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DEVELOPMENT OF ULTRASONIC TECHNIQUES FOR THE EVALUATION OF BRAZED JOINTS

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INTRODUCTION

To meet the need for a method of measuring boiling and condensing coefficients of liquids at temperatures of 1700 to 1800°F, the Heat Transfer and Physical Properties Section of the Reactor Division of the Oak Ridge National Laboratory (ORNL) developed a procedure for obtaining information on two-phase heat transfer in liquid metals. The ultrasonic techniques under discussion were developed to evaluate the brazed joints of the liquid-metal boiler comprising an essential part of the system.

The boiler[1] consists of a 0.375-in.-OD by 0.025-in.-wall type 347 stainless steel tube centrally bonded to a coaxial stack of twenty-one 2-in.-thick copper disks 5 in. in outside diameter. The copper disks are also brazed inside a type 310 stainless steel jacket or can for protection against oxidation during service. Stainless steel spacers 1/8 in. thick are located between the copper disks to prevent axial heat flow along the boiler. Chromel-Alumel thermocouples sheathed with stainless steel are positioned within each disk to measure the radial temperatures. A general cross section of a portion of the boiler is given in Fig. 1.

Essentially, a complete braze between the copper and tube is required; however, the can-to-copper braze is not quite so critical. Since very little nonbonding could be tolerated in either of the brazed areas, it was necessary to develop inspection techniques for the nondestructive evaluation of the bond conditions. The ultrasonic method was chosen as the most promising solution for measuring the integrity of each of the brazed areas. The final methods of evaluation indicated that an ultrasonic Lamb-wave[2] technique would best locate nonbonded areas in the braze

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[1] E. A. Franco-Ferreira, Fabrication of Boiler Section for Boiling-Liquid-Metal Loop, ORNL-TM-40 (Oct. 16, 1961).

[2] D. C. Worlton, J. Soc. Nondestructive Testing 15(4), 218–22 (1957).

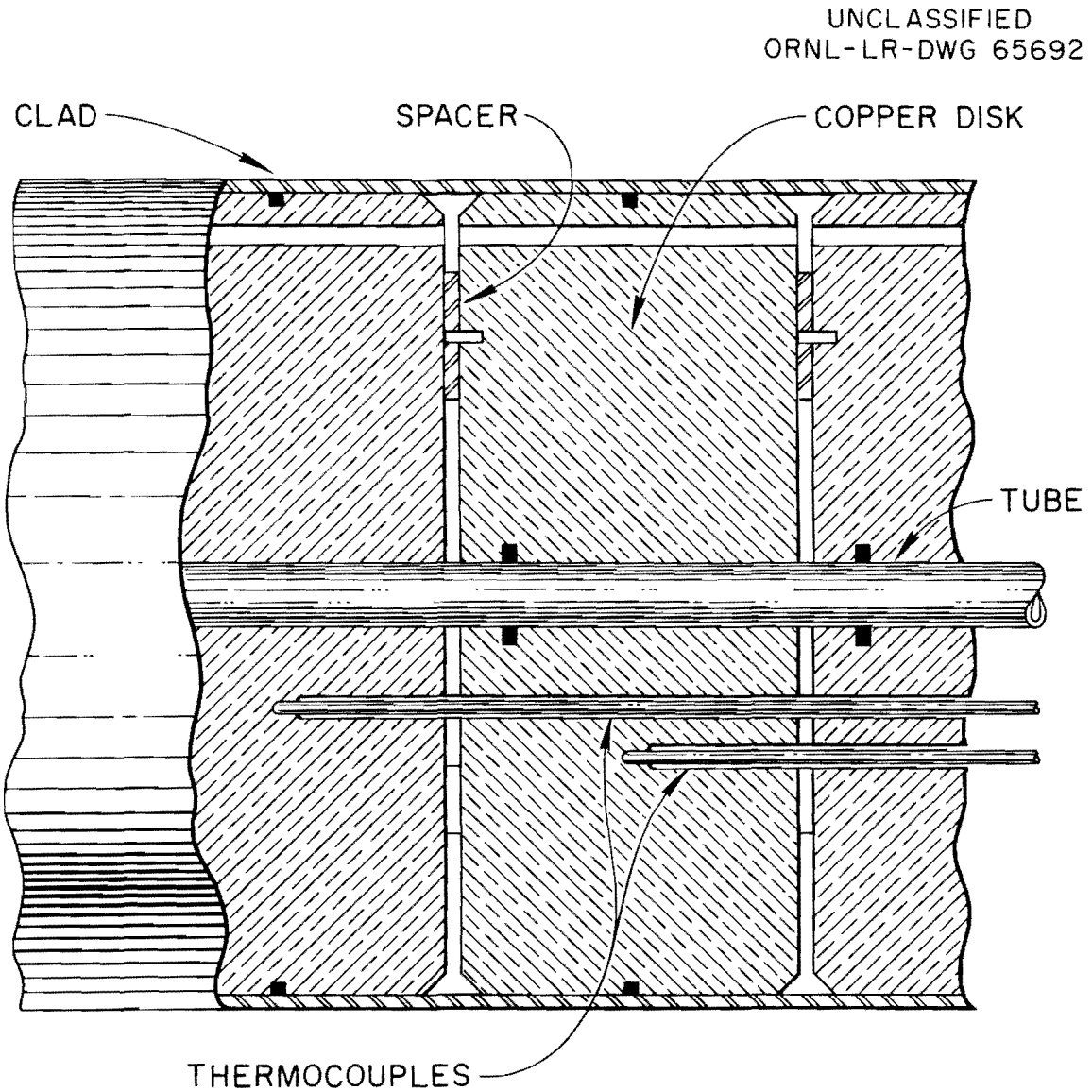

Fig. 1. General Cross Section of a Portion of the Liquid-Metal Boiler. Reduced 4%.

between the 3/8-in.-OD stainless steel tube and the large copper block. However, evaluation of the can-to-copper braze could best be done with either a "ringing" ultrasonic test[3] or a contact resonant ultrasonic[4] technique. The various stages of technique development are described along with the evolution and application of methods for nondestructively evaluating each brazed area.

ULTRASONIC TECHNIQUES AND THEORY

Lamb Waves

It has been postulated that an elastic plate may vibrate in an infinite number of modes.[5] The conditions under which any of these modes (commonly called "Lamb waves") may be generated are dependent upon the frequency of the vibration, the thickness, and the elastic properties of the plate. The phase velocity (in metal) of the Lamb waves is interrelated with these conditions. A plate may be caused to vibrate by being excited with an impinging ultrasonic beam under certain conditions. The sound beam causing the generation of the Lamb wave must have the same frequency as the generated Lamb-wave vibration and must satisfy the following equation:

$$\sin \alpha = V_m / V_\phi \quad ,$$

where V_m is the velocity of sound propagation in the couplant medium, V_ϕ is the phase velocity of the Lamb wave, and α is the angle of incidence of the ultrasound beam.

A typical arrangement for generation of Lamb waves is shown in Fig. 2. The incidence angles at which both the transmitting and the receiving crystals are set must be identical, because Lamb waves are emitted from the plate at an angle equal to the incident angle of the ultrasound beam

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[3]D. C. Worlton, Ultrasonically Bond Testing Hanford Fuel Elements, HW-43031 (May 10, 1956).

[4]R. C. McMaster (ed.), Nondestructive Testing Handbook, Sec. 50, Vol. II, Ronald Press, New York, 1959.

[5]H. Lamb, Proc. Roy. Soc. (London) 93(A), 114–28 (1916–17).

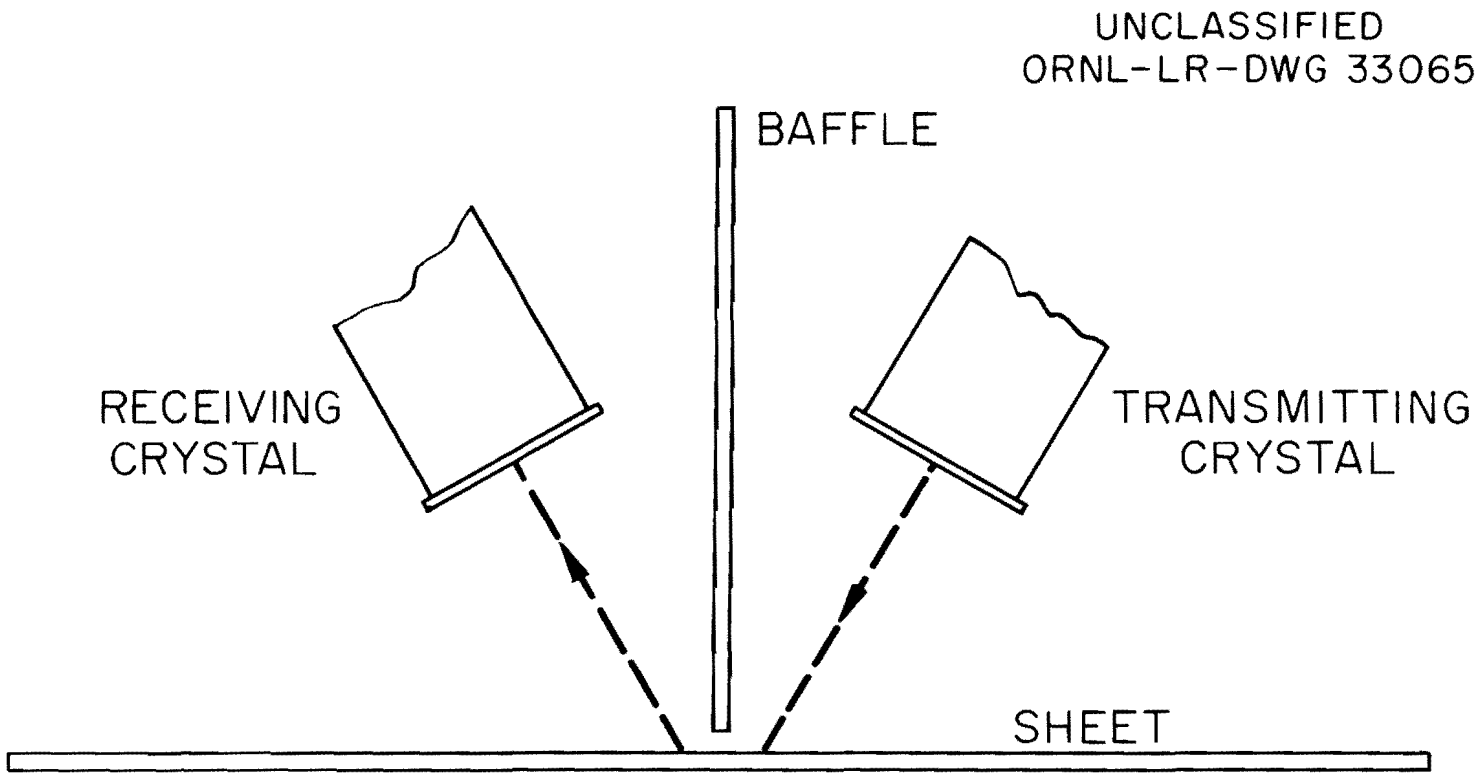

Fig. 2. Lamb-Wave-Generation Technique.

which generates the Lamb wave. As mentioned earlier, the frequency, plate thickness, and phase velocity conditions must be satisfied before a Lamb wave can be generated. The baffle between transmitting and receiving crystals simply blocks the large surface echo from the receiver, making it possible for the smaller Lamb-wave signal to be detected. As applied to cladding structures, the appropriate conditions of frequency and incident angle are chosen so that a vibration can be established in the thickness of the cladding material only. If the cladding is well bonded to the base structure, the large composite thickness will upset the condition for Lamb-wave generation and no such vibration may be initiated. If, however, there is nonbonding, it will be indicated by the thinner cladding allowing the Lamb wave to be generated. Both bonded and unbonded indications observed with the Lamb-wave probe are evident in Fig. 3.

Ultrasonic Ringing

Figure 4 illustrates both good- and poor-bonding indications detected by the ringing technique. Pulses of ultrasound are generated by a piezoelectric or electrostrictive transducer and transmitted through a couplant such as water into a metal specimen. If a good bond exists between the copper disks and the stainless steel can, the reflected pulse from the surface of the cladding will last only for a time equal to that of the driving pulse length. If, however, the stainless steel sheath is not bonded to the copper and an ultrasonic pulse of the correct frequency is used, a ringing of the reflected pulse from the surface will occur. The frequency required to ring the unbonded can must be such that the cladding thickness will be an integral number of half-wave lengths of the incident frequency. Normally, for this condition, there is a maximum transmission of ultrasound; however, in this case, a complete acoustic mismatch is encountered at the nonbond which prevents sound transmission. Thus, a storage effect occurs, and a ringing of the surface echo (which decays with time) is observed.

Ultrasonic Resonance

In the resonance method, continuous ultrasonic waves are transmitted through a thin film of couplant into a metal specimen. The frequency

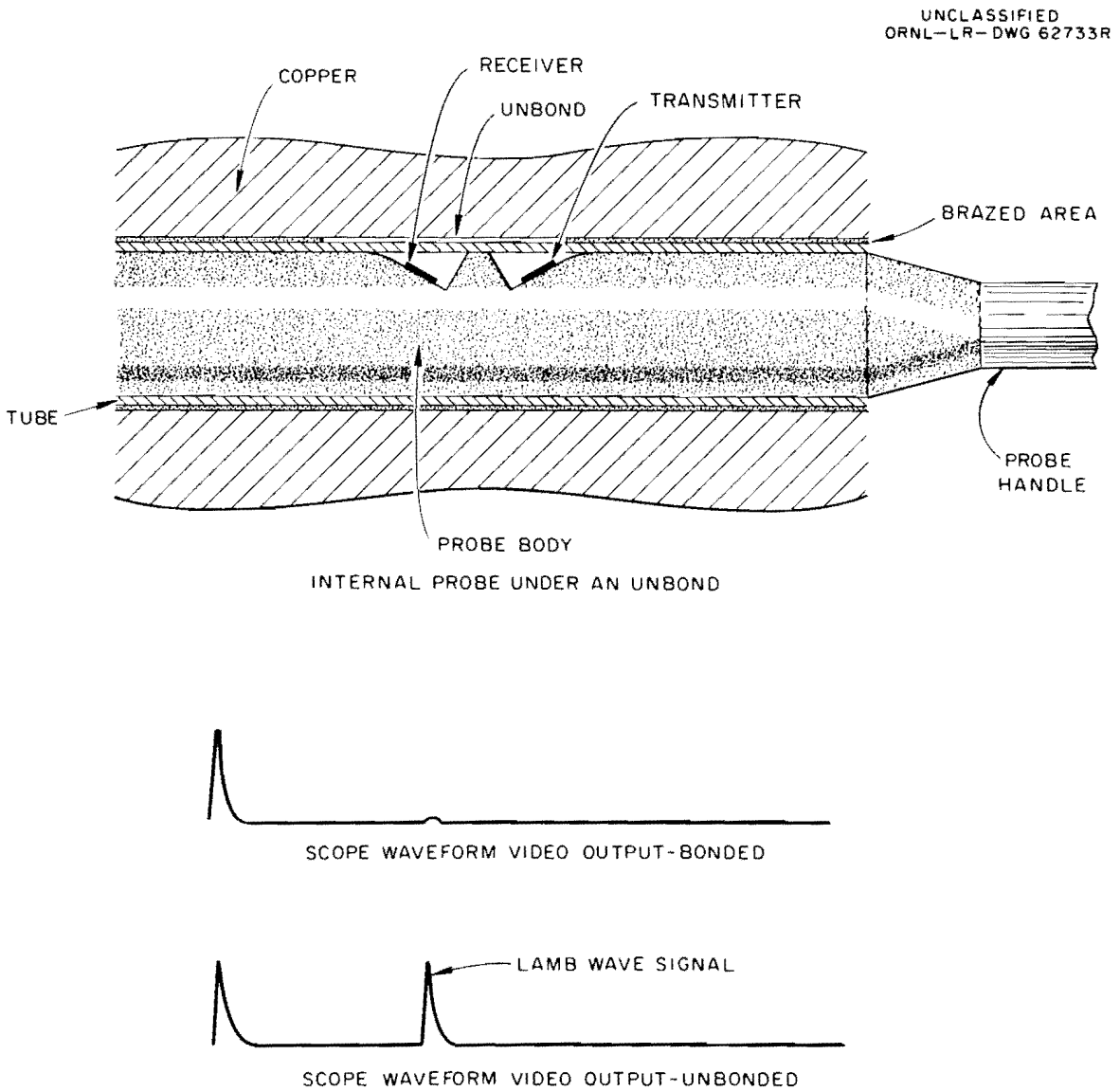

Fig. 3. Lamb-Wave Probe with Indications for Different Bonding Conditions. Reduced 11%.

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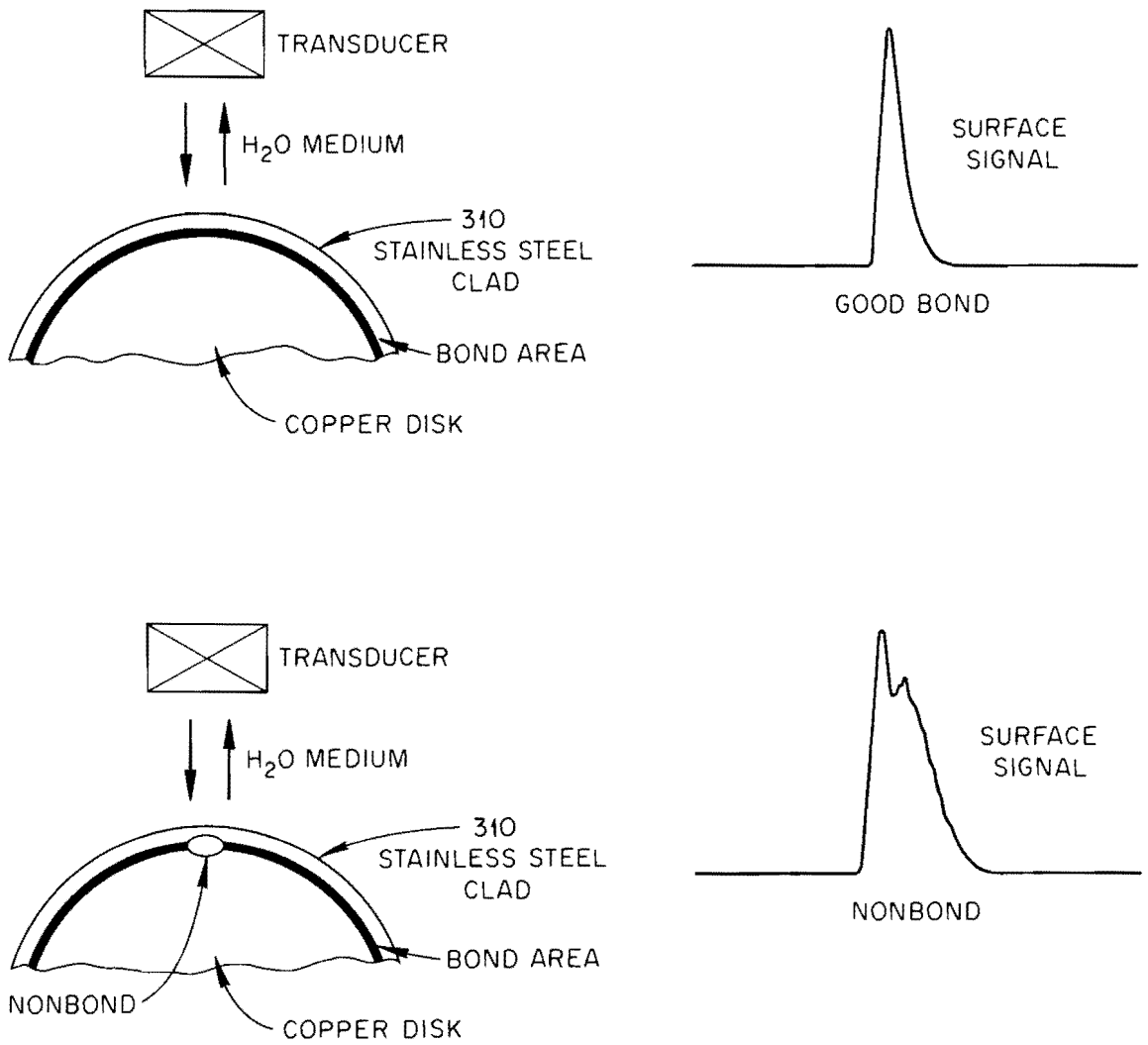

Fig. 4. Ringing Technique for Detection of Nonbonding. Reduced 9%.

(and thus the wavelength) of these waves is varied until a standing wave condition occurs which causes resonance of the specimen. Standing waves (illustrated in Fig. 5) are established in a metal sample or plate when the plate thickness equals one half the wavelength, or some multiple thereof. As applied to cladding, a sound-wave frequency is chosen which will cause a one-half wavelength condition to exist for the thickness of the cladding material only when such material is not well bonded to the basic structure.

Equipment

An Immerscope (manufactured by Curtis Wright, Inc.) was used in both the Lamb-wave and ringing evaluation techniques. This instrument generates an electrical pulse which, upon striking a piezoelectric or electrostrictive transducer, produces a transmitted ultrasonic pulse and detects, amplifies, and displays the received echo pulses. Monitoring and measurement of nonbonding indications were expedited by means of an electronic gating circuit and an audible alarm system in both tests.

A Vidigage (manufactured by Branson Instruments, Inc.) was used for the contact resonant evaluation of the can-to-copper braze. This device automatically sweeps the ultrasonic frequency through a predetermined band, and the conditions of resonance are displayed as vertical pips on the screen of a cathode-ray tube. The face of the screen can be calibrated directly in thickness; thus, if a nonbonded condition exists, the cladding thickness would be indicated.

PRELIMINARY WORK

Tube-to-Copper Braze

A Lamb-wave probe was designed, constructed, and used in conjunction with an Immerscope to detect nonbonded areas in the tube-to-copper braze. The probe contained two quartz crystals of approximately 5 Mc which were used for transmitter and receiver crystals, respectively, and a baffle to block out surface echoes. Incidence angles of the two crystals were adjusted to values of approximately 20 deg. Calibration of the probe, which is shown entering the boiler tube in Fig. 6, indicated that any

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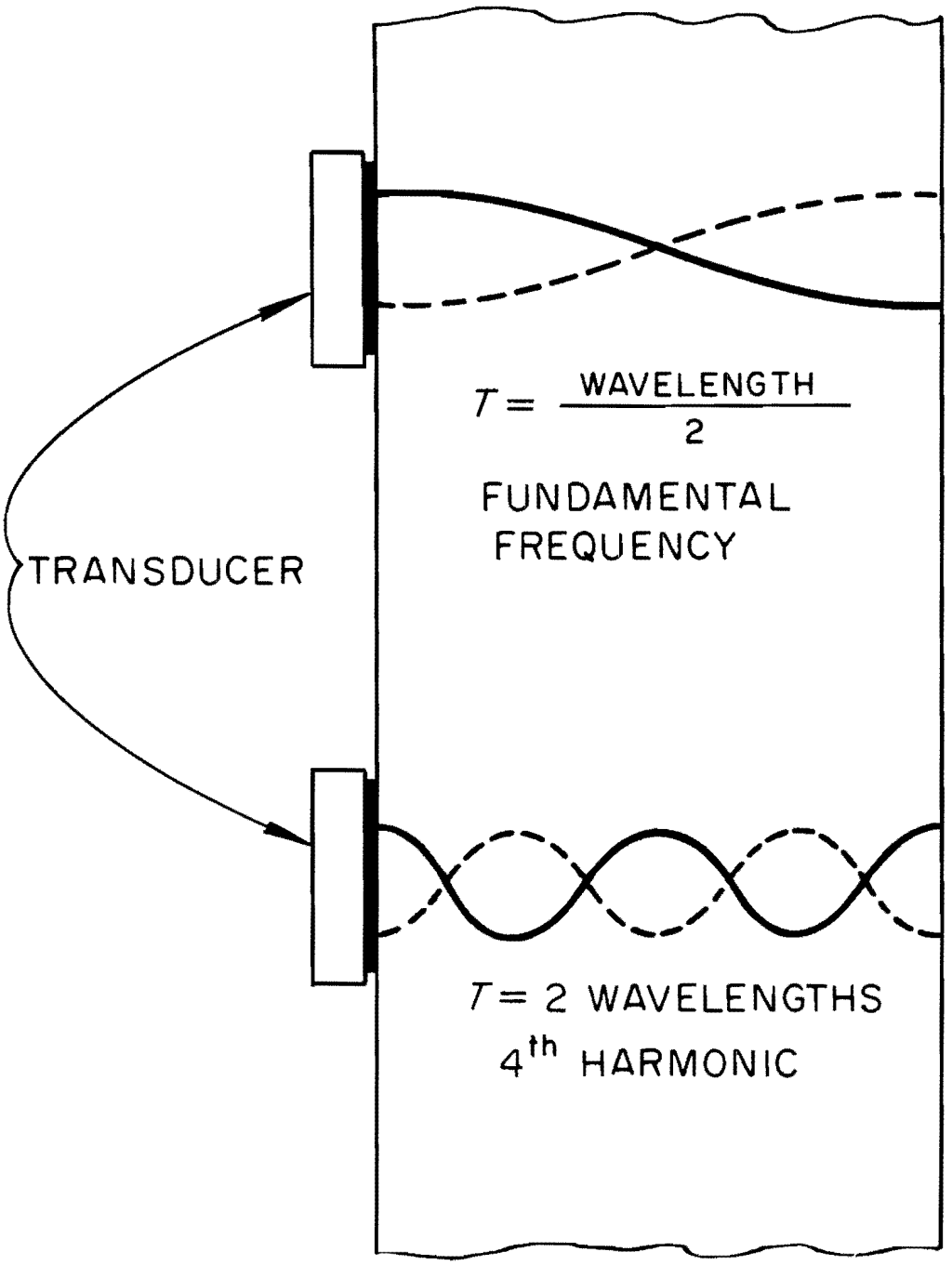

Fig. 5. Ultrasonic Resonance Technique.

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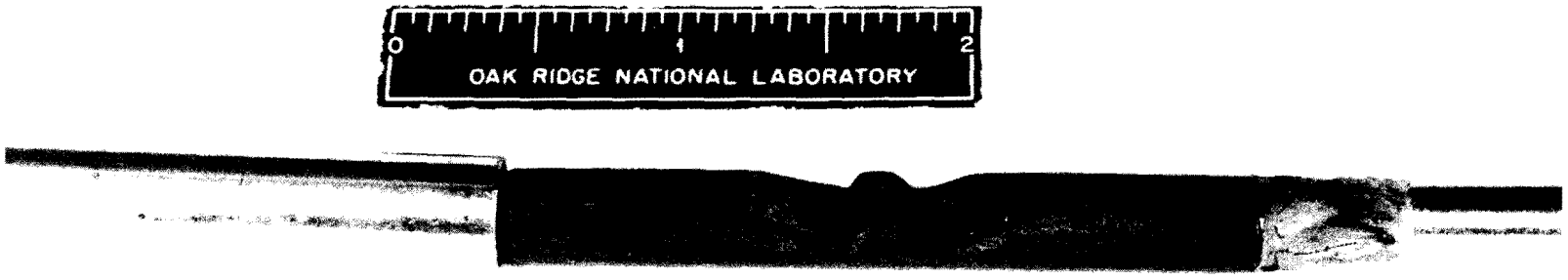

Fig. 6. Lamb-Wave Probe Entering Boiler Tube. Reduced 14%.

nonbonded area of 1/8-in. length × 1/16-in. width could be located. A number of samples supplied by the Welding and Brazing Group were evaluated and maps of the brazed areas compiled from ultrasonic data.

A form of frost testing[6] was also used in an attempt to correlate heat transfer with the ultrasonic findings. Split sections of tube-to-copper joints were chilled by dry ice until a thin coating of frost formed over the specimen. Warm air was then blown across the coating of frost. The frost was melted in nonbonded regions, since the defect restricted the heat transfer between the tube and the copper, thereby causing an increase in the temperature of the tube located over the nonbonded area. Figure 7 is indicative of the results obtained by frost testing; the dark areas illustrate nonbonding in the tube-to-copper braze.

Destructive peel testing was also used for correlation of inspection data. The tube was simply stripped or peeled from the copper block and the braze condition observed. Figure 8 shows a copper sample from which the tube has been pulled. The nonbonded areas, previously detected by ultrasonics, are revealed as smooth areas running away from both sides of the brazing alloy channel.

Metallographic samples were taken from different specimens. In all the tests mentioned, excellent correlation with ultrasonic findings was evident.

Can-to-Copper Braze

A technique for ringing the 0.065-in.-thick can was developed and applied to a number of specimens. Standard calibration indicated that a 3/32-in.-diam nonbonded area could be readily detected. A number of nonbonded areas were revealed by this method and a correlation was made with data from frost testing and metallographic sectioning. Typical results of the frost test are shown in Fig. 9. The darkened area from which the frost has been removed is an indication of nonbonding. Figure 10 is a metallographic section revealing a small nonbonded area near an alloy channel.

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[6]J. H. Monawick and W. J. McGonnagle, Am. Soc. Testing Mater. Spec. Tech. Publ. 223 (1958), p 352.

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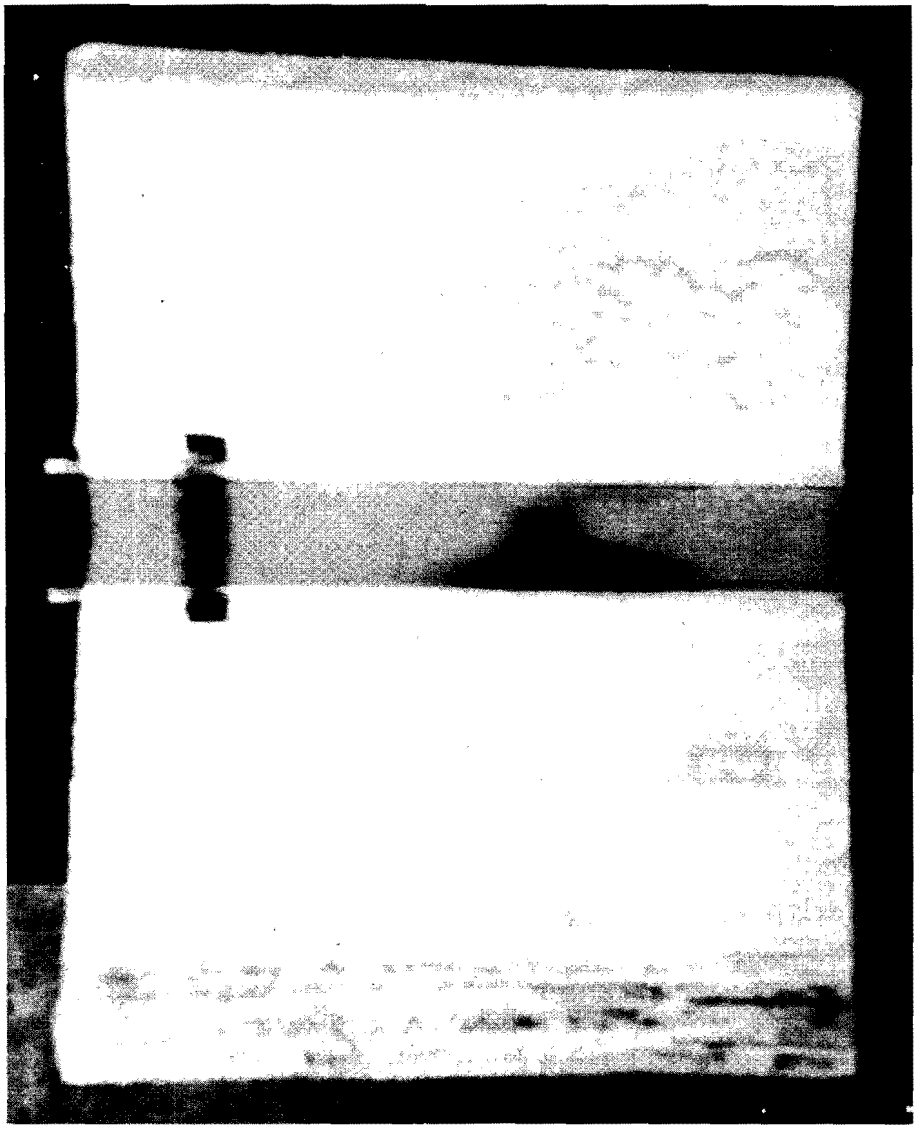

Fig. 7. Frost-Test Indication of Nonbonding in the Tube-to-Copper Braze. Approximately 2X.

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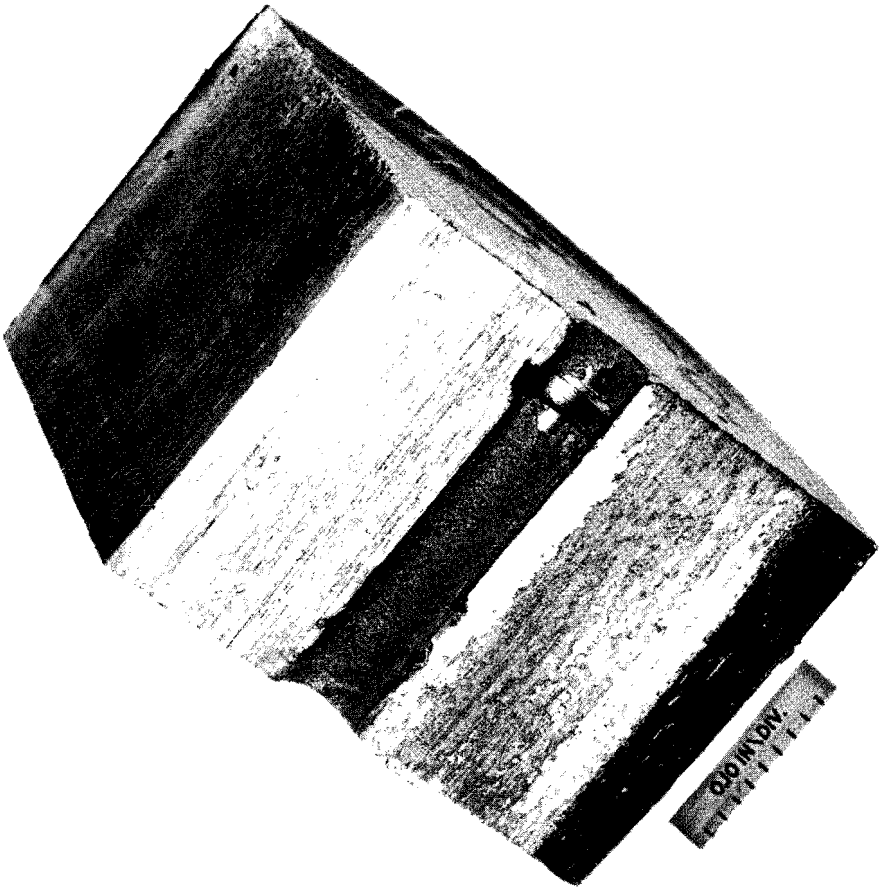

Fig. 8. Nonbonded Areas Observed After Peel Testing.

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Fig. 9. Frost-Test Indication of Nonbonding in the Can-to-Copper Braze. Approximately 2X.

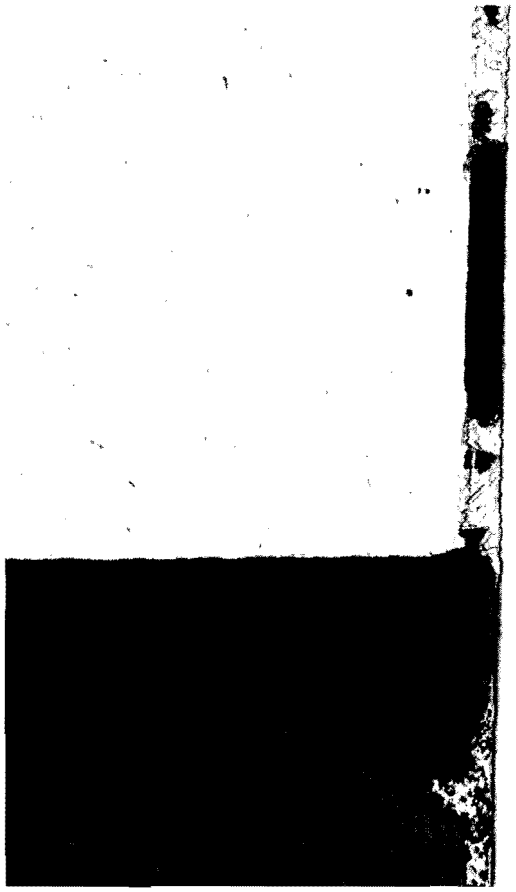

Fig. 10. Metallographic Section of Nonbonded Area in Can-to-Copper Braze. As-polished. 33X.

One sample, consisting of four copper disks canned in a stainless steel sheath, could not be completely inspected by the ringing technique because some of the braze material had flowed to the outside of the cladding and subsequent machining to remove the braze material had introduced excessive variations in the can thickness; the ringing technique depends upon the thickness of the can relative to the constant frequency condition of the pulses. For this sample, therefore, a resonance ultrasonic contact method of detection was used, although it is less sensitive and requires longer inspection time. When cladding thickness remains uniform, the ringing technique is considered to be a better test.

EVALUATION OF THE LIQUID-METAL BOILER

Tube-to-Copper Braze

The full-size prototype liquid-metal boiler shown in Fig. 11 was placed in a long immersion tank filled with water. Scanning of the braze was accomplished by passing the Lamb-wave probe, which was mounted on a 6-ft mandrel, longitudinally through the bore. Thus an evaluation was made of a linear strip of braze approximately 1/16 in. wide. Figure 12 shows the probe as it enters the bore of the liquid-metal boiler. Successive parallel longitudinal scans were offset from one another by rotating the probe approximately 11 deg (about 1/32 in. on the tubing circumference). This assured adequate overlapping between successive scans. A protractor attached to a clamping mechanism was used for calibration of probe rotation (Fig. 13). The probe handle, after being clamped securely to the apparatus, was pushed down the length of the two parallel bars on which it rested until a complete strip of braze was evaluated.

The system sensitivity was adjusted to detect nonbonded areas 1/8 in. × 1/16 in. in size. A few such areas were detected but most of them were adjacent to the brazing alloy channels which had been machined in the copper disks. The braze, which was better than 99% bonded, was considered to be adequate by those concerned with the boiler design.

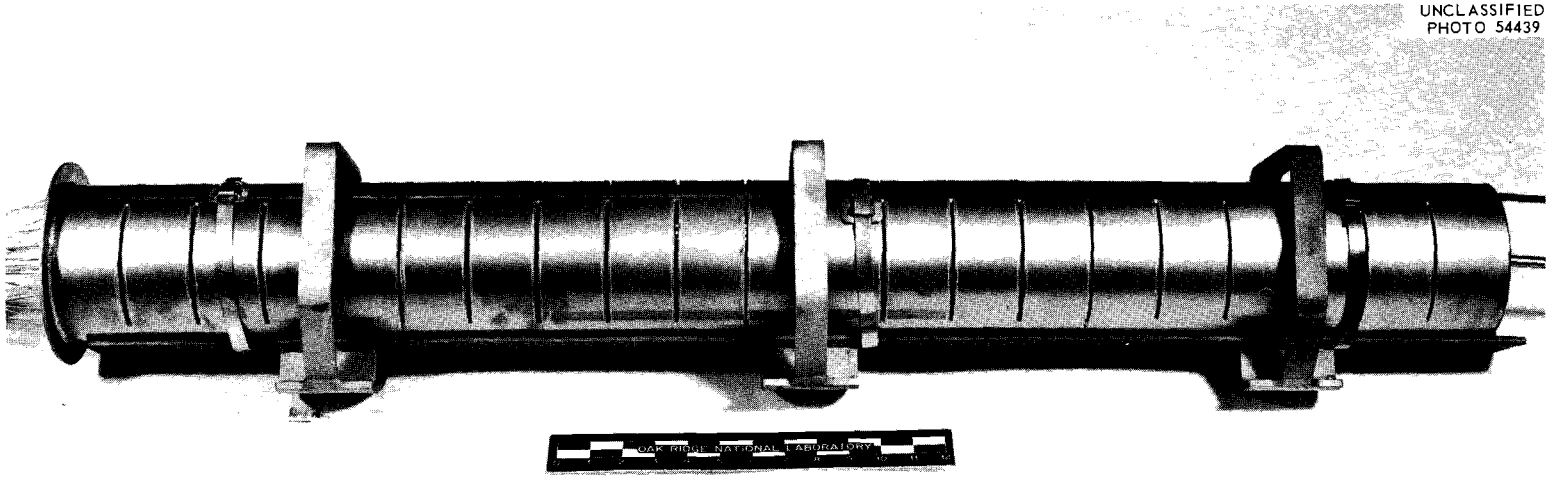

Fig. 11. Liquid-Metal Boiler in Transport Cradle. Reduced 17%.

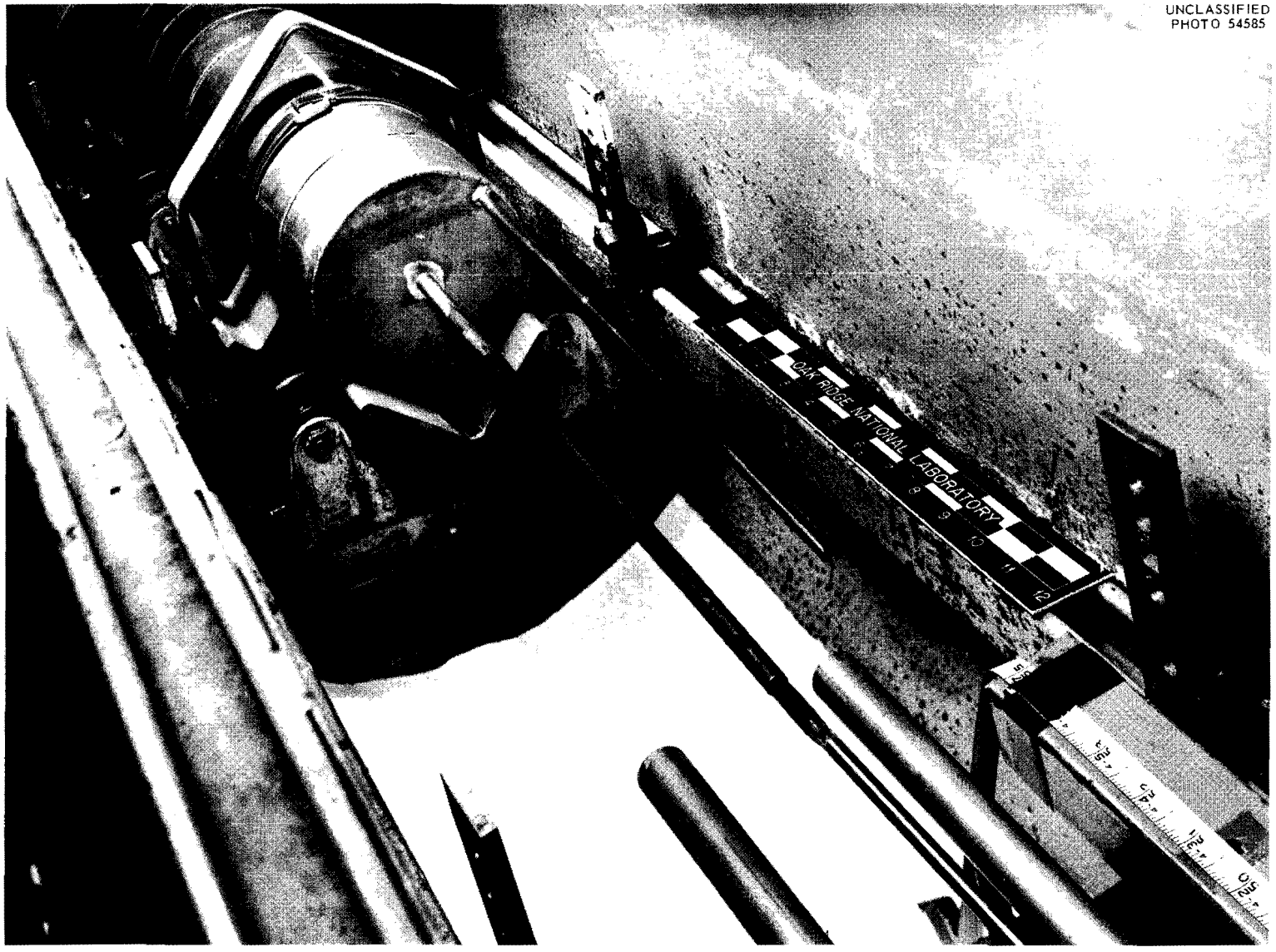

Fig. 12. Lamb-Wave Probe Entering the Bore of the Boiler. Reduced 17%.

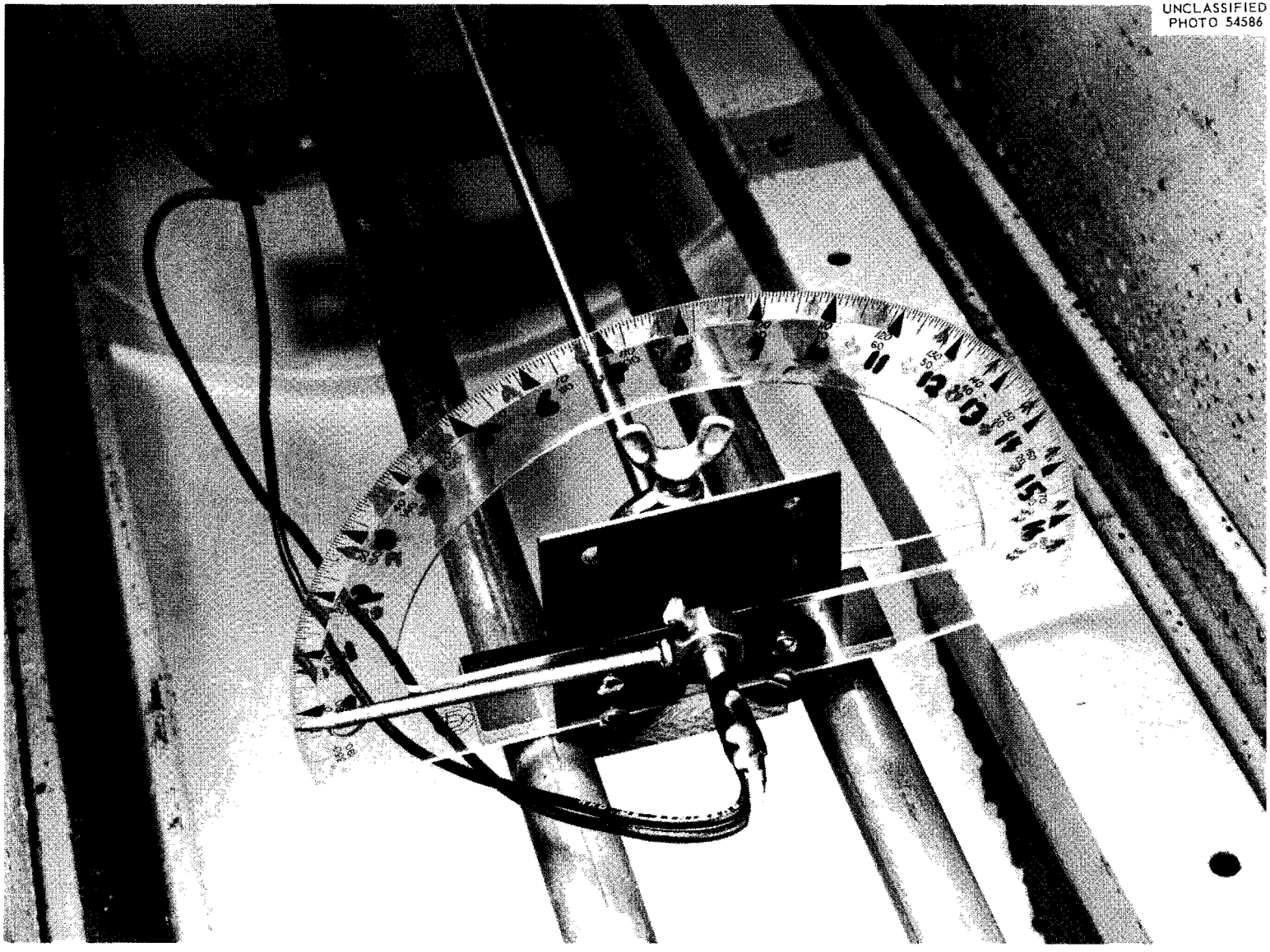

Fig. 13. Protractor and Clamping System for Calibrated Scanning. Reduced 16%.

Can-to-Copper Braze

Since the cladding thickness was rather uniform and therefore not a problem for the inspection of the actual prototype liquid-metal boiler, the ringing technique for evaluating the can-to-copper braze was used. The boiler was positioned on rubber rollers in a large immersion ultrasonic scanning tank. The thermocouple ends were waterproofed and supported to permit rotation of the test piece with the hand-crank mechanism shown in Fig. 14. Scanning was accomplished by completely rotating the boiler about its axis and indexing the ultrasonic search tube (Fig. 15) longitudinally along the boiler in 1/16-in. increments. The system sensitivity was adjusted to detect nonbonded areas of 1/8-in. diameter. Figure 16 represents the cylindrical area of the boiler as projected on a plane surface, with the nonbonding conditions indicated by the dark areas. Most of the nonbonded areas were in the portion of the boiler that was on top during the furnace brazing, which might be expected since the brazing alloy would tend to run toward the bottom because of the somewhat loose fit of the can-to-copper joint. Total nonbonding in the brazed areas was only approximately 8% of the total joint area and was considered acceptable to the loop designers.

CONCLUSIONS

Two ultrasonic techniques were demonstrated to be useful for the detection and evaluation of nonbonding conditions in brazed joints: (1) the Lamb-wave technique using two crystals, which allows the evaluation of bonding in restricted areas (such as those encountered in the tube-to-copper braze of the liquid-metal boiler) and (2) the ringing or modified resonance technique, in which a single transducer may be used and which is useful for evaluating brazes where access to the cladding material is not a problem (such as the can-to-copper braze in the large boiler assembly).

Brazes in a large boiler assembly, approximately 4 ft in length, were successfully evaluated by these two methods. The sensitivity of the two test methods was revealed by nonbonded areas 1/16 in. wide × 1/8 in. long being readily detected with the Lamb-wave technique and by nonbonded

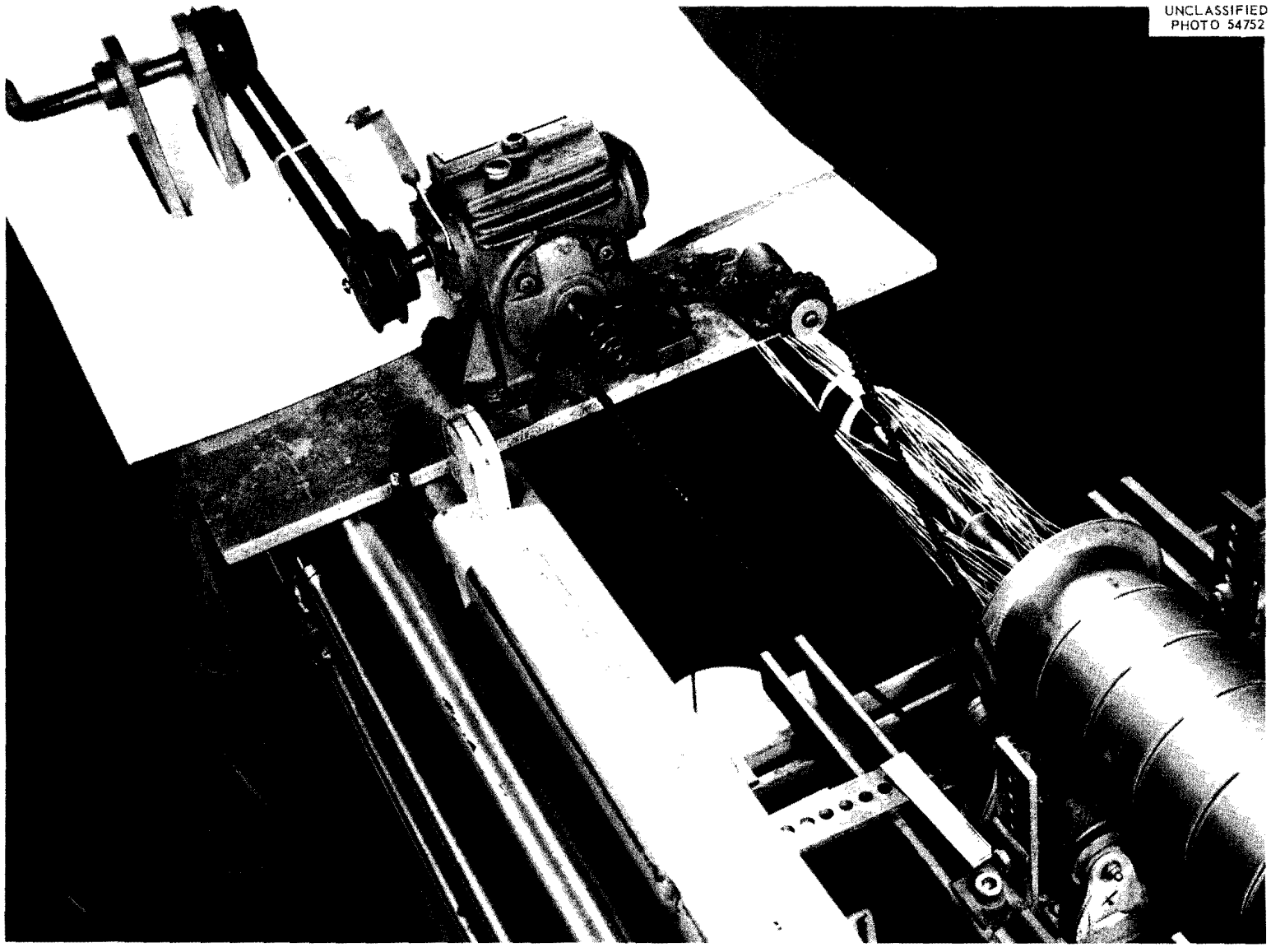

Fig. 14. Mechanism for Manual Rotation of the Boiler.
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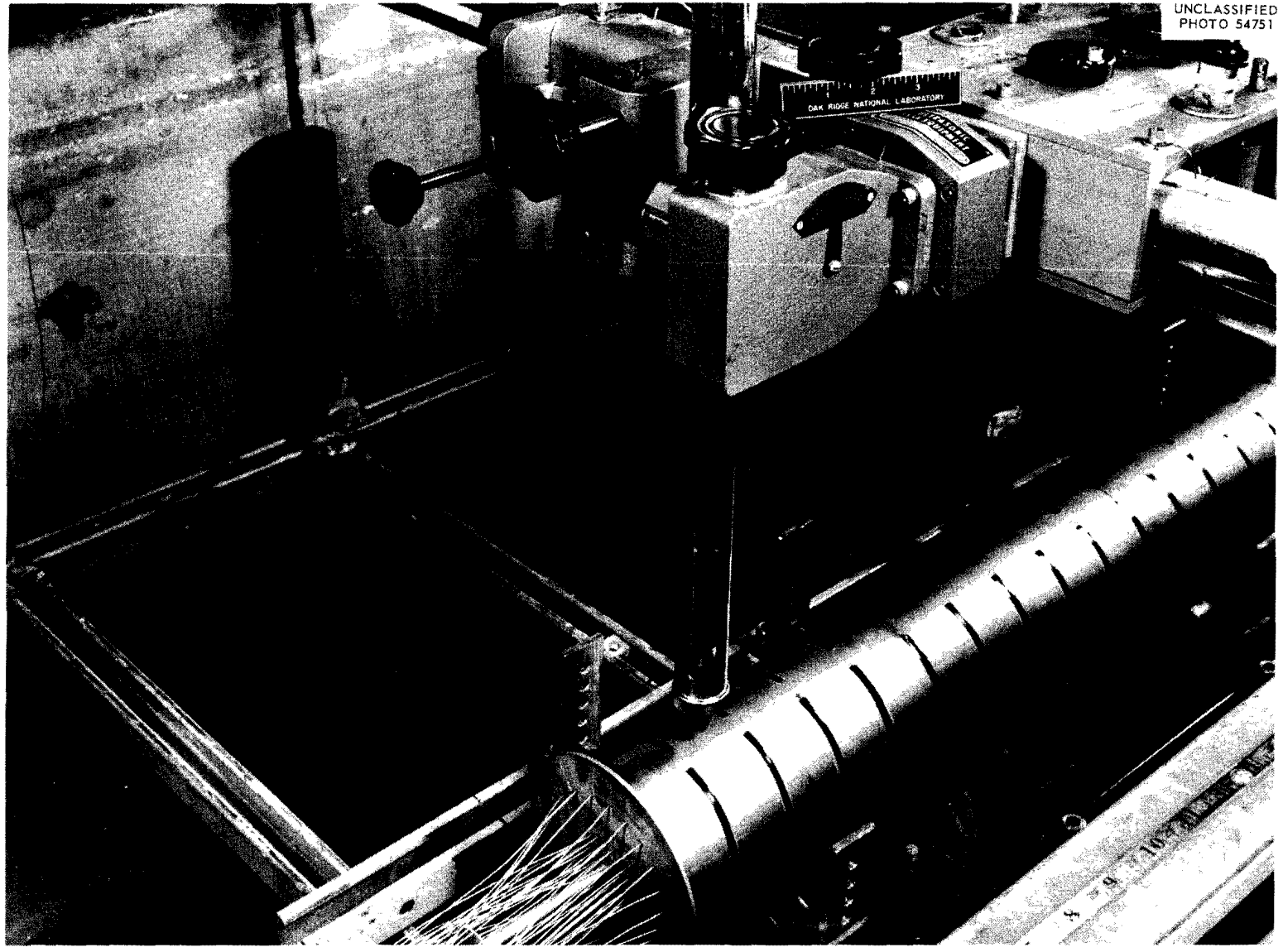

Fig. 15. Ultrasonic Search Tube in Position Over the Boiler. Reduced 17%.

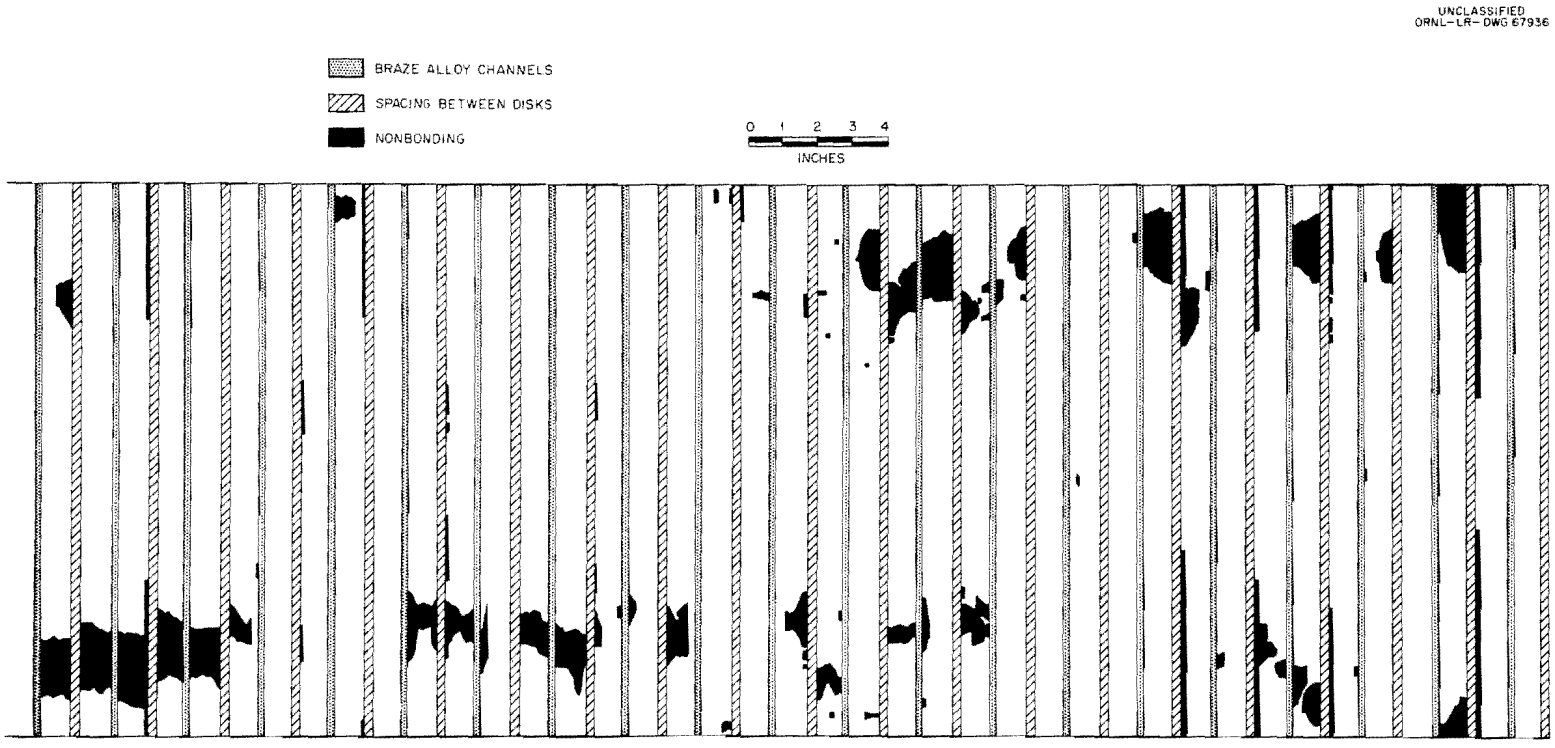

Fig. 16. Areas of Nonbonding Detected in Can-to-Copper Braze. Reduced 13%.

areas of 3/32-in. diameter being readily detected with the ringing technique. These values would vary somewhat with the test problems.

Results of both tests and correlation with other test methods demonstrated the reliability and reproducibility of the ultrasonic techniques for locating small nonbonded areas. The test results also indicated that acceptable bonding existed between mating surfaces of each joint.

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