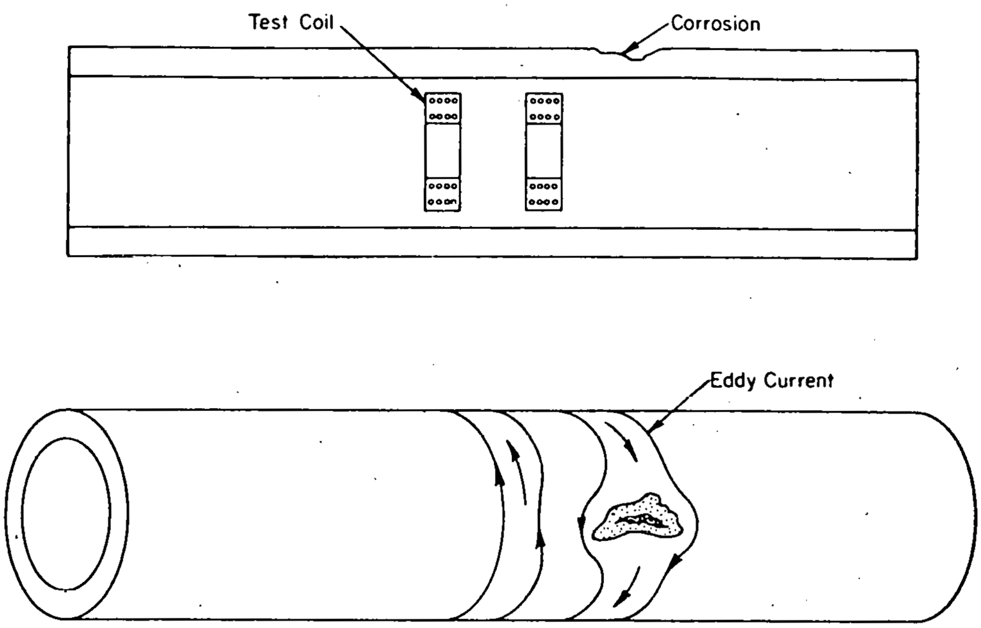

Figure 3. Differential eddy-current test coil and current flow inside tubing.

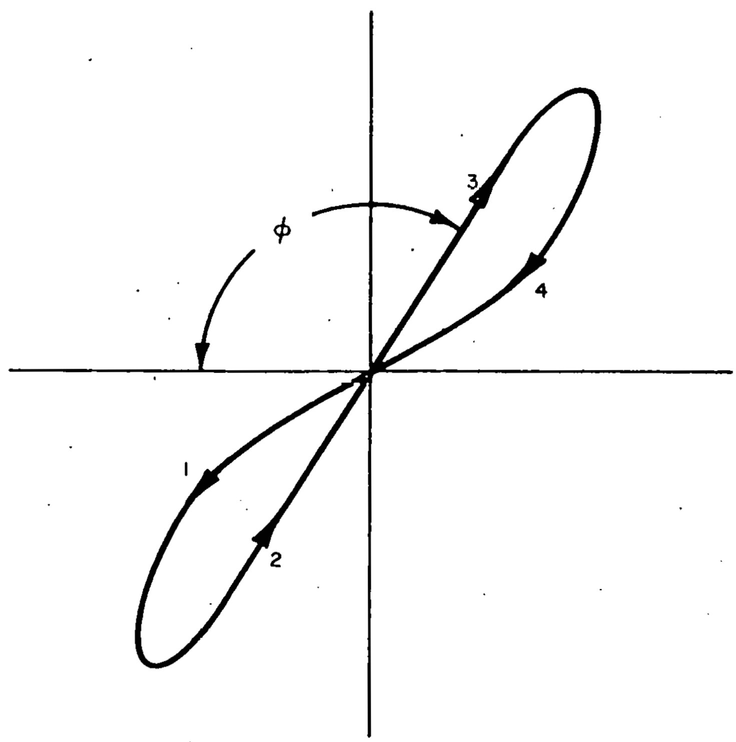

Figure 4. Dual-coil signal pattern which results from scanning an OD defect.

The phase rotation is adjusted before testing steam generator tubes so that transverse movement and tilt of the test coil cause a signal voltage that appears primarily in the H output. Tilt and wobble provide a test-coil response that is nearly constant in phase, but provides a change in the magnitude of the test-coil impedance. This results in a voltage at the H output. A relatively small voltage is seen at the V output for probe wobble after phase rotation has been adjusted properly.

Flat-bottomed holes drilled to various depths and diameters are used to calibrate each coil for measurement of defect depth. After initial phase adjustment and calibration, the test coil is ready to scan the tubes. The chart recorder provides an indication of the defects and their approximate location. The V output is the best indicator, since it displays a minimum amount of output when the probe wobbles. Tube supports serve as reference signal indications on both the V and H outputs for approximate location of defects along the length of the tube.

The output signals from defective areas are reexamined after the scan by playing the FM recorded V and H voltages into the vertical and horizontal inputs of the storage oscilloscope, respectively. Each position of the resultant beam on the oscilloscope screen represents the magnitude and phase of the impedance difference between the two coils. Signals caused by defects and tube supports make figure-eight patterns on the scope and are retained until they are erased by manual control.

The figure-eight pattern is a classic result of the dual-coil response. For example, as the first coil approaches a flat-bottomed hole its impedance changes in magnitude and phase. The magnitude reaches a maximum when the test coil is centered under the hole. Figure 4 shows how the figure-eight pattern is traced by the storage-oscilloscope display. Since the signal from the first coil is inverted by the bridge network, the phase of the impedance difference vector sweeps through an angle with respect to the horizontal and rotates into the first quadrant in the counterclockwise direction as it scans over the flat-bottomed hole. As the first coil leaves the hole and the second coil approaches the hole, the phase angle continues the shift in the counterclockwise direction.

Since signals from the two coils are subtracted, the vector rapidly decreases toward zero magnitude as the first coil leaves the hole region and the second coil approaches the hole. The zero position is the center of the oscilloscope display. Note that the effect of coil wobble and other unwanted variables prevent an exact zero from occurring. As the second coil scans the flat-bottomed hole, the mirror image of the defect is traced in the first quadrant of the oscilloscope screen. Estimation of defect depth is provided by measuring the angle, ϕ, shown in Figure 4. The angle ϕ is measured from the horizontal in a clockwise direction. As the flaw depth decreases, the entire signal pattern rotates in the clockwise direction.

Eddy-current response signals for various conditions are shown in Figure 5. The frequency used was 400 KHz which is the normal inspection frequency for the Series 51 Inconel 0.875-inch OD, 0.050-inch wall thickness tubing. Figure 5 (b) shows the signal patterns for discontinuities of various depths. A through-wall hole results in a pattern whose phase angle is nominally 40 degrees, whereas shallower OD defects give a phase angle greater than 40 degrees. OD defects tend to give phase angles which range from 40 through 160 degrees. Figure 5 (b) also shows the pattern for a 48 percent deep ID defect. ID defects will give patterns whose phase angle varies between nominally 0 and 40 degrees. Thus, defects which initiate at the ID surface and penetrate through the wall will show a total phase spread of approximately 40 degrees, whereas defects originating on the OD surface and propagating through the tube wall will exhibit a phase spread of approximately 120 degrees. The implication of this is that, because of the phase compression for ID defects, less precise estimates of defect depth will generally be obtained.

Interference signals of interest are shown in Figure 5 (a). The most prominent interfering signals include tube supports, wobble and dents. Figure 5 (b) patterns are at a frequency of 400 KHz, and at the same sensitivity as (a). Thus, a direct comparison of the interfering signals with discontinuity signals can be realized.

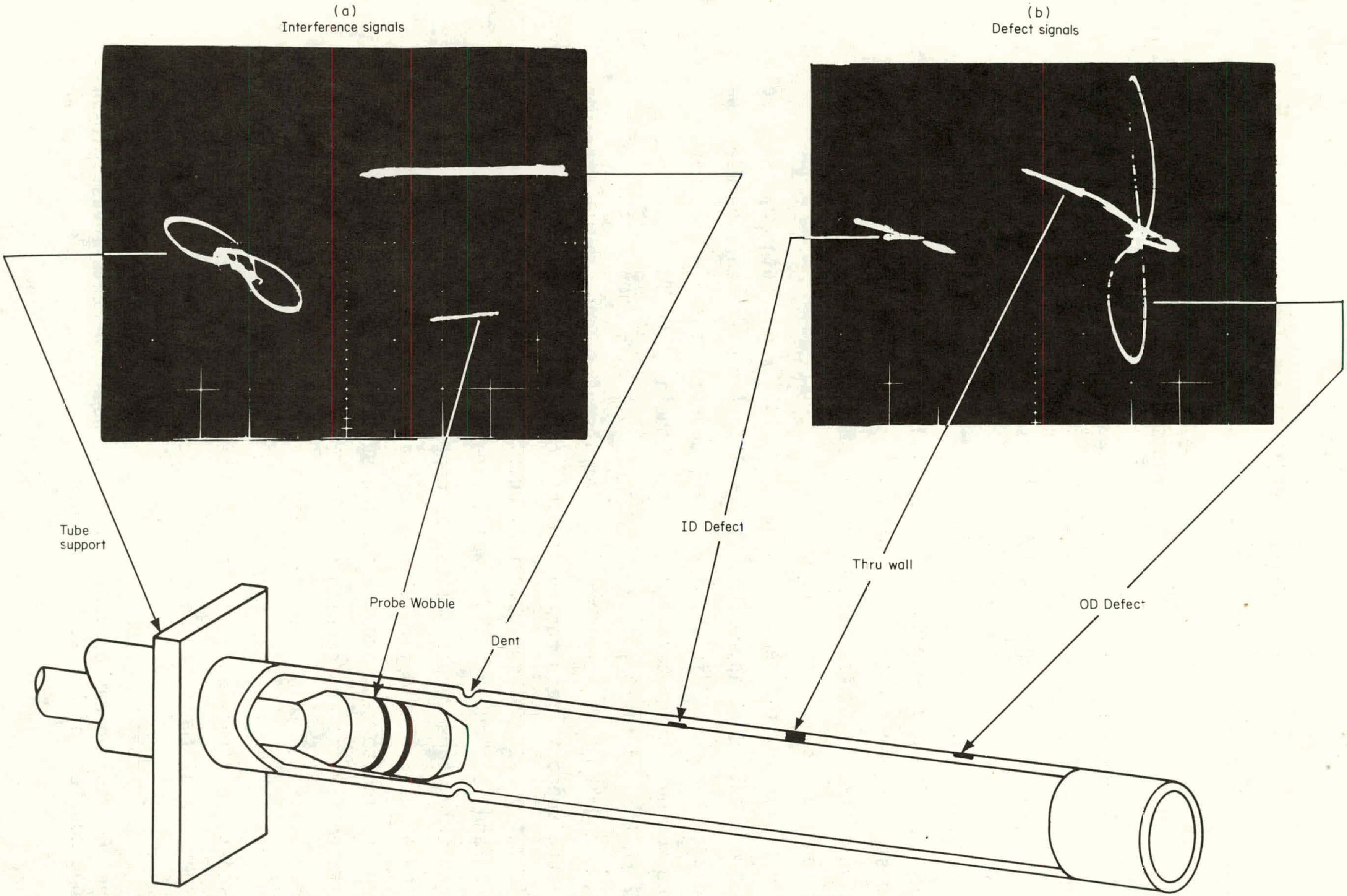

Figure 5. Typical eddy current response signals.

EXPERIMENTAL INVESTIGATION

Dent Fabrication

Experimental evaluation of the effects of denting on eddy-current ISI techniques required the fabrication of dents by artificial methods. This was accomplished by drilling, tapping and threading two 3/4-inch thick steel plates approximately 2 inches wide by 4 inches long. After the plates were tightly fastened by 1/4-inch steel bolts, a center hole was drilled and reamed to a size slightly smaller than the diameter of the steam generator tubing. The exact center hole diameter was a function of the dent size being induced. A die and an extreme dent are shown in Figure 6.

Clamping the dent die around the tube and tightening the steel bolts produced a dent approximately equal to the difference between the tube diameter and the die diameter. The edges of the die hole were rounded so that the greatest extension of the dent would occur in the center portion of the 3/4-inch thick die. Diametral dents of 1, 2, 3, 3-1/2, 9 and 100 mils were formed in samples of Inconel tubing.* Carbon steel tube supports machined to simulate corresponding degrees of magnetite formation were placed over the dents. The annular cavity between the tube and tube support plate was filled with powdered magnetite. The 3/4-inch thick tube support plate was capped on one end by a lucite plastic ring which was held firmly in place with epoxy. Close tolerance between the lucite ring and the outside surface of the Inconel tubing facilitated filling and packing the tube-to-tube support plate cavity with magnetite. A thin steel cylinder slightly larger in diameter than the Inconel tubing but less than the tube support plate hole diameter, was used to pack the magnetite in the tube cavity. After packing, the other end of the tube supports were sealed with a second lucite ring.

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*Inconel 600 tubing was provided by Westinghouse for this investigation through courtesy of Mr. W. D. Fletcher.

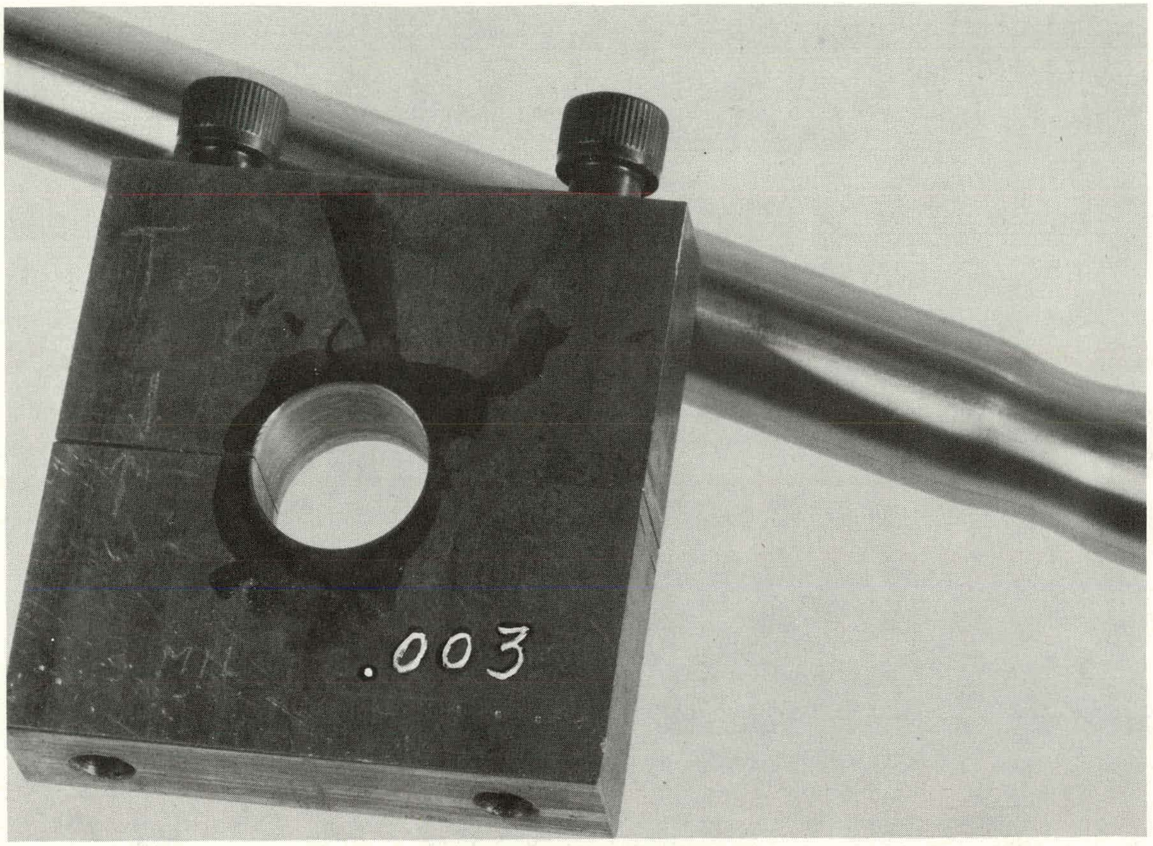


Figure 6. Typical dent die and large dent.

Instrumentation

The laboratory test equipment employed was compatible with the ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, Appendix IV, Eddy-Current Examination Method for Nonferromagnetic Heat Exchanger Tubing, December 31, 1975. A block diagram illustrating specific test equipment is shown in Figure 7. Zetec ID differential probe coils (OD 0.720 and 0.580 inch) were used. Coil cable length was approximately 65 feet. A Nortec NDT-15 eddy-current instrument was used to generate the conventional vertical and horizontal outputs for oscilloscope display and recording. The NDT-15 provides continuous adjustment of frequency beyond the range of frequencies usually incorporated in eddy-current instruments used for inspection of steam generator tubing. Instrumentation calibration procedures were performed in compliance with the Section XI inspection code.

Detection of Discontinuities in Dented Regions

Detection of simulated pits and cracks in the dented tube support region is illustrated in Figures 8 through 10. Figure 8 is a series of signal patterns caused by flat-bottomed holes in the tube support region. The flat-bottomed holes have a depth of 50 percent of the tube wall and are 7/64-inch in diameter. All holes are located in the center of the tube support region. The eddy-current measurements were taken with an excitation frequency of 400 KHz.

The sharp response from the flat-bottomed hole is clearly distinguishable when no dents are present as indicated by the signal pattern in the top left-hand portion of Figure 8. However, the signal from a small 0.001-inch diametral dent partially obscures the signal from the flat-bottomed hole. Larger dents provide even greater distortion in the signal patterns so that the 50 percent flat-bottomed holes are not even detectable.

A series of experiments were performed with Inconel-600 tubing containing long notches to simulate cracking in the tube support region.

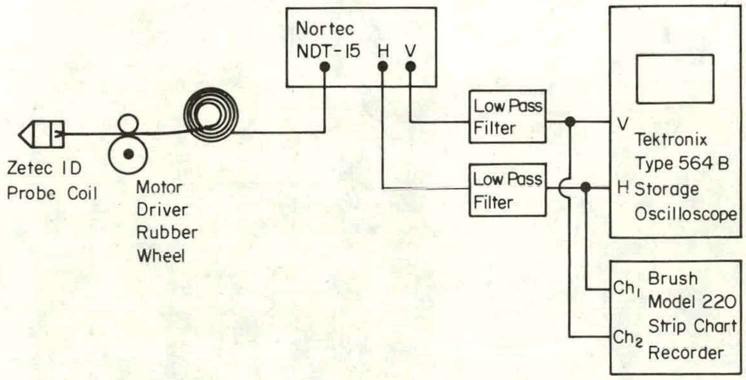
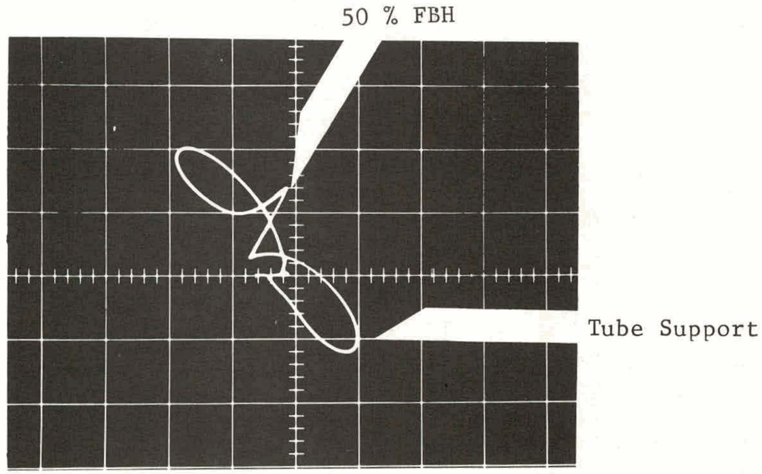
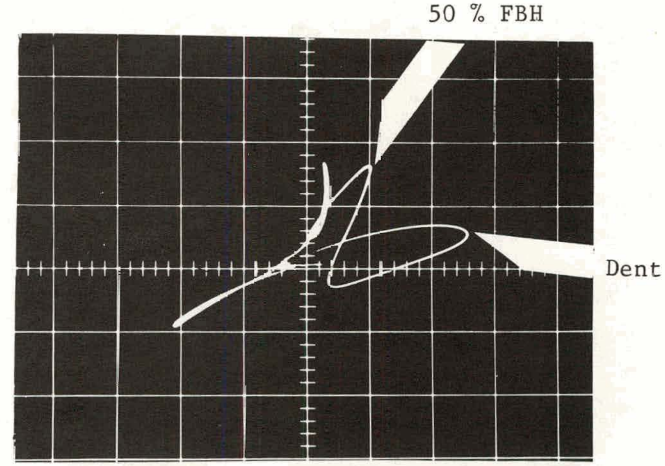


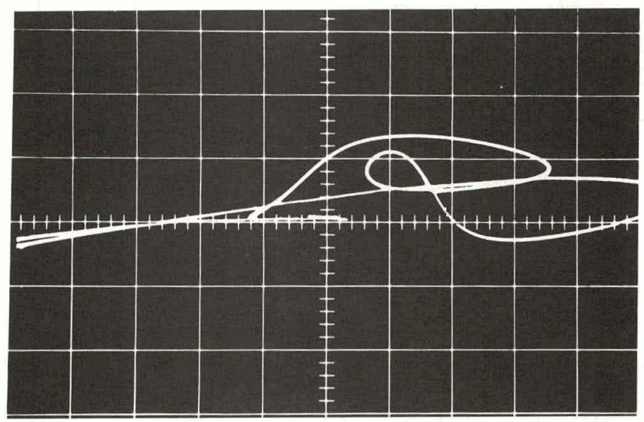
Figure 7. Laboratory instrumentation.



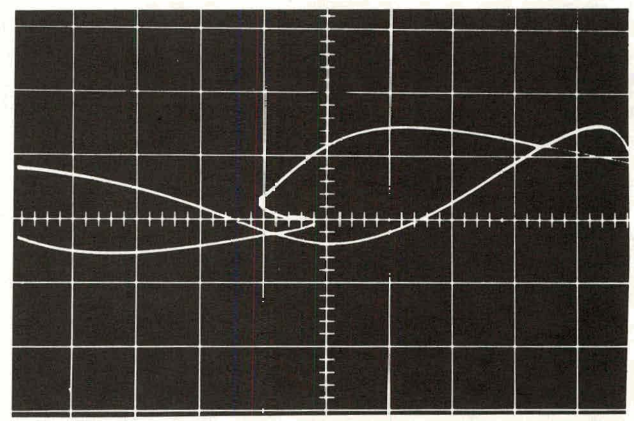
50% FBH + Tube Support



50% FBH + Tube Support + Fe_3O_4 + 1 Mil Dent



50% FBH + Tube Support + Fe_3O_4 + 3 Mil Dent



50% FBH + Tube Support + Fe_3O_4 + 5 Mil Dent

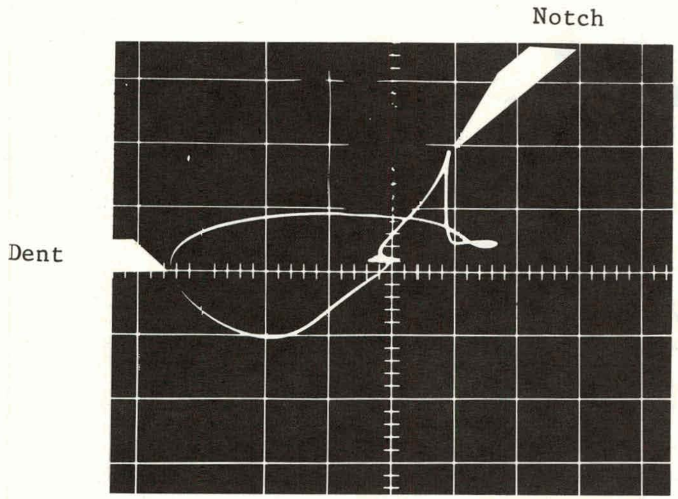
Figure 8. Signal patterns for flat bottomed hole in dent, 400 kHz, scale 0.5 v/div.

They were fabricated by electron discharge machining on the tube OD. The notches were 1-inch long and approximately 0.010-inch wide. The notches were machined with a gradual contour to simulate the gradual increasing depth of stress corrosion cracks which can occur in steam generator tubing. Shallow dents 0.001-inch diametral were induced at the longitudinal center of the cracks. Tube supports were then located over the crack centers and packed with magnetite.

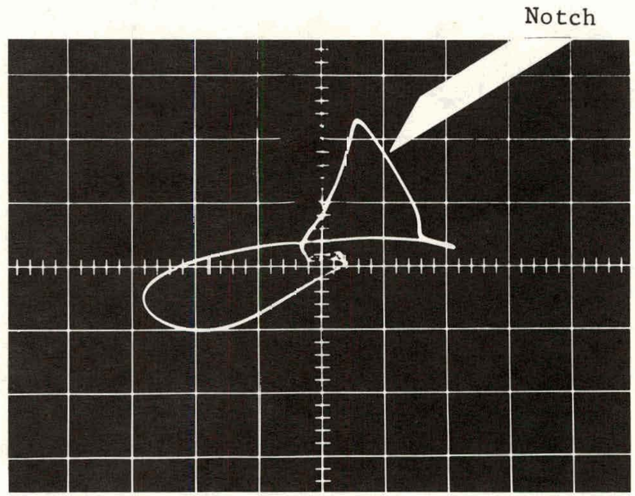
The signal patterns produced by these samples are illustrated in Figure 9. Of significance is the pronounced distortion in the crack response by the combined effect of the dent and tube support. The presence of a defect in the tube wall is suggested by the large vertical component of the signal patterns. The signal pattern distortion by the dent prohibits accurate measurement of defect depth. The presence of large dents, i.e., 5 mil diametral, completely obscures detection and measurement of longitudinal OD cracks.

Similar results were obtained with notches located on the ID of the tube near the dents in the tube support region. Short cracks of this type can occur after denting has caused stress on the tube ID. The signal patterns from a longitudinal ID notch, 1/8-inch long, are illustrated in Figure 10. Signal patterns from transverse ID notches of comparable depth could not be distinguished in the presence of signals caused by tube supports and dents. Narrow transverse notches produce small signals compared to longitudinal notches when the conventional eddy-current coils are employed.

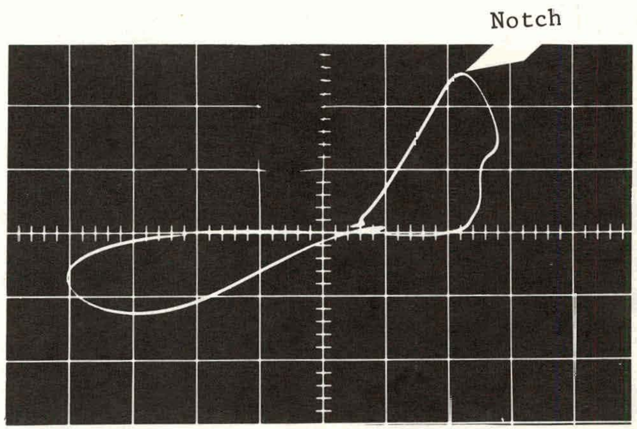
The signal patterns at the top of Figure 10 indicate the difficulty in detecting ID cracks in dented areas. Since the signal patterns from both ID crack and dents produce shallow angles with respect to the horizontal axis, i.e., less than 45 degrees, discrimination between ID cracks and dents is most difficult. Dents greater than 5 mils are expected to obscure the signal patterns from ID defects even though they are 50 percent of the tube wall in depth.



Notch 40% of Wall in 1 Mil Dent +
Tube Support + Fe_3O_4

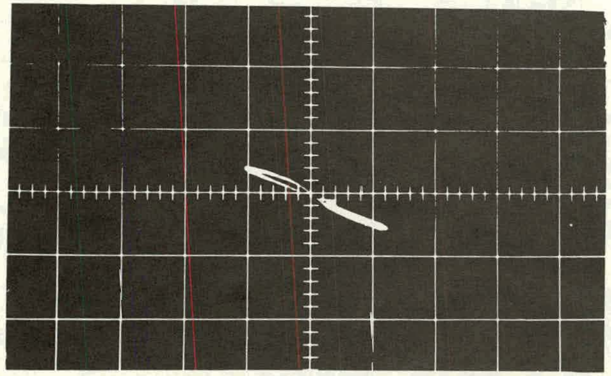


Notch 60% of Wall in 1 Mil Dent +
Tube Support + Fe_3O_4

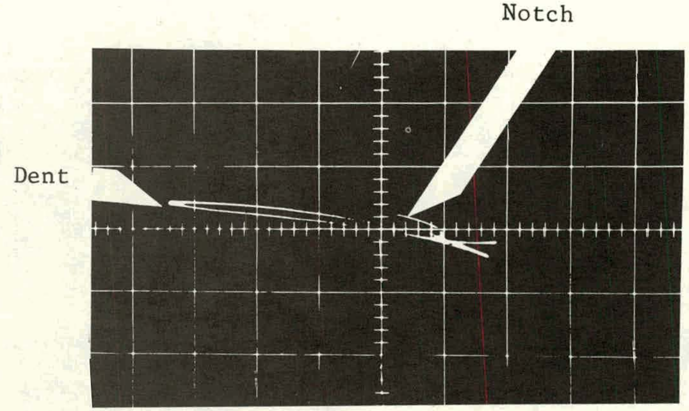


Notch 80% of Wall in 1 Mil Dent +
Tube Support + Fe_3O_4

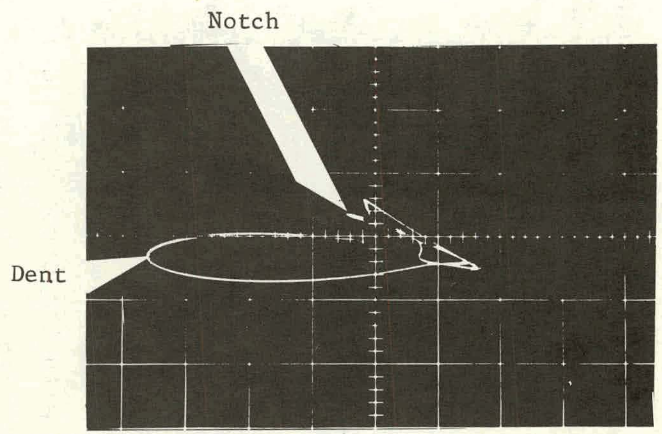
Figure 9. Signal patterns for longitudinal OD notch, 1 inch long in dents 400 kHz.



ID Notch Only



ID Notch + 1 Mil Dent



ID Notch + 1 Mil Dent + Tube Support + Fe_3O_4

Figure 10. Detectability of 60% longitudinal I.D. notch 1/8-inch long in dent, 400 kHz, scale - 0.5v/div.

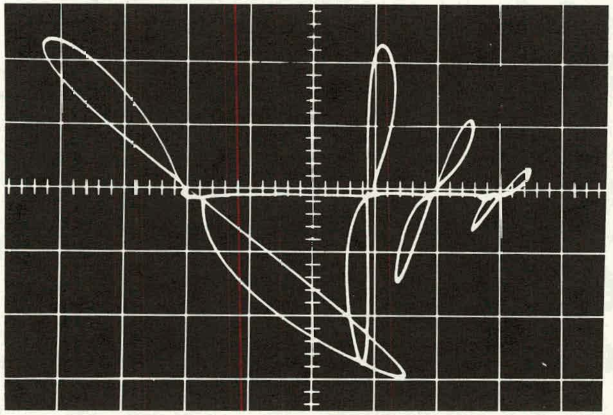
Effects of Reduced Probe Diameter For Inspection of Regions Beyond Restricting Dents

Denting greater than 0.03-inch will require inspection with a probe of reduced diameter for clear passage. Probe coils of this size have relatively small fill factor and therefore a corresponding lower level of sensitivity. If conventional probe coils are used, the small fill factor will allow greater lateral movement of the probe. This will increase wobble and cause a higher level of noise signal during inspection. Consequently, it is of interest to evaluate a small diameter probe coil and compare its performance to the conventional 0.720-inch diameter coil.

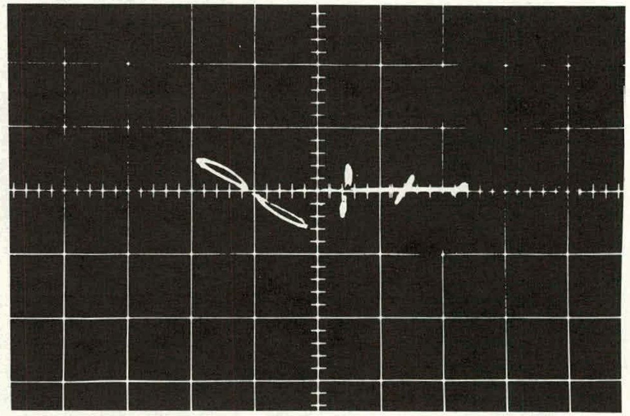
Tube samples have a nominal ID of 0.775-inch. Eddy-current probes having a diameter of 0.720-inch are usually employed to inspect straight sections of tubing. An appreciably smaller probe of 0.580-inch in diameter was procured from Zetec for comparison with the 0.720-inch diameter probe. The 0.580-inch probe can be used to inspect tubes with dents as large as 0.195-inch and, therefore, is considered to be representative of a worst-case condition.

Figure 11 illustrates signal patterns produced with the 0.580-inch diameter probe coil compared to signals produced by the 0.720-inch diameter coil. In each case the signal patterns caused by flat-bottomed holes, 40, 60, 80 and 100 percent of the tube wall, were recorded.

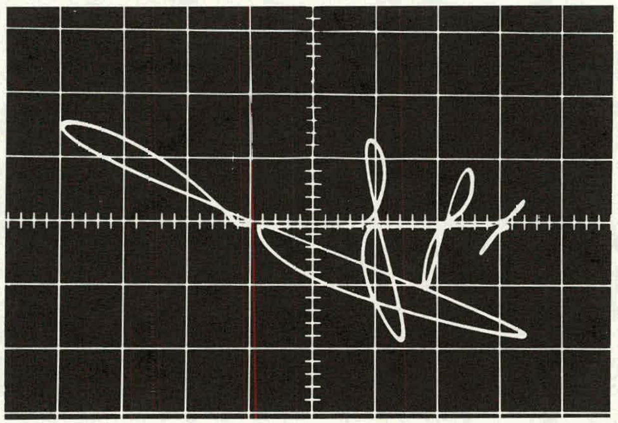
The signal patterns obtained with the 0.580-inch probe were obtained with the probe located in three lateral positions. Signal patterns obtained with the probe coil windings in close proximity to the flat-bottomed holes were accomplished by inserting the probe in an eccentric plastic sleeve. The probe was rotated in the tube so that the thin side of the sleeve, approximately 0.015-inch thick, was adjacent to the flat-bottomed holes. A second set of signal patterns was obtained by inserting the probe in a centering sleeve. The sleeve was machined with an ID of 0.590 inch and an OD of 0.720 inch so that the extent of wobble was essentially equivalent to that of the conventional probe. A third set of data was obtained by inserting the probe in the eccentric sleeve and rotating so that the coil windings were located at a maximum distance from the flat-bottomed holes.



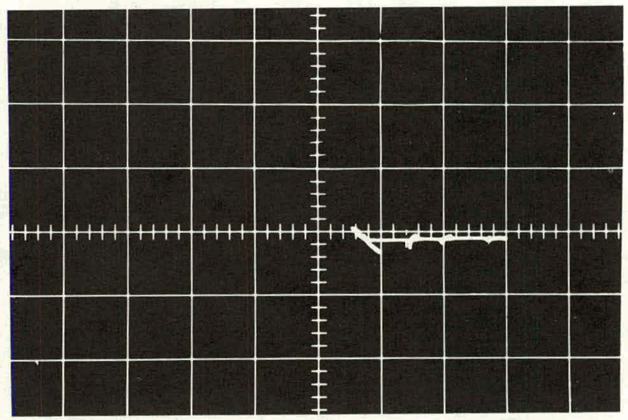
0.720 Inch Probe



0.580 Inch Probe Centered



0.580 Inch Probe Near FBH



0.080 Inch Probe Away from FBH

Figure 11. Signal patterns for large clearance probe caused by flat bottomed holes (FBH) 40, 60, 80, and 100% of wall, 400 kHz, scale - 0.5 v/div.

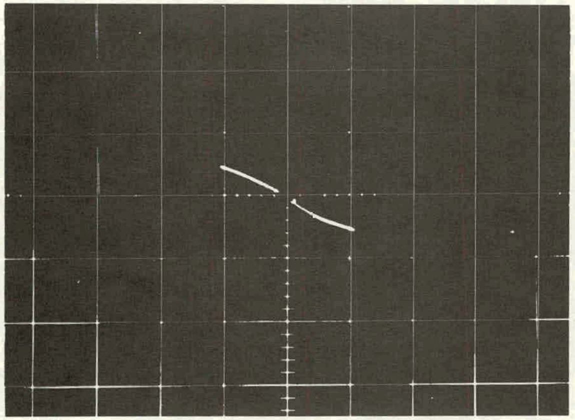
With the exception of a small difference in phase angle and a small decrease in amplitude, the signal patterns generated by the 0.580-inch probe are comparable to those generated by the 0.720-inch probe when the coil windings are located near the defects. However, considerable sensitivity is lost when the coil windings of 0.580-inch coil are located on the opposite side of the tubing. Noise signals caused by probe wobble and variations in electrical properties along the length of the tubing can easily mask the signal patterns from defects.

When the 0.580-inch probe is centered in the tube, the sensitivity is about one-third that of the 0.720-inch probe. If lateral movement of the 0.580-inch probe could be restricted to minimize wobble, it is estimated that the 0.580-inch probe could approach the performance of the 0.720-inch probe in detecting OD defects. This could be accomplished by development of a suitable centering mechanism. Consideration should also be given to optimization of excitation frequency since the coil diameter will effect eddy-current distribution of currents in the tube wall.

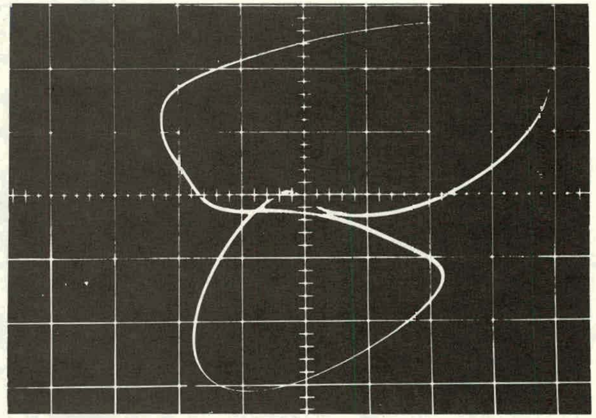
Detection of Small Dents

Initial evaluation of conventional eddy-current inspection of dents confirmed the belief that relatively large dents, 0.050-inch to 0.100-inch on the diameter, completely dominate the signal response obtained with the differential, annular coil. Detection of these larger dents is straight forward with the eddy-current test. Further studies have emphasized the evaluation of smaller dents 0.001- to 0.005-inch on the tube diameter. It has been of interest to determine detectability of these small dents and to evaluate eddy-current operating parameters such as excitation frequency, probe coil configuration, i.e., absolute versus differential and choice of phase reference.

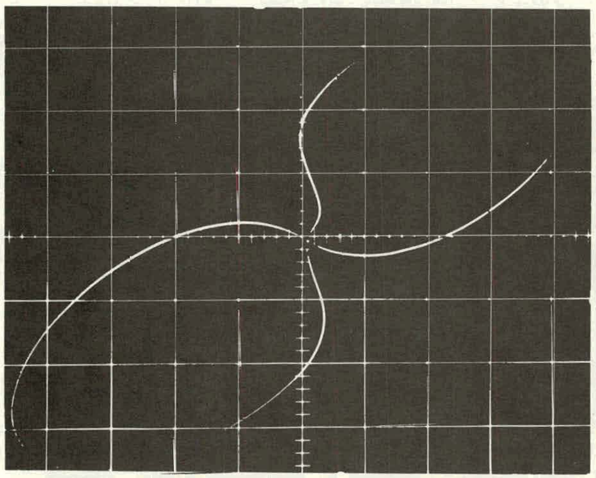
A series of eddy-current signal patterns recorded for frequencies ranging from 100 KHz to 700 KHz are illustrated in Figures 12 through 15. It is instructive to observe the signal patterns caused by isolated dents and tube supports as well as those attributed to combinations of these variables. The signal patterns produced by 7/64-inch



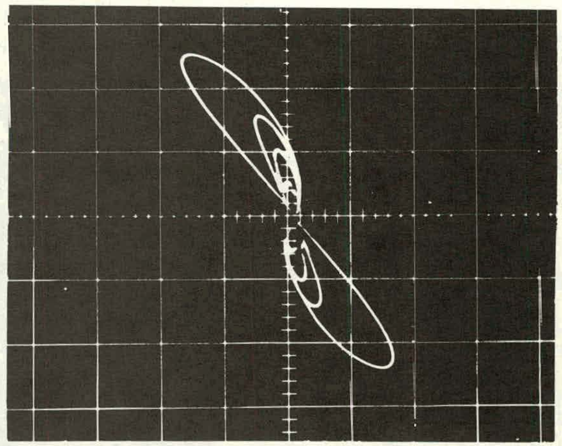
2-mil Dent Only



3-mil Dent + Tube Support + Fe_3O_4

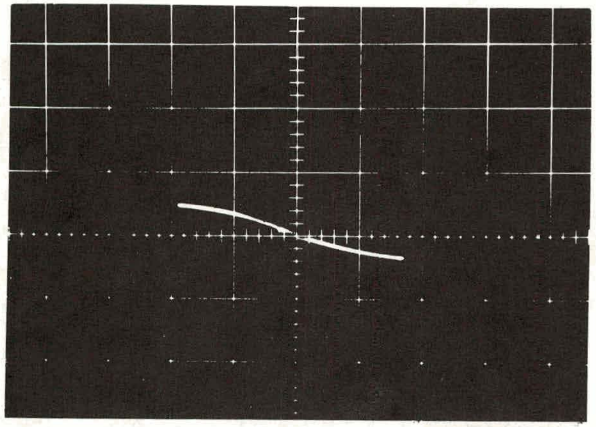


Tube Support Only

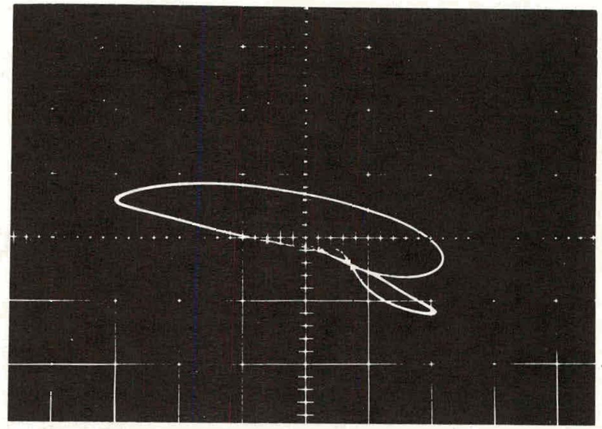


Flat Bottomed Holes - 40, 60, 80, 100% of Wall

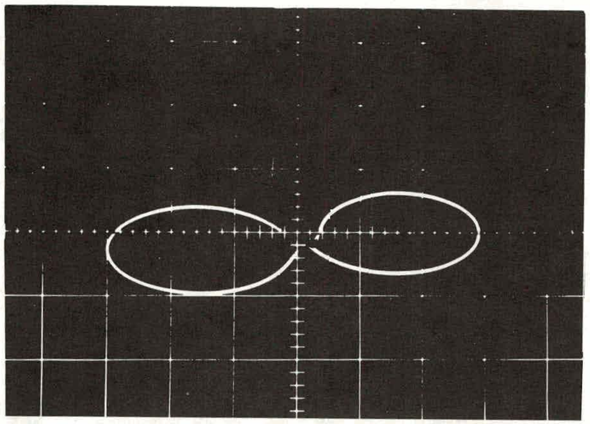
Figure 12. Signal patterns for dent and tube support,
100 kHz, scale - 0.5 v/div.



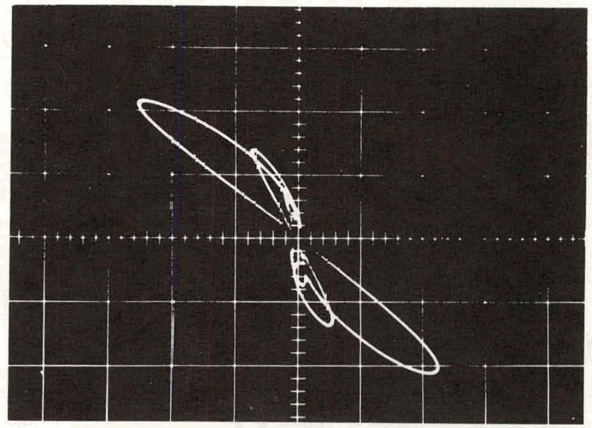
2-mil Dent Only.



3-mil Dent + Tube Support + Fe_3O_4

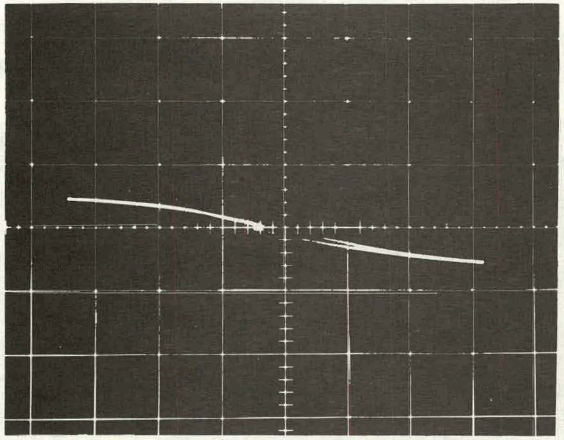


Tube Support Only

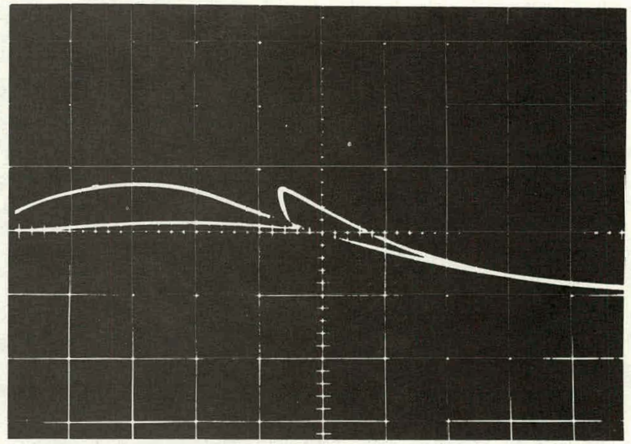


Flat Bottomed Holes - 40, 60, 80, 100% of Wall

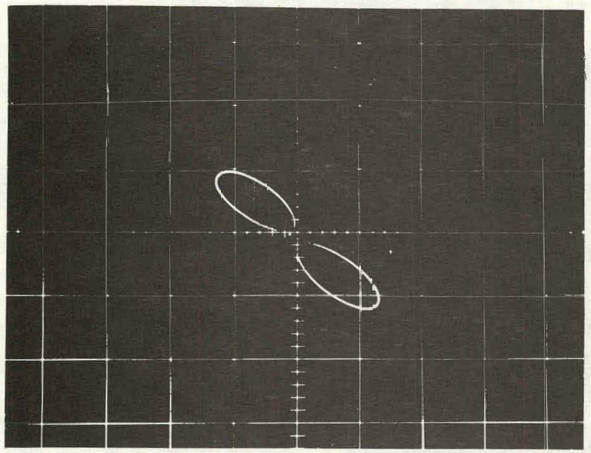
Figure 13. Signal patterns for dent and tube support, 200 kHz, scale - 0.5v/div.



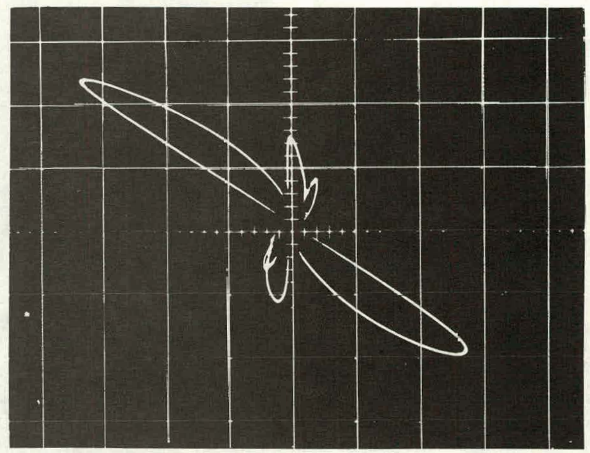
2-mil Dent Only



3-mil Dent + Tube Support + Fe_3O_4

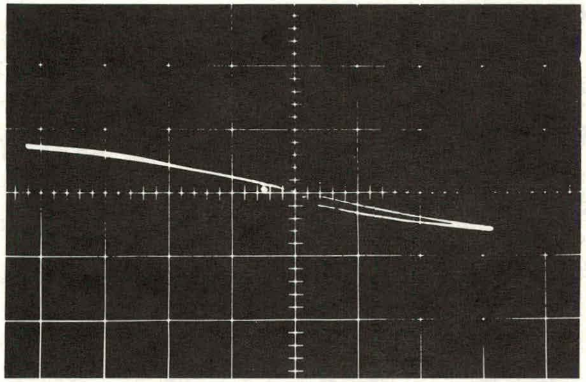


Tube Support Only

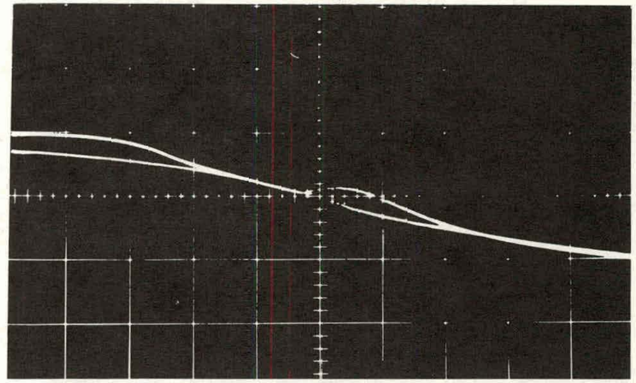


Flat Bottomed Holes - 40, 60, 80, 100% of Wall

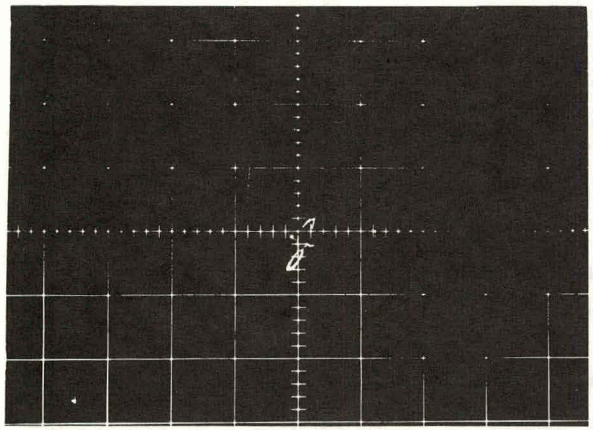
Figure 14. Signal patterns for dent and tube support, 400 kHz, scale - 0.5 v/div.



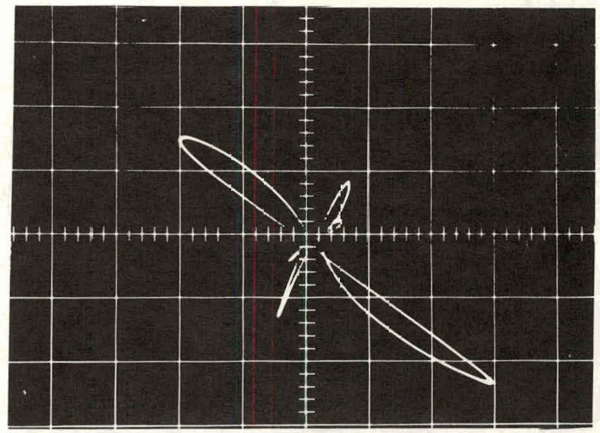
2-mil Dent Only



3-mil Dent + Tube Support + Fe_3O_4



Tube Support Only



Flat Bottomed Holes - 40, 60, 80, 100% of Wall

Figure 15. Signal patterns for dent and tube support, 700 kHz, scale - 0.5 v/div.

diameter flat-bottomed holes, 40, 60, 80 and 100 percent was also recorded at each frequency for comparison.

Figures 12 through 15 show a marked increase in sensitivity to the small 0.002-inch dent as frequency is increased. Conversely, the sensitivity to the carbon steel tube support decreases rapidly with frequency. Consequently, the combination of a tube support and small dent in the tube causes a slightly distorted tube support signal pattern at 100 KHz. However, at 700 KHz, the signal pattern, shown in the upper right-hand of Figure 15, is caused primarily by the 0.002-inch dent. Therefore, it is concluded that small dents can easily be detected by operating the eddy-current instrumentation at relatively high frequencies. Based on these experiments, it should be possible to detect dents on the order of 0.001-inch using the 400 KHz operating frequency. Although the frequencies above 400 KHz provide greater sensitivity to denting, certain disadvantages, such as increased sensitivity to wobble and problems associated with cable capacitance, may not warrant operation at higher frequencies with conventional instrumentation.

Additional enhancement of the small dent signal can also be achieved as follows. Since dents occur within the confines of the tube support area, the tube support can be considered as an extraneous noise signal. Existing ISI eddy-current procedures are such that at 400 KHz, the tube support signal makes an angle of approximately 45 degrees, i.e., the in-phase and quadrature components are equal. If the eddy-current phase rotation is chosen properly, the tube support signal can be minimized in the vertical channel and maximized in the horizontal channel. Dent presence is then determined by monitoring the output of the vertical channel. The dent signal is now a signal of interest, whereas the tube support is a noise signal. By minimizing the tube support signal, the dent-to-support signal-to-noise ratio is maximized enhancing dent detectability.

A comparison of the previously described procedures for detection of dents under supports is shown in Figures 16 and 17 for differential and absolute probe coils. Figure 16 illustrates results obtained with the differential coil. At the top of the figure, the normal ISI set-up is shown while the bottom of the figure shows results when the

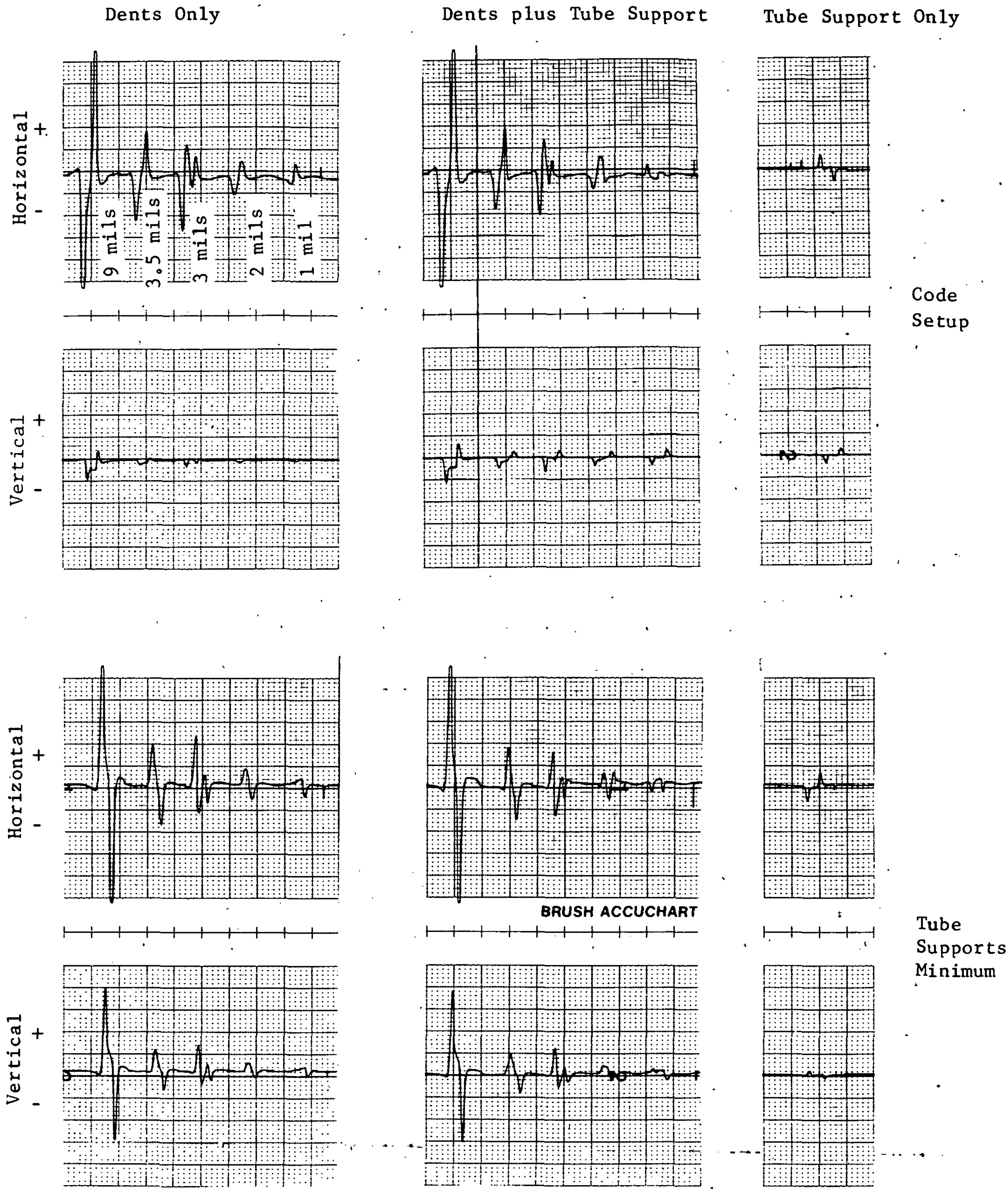


Figure 16. Strip chart recordings of differential coil illustrating detectability of dents under supports.

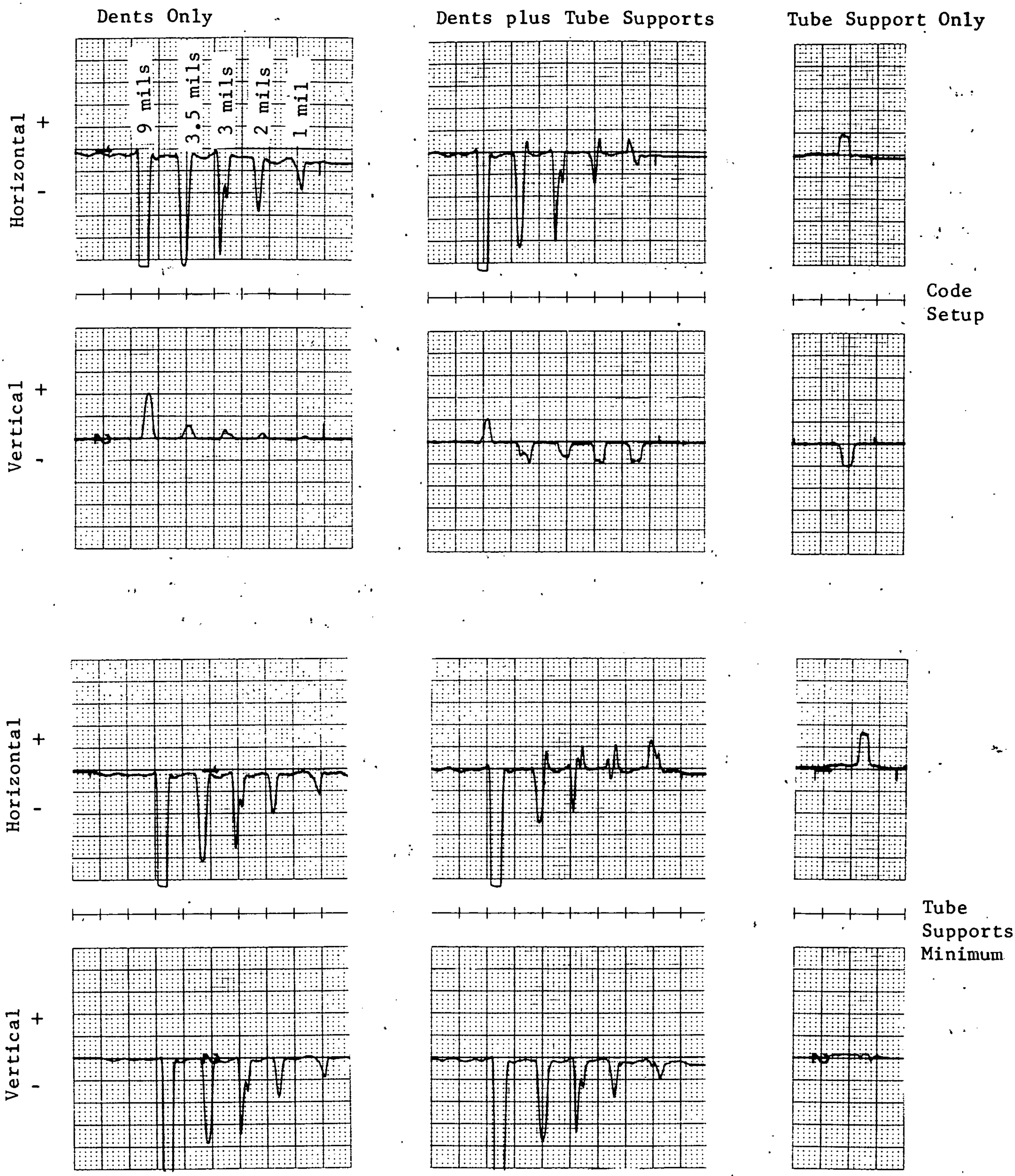


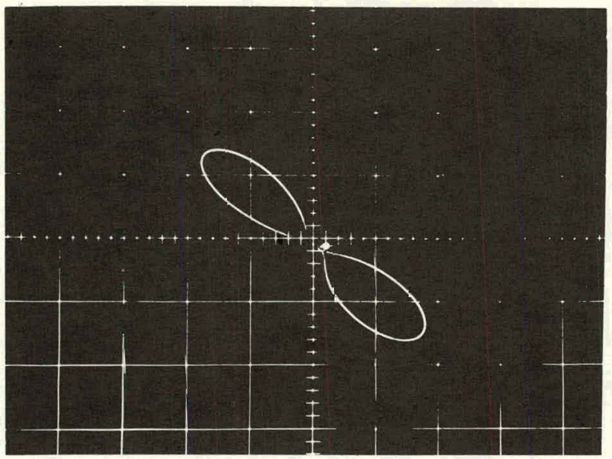
Figure 17. Strip chart recordings of absolute coil illustrating detectability of dents under supports.

phase rotation is set to minimize the tube support signal in the vertical channel. Left to right in Figure 16 are respectively dents only. dents under tube supports, and tube supports only. Five dent sizes were considered; these were 9 mils, 3.5 mils, 3 mils, 2 mils and 1 mil diametral. Figure 17 data layout is identical with Figure 16, except all data were taken with an absolute probe coil. The absolute coil configuration was achieved by utilizing the front half of a differential coil and balancing against one-half of another differential coil placed in a good section of Inconel-600 tubing.

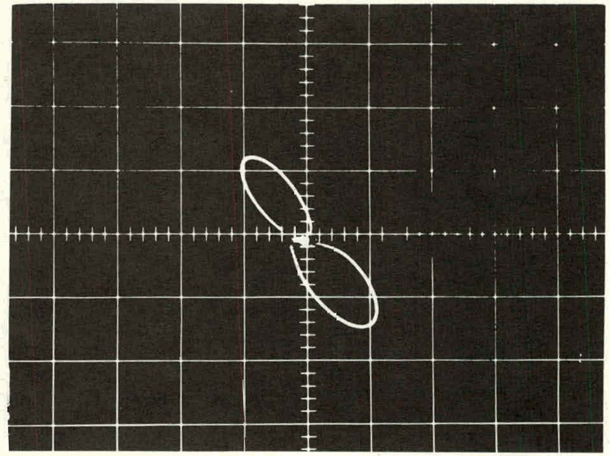
A detailed consideration of Figures 16 and 17 is rather involved, but in general, the following conclusions can be made: (1) In all four cases considered, i.e., absolute and differential probe coils, normal ISI set-up and tube supports minimized on the vertical channel, dents down to 2 mils can be readily identified within the tube supports; (2) For dents on the order of one mil, differences exist between the dents plus tube support waveform and the tube support waveform so that dent presence can in general be identified; (3) The maximum ratio of dent signal to tube support, i.e., maximum signal-to-noise ratio, is achieved for the case with the absolute probe with the tube support minimized in the vertical channel. This latter item can be seen in the lower half of Figure 17. Here a normal tube support signal swings positive on the horizontal channel, whereas a dent signal swings negative on the vertical channel.

Detection of Magnetite Formation

Early detection of denting would allow immediate alteration of the reactor operating condition to prevent further chemical attack on the tube supports. Therefore, it is of interest to detect the formation of magnetite between the tube and tube-support before denting occurs. Figure 18 shows the normal ISI set-up eddy-current response signals at 100 KHz and 400 KHz, for tube supports with and without magnetite packed within the tube/tube-support annular gap. A comparison of the signal patterns reveal a slight change in phase angle and about 30 percent reduction in signal amplitude when the magnetite is present. Analysis of

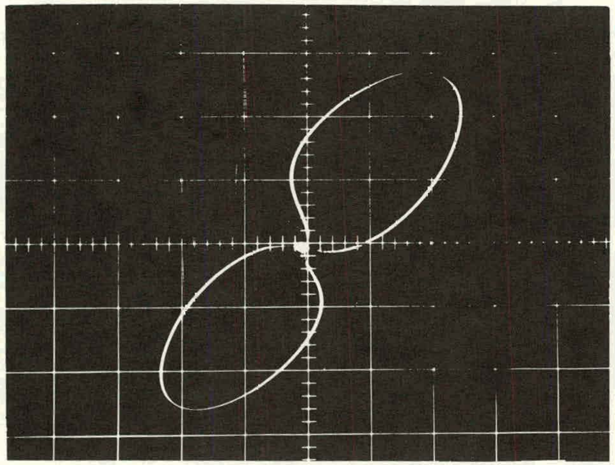


Tube Support Only

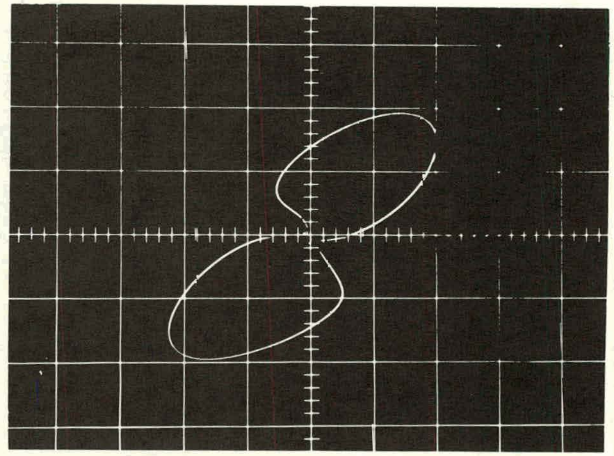


Tube Support + Fe_3O_4

Tube Support + Fe_3O_4



Tube Support Only



400 kHz, scale - 0.5v/div

100 kHz, scale - 1v/div

Figure 18. Signal patterns for tube support with and without magnetite.

the associated strip chart recordings indicate the change or reduced amplitude to occur in the horizontal component of the support signal. No change in waveform shape other than a reduction in amplitude was observed.

A magnetite packed tube-support and normal tube support was rescanned using an absolute coil configuration and the tube supports minimized procedure described previously. The resultant strip-chart recordings are shown in Figure 19. Comparing the signal responses, one can again see a reduction in support signal amplitude when magnetite is present under the tube support. The presence of the magnetite also appears to change the signal shape slightly. The tube support with magnetite waveform is less rounded than the support plate only case. Thus, the absolute coil may offer advantages in the detection of magnetite because of changes in normal support plate signal amplitude as well as signal wave shape.

Estimation of Dent Size

The feasibility of estimating dent size using eddy-current techniques was considered by scanning a series of known dents and observing the resultant signal response. Both absolute and differential probe coils were utilized. Initially it was reasoned that the differential coil would be sensitive to axial dent contour changes since it acts as a differentiator. Hence, an absolute probe coil might be expected to provide a more accurate measure of dent size.

The resultant eddy-current response signals are shown in Figure 20, for five dent sizes, i.e., 1, 2, 3, 3.5 and 9 mils, for both the absolute and differential probe coil. All dents were positioned under tube supports. The horizontal channel positive peak deflection amplitude of Figure 20 (b) and the vertical channel negative peak deflection amplitude of Figure 20 (a) are plotted in Figure 21. The relationship between peak amplitude and dent size is approximately linear on a log-log plot over a dent size range of 2 to 9 mils, for both the absolute and differential coil. For the absolute coil there is an apparent curvature below 2 mils. The same dents without tube supports were rescanned several times independently using absolute and differential probe coils and the resultant

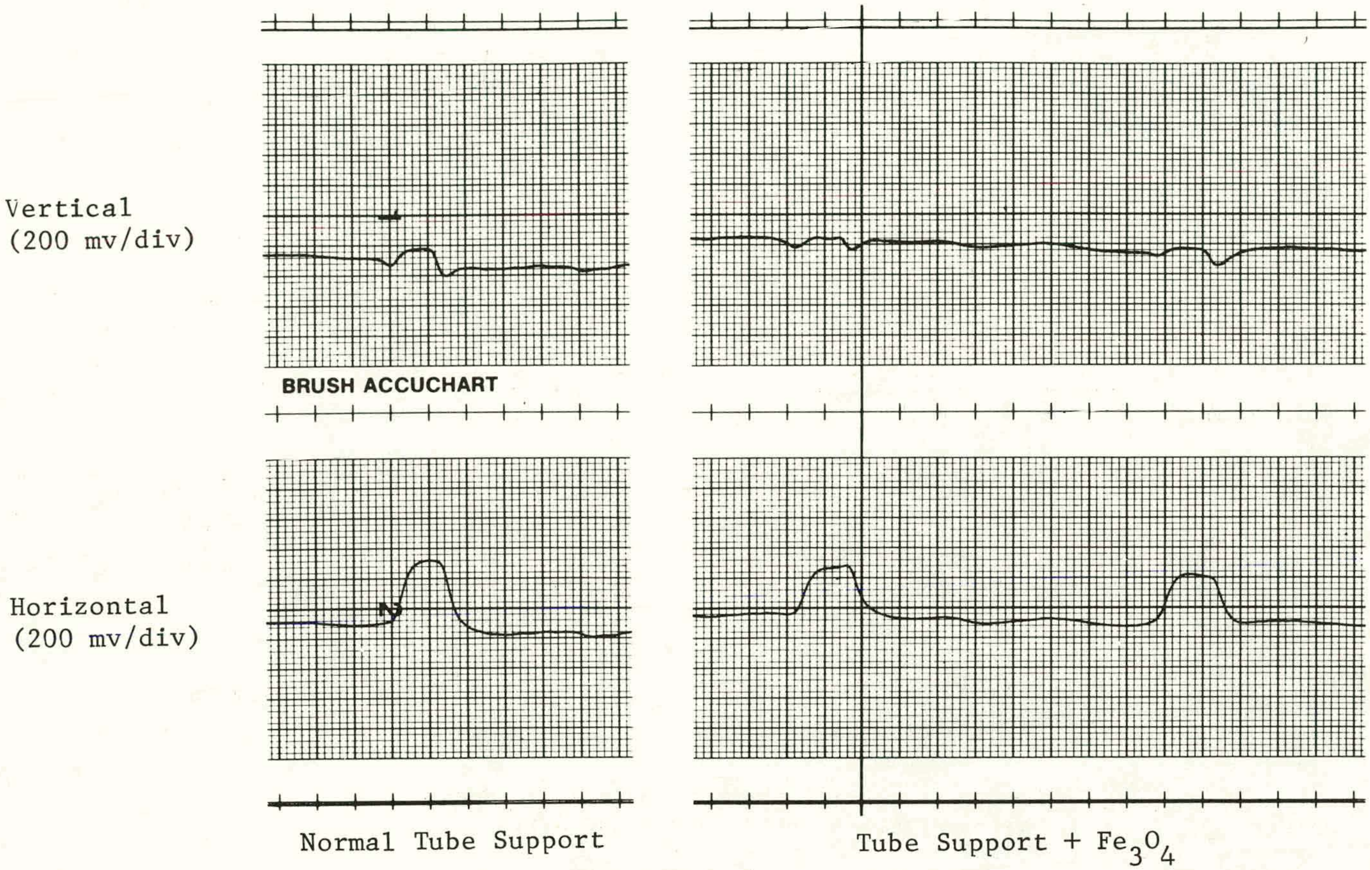


Figure 19. Absolute coil response to tube supports, 400 KHz.

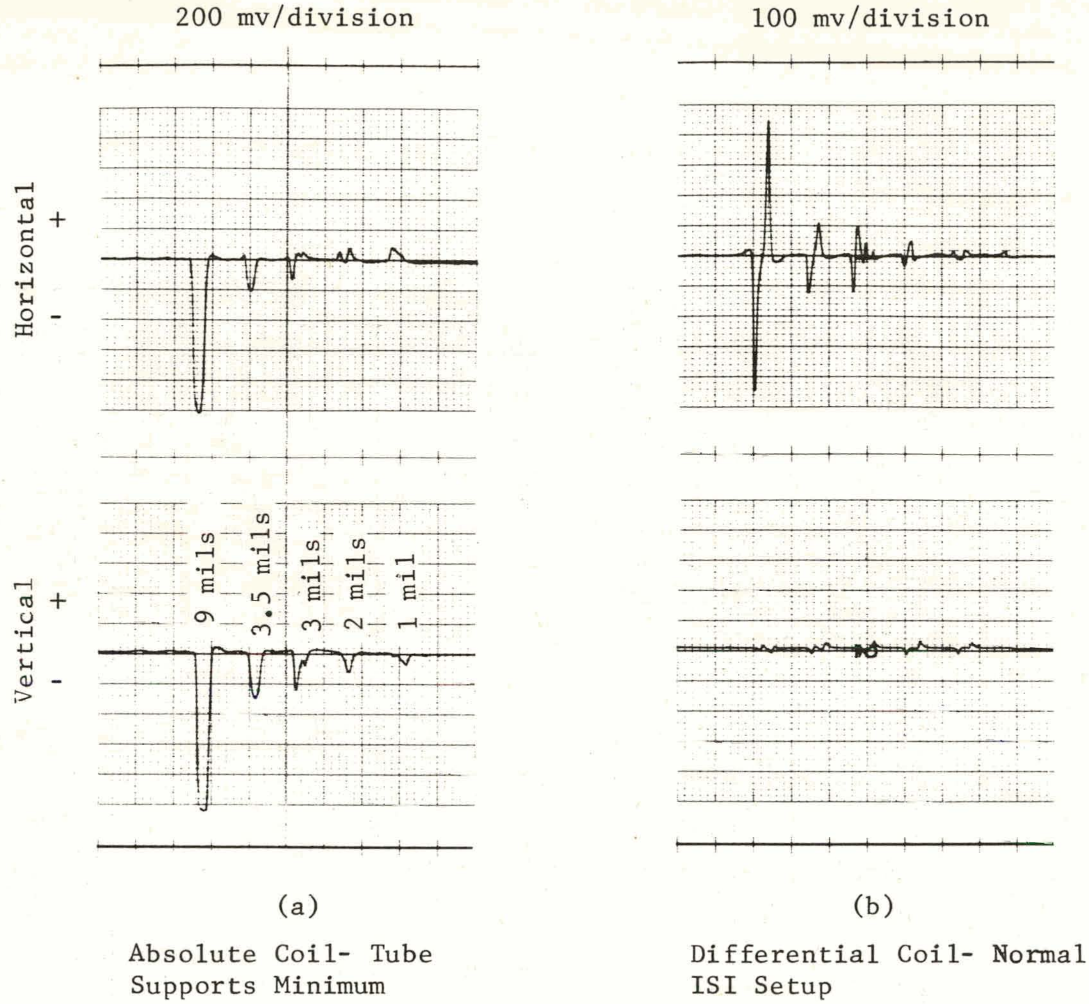


Figure 20. Strip chart recordings of dents of various sizes using absolute and differential coils.

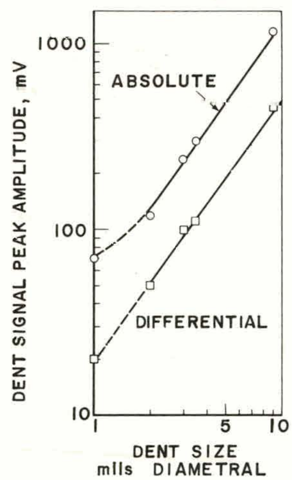


Figure 21. Dent size calibration charts for both absolute and differential coils.

calibration curves are sometimes linear or curved below 2 mils diametral. This discrepancy has not been resolved but may be due to probe positioning.

In order to investigate the ability of the eddy-current technique to estimate dent size, the following experiment was conducted. Two additional dents were fabricated. The dents were measured subsequent to the experiment and found to be 2 mils diametral. The eddy-current instrument was set up using a differential probe coil with the supports signal non-minimized, i.e., normal ISI procedures. The dent calibration standard used to establish the calibration curve in Figure 21 was scanned and the eddy-current sensitivity was adjusted until a similar curve was obtained. The two additional dents were then scanned four times with the resultant peak signal amplitude on the strip-chart recorder noted.

The average peak amplitude obtained was 69.25 mv, with extremes being 65 mv and 72 mv. If the average peak amplitude is used to enter the lower calibration curve in Figure 21, a diametral dent size of about 2.5 mils is obtained. This gives an error on the order of 25 percent.

The interaction between an eddy-current probe coil and a dent is relatively complex. The dent volume and axial dent contour can be expected to affect the resultant dent signal. Both the absolute and differential probe coils are sensitive to dent contour as can be seen by comparing the 3-mil dent signatures of Figure 20, i.e., horizontal channel in (b) and the vertical channel of (a). The perturbation on the 3-mil dent signature is possibly due to axial variations in the dent.

The effect of dent volume is illustrated in Figure 22, where the response from a 7-mil radial ding is shown. A ding is an indentation of the tube wall which is localized in area, as opposed to a dent which exists over the entire circumference of the tube. The resultant eddy-current response is similar to that from a dent but the amplitude of the response is reduced significantly. The ding in Figure 22 was scanned at the same sensitivity used to establish the dent calibration curve in Figure 20 (b). The strip-chart sensitivity in Figure 22 is twice that of Figure 20. Thus, if the differential coil calibration chart in Figure 20 (b) is used to estimate the size, an underestimation would result.

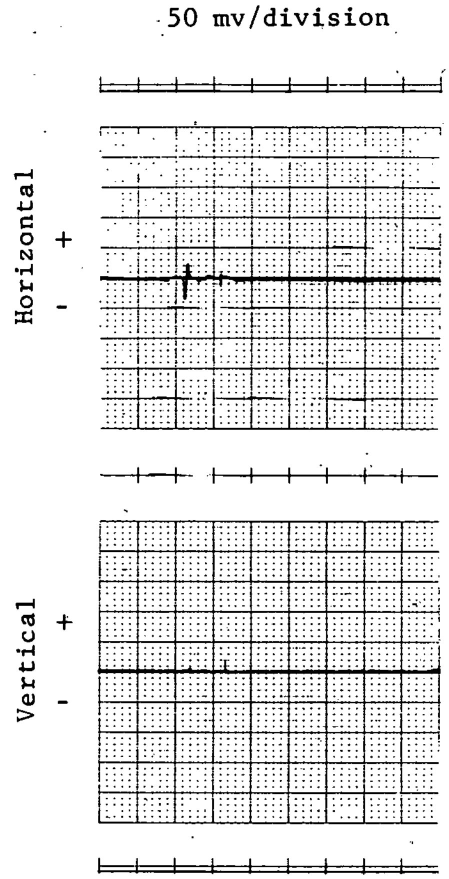


Figure 22. Strip chart recording of seven mil Ding. (Localized tube indentation.)

CONCLUSIONS

- Dents greater than 2 mils diametral are reliably detected using either a differential or absolute probe coil. Dents on the order of 1 mil diametral are more reliably detected using an absolute probe coil with the phase rotation such that the tube support signal is minimized in the vertical channel of the eddy-current strip chart recorder. A dent detection frequency of 400 KHz, i.e., the normal inspection frequency for (W) Series 51 PWR steam generators, is a reasonable compromise between enhancement of the small dent signal and minimizing effects of probe wobble.
- Laboratory experiments indicate that conventional eddy-current ISI procedures can be used to detect the presence of magnetite located between the tube and tube support prior to the formation of denting. Actual implementation into existing inservice inspections is dependent on adequate pre-service baseline data and careful analysis of tube support signals.
- Denting has a significant effect on the detectability and measurement of discontinuities in the dented region. A 50 percent through-wall FBH is undetectable in dents 3 mils diametral or greater. It is estimated that small volume defects, i.e., cracks, will not be reliably detected and measured in dents greater than 1 mil diametral.
- Probes of reduced diameter, which can pass through severely dented regions, can be used to detect discontinuities in undented sections of steam generator tubing if a centering mechanism is employed to maintain collinear alignment of the coil central axis with that of the tube. Excessive wobble or lateral shift of the probe coil will cause significant changes in probe sensitivity.

- The absolute probe coil, in conjunction with an eddy-current setup procedure in which the tube support signal is rotated such that is appears predominantly on the horizontal axis of the strip chart recorder, appears to offer advantages in dent detection reliability. For the case of small dents, it should also offer an advantage in dent measurement since the effects of tube supports are more readily minimized. The effects of temperature changes, wobble and tube ID changes need to be more carefully evaluated.

SUGGESTED AREAS FOR FURTHER RESEARCH

With emphasis on the denting phenomenon, suggested areas for further research activities are best directed towards test coil design. Specific coil configurations are as follows:

Pancake Coil

Enhancement of the detection of discontinuities in dented regions can be expected by use of a small diameter pancake coil. This type of coil would induce eddy currents both perpendicular and parallel to the longitudinal axis of the tube and hence be equally sensitive to transverse and longitudinal defects. Use of a small diameter coil would increase the defect signal to dent signal ratio improving detection reliability. This type of coil would be applicable to small and large dents.

Cross-Wound Coil

Small dent signals and the effects of tube supports may be reduced by the use of a circumferential differential coil as opposed to the existing axial differential coil. Since small dents and tube supports are circular symmetric, a cross-wound coil would tend to subtract or minimize these interfering signals enhancing a defect signal.

Electronic Absolute/Differential

Both the absolute and differential coil configurations offer advantages in the inspection of steam generator tubing. Rather than paralleling two separate coil systems, appropriate electronic signal processing may achieve the desired results. As an example, the output of a single absolute probe may be electronically differentiated, i.e., high-pass filtered, and paralleled simultaneously with the unfiltered output. The outputs of a differential coil can be integrated, i.e., low-pass filtered and again paralleled simultaneously with the unfiltered output. In either case, a single coil configuration if appropriately processed may offer the advantages of a two-coil system.