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NUREG/CR-2824
Volume 1
ORNL/TM-8418/V1

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Eddy-Current Inspection for Steam Generator Tubing Program Quarterly Progress Report for Period Ending March 31, 1982

C. V. Dodd
W. E. Deeds
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Prepared for the
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreement DOE 40-551-75

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UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY

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5285 Port Royal Road, Springfield, Virginia 22161

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NUREG/CR-2824
Volume 1
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Dist. Category R5

METALS AND CERAMICS DIVISION

EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM QUARTERLY
PROGRESS REPORT FOR PERIOD ENDING MARCH 31, 1982

C. V. Dodd, W. E. Deeds, and R. W. McClung

Manuscript Completed - September 1982

Date Published - September 1982

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

Prepared for the
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555
Under Interagency Agreement DOE 40-551-75

NRC FIN No. B0417

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY
Under Contract No. W-7405-eng-26

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EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM QUARTERLY
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SUMMARY

Eddy-current methods provide the best in-service inspection of steam generator tubing, but these techniques can produce ambiguity because of the many independent variables that affect the signals. This development program has used mathematical models and has developed or modified computer programs to design optimum probes, instrumentation, and techniques for multifrequency multiproperty examinations. Interactive calculations and experimental measurements have been made with modular eddy-current instrumentation and a minicomputer. These establish the coefficients for the complex equations that define the values of the desired properties (and the attainable accuracy) despite changes in other significant variables. The computer programs for calculating the accuracy with which various properties can be measured indicate that the tubing wall thickness and the defect size can be measured much more accurately than is required, even when other properties vary. Our experimental measurements have confirmed these results. Recent calculations show that an array of small pancake coils pressed against the inner wall of the tubing can detect and locate small flaws on the outer wall of the tubing with much greater accuracy and reliability than can the usual large circumferential coils. We are continuing to investigate such arrays.

INTRODUCTION

This program was established to develop improved eddy-current techniques and equipment for the in-service inspection of steam generator tubing. Our goal is to separate the effects of variables such as denting, probe wobble, tubesheets, tube supports, and conductivity variations from defect size, depth, and wall thickness variations. Computer design of probes, instrumentation, and techniques is emphasized.

BACKGROUND OF PROGRAM FOR IMPROVED INSPECTION

The Oak Ridge National Laboratory (ORNL) program to develop improved eddy-current in-service inspection for light-water-reactor steam generator tubing consists of design calculations based on theoretical models,

construction of optimum equipment, laboratory tests of the best design, and field tests of the equipment. Using models established for eddy-current coils in multiple cylindrical conductors, we calculated the electrical signals produced in the instrument for different frequencies, probe designs, and instrument designs for many test property variations. These variations span the range of those expected in the actual tests. A least-squares fit of the test properties to the instrument readings and nonlinear functions of the instrument readings was then carried out. We repeated these calculations a number of times with different coil and instrument parameters until an adequate system was obtained.

We have assembled prototype instruments from modular plug-in components, outfitted a mobile test laboratory on a pickup truck, and made in-service inspections at scheduled outages of the Robert E. Ginna and Point Beach reactors. These tests have shown that the equipment works very well in the field under actual operating conditions. The tests have also shown unanticipated problems in steam generator tubing, such as contaminant buildup on the outside of the tubing and intergranular attack.

New computer calculations have shown that greatly improved detection of small flaws on the outside of the tubing and decreased sensitivity to tube support plates can be obtained with an array of small coils flat against the inner wall of the tubing, and we are proceeding to design and develop such an improved probe.

PROGRESS DURING QUARTER ENDING MARCH 31, 1982

We are continuing our task to improve the inspection of steam generator tubing, emphasizing intergranular attack and contaminant buildup in the tubesheet region.

We now record the raw eddy-current data, rather than the calculated tubing properties, directly on digital magnetic tape. This enables us to process the data later in unanticipated ways if unusual conditions are encountered and prevents our losing the raw data during the very limited time allowed for the on-site inspections. The calculated properties are still recorded on the strip chart as the tube is scanned.

As part of the computer modeling method, we used previously developed multifrequency computer programs¹ to make calculations of the normalized magnitude change produced by a defect (the actual change in the coil impedance divided by the impedance of the coil in air) when the defect was on the far side of a flat sheet. Figure 1 shows the results for a coil of square cross section, 1.27×1.27 mm (0.050×0.050 in.), with a mean radius of 9.208 mm (0.3625 in.) above a sheet 1.27 mm (0.050 in.) thick with a spherical flaw having a diameter of 0.127 mm (0.005 in.) on the back side. The lower curve, labeled "LIFTOFF = 0.699 mm (0.0275 in.)," should be similar to one for the same coil with a radial clearance of 1.27 mm (0.050 in.) inside a tube with an inner diameter of 22.2 mm (0.875 in.). There is obviously a value of $\bar{r}^2 \omega \mu \sigma$ (where \bar{r} is the mean coil radius; ω is the frequency; μ , the permeability; and σ , the conductivity) that will produce the maximum normalized magnitude change for a given defect. We ran similar curves for coils of other cross sections and found that flatter pancake coils gave greater defect-produced

DEFECT SENSITIVITY, COIL $\bar{r} = 9.208$ mm (0.3625 in.)
 $R_2 - R_1 = 1.27$ mm (0.050 in.); $L = 1.27$ mm (0.050 in.)

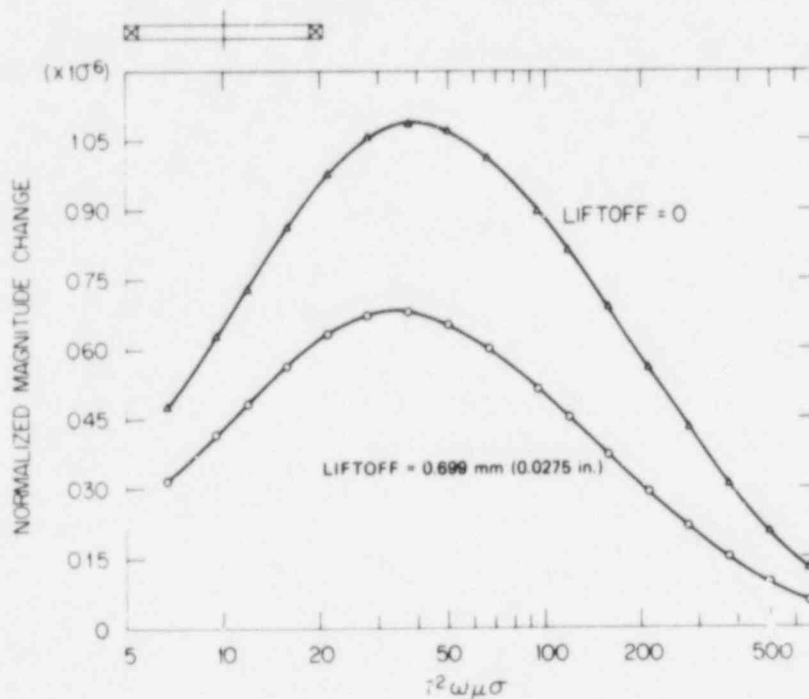


Fig. 1. Defect-produced magnitude change for a 10% of wall spherical defect on the far side of a 1.27-mm (0.050-in.) flat plate.

magnitude changes. Figures 2 and 3 show results for coils with many different mean radii but with identical cross sections, radial widths [1.27 mm (0.050 in.)], and axial lengths [0.63 mm (0.025 in.)]. It appears that a coil with a mean radius equal to about 2 mm (0.08 in.) will produce the maximum defect signal (right-hand scale) at a value of $r^2 \omega \mu \sigma$ equal to about 6 (left-hand scale, dimensionless numbers). Such a small coil with a mean radius of about one-tenth of the inside diameter of steam generator tubing can be fairly well approximated by a coil above a flat sheet. Even flatter pancake coils gave greater normalized magnitude changes produced by the 10% of wall far-side defects. Figure 4 shows the results for coils with radial widths of 2 mm (0.080 in.) and axial lengths of 0.63 mm (0.025 in.). They produce an even greater magnitude change at approximately the same value of $r^2 \omega \mu \sigma$. The relative impedance change for a given size defect is larger for the pancake coil than for the large circumferential coil normally used for tubing inspections. The circumferential coils are also insensitive to circumferential cracks. They generate large-scale circumferential eddy currents that can easily bypass small flaws with little impedance change and induce large currents in surrounding materials, such as support plates. Finally, they must have considerable radial clearance in order to pass through indented regions, and this weakens the induced eddy currents in indented regions and spreads them over a greater length of the tubing.

DEFECT SENSITIVITY

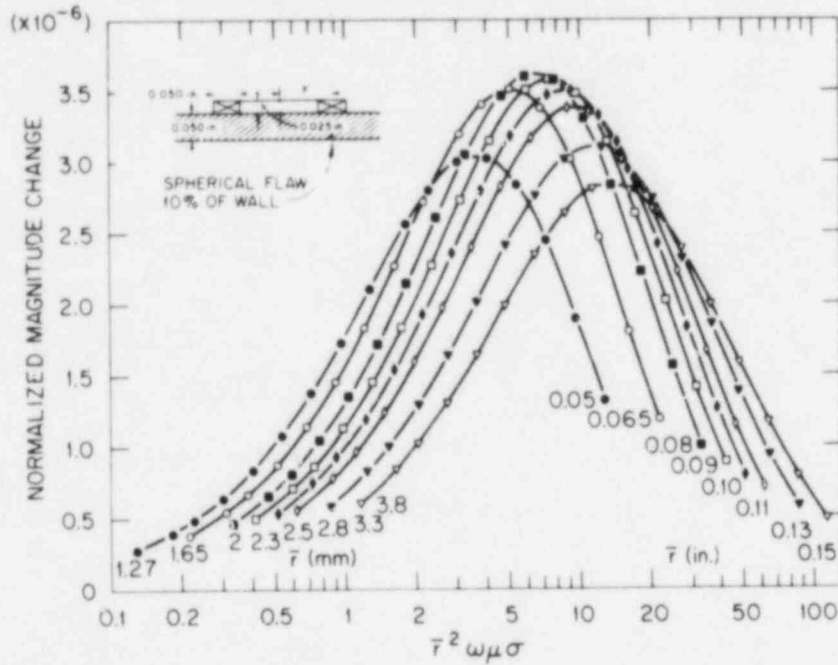


Fig. 2. Defect sensitivity for pancake coils of different mean radii; 0.050 in., 1.27 mm; 0.025 in., 0.64 mm.

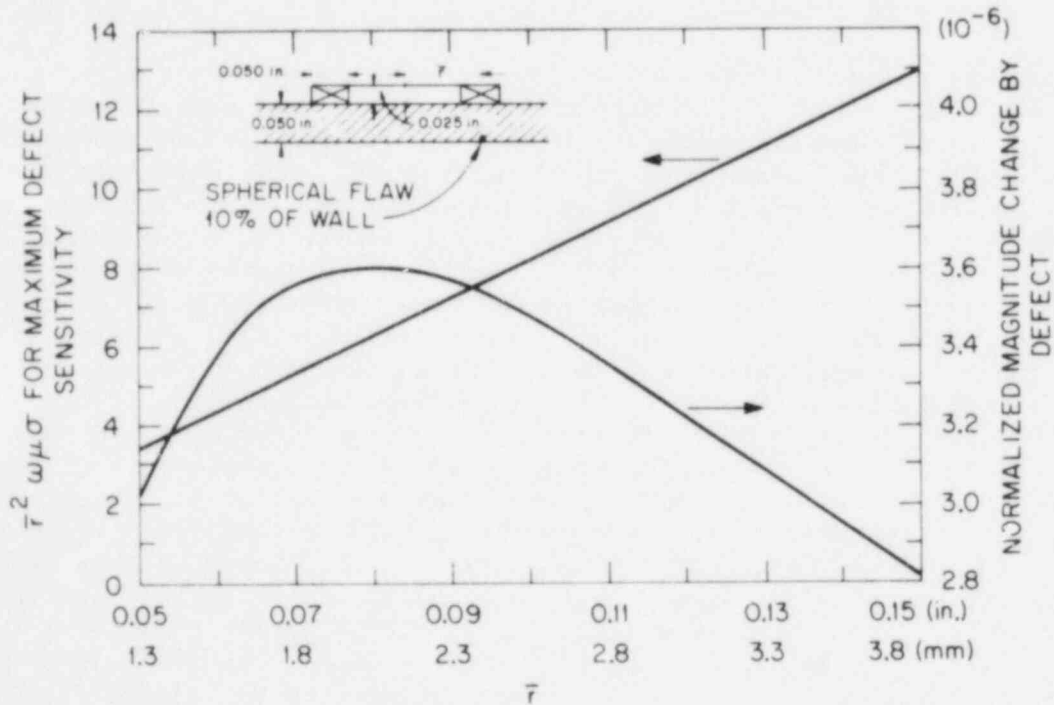


Fig. 3. Optimum values of \bar{r} and $\bar{r}^2 \omega \mu \sigma$ for defect detection by a pancake coil; 0.050 in., 1.27 mm; 0.025 in., 0.64 mm.

DEFECT SENSITIVITY

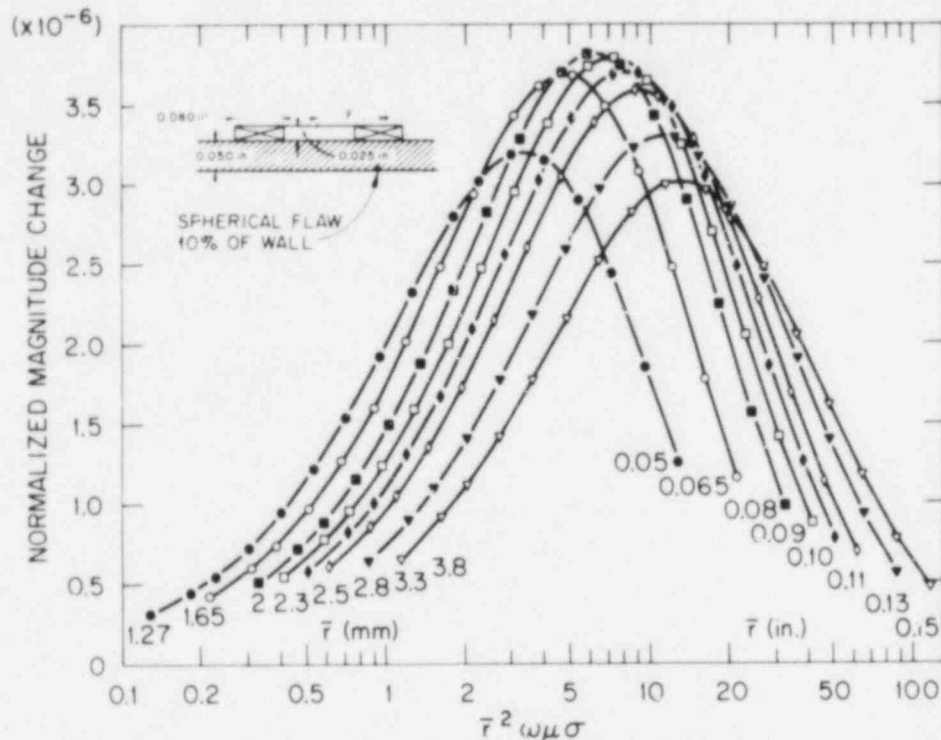


Fig. 4. Defect sensitivity for pancake coils with radial width 2.03 mm (0.080 in.), axial length 0.64 mm (0.025 in.), and different mean radii.

Conversely, a small coil that can be pressed in close contact with the wall of the tubing has several advantages: the liftoff can be kept small for better coupling of the coil to the metal tubing; the induced currents are much more localized so that a small flaw produces a proportionately much larger change in the eddy currents; and the perturbing effects of surrounding materials, such as tube supports, are greatly reduced.

These calculations were made with a MGD COMP IV minicomputer by use of previously developed theory for coils above layered conductors.¹ The calculations for flat specimens offer a reasonable approximation for a small pancake coil pressed against the inner surface of a tube whose inner diameter is 15.5 times the wall thickness and 31 times the thickness of the coil.

To inspect the tubing adequately in a single pass with such small coils, it is necessary to have a number of individual coils in an overlapping array, as shown in Fig. 5(a). Because each coil induces currents in the tube essentially like the currents in the coil itself and only in its immediate vicinity and because the induced currents must not be parallel to a crack in order to be interrupted and permit detection of the crack, the coils must form an overlapping array to ensure that both axial and circumferential cracks will encounter currents that will be affected by the crack. With the given sizes of tubing and coils, an array of 16 coils in two staggered rows can cover both types of flaw, as shown in Fig. 5(b).

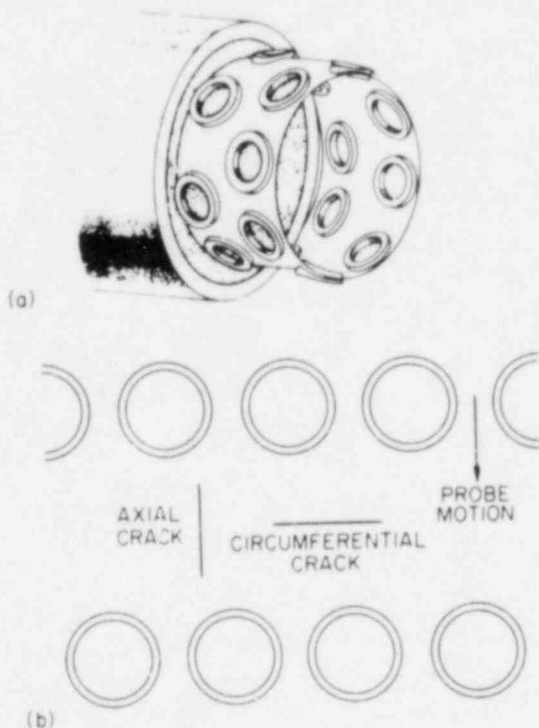


Fig. 5. Array of pancake coils for boreside inspection of tubing.

The extra complexity of the multicoil array will increase the cost of the probe and require a somewhat more elaborate eddy-current instrument, but it will also increase the sensitivity and reliability for detecting small flaws by an order of magnitude over that possible with present circumferential coils. Therefore, although the probes may well become contaminated or damaged during in-service inspections, the great improvement in sensitivity and reliability should be worth the added expense and is insignificant when compared with even one day's downtime for a reactor.

To test these theoretical calculations, we have constructed pancake coils in a range of sizes, with mean coil radii of 1.5, 2.26, 3.8, 5.2, 6.3, and 7.6 mm (0.060, 0.089, 0.149, 0.204, 0.247, and 0.300 in.), and have also obtained some small Zetec² coils. To expedite the measurements, we have obtained a Hewlett-Packard 4192A low-frequency impedance analyzer and have machined plate standards of aluminum and type 321 stainless steel.

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2. Zetec, P.O. Box 140, Issaquah, Wash.

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