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Eddy-Current Inspection for Steam-Generator Tubing Program Quarterly Progress Report for Period Ending March 31, 1978

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EDDY-CURRENT INSPECTION FOR STEAM-GENERATOR TUBING PROGRAM QUARTERLY PROGRESS REPORT FOR PERIOD ENDING MARCH 31, 1978

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SUMMARY

Eddy-current methods provide the best in-service inspection of steam generator tubing, but present techniques can produce ambiguity because of the many independent variable that affect the signals. The current development program will use existing mathematical models and develop or modify computer programs to design optimum probes, instrumentation, and techniques for multifrequency, multiproperty examinations. Interactive calculations and experimental measurements are made with the use of 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 final eddy-current instruments will contain on-board microcomputers for real-time data processing and interpretation. Current progress is being made in establishing the necessary computer codes, beginning in construction of some of the basic modules for the instrumentation, and acquisition of selected tubing reference standards.

INTRODUCTION

This program is established to develop improved eddy-current techniques and equipment for the in-service inspection of steam generator tubing. Its goals are to separate the effects of variables (e.g., denting, probe wobble, tube supports, and conductivity variations) from defect size, depth, and wall thickness variations. Computer design of probes, instrumentation, and techniques is emphasized. This first quarterly report includes, in addition to current progress, an overview of the steps that will be taken during the project.

BACKGROUND

Steam generators are a vital component in both fossil- and nuclear-fired power plants. Tube leaks in the steam generators will result in consequences ranging from loss of efficiency to plant shutdown. A method of predicting which tubes will leak (and which tubes will not) during the time interval between routine maintenance shutdowns is clearly needed, and a rapid, accurate, easy-to-use inspection is an integral part of any method of prediction.

Of the various nondestructive tests, eddy-current inspections most nearly meet these criteria, but they sometimes give erroneous results. We will discuss the reasons that the present eddy-current tests lack the desired accuracy and how the current development by ORNL is directed toward overcoming these limitations.

PRESENT EDDY-CURRENT INSPECTIONS

Present eddy-current inspections of steam generators are performed by moving a probe consisting of one or two coils through the bore of the tube, as shown in Fig. 1. The inspection is performed with a

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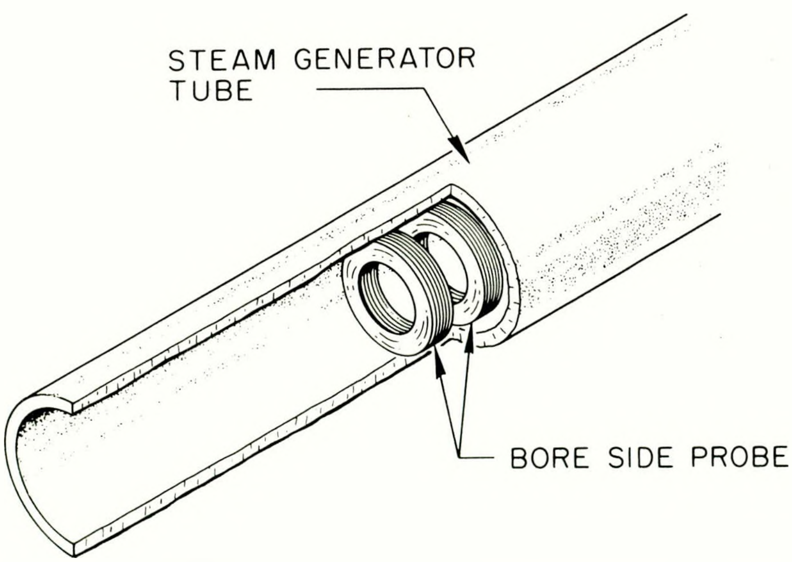

Fig. 1. Eddy-Current Inspection of the Bore of Steam Generator Tubing.

bridge-type instrument operating at one or two frequencies. The inspections are fast, but the results are not immediate. Although it is desirable to know if a tube passes inspection before the probe is indexed to the next tube, the most common practice is to record the inspection data on magnetic tape for later playback and interpretation. The results of a test are hard to interpret and are sometimes ambiguous. The reason for the potential ambiguity is apparent if we examine the test properties that can affect an eddy-current steam generator test. Figure 2 shows the test properties that may vary during the eddy-current inspection. An eddy-current instrument is capable of measuring only two

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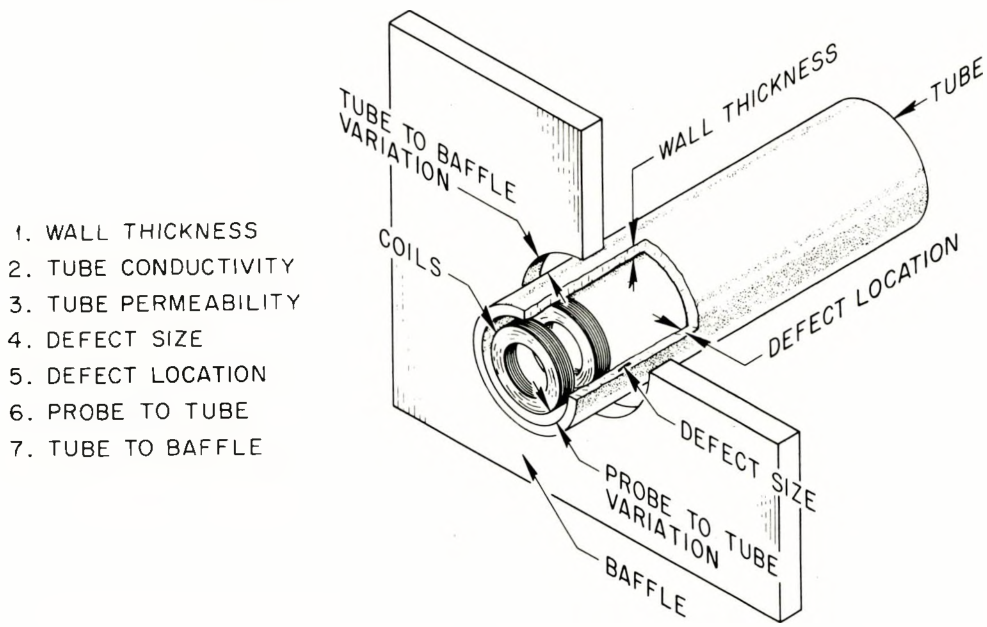

Fig. 2. Property Variations That Affect Eddy-Current Tests in a Steam Generator.

test property variations per frequency, and when more than two property variations occur at the same time, the resulting signals cannot be separated. (If a particular test property variation produces a uniform response as the probe is moved along the tube, its effect can be subtracted out, but this technique is not always reliable.) Unfortunately, the tube is most likely to develop leaks at regions where other test properties are also changing. Even property variations that may not be detrimental to the service of the tube, such as magnetic permeability or defect location (radially within the tube wall) must be included as a variable affecting the data, since they affect the eddy-current signal. To resolve these different variations, the eddy-current instrument must make as many independent readings as there are test property variations. A multiple-frequency instrument can make two independent readings per frequency, or a pulsed instrument can make independent readings at various time intervals along the pulse. The frequencies or time intervals should be chosen so that the response of the different test properties is different.

ORNL Program for Improved Inspection

The 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 test of the equipment.

Design Calculations

A theoretical analysis[1] has been made for eddy-current coils in the presence of multiple cylindrical conductors, as shown in Fig. 3. The electrical signals produced in the instrument for different frequencies, probe designs, and instrument designs will be calculated for a large number of different test property variations. These variations will span the range of variations expected in the actual

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[1] C. V. Dodd, C. C. Cheng, and W. E. Deeds, "Induction Coils Coaxial with an Arbitrary Number of Cylindrical Conductors," *J. Appl. Phys.* 45(2): 638–47 (February 1974).

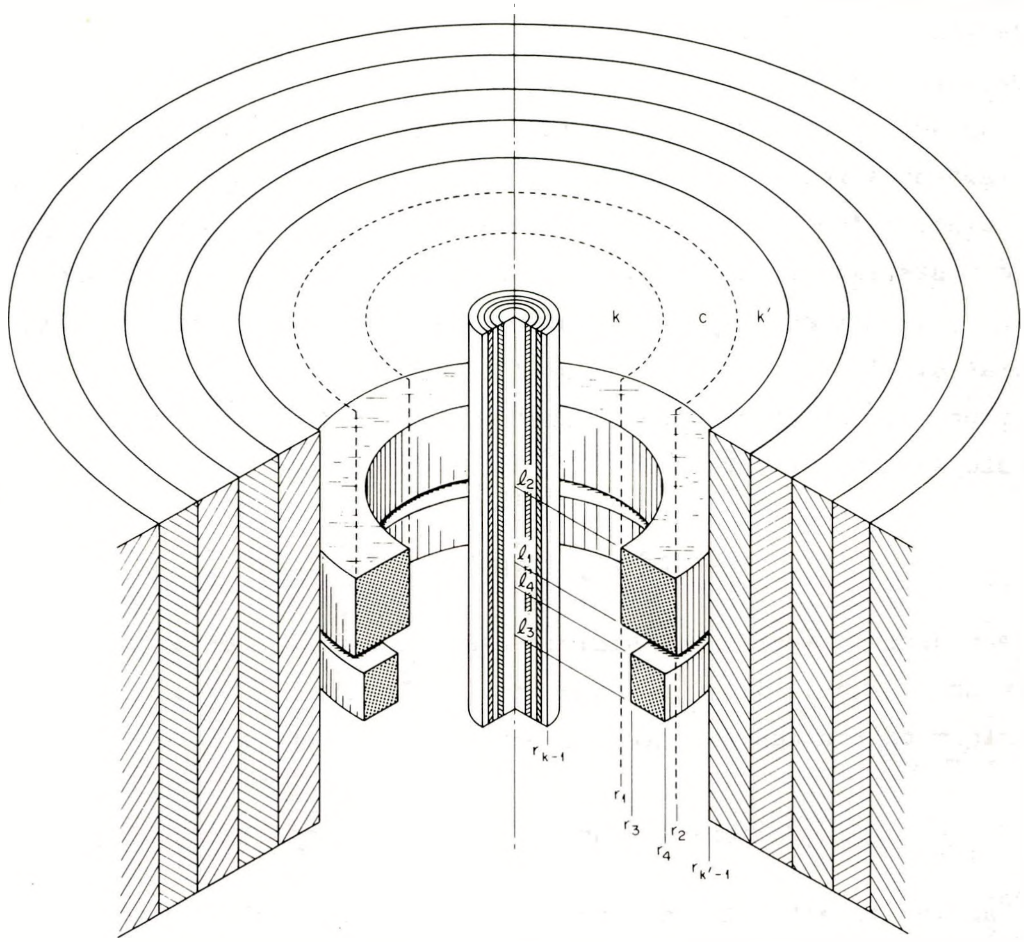

Fig. 3. Multiple Cylindrical Conductors Encircling and Encircled by Two Coils in the Same Radial Region.

tests. Next, a least squares fit of the test properties to the instrument readings (and different nonlinear functions of the instrument readings) will be done.

If the test property we wish to calculate is thickness, and the instrument readings are the magnitudes and phases at different frequencies, the fit may be of the form:

$$\text{THICKNESS} = C_0 + C_1 \ln M_1 + C_2(\ln M_2)^2 + C_3 Ph_1 + C_4(Ph_1)^2 + C_5 \ln M_2 + C_6(\ln M_2)^2 + C_7 Ph_2 + C_8(Ph_2)^2 + \ldots , \quad (1)$$

where the *C*s are the coefficients that are determined by the least squares fit and M_i and Ph_i represent the magnitude and phase at the *i*th frequency.

The amount of error due to lack of fit (the equation for the thickness does not give exactly the same thickness that was originally used to determine coefficients and calculate the readings) and the error due to instrument drift (small changes in the apparent magnitude and phases at each frequency due to a variation in the instrument) will be calculated. These calculations will be repeated a number of times with different coil and instrument parameters until the best system (or an adequate system) is obtained.

Instrument Construction

A prototype instrument will be assembled from modular plug-in components. A coil will be wound and the instrument will be adjusted to conform to the design calculations described above.

Calibration and Test Measurements

The instrument will be connected to the parallel input-output ports of the ModComp IV minicomputer. Readings will be made on tubing test samples that cover the range of anticipated test property variations. These readings will be made by use of a program, TUBRDG, to prompt the user through the instrument calibration, to prompt the user to place the probe on the proper samples in the proper order, to average the results, to print out a summary, and to record the results on a magnetic disk.

Then the process will be reversed, and the test properties will be calculated from the readings. This will be done in two different ways. The first uses the original coefficients determined in the design calculations with an offset and gain correction for data channel (magnitude or phase). Next, a least squares fit for all the coefficients will be done directly from the experimental data. The set of coefficients that matches best will be used. The first way has the advantage that with the analytical calculations, more test properties can be used and a smooth curve between the test property variations can be obtained. The second way has the advantage that constructional differences between the designed coil and actual coil are taken into account, and also certain test property variations that cannot be calculated can be included.

Once the coefficients are determined, the process is reversed so that our in-house minicomputer, the ModComp IV, continuously takes readings, calculates the properties directly, and displays the results on a CRT terminal in real time. The calculated properties change in the proper manner as the probe is scanned by defects, tube supports, and thin wall regions. The instrument is next tested in the laboratory on the tubing samples. If it passes these tests, the instrument's on-board microcomputer is programmed to calculate the properties in place of the ModComp IV, and the instrument is retested.

Field Testing

The instrument is finally tested in the field under actual operating conditions. Changes are made in the programming at this point to improve the accuracy of the tests, the ease of calibration, and the use of the instrument. The instrument will contain an internal passive calibration circuit and will be tested against a set of reference standards.

Operating instructions and testing procedures will be written.

PROGRESS ON PROGRAM DURING QUARTER ENDING MARCH 31, 1978

This technique for solving multiple property variations has been tested with probe-type coils and two-frequency instruments. (This probe coil work was performed and funded on a separate project, but the technique demonstration is a necessary step in proving the approach and has direct benefit to this project for LWR steam generator in-service inspection of tubing.) The equipment designs that have been produced thus far have been quite successful. Table 1 shows the results of a two-frequency measurement of resistivity, thickness, and lift-off. The first two values of maximum errors in the table are calculated, and the last two are measured.

Table 1. Measurement of Resistivity, Thickness, and Lift-Off of Aluminum Samples

	Resistivity (nΩ m)	Thickness (mm)	Lift-Off (mm)
Range	40–60	1.3–2.0	0.00–0.10
Fit error	0.11	0.008	0.0003
Drift error	0.08	0.005	0.002
Average absolute error	0.11	0.018	0.005
Average repeatability error	0.02	0.002	0.006

The agreement between the fit error and the average absolute error is very good for the resistivity and much better than for the thickness. (The thickness nonuniformity of the individual samples tended to increase the measured absolute error.) The average repeatability error (measured) was better than the drift (calculated) for the resistivity and thickness because the drift represents a worst-case calculation, which usually does not occur in practice. The lift-off measurements are worse than the calculation shows because the probe was hand-positioned on plastic shims, a method that is repeatable only to about 0.005 mm (0.0002 in.).

These measurements have also been performed with test property variations consisting of size of flaw, location of flaw within the wall, plate thickness, and lift-off. The size of the pitlike surface flaws could be measured to within 3% of the plate thickness. No significant edge effects that could give erroneous readings were observed as the probe was scanned over the defects.

These measurements give an excellent demonstration and experimental verification of the multiple-property technique, and represent a significant increase in the accuracy of this type of eddy-current measurement.

The computer program to calculate the signals from multiple cylindrical conductors without defects, ENCIRM, has been completed and tested on the ModComp IV. We are now adding defect calculations to the program. The change in signal due to a defect placed at a lattice of points around the coil will be calculated. The least squares program that will fit the test properties to the instrument readings, MULLSQ, is working.

A program, TUBRDG, to take calibration readings, prompt the operator to place the probe in the proper tube sample, reduce the data, and store the data has been written. Another program, TUBFIT, to take the readings produced by TUBRDG, do a least squares fit of the properties to the readings, and calculate the properties from the readings, has been written. We are testing and debugging these two programs.

We are constructing modules for a three-frequency instrument and a pulsed instrument, both of which will operate either from the ModComp IV or from an on-board microcomputer. These modules will include both differential and absolute coil inspections.

We have collected a small supply of tubing, defect, and tube support standards. Through discussion with J. Mascara, our program manager of NRC-RSR, we expect to receive additional tubing material from a project being conducted at BNWL.

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