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ULTRASONIC TESTING WITH LAMB WAVES

BY

D. C. WORLTON

FUELS PREPARATION DEPARTMENT

SEPTEMBER 25, 1956

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Metallurgy and Ceramics
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By

D. C. Worlton

Testing Methods
Fuels Engineering Operation

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September 25, 1956

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

Work performed under Contract No. W-31-109-Eng-52 between the Atomic Energy Commission and General Electric Company

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ABSTRACT

A method is described whereby many types of flaws lying close to the surface of a metal can be ultrasonically detected, regardless of the time duration of the interrogating pulses. Lamb waves are established in the metal between a flaw and the surface by an ultrasonic beam which impinges at the proper angle of incidence. A suitably positioned receiver transducer picks up the waves to reveal the flaw. In this method the usually trouble-some surface echo is eliminated from the receiver by an acoustic barrier, making it well suited for routine and automatic testing. Results of applying the technique to several testing problems are discussed.

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ULTRASONIC TESTING WITH LAMB WAVES

INTRODUCTION

In 1916 Horace Lamb published a paper[1] in which he proved mathematically that an elastic plate could vibrate in an infinite number of modes. In 1951 Firestone and Ling[2] patented a method of experimentally producing in plates the waves theoretically discovered by Lamb, and these waves have subsequently come to be known as Lamb waves.

To date very little has been written concerning the application of these waves to practical ultrasonic testing problems. Experimental studies at Hanford have revealed that they do have valuable properties from a testing viewpoint, particularly in revealing some types of flaws positioned close to the surface of a test metal, and the object of this paper is to describe some of these applications. A detailed discussion of the theory of Lamb waves will not be given here; rather, their properties will be described only in relation to the problems to which they are applied. For a more detailed discussion of the waves the reader is referred to the references cited.

SUMMARY

Lamb waves can be applied with advantage to many ultrasonic testing problems. For example, they offer a more simple and direct solution to the problem of detecting unbonded areas in Hanford type reactor fuel elements than can be obtained with the more conventional pulse-echo method previously developed. In other problems such as testing thin metal strip for laminar defects or grain size, the use of Lamb waves resulted in the only solution found. The salient feature of this technique is the elimination of the troublesome surface echo so that flaws close to the surface can be detected

(1) Lamb, Horace, "On Waves in an Elastic Plate", Proceedings of the Royal Society of London, Series A, Volume XCIII, Page 114.

(2) Firestone, F. A. and Ling, D. S., "Methods and Means of Generating and Utilizing Vibrational Waves in Plates", U. S. Patent No. 2,536,128 (January 2, 1951)

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with long time duration ultrasonic pulse.

PROPERTIES OF LAMB WAVES

Lamb grouped the infinite number of modes in which an elastic plate may vibrate into symmetrical and antisymmetrical types, according to the direction of the particle displacement. Unlike the more familiar longitudinal and shear modes, however, these waves travel in the metal with a phase velocity that is dependent upon the order of the mode, the frequency of the waves, and the thickness of the plate. The phase velocity is the velocity with which a disturbance (say the crest of a wave) runs along the plate and is to be distinguished from the group velocity which refers to the velocity of a short train of waves.

Figure 1 shows how the phase velocity in aluminum varies with the mode, frequency and thickness of the plate for the first three modes of the symmetrical and antisymmetrical types. To establish any given mode of vibration in a plate, the incident ultrasonic beam must satisfy the following relation,

$$\sin X = \frac{V_L}{V_P}$$

where V_L is the velocity of propagation in the incident medium, V_P is the phase velocity given from Figure 1, and X is the angle of incidence. Furthermore, to determine whether the plate is vibrating in the desired mode, one may simply place a receive transducer in a position to pick up a portion of the vibrational energy as it emits from the plate at the same angle X.

Consider, for example, a laminar flaw close to the surface of a metal, like the built-in flaw of the test block shown in Figure 2. It has been observed that the presence of flaws of this type can clearly be revealed by Lamb waves, presumably because a flaw allows the metal between it and the surface to vibrate as though it were a section of a thin plate. With

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the send and receive transducers at the proper angle to induce a Lamb wave mode in the region above the flaw, a large signal is received as shown by the waveforms (A). The signal disappears, however, when a flaw-free section of the block is inspected since in this case no Lamb waves are established. The Lamb wave shown is believed to be of the first symmetrical mode, since the transducers were set at about 30 degrees, in good agreement with the value calculated from equation (1) with V_L taken as 57,000 in. /sec (the velocity of sound in water) and V_P obtained from Figure 1 as 120,000 in. /sec. Any desired mode could be established simply by adjusting the angle to the suitable value.

Some important aspects concerning applying Lamb waves to practical testing problems can now be pointed out. The most striking thing, of course, is the fact that the flaw so close to the surface is clearly detected with the comparatively low ultrasonic test frequency of 2. 25 megacycles. This is emphasized by the waveforms (B) in Figure 2 which were obtained by testing the block at the same frequency by the conventional single crystal method.

It will be noted from the waveforms that in testing with Lamb waves the usually troublesome surface echo is almost absent. This is because, fortunately, the required angular position of the transducers is different than that in which the reflected surface echo is a maximum. In practice the small amount of surface reflected energy that reaches the receiver can be eliminated effectively by inserting a barrier between the transducers, as shown in the sketch. Whereas with conventional testing methods the problem of distinguishing the flaw echo from the surface echo becomes increasingly difficult as flaws come closer to the surface, with Lamb waves this requirement is eliminated since the surface echo is not present. Consequently, the testing pulse may have a time length as long as desired and the expense and complexities of a wide band electronic system can be avoided.

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Secondly, we see from Figure 2 that the first mode curves are horizontal for frequency-depth products larger than about 1.4×10^5 cycles in./sec. This means that with a given test frequency and metal, flaws may vary in depth up to a minimum value, and be detected by a fixed angular setting of the transducers. Moreover, increasing the test frequency extends the range closer to the surface. At ten megacycles, for example, the minimum depth in aluminum is extended to within 0.014 inches of the surface.

It is often desirable, particularly in automatic testing, to make a discrimination of the defects encountered according to flaw size. This permits acceptance of test pieces that contain flaws small enough to be considered satisfactory for the particular application for which the pieces are intended. With single crystal testing, some information pertaining to the size of a flaw can usually be ascertained from the amplitude of its echo pulse, although not very precisely since the echo amplitude is dependent upon other factors as well. Lamb wave testing offers an advantage in this regard because the magnitude of the response of any given flaw can be controlled by adjusting the spacing of the send and receive transducers relative to one another. In other words, small flaws can be ignored simply by separating the transducers the proper distance. This is illustrated by the curves in Figure 3, which were obtained from a test block containing built-in defects of different size.

With a fixed angular setting, the test head was twice scanned along the test block. In the first scan the transducers were placed as close together as possible, and both flaws were observed to respond with nearly the same amplitude. On the second scan with the transducers separated, the amplitude response of the smaller flaw was greatly reduced. Thus by properly spacing the transducers, an automatic test can be devised in which only flaws of the desired magnitude are rejected. The flaw sizes are distinguished by electronically monitoring the amplitude of the received pulse. This feature was an advantage in applying Lamb waves to the problem described below.

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BOND TESTING HANFORD FUEL ELEMENTS

The Hanford fuel element consists of a uranium cylinder encased in and metallurgically bonded to a thin aluminum jacket. The uranium core is slightly less than one and one-half inches in diameter by about eight inches long, and the aluminum sheath is about 0.045 inches thick. Because of dimensional tolerances and the process by which the components are assembled, the bonded uranium-aluminum interface in finished elements varies from about 0.030 to 0.070 inches below the surface of the aluminum. Without describing the canning process, it will be sufficient for our purposes to say that elements may be produced with improperly bonded areas at the uranium-aluminum junction. Unbonded areas are objectionable because they impede the flow of heat that is generated internally within the core by the nuclear reaction.

Although it may seem surprising in view of the cylindrical shape of the pieces, such flaws can be readily detected with Lamb waves Figure 4 is the result of plotting received pulse amplitude versus the angle of incidence as the ultrasonic beam is directed at a typical unbond flaw. The curves show the angles of four Lamb wave modes and it is evident that any one of these clearly reveals the flaw. In the waveforms of the figure, for example, the settings were fixed at 17 degrees while the region of the element containing the flaw was rotated into the ultrasonic beam. In Figure 5 the response obtained from the flaw is compared with that obtained from a flaw-free section, and these are shown together with a cross-sectional view of the element. The latter was obtained by destructively cutting the element through the plane of the flaw.

The photograph in Figure 6 shows the laboratory arrangement used in these studies A water tank is mounted on a conventional metal working lathe, with the test head attached to the lead screw so that the surface can be completely scanned as the elements are rotated. It was found that good results are obtained with the element rotating at about 900 rpm and the lead screw set at a 1/16 inch pitch, so that an element is completely scanned in about 9 seconds.

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In this case it is desirable that the alarm circuit of the automatic scanning equipment is not initiated for many of the smaller unbonded areas that are encountered. This is because the extent to which a given flaw impedes the flow of heat is proportional to its area, and in the interest of economy flaws smaller than a specified area are considered satisfactory for nuclear exposure. Consequently, a transducer spacing was determined which detects only those flaws extending more than a specified value in the scanning direction (along the axis of the element).

An interesting testing problem presented itself with the so-called Internally-Externally cooled fuel element. This element is similar to the standard Hanford element described above, except that an axial hole approximately three-eighths of an inch in diameter runs throughout its length. The surface exposed by the hole is bonded to an aluminum sheath, like the outside surface, and water is circulated through it to provide additional cooling. Unbonded areas appearing at the inside uranium-aluminum interface are objectional, of course, for the same reason as they are on the outside.

It was found after considerable experimentation that Lamb waves could also be applied to the testing of the inside surface for unbonds. An experimental probe that has been used to test many elements is shown in Figure 7. The main problem in the construction of this type of probe is setting the angular position of the transducers properly. In practice these settings are obtained experimentally, and then secured by potting the assembly in epoxy resin. Nylon bearings placed at each end of the transducers rotate with the element as it is scanned and serve to orient the transducers with respect to the tube wall.

Destructive examination has shown good correlation between the signal echoes and actual flaws. This test is operated at about the same scanning rate as the test of the outside surface. The transducer assembly shown operates at a test frequency of 20 megacycles per second.

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TESTING THIN STRIP

Lamb waves also offer a convenient method of testing thin metal strips. One such application investigated concerns the testing of brass strips 0.024 inches thick for the purpose of detecting abnormal grain structure. Many workers have observed in metals an increase of ultrasonic absorption with increasing grain diameter, and an experimentally determined relationship between grain size, the wave length of ultrasound, and absorption in brass has been previously reported.[3]

However in applying these results to testing thin sections with conventional methods, difficulty is encountered in providing a transmitting pulse short enough in time to resolve the front and back surface echoes. Lamb waves offer a neat alternative approach to the problem since they are readily established in thin sections, and since these waves also travel in metals with an attenuation that increases with the size of the grain structure. The results of testing 0.024 inch brass and 1/16 inch steel strip with this technique are shown in Figure 8. The transducer angles were set to establish a given mode in the sample under test, and then left fixed as other samples with different grain structures were tested. It is apparent that abnormal structures can be detected from their effect on the amplitude of the received signal.

The testing of thin strip for laminar flaws also suggests itself as another application of Lamb waves. In this case the absence rather than the presence of waves could reveal the flaw in much the same way as the loss of back reflection is sometimes used to reveal flaws in single crystal testing. Suppose, for the sake of illustration, that we wish to test aluminum strip 0.030 inches thick. If we choose a test frequency of five megacycles per second, the first symmetrical mode would be established in a flaw-free section of the strip at an angular setting of the transducers of approximately

(3) Worlton, D. C., "Nondestructive Grain Size Measurements with Ultrasonics", Journal of Nondestructive Testing, Volume XIII, No. 6 (November-December 1955), pages 24-26.

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30 degrees. With the transducers so set, a large response would be present at the receive transducer. If now a section of strip containing a laminar flaw were tested, the received signal would disappear since the flaw would in effect reduce the thickness of the plate. As seen from Figure 1, frequency depth products smaller than the value under consideration (1.5×10^5 cycles in./sec) rapidly changes the angular settings at which Lamb waves are established. This is a good example of an application where conventional testing methods have been of little value.

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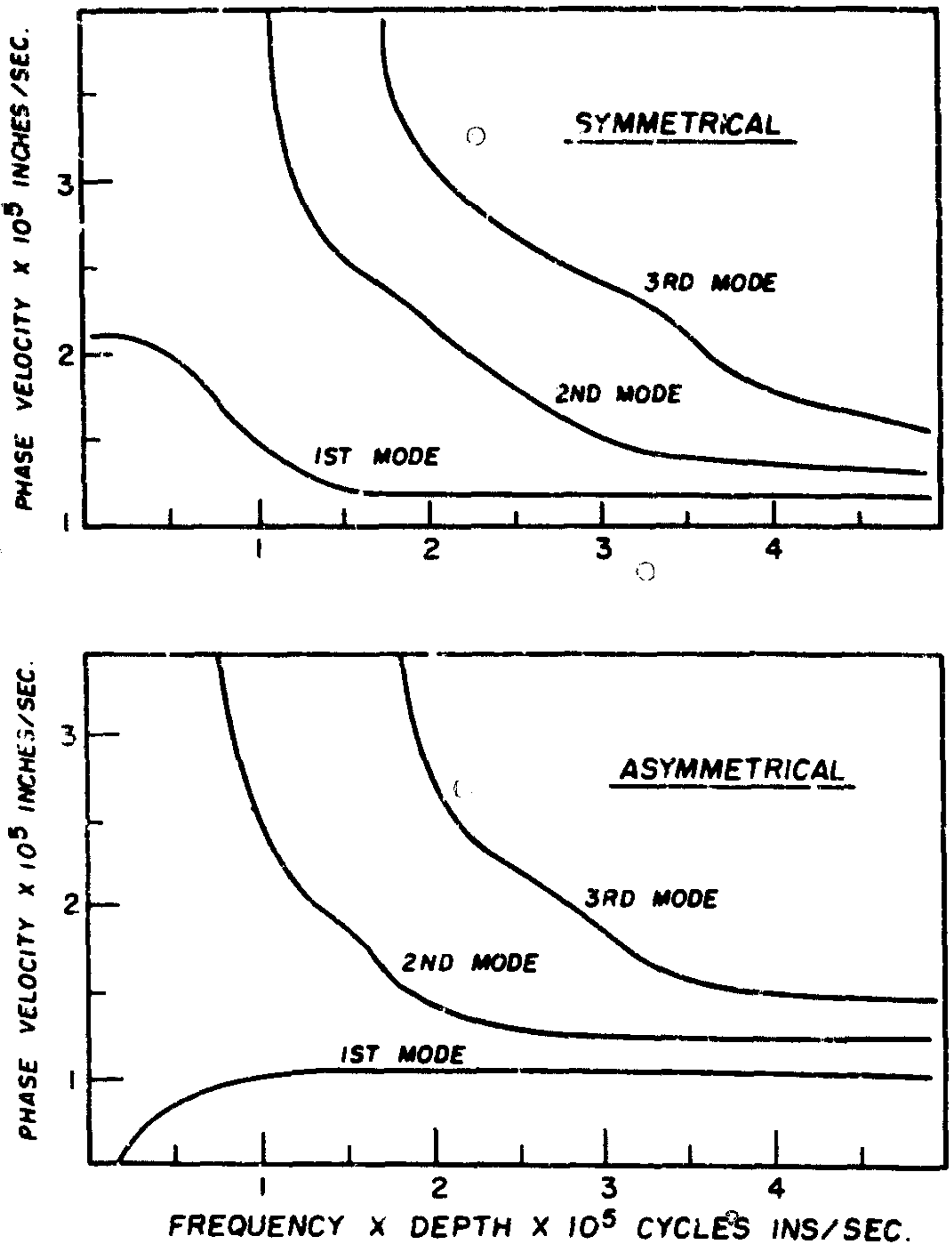

FIGURE 1

Lamb Wave Phase Velocity Versus Product of Depth Times Frequency for First Three Symmetrical and Antisymmetrical Modes

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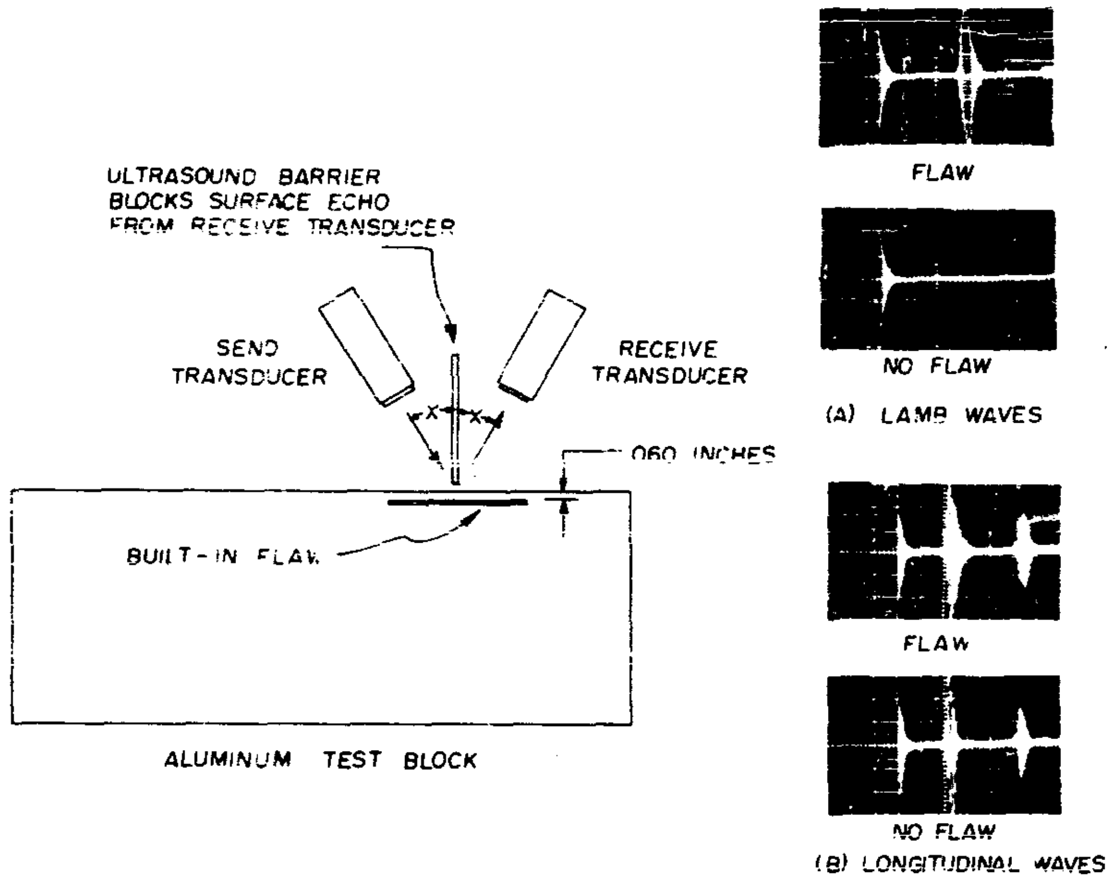

FIGURE 2

Testing Aluminum Block with Lamb Waves.
Waveforms (A) Show Lamb Waves Established.
Near Region of Flaw, Waveform (B) Shows Results of Testing for Flaw With Single Crystal Method.

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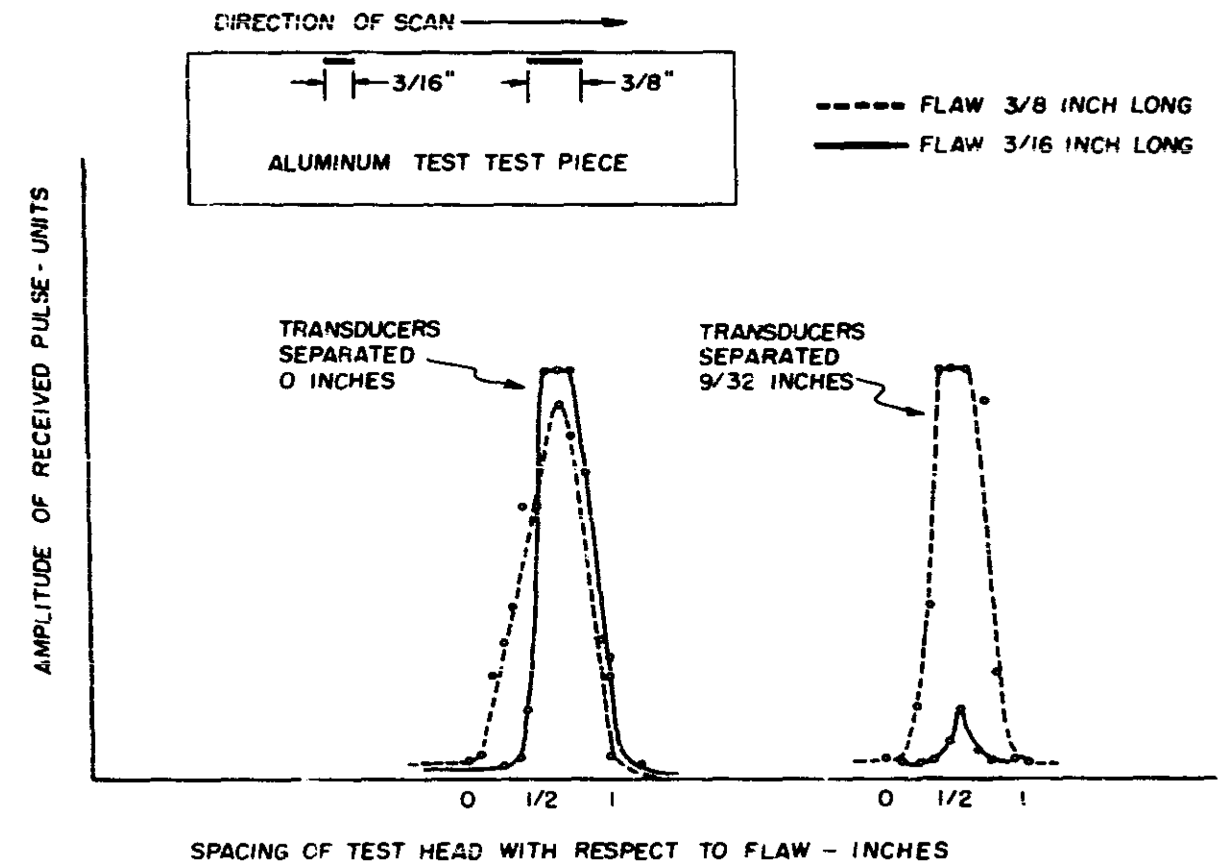

FIGURE 3

Curves Showing the Effect of Increasing the Distance between Send and Receive Transducers on the Amplitude Response of Different Size Flaws.

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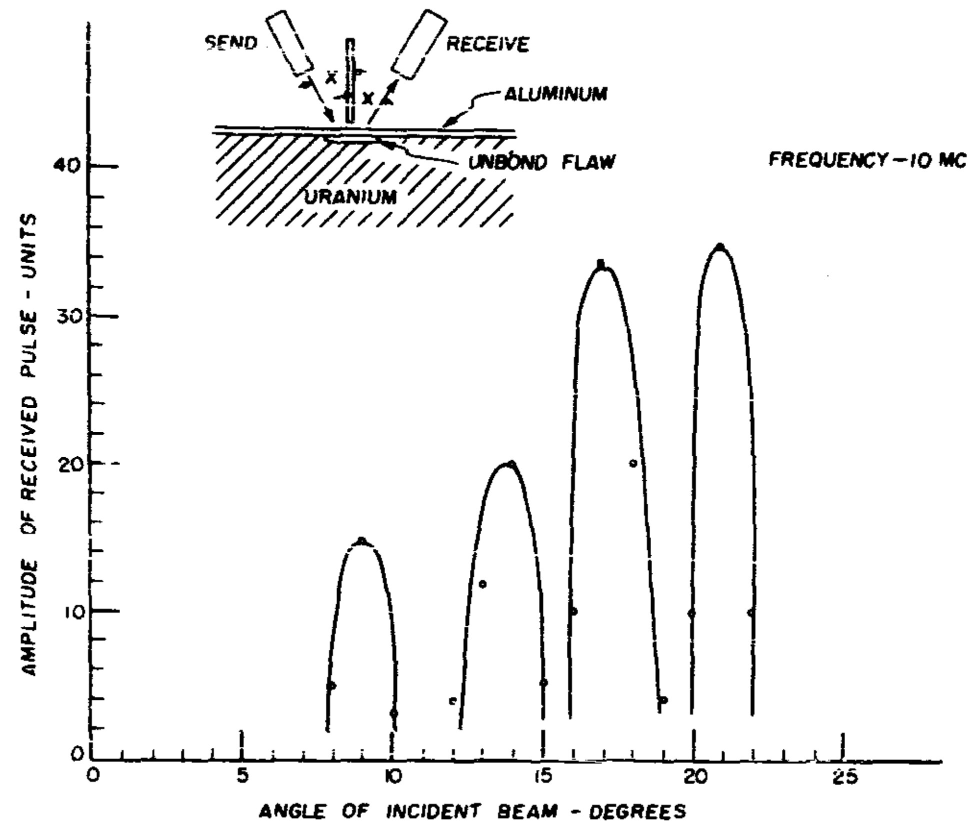

FIGURE 4

Curves Showing Four Lamb Wave Modes Established in a Typical Unbond Flaw. The Flaw is Destructively Revealed in Figure 5. The Waveforms Were Obtained with Transducer Setting of Seventeen Degrees and Show the Change in Signal Caused by the Flaw.

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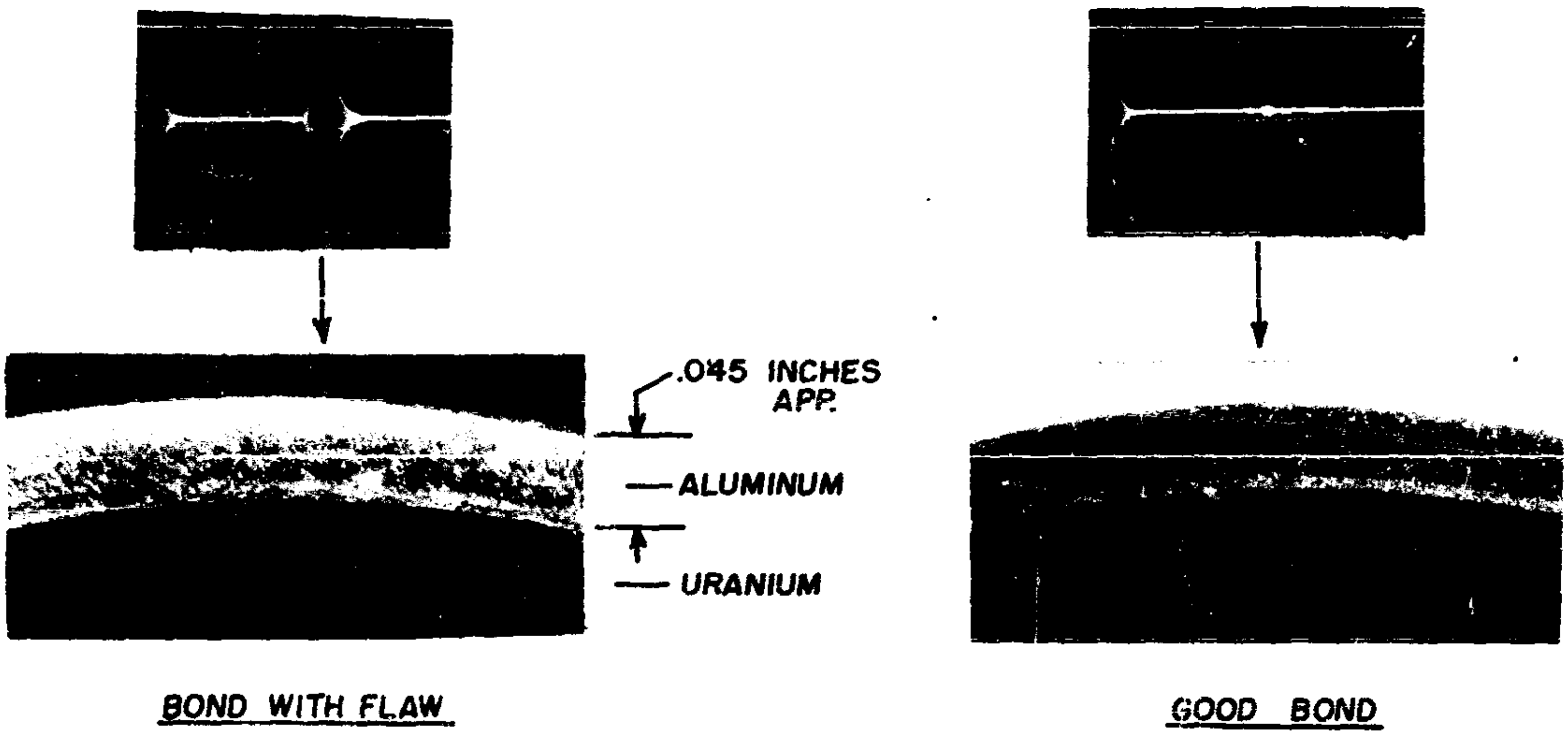

FIGURE 5

Typical Signals Obtained from a Bond Defect and a Good Bond with Cross-Sectioned Views of the Respective Bonds.

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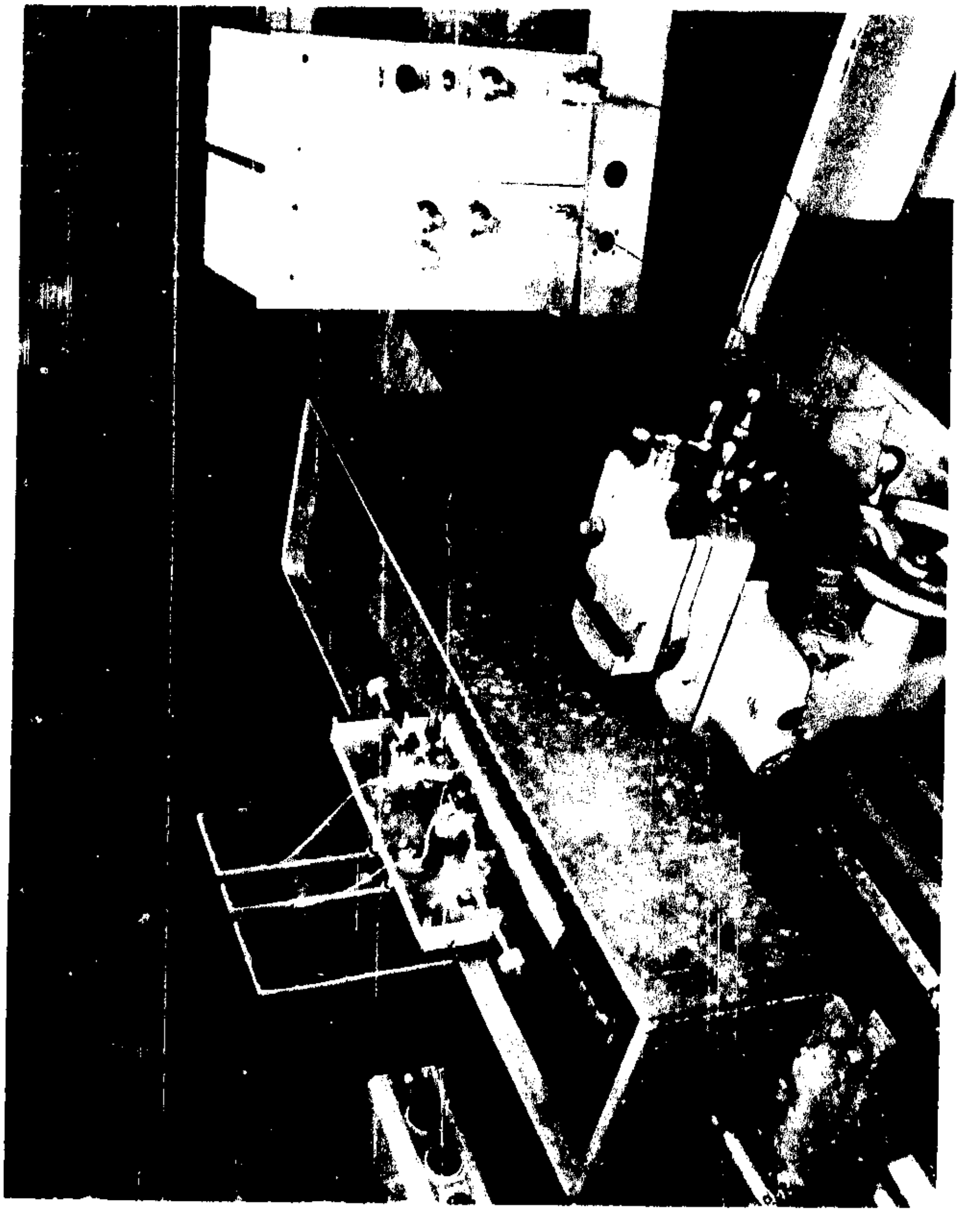

FIGURE 6

Laboratory Arrangement for Testing Fuel Elements with Lamb Waves

Photograph Unclassified

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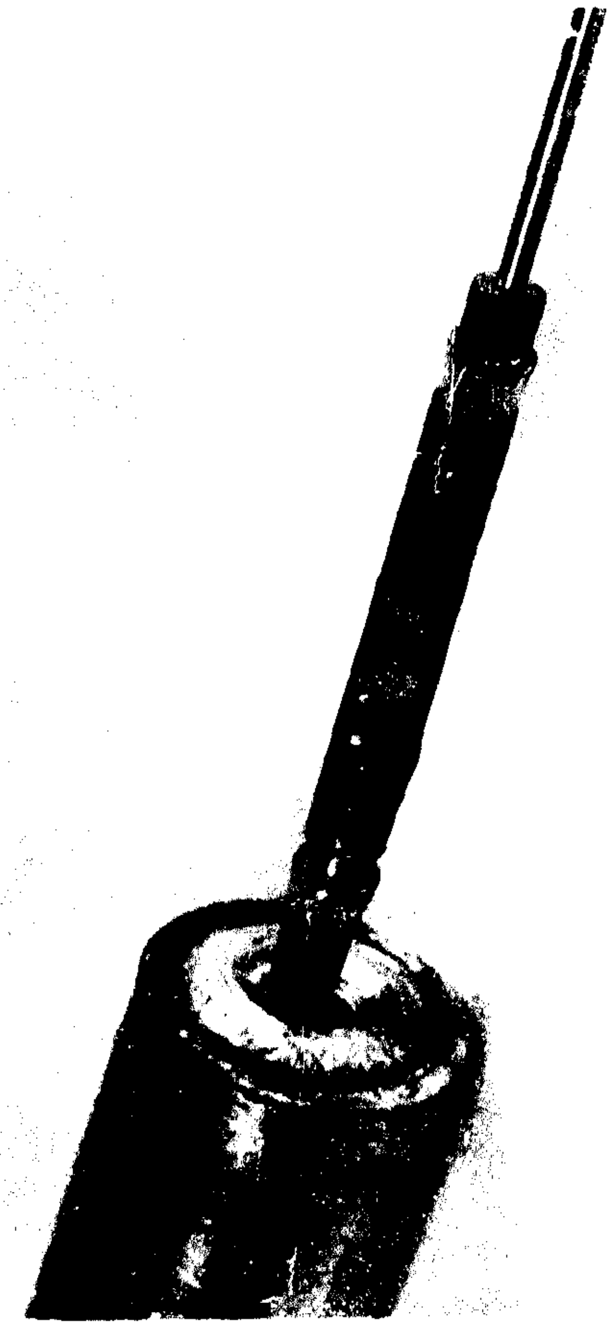

FIGURE 7

I and E Fuel Element with Ultrasonic Probe

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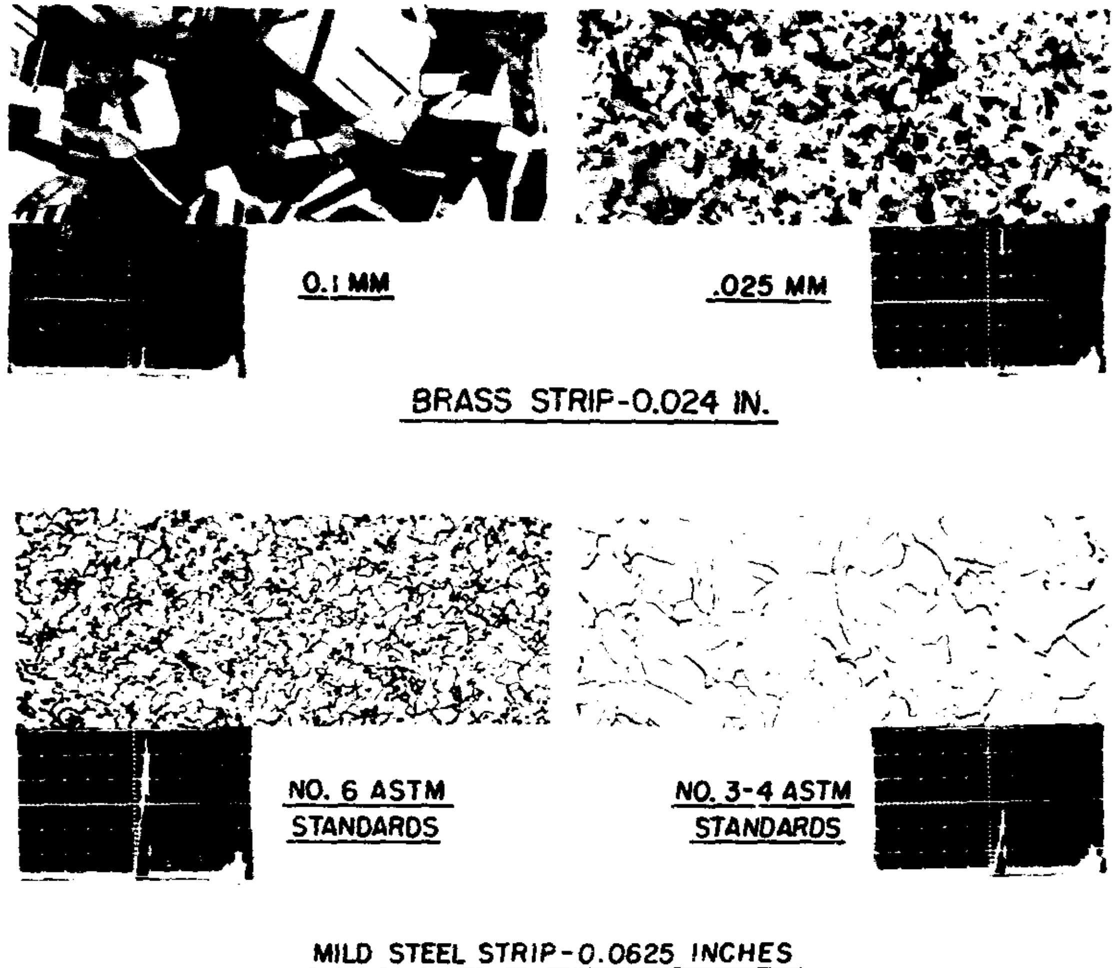

FIGURE 8

Results of Testing Thin Brass and Steel Strip for Grain Structure