CONF-810615--3

TECHNIQUES FOR IN-SERVICE INSPECTION OF HEAT-TRANSFER TUBES IN STEAM GENERATORS

R. W. McClung (Oak Ridge National Laboratory*)

R. A. Day (General Electric Company)

H. H. Neely (Energy Technology Engineering Center)

T. Powers (Babcock and Wilcox Company)

ABSTRACT

A multifaceted development program is in progress in the United States to study techniques for in-service inspection (ISI) of heat transfer tubes in breeder reactor steam generators. Several steam generator designs are involved. Although there are some similarities in the approaches, many of the details of techniques and capabilities are specific to the steam generator design. This paper describes the ultrasonic, eddy-current and penetrating radiation techniques being studied for the various steam generators, including the Large Leak Test Rig, the Clinch River Breeder Reactor design, and alternate steam generators being developed by Westinghouse and Babcock and Wilcox.

---

*Operated by the U.S. Department of Energy under Contract W-7405-eng-26 with the Union Carbide Corporation.

For presentation at Second U.S./Japan LMFBR Steam Generator Seminar, June 1981.

DISCLAIMER

DISCLAIMER

1.0 INTRODUCTION

The in-service inspection (ISI) of heat transfer tubes in LMFBR steam generators is necessary to assure the continuing integrity of the tubes and to minimize the possibility of an undesirable contact and reaction between the two working fluids — sodium and water. The scope of the ISI includes periodic assessment not only of the possible wall thickness reductions due to such mechanisms as corrosion or mechanical fretting but also the presence and growth of discrete flaws (e.g., pits or cracks) that could compromise the tubing integrity and thus permit a leak. In the event of a leak, the ISI technology would be necessary to determine the amount of damage or degradation of the tubes affected by the leak.

There are several programs in progress for the development of ISI techniques and equipment for steam generator tubing. These are closely allied with design, fabrication, or operational studies of different steam generators. In most cases the details of the techniques and their capabilities are unique to the specific design of the steam generator and the tubing dimensions. However the methods and general approaches share many similarities. The several steam generators on which ISI will be discussed in this paper include the large leak test rig [(LLTR) containing a model of the straight section of the steam generator of the Clinch River Breeder Reactor (CBBR)] at the Energy Technology Engineering Center (ETEC), the CRBR steam generator, the helical tube steam generator of Babcock and Wilcox (B&W), and the double-wall tube design of Westinghouse-Tampa Division (W-TD). The tubing in each case is 2 1/4 Cr-1 Mo alloy steel. On some of the steam generators the development and application of ISI are essentially complete and therefore the capabilities are reasonably well established. On others the development is still in progress, and this paper can report only on the approaches being taken and the capabilities demonstrated thus far on model tests or in the laboratory. On the LLTR, ultrasonic techniques were developed for measurement of wall thickness and inner diameter, and isotope scanning techniques were developed for measurement of tube and spacer deformation and the deposition of sodium-water reaction products. On the CRBR steam generator ultrasonic techniques were developed for measurement of wall thickness and detection of flaws in the tubing and tube-to-tubesheet weld joints. Eddy-current techniques are being developed for the evaluation of wall thickness, inner diameter, and flaws. On the B&W helical tube steam generator, ultrasonic techniques are being emphasized, coupled with a hydraulic transport system to propel the probes through the approximately 180-m (600-ft) length of the tubing. On the W-TD double-wall tubing, ultrasonic and eddy-current techniques are being studied for measurement of wall thickness, inner diameter, and flaws. The following sections of this paper will cover pertinent details of techniques, equipment, and capability for the above systems.

2.0 STEAM GENERATOR SYSTEMS

As noted in the introduction, development and application of ISI techniques have been made for several different designs of steam generators. Since details of the techniques are influenced by details of the design, the discussion will be organized according to the steam generator system.

2.1 Large Leak Test Rig

The large leak test rig (LLTR) was designed to provide information on the results of sodium-water reaction (SWR) testing of LMFBR-type steam generators in event of tube failure. The tests simulate various types of steam tube failure at predetermined locations at specified conditions. As noted earlier the present test article is a model of the straight section of the CRBR steam generator. The 2 1/4 Cr-1 Mo steel tubes are 15.9 mm (0.635 in.) outside diameter by 10.1 mm (0.4 in.) inside diameter.

Development of special ISI equipment and techniques was necessary to understand the consequences of the exothermic reaction produced by the injection of the high pressure water/steam into high temperature sodium. It was assumed that one of the consequences of SWR testing would be wastage of neighboring tubes; therefore a boreside ultrasonic inspection device was developed.

2.1.1 Ultrasonics for Wall Thickness Measurement

The ultrasonic technique utilized a boreside probe with a 15-MHz PZT crystal that projected a longitudinal ultrasonic wave perpendicularly into the wall of the tube. Measurement of the time interval between reflections from the inner and outer surfaces of the tube (the ultrasound having traversed the wall in a radial direction) allows determination of the wall thicknes. Information was also obtained on the tubing inner diameter from the inner surface reflection. (The transducer housing has two spring fingers that press the probe to the tube wall for accurate diametrical measurements.) The first-generation device provided a linear scan through the tube being examined. Typically, selected tubes were scanned in four azimuthal directions. If wastage greater than 0.1 mm (0.004 in.) was encountered, successive scans were made every 22.5°. The electronic signals relating to thickness and diameter are processed for strip-chart recording and logging by computer. The ultrasonic device measures tube wall and inside diameter to better than 0.1 mm (0.004 in.), with reference being made to the axial location and radial directions. In performances on SWR tests, tubing wastage up to 0.35 mm (0.14 in.) has been measured; increased inner diameter measurements as much as 0.1 mm (0.004 in.) have been observed.

A second-generation probe with a rotating beam[1] is in the final stages of checkout. This permits a helical scan of the tube with axial motion on the probe [e.g., 25 mm/s (1 in./s)]. The new device again uses a 15-MHz PZT crystal but the ultrasound beam is transmitted axially before impinging on a 45° mirror that diverts the sound radially to the tube wall. The 45° mirror is housed in a turbine wheel that rotates with the flow of water used as a couplant. Fig. 1 is a photograph of the probe head with the focusing mirror. Window struts on the turbine cage cause signals that allow determination of the azimuthal direction in the steam tube. The rotation speed is variable from 20 to 40 Hz. The axial position is determined by time-of-flight measurements between separate transducers on the probe and at the tubesheet. Axial accuracy is approximately 3 cm (1.2 in.).

2.1.2 Isotopic Scanning Technique for Measurement of Tube Deformation and Reaction Product

Sodium-water reaction (SWR) testing in the LLTR resulted in steam tube deformation and SWR product deposition. Equipment and techniques using radioactive isotopes were developed to detect and measure these phenomena.[2] The isotope scanning test (IST) traverses an isotopic gamma source and a Geiger-Muller (GM) tube simultaneously through adjacent steam tubes and the count rate versus axial distance is recorded (see Fig. 2). Cobalt-60 was selected as the isotope for measuring deformation because of its long half-life (5.4 years) and high energy gamma (1.17 and 1.34 MeV). Calculations have shown that the gamma intensity (which varies inversely with the square of the distance) for adjacent tubes with a 1-cm bend (0.4 in.) increases by 100% for an inward bend and decreases by 45% for an outward bend. Additional important parameters after an SWR event are the location of spacer plates and possible bowing of those plates. Computer control of the drive motor for the source and detector allow adjustment of the speed to achieve slower scans and higher sensitivity in areas where damage may be expected. Scan speeds during tests have been 2.5 mm/s (0.1 in.). Fig. 3 is a composite of IST scans on several tubes after an SWR event showing the spacer plates and tube deformation. This is shown for qualitative information only and detailed discussion of data will not be made. If measurements are made in third-row tubes (with additional tubes between the source and detector), then added attenuation of intervening tubes must be taken into consideration. A computer-assisted tomography program is being generated to analyze the complicated deformation tube array that results from a small leak allowed to propagate to sequential failures. The deformation and spacer location/deformation can be measured to 1 mm (0.04 in.).

A parallel activity was pursued for the measurement of SWR product deposition in the area on top of the spacers. Cobalt-57 (with an energy of 0.1 MeV and a half-life of 271 days) was selected for study. The lower energy (than Cobalt-60) provides greater attenuation for measurement of reaction product and better definition of the edge of the spacer plate. Calculations indicate a 5-mm (0.2-in.) deposition will be detectable.

2.2 Clinch River Breeder Reactor Steam Generator

The tubing for the CRBR steam generator is approximately 21 m (70 ft) long, 15.7 mm (0.625 in.) outer diameter, and has a 2.7 mm (0.109 in.) wall thickness. The steam generator is designed to have a 90° bend near the upper end, leading to the name, "hockey stick" design. The tubes are butt welded to machined projections on the sodium side of the tubesheet; thus the butt weld becomes an integral part of the tubing. Development and application studies for ISI include ultrasonic wall thickness measurements that have been applied on several smaller models, ultrasonic techniques for examination of the tube-to-tubesheet welds, and eddy-current techniques for ISI of the tubing.

2.2.1 Ultrasonic Measurements of Wall Thickness

The principal activities for ultrasonic measurement of wall thickness for the CRBR steam generator have been conducted on smaller models containing tubes that are prototypic of the CRBR steam generator. The models are intended to provide additional information on the corrosion and wear-induced changes in the steam tubes. The departure-from-nucleate-boiling (DNB) test used a single tube; the Few-Tube Test Model (FTTM) was an evaporator and superheater containing 10 tubes in a sodium loop.

2.2.1.1 Departure-from-Nucleate-Boiling (DNB) Test

The DNB single tube model was run for 2820 h under expected "worst case" thermal and water chemistry conditions. The ultrasonic techniques[3] for measuring wall thickness required a precision of 8 μm (0.0003 in.) to allow detection of significant changes.

Special ultrasonic probes were obtained from a commercial source to fit the 10-mm (0.4-in.) inner diameter of the tube and measure the 2.7-mm (0.110-in.) wall thickness. Both spring-loaded fingers and external rings were used on different probes to maintain alignment with no significant difference in performance. 15-MHz, highly damped transducers were used to send the longitudinal ultrasonic pulses into the tube wall. A special mechanical fixture for the manual adjustments of the probe and handle assured the rotational and axial positioning with an accuracy of 15° and 3.18 mm (0.125 in.). A reference standard was machined to represent the maximum and minimum anticipated wall thicknesses. A commercial ultrasonic instrument with digital display was used. Statistical analysis of data and investigation of potential sources of error (e.g., changes in ultrasonic velocity and tubing shrinkage) indicated an accuracy of 10 μm (0.0004 in.). No significant changes in wall thickness or evidence of corrosion were found. Some difficulties were encountered due to entrapped sodium at tube spacer plates.

2.2.1.2 Few Tube Test Model (FTTM) Examination

The FTTM contained 10 tubes and was concerned with tube damage induced by vibration and wear at spacer plates and vibration suppressors. The same probes used for the DNB test were used on the FTTM.[4] An automated, motor-driven "pusher-puller" was used to drive the probe linearly through the tubes. Because the bend of the "hockey stick" design of the tubes misaligned the DNB probes, measurements were made only in the straight sections with a repeatability of about 25–30 μm (approximately 0.001 in.). Figure 4 shows a comparison of two wall thickness scans of the same tube. Again problems were noted with entrapped sodium at tube spacer plates. A flaw detection probe with a 10-MHz element inclined to produce a shear wave in the tubing demonstrated a capability to detect circumferential flaws with a depth equivalent to 3% of the tube wall thickness.

2.2.2 Ultrasonic Flaw Detection in Tube-to-Tubesheet Welds

Pulse-echo shear wave ultrasonic techniques and equipment[5] have been developed for the detection of flaws parallel to the circumferential butt weld. A key element is the modular probe that has been designed and fabricated to allow interchange and adjustment of miniature transducers and reflectors. Figure 5 is an isometric drawing of the probe. The pulses of sound are emitted in the axial direction to impinge on a reflector that diverts the sound back into the tube wall or weld as an angle beam shear wave. Intercepted flaws will reflect the sound along the reverse path to the initial transducer for a near-conventional pulse-echo examination. This works well for outer surface flaws. However, because of the small radius of curvature of the tubing and the resultant focusing and defocusing of the sound beam as it encounters the tube surfaces, it was necessary to add a second channel for flaws near the inner surface to attain desired sensitivity. This was accomplished by adding a second reflector and transducer to the modular probes. The detected signals are processed by separate electronic receiver and data display. A motor-driven scanning device (see Fig. 6) was developed to provide simultaneous rotary and axial motions to the probe and thus perform a helical scan of the weld area. Positional signals are obtained to allow data display of detected flaws on a C-scan map. The sensitivity as determined by machined notches and specially prepared cracks is for flaws approximately 7% of the wall in prototypic welds. The same techniques in tubing were demonstrated to be capable of detecting flaws 3% of the wall. A more recent addition of computer control for scanning and data processing has improved the apparent sensitivity to about 5% in the welds.

2.2.3 Eddy-Current Development

Since the 2 1/4 Cr-1 Mo steel tubing is ferromagnetic and has a large wall thickness-to-diameter ratio, it poses difficult problems for the eddy-current development. Commercial eddy-current examination of ferrous tubing with external encircling coils uses large magnetizing coils to reduce the effective permeability and permits the eddy currents to penetrate the wall of the tubing. The design of the boreside ISI probe for CRBR incorporates dc magnetization (as shown in Fig. 7) in addition to the eddy-current coil(s). Because of the many variables (e.g., tube wall thickness, tube diameter, flaws, permeability, tube supports, et al.) in the examination, conventional single-frequency sinusoidal techniques were determined to be inadequate because of signal ambiguity. A three-frequency multiparameter eddy-current instrument was designed and developed for use on this problem. Figure 8 is a block diagram showing the separation of the received signal into separate components of magnitude and phase of the three inspection frequencies. Development of complex equations allows the determination of desired tubing properties from various nonlinear combinations of the detected magnitude and phases. The equations are programmed for solution on a laboratory minicomputer (during laboratory studies for standardization or for processing of raw data on magnetic tape obtained during an ISI) or ultimately on a microcomputer which is an integral part of the eddy-current instrumentation. The eddy-current development for the CRBR steam generator is very closely coupled and shared with that for the double-wall tube (DWT) design discussed in Section 2.4. Although the development of eddy-current ISI began on the CRBR steam generator prior to the DWT design (leading to the development of the basic three-frequency instrument and many of the computer codes for technique design), the schedules for the Few-Tube Model of the double-wall design required emphasizing application studies on the latter. This, in turn, provides a significant feedback benefit to CRBR. Detailed sensitivities for wall thickness measurement and flaw detection have not yet been established.

2.3 Babcock and Wilcox Design with Helical Tubing

The Babcock and Wilcox design for a breeder reactor steam generator used thick-walled [4.6-mm (0.180-in.) with a 32-mm-diam

(1.25-in.)] helical tubing arranged in concentric cylinders with 23-cm (9-in.) radius bends on each end to mate into the tubesheets. The diameter of the cylinder formed by the helically-coiled cylinders ranges from 1 to 3.6 m (40 to 140 in.). With the helical tubing length greater than 135 m (450 ft) and 23 cm (9-in.) radius bends at the ends, it was determined to be unfeasible to mechanically rotate a probe. Anticipated difficulties with eddy currents for the thick-wall ferromagnetic steel led to development of an ultrasonic system with nonrotating transducers. The project plan (concurrent with the design and fabrication of the prototype steam generator) consists of three major efforts:

1. ultrasonic test concept and transducer designs,
2. electronics to excite transducers and receive ultrasonic signals over 180 m (600 ft) of cable, and
3. a transport system to insert and remove the long cable in each tube.

Although the program is not yet completed, sufficient detail is available to discuss the technical approach and both current and anticipated capabilities.

2.3.1 Ultrasonic Technique and Transducers

The basic test requirements were to measure wall thinning to within $\pm$0.2 mm (0.005 in.), and detect axially or circumferentially oriented flaws greater than 15% of through-wall dimension (recognizing 30% flaws as rejectable). The entire tube wall volume must be examined for flaws and the inspection time for each tube must be 30 min or less. Theoretical and empirical methods were used to design the technique and hardware around a multiple-transducer nonrotating probe head (with each transducer element covering an arc of the circumference). Three independent tests are performed simultaneously for thickness (with longitudinal waves) and circumferential and axial flaws (with shear waves). A unique feature is the curved (convex) shape of the transducer elements to defocus the ultrasonic beam and extend the volumetric coverage of the beam of each element. The design and development activities for the probes and techniques are addressing the influence of (1) the shape, material, and position of the transducer elements, (2) the transducer coverage, flaw sensitivity, and dependence on wobble and alignment, (3) external factors such as tube clamps, 90° 23-cm (9-in.) radius bends, weld areas, and (4) effect of cross talk on multielement probes. Lead metaniobate ($PbNb_2O_6$) was selected as the transducer material because of broad-band characteristics, and good temperature and aging stability. Frequencies of 7.5 and 3.5 MHz were selected for wall thinning and flaw detection respectively. Laboratory studies indicated that wall thickness measurements of $\pm$0.2 mm (0.005 in.) and flaw detection sensitivity of 10% could be achieved with adequate coverage of the tube wall.

2.3.2 Electronic Development

The concept of multiple transducer elements introduced electronic requirements different from more conventional nondestructive examinations. A multiplexing approach was selected with miniaturized electronics with power supply, high voltage pulsing circuit, synchronization signals, and a switching network based on special diodes. These "down-hole" electronics that travel with the transducers must be packaged in modules approximately 12.5 mm (0.5 in.) in diameter by 32 mm (1.25 in.) long. The multiplexing must not allow electrical or acoustical crosstalk between transducers, and must be rapid enough to accomplish the inspection within 30 min per tube (determined to require a pulsing rate of 3 kHz). A single coaxial cable is an integral part of the transport system for propelling the electronics and transducers through the tubing and transmits all signals between the up-hole and the down-hole electronics.

2.3.3 Probe Line and Transport System

Because of high drag forces on a cable pushed or pulled through coiled tubing, it was necessary to use a patented B&W Limited process with beads (acting as pistons) placed at regular intervals along the cable to provide a uniformly distributed driving force as fluid is flowed through the tubing. Tests on a helical tube mockup at B&W demonstrated that the probe line could be driven through more than 130 m (444 ft) of tubing using a pinch belt drive at the cable storage vessel and a water pressure of 0.35 MPa (50 psi) with a flow rate of 126 cm^3/s (2 gal/min). When the probe passes through the top 23-cm (9-in.) radius section, the pressure exceeded 0.7 MPa (100 psi). With different pressures and flows, the probe velocity varied from 0.1 to 0.4 m/s (20—80 ft min).

2.3.4 Status

The results of the feasibility tasks provide confidence that the major hurdles have been overcome. Transducer configurations have been built and tested to verify coverage and performance. Electronics for down-hole multiplexing and operation through the required length of tubing have been demonstrated and can be miniaturized. A probe drive system has been demonstrated.

2.4 Double-Wall Tube Design of Westinghouse-Tampa Division

The steam generator design of the Westinghouse-Tampa Division (W-TD) features double-wall tubing with a third fluid (helium) between the inner and outer tube to serve as an indicator of potential leaks in either the inner or outer tube. The inner surface of the outer tube also has four longitudinal grooves that run the length of the tube to facilitate the flow of helium for detection. The nominal dimensions of the outer tube are 20.6-mm (0.825-in.) outer diameter and 2-mm (0.076-in.) wall thickness. The inner tube that fits snugly in the outer tube has nominal dimensions of 16.6-mm (0.67-in.) outer diameter and 2.8-mm (0.112-in.) wall thickness. Thus the aggregate nominal dimensions of the integral double wall tube are 20.6-mm (0.825-in.) outer diameter and 4.8-mm (0.188-in.) wall thickness. Both eddy-current and ultrasonic techniques are being studied and developed for the ISI of the double-wall tube (DWT). The primary examination technique for the volumetric examination of the entire tube is eddy currents. Ultrasonics are being pursued both as a backup to eddy currents because of uncertainties about the ultimate sensitivity for flaws on the exterior surface of the tubing and also to provide a higher resolution technique for evaluation of areas determined to be suspect by eddy currents. For example, the boreside circumferential coil for eddy currents cannot identify the circumferential position of a detected anomaly; the ultrasonic probe can.

As a part of the design and fabrication program of W-TD for the DWT steam generator, a few-tube model (FTM) has been fabricated and is being tested prior to fabrication of a prototype steam generator. As part of the ISI development program, the eddy-current and ultrasonic techniques are being applied to the pretest, interim, and post-test examinations of the FTM to provide evaluation data and to check the inspection techniques during their development. Inspection requirements for tubing for the FTM include the capability to detect a loss of 25% of the total DWT thickness with the loss being on either the inner or outer surface, to detect a 1.5-mm-diam (0.62-in.) hole through either the inner or outer tube, and to detect a notch (crack-like flaw) with a depth 25% of the DWT thickness on either surface of either tube. The projected requirements for the prototype steam generator are more stringent.

2.4.1 Ultrasonic Development

Ultrasonic techniques are being developed both for measurements of wall thickness and for detection of discrete flaws. Although the techniques are similar to some noted earlier (particularly for wall thickness), the presence of the mechanically-bonded interface between the two tubes of the DWT present problems and uncertainties related to the capability of ultrasound transmission through the interface.

Work thus far on the wall thickness has used probes with 7.5- and 5-MHz commercial transducers projecting the ultrasound beam axially to impinge on a fixed 45° reflector that diverts the ultrasound into the tube wall in a radial direction. In the preliminary scanning of the FTM, manual movement of the probe has been used primarily although one test has been performed with the probe cable attached to the mechanical scanning system used for flaw detection (discussed below). In work done to date, both in the laboratory and on the FTM, the accuracy and precision of measurements seems to be approximately 0.05 mm (0.002 in.). However it should be noted that the quality of interface permits the transmission of ultrasound only over about one-half of the area; providing double-wall thicknesses with adequate transmission and single-wall thickness (of the inner tube) when the ultrasound does not pass through the interface. With the small radius of curvature of the inner diameter, care must be exercised to limit the size of the ultrasound beam lest complex mode conversions occur and spurious thickness values be obtained.

The probe designs for flaw detection are based on those developed for the examination of the tube-to-tubesheet welds for the CRBR. As noted earlier, the interface adds new complications. When poor transmission quality is present there is decreased (or no) capability to detect flaws in the outer tube. Further, when this occurs, higher intensity ultrasound is retained in the inner tube and sensitivity to flaws increases in the inner tube. The converse is true with better transmission through the interface. Special probe designs have been investigated and developed to evaluate the relative interface condition and allow a recognition of the relative inspectability of the outer tube, and a correction capability for flaw sensitivity. Thus far in the ongoing development program, sensitivity has been demonstrated to both circumferential and longitudinal flaws with a depth of 10% of the wall thickness (or smaller) in both tubes when adequate interface transmission is present. As may be expected, with poor (or no) transmission, even flaws with depths up to 95% of the outer wall thickness are undetectable. An added complication, especially for longitudinal flaws in the outer tube, is the presence of the four longitudinal grooves. These not only mask a portion of the outer tube, preventing transmission, but also generate large reflections. Further study and development are needed to determine the possibility of detecting outer tube flaws despite the presence of the grooves.

Examinations in the FTM have emphasized a few discrete areas — the departure from nucleate boiling (DNB) zones and areas selected by the eddy-current scanning. Since 100% volumetric examination was not intended, an adaptation of the scanner developed for the CRBR tube-to-tubesheet joints has been adequate for helical scanning of short sections [e.g., 40 mm (10 in.)] of the tubing.

2.4.2 Eddy-Current Development

The eddy-current technology[6] is essentially the same as that described earlier for the CRBR steam generator tubing. However, the double-wall tubing has a significantly thicker wall with no significant increase in bore diameter. This restricts the magnetic saturation of the wall and increases the difficulty of examining the outer surface. In addition to the axial saturation probe design used for CRBR, a radial saturation probe was developed and tested to improve the penetration depth of the eddy currents. Although the solution to this difficult problem is still in development, laboratory studies of the two types of probes show the apparent capability for detecting the 25% wall thinning with a precision of about 0.1 mm (0.004 in.) with the radial probe providing the better results.

Because of the need to perform field evaluation of the FTM before such examinations on the CRBR steam generator, some of the engineering development for implementation of the ISI has been done for the FTM. This includes establishment of a mobile inspection laboratory (see Fig. 9) and portable systems for data logging and display including digital magnetic tape recording for raw data at the three frequencies, and analog strip-chart recording of either raw data or (after further laboratory standardization) processed data displaying tube properties of interest (e.g., wall thickness, flaws, inner diameter, et al.).

3.0 CONCLUSION

Several nondestructive testing techniques are being developed for application to the in-service inspection of heat transfer tubes for steam generators. Although there are similarities in some of the approaches, the variations in design may alter the selection of the optimum technique and ultimate capabilities. Ultrasonic techniques have shown applicability for wall thickness measurements and potential for flaw detection; multifrequency eddy-current techniques are showing strong potential for rapid measurements of wall thickness and flaw detection. Penetrating radiation techniques have been demonstrated for evaluation of tubing deformation after a sodium water reaction. The programs provide assurance that useful ISI can be performed to meet requirements in steam generators.

4.0 ACKNOWLEDGMENT

The authors acknowledge the valuable contributions of many co-workers at their respective organizations for the developments noted in this paper. In addition recognition is given to K. J. Reimann and his colleagues at Argonne National Laboratory for their work on the ultrasonic wall thickness measurements on the Westinghouse double-wall tube steam generator.

5.0 REFERENCES

1. H. H. Neely and H. L. Renger, "Boreside Rotating Ultrasonic Tester for Wastage Determination of LMFBR-type Steam Generator Tubes," *ASNT Paper Summaries, National Fall Conference, Oct. 15–18, 1979,* St. Louis, Missouri.

2. H. H. Neely, "Nondestructive Examination of LMFBR Steam Generator Inspection — Present Problems and Solutions," Preprint, *Joint Power Generation Conference, Charlotte, North Carolina, October 1979.*

3. C. G. Valente, *In-Situ Laboratory Nondestructive Evaluation of the DNB Evaporator Tube After 2820 Hours*, GEFR-0072L, General Electric Company (March 22, 1977).

4. R. A. Day, *Second Baseline In-Service Inspection of the Few Tube Test Module*, XL-898-80839/P2580 G4 (November 30, 1978).

5. K. V. Cook, R. A. Cunningham, Jr., and W. A. Simpson, Jr., *Ultrasonic Techniques for Boreside Inspection of Tube-to-Tubesheet Welds*, ORNL/TM-7224 (May 1980).

6. G. W. Scott and L. D. Chitwood, *Field Assessment of Ferritic Double-Walled Tubing for a Westinghouse Breeder Reactor Steam Generator Model with a Boreside Eddy-Current Method*, ORNL/TM-7187 (March 1980).

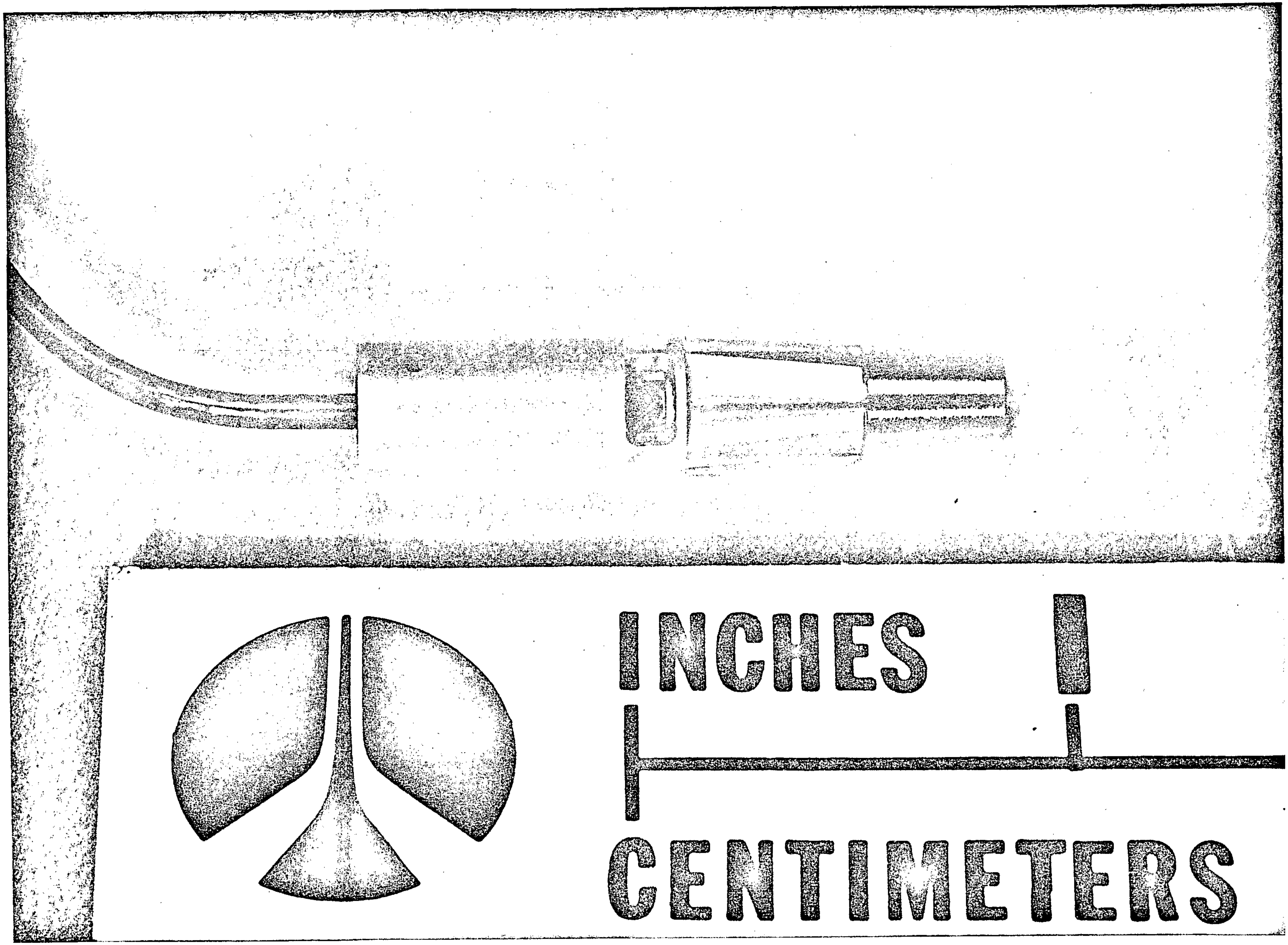

Fig. 1. Ultrasonic probe with turbine-mounted rotating mirror for wall thickness measurements.

ISOTOPE SCANNING TEST (IST)

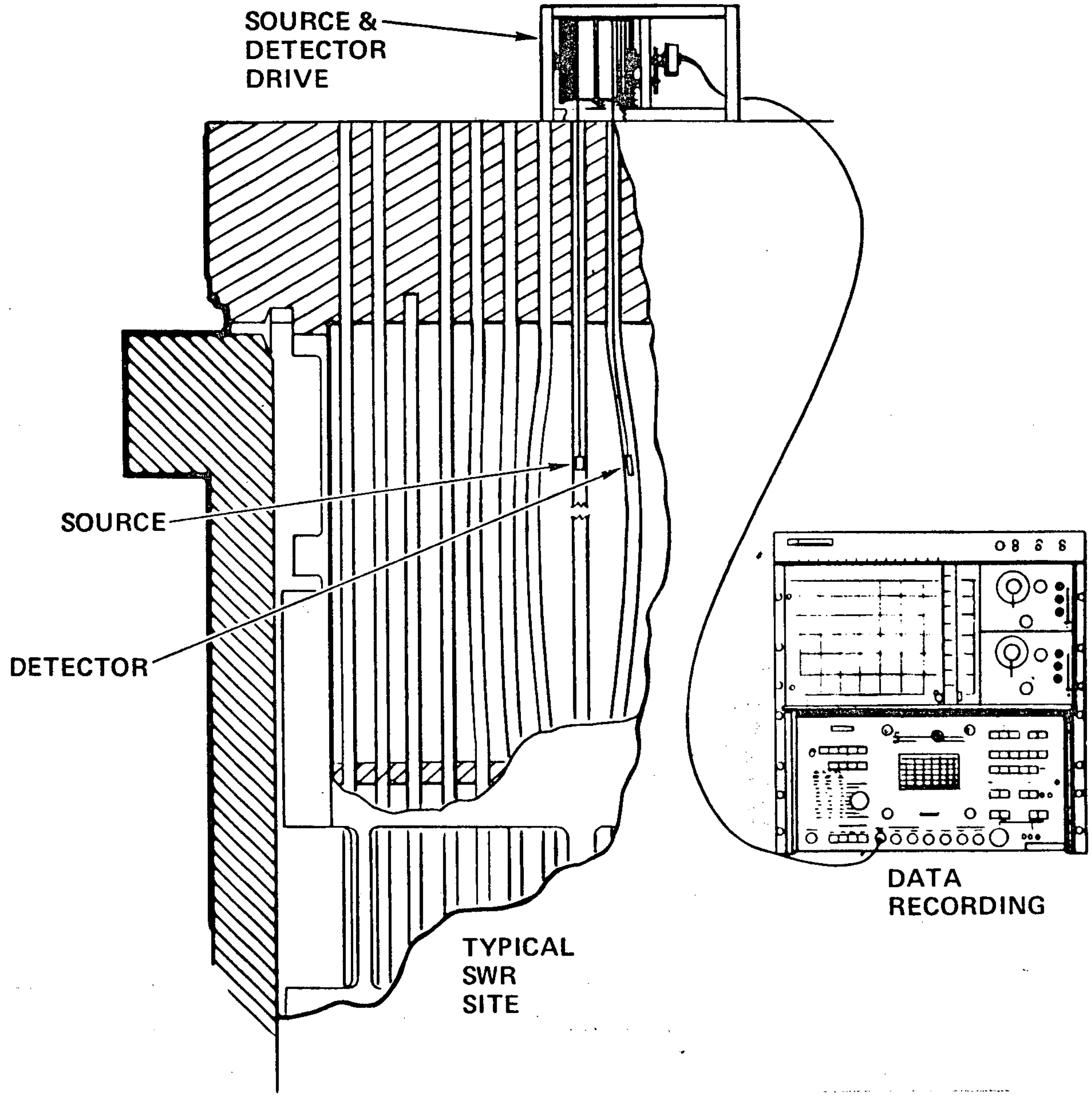

Fig. 2. Sketch of system for isotopic scanning for measurements of tube deformation and sodium-water reaction product.

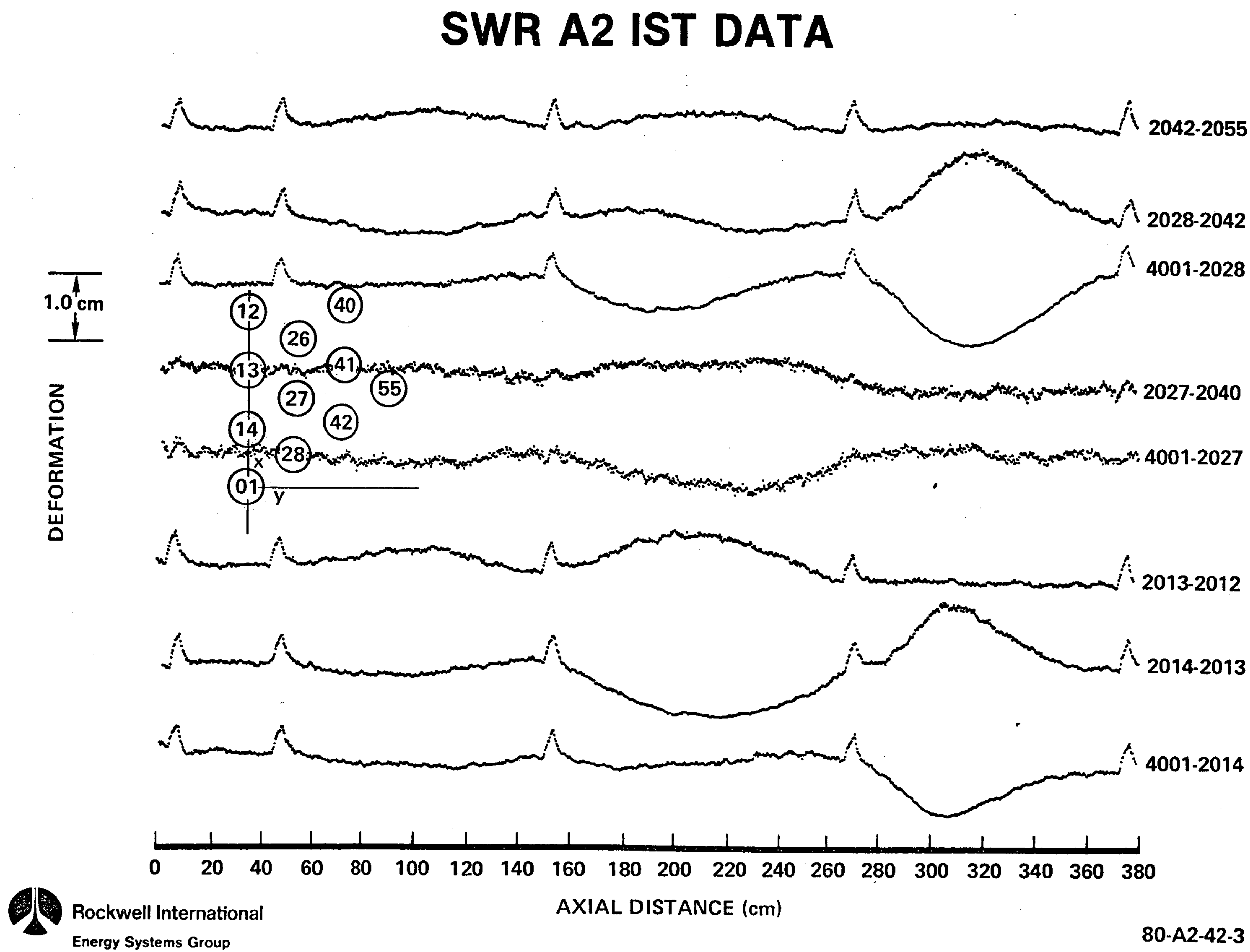

Fig. 3. Scan data for isotopic measurement of tube deformation.

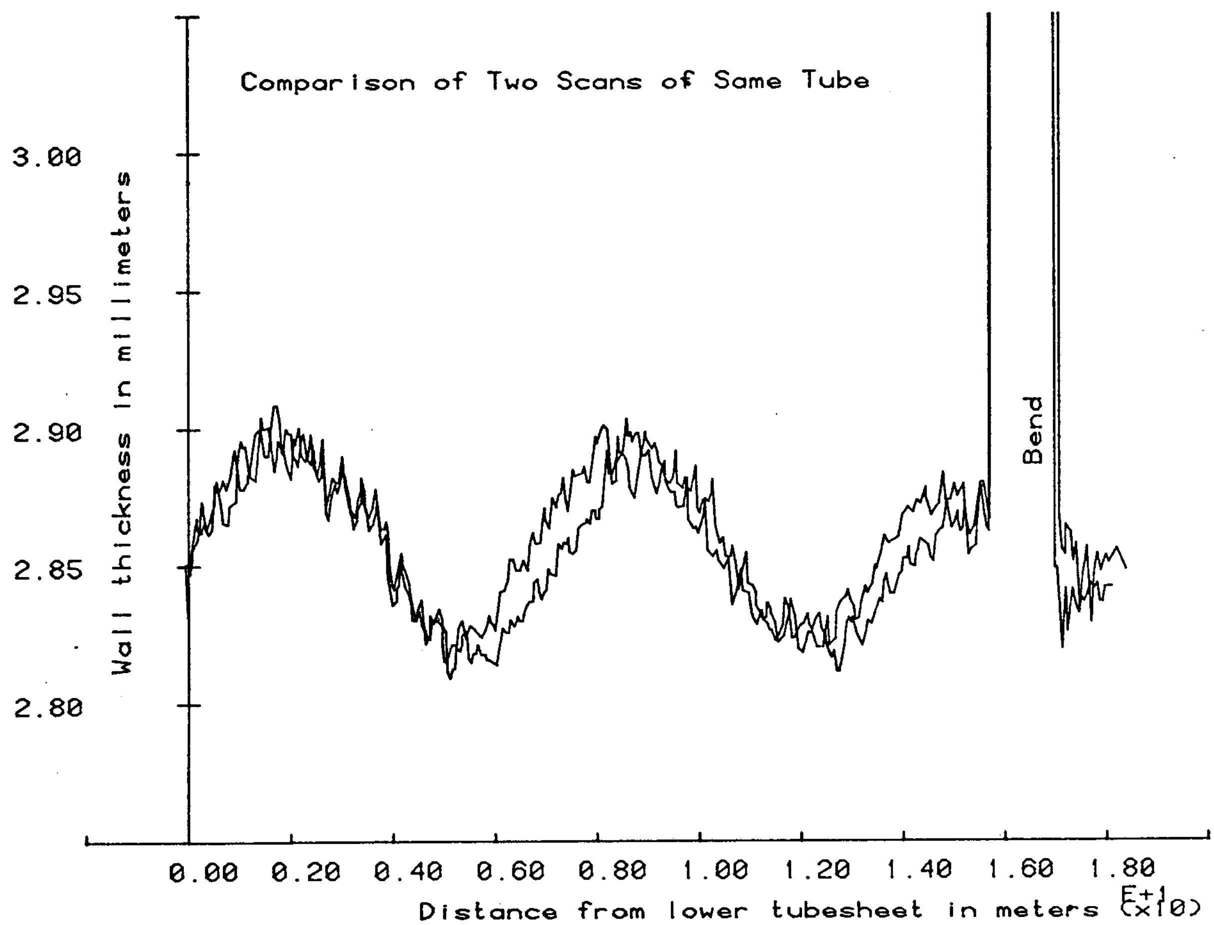

Fig. 4. Comparison scans of wall thickness measurement of same tube in FTTM.

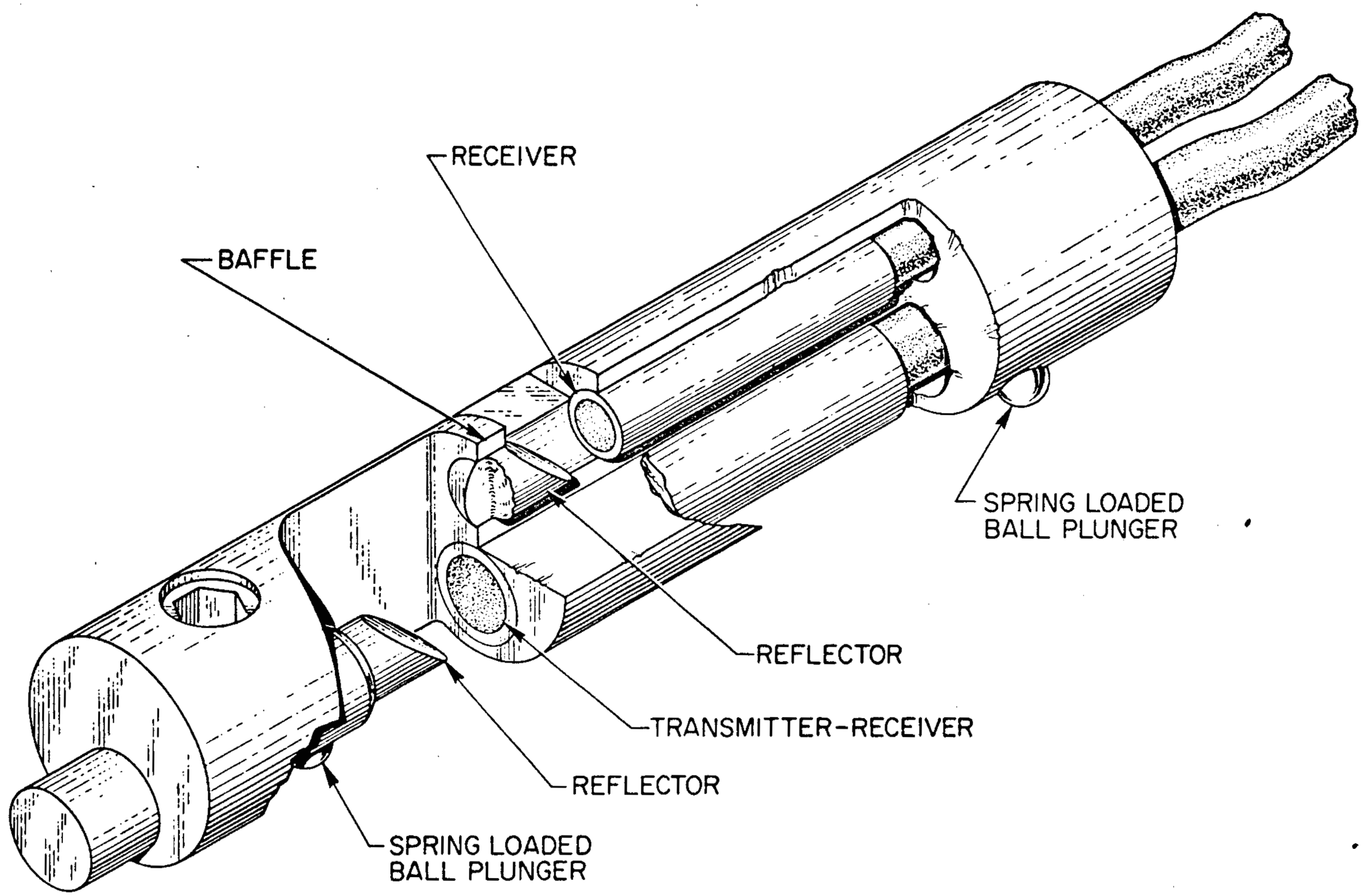

Fig. 5. Isometric sketch of two-transducer ultrasonic probe for in-service inspection of CRBR tube-to-tubesheet welds.

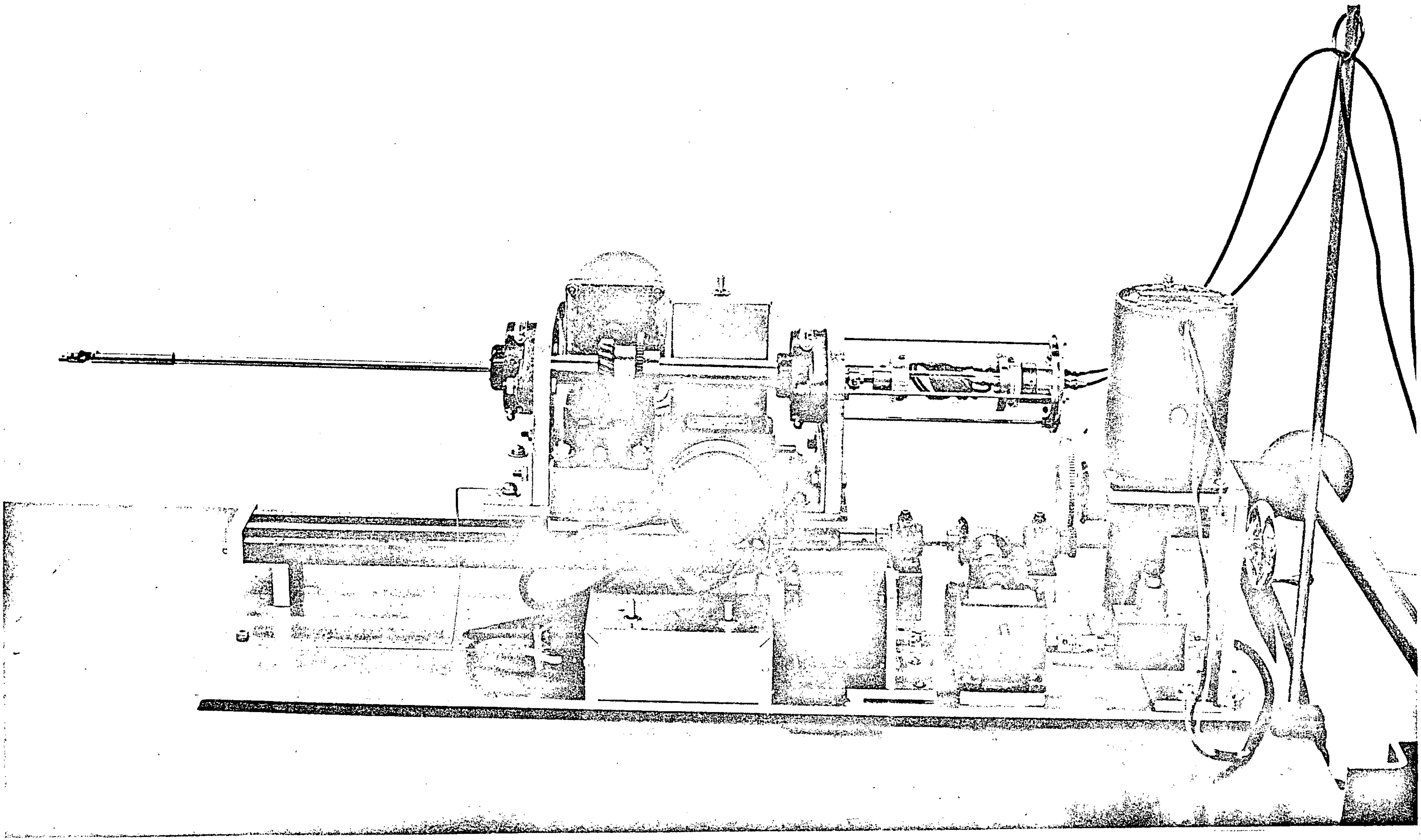

Fig. 6. Mechanical scanner for ultrasonic examination of CRBR tube-to-tubesheet welds.

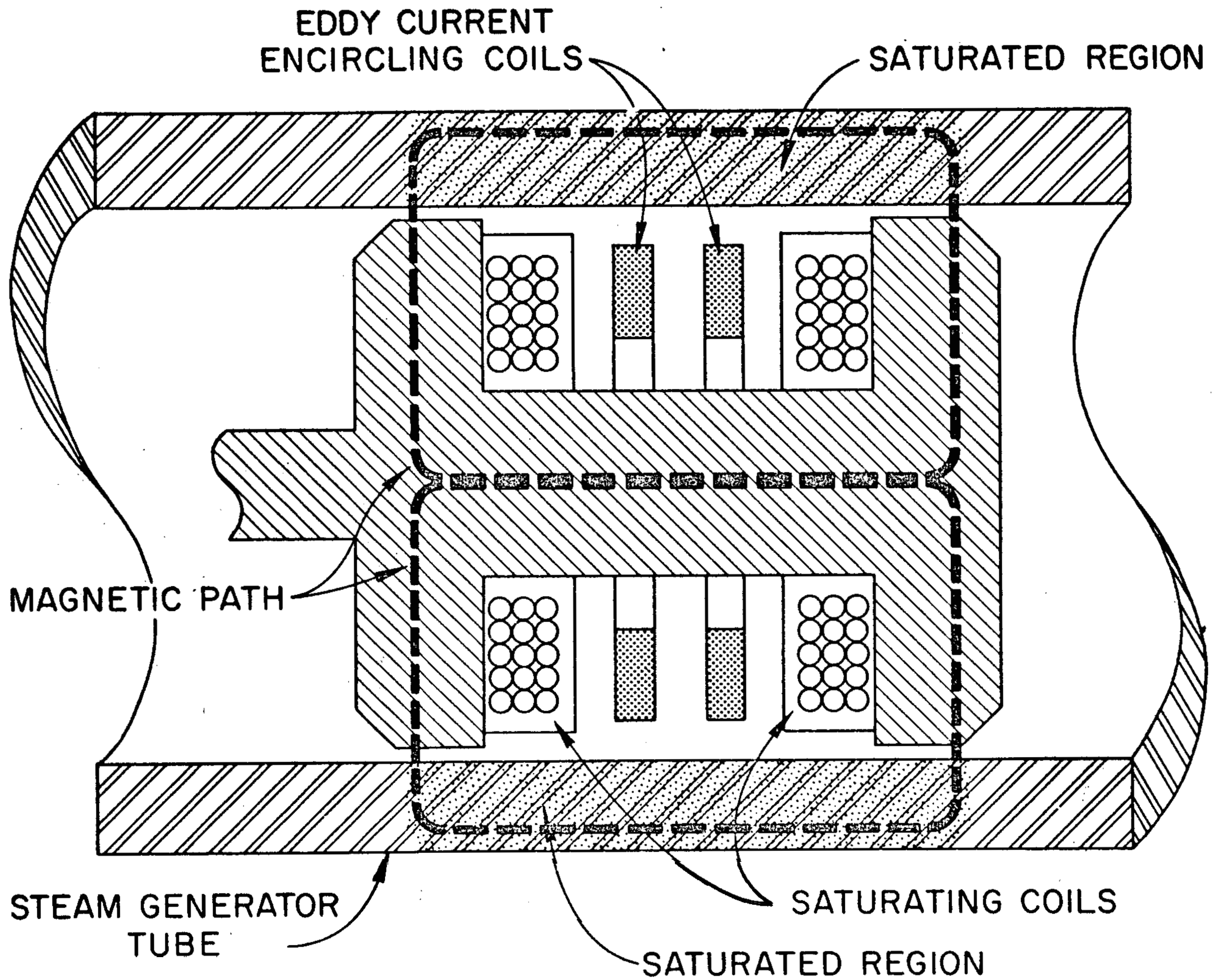

Fig. 7. Conceptual drawing of boreside eddy-current probe with magnetic saturation circuit for ISI of CRBR tubing.

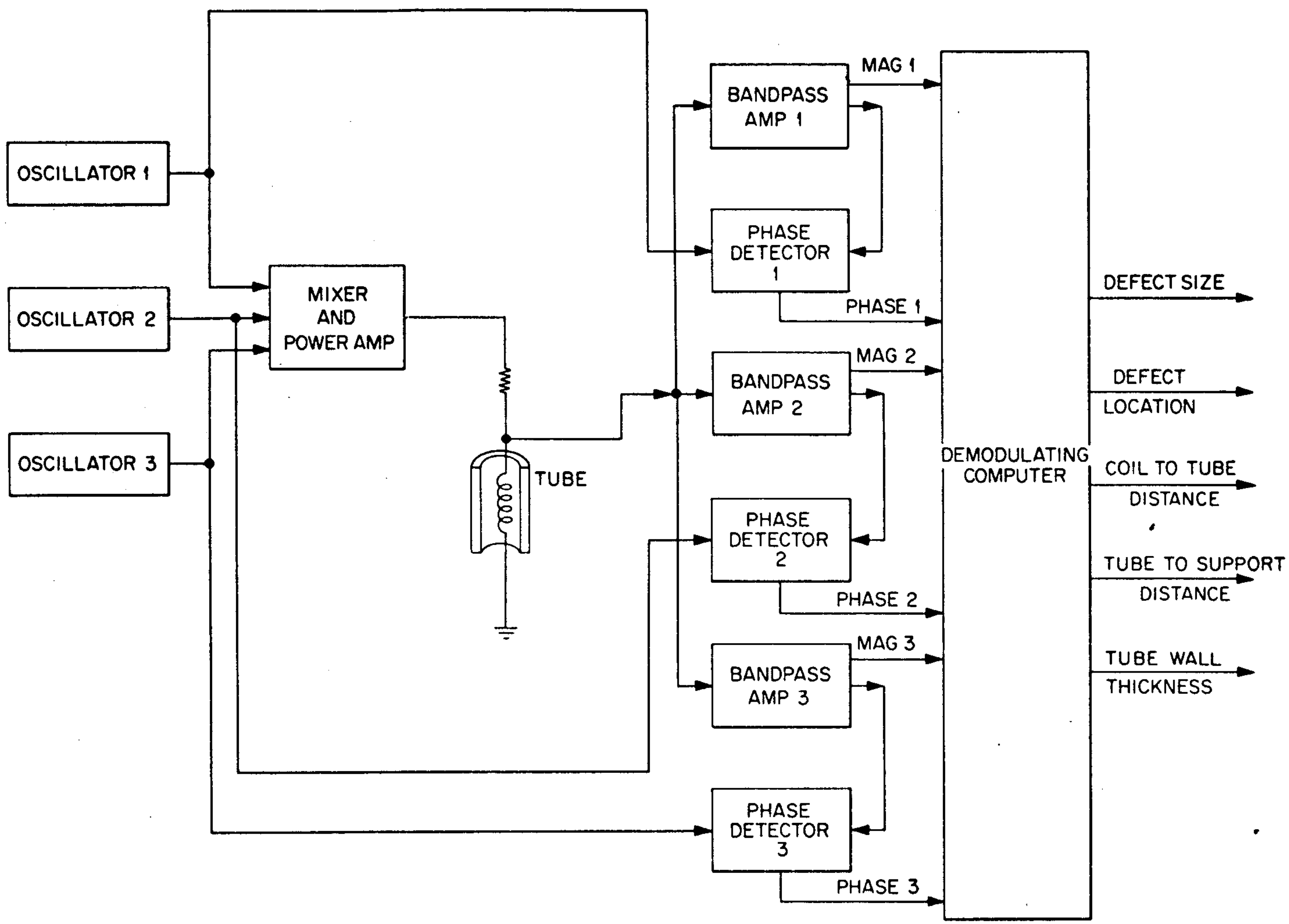

Fig. 8. Block diagram of three-frequency eddy-current instrument for ISI of CRBR tubing.

Fig. 9. Interior view of mobile inspection laboratory for on-site eddy-current ISI of steam generator tubing.