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

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W. E. Deeds

Prepared for the U.S. Nuclear Regulatory Commission
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EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1978

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

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CONTENTS

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

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 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 complicated 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. Progress has been made in establishing the necessary computer codes, constructing some of the basic modules for the instrumentation, and acquiring selected tubing reference standards. To date, our results show that eddy-current inspection does work and can make far better measurements than are possible with existing commercial instruments.

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, tube supports, and conductivity variations from defect size, depth, and wall thickness variations. Computer design of probes, instrumentation, and techniques is emphasized. This first annual report includes current progress and an overview of the steps that will be taken during the project.

BACKGROUND

Steam generators are vital components in both fossil- and nuclear-fired power plants. Tube leaks in the steam generators can result in consequences ranging from loss of efficiency to plant shutdown. A method of predicting which tubes will leak and which 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. Unfortunately, they sometimes give erroneous results. We will discuss why the present eddy-current tests lack the desired accuracy and how we are currently trying to overcome this limitation.

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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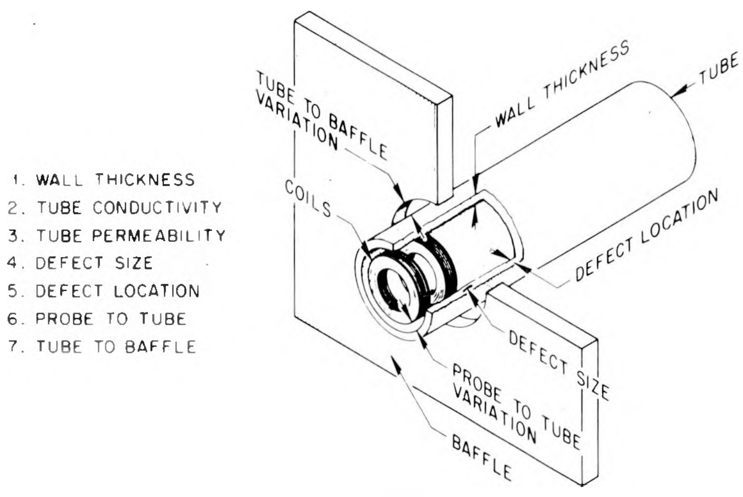

Fig. 1. Eddy-Current Inspection of the Bore of Steam Generator Tubing.

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 thus subject to interpretation by an operator and may be ambiguous. The reason for this potential ambiguity is the large number of test properties (Fig. 2) that can affect an eddy-current steam generator test.

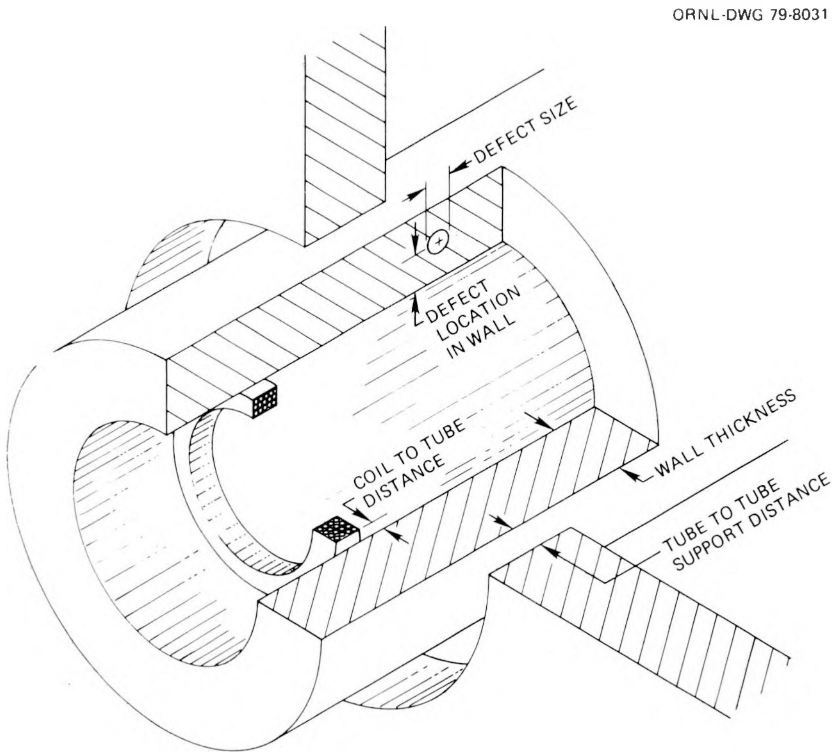

Fig. 2. Property Variations That Affect Eddy-Current Tests in a Steam Generator.

An eddy-current instrument is capable of measuring only two test property variations per frequency, and when more than two occur at the same time the resulting effects cannot be distinguished. If a particular test property variation produces a uniform response as the probe is moved along the tube, its effect can be subtracted out. However, this technique is not always reliable. Unfortunately, a tube is most likely to develop leaks at regions where other test properties are also changing. Even a property variation that may not impair 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 it affects the eddy-current signal. To distinguish these 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, and 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 INSPECTIONS

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 tests 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 many different test property variations. These variations will span the range of variations expected in the actual tests. Next, a least-squares fit of the test properties to the instrument readings and nonlinear functions of the instrument readings will be carried out.

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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).

ORNL-DWG 73-4858

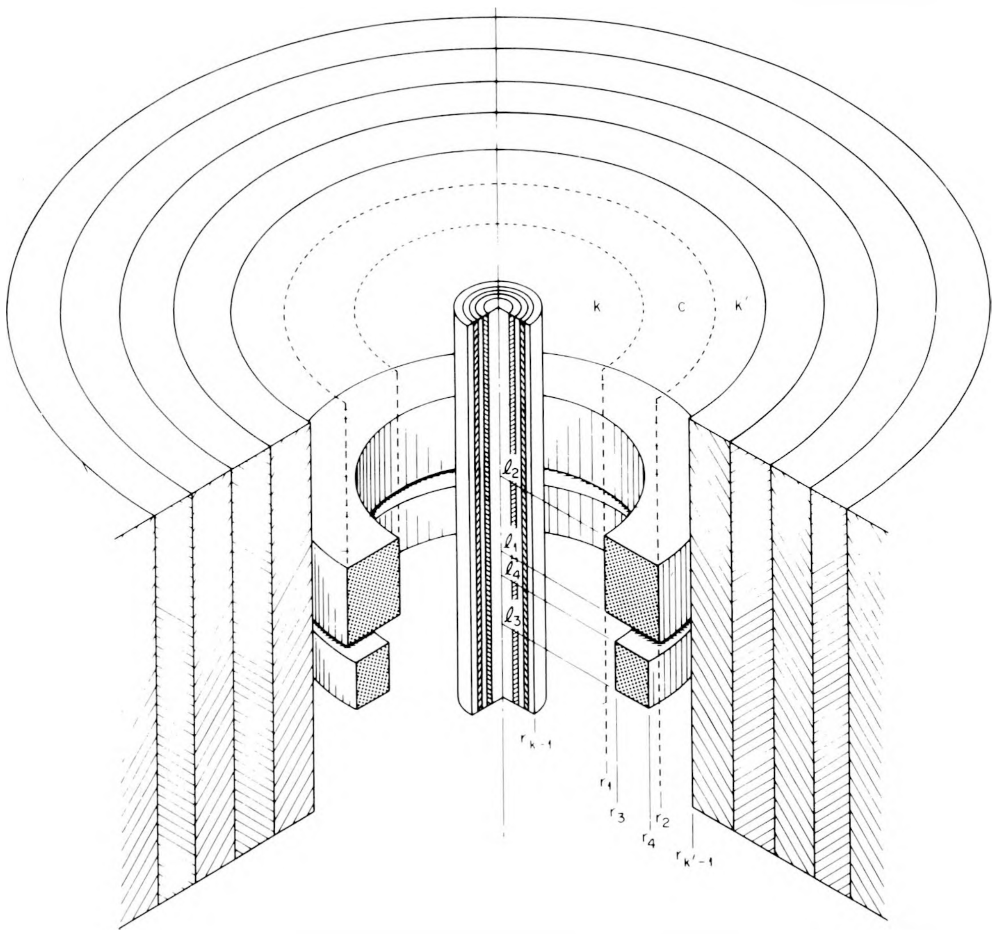

Fig. 3. Multiple Cylindrical Conductors Encircling and Encircled by Two Coils in the Same Radial Region.

If we wish to calculate thickness, and the instrument readings are the magnitudes and phases at different frequencies, the fitting function may be of the form:

$$\text{THICKNESS} = C_0 + C_1 \ln M_1 + C_2(\ln M_2)^2 + C_3 Ph_1 + C_4(Ph_1)^2$$

$$+ C_5 \ln M_2 + C_6(\ln M_2)^2 + C_7 Ph_2 + C_8(Ph_2)^2 + \ldots , \qquad (1)$$

where the Cs are the coefficients that are determined by the least-squares fit, and M_i and Ph_i represent the magnitude and phase at the ith frequency.

We will then calculate 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 instrumental errors). These calculations will be repeated several times with different coil and instrument parameters. The best results will be used in the design system.

Instrument Construction

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

The first instrument will have discrete-frequency design, as shown schematically in Fig. 4. As time and resources permit we will develop a pulse-type instrument, as shown schematically in Fig. 5. We are temporarily using an instrument that was developed for an extra and separately funded project.

Calibration and Test Measurements

The instrument is connected to the parallel input-output ports of the ModComp IV minicomputer. By using the TUBRDG program, readings are made on tubing tests samples that cover the range of anticipated test property variations. This program prompts the user through the instrument calibration and then directs him to place the probe on the proper samples in the proper order. It then averages the results, prints out a summary, and records the results on a magnetic disk.

The process is then reversed, and the test properties are calculated from the readings. Next, a least-squares fit for all the coefficients is calculated from the experimental data. Both constructional differences between the designed coil and actual coil and also certain test property variations that cannot be calculated (such as the edge effects from the tube supports) are taken into account.

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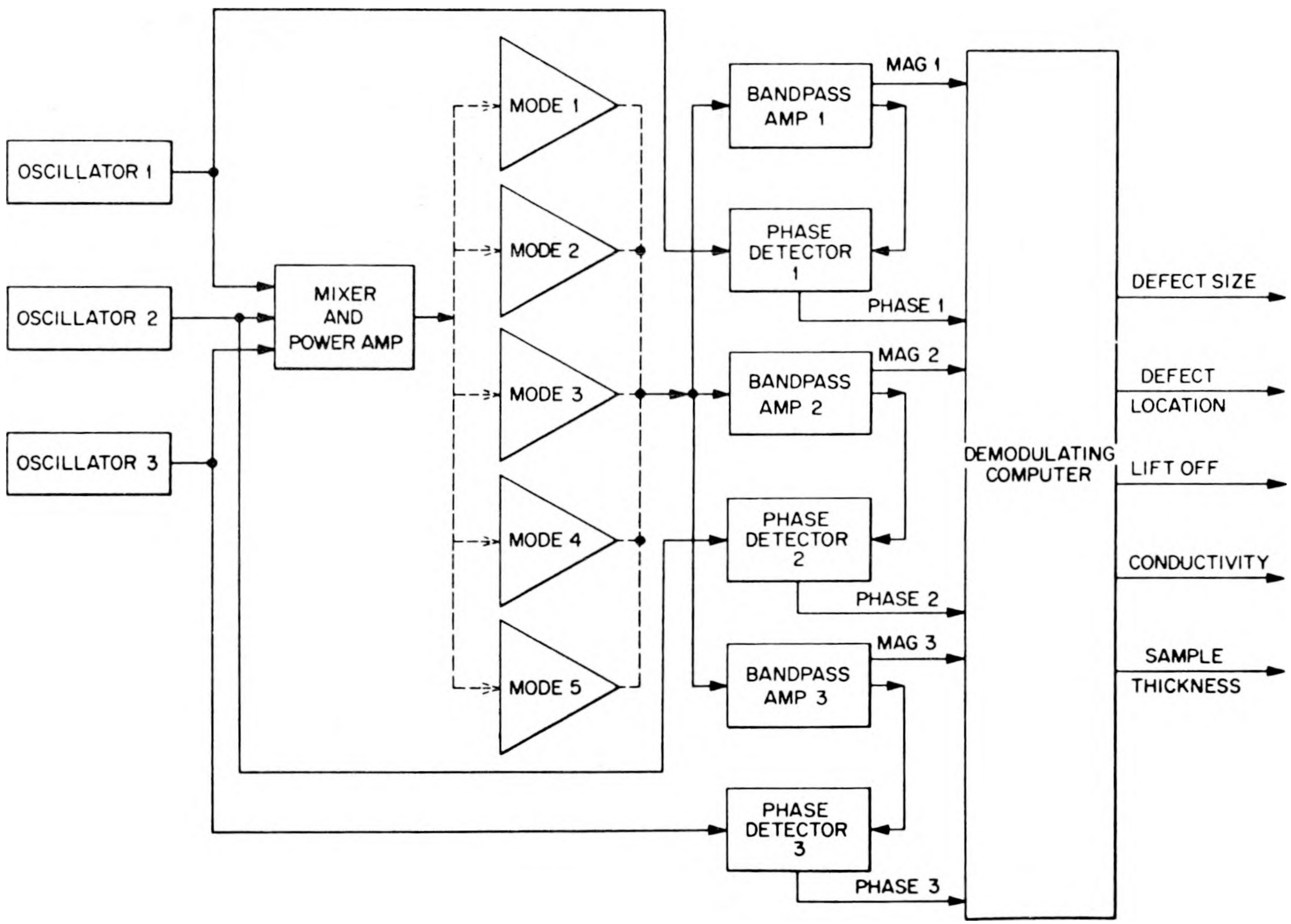

Fig. 4. Block Diagram of a Three-Frequency Instrument.

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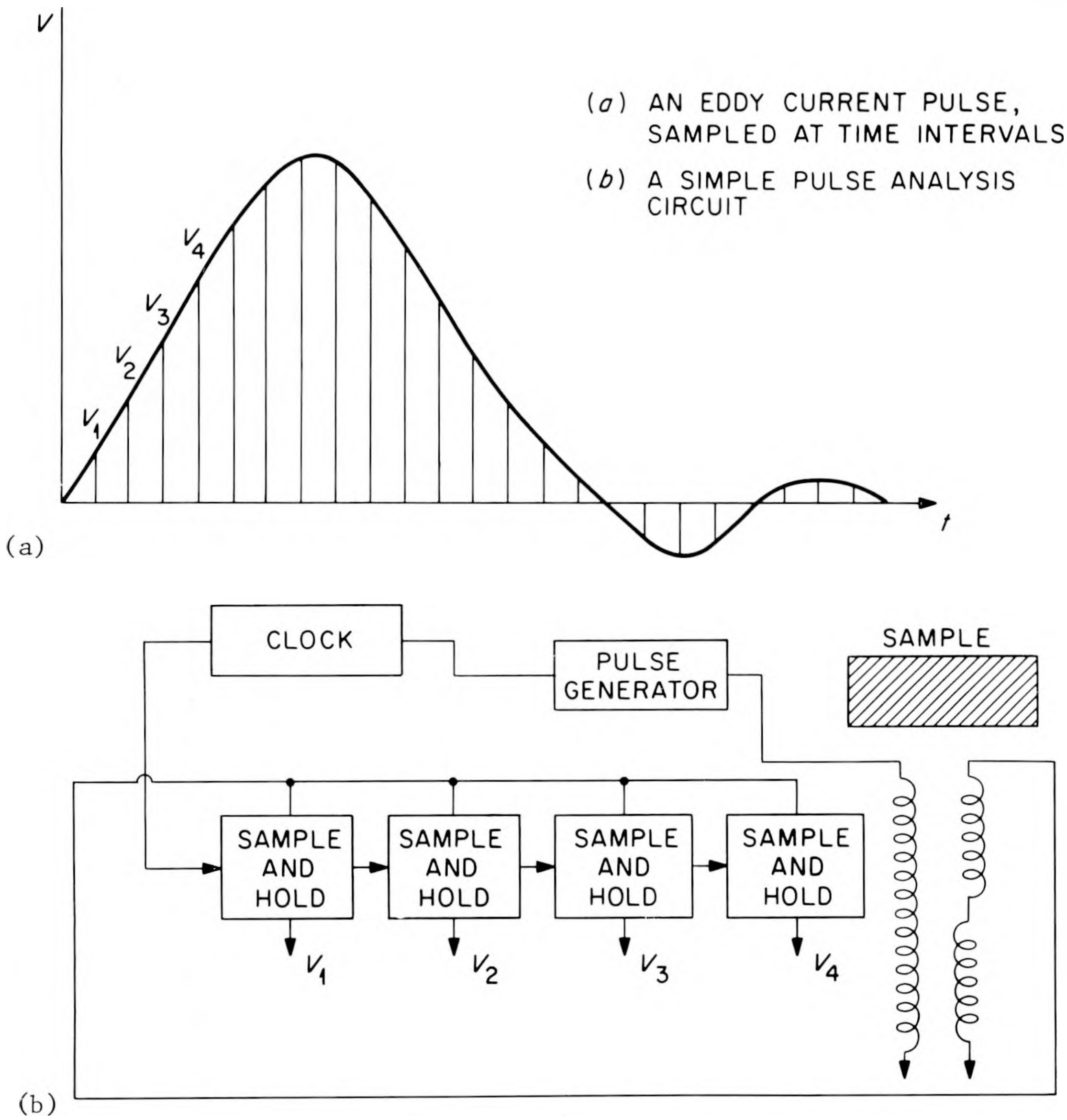

Fig. 5. Operation of a Pulse-Type Instrument. (a) An eddy-current pulse sampled at time intervals. (b) A simple pulse analysis circuit.

Once the coefficients are determined from the standards, the process is reversed. Our in-house minicomputer — the ModComp IV — continuously takes readings and by using these coefficients calculates the properties directly. It then displays the results on a CSRT 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

Finally, the instrument is tested in the field under actual 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 YEAR ENDING DECEMBER 31, 1978

Multiple-Property Reflection Test Demonstration

The technique for solving multiple-property variations has been tested with reflection probe coils and two-frequency instruments, as shown in Fig. 6 (except that the instrument in the figure has three frequencies). Figure 7 shows the reflection-mode coil. This work was performed and funded on a separate project but was a necessary step in proving the approach. Furthermore, it directly benefited this project for LWR steam generator in-service inspection of tubing. Thus far the equipment designs that have been produced have been quite successful.

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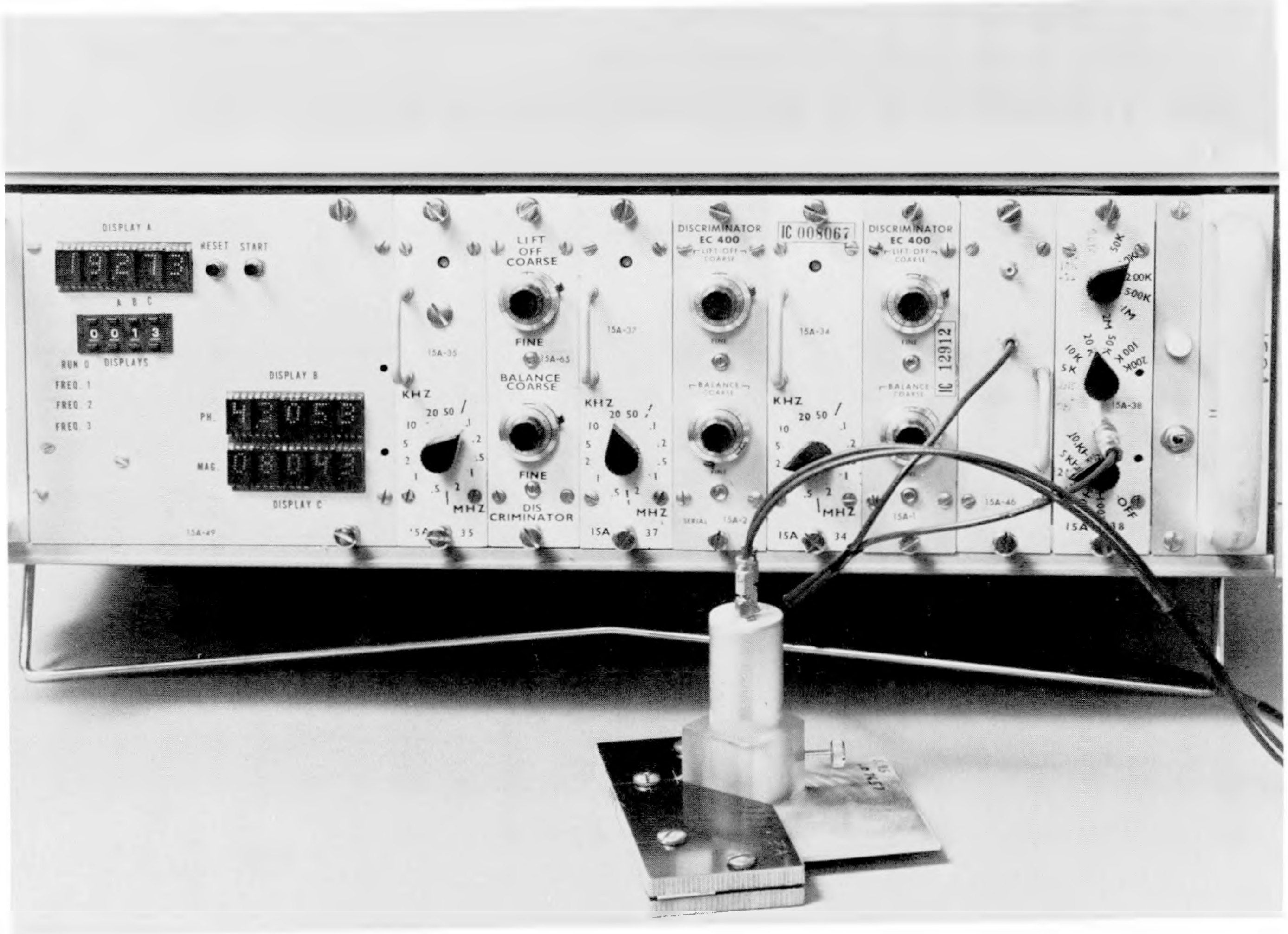

Fig. 6. Multifrequency Instrument, Reflection-Coil Probe, Specimen, and Specimen Positioner.

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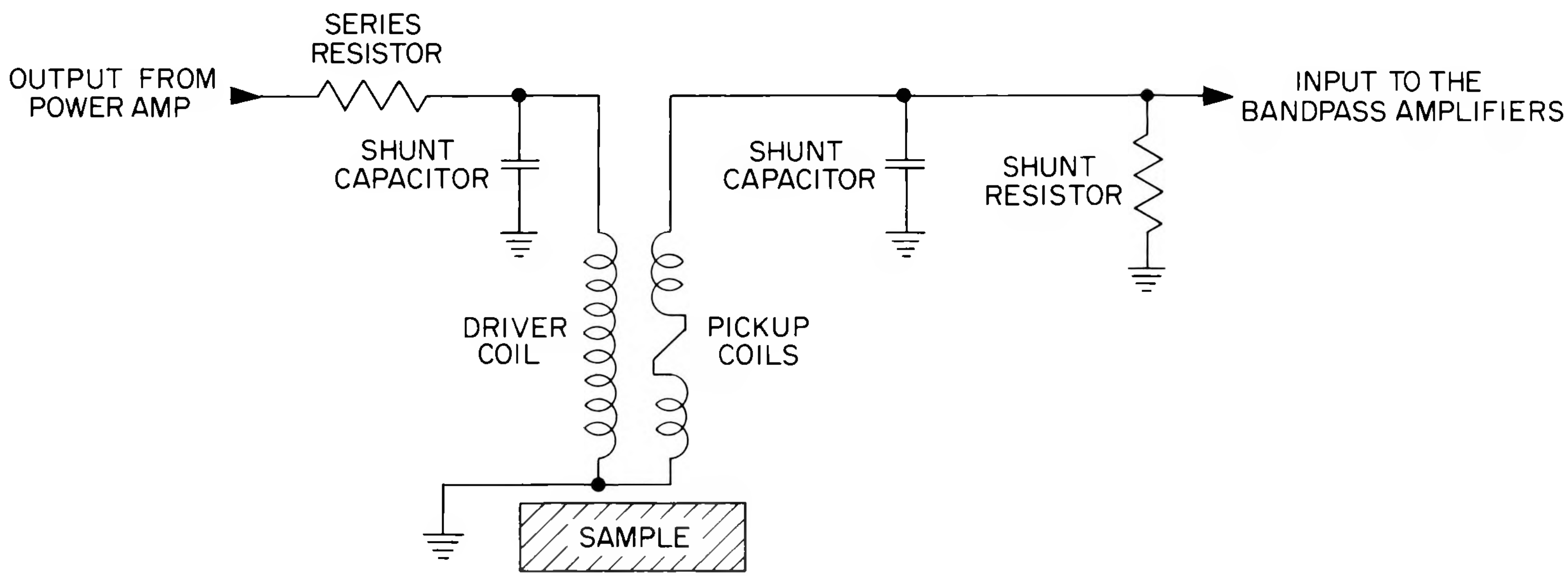

Fig. 7. Reflection-Mode Coil.

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 calculated values 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 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.

Computer Design of Tubing Tests

The batch version of the design program for multiple cylindrical conductors — ENCIRM — has been written and debugged. The effect of changes in conductivity, permeability, wall thickness, tube inner diameter, tube supports, and tube defects can be calculated. The electrical circuit in the program can be either an absolute coil (Fig. 8) or a two-coil send-receive network. Other types of electrical circuits are being added to the program, and the program has been interfaced to a least-squares program — MULLSQ — to fit the properties to the readings.

The TUBRDG program, which takes calibration readings, prompts the operator to place the probe in the proper tube sample, reduces the data, and stores the data, has been written. Another program — TUBFIT — which takes the readings produced by TUBRDG, does a least-squares fit of the properties to the readings, and calculates the properties from the readings, has been written. These programs have been tested under separate funding on ferromagnetic tubing with a three-frequency eddy-current instrument.

The wall thickness, tubing inner diameter (and therefore the clearance between the probe and the tube), and the saturating current (and therefore magnetic permeability) were varied, and measurements were made. A summary of the preliminary measurements is shown in Table 2. The permeability is only estimated. Most of the errors were due to either the type of saturating current drive — constant voltage rather than constant current — thermal heating, or too small a saturating current. We believe that these errors can be reduced with further testing and modifications. We do not expect to require magnetic saturation; during development saturation allows planned control of magnetic permeability.

Although there were some defects in the tubes, we did not have enough samples to do a least-squares fit of the defects to the instrument readings.

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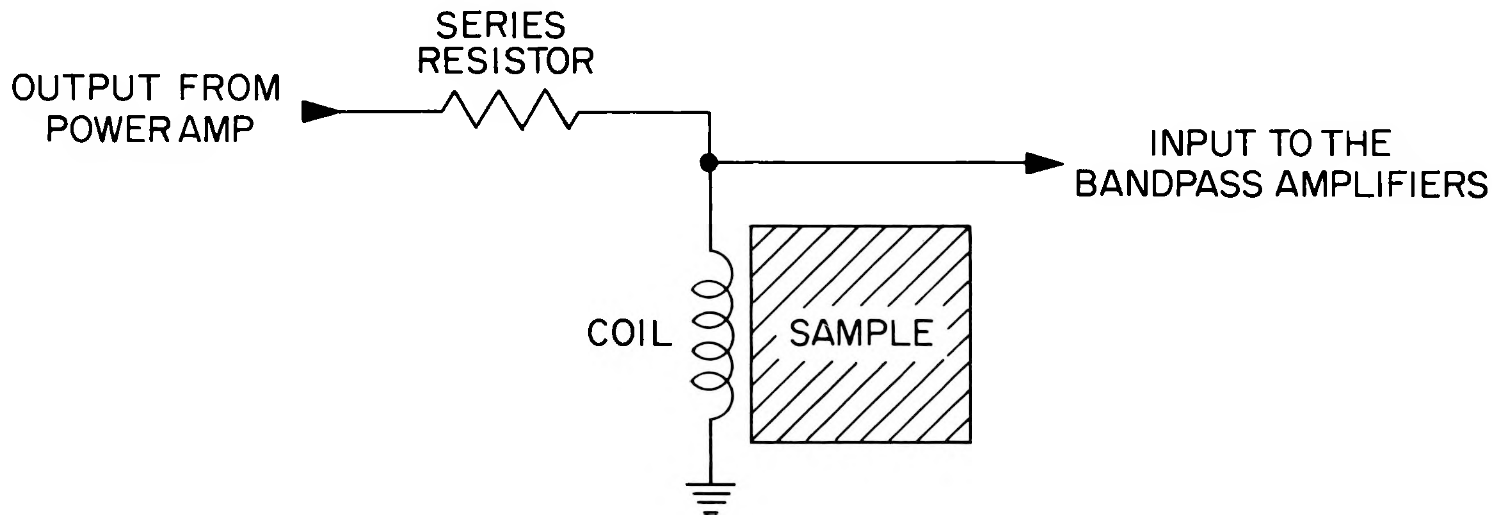

Fig. 8. Absolute-Mode Coil.

Table 2. Measurement of Wall Thickness, Radial Clearance, and Permeability in Ferromagnetic Tubing

	Thickness (mm)	Radial Clearance (mm)	Permeability (Relative)
Range	1.9–3.0	0.14–1.14	8–10
Fit error	0.013	0.037	0.41
Drift error	0.019	0.023	0.21
Absolute error	0.15	0.13	0.4
Repeatability error	0.05	0.14	0.4

We have used our program — ENCIRM — to calculate the magnitudes and phases of an absolute eddy-current coil (Fig. 2) inside a 22-mm-diam (7/8-in.) alloy 600 tube. The calculations were performed for different combinations of tube wall thickness, tube inner diameter, tube-to-tube support spacing, defect size, and defect location within the wall. The instrument readings were calculated for the various test properties for frequencies of 5, 10, 20, 50, 100, 200, 500, and 1000 kHz and stored on disk. Next the properties were fitted to the readings by a least-squares program, and the fit and drift errors were determined.

We wrote an automatic search program that takes all combinations of frequencies, 3 at a time, and calculates the properties from nonlinear combinations of the calculated readings (approximately 1,000 reading combinations are calculated for each frequency set). If the property fit and drift error are less than a preset amount, a one-line summary of the fit type and results are printed out. Thus, the best frequencies and reading combinations can be chosen to calculate any given property. It takes about 56 h to test all combinations for all 8 frequencies, but the program is completely automatic and can be left running over a weekend.

We used the automatic search routine to find the best fit and least drift for detecting defects and measuring thickness changes in the presence of ferromagnetic support plates. A summary of the results is shown in Table 3.

Table 3. Summary of Calculations of Test Properties for 22-mm-Diam (7/8-in.) Inconel Tubing

Property	Support Clearance (Radial) mm (in.)	Wall Thickness mm (in.)	Probe Clearance (Radial) mm (in.)	Location in Wall mm (in.)	Depth of 4.8-mm-Diam (3/16-in.) Hole mm (in.)
Range	0–5.3 (0.0–0.21)	0.64–1.40 (0.025–0.055)	0.19–0.700 (0.0075–0.0275)	0.10–1.2 (0.005–0.046)	0–0.19 (0–0.0075)
Fit Error (RMS Variation)	0.038 (0.0015)	0.008 (0.0003)	0.005 (0.0002)	0.2 (0.007)	0.053 (0.0021)
Drift Error (RMS Variation)	0.081 (0.0032)	0.01 (0.0005)	0.005 (0.0002)	0.1 (0.004)	0.038 (0.0015)

The results for thickness measurements and defect size measurements were particularly good. The 1.29-mm (0.051-in.) wall thickness measurement had a fit error of 8 μm (0.0003 in.) and a drift error of 13 μm (0.0005 in.). The measurement of the depth of a 4.8-mm-diam by 0.19-mm-deep (3/16 by 0.0075-in.) hole had a fit error of 53 μm (0.0021 in.) and a drift error of 38 μm (0.0015 in.). Although the 0.19-mm-deep by 4.8-mm-diam hole is quite large, its volume is only 1/20 that of the present commercial standard. Because our calculations indicate that these two property measurements have high sensitivity, we have decided to verify this experimentally as our first priority and make further optimization calculations as a lower priority.

We have performed a series of experimental measurements to verify the calculated results for the 22-mm-diam (7/8-in.) Inconel 600 steam generator tubes. We did not run the same set of properties for experimental samples as for calculated results (it is easy to add thickness to a tube sample on the computer but is hard to do experimentally). However, the two sets of properties were close enough to get a good indication. The only two properties that we will examine in detail are wall thickness and defect size. They are shown in Table 4. While the agreement is very good between the calculated and experimental property determinations, there are some additional improvements that must be made.

The size error is much greater for outer surface than for inner surface defects. The calculated readings and experimental measurements were rerun with more weight given to the outer surface defects. Table 5 shows the results of measurements and calculations that compare present commercial practice (as determined by Battelle, Columbus)[2,3] to ORNL results for the tube support, which varied from fitting tightly on the tube to being completely away from the tube in a single range. Next,

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[2]J. H. Flora and S. D. Brown, *Evaluation of the Eddy Current Method of Inspecting Steam Generator Tubing,* BNL-NUREG-50512R (September 30, 1976).

[3]S. D. Brown and J. H. Flora, *Evaluation of the Eddy Current Method for the Inspection of Steam Generator Tubing-Denting,* BNL-NUREG-50743 (September 30, 1977).

Table 4. Summary of Experimental and Calculated Results for Measurement of Properties of 22-mm-Diam (7/8-in.) Inconel Tubing

Property	Wall Thickness, mm (in.)		Depth of 3.18-mm-Diam (0.125-in.) Hole, mm (in.)[a]	
	Calculated	Measured	Calculated	Measured
Range	0.64–1.4 (0.025–0.055)	0.89–1.3 (0.035–0.051)	0–0.389 (0–0.0153)	0–0.53 (0–0.021)
Fit Error (RMS Variation)	0.005 (0.0002)	0.005 (0.0002)	0.12 (0.0049)	0.13 (0.0051)
Drift Error (RMS Variation)	0.008 (0.0003)	0.005 (0.0002)	0.086 (0.0034)	0.074 (0.0029)

[a]Results represent mean values for outer surface and inner surface holes.

Table 5. Accuracy of Property Measurements (All Properties Varying)

Property Measured	Depth of 4.762-mm-Diam (0.1875-in.) Outer Surface Hole mm (in.)	Tube Wall Thickness mm (in.)	Tube Inner Surface mm (in.) (Denting Measurement)
Present Commercial Calculations[a]	0.76 (0.030)	0.1 (0.005)	0.02 (0.001)
Total Support Plate Range			
ORNL Calulations	0.2 (0.006)	0.005 (0.0002)	0.005 (0.0002)
Measured	0.2 (0.007)	0.005 (0.0002)	0.005 (0.0002)
Incremental Support Plate Range			
ORNL Calulations	0.02 (0.0006)	0.005 (0.0002)	0.005 (0.0002)
Measured	0.030 (0.0012)	0.005 (0.0002)	0.005 (0.0002)

[a]Based on data from:
J. H. Flora and S. D. Brown, *Evaluation of the Eddy Current Method of Inspecting Steam Generator Tubing,* BNL-NUREG-50512R (September 30, 1976);
S. D. Brown and J. H. Flora, *Evaluation of the Eddy Current Method for the Inspection of Steam Generator Tubing-Denting,* BNL-NUREG-50743 (September 30, 1977).

the test was performed for the tube support spacing by varying it a number of incremental ranges. The results are for a 0.0 to 0.01 denting variation for the commercial measurements and 0.0 to 0.05 denting variation for the ORNL tests.

The calculated readings cannot include the effect when the tube support is at the edge of the coil. Nevertheless, this can be included in the experimental measurements. However, when not included there was a 0.08-mm (0.003-in.) change in the thickness reading as the support was moved by the coil. Preliminary experimental measurements show that this error can be reduced to 0.005 mm (0.0002 in.).

The LSQENC program has been modified so that different properties can be omitted from the data set. We used this program to determine which property variations cause the most errors and will try to get better fits on these properties.

Instrument Development

We have completed a three-frequency instrument (shown with the tube probe in Fig. 9) and then tested it with its own internal microcomputer. This instrument was originally developed for a related DOE breeder reactor project with an earlier schedule for completion. Its design is flexible enough to allow its use for these studies with minor though somewhat time-consuming adjustments. The instrument performed the desired property calculations using coefficients that are programmed into it by the ModComp IV minicomputer. The microcomputer in the instrument is the NDT-COMP 8, which has inadequate speed and accuracy for steam generator inspections. An advanced model — the NDT-COMP 9 — which does have adequate performance, has been designed, laid out on a printed circuit board, constructed, and successfully tested. The multifrequency instrument now under construction for this project incorporates the NDT-COMP 9.

A pulsed module has been designed and tested with the ModComp IV computer. It is much cheaper and can make more independent readings than the three-frequency instrument (this will be particularly important if six readings will not resolve all the test properties). Development of the pulsed instrument was begun on another project and with separate funding. Schedules have been such that its technology lags behind that of the multiple-discrete-frequency instrument. Consequently, it cannot meet the time requirements for this project.

We redesigned our pulsed eddy-current instrument and replaced ten of the timing integrated circuits with a single counter-timer circuit. This should make the instrument more versatile, improve its performance, and reduce its cost. We will test the pulsed instrument and the multiple-frequency instrument on the standard tubing. If the pulsed module can make readings as accurate as the multifrequency instruments, it could be used in their place with some additional development. Programs like TUBRDG and TUBFIT have been written to test the module on eddy-current problems.

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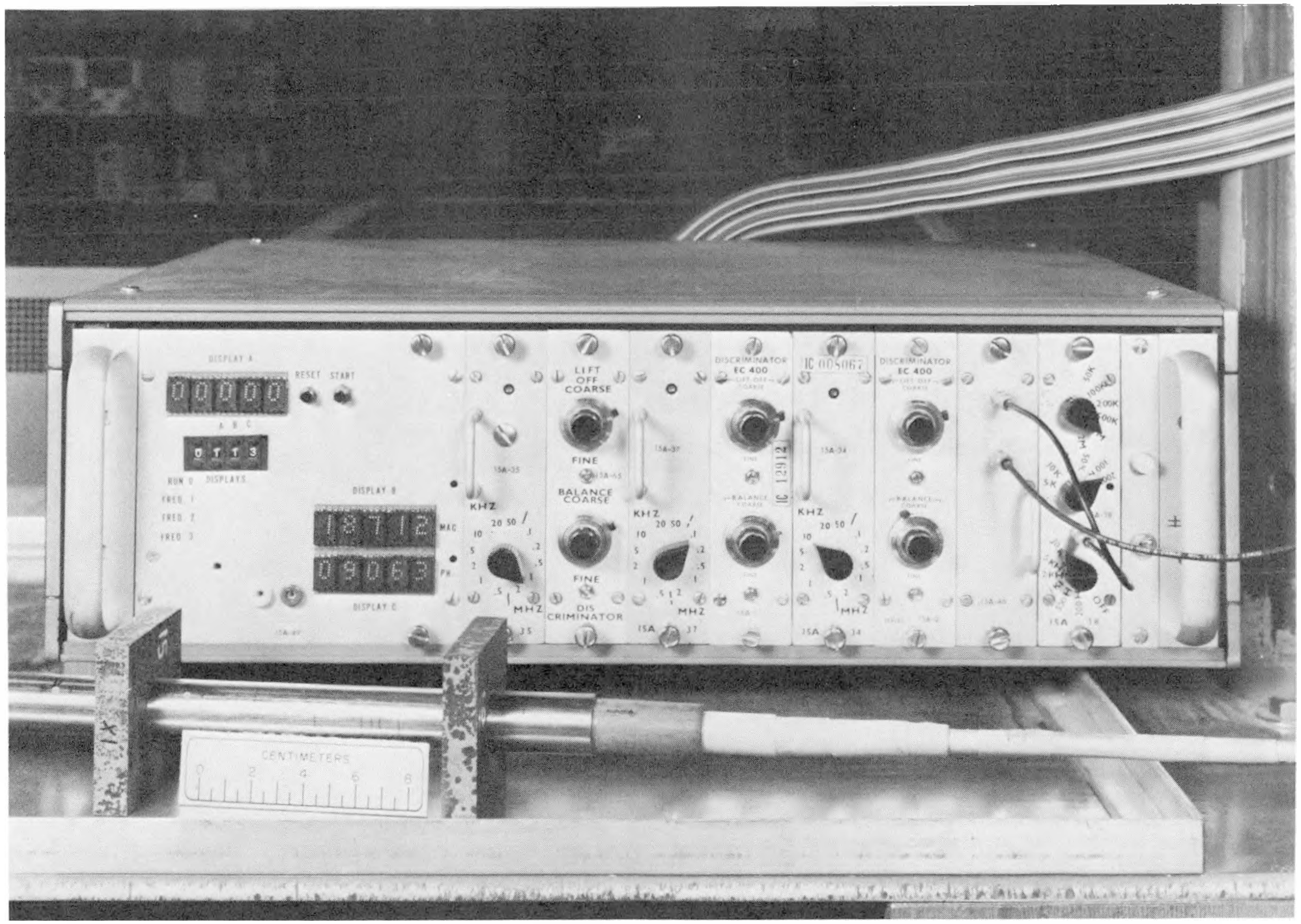

Fig. 9. Three-Frequency Modular Eddy-Current Instrument, Tubing Probe, and Specimen.

We have interfaced a Versatec Printer/Plotter to our ModComp IV computer. We will use the Versatec as a digital strip chart recorder for the property data as the tube is scanned and for normal plotting to show trends, sensitivity, etc. The complete system is shown in Fig. 10.

Standards Fabrication

We are collecting standards so that a series of readings can be made on light-water reactor steam generator tubing. We have received three Inconel tubing reference standards from a commercial source. The tubes are 19.1 by 1.27-mm (3/4 by 0.050-in.) wall; 22.4 by 1.27-mm (7/8 by 0.050-in.) wall; and 19.1 by 1.09-mm (3/4 by 0.043-in.) wall, and each contains the reference flaws conforming to current practice for in-service inspection of steam generator tubing.

Three sets of alloy 600 tubing standards have been machined. These include variations in thickness and in tube inner and outer diameters and both inner and outer surface defects. Tube support plates with several different inner diameters have been machined. These are being tested with the computer-designed probe and the three-frequency instrument, as shown in Figs. 9 and 10. Figure 11 is an enlarged view of a tube support plate specimen.

Fig. 10. Three-Frequency Eddy-Current Instrument, Tubing Test Bed, ModComp IV CRT Terminal, and Versatec Plotter.

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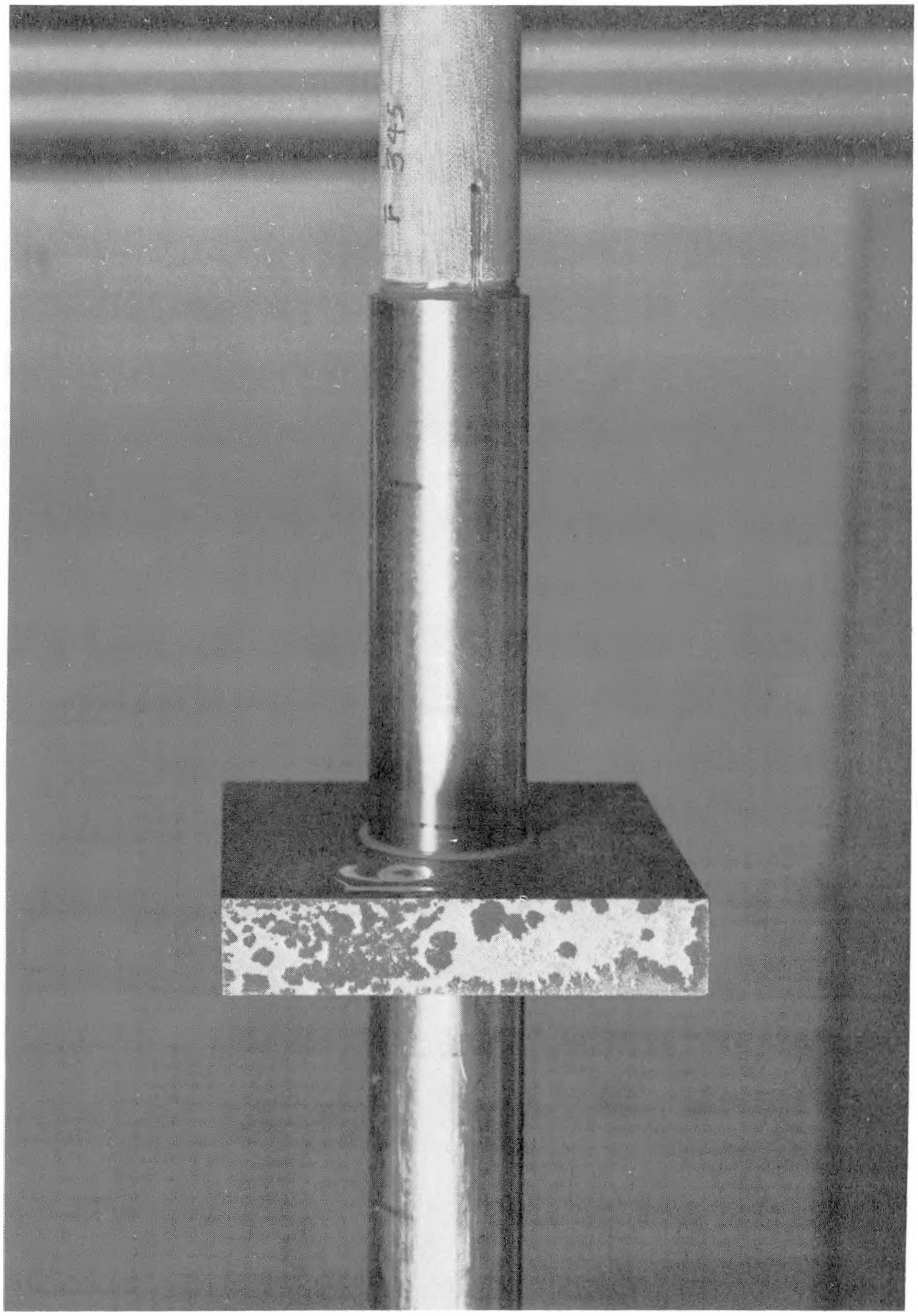

Fig. 11. Close-up of Tube Support Plate Specimen.

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