RECENT IMPROVEMENTS TO THE ASTM-TYPE ULTRASONIC REFERENCE BLOCK SYSTEM

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Lee R. Gulley

LEE R. GULLEY, JR.
Project Engineer

FOR THE COMMANDER

THOMAS D. COOPER, CHIEF
Materials Integrity Branch
Systems Support Division

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Recent activities aimed toward improving the ASTM-type ultrasonic reference block system are described. On the aluminum block system (ASTM E127 and NBS TN 924), efforts were focused on better definition of the measurement equipment (transducer and instrument), the implementation of a Measurement Assurance Program and Loaner Block Service, and modeling of the distance-amplitude relationship. It is shown that a large increase in the precision of reference block readings is easily achievable by implementing simple changes and

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controls in the measurement procedure. On steel and titanium blocks (e.g. ASTM E-428), efforts were directed toward quantifying the extent of reproducibility possible among blocks fabricated by both conventional drilling and by diffusion bonding. Reasonable reproducibility is achievable by both, with the diffusion-bonding process offering both advantages and disadvantages.

FOREWORD

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SECTION I

INTRODUCTION

The ASTM-type ultrasonic reference blocks [1,2] are cylinders of metal with flat-bottomed holes drilled into one end of the cylinder. The flat bottom is a reference reflector for the standardization of ultrasonic systems, either for verifying system operating characteristics, for reference gain setting for a particular inspection procedure, or for accept/reject decisions for materials or structures. Typically these blocks are grouped into sets, either with different lengths and the same size hole (distance-amplitude set), or with different hole sizes and the same length (area-amplitude set). Even after numerous revisions in the standards documents, unacceptable differences in nominally identical blocks still exist, and inconsistencies or inadequacies in the equipment and procedure specifications make reproducing data very difficult. Two previous reports [3,4] have described initial NBS activities directed toward quantifying, understanding, and minimizing the variability of measurements taken with the ASTM-type reference block system. These studies identified metallurgical variables as an important consideration in the manufacture of repeatable reference blocks, identified and quantified some system parameters that must be controlled if repeatable measurements are to be obtained, reported results on pilot experiments for new manufacture concepts, and formed the technical rationale for the establishment of a calibration and loaner service for aluminum blocks [5].

This report describes further work in this area intended to extend these concepts to steel and titanium blocks and to better define the system variables and their effects on measurements. The goal of this activity, ultimately, is a measurement protocol by which repeatable measurements can be made on different systems by different operators. An ideal result would also include the mechanism to transfer measurements between materials with different acoustic properties. This would allow a single set of physical standards to be used for the inspection of a variety of materials.

SECTION II

TECHNICAL PROGRESS

1. IMPROVEMENTS TO THE ALUMINUM REFERENCE BLOCK SYSTEM

Most of the early effort was expended on aluminum reference blocks, since the system for these blocks probably has a better technical foundation in terms of supportive data. It was thought that improvements made in the aluminum system could be applied directly to steel and titanium, or negatively speaking, if you can't make repeatable measurements in aluminum, you definitely can't in steel or titanium.

a. Transducer Characterization

The weak link in most ultrasonic measurement systems is the transducer. Transducers are not reproducible, are unstable, are damaged easily, and wear out. Unfortunately, their characteristics significantly affect quantitative results obtained in a test. The ASTM working section on aluminum reference blocks, E7.06.02, is actively pursuing an improved specification for transducers used to check reference blocks.

Posakony [6] has been studying the effects of transducer design and excitation waveform on the output of quartz transducers. At NBS, we completed a study* intended to quantify the extent of the difference in reference block response when measured with different but very similar transducers, and to identify what characteristics of the transducers contributed to these differences [7]. A critical parameter, seldom specified explicitly or exactly, was the shape

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*partially supported by this project

of the far-field on-axis pressure amplitude. Among six nominally identical, 5-MHz, 0.375-in (9.52-mm) quartz transducers, readings from the same reference blocks, taken in accordance with the procedures and equipment specified in ASTM E-127-75*, differed by more than 25 percent (table 1 and fig. 1), while axial pressure amplitude varied by as much or more (table 2). Further, the two were highly correlated (fig. 2). Other commonly-measured characteristics were fairly uniform among the six transducers (table 3). This suggested that far-field axial pressure amplitude is an important parameter that must be controlled, or corrected for, if reproducible results are to be obtained with different transducers.

To test this hypothesis, a new experiment was run, whereby, for each transducer, the system gain was reset at the equivalent water distance for each reference block being read. This operationally forces the axial profiles of the transducers to be the same on a point-by-point basis. For this experiment, the differences among readings of the same reference block, taken using the six transducers, were less than about 5 percent (table 4). These experiments are described in more detail in [7].

Subsequent to the publication of [7], these experiments were repeated with two 5-MHz, 0.375-in (9.52-mm) ceramic transducers. These were significantly more broadband than the six quartz units, and some other characteristics also varied (table 3). The second experiment, forcing the axial profiles to be the same as for the quartz transducers, failed to bring the reference block readings in line with the results obtained with the quartz transducers (table 4). This suggests

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*The equipment used in the experiments reported herein is described in more detail in Appendix A.

that axial profile is a necessary though not sufficient transducer parameter, and possibly points to bandwidth as a parameter requiring additional study.

The goal of these studies is a comprehensive performance specification for transducers that will allow repeatable measurements to be made, at different times and places, on either reference blocks or real parts. At present, quartz transducers are specified in ASTM E 127 and our calibration service because they were thought to be more stable and uniform. The data shown in figure 1 show that the present specification is not sufficient. We are having fabricated two ceramic transducers with the same characteristics as our two lab standard quartz transducers (LS-3 and LS-4 in table 3), including the same axial pressure amplitude. If, as anticipated, these new transducers yield the same reference block readings as the two quartz transducers, we may indeed have a viable performance specification for transducers used for checking reference blocks. Since most ultrasonic inspection systems in use today incorporate ceramic transducers and solid-state broadband pulser-receivers (which lack sufficient power output to drive quartz transducers), this transfer to ceramic transducers should be a significant improvement to the system.

b. Other System Effects

An earlier report [4] documented some experiments performed to determine the effects of certain system operating adjustments on reference block response. These adjustments included cable type and length, pulse length, and fine gain control (called "cal" pot in [4]). The conclusion drawn from these experiments was that reference block response relative to a ball standard is much more sensitive to changes in system parameters than is reference block response relative to a reference block standard. This conclusion was a contributing factor in our decision to use a reference block as the primary standard in our calibration service, rather than a steel ball as in ASTM E 127. This minimizes the effect of small or unaccounted for changes in the system.

In defining a system for taking reference block measurements, it is fairly easy to standardize on cable and fine gain. However, variable pulse length is a desirable feature in order to achieve good front-surface resolution in short metal-travel blocks and good sensitivity in long blocks.

In order to more accurately specify the procedures for our calibration and loaner services [5,8], a new series of experiments to determine the effects of changing the pulse length was performed. The gain was adjusted so that a certain response was obtained from a steel ball, then a 5-0050 reference block was read per the ASTM E 127 procedure, at pulse length settings of minimum, approximately one-half, and maximum. The procedure was repeated with three transducers. The results are shown in figure 3. The reference block readings, relative to the ball standard, differed by as much as 13 percent for different pulse length settings, with significantly more difference noted from one-half to maximum than from minimum to one-half. Since changing the length of the output pulse changes the frequency spectrum of the transducer output, these data reinforce the concept that output bandwidth is an important parameter as noted in section 2a. Qualitatively, for constant pulse length, the reference blocks read higher with a more broadband transducer (see table 4). Figure 3 shows that reference block readings are increased, generally, by broadbanding the pulser (decreasing pulse length) for a given transducer. In actuality, the bandwidth of radiated field reflects the characteristics of the electrical pulse and the transducer, and the system response must be controlled if reproducible results are to be obtained.

c. Measurement Assurance Program and Loaner Blocks

The key elements of a Measurement Assurance Program are a well defined measurement algorithm that will allow reproducible measurements to be made in different laboratories, a mechanism for transferring standards or baselines between laboratories, and a data feedback/analysis scheme to assess measurement quality. To test the appropriateness of our calibration procedure for the MAP algorithm, we measured the ultrasonic responses of a distance amplitude set of blocks with five sets of equipment, i.e. two CRT's and four pulser/receivers in various combinations. Since we had already identified transducer variability as a major source of irreproducibility in reference block readings, we used transducer LS-4 for all readings in this series of tests in order to assess only instrument variability effects. The pulse lengths of all systems were adjusted to achieve the electrical output characteristics of our calibration system [5] as closely as possible. The results of these tests are shown in table 5. The standard deviation of the readings taken with the different equipments was generally less than 1 percent of upper linear limit*. For a standards system in which 40 percent difference among "standards" is not uncommon, this 1 percent is extremely good reproducibility.

To provide the transfer mechanism, sets of loaner blocks were fabricated. A special batch of aluminum alloy 7075-7651 extruded rod was purchased for the

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*Ultrasonic flaw detector amplitude readings are relative amplitude readings taken from a cathode ray tube (CRT) display. In practice, the receiver-amplifier-display circuits are usually nonlinear above a certain vertical deflection. This deflection is determined and defined as the "upper linear limit." Vertical amplitude values can then be expressed in "percent of upper linear limit."

fabrication of these blocks. This material was examined metallurgically for uniformity of texture and grain size among the different bars and was found to be suitable for this work [9].

Eighteen reference blocks were fabricated in the NBS machine shop from this material. Of these eighteen, twelve were extremely close to the average of all data taken to date on the NBS system, and were anodized, plugged, engraved, and calibrated as NBS Loaner Blocks. The data for one set of these, designated NBS Loaner Set 1, compared to the average values and the empirical master curve (described later in sec. 2d) are shown in figure 4.

Loaner Set 1 was used to test the effectiveness of the transfer mechanism and further quantify system effects, by a complete interlaboratory intercomparison on three distance-amplitude sets of reference blocks. These sets were shipped to NBS and calibrated, by us, on our system, directly against the master standard. They were also checked against ASTM E 127-75 (steel ball standard). They were then returned to the owner, along with Loaner Set 1 and our transducer LS-3.

The owner then rechecked his blocks on his instrument, with our transducer, following the NBS calibration procedure [5], with the system gain set such that the 5-0050 block in the loaner set read its calibrated value of 80.5 percent of upper linear limit. Thus the loaner block functions as a secondary, or transfer, standard in the calibration pyramid in much the same way that working-standard masses or gage blocks are used in a standards lab. The data taken using transducer LS-3 are shown in table 6. The average difference between the NBS reading and the owner's reading for all thirty-six blocks is only 1.3 percent of the upper linear limit. The data taken using the ASTM E 127-75 procedure are shown in table 7. Here the average difference in readings is 5.8 percent of the upper linear limit. This intercomparison is an important demonstration that reasonably precise measurements can be transferred to the field if the problems of transducer variability can be eliminated. It also points to a weakness in the ASTM system, in which the use of ball standards introduces a sensitivity to subtle differences in system parameters that results in larger differences in reference block readings.

d. Distance-Amplitude Modeling

Originally a calibration report for a set of blocks was accompanied only by the average of all data taken to date for comparison purposes [5]. This was because no suitably accurate theoretical or empirical model for the ultrasonic response of distance-amplitude sets of reference blocks existed. Such a model would serve at least three useful functions: 1) it would serve as a basis for comparison for reference block calibrations, 2) it could serve as the transform algorithm between materials and possibly lead to the use of single-material reference blocks, and 3) it could be used to assess the accuracy of or improve the use of the automatic distance-amplitude-compensation (DAC) systems which are used with many ultrasonic flaw detectors.

We have accumulated a data base of the ultrasonic response from over 200 aluminum reference blocks read with one system. The least-squares best fits to this data base were calculated for seven models, some suggested by theory, some by the electronics used in DAC systems, some by the data [8]. The nonlinear least squares fitting routines recently developed in DATAPLOT [10] made this a relatively simple computational task. The data base and selected fits are shown in figure 5.

The best fit, among the models tested, was provided by the generalized exponential over quadratic, $y = \exp(\alpha x)/(a+bx)^2$. This is theoretically founded, in that the exponential accounts for material attenuation, and the inverse quadratic is the predicted relation for reflection from a disc in the far-field (the DGS diagram [11]). For the aluminum reference block data, the α coefficient was computed to be essentially zero, as one might expect because of the relatively low attenuation in aluminum at 5 MHz. The a and b coefficients should be related to transducer characteristics, transducer-to-top surface water distance, ratio of sound speeds in aluminum and water, reflection and transmission coefficients, etc. In its present form, this model is useful for comparison purposes in reference blocks and may be useful in sorting out some of the problems in DAC systems. Further work will include attempts to relate the coefficients to physical quantities, system parameters, and material properties. This could lead to transform algorithms for different materials, including the use of single-material reference blocks.

e. Intercomparison with AQD Labs

In the United Kingdom, the Aeronautical Quality-Assurance Directorate (AQD) Laboratories maintains a master set of aluminum reference blocks and provides a service for calibrating user blocks against the master set [12]. We obtained from AQD Labs a set of their "Working Standards" and calibrated them on our system. The correction factors for these working standards, as assigned by AQD by comparison to their master set, ranged from -3.2 to +2.6 dB at 5 MHz. However, even when corrected by these amounts, the blocks read systematically about 2 dB low when compared to our master curve and data base (fig. 6). No reason for this large, systematic difference is immediately obvious.

2. DEVELOPMENT OF STANDARDS FOR OTHER MATERIALS

a. Quartz

If the appropriate transfer algorithms can be developed, a single material could then be used to standardize for a test of any material. Microstructural uniformity, low attenuation, and optical transparency make quartz or crown glass possible candidates for these standards. We have fabricated flat-bottomed-hole blocks in quartz by conventional methods in one piece, by wringing together two pieces, one with a through-hole, and by thermally fusing together two pieces. The wringing technique appears to be the more promising technique, as corner-radius and crazing cracks are difficult to eliminate in machining quartz and the exact thermo-mechanical cycle for fusion is difficult to achieve. One disadvantage of all three techniques is the relatively high fabrication cost compared to metal blocks. An interesting spin-off advantage of transparent blocks is that they provide a medium for visualizing the sound-beam interaction with the flat-bottomed hole by techniques such as photoelasticity [13].

b. Steel and Titanium

Our plan is to establish calibration services and loaner services for steel and titanium reference blocks similar to those established for aluminum. As a first step, special order uniform lots of bar stock were procured. The steel was 4340 alloy, aircraft quality, vacuum remelted, purchased from a reference block manufacturer, having already passed his quality control checks. The titanium was 6 Al-4V alloy, special purity and uniformity, purchased from a titanium producer. Approximately 25 feet of steel and 50 feet of titanium were purchased.

A primary objective of this study was to determine the relative merits of the diffusion bonding [14, 15, 16] process versus conventional drilling for making flat-bottomed-hole reference blocks in titanium and steel. The advantages of diffusion bonding include: 1) the elimination of the need to drill relatively deep (at least 0.5 in, 1.2 cm) flat-bottomed holes with tight tolerances on diameter, flatness, corner radius, and parallelism of the bottom to the entry surface; 2) when fabricated in the three-piece geometry as shown in figure 7, each block is really two blocks. The metal distances can be selected and paired so that all blocks are the same length, thus obviating the need for special holders or continual adjustment to maintain constant water path in immersion testing. 3) reference reflectors with other geometries, such as spheres, hemispheres, ellipsoids, etc. can be easily fabricated. The disadvantages are mainly cost of fabrication and metallurgy. The bond must be formed in an inert atmosphere or a vacuum, and a high-temperature furnace in which axial pressure can be applied is required. When the induction heating coil technique is used, a very non-uniform heat treatment is applied to the sample. Post-fabrication thermal aging is required. Since the blocks are made individually, each could experience a slightly different thermal cycle, thus introducing microstructural variations affecting sound-beam propagation.

We were able to borrow, at different times, two area-amplitude sets of diffusion-bonded steel blocks. The first set was evaluated only for a 3-in (76-mm) metal distance. The second set was evaluated for both a 3-in (76-mm) and a 0.75-in (19-mm) metal distance. Unfortunately, these two sets were evaluated at different times, and the same ultrasonic equipment was not available to us at both times. Therefore no direct absolute comparison between the two sets, on an amplitude basis, could be drawn. However, other conclusions about the applicability of diffusion bonding could be drawn.

The data for the three "sets" [two at 3-in (76-mm) and one at 0.75-in (19-mm) metal distance] are shown in table 8 for evaluation at 5 and 10 MHz. The data for the two 3-in (76-mm) sets are shown in figure 8. The linearity of these sets is, in general, quite good. Down to the two smallest blocks, where the 1 or 2-unit reading error is greater than 1 dB, the blocks were all within about ± 1 dB of the least-squares straight line. The residual standard deviations, measuring the "average" dispersion of the data from the fitted curve, were 7.7 percent and 12.5 percent for the two 3-in (76-mm) sets, both within about 1 dB. Current state-of-the-art (e.g. ASTM E 127 or E 428) is about ± 2 dB, although better results can be achieved with judicious material prescreening or selection among replicates to match blocks into a good set. No prescreening or matching was done with the diffusion-bonded blocks. Additionally, the relative responses of a given hole, in the second set, are generally close when inspected from both ends (see table 8), with the notable exception being the No. 6 hole.

This would indicate good control over the fabrication process, with little distortion of the hole during bonding. The owner of these blocks intends eventually to section them for optical inspection. We hope this will show the cause for the variation in the No. 6 block.

To evaluate more precisely the reproducibility among replicate blocks we had some blocks fabricated by the two techniques. For conventional drilling, we contracted a reference block manufacturer to supply, from the material described previously, five replicates each of 5-0050 and 5-0300 reference blocks of steel and titanium (total 20 blocks). The intent of the study was not revealed to the fabricator beforehand, and no material prescreening or over production and selection was permitted. The results of the evaluation of these blocks, at 5 MHz, are shown in table 9. All blocks were within about ± 10% of the average, and all but 2 were within ± 5%. This reinforces the concept, stated earlier for aluminum [4], that blocks reproducible within ± 5% can be produced by competent, experienced machinists, from a single lot of uniform, metallurgically clean material.

We also fabricated, in the NBS Instrument Shops, two diffusion-bonded blocks, from each material, with the geometry shown in figure 7. Since the metal distance, to the hole, is the same on both ends, this gave us four replicates for each material. The details of the diffusion bonding process, and the techniques used to evaluate the quality of the bonds, are given in Appendix B.

One immediately noticeable difference in the diffusion-bonded blocks, compared to the conventional blocks, is the increased noise level in the heat-affected zone in titanium. This was not so obvious in steel. Figure 9 shows A-scan presentations of the signals from diffusion-bonded and conventional blocks of titanium showing an increase, by a factor of about 2, in noise in the heat-affected zone. This was not removed by a thermal aging cycle of 900°F (482°C) for 8 hours and air cool. This obvious metallurgical variation could well be responsible for the variation in ultrasonic response of these blocks. Also, the two steel blocks were slightly skewed (about 1.8 degrees) after fabrication (fig. 10). However, this did not appear to seriously affect the usefulness of the blocks for our purposes.

The ultrasonic response values, at 5 MHz, of the diffusion bonded blocks are shown in table 10 (A). All readings were taken with the transducer angulated to maximize the top-surface reflection. It is interesting that the average responses of the blocks are quite close to the average responses of the corresponding blocks made by conventional drilling (table 9). However, the variation among the four readings is somewhat higher for steel and significantly higher for titanium. Only titanium specimen 1 (A and B) has been thermally aged subsequent to the bonding process. It should be noted that these were first efforts, and with experience and refinements in the fabrication procedures the quality of the end product should improve. As a pilot quantitative assessment of the inherent variability of blocks made by diffusion bonding, these statistics could be considered upper bounds.

To determine whether the variation in diffusion-bonded block readings was possibly caused by non-parallelism of the front surface and the bonded surface, i.e. the flat-bottom hole, the transducer was angulated a few degrees in two planes and repositioned laterally to obtain maximum flat-bottom hole response. This is the technique prescribed in [1] for determining the parallelism of hole bottom-to-top surface, with a 10 percent increase in flat-bottom hole response, relative to the response with the beam normal to the top surface, being acceptable. The changes in the response values for the steel blocks were not significant (table 10 B), possibly indicating that the non-axial deformation resulting in the skewness occurred mainly in the 0.25-in (6.4-mm) wafer, thus leaving the top surface and FBH-surface essentially parallel. Although no alignment problem was suspected in the titanium blocks, the maximized flat-bottom-hole responses were significantly higher than the normal response values. However, similar experiments on conventional blocks of aluminum, steel, and titanium showed this to be typical of titanium, not typical of steel and aluminum. Conversations with a reference block manufacturer [17] revealed that, in his experience, this is not atypical of titanium and some steels, and is not necessarily related to parallelism of the top surface and flat-bottom hole. It could be that the attenuation is so nonuniform that changing the ultrasonic path only slightly by reangulating and repositioning the transducer decreases the attenuation enough to offset the decrease in response due to misalignment.

Future plans include sectioning the diffusion-bonded blocks to evaluate the quality of bond, geometry of the hole, attenuation characteristics of the parent material, etc. For diffusion bonding to become a viable alternative for reference block manufacture, the question of how to evaluate nondestructively the parallelism of the top surface and FBH surface must be answered. Procedures for carefully controlling the fabrication parameters (temperature, pressure, time, alignment) must be developed. Appropriate thermal treatment cycles must be documented. Others working in this area may have already solved a few of these, but these fabrication and evaluation procedures must be documented and reevaluated before they can reach the standards stage.

SECTION III

DISCUSSION AND CONCLUSIONS

1. ALUMINUM BLOCKS

a. Transducer Characterization

The specification in E 127-75 is not sufficient to allow reproducible results to be obtained with different transducers. The bandwidth must be specified, and the far field axial profile must be specified numerically, not just by "similar to," out to 20-25 inches (51-64 cm) of water. We hope the data with our new ceramic transducers, when available, will show that transducer material is not important, as long as it meets the performance specifications.

b. System Effects

Variable pulse length can introduce errors as large as ± 0.5 dB. A definite pulse shape (center frequency and bandwidth) must be specified. If the equipment is properly tuned to specification, results reproducible within about 1 percent of upper linear limit are achievable, with a given transducer, on different instruments. Steel ball targets, as standards, introduce a sensitivity to subtle changes in equipment characteristics. Flat disc reflectors, either in metals or water, yield more consistent results.

c. MAP

Aluminum loaner blocks are available as transfer standards for in-house calibrations. For a given transducer, results are reproducible within 1.3 percent of upper linear limit if the NBS TN 924 procedures are followed. This precision is more than four times better than that obtainable with E 127-75.

d. Distance-Amplitude Model

The best model, among seven tested, was the generalized exponential over quadratic $y = \frac{\exp(-\alpha x)}{(a+bx)^2}$. This is, theoretically, the response of a disc reflector in the far field, corrected for attenuation. This model and our large data base will serve as a basis for comparison for future calibrations.

e. AQD Intercomparison

The measurement system used in the United Kingdom is quite different from ours, using specially designed, rather than commercial, equipment. This appears to yield no improvement in the reproducibility of results. The AQD standards are systematically about 2 dB low in response when compared to typical blocks in this country.

2. OTHER MATERIALS

a. Quartz

Good reference blocks can be made from optical quartz by wringing together two pieces, one with no hole, one with a through-hole. The material and machining is expensive compared to metal blocks. Drilling flat-bottomed holes is not easy in quartz due to crazing. This type of block is useful for visualizing by photoelasticity, the sound beam interactions with flat-bottomed holes.

b. Steel and Titanium

Excellent results have been obtained in fabricating area-amplitude sets of steel blocks by diffusion bonding. With no material prescreening or block matching, the sets are linear within ± 1 dB.

From uniform lots of steel and titanium, replicate blocks fabricated by conventional drilling are generally reproducible within about ± 5 percent when made by an experienced machinist.

Diffusion-bonded blocks have been made with a variability of about ± 10 percent for steel and ±20 percent for titanium. Metallurgical differences caused by uneven thermal treatment and means for the nondestructive determination of hole condition appear to be problems in titanium blocks. There does not appear to be a lower variability of response in diffusion-bonded blocks as compared to conventional blocks, but the other advantages may make this process a practical alternative. Also, improvements in manufacturing processes may further improve the quality of blocks made by this technique.

SECTION IV

RECOMMENDATIONS AND FUTURE DIRECTIONS

Many of the tasks described in this report are continuing. Based on the results reported here and in previous reports, the following areas appear to be potentially fruitful:

1. The new ceramic transducers built to specification to match the quartz transducers now used will be evaluated. The specification will be revised as necessary so that reproducible transducers can be fabricated.

2. Detailed procedures and equipment for calibration and loaner services for steel and titanium reference blocks will be documented.

3. Further data gathering and modeling will be performed to correlate the modeling parameters to transducer characteristics and material properties. This could lead to material-independent reference blocks.

4. Further refinements in the diffusion bonding process will be attempted.

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Table 1 - Ultrasonic Reference Block Readings
Taken with Eight Nominally Identical Search Units

	LS-1	LS-2	LS-3	LS-4	LS-5	LS-6	Spread/Average Percent	α	γ
1/8-in ball (3.2-mm ball)	80	80	80	80	80	80	——	80	80
3-0050	93.0	82.2	97.7(a)	92.3	91.2(a)	94.8(a)	+ 6.3 -10.5	65	66
3-0100	49.7	50.0	58.5	54.5	51.7	61.3	+12.9 - 8.4	37	36.5
3-0225	20.3	20.2	24.5	23.2	21.7	25.5	+13.0 -10.5	14	14
5/16-in ball (7.9-mm ball)	80	80	80	80	80	80	——	80	80
5-0050	78.7	74.7	90.8	85.5	78.8	84.5(a)	+10.5 - 9.1	63	64.5
5-0100	47.5	48.8	61.3	56.8	50.5	56.8	+14.3 -11.4	37	39.5
5-0225	18.2	18.2	24.8	22.3	19.8	22.7	+18.1 -13.3	14	13.5
11/16-in ball (17.5-mm ball)	80	80	80	80	80	80	——	80	80
8-0050	78.8	77.7	91.0	86.5	80.8	86.0	+ 9.0 - 6.9	75.5	72
8-0100	50.3	50.8	63.5	59.0	53.0	59.7	+13.3 -10.3	47	44.5
8-0225	20.5	20.2	26.8	24.7	21.2	24.8	+16.3 -12.3	19	18

LS-1 through LS-6 are quartz; Alpha and Gamma are ceramic
All values are in percent of upper linear limit
All values are averages of three independent readings
(a) Not 100% resolved from front surface echo

Table 2 - Relative Axial Pressure Amplitude Values for Selected Water Distances

Water Distance		LS-1	LS-2	LS-3	LS-4	LS-5	LS-6	Spread/Average Percent	α	γ
in	cm									
3.5	8.9	100	100	100	100	100	100	——	100	100
5.62	14.3	59.8	59.5	71.7	66.3	60.3	66.7	+11.9 - 7.1	57	43.5
7.75	19.7	32.8	32.5	41.3	37.7	33.5	38.0	+14.8 - 9.6	29	21
13.1	33.3	8.8	9.0	12.2	10.5	8.7	10.7	+22.2 -12.8	6.5	4

LS-1 through LS-6 are quartz; Alpha and Gamma are ceramics.
All values are in percent of upper linear limit
All values are average of three independent readings.

Table 3 - Characteristics of Eight Nominal 5 MHz, 0.375 in (9.52-mm) Search Units

		LS-1	LS-2	LS-3	LS-4	LS-5	LS-6	α	γ
Yo^+ (a)	in (cm)	3.25 (8.3)	3.25 (8.3)	3.50 (8.9)	3.25 (8.3)	3.25 (8.3)	3.50 (8.9)	2.25 (5.7)	2.0 (5.1)
Y_1^- (a)	in (cm)	1.6 (4.1)	1.6 (4.1)	1.75 (4.4)	1.6 (4.1)	1.50 (3.8)	1.50 (3.8)	1.0 (2.5)	1.0 (2.5)
Y_1^- peak ratio		1.23	1.09	1.07	1.14	1.12	1.02	1.12	1.18
-6dB beam width at Yo+ (a)	in (cm)	0.09 (0.23)	0.10 (0.25)	0.10 (0.25)	0.10 (0.25)	0.10 (0.25)	0.10 (0.25)	0.08 (0.2)	0.08 (0.2)
Center frequency (b)	MHz	4.95	5.05	4.85	4.9	5.05	5.1	5.30	5.10
Center frequency (c)	MHz	4.95	5.0	4.9	4.85	5.1	5.2	—	—
-6dB bandwidth (b)	MHz	1.3	1.2	1.0	1.0	1.2	1.2	3.8	1.8
-6dB bandwidth (c)	MHz	1.4	1.3	1.0	1.0	1.3	1.2	—	—
Damping (No. cycles > 10%) (b)		7	7	8	8	6	7	3	6
Crystal Material		Quartz	Quartz	Quartz	Quartz	Quartz	Quartz	Ceramic	Ceramic

(a) Tuned pulser receiver, 1/2-in (12.7-mm) ball target
(b) Broadband pulser, return signal from flat plate
(c) Frequency at maximum power output, continuous wave excitation

Table 4 - Reference Block Readings with Sensitivity Set At Equivalent Water Distance for Each Block

	LS-1	LS-2	LS-3	LS-4	LS-5	LS-6	Spread/Average Percent	α	γ
5/16-in ball at 5.62 in (7.9-mm ball at 14.3 cm)	60	60	60	60	60	60		60	60
5-0050 block	97.6	95	96	96	96.3	95.2	+1.7 -1.0	95.5	107
5/16-in ball at 7.75 in (7.9-mm ball at 19.7 cm)	40	40	40	40	40	40		40	40
5-0100 block	74.3	76.8	76.5	78.3	74.5	76.3	+2.9 -2.4	81.5	90
5/16-in ball at 13.12 in (7.9-mm ball at 33.3 cm)	30	30	30	30	30	30		30	30
5-0225 block	76.5	76.5	77.3	78.5	77.8	79.7	+2.6 -1.5	89.5	94.5

LS-1 through LS-6 are quartz; Alpha and Gamma are ceramic

All values are in percent of upper linear limit

All reference block values are average of three independent readings

Table 5 - Ultrasonic Response of Block Set 122 Measured with Five Different Instrument Combinations

CRT	1	1	1	2	1		
P/R	A	C	B	B	D		
Block	Response	Response	Response	Response	Response	Average	Standard Deviation
5-0050	80.0	80.0	80.0	80.0	80.0	80.0	—
-0062	79.0	80.0	79.8	78.4	77.8	79.0	0.8
-0075	63.8	65.2	64.2	63.6	63.0	64.0	0.7
-0088	57.2	59.5	58.2	56.8	57.0	57.7	1.0
-0100	53.2	55.0	54.5	54.4	53.0	54.0	0.8
-0125	42.5	43.8	43.8	42.0	42.5	42.9	0.7
-0175	26.8	27.0	27.2	26.4	26.5	26.8	0.3
-0225	20.4	21.0	21.2	21.2	20.5	20.9	0.3
-0175	71.6	74.5	74.5	—	72.0	73.2	1.4
-0225	56.0	59.5	58.0	—	57.0	57.6	1.3
-0275	43.9	46.8	46.0	—	44.8	45.4	1.1
-0325	33.4	36.0	35.5	—	34.2	34.8	1.0
-0375	28.1	30.0	29.8	—	28.5	29.1	0.8
-0425	22.9	24.8	24.5	—	23.8	24.0	0.7
-0475	19.0	20.0	20.0	—	19.5	19.6	0.4
-0525	16.3	16.5	17.2	—	16.8	16.7	0.3
-0575	15.9	16.5	16.8	—	16.0	16.3	0.4

All Response Values are in Percent of Upper Linear Limit

All Data taken with Transducer LS-4

Table 6 - Summary of Intercomparison Data on Set DA 55 Taken with Transducer LS-3 and NBS TN 924 Procedure

	3/64 Hole			5/64 Hole			8/64 Hole		
Metal Distance	Lab 1	Lab 2	Diff.	Lab 1	Lab 2	Diff.	Lab 1	Lab 2	Diff.
-0050	70.8	67.6	3.2	80.7	80.0	0.7	66.7	66.7	0.0
-0075	54.7	54.2	0.5	61.3	63.1	1.8	59.2	60.0	0.8
-0100	48.0	48.0	0.0	47.5	48.9	1.4	40.8	42.2	1.4
-0150	39.8	40.9	1.1	29.0	31.1	2.1	30.7	32.0	1.3
-0200	29.8	31.1	1.3	24.0	24.4	0.4	25.7	26.7	1.0
-0250	23.7	23.1	0.6	17.7	17.8	0.1	16.3	16.9	0.6
-0200	79.0	82.2	3.2	65.5	66.7	1.2	69.3	73.3	4.0
-0250	63.5	66.7	3.2	49.8	49.8	0.0	45.2	44.4	0.8
-0300	47.2	53.3	6.1	43.3	44.4	1.1	35.6	35.6	0.0
-0400	30.8	33.3	2.5	23.3	23.1	0.2	23.0	23.1	0.1
-0500	16.2	18.7	2.5	21.0	21.3	0.3	19.2	20.0	0.8
-0600	13.7	15.6	1.9	17.8	17.8	0.0	17.7	17.8	0.1
	Average Diff.:		2.2	Average Diff.:		0.8	Average Diff.:		0.9
	Standard Dev.:		1.6	Standard Dev.:		0.7	Standard Dev.:		1.04

Grand Average Diff.: 1.3
Total Standard Dev.: 1.3

All response values are in percent of upper linear limit

Table 7 - Summary of Intercomparison Data on Set DA 55 Taken with Transducer LS-3 and ASTM E 127-75 Procedure

	3/64 Hole			5/64 Hole			8/64 Hole		
Metal Distance	Lab 1	Lab 2	Diff.	Lab 1	Lab 2	Diff	Lab 1	Lab 2	Diff
-0050	72.0	77.8	5.8	90.0	94.7	4.7	80.0	88.0	8.0
-0075	56.0	63.1	7.1	68.4	75.6	7.2	70.8	79.1	8.3
-0100	49.0	54.2	5.2	53.0	60.0	7.0	48.8	55.6	6.8
-0150	40.5	44.9	4.4	32.3	35.6	3.3	36.7	42.2	5.5
-0200	30.4	34.7	4.3	26.8	30.2	3.4	30.7	35.6	4.9
-0250	24.2	27.1	2.9	19.7	22.2	2.5	19.5	22.2	2.7
-0200	78.0	88.9	10.9	70.7	80.0	9.3	80.2	93.3	13.1
-0250	62.7	71.1	8.4	53.8	62.2	8.4	52.3	60.0	7.7
-0300	46.6	54.2	5.6	46.7	53.3	6.6	41.2	45.3	4.1
-0400	30.4	35.6	5.2	25.1	28.9	3.8	26.6	32.0	5.4
-0500	15.7	22.2	6.5	22.7	27.6	4.9	22.2	26.7	4.5
-0600	13.8	16.0	2.2	19.0	22.2	3.2	20.5	25.8	5.3
	Average Diff.:		5.7	Average Diff.:		5.4	Average Diff.:		6.4
	Standard Dev.:		2.3	Standard Dev.:		2.2	Standard Dev.:		2.6

Grand Average Diff.: 5.8
Total Standard Dev.: 2.4

All response values are in percent of upper linear limit.

Table 8 - Evaluation of Three Area-Amplitude Sets of Diffusion-Bonded Steel Reference Blocks

Set No. 1

	Ultrasonic Response	
Block	5 MHz	10 MHz
8-0300	67	97.5
7-0300	49	78
6-0300	33	57
5-0300	26	46
4-0300	17	29
3-0300	8	13.5
2-0300	3.5	6
1-0300	1	1

Set Nos. 2 (a and b)

	Ultrasonic Response			Ultrasonic Response	
Block	5 MHz	10 MHz	Block	5 MHz	10 MHz
8-0075	67	100	8-0300	67	100
7-0075	57.5	89	7-0300	57.5	90
6-0076	35.5	52	6-0300	41	63.5
5-0075	28	44	5-0300	29	49
4-0075	19	34	4-0300	20.5	31.5
3-0075	10	16	3-0300	9.5	15
2-0075	2.5	6	2-0300	2.5	4
1-0075	0.5	1	1-0300	1	0.5

All response values are in percent of upper linear limit.

Table 9 - Ultrasonic Response of Nominally Identical Steel and Titanium Reference Blocks Fabricated by Conventional Drilling

(a) Steel Blocks

Block	Ultrasonic Response	Block	Ultrasonic Response
5-0050-1	87.2	5-0300-1	64.7
5-0050-2	86	5-0330-2	63
5-0050-3	85.3	5-0300-3	65.3
5-0050-4	92.5	5-0300-4	66.3
5-0050-5	90.8	5-0300-5	64.8
Average	88.4	Average	64.8
Spread/Average	-3.5% +4.6%	Spread/Average	-2.8% +2.3%
Rel. St. Dev.	3.2%	Rel. St. Dev.	1.7%

(b) Titanium Blocks

Block	Ultrasonic Response	Block	Ultrasonic Response
5-0050-1	89.8	5-0300-1	76.3
5-0050-2	94.8	5-0300-2	75.3
5-0050-3	95	5-0300-3	66.8
5-0050-4	95.7	5-0300-4	80
5-0050-5	94.2	5-0300-5	73.8
Average	93.9	Average	74.4
Spread/Average	-4.4% +1.9%	Spread/Average	-10.3% +7.5%
Rel. Std. Dev.	2.2%	Rel. Std. Dev.	5.8%

All individual block response values are average of three readings.

All response values are in percent of upper linear limit.

Table 10 - Ultrasonic Response of Nominally Identical Steel and Titanium Reference Blocks Fabricated by Diffusion Bonding

A. Transducer Beam Normal to Top Surface

Steel		Titanium	
Block	Ultrasonic Response	Block	Ultrasonic Response
5-0300-10A	66.7	5-0300-1A	59.3
5-0300-10B	58.5	5-0300-1B	91.5
5-0300-11A	69.3	5-0300-2A	83.0
5-0300-11B	68.5	5-0300-2B	70.0
Average	65.8		76.0
Spread/Average	-11.1% + 5.3%		-22.0% +20.4%
Rel. Std. Dev.	6.5%		16.2%

B. Transducer Angulated and Positioned for Maximum FBH Response

Steel		Titanium	
Block	Ultrasonic Response	Block	Ultrasonic Response
5-0300-10A	67.5	5-0300-1A	75
5-0300-10B	63.5	5-0300-1B	93
5-0300-11A	71	5-0300-2A	100
5-0300-11B	71.2	5-0300-2B	90
Average	68.3		89.5
Spread/Average	- 7.0% + 4.2%		-16.2% +11.7%
Rel. Std. Dev.	4.6%		10.2%

All response values are in percent of upper linear limit.

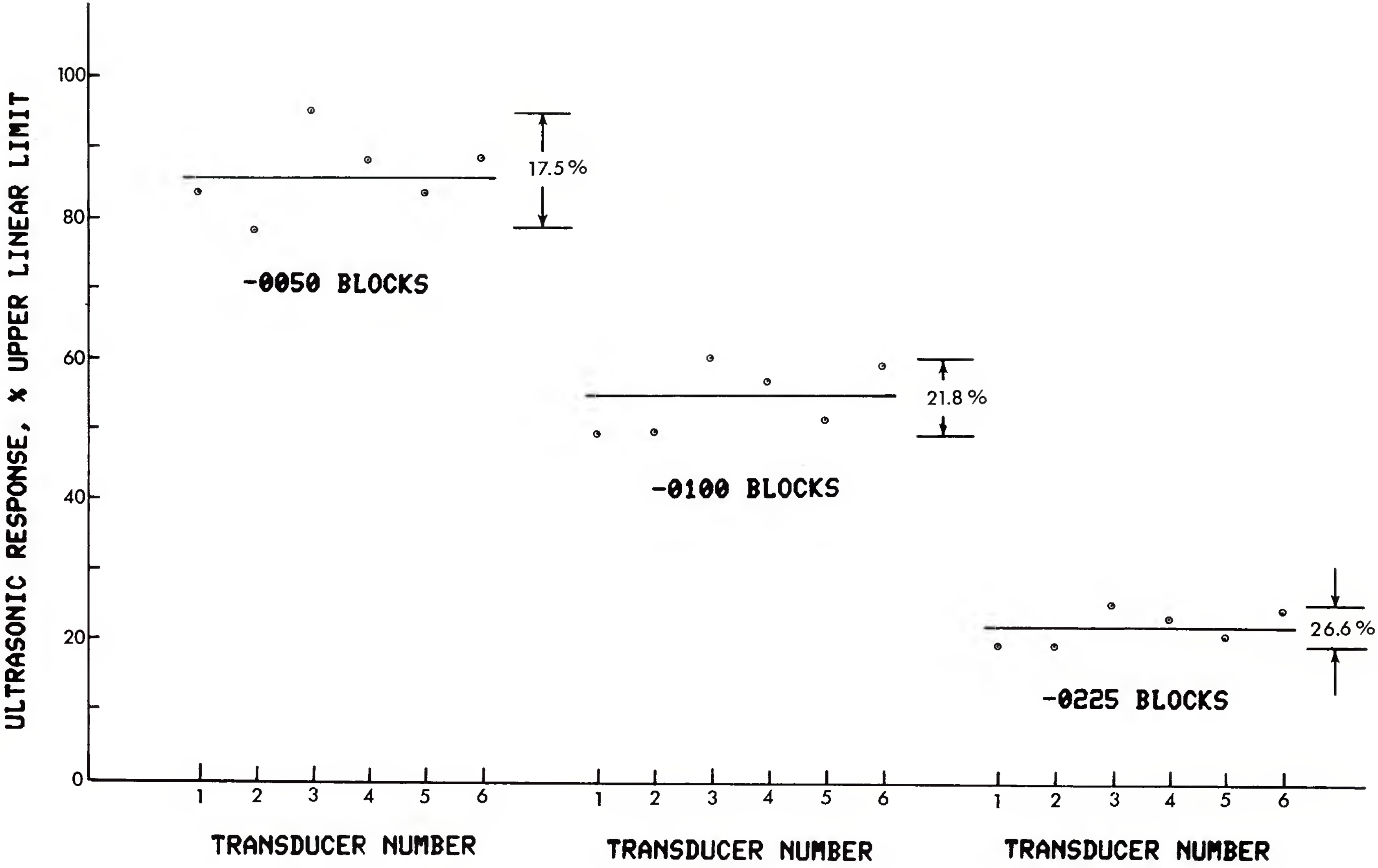


FIGURE 1 - VARIABILITY IN REFERENCE BLOCK READINGS TAKEN WITH SIX NOMINALLY IDENTICAL QUARTZ TRANSDUCERS.

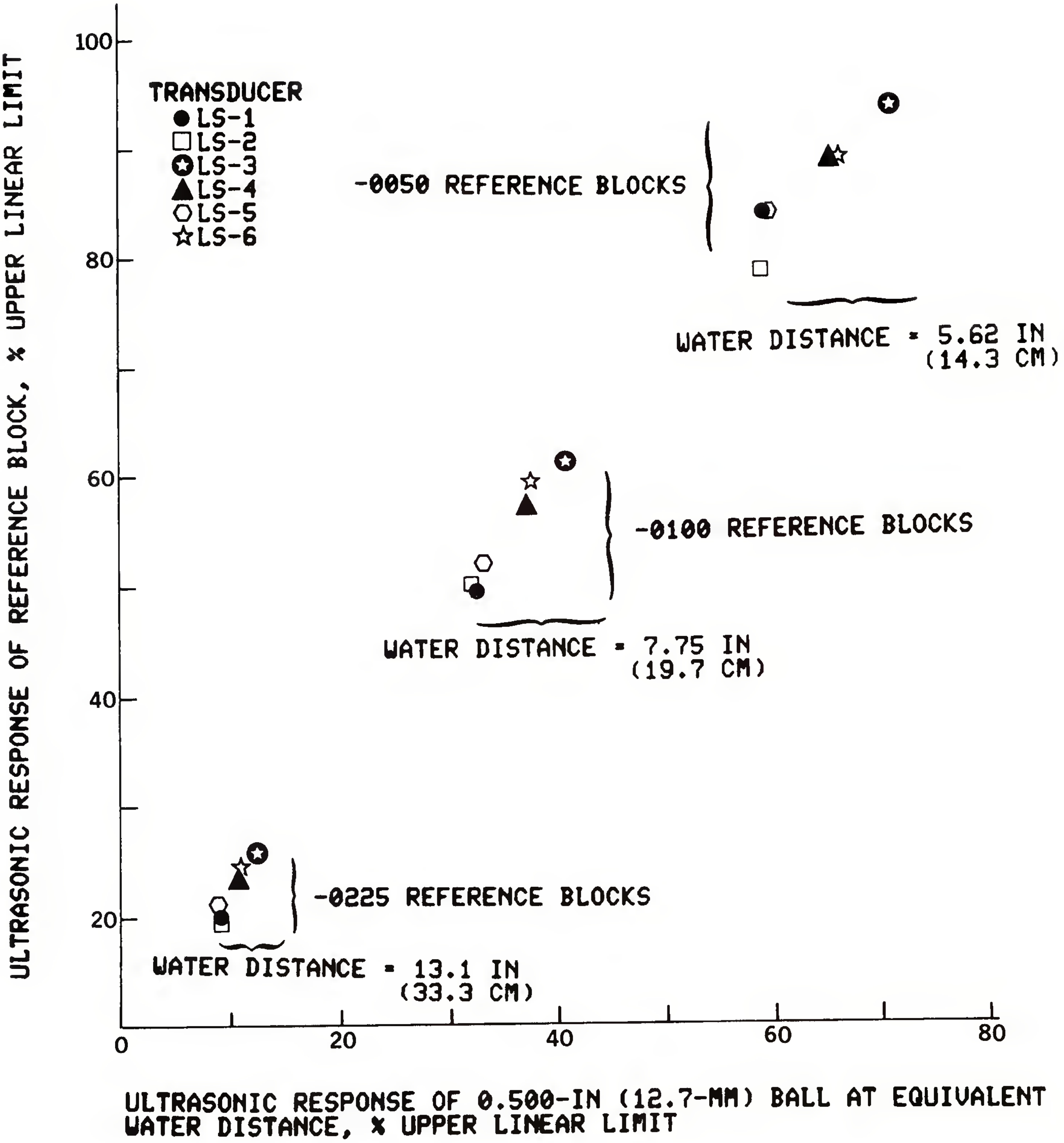


FIGURE 2 - CORRELATION OF REFERENCE BLOCK READINGS WITH TRANSDUCER AXIAL PRESSURE AMPLITUDE.

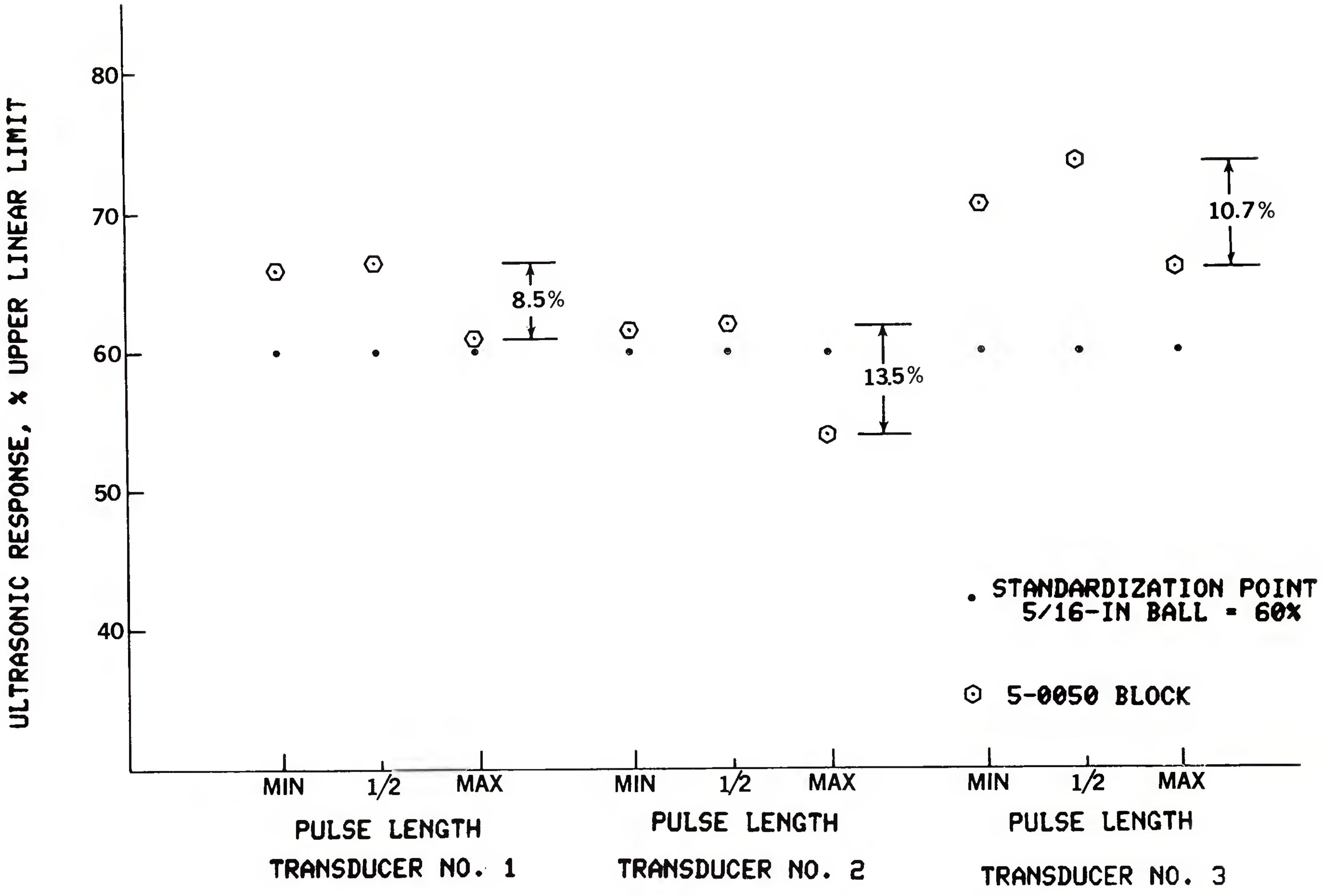


FIGURE 3 - EFFECTS OF PULSE LENGTH ADJUSTMENT ON ULTRASONIC RESPONSE OF A REFERENCE BLOCK.

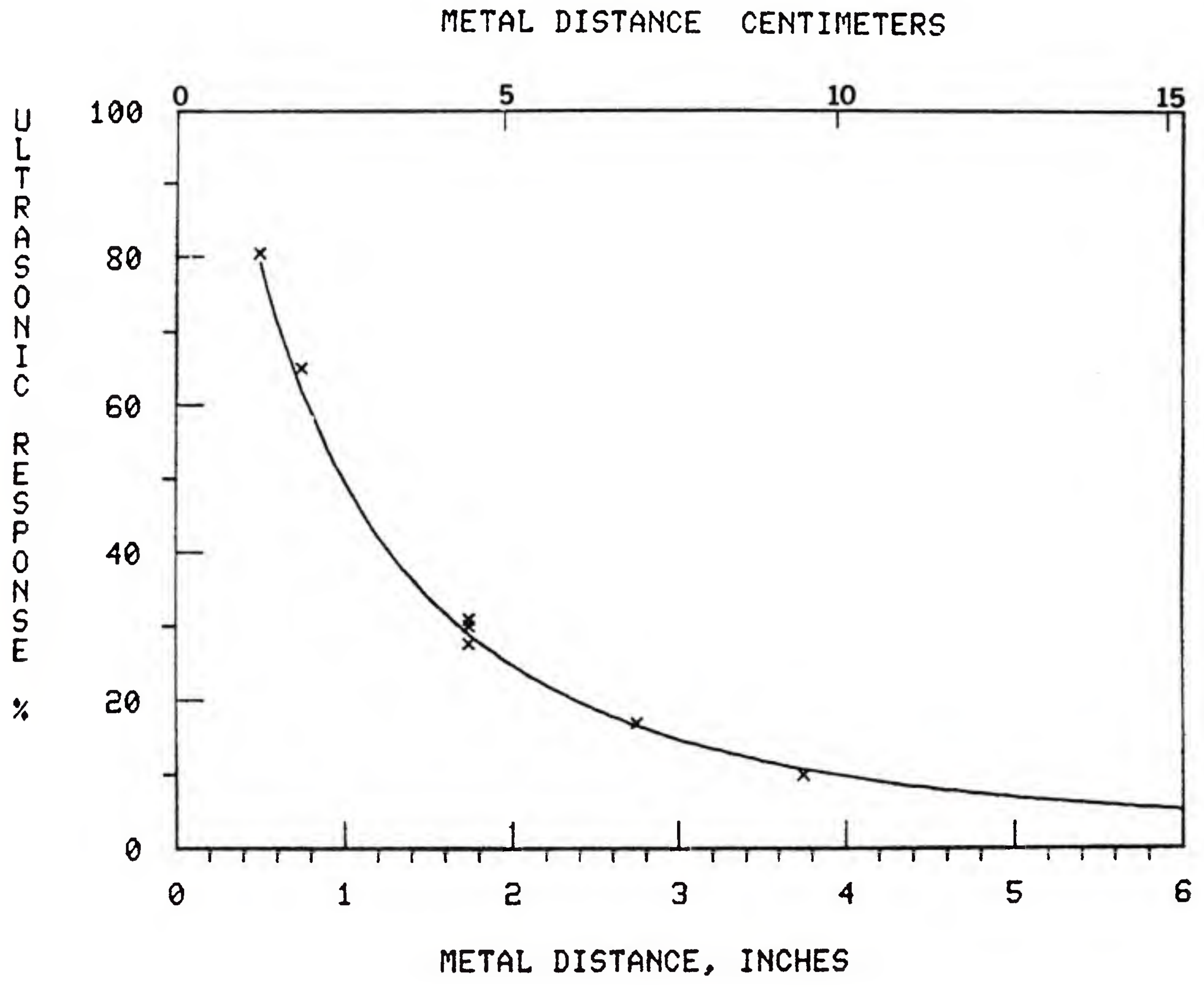


FIGURE 4 — ULTRASONIC RESPONSE OF NBS LOANER SET 1 COMPARED TO EMPIRICAL MASTER CURVE.

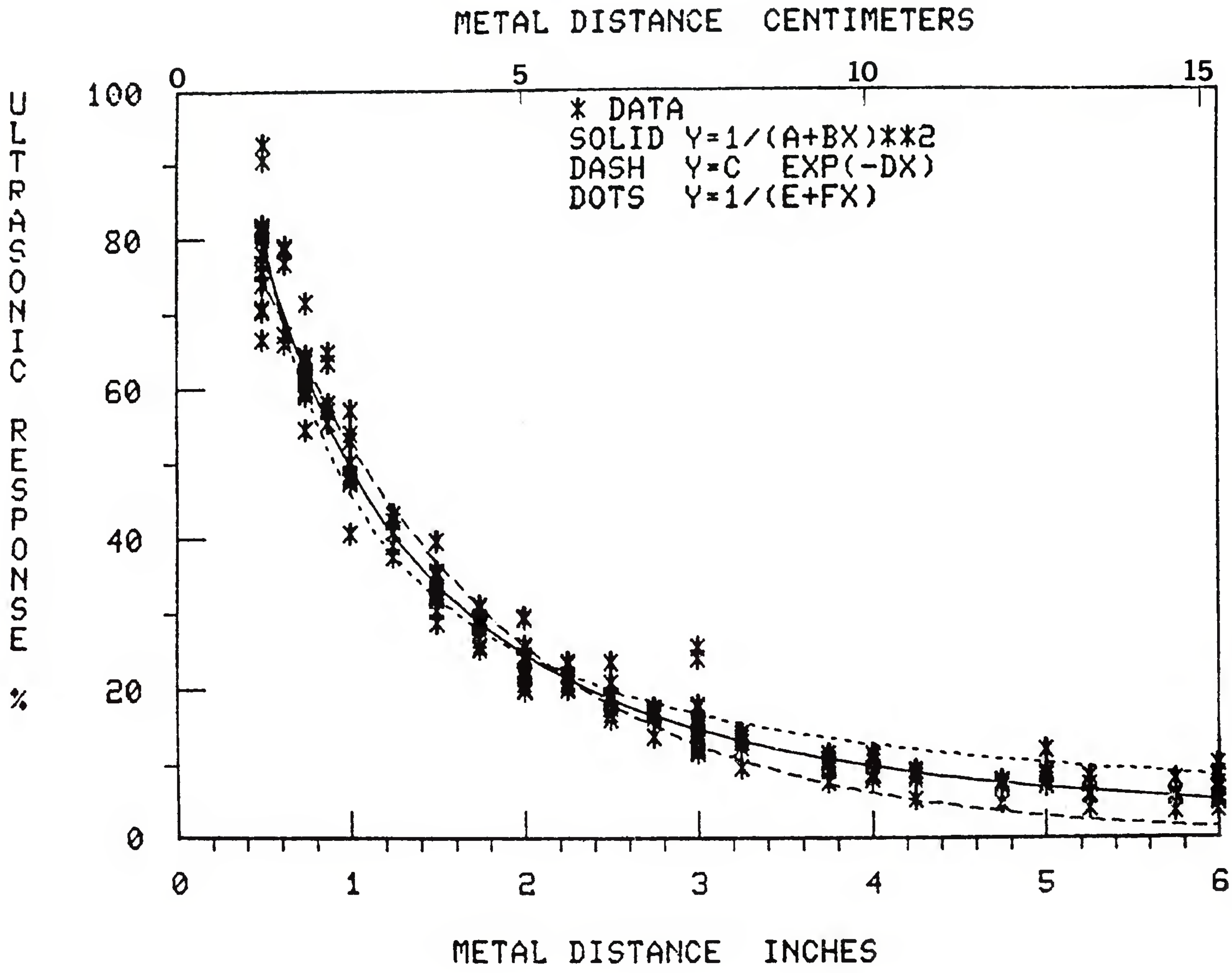


FIGURE 5 — DISTANCE – AMPLITUDE RELATIONSHIP OF ALUMINUM REFERENCE BLOCKS WITH LEAST SQUARES BEST FITS FOR VARIOUS MODELS.

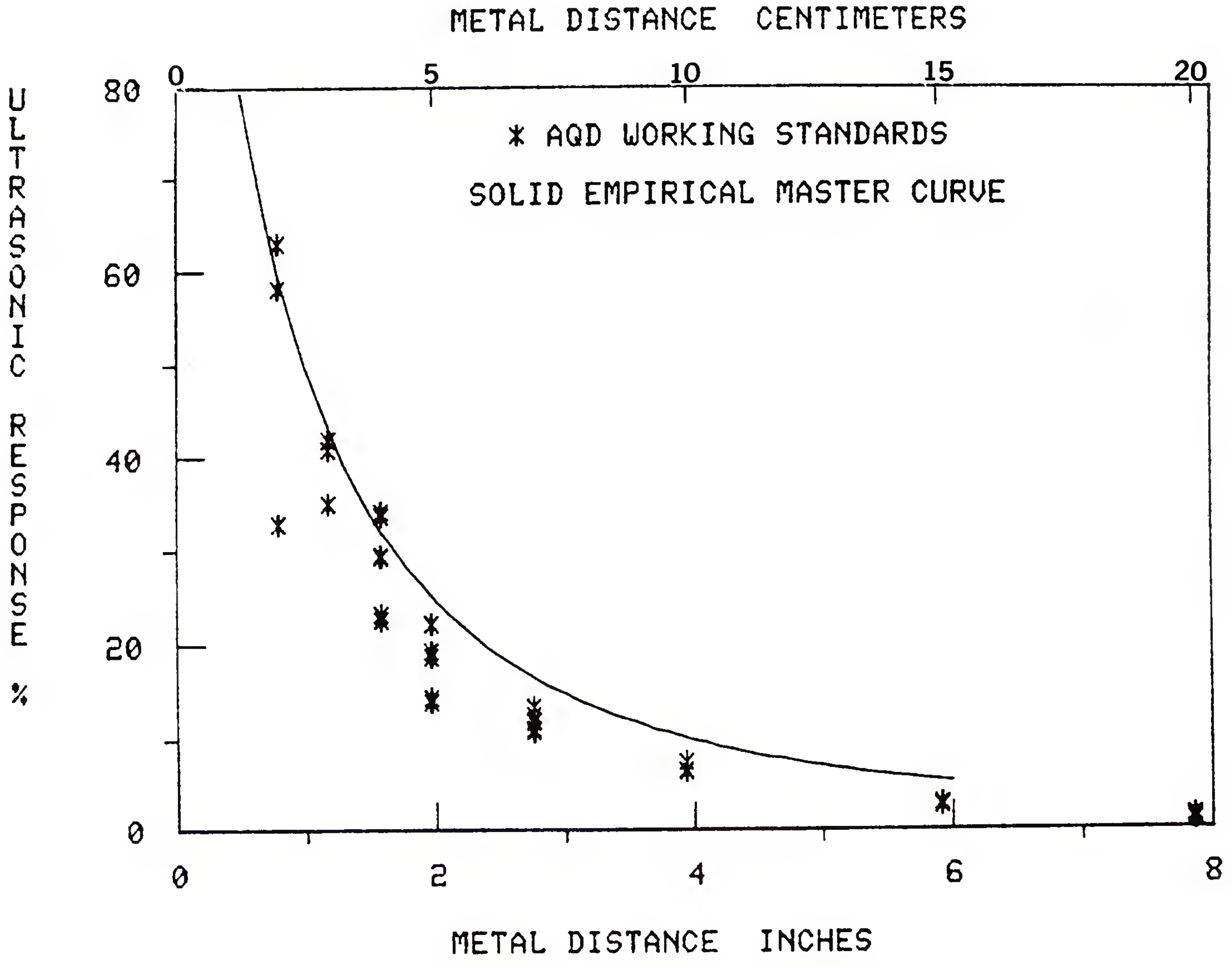


FIGURE 6 — CORRECTED CALIBRATION RESULTS FOR AQD WORKING STANDARD BLOCKS COMPARED TO EMPIRICAL MASTER CURVE.

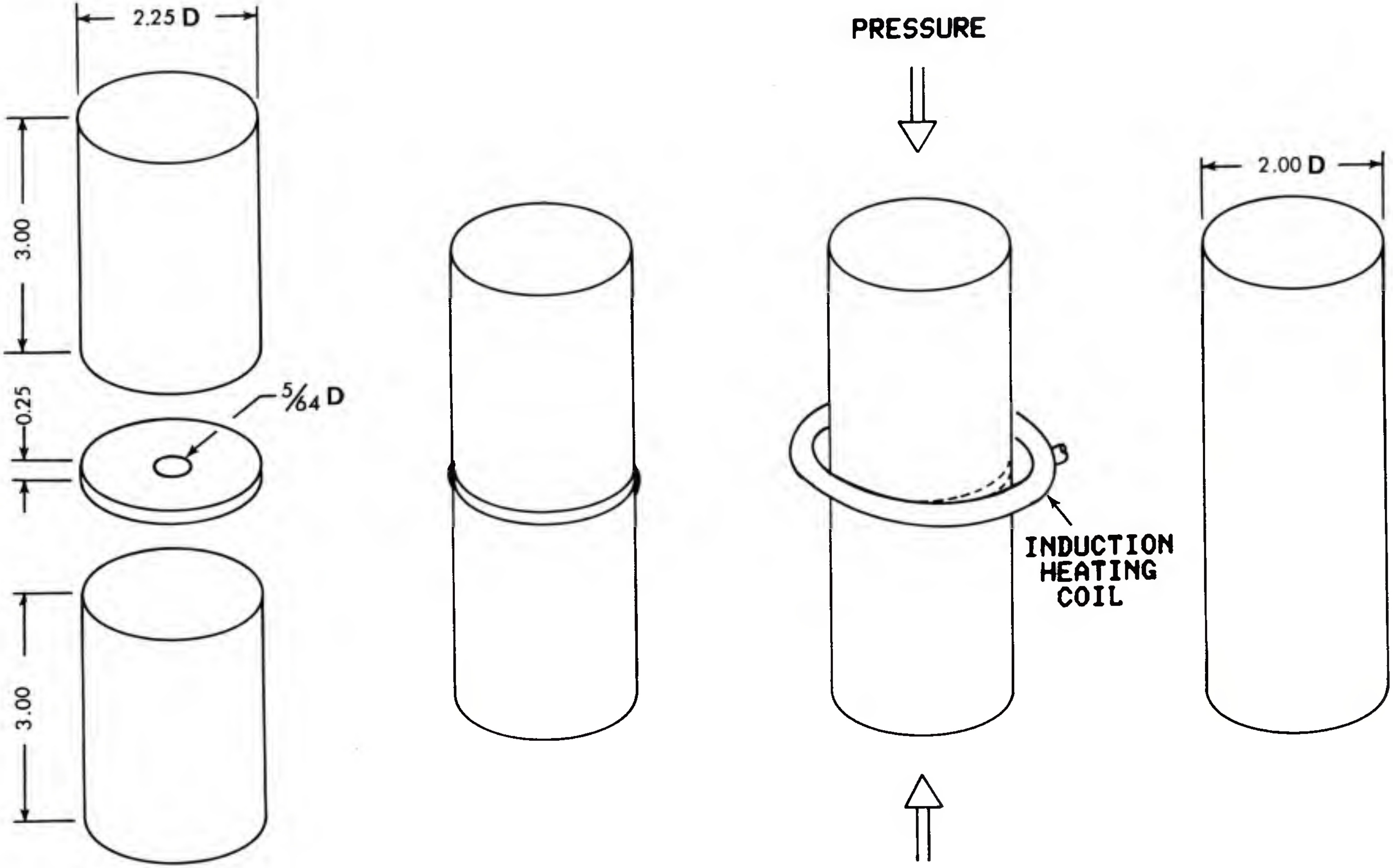
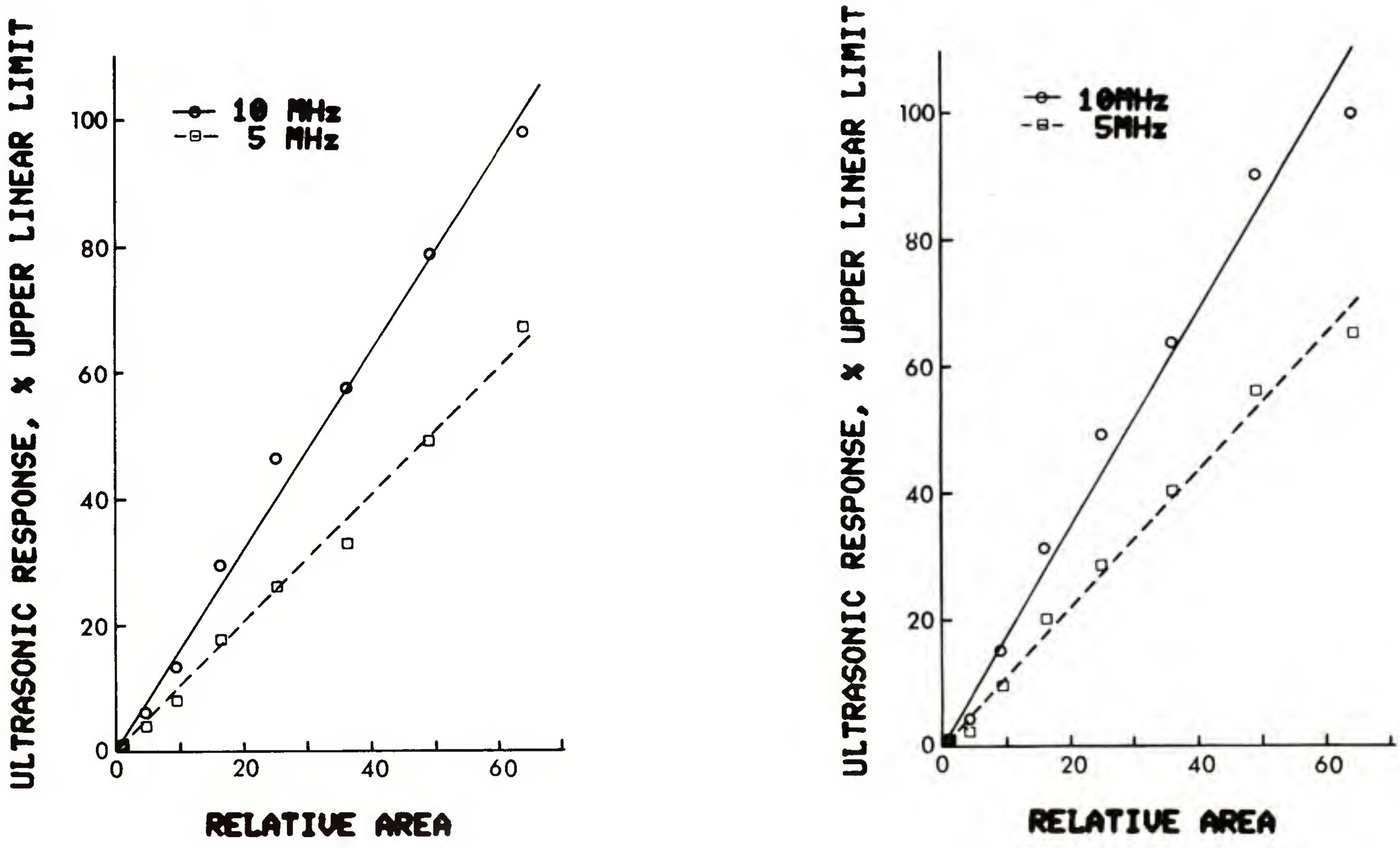


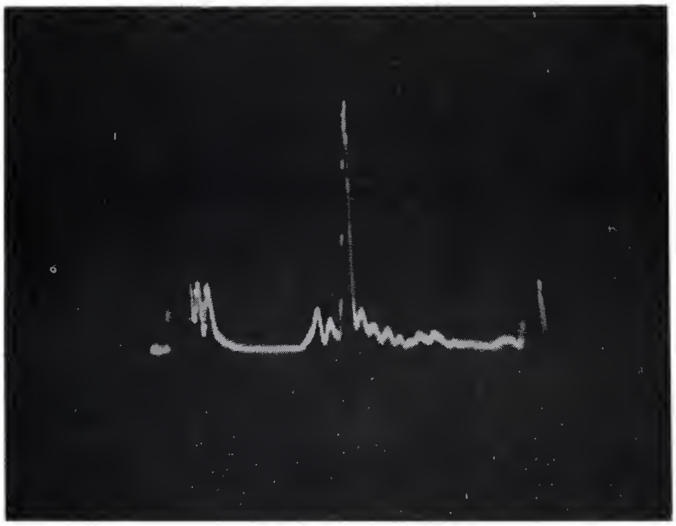
FIGURE 7 - FABRICATION OF DIFFUSION-BONDED REFERENCE BLOCKS.



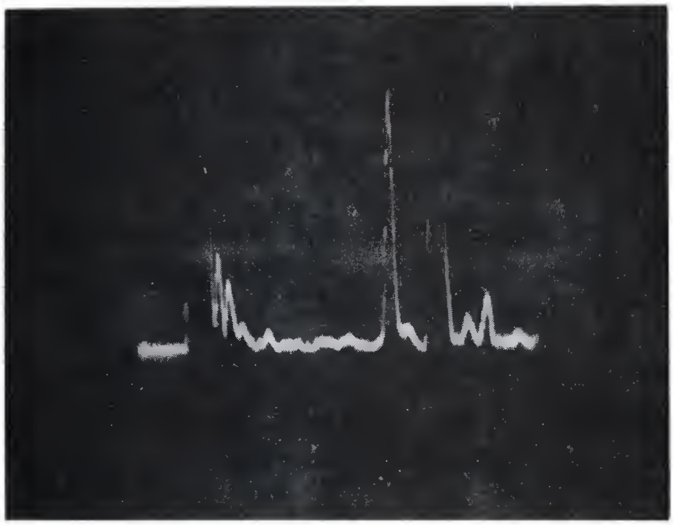
SET NO. 1

SET NO. 2

FIGURE 8 - ULTRASONIC RESPONSE DATA FOR TWO AREA-AMPLITUDE SETS OF DIFFUSION-BONDED REFERENCE BLOCKS.

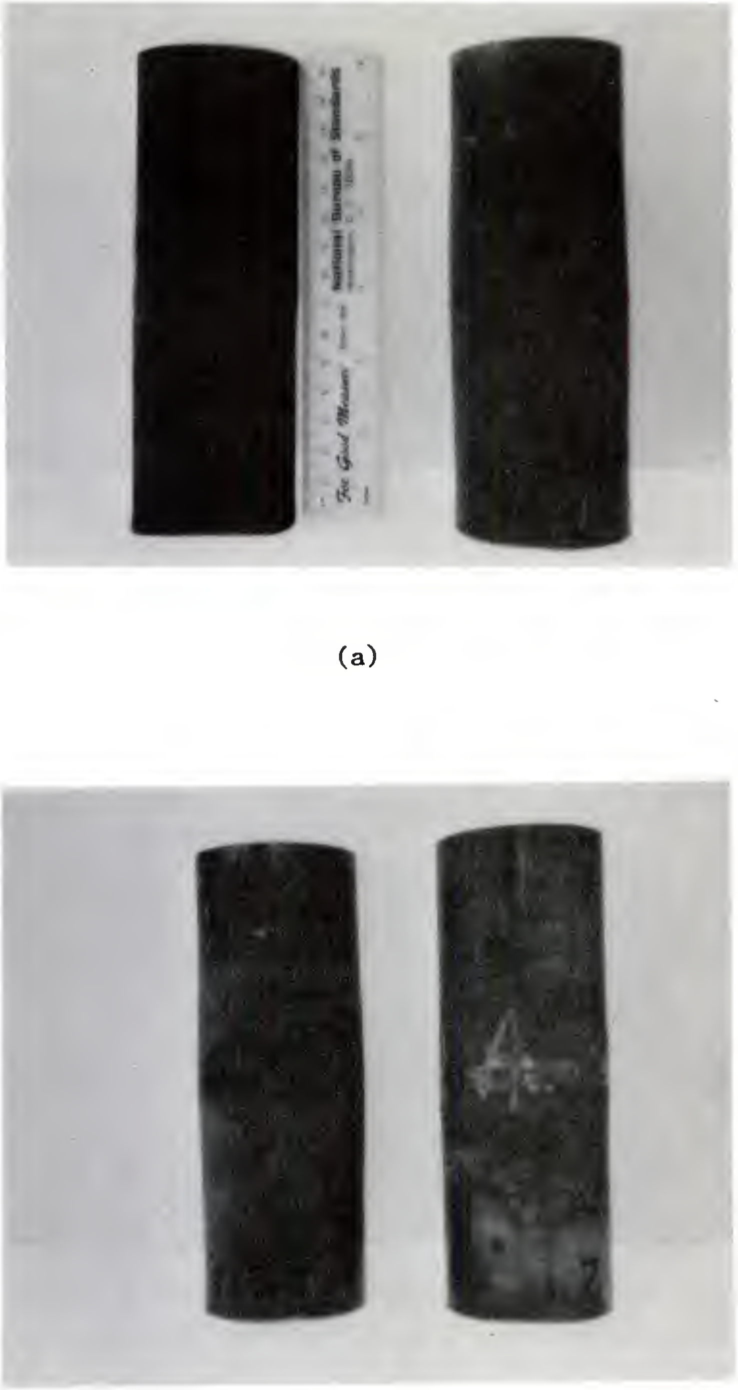


(A)



(B)

FIGURE 9 - A-SCAN PRESENTATION OF RESPONSE OF TWO 6AL-4V TITANIUM REFERENCE BLOCKS. (A) DIFFUSION-BONDED 5-0300 BLOCK. (B) CONVENTIONAL 5-0325 BLOCK. NOTE HIGHER NOISE LEVEL IN HEAT-AFFECTED ZONE IN DIFFUSION-BONDED BLOCK.



(a)

(b)

Figure 10 - Diffusion-bonded reference blocks prior to final machining, (a) 4340 steel, and (b) 6Al-4v titanium. Note skewness in steel blocks.

Appendix A

Description of Ultrasonic Instrumentation

The ultrasonic pulser/receiver/display system used for the majority of the tests described in this report was manufactured by Automation Industries Sperry Products Division*. The mainframe is a model UM 771B, with 10 N dB pulser/receiver, D Timer, and H Transigate plug-in modules. The pulser produces a tuned output electrical pulse at the required frequency. The received signals are amplified as RF pulses, rectified and filtered, and delivered to the display as video signals. This system is described in more detail in [5].

For some of the transducer characterization tests (table 3) a broadband pulser/receiver system was used in conjunction with a broadband oscilloscope and RF Spectrum analyzer. This pulser/receiver was manufactured by Xenotec, Ltd., model XP/R-2. This system is described in more detail in [3].

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*Commercial equipment and instruments are identified by brand name and model in order to fully specify the experimental procedure. In no way does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

Appendix B

Diffusion Bonding Procedure for Reference Blocks.

The procedure used for the fabrication of diffusion-bonded reference blocks was essentially the same as that used by Don Conn at Armco, Inc. Research Center, (Reference 15 of the text) although not described in detail in that paper. A three-piece block is used so that each block takes the place of two reference standards, depending on which end is interrogated by the transducer. Usually, the metal distances to the hole would be different on each end, but for our purpose, i.e. to check for differences in nominally identical blocks, the two ends were the same, thus giving two measurements from each block.

The sequence of fabrication is shown schematically in figure 7 of the text. The three pieces were machined to size, the through-hole drilled in the wafer, and the four interfaces to be bonded rough ground (approximately 10 μ in (0.25 μm)). The three pieces were then circumferentially welded together in an argon atmosphere, thus sealing the to-be-bonded region and obviating the need to perform the actual bonding process in a vacuum or inert atmosphere.

The diffusion bonding itself was done in air, with the heat supplied by induction heating coils and the pressure by a small manual hydraulic press. The bonding parameters for steel were 2000°F (1092°C) and 2000 $\mathrm{lbf/in^2}$ (1.38 MPa) for 30 minutes (ref. Conn, private communication), and for titanium 1700°F (926°C) and 500 $\mathrm{lbf/in^2}$ (0.35 MPa) for 30 minutes (Reference 14 of text). After bonding, the blocks were machined to final diameter.

To test the procedure at NBS, a blank (no hole) two-piece block was fabricated from 4340 steel. A modified ultrasonic C-scan, showing a perspective view of signal amplitude versus X and Y position[18], is shown in figure B-1. The signal is gated from the interface region only. Significant reflections can be seen around the circumference, but none in the important central region. The signal is null over the central 1.5 in (3.8 cm) of the block at a gain of 20 dB greater than that which gives full-scale first back reflection. Possibly the circumferential weld is resisting the applied pressure and preventing a good bond from forming near the edge. A photomicrograph of the central region is shown in figure B-2. The quality of the bond appears to be typical of those reported in the literature [14,15]. Modified C-scan perspective plots for both conventional and diffusion bonded steel and titanium blocks are shown in figures B-3 and B-4.

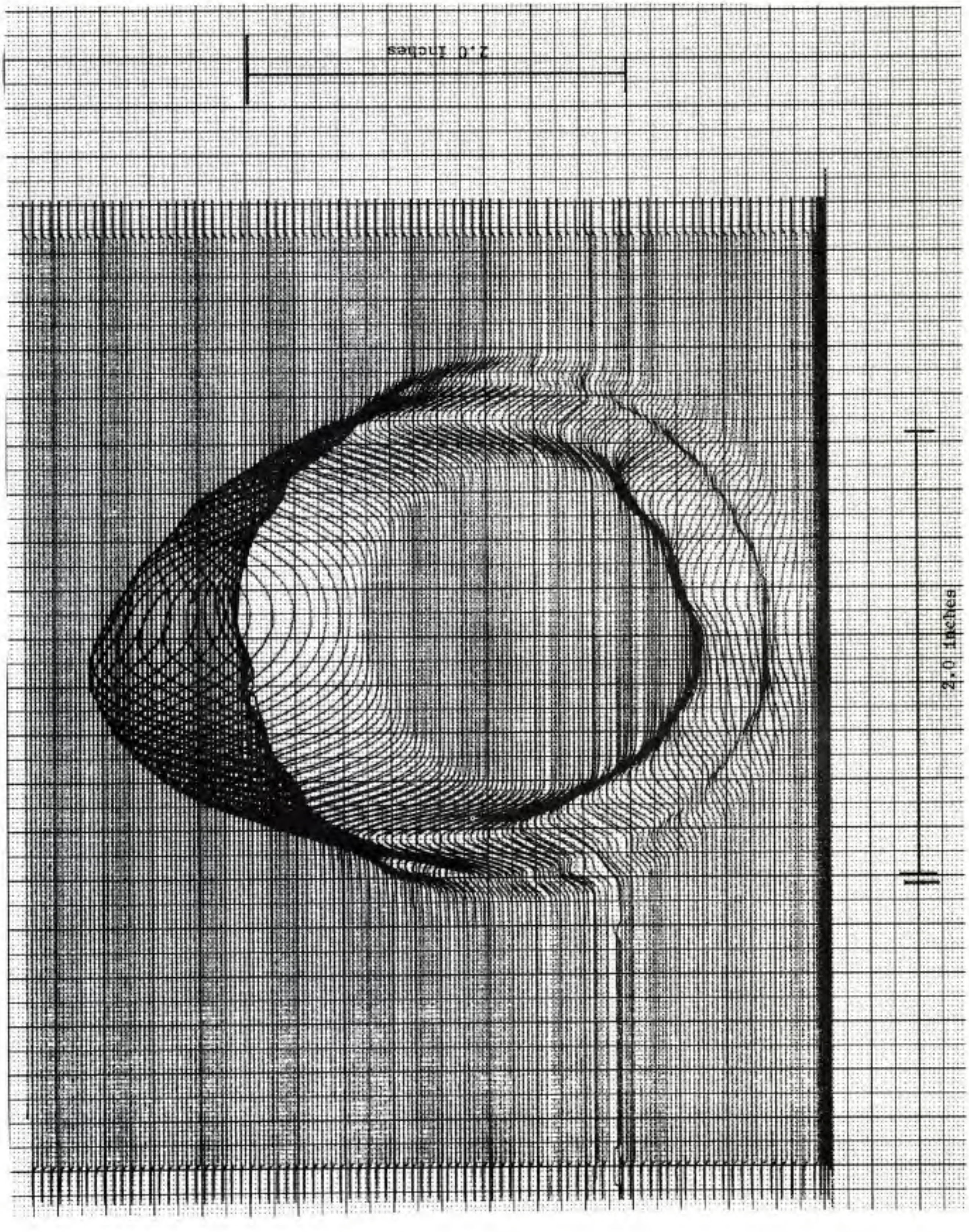
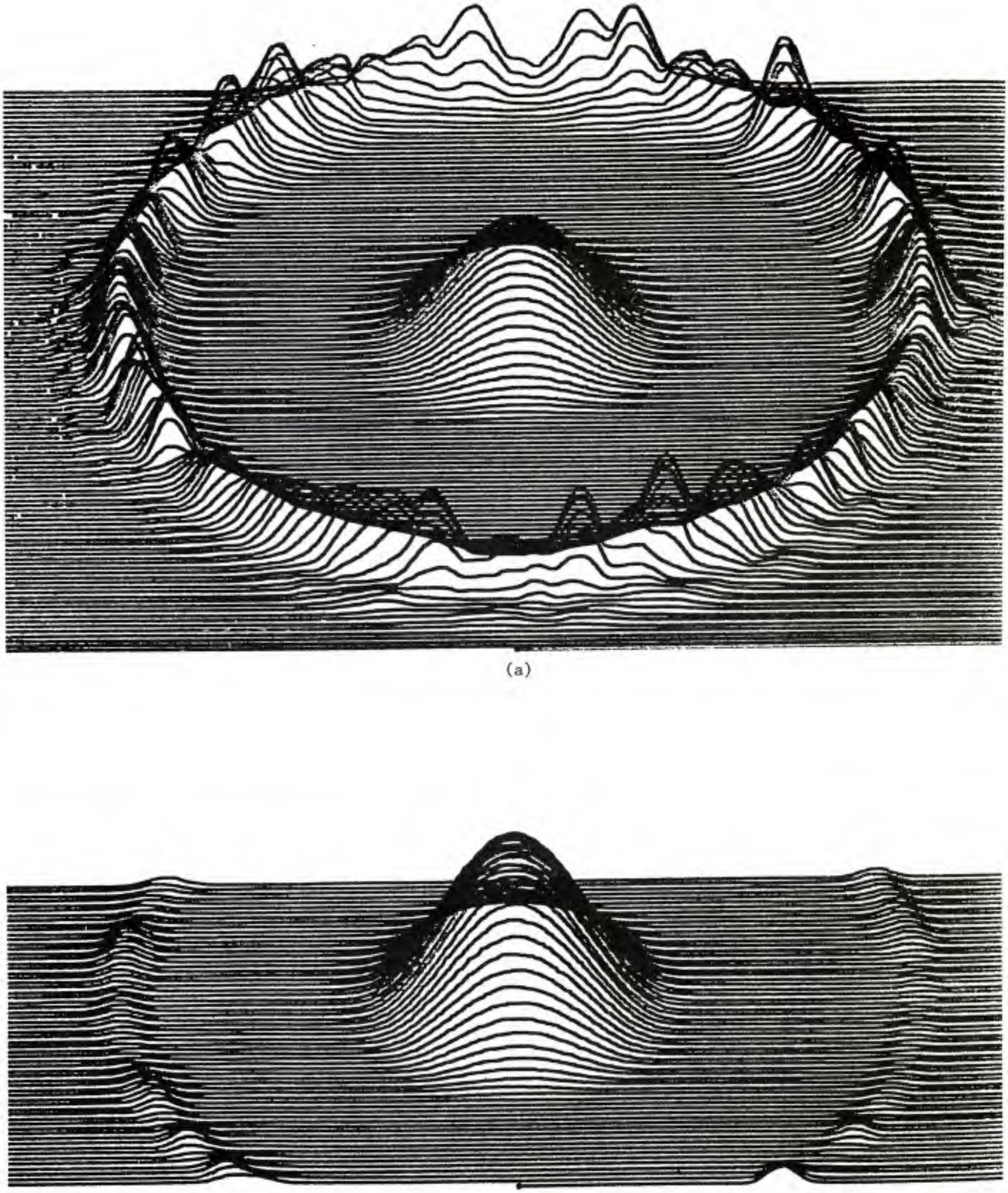


Figure B-1 - Modified C-scan interface region of blank (no-hole) diffusion-bonded steel block

200 X

500 X

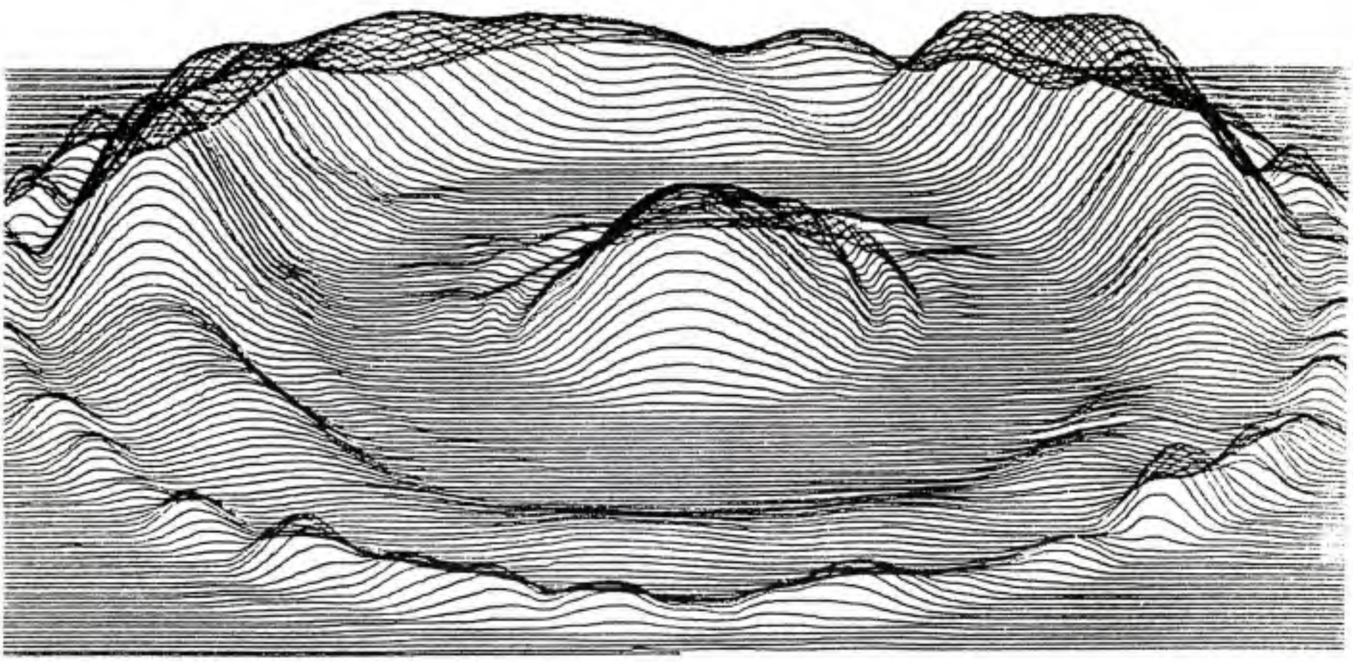
Figure B2 - Photomicrographs of diffusion bondline in blank (no hole) 4340 steel block.



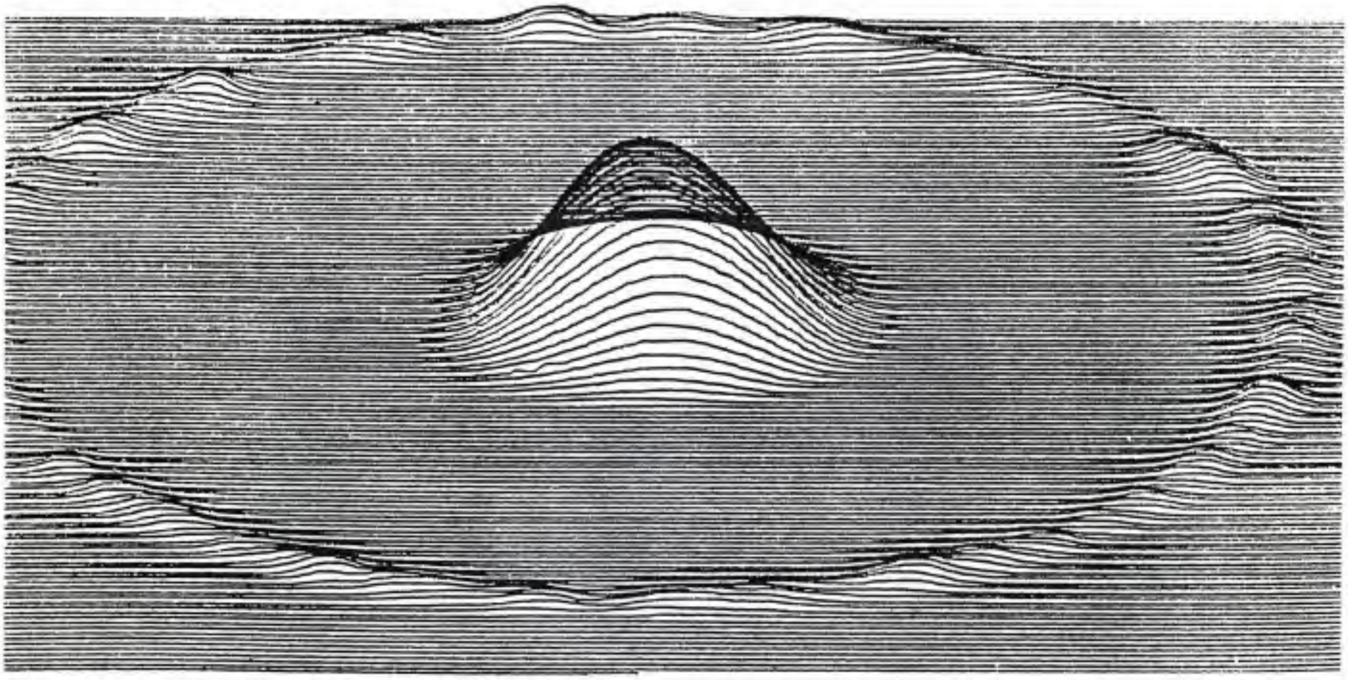
(a)

(b)

Figure B-3 Modified C-scan recordings of flat-bottom hole plane in (a) diffusion bonded and (b) conventional 4340 steel blocks



(a)



(b)

Figure B-4 Modified C-Scan recordings of flat-bottom hole plane in (a) diffusion bonded and (b) conventional 6Al-4V titanium blocks

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