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Eddy-Current Inspection for Steam Generator Tubing Program Annual Progress Report for Period Ending December 31, 1979

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

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75

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UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road Springfield, Virginia 22161

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

NUREG/CR-1563
ORNL/NUREG/TM-398
Distribution
Category R5

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1979

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

Manuscript Completed — June 27, 1980

Date Published — July 1980

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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

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

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 variables that affect the signals. The current development program has used mathematical models and 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 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 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 currently required, even when other properties are varying. Our experimental measurements have confirmed these results, although more testing is needed for all the different combinations of cases and different types of defects.

To facilitate the extensive laboratory scanning of the matrix of specimens that are necessary to develop algorithms for detection and analysis for all the possible combinations of positions of flaws, tube supports, and probe coils, we have designed, constructed, and begun operation of a computer-controlled automatic positioner. We have demonstrated the ability to overcome the large signals produced by the edge of the tube supports. An advanced microcomputer has been designed, constructed, and installed in the instrumentation to control the examination and provide real-time calculations of the desired properties for display recording during the scanning of the tube.

We are continuing to design and construct instrumentation systems that will be used in the field.

INTRODUCTION

The Oak Ridge National Laboratory has undertaken a program to improve the eddy-current inspection capabilities for in-service inspection of steam generators for the Nuclear Regulatory Commission.

The main objective is to improve the ability to detect and size defects that affect the safety of the plant. The accident situations that the steam generator must withstand are a loss-of-coolant accident, a safe shutdown earthquake, and main steam line break (MSLB), with the last imposing the most severe conditions. Under such conditions the entire primary pressure [between 1.0 and 1.7 MPa (1500 and 2400 psig)] may be developed across the tubing wall, causing it to burst. If a relatively small number of tubes (10 to 30) burst in a "fish mouth" mode, the plant may not be able to achieve a cold shutdown.

The present examination methods cannot detect the cracking and some of the corrosion around dented tube supports. Low-volume flaws are also lost at the edges of the tubesheet, at the tube supports, and sometimes in the bend region.

Also, accurate measurements of the wall thickness and tube inside diameter are needed to detect continued degradation of the tubing. For some reactors if the average degradation rate is greater than 1% between inspections, a growth factor must be incorporated in the plugging limit (Reg. Guide 1.121).[1] However, the present eddy-current tests cannot approach the accuracy required for this measurement.

The three-frequency eddy-current inspection being developed by ORNL has the potential for solving these problems. The design and development program at ORNL is following the outline listed below:

1. Calculate the instrument readings that would be obtained for a large set of test properties.

2. Perform a least squares fit of the properties to the readings. Determine how well the properties can be measured from the readings.

3. When steps 1 and 2 show the best (or adequate) accuracy, construct the system.

4. Measure the instrument readings for a large set of test properties. Perform a least squares fit for the properties to the measured readings.

5. Calculate the properties from the readings in real time by using a minicomputer.

6. Program a microcomputer in the instrument to perform the property calculations as the tube is scanned.

7. Test the instrumentation in the field.

8. Make the needed improvements on the system and retest.

ANALYSIS OF PROBLEM

A typical steam generator tube is shown in Fig. 1, along with an absolute eddy-current coil. The test properties that may vary in the eddy-current test are probe-to-tube wobble, tube wall thickness, the size and location of defects in the tube, the tube-to-support distance, and the tube support axial location along the tube. We can uniquely determine these test properties from the instrument readings if there are at least as many independent readings as there are property variations. We can get two independent readings at each frequency, and the frequencies should be at least a factor of 2 apart. The problem therefore is to determine which frequencies and coil designs will give us the best determination of the test properties.

The problem can be approximated by multiple cylindrical conductors, as shown in Fig. 2. This problem has been solved to a high degree of accuracy.[2] The main approximation is that the effects of the edge of the tube support plate cannot be calculated accurately (these are included in the experimental measurements).

There are computer programs (ENCIRM) to calculate the effect of the properties shown in Fig. 2 to a high degree of accuracy. The magnitude and phase shifts are calculated to within about 100 ppm for changes in the properties such as tube inside diameter, tube wall thickness, tube support dimensions, and electrical conductivity. The signal changes due to permeability variations are accurate to only about 1%. The effects of small discontinuities can be calculated to within 10 to 15%, but the accuracy is

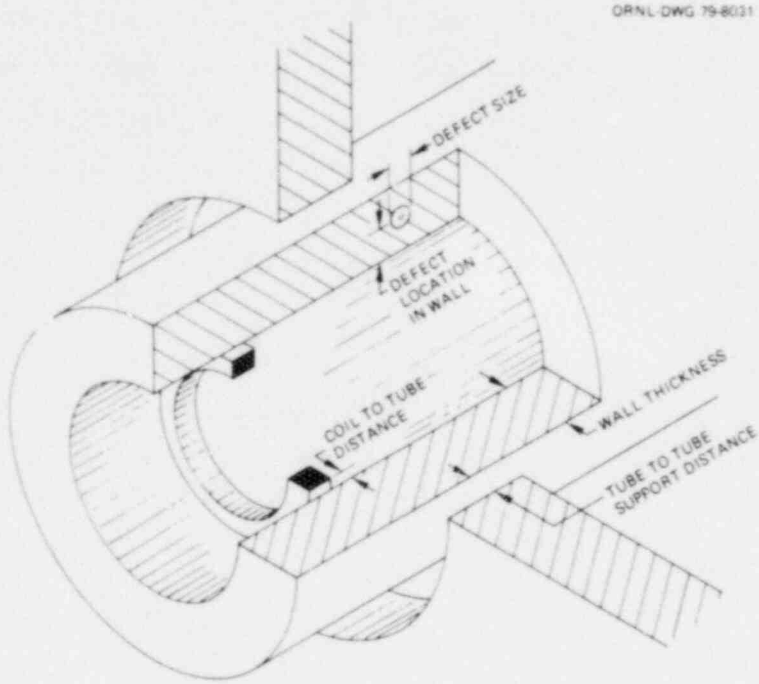

Fig. 1. Test Properties that Vary During a Steam Generator Inspection.

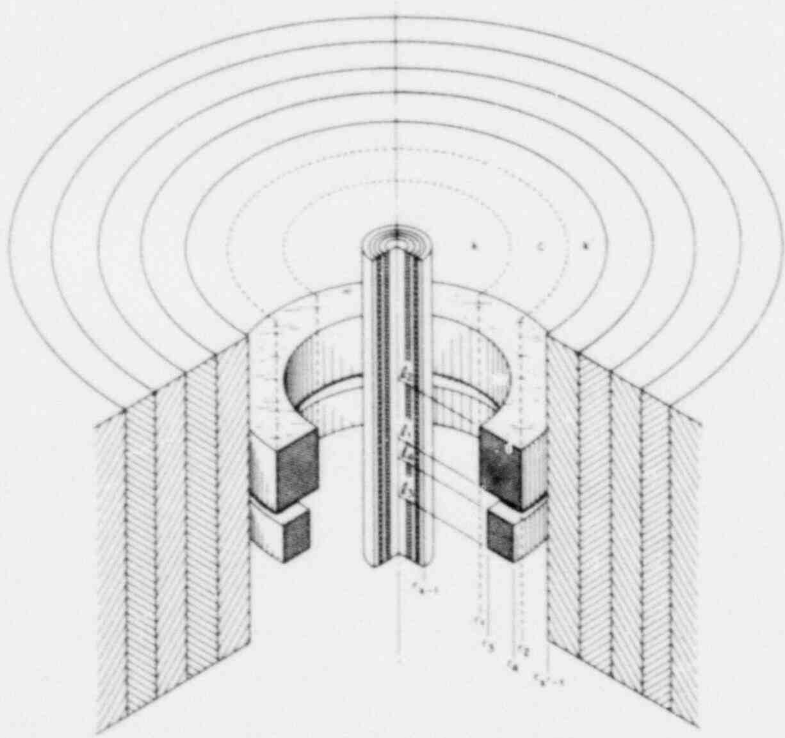

Fig. 2. Multiple Cylindrical Conductors Encircling and Encircled by Two Coils in the Same Radial Region.

sufficient for our purposes. It should be noted that small flaws produce a small signal change that is difficult to measure. The signals from larger and irregularly shaped defects can be estimated by dimensional analysis.

The program ENCIRM was run for a wide range of test property variations, with five values of support plate to tube clearance, three values of thickness, three values of probe-to-tube clearance, three values of flaw location and one value for no flaw. This gave the magnitudes and phases for $5 \times 3 \times 3 \times (3 + 1)$, or 180 different cases. The magnitudes and phases were also calculated for eight different frequencies, going from 5 kHz to 1 MHz in a 5, 10, 20 sequence. The calculated values are stored on a disk file along with the values of the property set for all 180 different cases. We then fit the properties to the readings using a least squares technique.

A general discussion of the least squares technique is given in the appendix. The program, LSQENC, reads the data back from the file and fits the readings to the magnitudes and phases using the least squares fit of a given property to various nonlinear combinations of the magnitudes and phases of three of the eight frequencies. All combinations of the eight frequencies taken three at a time are computed, and a large number of nonlinear combinations of the readings are computed. Only a summary of the best results at a given frequency is printed out. The summary includes the "lack of fit" error, which is a measure of how well the nonlinear combination of the readings can fit the calculated property to the actual property (the one that was inserted to calculate the readings in the first place). Also included is a "drift" error, which gives the variation in the property for the "worst case" combination for a $\pm 0.01°$ change in the phase and a $\pm 0.01\%$ change in the magnitude.

The effects of the variation of some properties may be too severe to fit by using a single range for the property variation. In this case, the property variation can be broken up into several smaller, overlapping ranges, with a least squares fit performed for each range. A rough fit would be run first to determine the approximate value of the property. Then a more exact fit would be run for the specific range, using the coefficients determined by the least squares fit for the smaller range.

Both the program ENCIRM, to calculate the readings from the properties, and LSQENC, to calculate the least squares fit of the readings back to the properties, are quite long running and require several days to finish. They are therefore run as a low-priority background task that uses otherwise wasted time on the MODCOMP IV minicomputer.

RESULTS OF CALCULATIONS

The programs ENCIRM and LSQENC have been run for a number of different coil and conductor configurations. The more important results of the tests, run for a single square cross-section coil with the coil length equal to the wall thickness, are summarized in Table 1. The range of the variation of the tube support inside diameter has turned out to be the most important factor affecting the measurement of all of the properties. The most difficult property to compute was the flaw size. The flaw used in the calculations was a spherical cavity with a radius 0.1 of the mean coil radius. This size sphere has been related to a 0.125-in. diam (3.2 mm) hole, which is more familiar as a reference standard in this type of eddy-current testing and gives a similar signal. The volume of the hole is varied by changing the depth. The tube support measurement is the radial clearance of the maximum size tube, with the tube centered in the support. Both the fit and drift errors are standard deviations. Both contain the round-off error in the calculations. The flaw size is the only property that requires the range of tube support variation to be divided into smaller increments. The hole size fit error decreases from 0.142 mm (0.0056 in.) to 0.033 mm (0.0013 in.) as the tube support range is decreased. The maximum fit error of 0.142 mm actually represents practically no fit, since the maximum hole size is 0.445 mm (0.0175 in.), with an average hole size of 0.330 mm (0.013 in.). However, a good fit can be obtained when the changes due to the tube support are divided into smaller increments. The drift error tends to increase as the ability to calculate the flaw size from the instrument readings increases. The large final value indicates that we will have drift and noise problems with this particular property. The large values of the tube support clearance

Table 1. Variation in Property Measurements for Various Ranges of Tube-to-Tubesheet Distances

Measurement	Error	Variation, mm (in.) for Each Tube Support Range				
		0–13 mm (0–0.5 in.)	0–0.76 mm (0–0.030 in.)	0–0.25 mm (0–0.10 in.)	0.025–0.076 mm (0.001–0.003 in.)	12.7–13.0 mm (0.50–0.51 in.)
Hole size[a]	Fit	0.142 (0.0056)	1.109 (0.0043)	0.074 (0.0029)	0.030 (0.0012)	0.033 (0.0013)
	Drift	0.028 (0.0011)	0.048 (0.0019)	0.234 (0.0092)	0.561 (0.0221)	0.513 (0.0202)
Thickness	Fit	0.006 (0.00025)	0.004 (0.00017)			0.0028 (0.00011)
	Drift	0.009 (0.00035)	0.005 (0.00020)			0.003 (0.00012)
Probe radial clearance	Fit	0.005 (0.0002)				
	Drift	0.005 (0.0002)				
Tube support radial clearance	Fit	0.229 (0.0090)				
	Drift	0.305 (0.012)				

[a]Depth of 3.2-mm-diam (0.125-in.) hole.

represent the freestanding tube, and the small values represent the support fitting tightly on the tube, but the intermediate values are not a true representation of the actual case as the probe is entering the tube support and are only used as stand-ins for early calculations. The actual case could not be calculated by our present theoretical analysis so it was determined experimentally.

The experimentally measured edge effect of the tube support has presented less of a problem to fit than the calculated values for large diameter variations.

A differential coil was considered as a possibility but not used. The differential coil is identical with two absolute coils, side by side. They may be wound so that their turns go in the same direction and the mutual inductance adds, or they may be wound in opposition. The latter will cause a slight decrease in the circuit inductance, which will give a small improvement in the ability to drive long cables. Since the differential coil system compares the signal from the adjacent coils it has the ability to provide little or no response to slow variations in some of the test properties, such as gradual changes in wall thickness, tube inside diameter, and tube conductivity. The signals from point flaws depending upon coil configuration and flaw size also tend to subtract, but not as much as the slow variations. The differential coil can completely miss slowly varying wastage on the tube and has no discrimination against the edge effect of the tubesheet and tube supports or dents. The differential coil uses the motion of the probe past the flaw to produce a signal that gives an indication of both the size and location of the discontinuity.

As a contrast, the multiple-frequency system with either differential or absolute coils uses the signals at various frequencies to separate the effects of the tube wall thickness, the tube inside diameter, the flaws, and also the tube supports, the tubesheet, and dents. Since these properties can be separated by the multiple-frequency system itself, an absolute coil can be used. The absolute probe is more susceptible to dc drifts and requires more frequent calibration. The flaw signal is about 20% larger than the signal produced as the flaw passes under each differential coil, but 60% smaller than the total. The electronic system for the absolute coil requires a larger dynamic range than is normally used by a differential system, but the differential system also needs the large range if the same large dent signals are present. The multiple-frequency system with the absolute probe produces signals that are easier to fit to properties and can make readings while the probe is at rest.

The same information is present in a pulsed signal as in a multiple-frequency system, and the same analysis can be used for either. The pulsed system can be constructed with much simpler and cheaper electronics than the multiple-frequency instruments, and the pulsed instrumentation is easier to control with digital circuits. Although this type of instrumentation will probably predominate in the future, we have not been able to achieve the signal-to-noise ratio in our early pulse instrumentation that we can in our multiple-frequency instruments. This seems to be due to the low signal power of the pulses in realtion to the signal power of continuous sinusoidal signals. We can use signal averaging, which will result in slow inspection speeds, or wait until semiconductor devices are available that will switch high voltages and currents in a very repeatable manner. Since it will be several years before the pulsed system can be developed, we proceeded with the multiple-frequency system.

EXPERIMENTAL MEASUREMENTS IN THE LABORATORY

Experimental measurements were performed on steam generator tubing samples to verify the analytical results and to include the tube support and tubesheet edge effects, which the theory neglected. Also, second-order effects such as variations in some of the coil and cable construction details are included in the measurements.

A block diagram of the three-frequency instrument is shown in Fig. 3. The instrument consists of three separate oscillators from which the signals are mixed before the composite signal is transmitted to the probe through a power amplifier. The signal from the probe is separated back into three discrete frequencies by using bandpass amplifiers. The magnitude and phase of each signal are then sent to a demodulating computer, which digitizes the readings and calculates the different properties.

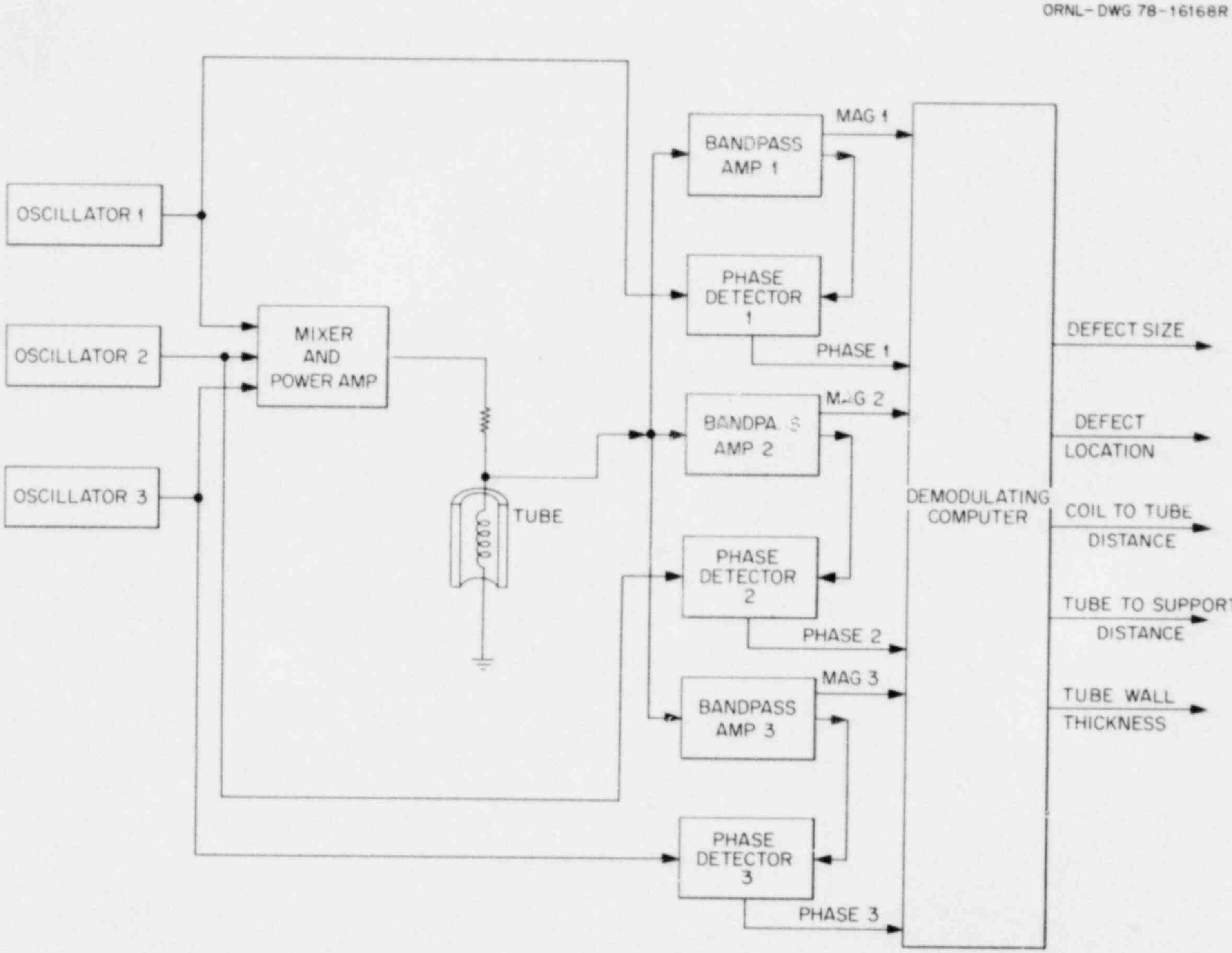

Fig. 3. Block Diagram of a Three-Frequency Instrument.

The demodulating computer in our developmental program can be either the MODCOMP IV minicomputer or the NDT-COMP9A microcomputer that is in the instrument. The three-frequency instrument[3] that has been developed at ORNL is shown in Fig. 4. A few of the modifications and improvements to the instrumentation package have been discussed in the three preceding quarterlies.[4–6] These include the automatic calibration module, the magnetic tape drive, the COMP9A microcomputer, and the analog-to-digital converter module. The instrument has a calibrator module that can be controlled by either the microcomputer or the minicomputer. The calibrator will switch in passive *R-L-C* networks that will produce a known magnitude and phase in the instrument. The computer then records these readings and does a least squares correction of all subsequent readings.

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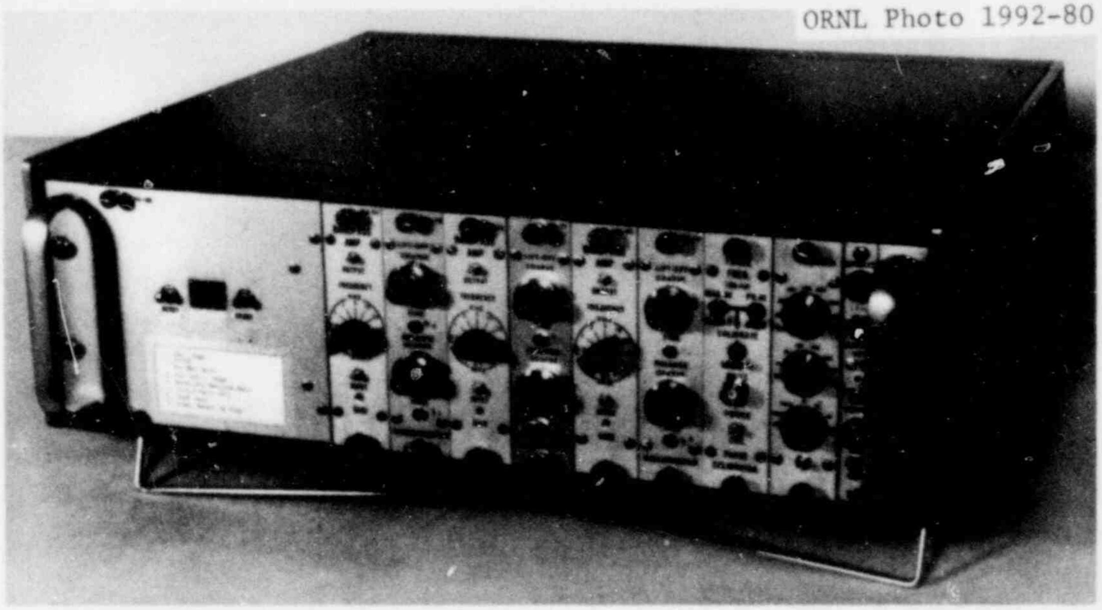

Fig. 4. The Three-Frequency Eddy Current Instrument.

The NDT-COMP9A microcomputer,[7] which is used to control the instrument in the field, is shown in Fig. 5, in the computer module of the instrument. The microcomputer can have as much as 16K bytes of memory, divided between PROM and RAM, and it has a floating point hardware chip. The microcomputer is 8080 based and has 72 parallel input-output ports, one serial port, and three counter chips.

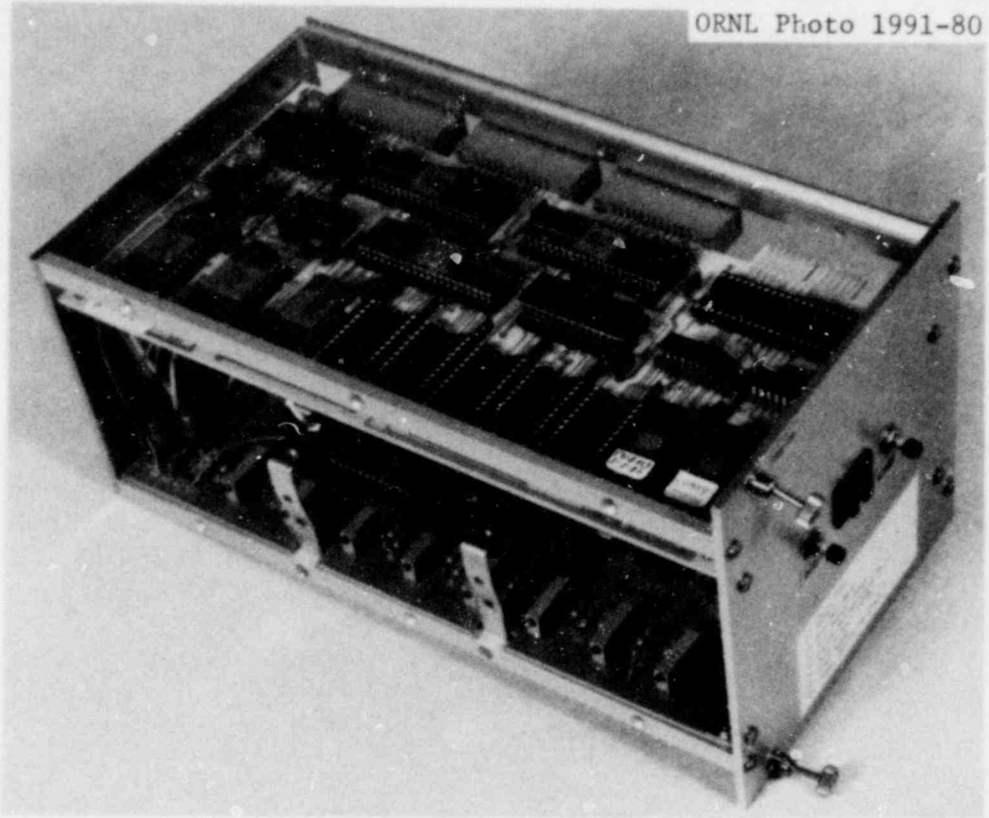

Fig. 5. The NDT-COMP9A Microcomputer in the Three-Frequency Instrument Computer Module.

The MODCOMP IV computer is used to run the test while the instrument is in the laboratory because of the ease in programming the MODCOMP IV, its larger data taking capacity, and its faster operating speed. For the experimental measurements, as well as the analytical calculations, a large number of different properties are considered. For instance, if an experiment has three variations of tube wall thicknesses, three variations in tube inner diameters, two different flaw sizes, two different flaw locations, three variations in tube support diameters, and ten different locations of the tube support along the tube (e.g., relative to flaws, probe, etc.), there are 2160 different combinations for these parameters. Because of the large number of possible variations of the tube and tube-support positions with respect to the coil, the accurate positioning for all these cases without making any mistakes is very difficult. Therefore we have constructed an automatic positioner, shown in Fig. 6. This positioner is controlled by the MODCOMP IV and is accurate and repeatable to within ±0.05 mm (0.002 in.).

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Fig. 6. Automatic Positioner to Locate Tube and Tube Supports with Reference to the Coil.

The program TUBRDG is used to run the positioner and take the readings at the proper positions. Once the calibration has been verified, the program is completely automatic and will run unattended. About 2 h is needed to perform a complete set of readings that requires 1350 positions.

After the data are taken, the program TUBFIT is used to perform the least squares fit of the measured readings to the properties of the standards. We have issued a report[8] that describes the progreams TUBRDG and TUBFIT in more detail. The fit and drift errors similar to those noted in the analytical design calculations are also printed out, although the fit error now includes the experimental errors in the measurements of the standards. Some of these measurements are summarized in Table 2 along with the calculated accuracies and the present commercial practice (as estimated from a Battelle-Columbus report). The accuracy of the measurements depends to some extent on the range of all the property variations, so that these values will vary as the ranges vary.

Rather than dividing the tube support up into different ranges of radial clearance, we took one small range going from a diameter of 22.5 to 23.2 mm (0.888 to 0.913 in.), which covers the range of variation of the tube supports and tubesheets for Westinghouse model 44 steam generators. We then made measurements at ten different distances along the tube from

Table 2. Accuracy of Property Measurements by Eddy-Current Methods

Property Measured	Depth of 4.76-mm-diam Outside Hole		Tube Wall Thickness		Tube ID (Denting Measurement)	
	(mm)	(in.)	(mm)	(in.)	(mm)	(in.)
Present commercial capability[a]	0.62	0.025	0.13	0.005	0.03	0.001
Total support plate range						
ORNL calculated	0.15	0.006	0.01	0.0002	0.01	0.0002
Measured	0.18	0.007	0.01	0.0002	0.01	0.0002
Incremental support plate range						
ORNL calculated	0.02	0.0006	0.01	0.0002	0.01	0.0002
Measured	0.03	0.0012	0.01	0.0002	0.01	0.0002

[a]J. H. Flora, S. D. Brown, and J. R. Weeks, *Evaluation of the Eddy-Current Method of Inspecting Steam Generation Tubing*, BNL/NUREG-50512 (Sept. 30, 1976)

the support, from the center of the support up to about 38 mm (1.5 in.) from the center, and ran the measurements for all different combinations of tube inside diameter, tube thickness, and flaws. The fit error for the 4.8-mm-diam (0.19 in.) holes was 0.068 mm (0.0027 in.), which seems adequate for our tests. Thus it appears that we can measure fairly small flaws without breaking the support plate inside diameter into a number of smaller ranges.

Another program, PLTRDG, will take the coefficients determined by TUBFIT, multiply them by the readings to calculate the properties as the tube and supports are being moved past the probe (in our laboratory studies), and plot the results on the Versatec plotter. This gives a quick verification of how well the system will work with a given set of coefficients, determined from measurements on a particular set of standards.

Figure 7 shows a plot of the raw readings of magnitude and phase at the different frequencies as the tube is scanned. One horizontal division is 25.4 mm (1.00 in.) along the tube, and one vertical division is 0.1 V for the magnitude and 0.10° for the phase. The tube support signals, the tube inside diameter changes, and the tube wall thickness variations are all much larger than the flaw signal [3-mm-diam (1/8-in.) holes drilled to 10% depth on both inner and outer surfaces]. Figure 8 shows the values calculated by the instrument from raw data readings as the tube is scanned for wall thickness, radial clearance between the probe and the tube, and flaw size. The tube support signal is barely visible on the wall thickness and radial clearance channels and less than the flaw signal on the flaw channel. The tube inside diameter changes represent gradual uniform denting. This standard was constructed by joining several different standards together, and a gap at each interface causes some signals on the different channels.

We are continuing to run different sets of standards to determine the instrument performance and the best set of standards to calibrate the instrumentation for a particular job.

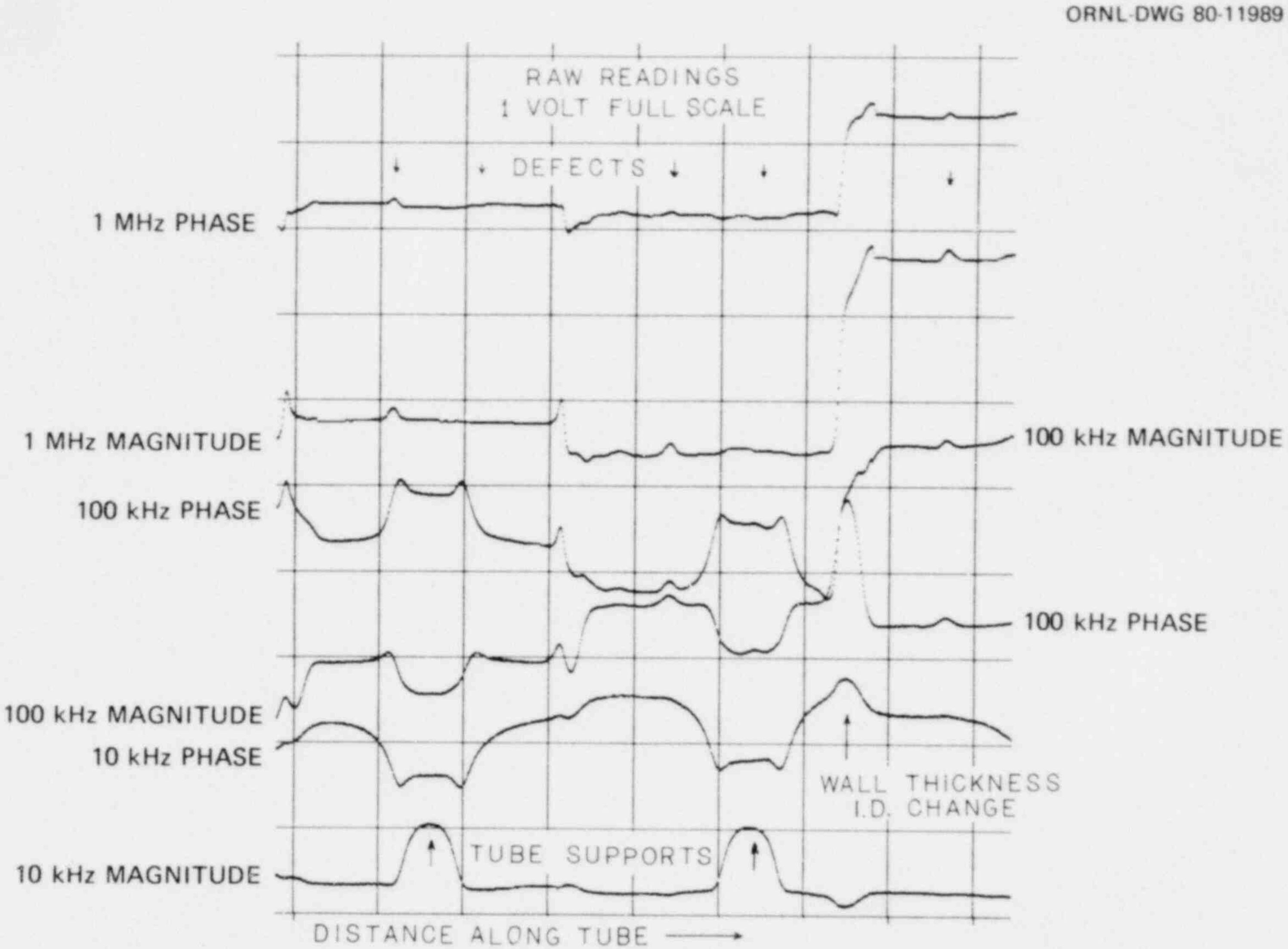

Fig. 7. Raw Voltage Readings from a Scan Along a Tube with Defects and Tube Supports. Wall thinning is on both surfaces of the tube.

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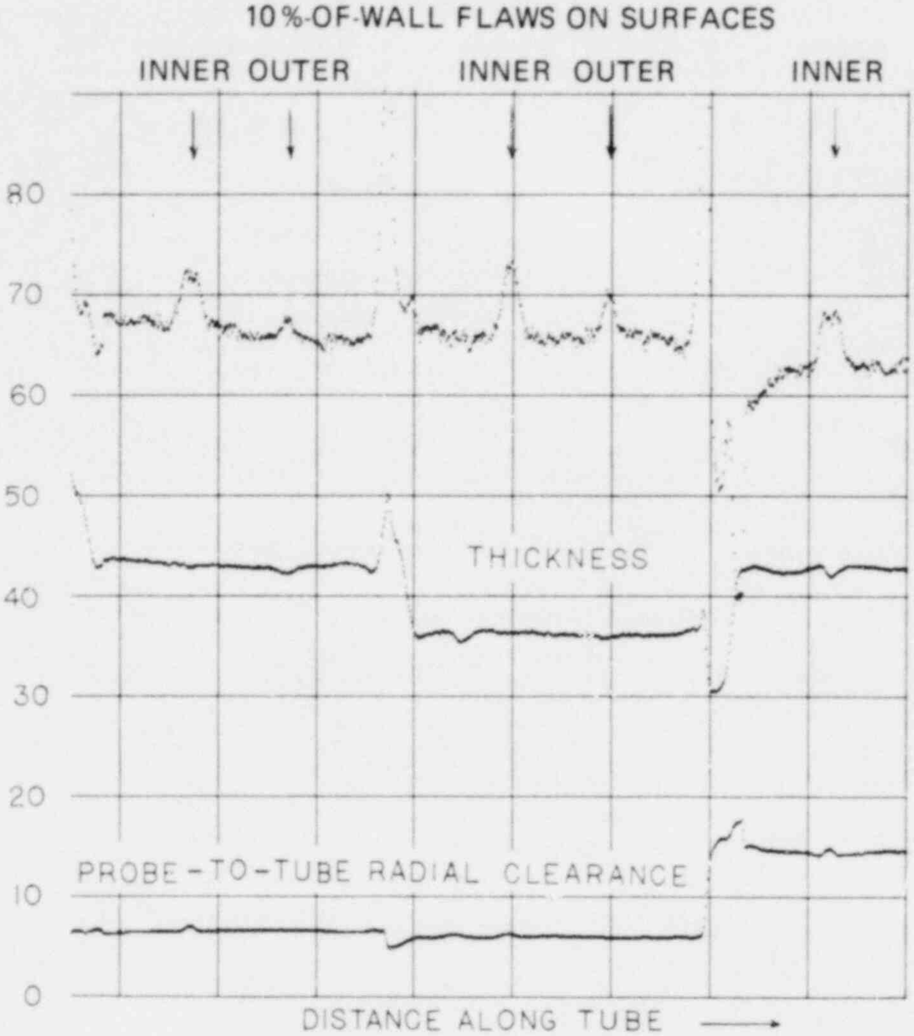

Fig. 8. Converted Properties for Wall Thickness, Radial Clearance between the Probe and Tube, and Defect Size (determined by instrument from raw data shown in Fig. 7).

DEVELOPMENT OF INSTRUMENTATION FOR FIELD TESTING

We are developing the instrumentation for use in the field. Figure 9 shows the instrument mounted along with a strip chart recorder for use in the field. A magnetic tape recorder can also be used. The operating cabinet can also be used as a shipping cabinet by latching the front and rear covers to it. The probe motion controller is also in the cabinet. The probe drive uses a stepping motor and controller, so that a very wide

ORNL Photo 1993-80

Fig. 9. Eddy-Current Instrument Mounted in Operating and Shipping Cabinet with Strip Chart Recorder and Motor Controller.

range of probe motion is available. For a typical operating sequence the probe is inserted by the microcomputer, the instrument is recalibrated, and the instrument starts making readings as the probe is withdrawn. The instrument reads the data from the prior set of readings and then starts the six integrating 12-bit analog-to-digital (a/d) converters to making a new reading. The instrument then calculates the properties, feeds the property data to the five digital-to-analog converters that furnish the analog signal to the strip chart recorder, sends the digital data to a tape recorder, and then sends a signal to advance the probe a given number of steps. The integrating a/d converters are set to a period of 16.6 ms, so that the effects of 60-Hz noise will cancel. If the computer takes a longer time calculating the properties, because of some anomaly in the tube, the drive will automatically slow down so that none of the tube is missed.

Although the system does work now, we are making improvements in the accuracy, speed, and ease of use by operators in the field.

PRESENT STATUS OF DEVELOPMENT

The tests that have been run in the laboratory show, for small amounts of uniform denting, the multiple-frequency technique works much better than the previous single-frequency technique. The self-contained unit for use in the field also works but is noisy. The laboratory tests need to be extended to the larger numbers of tube samples, the signal-to-noise ratio of the field unit needs to be improved, and the system needs to be tested in the field.

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APPENDIX

Least Squares Fit of Properties to Readings

If we have a series of independent equations containing unknowns, we can solve for the unknowns with standard algebraic techniques. If the relationship is between test properties, p_i, and instrument readings, r_j, the equations may appear as:

$$r_1 = c_{11}p_1 + c_{12}p_2 ,$$

$$r_2 = c_{21}p_1 + c_{22}p_2 ,$$

We can solve for these two properties in terms of the two readings. The coefficients must be det rmined by either experimental measurements or theoretical calculations. This is done by varying the property over its expected range and calculating or measuring the readings. We may use the readings directly or use nonlinear functions of the readings as well as various cross terms between the readings. The readings may be the magnitude and phase at each of several frequencies or the magnitude of a pulse at various time intervals. According to information theory, we have two independent readings for each separate frequency, and the information obtainable by using multiple-frequency and pulse techniques is the same. Only the instrumentation is different. At the present, pulse systems are simpler and cheaper, but noisier. We have had much more experience with and done more independent development with multiple-frequency instrumentation, so we have concentrated on this type for the present. The only actual requirement is that we have at least as many instrument readings as we have test properties and the frequencies are far enough apart so that the readings vary in a different manner with the properties.

We can represent the equations between the readings and the properties in matrix notation as:

$$\overline{r} = \overline{\overline{c}}\,\overline{p} ,$$

and the notation for the solution as:

$$\overline{p} = \overline{\overline{c}}^{-1}\,\overline{r}\ ,$$

where $\overline{\overline{c}}^{-1}$ denotes the inverse of the matrix $\overline{\overline{c}}$.

Generally, when we initially determine the coefficients, we have many more sets of equations between the readings and the properties than we actually need, resulting in an overdetermined system. The overdetermination allows us to minimize the errors caused by inaccuracies of measurement or calculation and by inaccuracy in the assumed functional dependence of the properties on the readings.

We shall consider the calculation of only one property at a time, the property p_n. This property will be determined while all the other properties are varying over their entire range. We can write an equation for each of m sets of property values as

$$p_{nm} = \sum_{i=1}^{I} r_{mi}c_{mi}\ ,$$

where we are summing the product of the r_i readings times the c_i coefficients for each set of m property values. If we have 5 properties, and take 3 values for each property (maximum, minimum, and nominal), m would be 3^5 or 243. The readings can be actual readings, such as magnitude or phase, or "constructed" readings, consisting of polynomials of various functions of the readings, each with a different coefficient. Since our equation will not be exact, we shall rewrite it to include an error term, e_m, as

$$p_{nm} - \sum_{i=1}^{I} r_{mi}c_i = e_m\ ,$$

or in matrix notation

$$\overline{p}_n - \overline{\overline{r}}\,\overline{c} = \overline{e}\ .$$

This is the least squares problem, and we wish to determine $\overline{c}$ so that $\overline{e}$ will be minimum. There are a number of standard computer programs to perform this calculation and determine the coefficients that give the least error.[1]

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