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Eddy-Current Inspection for Steam Generator Tubing Program Annual Progress Report for Period Ending December 31, 1981

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

Prepared for the
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EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1981

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

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EDDY-CURRENT INSPECTION FOR STEAM GENERATOR TUBING PROGRAM ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1981

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.

To facilitate the extensive laboratory scanning of specimens that are necessary to calibrate the instrumentation for all the possible combinations of positions of flaws, tube supports, and probe coils, we have designed, constructed, and used a computer-controlled automatic positioner. 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 and recording during the scanning of the tube.

We have outfitted a mobile laboratory, mounted in a pickup truck, with the equipment needed to make in-service inspection of steam generator tubing at various reactor sites, and we have successfully inspected steam generator tubes at the Robert E. Ginna and Point Beach reactors, as well as sections of tubing that had been removed from a steam generator. These tests have demonstrated the capability of detecting intergranular attack and contaminant buildup on steam generator tubes during scheduled in-service inspections.

INTRODUCTION

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

As the interface between the primary and secondary coolant systems, the steam generator is a crucial component. Degraded tubes in the steam generator may increase the risk of a loss-of-coolant (LOC) accident from the coincident failure of several tubes either as the initial failure in an accident or as the result of pressure surges in the system resulting from a break and depressurization of either the primary or secondary system. The coincident failure of several (10 to 30) tubes would result in a complex LOC accident that would substantially challenge both the emergency cooling system and containment isolation. The main objective of this program is to improve the ability to detect and determine the size of tubing defects and thereby provide greater assurance of steam generator integrity.

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 U-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.

Measurements made at the Robert E. Ginna and Point Beach reactors during scheduled in-service inspections (ISI) showed intergranular attack (IGA) and contaminant buildup on steam generator tubes. Therefore, tests were run on fabricated samples and on sections of tubing that had been removed from a steam generator, in order to calibrate our instruments more accurately and to help in reducing the data taken during the ISI at Ginna and Point Beach.

ANALYSIS OF PROBLEM

We have analyzed in the general way the problem shown in the block diagram of Fig. 1. The eddy-current probe, of whatever type, is fed with a complex signal containing multiple amplitude or frequency information. The part being inspected interacts with the probe to modify the output

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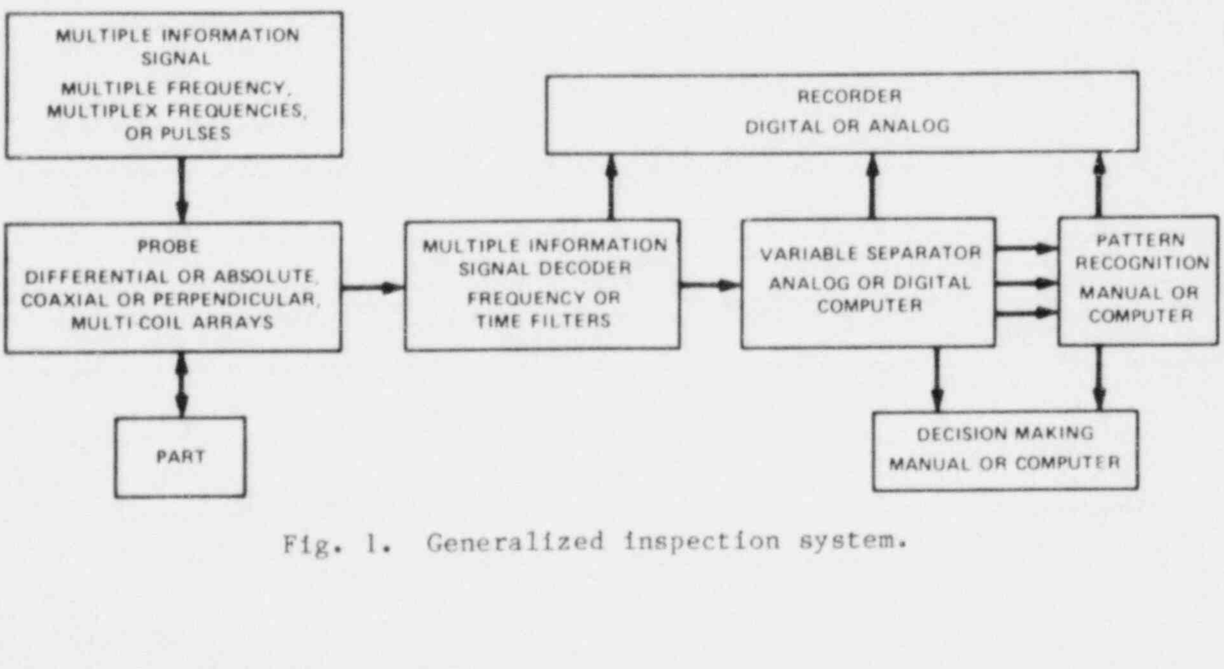

Fig. 1. Generalized inspection system.

signal, which is then decoded into the separate frequency or time components, which can in turn be sent to the variable separator (and possibly recorded). The variable separator uses the multiple pieces of information, such as amplitudes and phases at various frequencies or amplitudes at various times in a pulse, to calculate the various properties or "variables" *via* programs that have been stored in a computer. The output variables can be recorded, used for making decisions, or fed into a pattern recognition system. The latter can be programmed to recognize certain patterns of variables as benign or dangerous, and the types of patterns can be recorded as well as used for making decisions.

The three-frequency eddy-current inspection being developed by ORNL includes these various systems. 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.

A typical steam generator tube is shown in Fig. 2, 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, the tube support axial location along the tube, and changes in the electrical or magnetic properties of the tubing, such as might be caused by IGA or contaminant buildup. 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. 3. This problem has been solved to a high degree of accuracy.[2,3] The main approximation is that the effects of the edge of the tube support plate cannot be calculated accurately.

Computer programs have been written to calculate the eddy current readings for coils encircled by an arbitrary number of coaxial cylindrical regions as in Fig. 3. The programs have been expanded to include separate pickup and driver coils, absolute coils, and matched coils in a bridge circuit. The computer program calculates the effect of the properties to

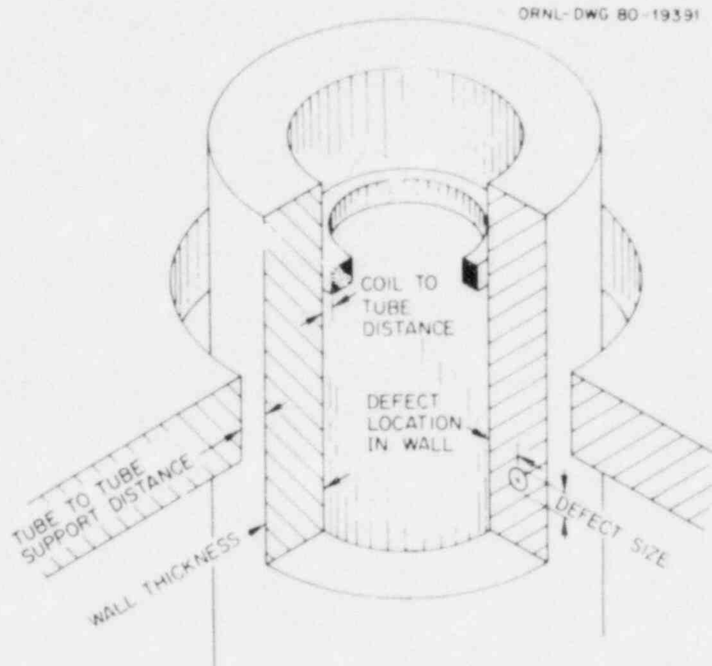

Fig. 2. Test properties that vary during a steam generator inspection.

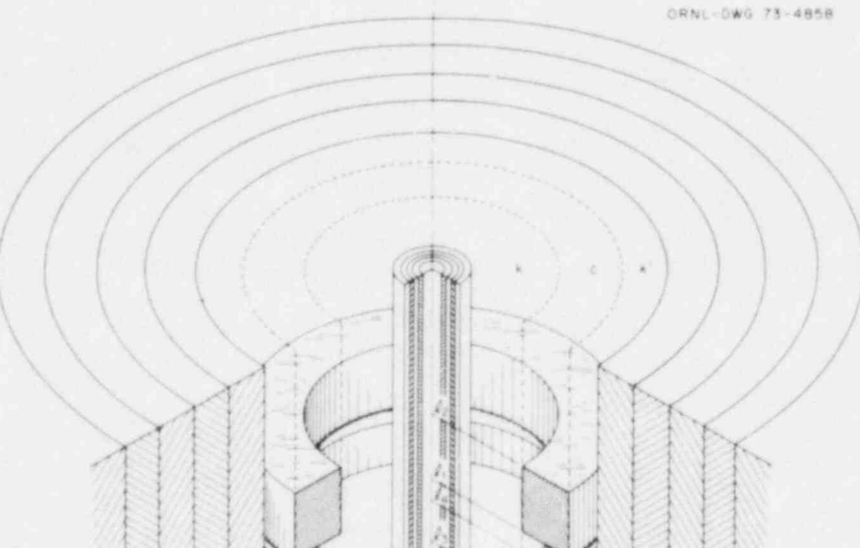

Fig. 3. Multiple cylindrical conductors encircling and encircled by two coils in the same radial region.

a high degree of accuracy and performs a least squares fitting to find the best polynomial of a user-chosen type for calculating any desired property from the computed data.

The fit between calculated and actual properties is somewhat better if we treat the tube differently in different regions of its length. The three essentially different types of regions are shown in Fig. 4. Our computer simulations can predict the instrument response when the tube is not surrounded by tube support or when it is completely inside the tube support region but cannot when the probe is in the interface region. However, experimental measurements can be made as well in the interface region as in the others. Therefore, we have arranged the programs so that the computer can determine if the probe is in the free tube, the tubesheet, or an interface between the tube and tubesheet and then pick the proper set of coefficients to give the best fit. Although all property calculations are improved by this technique, the improvement is necessary only for the defect calculations.

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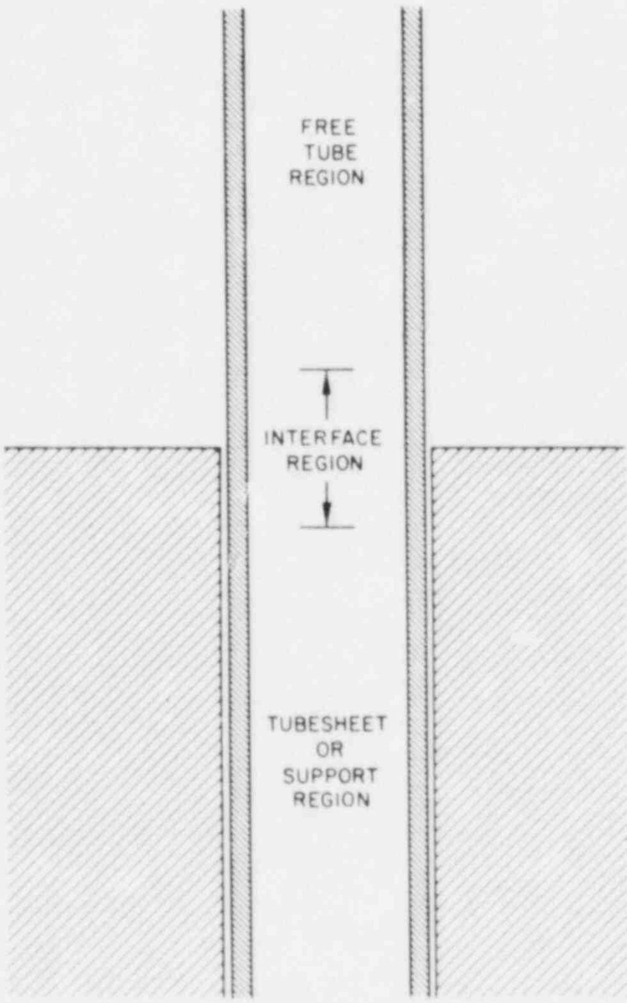

Fig. 4. Types of inspection regions.

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[4] is shown in Fig. 5. 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,[5] which digitizes the readings and calculates the different properties.

Figures 6 and 7 show calibration checks on the wall thickness and radial clearance measurements, respectively, on machined standards. The "measured" curves are those calculated by the eddy-current instrument, and the "actual" values are micrometer measurements.

To test the effect of copper buildup on the outside of the tube, because of observations at the Point Beach reactor, samples were prepared

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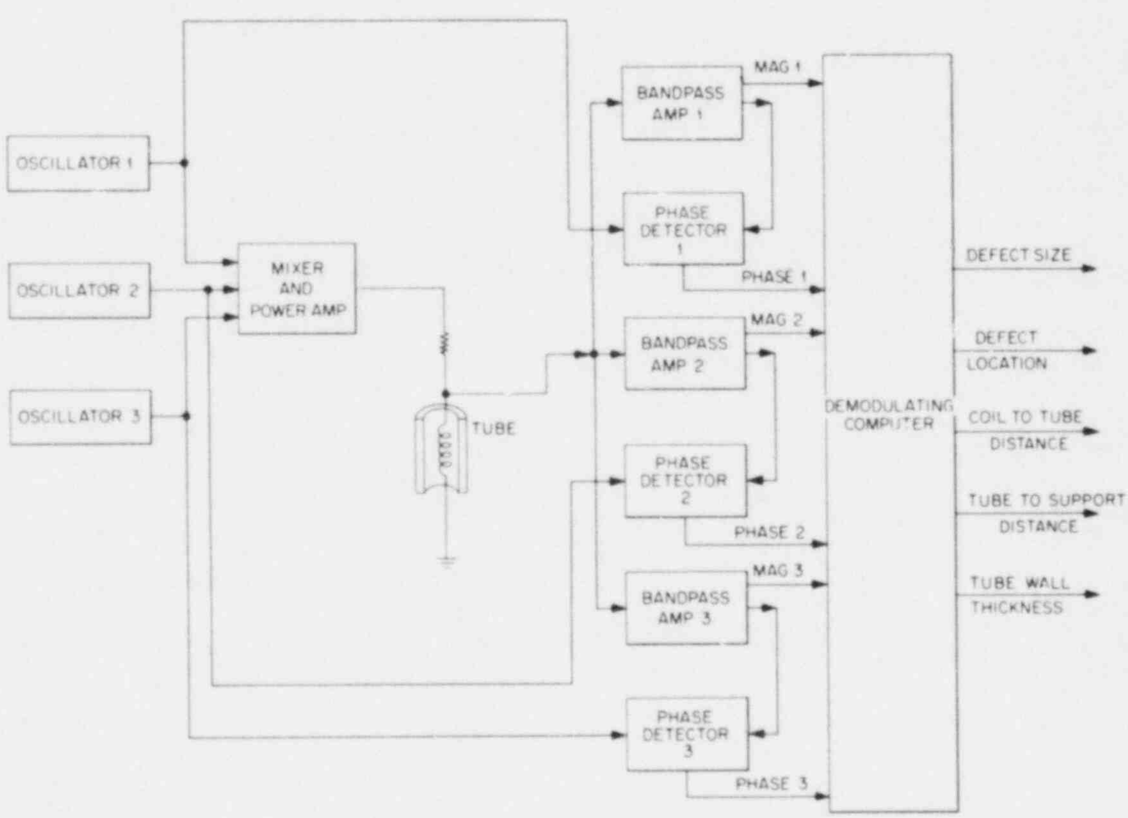

Fig. 5. Block diagram of a three-frequency instrument.

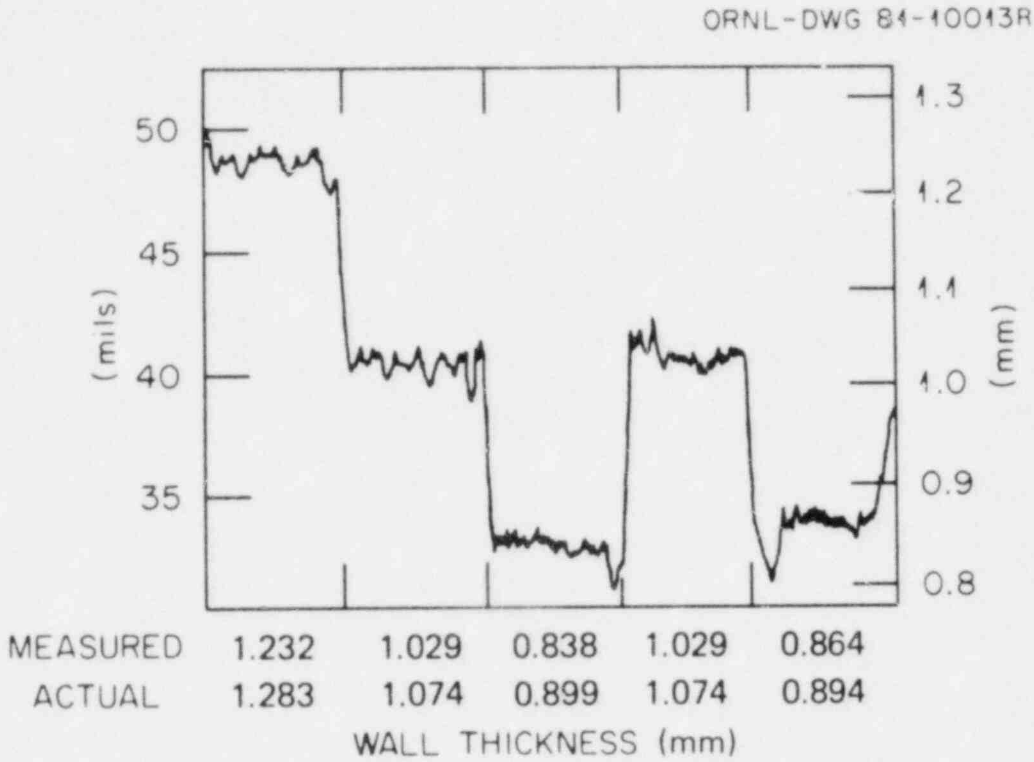

Fig. 6. Calibration check on wall thickness measurements.

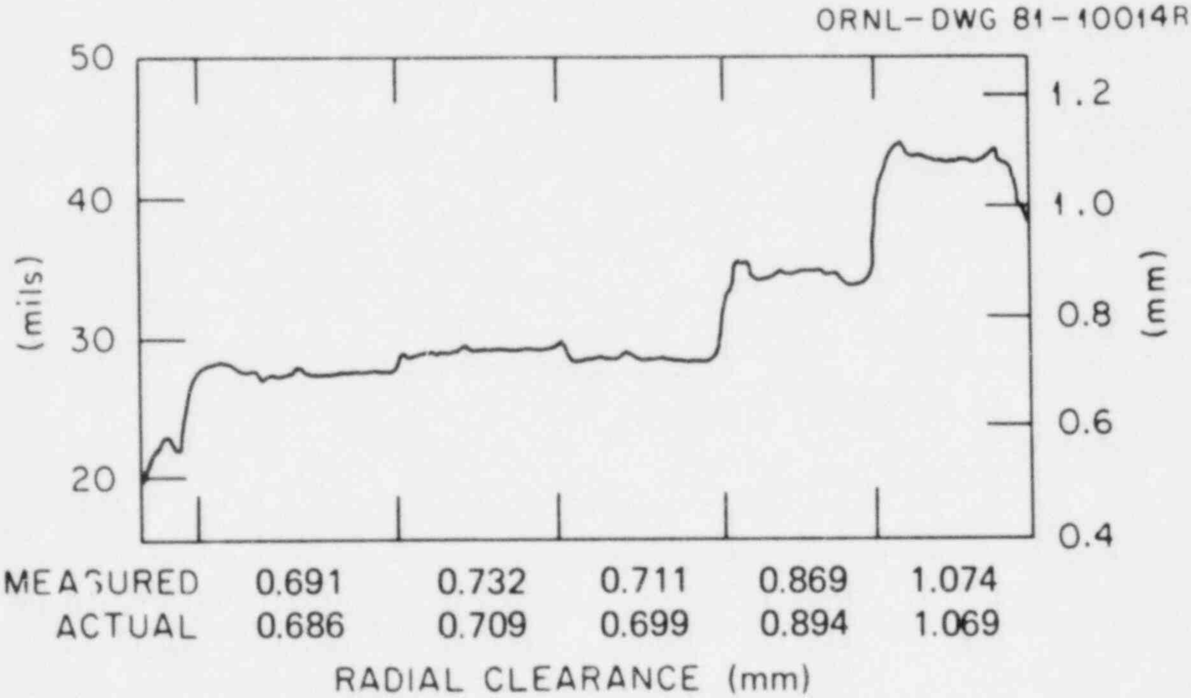

Fig. 7. Calibration checks on radial clearance measurements.

with copper plated on the outside of otherwise normal tubes. Figure 8 shows the raw readings for a sample with copper plated for a short distance on either side of a simulated tubesheet 75 mm (3 in.) thick, and Fig. 9 shows the corresponding calculated properties. The radial clearance channel remains essentially constant, as it should; the tubesheet channel

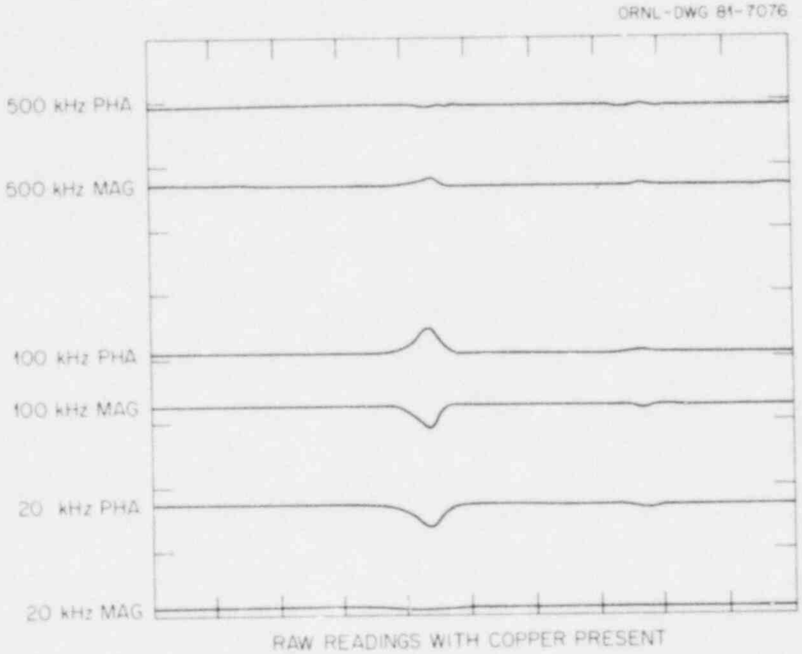

Fig. 8. Raw readings of magnitude and phase at three frequencies with copper plated on outside of tube.

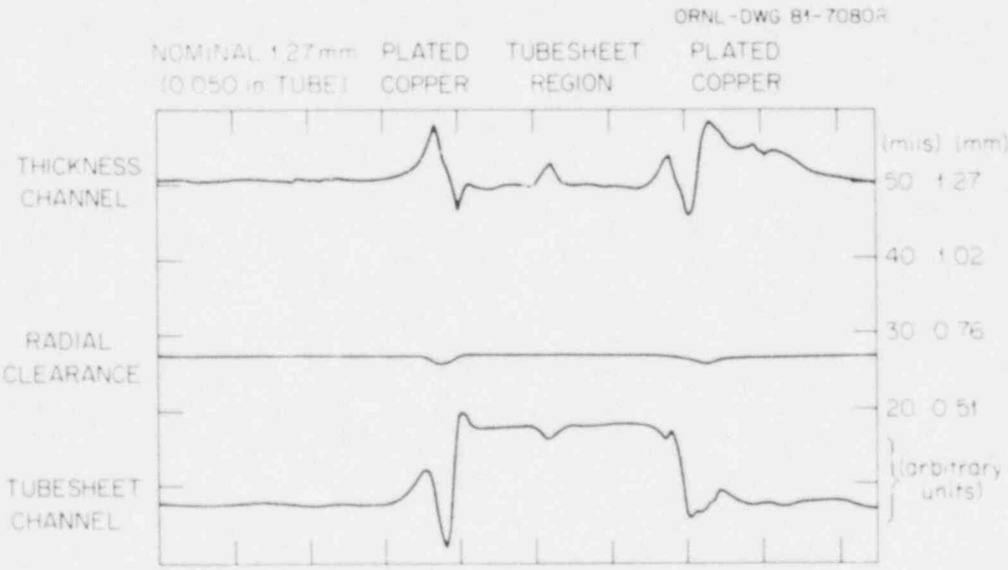

Fig. 9. Calculated properties for tube with copper plated on outside of tube on either side of simulated tubesheet.

clearly shows the presence of the tubesheet; and the thickness channel rejects the tubesheet (as it should) and indicates the presence of more material where the copper is plated.

To test for possible buildup of magnetite (Fe_3O_4) on the outside of the tubes, tests were made with a powdered iron ring 19 mm (0.75 in.) wide surrounding a tube. Figures 10 and 11 show the raw readings and calculated

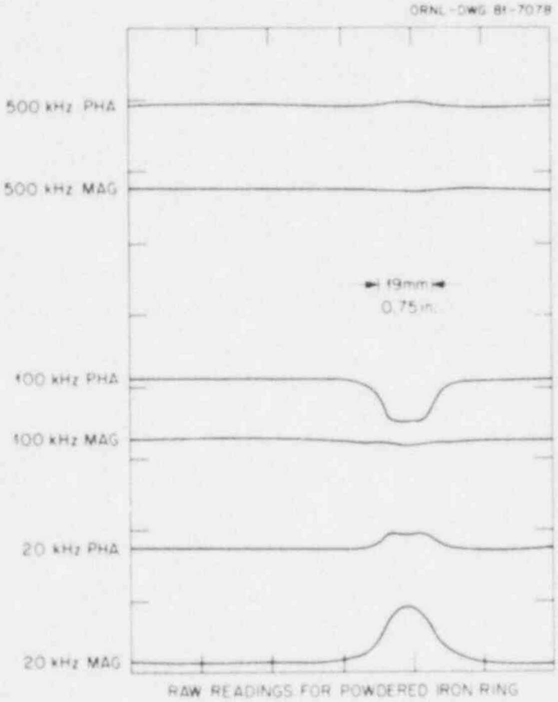

Fig. 10. Raw readings at three frequencies with a powdered iron ring around outside of tube.

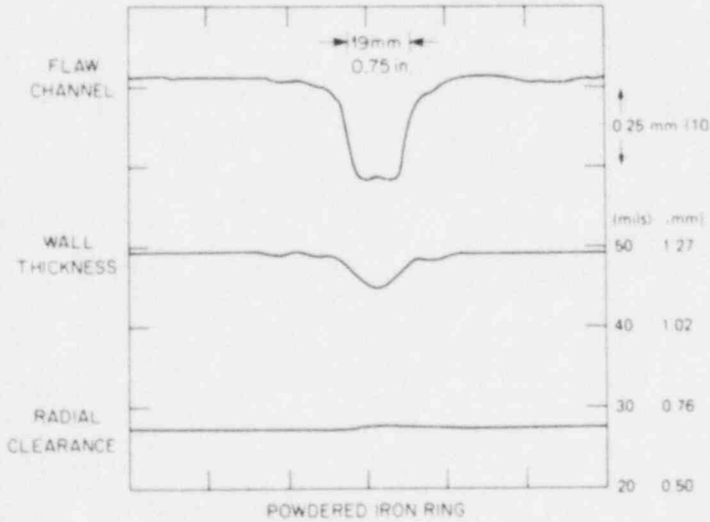

Fig. 11. Calculated properties for tube surrounded by a powdered iron ring 19 mm (0.75 in.) wide.

properties, respectively, measured on the sample. The radial clearance channel correctly shows no effect; the wall thickness channel shows a slight decrease, probably caused by overcompensation for a supposed tubesheet; and a large indication occurs on the flaw channel. The least squares fit must be run with the magnetite around the tube. This will allow us to eliminate this signal from the thickness and defect channel and to measure the buildup on a magnetite channel if desired.

Tests have also been made on dented tubing. Figure 12 shows the calculated properties for a flat-bottom dent 0.19 mm (7.5 mils) deep. The radial clearance channel clearly shows the correct amount of decrease,

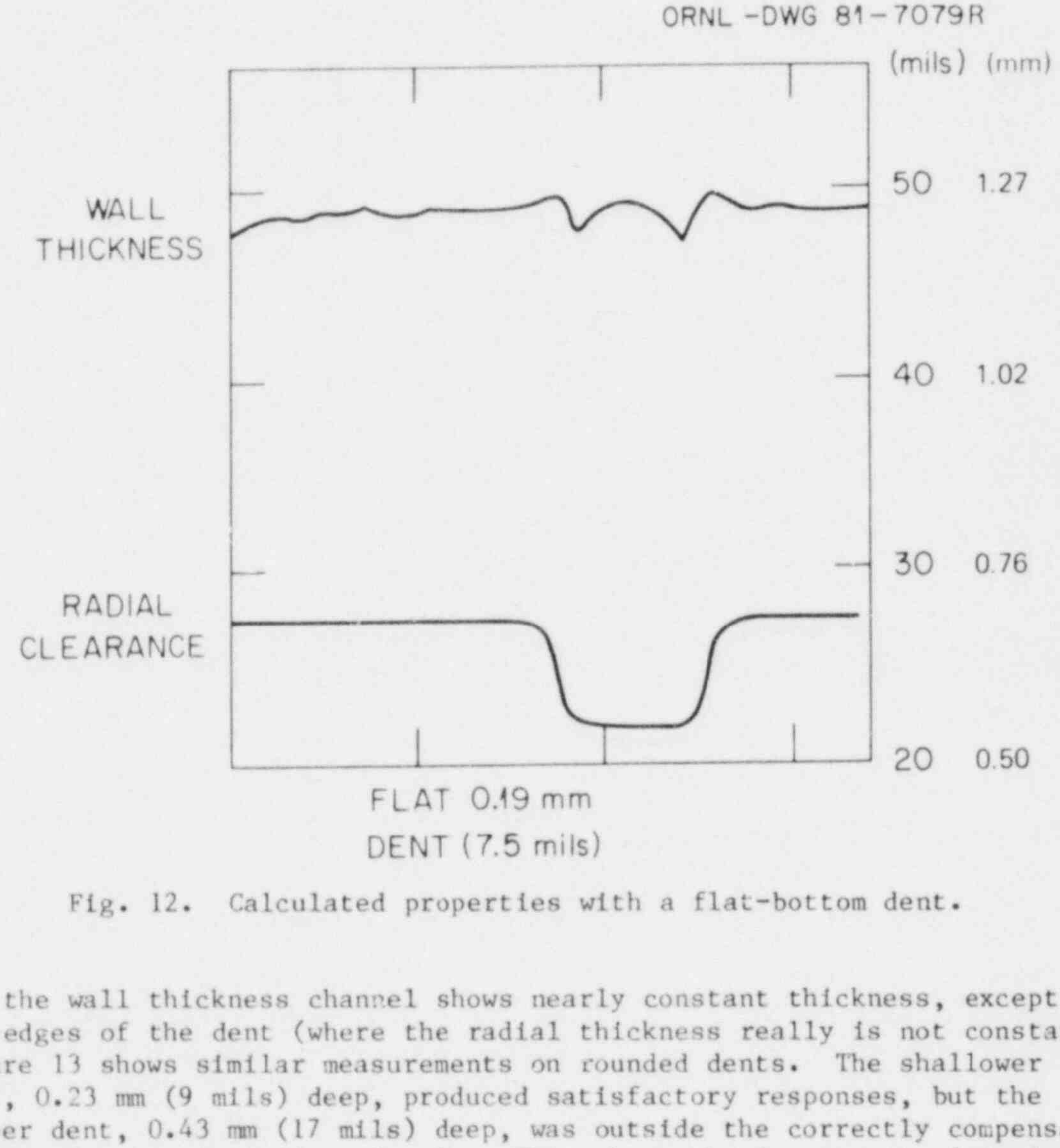

Fig. 12. Calculated properties with a flat-bottom dent.

and the wall thickness channel shows nearly constant thickness, except at the edges of the dent (where the radial thickness really is not constant). Figure 13 shows similar measurements on rounded dents. The shallower dent, 0.23 mm (9 mils) deep, produced satisfactory responses, but the deeper dent, 0.43 mm (17 mils) deep, was outside the correctly compensated range and gave misleading signals. This shows the importance of including the full range of expected property deviations when calibrating the instrument. Future studies will include the full range of dents, which should correct this problem.

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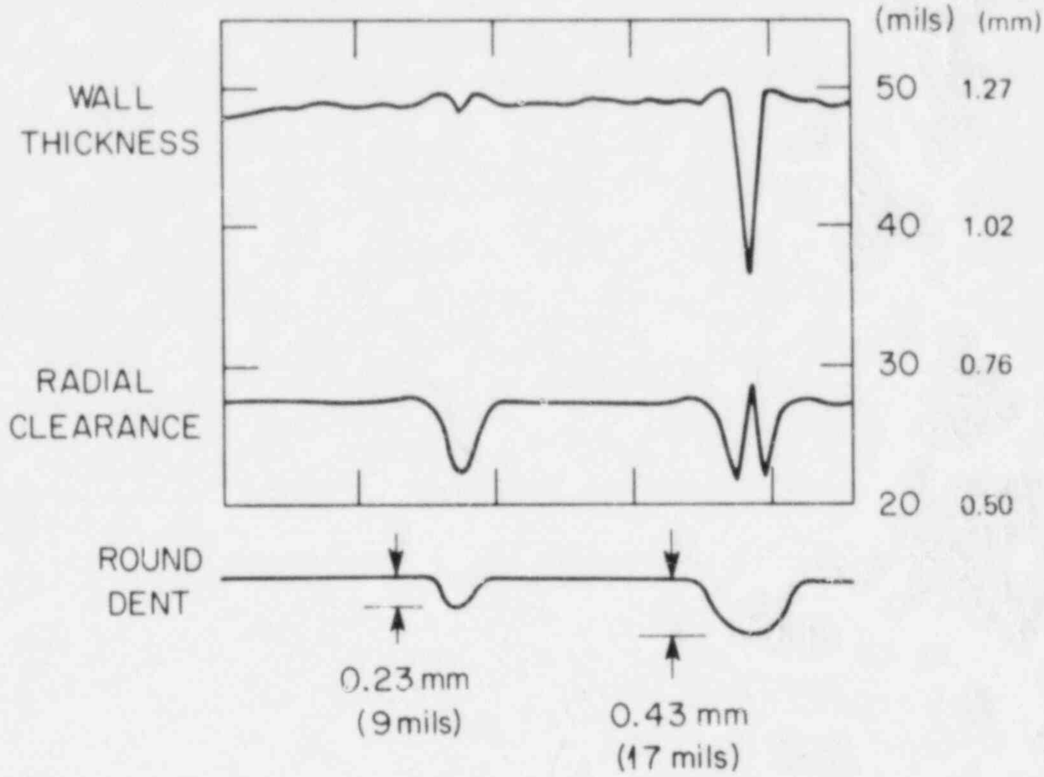

Fig. 13. Calculated properties with round dents.

DEVELOPMENT OF INSTRUMENTATION FOR FIELD TESTING

We have developed remote controls for the instrumentation. Only the eddy-current instrument and the probe pusher-puller need to be placed inside the containment, with the controls and the recording equipment inside a van about 120 m (400 ft) from the instrument, as shown in Fig. 14. The remote operation will allow us to use trained operators at our remote data station for the entire inspection without fear of their becoming "burned out."

We have made, wired, and tested a new printed circuit board for the transceiver unit, which is shown in Fig. 15 and used in the mobile laboratory. The transceiver unit connects the eddy-current instrument inside the containment building with the tape and strip-chart recorders, the computer terminal, and the remote control box for the probe positioner, which are all located inside the mobile lab.

The new printed circuit board will replace the hand-wired board now used in the mobile lab. The circuit board contains digital-to-analog converters and twisted-pair drivers and receivers for digital data and control transmission. The twisted-pair drivers and receivers permit the reliable transmission of digital data over the 120-m-long (400-ft) wires between the mobile lab and the eddy-current instrument inside the containment. The twisted-pair drivers, receivers, and digital-to-analog converters have been thoroughly checked and work satisfactorily.

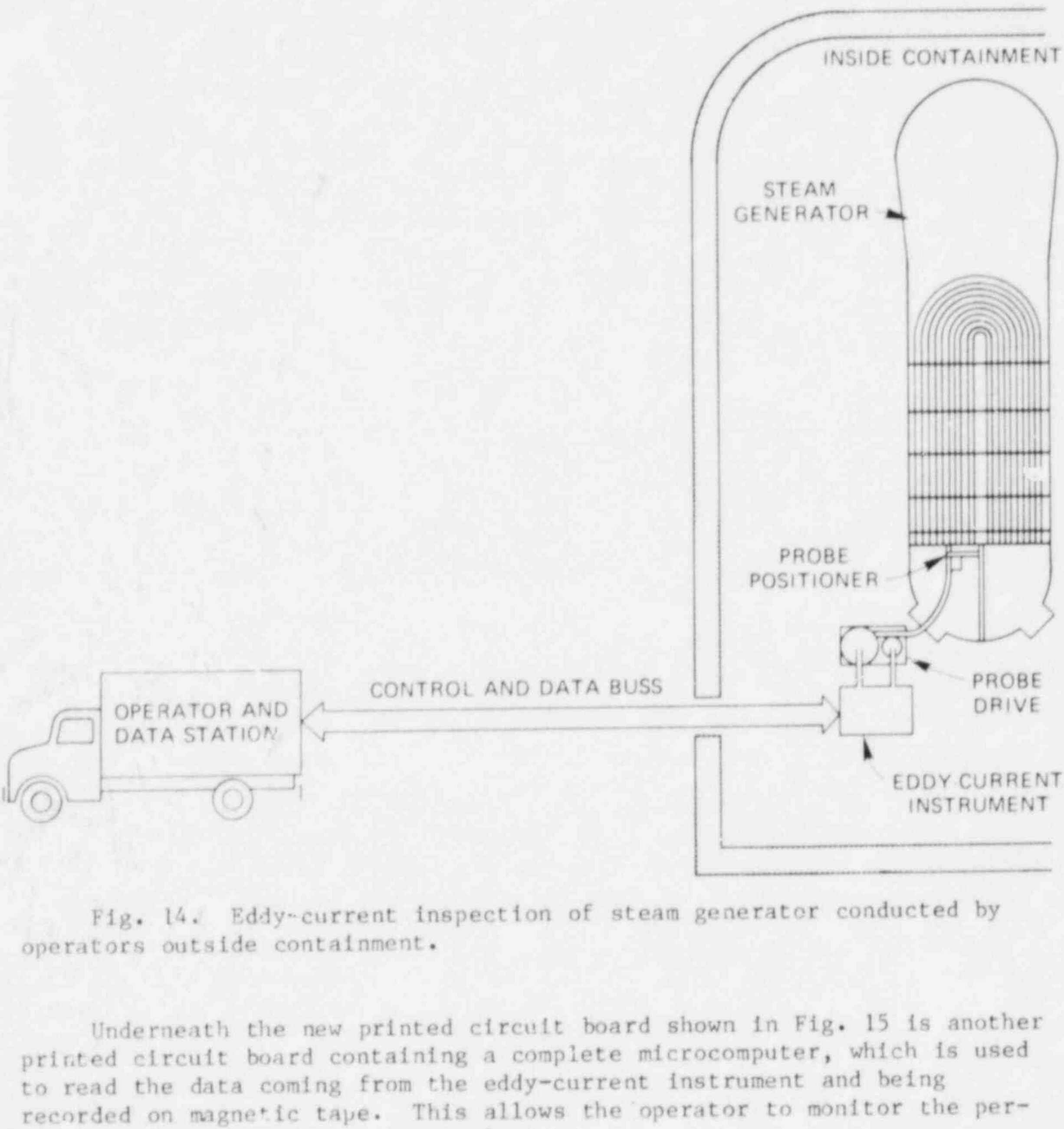

Fig. 14. Eddy-current inspection of steam generator conducted by operators outside containment.

Underneath the new printed circuit board shown in Fig. 15 is another printed circuit board containing a complete microcomputer, which is used to read the data coming from the eddy-current instrument and being recorded on magnetic tape. This allows the operator to monitor the performance of the system continuously.

A switch on the front of the transceiver unit allows th[illegible]rator to switch between the internal ("local") microcomputer and the [illegible]ne in the eddy-current instrument. Push buttons allow the operator t[illegible]nterrupt the microcomputer and reset the instrument.

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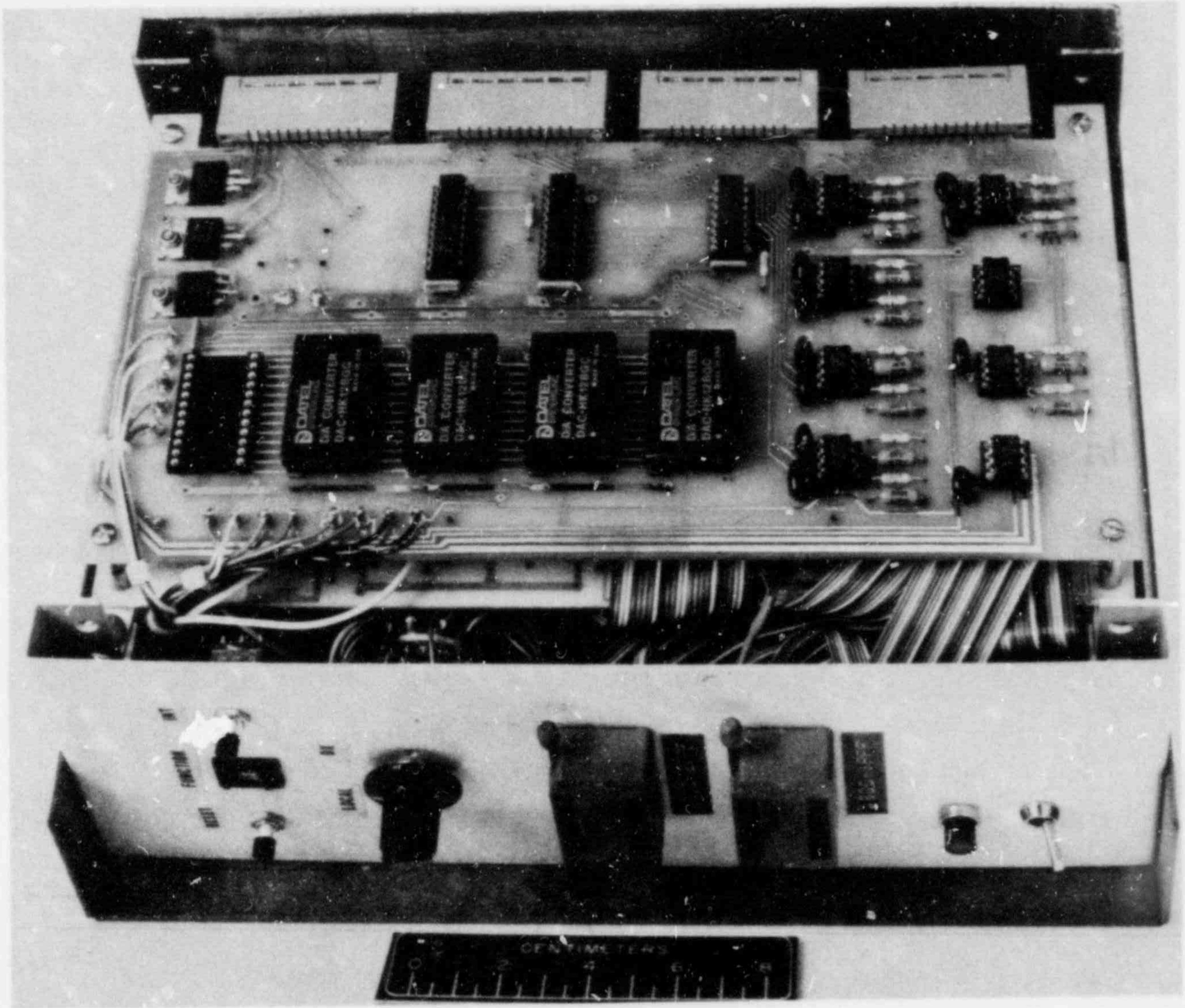

Fig. 15. Transceiver unit for mobile laboratory.

PRESENT STATUS OF DEVELOPMENT

Eddy-current field inspections have been made on the steam generators at Point Beach and Robert E. Ginna reactors for intergranular attacks in the crevices, which was a first field test for our equipment. Some preliminary results are shown in Fig. 16. We arranged with personnel at both plants to intermesh our inspection with their inspections. Although additional improvements can be made in the calibration, data acquisition, and data reduction, the reactor schedule was paramount. Our inspection at Ginna was on the critical path and added about 6 h to the down time. The Point Beach inspection was outside the critical path and required no additional down time.

Excellent data were obtained at both sites. Approximately 100 tubes were scanned up to the first support at both plants. The system was operated at Ginna at frequencies of 10 and 100 kHz and 1 MHz. An offset of all the data [the wall thickness gave a value of 1.60 mm (63 mils) rather than 1.27 mm (50 mils)] was observed at Ginna. This offset was caused by temperature and cable differences between our laboratory and Ginna. Otherwise, the data were good, and a vector correction of the raw magnitudes and phases made with the minicomputer restored the readings to their correct values. This correction technique was programmed into the minicomputer for the Point Beach tests. The frequencies were changed to 20, 100, and 500 kHz to reduce the potential for offset errors. These two changes eliminated the offset problem. The results from both Ginna and Point Beach showed slight wall thinning in some of the tubesheet regions, which could be attributed to intergranular attack, but the wall thinning was less than that observed in samples removed earlier from the steam generator.

The wall thickness of the Point Beach tubes appeared to be several mils thicker above the tubesheet. After a study of the effects of simulated sludge of different nonconducting ferromagnetic materials, we speculated that the difference might result from a small layer of a good conductor such as copper that had plated out on the tubes. The presence of only a thin layer of the high-conductivity metal would appear like thicker Inconel. After we had reported our findings, Westinghouse acknowledged that they had also seen these "copper signals" in their inspections and indicated that the signals were present in several different generators, with Point Beach being one of the worst. Readings were excellent when made on standards immediately after the probe was removed from the steam generator at Point Beach. The tube scans at Ginna were much cleaner and showed little if any thickness change as the tube entered the tubesheet.

Figure 17 shows the raw readings of magnitudes and phases at the three test frequencies and the corresponding calculated properties measured near the tubesheet region of the steam generator at Point Beach, and Fig. 18 shows the corresponding quantities from the Ginna steam generator. The wall thickness readings are greater above the tubesheet on the Point Beach tubing, indicating a buildup of some conducting material. The Ginna wall thickness is much more uniform.

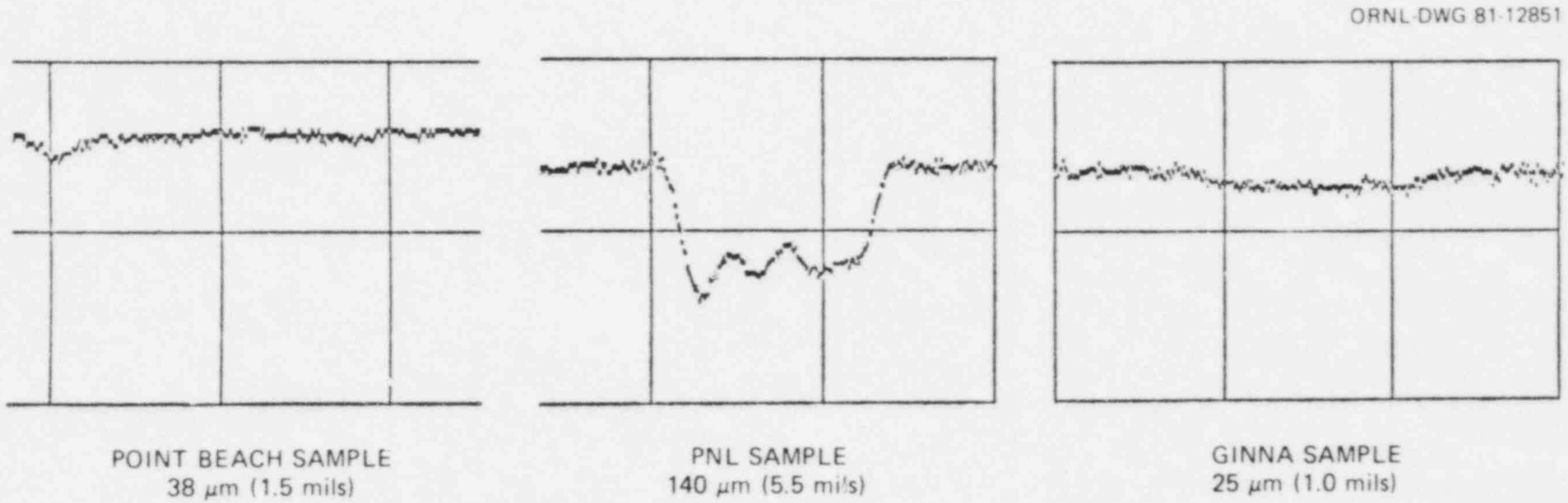

Fig. 16. Preliminary results of intergranular attack measurements.

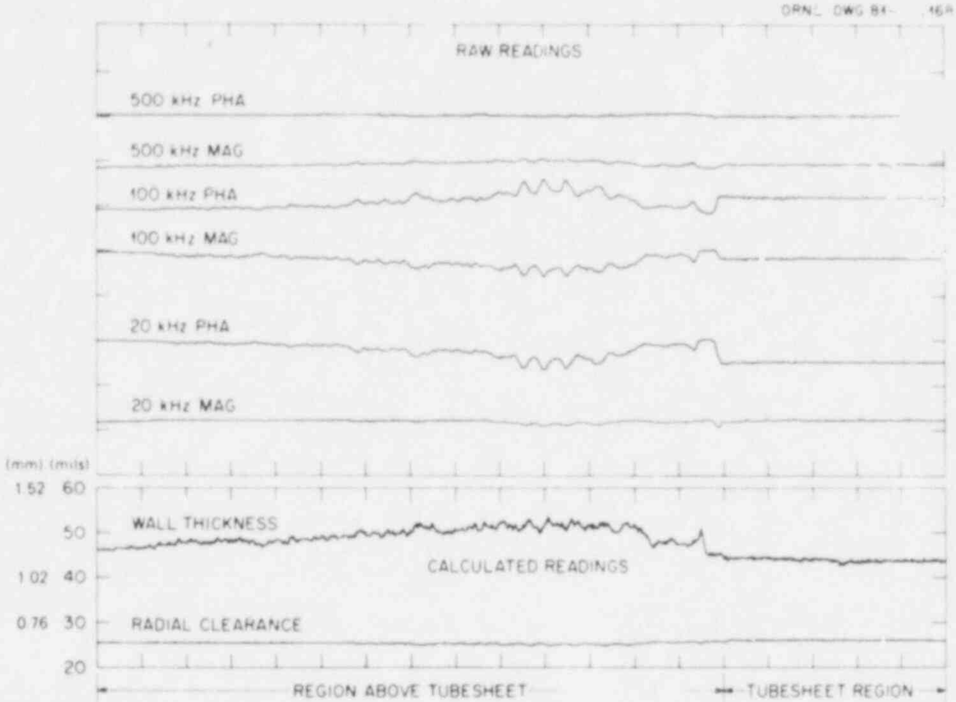

Fig. 17. Raw readings and calculated properties near tubesheet of Point Beach steam generator.

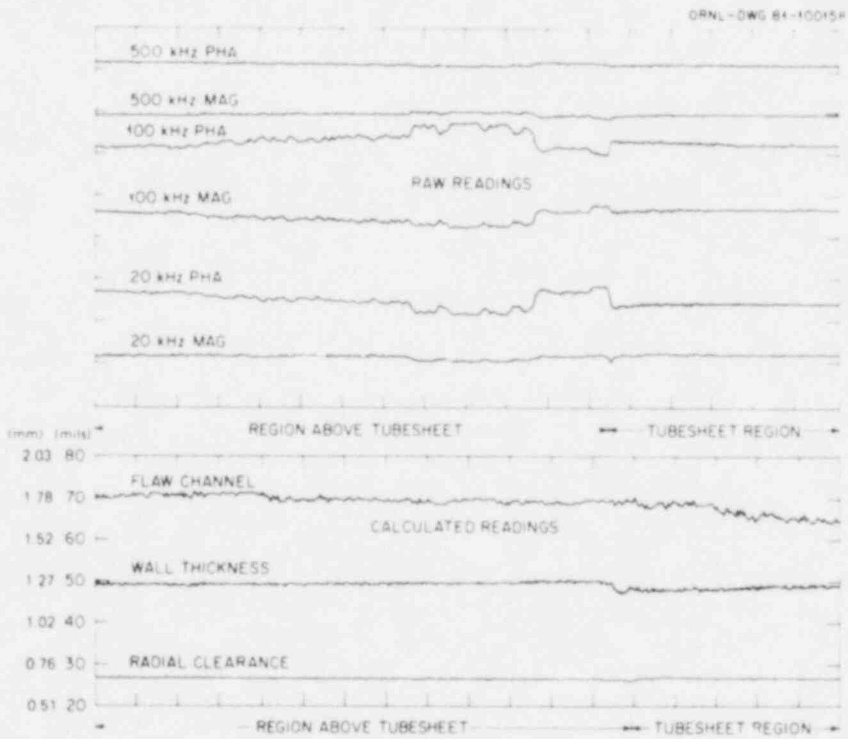

Fig. 18. Raw readings and calculated properties near tubesheet of Robert E. Ginna steam generator.

The mobile eddy-current laboratory was also taken to Lynchburg, Virginia, where it was used to inspect samples of tubing pulled from the steam generator of the Robert E. Ginna reactor. The samples were known to have intergranular attack and had to be examined in a hot cell. Eddy-current measurements were made with an absolute boreside probe, a reflection probe from the outside, and a through-transmission probe. The probe was contaminated during the inspection, and a replacement probe has been ordered.

In summary, this type of multiple frequency inspection could show buildup of sludge, deposition of products on the tube walls, magnetite formation, and other detrimental conditions so that corrective action can be taken before they start producing wastage, cracks, and other defects that are detrimental to the safety of the reactor. The system has demonstrated the ability to calculate the desired properties in real time and to allow the analysis or reanalysis of additional properties back in the laboratory. Various causes for the apparent wall thickness changes above the tubesheet will be investigated.

Personnel from Westinghouse and Zetec, as well as the reactor operation personnel, were impressed with the system and expressed the desire to incorporate parts of it into their equipment. We will release these designs as they are completed.

The instrument readings were recorded on magnetic tape and then metallography was performed on the tubes. As soon as the results are made available, we will determine the coefficients to calculate the intergranular attack from the instrument readings. We will then attempt to reprocess the field recordings from Point Beach and Ginna to see if the actual intergranular attack at various points in the steam generators can be determined.

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