TECHNICAL REPORT 67-59

DEVELOPMENT OF THE ULTRASONIC TECHNIQUE FOR ALUMINUM WELDS AND MATERIALS

PHASE I

2 OCTOBER 1967

by

K. J. Hannah
B. T. Cross

Prepared under Contract No. NAS8-18009 (DCN 1-6-60-00044) for National Aeronautics Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama by the Research Laboratory, Automation Industries, Inc., Boulder, Colorado 80302

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FOREWORD

This technical report covering Phase I of Contract No. NAS 8-18009 (DCN 1-6-60-00014) was prepared by Automation Industries, Inc. The purpose of this program was to develop the Delta Technique for Ultrasonic Weld Inspection of Aluminum Butt Welds. This report includes: an analysis of the physics of redirected sound energy, empirical determination of optimum parameters for Delta operation, destructive analysis of aluminum weldments, and recommendations for incorporating the Delta Technique into a tool for weld evaluation.

Personnel involved in the execution of this program include: (a) Automation Industries, Inc., Mr. G. J. Posakony, Mr. C. M. Peterson, Mr. B. T. Cross, Mr. W. M. Tooley, and Mr. K. J. Hannah, and (b) Marshall Space Flight Center, Mr. James Hoop and Mr. George Kurtz (R-QUAL-AMR).

ABSTRACT

The Delta Technique is a unique, multi-crystal inspection method that is relatively insensitive to defect orientation. Internal weld defects including lack of penetration and lack of fusion were readily detected when using this technique. This technique is capable of rapid scanning rates while providing a simultaneous and permanent record of the test results.

Test demonstrated that the Delta Technique successfully detected the weld defect of primary concern in 2014 and 2219 aluminum alloy weldments at inspection rates of 50 feet per hour. Lack of penetration of a 0.030" x 0.060" size and lack of fusion as narrow as 0.025" were reliably detected by the Delta Technique. Microfissuring, a laminar shrinkage type defect found in 3/16" and 1/4" weld sections was detected by the Delta Technique where radiographic techniques failed because of unfavorable defect orientation.

Correlation of the nondestructive tests was made by destructively analyzing 18 feet of weld for total defect content. Findings of this study show that for a quantity of weldments containing tight lack of penetration up to 80% of the total defects were detected by the Delta Technique while only 36% of the total defects were detected with radiography.

A prototype manual Delta was constructed and evaluated in the laboratory. The manual Delta Technique achieved the same quality of weld inspection obtained during the immersion study of the Delta Technique. A preliminary design was made for a wheel mounted Delta which is compatible with the standard Sperry wheel design and the Automatic Scanning System at MSFC.

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INTRODUCTION

The Marshall Space Flight Center sought a nondestructive testing technique to rapidly inspect butt welds in aluminum alloys and detect lack of penetration not readily seen in the radiographs. With the increasing demands for high vehicle reliability only a nondestructive test system having exceptional capabilities could achieve the level of defect detection required by MSFC. Since welding is an essential part of fabrication of space vehicles, accurate nondestructive evaluation of weldments requires use of the most advanced methods that are available. The Delta Technique, an ultrasonic weld inspection technique developed by the Research Laboratory of Automation Industries, Inc., offered much promise for accomplishing the weld inspection requirements of MSFC. This technique was developed to detect randomly oriented weld defects. In the laboratory, the Delta Technique had been used successfully for detecting randomly oriented weld defects. The objective of this study program was to transform the Delta Technique from a laboratory tool into a reliable inspection method for production weld evaluation.

The study program was performed in three steps: (1) analytical, (2) experimental, and (3) design. Each step is outlined below:

Part 1 - An analytical and empirical analysis was conducted to determine the physical characteristics of the Delta Technique for 2014 and 2219 aluminum alloys.

Part 2 - A series of tests were performed to establish the exact operating parameters for optimum performance of the Delta Technique for 2014 and 2219 aluminum. Next, destructive metallurgical examinations were made on selected weld panels for comparison with the Delta test results.

Part 3 - A preliminary design to incorporate the Delta Technique into devices suitable for non-immersion testing was made. A manual probe for contact testing and a wheel transducer search unit assembly using a liquid couplant were the specific devices.

I. DISCUSSION, DELTA PHENOMENA

1.0 Theory of Delta Operation

The Delta Technique is an ultrasonic inspection method which uses redirected energy for flaw detection. To understand the mechanism of energy redirection, it is necessary to examine the physics of the Delta concept. An explanation of the Delta phenomena was developed from classical energy equations[18, 34, 41] and empirical data collected during past studies[13, 14, 15] of the Delta Technique. In the Delta analysis, we assigned specific meanings to certain terms. These terms are used throughout the text and are defined as:

A. Transmitted Beam - The transmitted beam is the longitudinal wave originating at the transmitter search unit and incident upon the part surface at a specified angle (α).

B. Transmitted Shear Beam - The transmitted shear beam is the refracted shear wave propagating in the part as a result of the transmitted beam striking the part surface. The angle of incidence between the transmitted beam and the part surface is beyond the critical angle for transmission of longitudinal energy into the part.

C. Interface - The surface forming the boundary between two adjacent media of different acoustical impedance.

D. Redirected Energy - Any energy propagating in the part in a direction different than that of the transmitted shear beam. Redirection is caused by an interaction between the transmitted shear beam and an interface. Redirected energy can be reflected, mode converted, or reradiated energy.

E. Mode Conversion - Ultrasonic energy will propagate in an elastic media in three principle modes: longitudinal, shear, and surface. Mode conversion is the change of ultrasonic energy from one mode of propagation to another as a result of striking an interface.

F. Reradiated Energy - An omnidirectional, coherent ultrasonic wave generated at an interface as a result of interface excitation caused by an impinging ultrasonic beam. This definition is based on a hypothesis formed by this research group.

The Delta phenomena is described in this way: (See the ray analogy in Figure No. 1.)

A. The transmitted shear beam propagates in the part in an angular direction determined by the incident angle (α) of the transmitted beam.

B. Three distinct ultrasonic waves can occur as a result of the transmitted shear beam striking an interface within the material. The first ultrasonic wave is a reflection of the transmitted shear beam. The second ultrasonic wave is a mode converted longitudinal wave which will occur when the transmitted shear beam is incident upon an interface within a specified angular region. This angular region is:

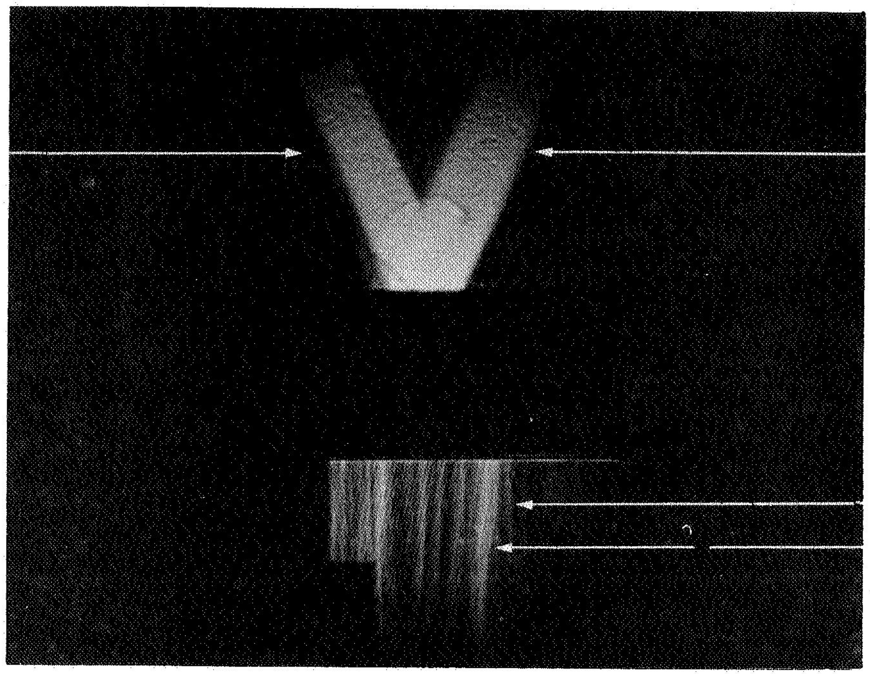
$$0° < \beta < \mathrm{Sin}^{-1}\ V_s/V_l, \tag{1}$$

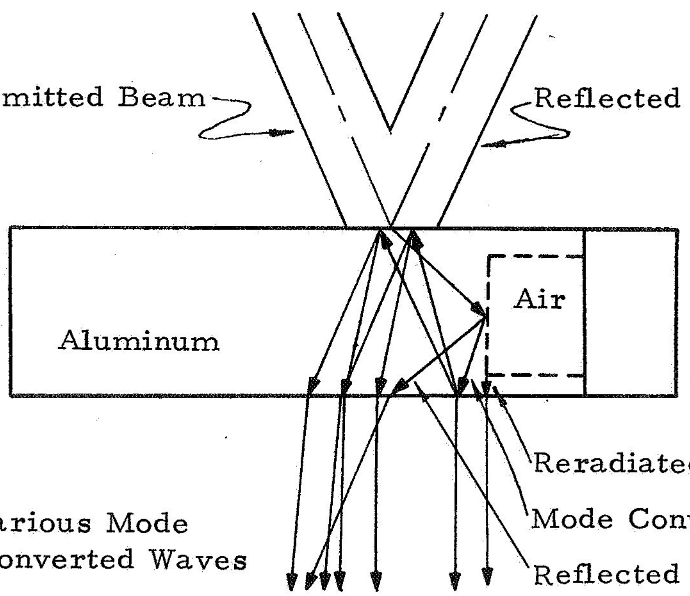
where β is the angle between the transmitted shear beam and the interface and V_s and V_l are the shear and longitudinal wave velocities for the material. The third ultrasonic wave is a reradiated wave which propagates at longitudinal wave velocity.

C. These three ultrasonic waves are the redirected energies used for flaw detection with the Delta Technique. The redirected paths for reflected and mode converted waves are influenced by the shape and orientation of the defect. Reradiated waves originate at the interface and propagate outward from its surface. See sketches in Figure No. 2. These sketches illustrate some of the various paths that redirected energy might follow for different defect shapes and orientations.

D. The flaw information is detected at the top surface of the part with a receiver search unit placed normal to the part surface. Since the propagation path for reradiated energy is outward and away from the defect, reradiated energy is detected directly above the defect. The two remaining ultrasonic waves are detected at some point between the transmitter and receiver search units--the exact position is determined by the defect shape and orientation.

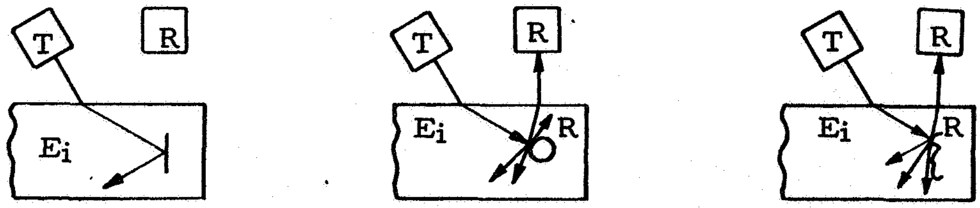
This has been a brief and simple explanation of the Delta phenomena. The facts were established and verified by experiments designed to prove or disprove the assumptions. Although a rigorous mathematical proof has not been established for the mechanics of reradiated energy, this energy has been measured and its behavior predicted. The general theory for the





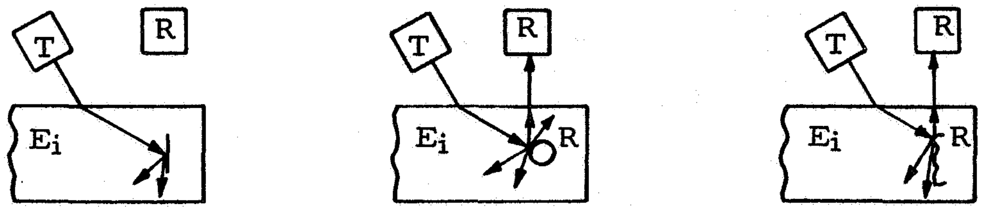
Schlieren Photograph and Ray Analysis
of the Delta Phenomena

Figure No. 1



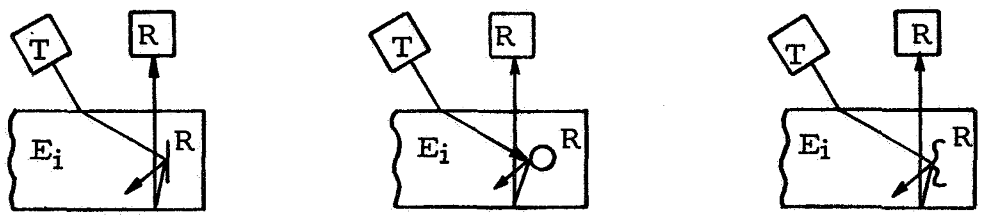
Smooth Vertical Defect | Spherical Defect | Irregular Defect

Figure 2A. Reflected Energy



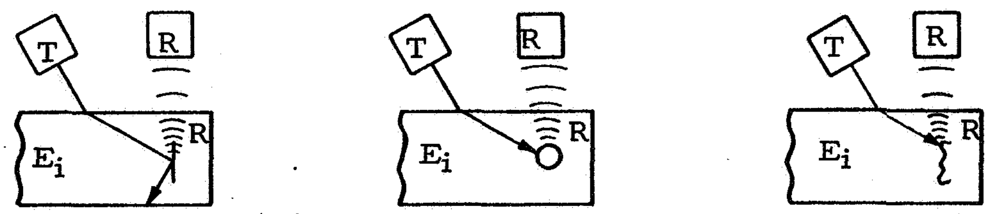
Smooth Vertical Defect | Spherical Defect | Irregular Defect

Figure 2B. Mode Converted Energy (Direct)



Smooth Vertical Defect | Spherical Defect | Irregular Defect

Figure 2C. Mode Converted Energy (Indirect)



Smooth Vertical Defect | Spherical Defect | Irregular Defect

Figure 2D. Reradiated Energy

Redirected Sound Energy

Figure No. 2

Delta phenomena explains why it can be used for the detection of randomly oriented defects. Parameters which govern the Delta operation must be developed for each material and weld configuration.

1.1 Test Parameters

The various parameters which govern the Delta operation must be defined and specific values assigned if this technique is to be used for successful weld inspection. Because of the different physical characteristics of materials, it is desirable to establish a data sheet for each material type, thickness, and weld configuration. These data sheets would allow Delta inspection of any butt weld by simply selecting the proper parameters. The parameters which govern the Delta operation are defined below:

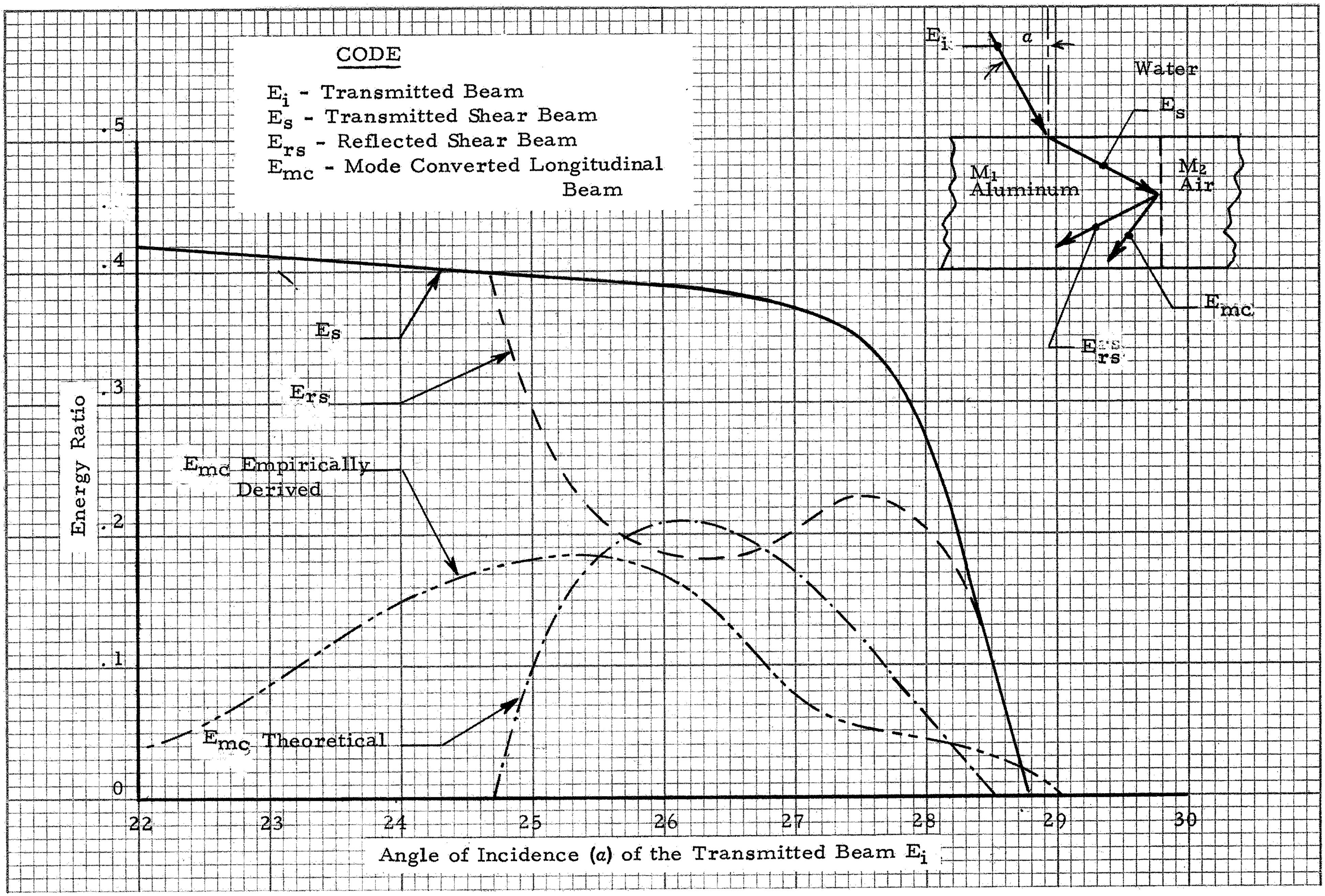
A. The Incident Angle (α) of the Transmitted Beam

This angle determines the quantity of ultrasonic energy that will be transmitted into the material. It also determines the direction that redirected energy will follow. Since all three types of redirected ultrasonic waves are used for flaw detection, it is important to select a reference point that will satisfy the condition for redirection of all three waves. The selected reference was a vertical interface. Figure No. 3 illustrates the type of energy partition curves that were calculated and measured for the energy partition at the vertical interface. An angle of 24.5° incidence was chosen because it provided equal quantities of energy in each redirected wave. An angle of incidence for maximum response from the reradiated energy could not be calculated since classical energy equation makes no provision for the existence of this energy. Empirical studies have shown that sufficient response for reradiated energy is obtained in the same angular region chosen for the other waves. A statistical analysis shows that a refracted angle of approximately 60° for the transmitted shear beam is generally satisfactory for Delta inspection of the material.

B. The Separation Distance and Water Path of the Search Units in the Delta Configuration

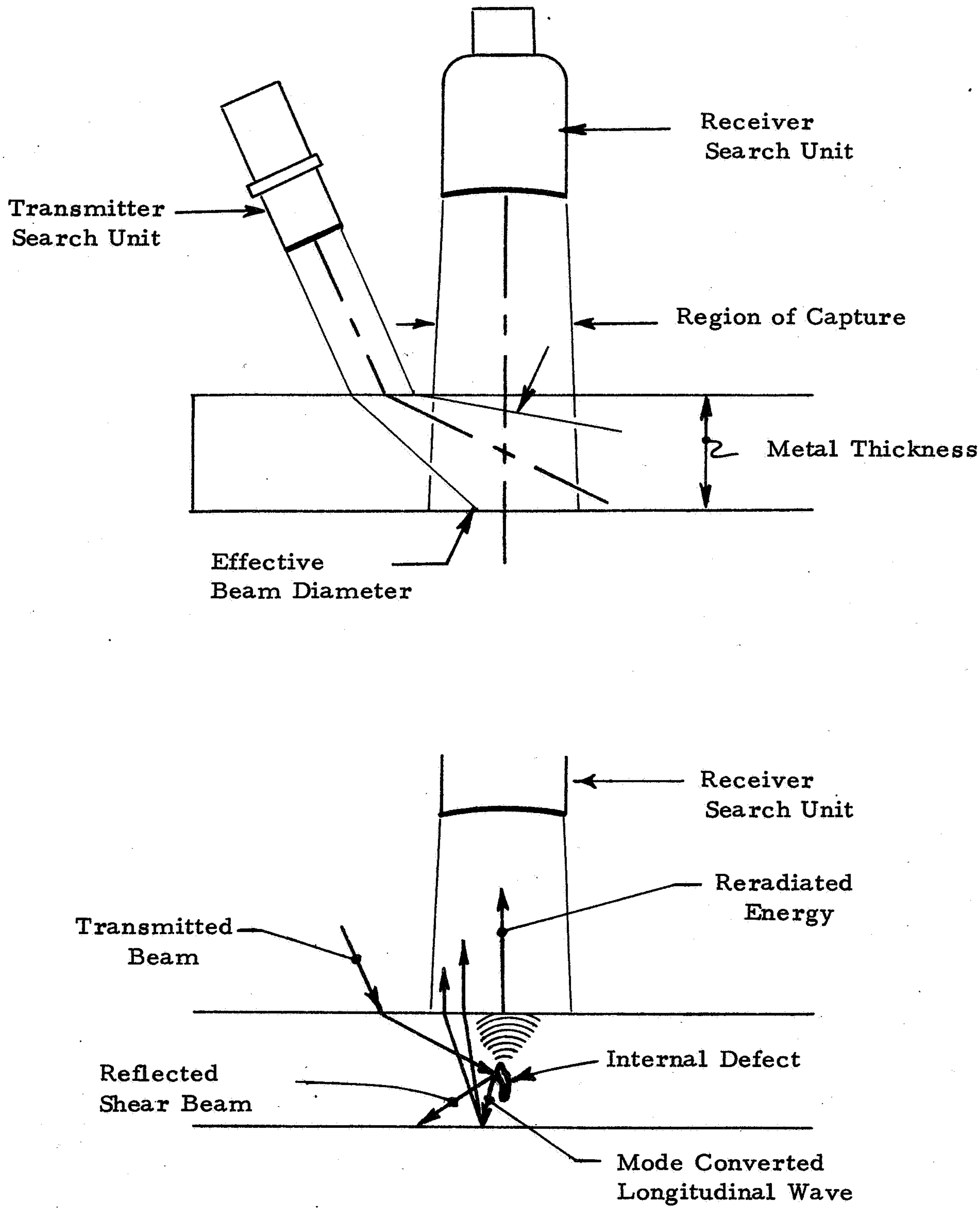
Separation and water path distances determine the thickness of material which can be inspected with a given test condition. The separation distance between the two search units, and the water path must meet the following requirements: (See Figure No. 4)

(1) The intersection of the transmitted shear beam and the receiver search unit axis must occur in the center or mid-thickness of the plate.



Energy Partition at Aluminum Air Interface

Figure No. 3



Search Unit Relationship in the
Basic Delta Configuration

Figure No. 4

(2) The transmitter search unit must have a water path that positions the most usable portion of the transmitted shear beam in the weld region directly under the receiver search unit.

(3) The receiver water path must be set for the most effective region of capture for the particular search unit used. Effective region of capture is that conical region in which any ultrasonic wave striking the search unit will cause a resulting electrical response from the piezoelectric crystal element. For example, a 0.750 inch diameter element with a 1.125 inch radius lens has an adequate region of capture for inspecting 0.500 inch to 0.750 inch weld thicknesses.

C. The Transmitter Search Unit

The transmitter search unit must have an effective beam diameter large enough to cover the material thickness when measured in the receiver region. (See sketch in Figure No. 4.) Various methods may be used to increase the effective diameter of a given transmitter search unit size. A fixed divergent lens will increase the beam spread of the transmitted shear within the material. The transmitter search unit can be moved perpendicular to the weld seam in an in-and-out motion which increases the effective beam diameter by scanning. Curved or shaped crystal elements can be used in construction of the search unit to increase the beam diameter.

D. The Receiver Search Unit

The receiver search unit must have an effective region of capture sufficient to collect the desired flaw information. The region of capture is determined by the amount of flaw information which must be collected from a given weldment. Refer to Figure No. 4. For example, if all flaw information is to be received, the region of capture must be great enough to collect all redirected waves. The redirected waves leave the part surface as shown in Figure No. 4.

E. Test Frequency

The size of defect which can be detected is influenced by test frequency, defect shape, and defect orientation. Since frequency can be controlled, it is important to select a frequency which will enhance the detection capabilities of a system. A flaw or interface is essentially an energy radiator; therefore, more energy will be redirected from a given flaw at higher frequencies than at lower frequencies. The choice for test frequencies is governed by the sound beam attenuation in the material.

1.2 Verification of Delta Parameters for Aluminum Weld Inspection

Experiments were conducted to verify the critical parameters discussed in Section 1.1 and their effect upon the operation of the Delta Technique. Before each test was made, a single parameter was changed. Special test blocks and weld sections were inspected using the correct parameter values and again using an incorrect value. The observed results were summarized for each parameter and are discussed in the following text.

A. Incident Angle of the Transmitted Beam (α)

For aluminum, the proper angle of incidence (α) was 24.5°. Signal amplitudes of the redirected energies were measured for reference holes at different depths in the test block at angle (α) = 24.5°. These tests were repeated at the same gain setting but the incident angle (α) was set above and below the 24.5° position. With a constant gain level, any changes observed in signal amplitude were indicative of the quantity of energy transmitted into the part and the efficiency of energy redirection caused by the interface. Signal amplitude was highest when α equaled 24.5° and dropped rapidly for angular settings on either side. This range was 23° to 27°. Reference holes near the top and bottom of the part were not detected when the incorrect incident angle was used.

B. The Distance Separating the Transmitter and Receiver Search Units

A test was made with the separation distance extended 1/2 inch beyond the proper value. The extreme length resulted in a decrease in ultrasonic signal amplitude from the top reference hole and increased the signal amplitude from the bottom reference hole. Next, the separation distance was reduced 1/2 inch below the proper value. Signal amplitude from the top hole was increased and no signal was received from the bottom hole. Incorrect search unit separation was avoided by establishing discrete distance values for individual plate thicknesses.

C. The Transmitter Search Unit

Transmitter beam evaluation was accomplished by changing only the transmitter search unit diameters in a series of test. An aluminum test plate containing three horizontal, flat bottom reference holes of various depths was scanned with the Delta

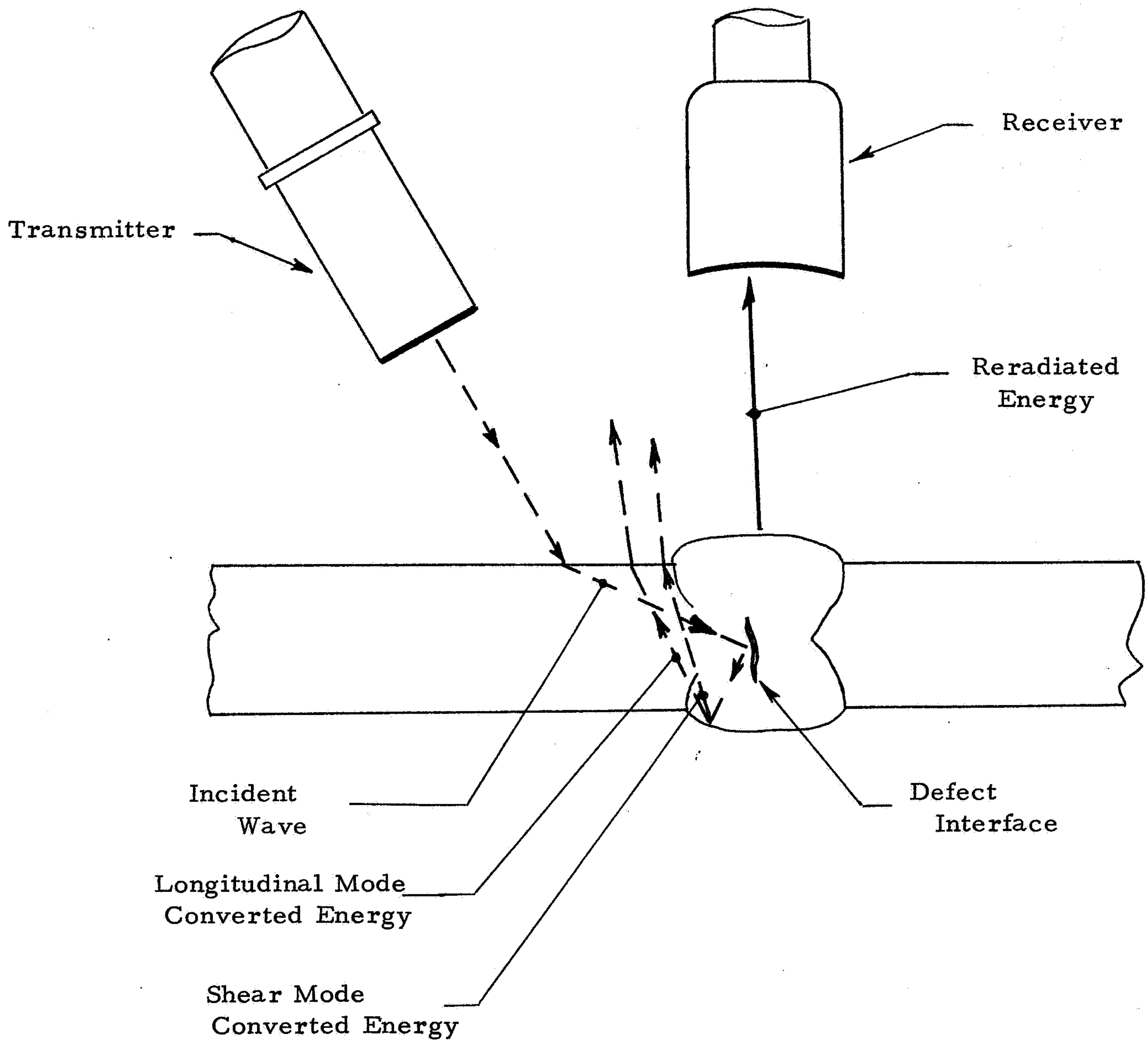
Technique and the flaw information recorded. All three reference holes were recorded using a 0.500 inch diameter,, flat, 5.0 MHz search unit. Next, a 0.375 inch diameter, flat, 5.0 MHz search unit was used for the Delta transmitter. This Delta recording contained only the middle and bottom reference holes. A loss of flaw information due to inadequate transmitter beam coverage must be considered when selecting a Delta transmitter search unit.

D. Receiver Search Unit

The receiver search unit influence was determined by observing the relative amount of flaw information received with each unit. Delta inspection of a weld panel containing lack of penetration was made using progressively larger receiver search units. This weld panel was 0.500 inches thick. The largest quantity of flaw information was recorded using a 0.750 inch diameter receiver and did not change for receivers larger than 0.750 inches. However, the quantity of flaw information decreased accordingly for receiver diameters smaller than 0.750 inches. Mode converted and reflected energies exit through the panel surface behind the actual flaw location. See Figure No. 5. In this case, it exited through the panel surface outside the weld bead. Therefore, the region of capture for a receiver search unit must cover this region if all the flaw information is to be received.

E. Test Frequency

The test frequency was varied from 2.25 MHz to 10.0 MHz to determine an optimum frequency for Delta weld inspection of 2014 and 2219 aluminum alloys. At 2.25 MHz, only gross defects such as large lack of penetration (LOP) and lack of fusion (LOF) were detected. The recorded indications for LOP and LOF were not representative of the actual flaw size. Delta scans made at 5.0 MHz contained all flaw indications recorded at 2.25 MHz and additional indications from the smaller defects. Most of the flaw information recorded at 5 MHz was missed in the 10 MHz tests. The loss of flaw information was attributed to energy attenuation at the higher frequency. Small defects in the range of 2/64 inch diameter were detected at 5.0 MHz. The smallest defect detected at 2.25 MHz was 5/64 inches in diameter. An accurate determination of defect size recorded at 10.0 MHz could not be made because of the energy attenuation.



Sound Beam Behavior in Part Due to Interface Conditions in Weldment

Figure No. 5

II. TECHNICAL DISCUSSION OF THE DEVELOPMENT OF A DELTA WELD INSPECTION FOR ALUMINUM WELDS

1.0 Description of Weld Panel

A butt weld was used to fabricate the 6 x 30 inch test panels studied in this program. The material was 2014 and 2219 aluminum alloy. Material thicknesses were 0.15", 0.25", 0.50", 0.75", and 1.0". These welds were made to contain flaws such as lack of penetration (LOP), lack of fusion (LOF), gas porosity, and foreign metallic inclusions. All welds were intended to represent the production weld configuration. The program began when the weld panels were received from Marshall Space Flight Center.

1.1 Initial NDT Inspection of the Weld Panels

The welds were first evaluated by radiographic, ultrasonic C-Scan, and liquid dye penetrant nondestructive tests. Records of these tests were used to evaluate the flaw information obtained with the Delta Technique. By studying the number and size of flaw indications, we were able to evaluate the progress of the Delta development prior to destructive analysis of the weld panels. After all nondestructive tests were completed, a number of welds were destructively analyzed. Results of the nondestructive tests are recorded and discussed in the following text.

A. Liquid Dye Penetrant

Surface porosity in the weld bead was detected by dye penetrant examination. Other surface discontinuities such as weld crater pits, caused by starting and stopping of the welding machine, were located at both ends of the weld beads. A crater pit was readily visible and did not represent a production weld condition; hence, the end portions of the weld beads were disregarded in this testing program.

B. Radiographic Examination

All weld panels were radiographed at a 2T image quality level. Porosity and lack of penetration was detected. These results correlated closely with the weld history supplied by MSFC. Radiographic records, although not conclusive evidence of the total defect content, provided the primary means for comparison of the Delta Technique prior to destructive analysis.

C. Ultrasonic C-Scan Inspection

Ultrasonic C-Scan immersion tests were conducted to obtain facsimile recordings of the weld panels. This test employed longitudinal beam, pulse-echo techniques for locating material defects lying parallel to the material surface. All C-Scan recordings were made at 5.0 MHz using a 0.750" diameter, medium focus search unit. Reference standards were used for setting test sensitivity. A 3/64 inch diameter reference hole was used for all weld panels. Two depths, 0.375 inch and 0.500 inch were used respectively for plate thicknesses up to 0.500 inches and greater than 0.500 inches. Test sensitivity was set so the ultrasonic response from the reference hole had an amplitude of 75% of full scale deflection (FSD). The "write level" for the recording system was set to start at 30% FSD.

The C-Scan recordings contained information that did not correlate with radiographic test records. The C-Scan tests contributed little because the majority of defects in the weld zone were not oriented in a plane parallel to the material surface. This type of testing is not particularly suited to the detection of randomly oriented defects.

2.0 Test Configuration

Three configurations of the Delta Technique were employed during the evaluation phase of this program.

(1) Basic Delta Configuration - A single fixed transmitter search unit and a single fixed receiver search unit. See Figure No. 6.

(2) Duo-Delta - Dual fixed transmitter search units and a single fixed receiver search unit. See Figure No. 7.

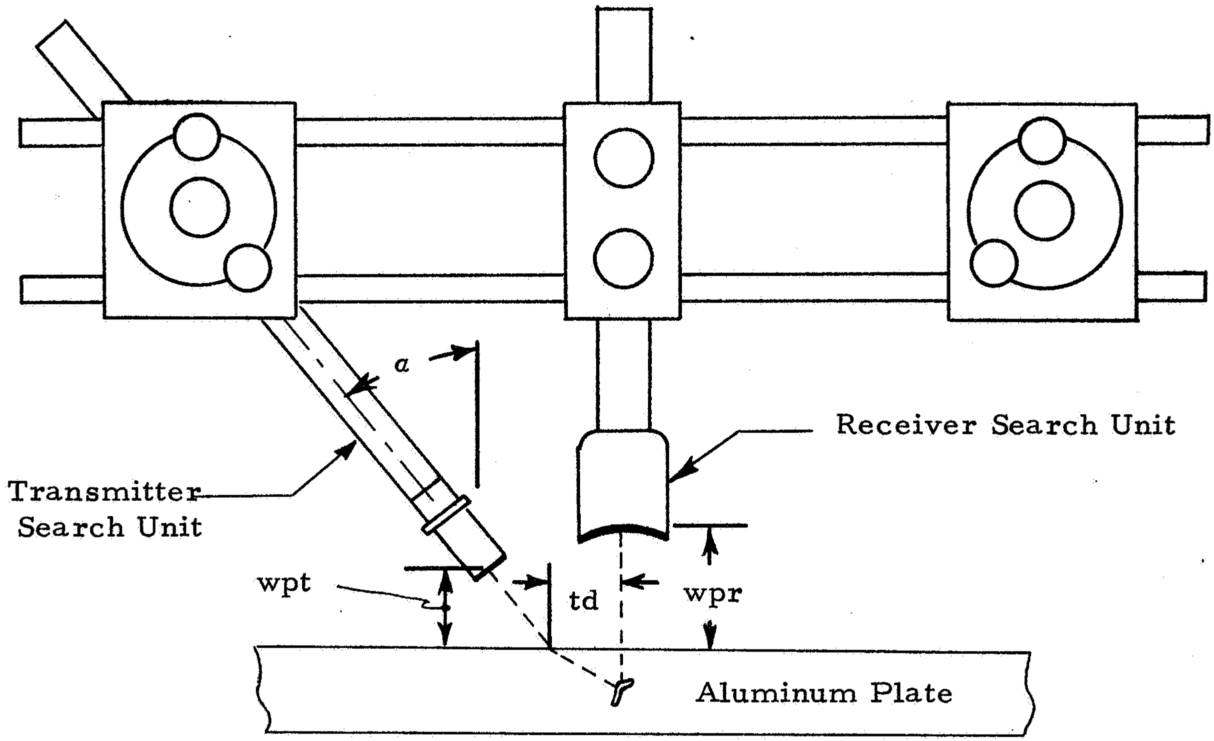
(3) Transmitter Array Delta Configuration - Multiple fixed transmitter search units and a single fixed receiver search unit. See Figure No. 8.

In developing the Delta Weld Inspection Technique, the multiple transmitter array was considered as a means for increasing the ultrasonic energy radiated into the weld zone.

2.1 Basic Delta Configuration

The Basic Delta Configuration was the most elementary form of the Delta used in this program. Each parameter affecting the operation of the Basic Delta is identified on the sketch in Figure No. 6.

Delta weld inspection is an ultrasonic, transmit-receive method of testing. In this method of testing, two separate search units are used, one search unit is a transmitter only, and the other is a receiver only. Therefore, a primary consideration in selecting search units for the Delta was the loop



td - distance between the receiver axis and the point of incidence of the transmitted beam.

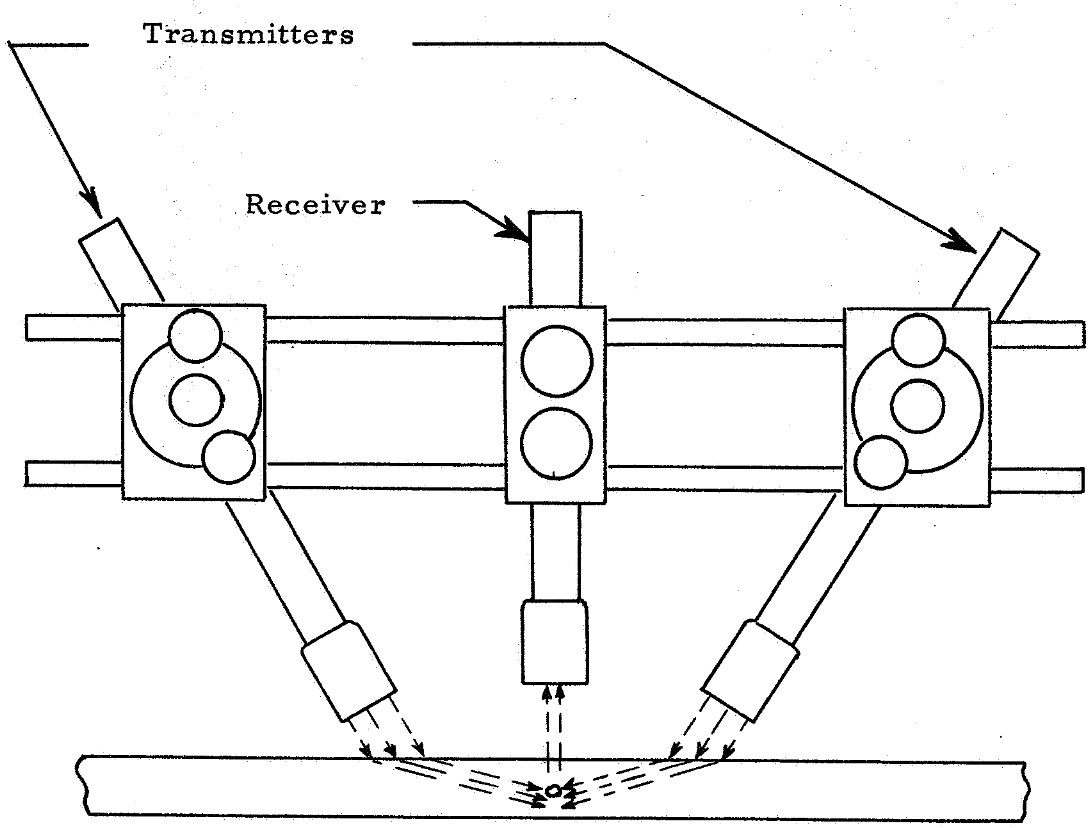
wpr - receiver water path

wpt - transmitter water path

a - transmitter angle of incidence

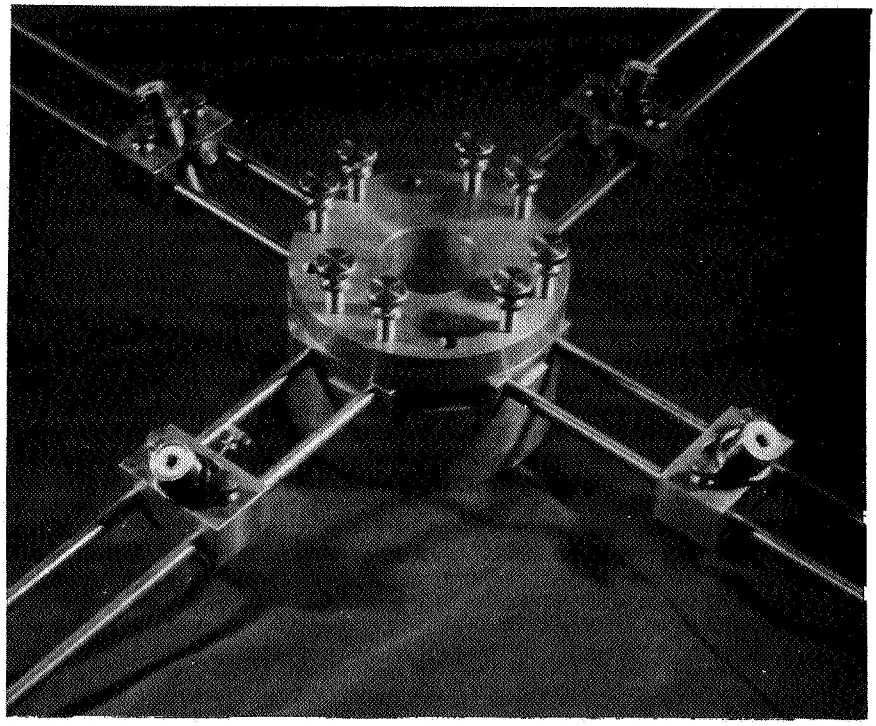
Basic Delta Configuration

Figure No. 6

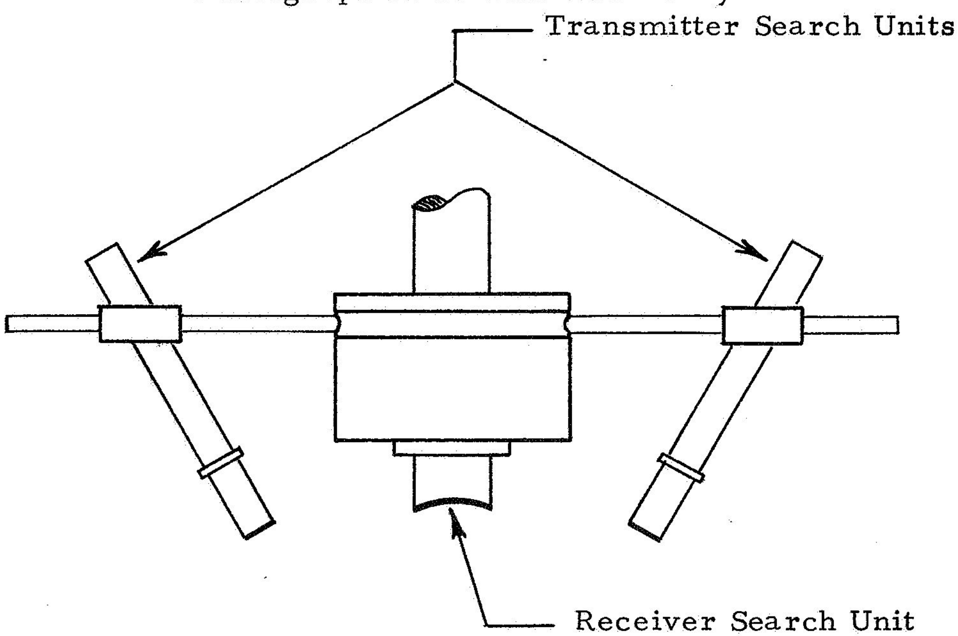


Duo-Delta Configuration

Figure No. 7



Photograph of Transmitter Array



Side View & Center Section of Transmitter Array

Figure No. 8

gain of the pair. A ceramic piezoelectric element was used in the transmitter because ceramic crystals are the most efficient convertors of electrical to mechanical energy. Lithium sulphate elements were used in the receiver search units for a maximum conversion efficiency from mechanical to electrical energy. In this report all transmitter search units are ceramic and all receiver search units are lithium sulphate.

Test setup procedure for the Basic Delta was accomplished in this order:

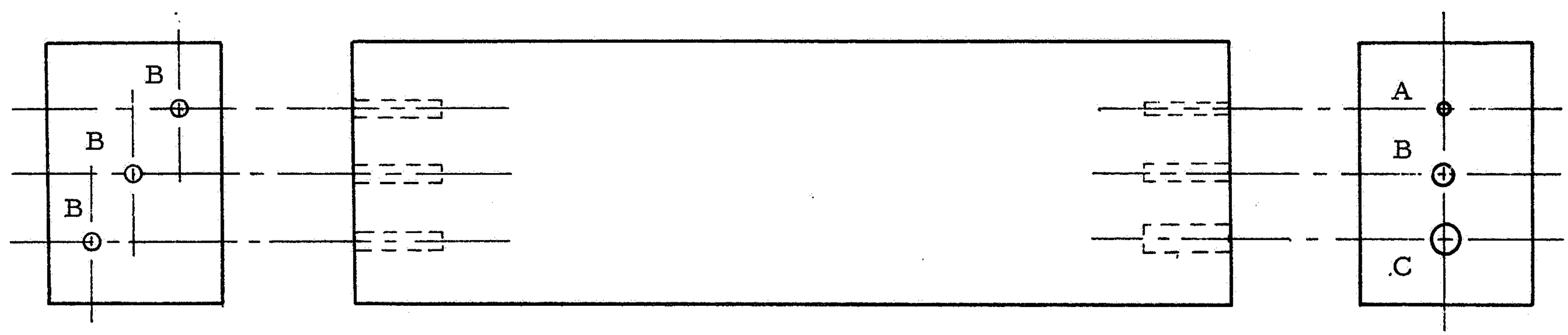
A single receiver search unit was positioned normal to the part surface at the proper water path. With the receiver search unit placed directly over a reference hole, a transmitter search unit was positioned perpendicular to the weld seam at a 24.5° incident angle with the part surface. A reference standard made from the same material and material thickness was required to set the proper separation distance between the search units. Figure No. 9 illustrates the type of reference standard used in this procedure. To obtain the proper separation distance between search units, the receiver search unit was placed directly over the reference hole and the transmitter moved perpendicular to the weld seam until the reradiated signal response was peaked. Two methods were used to set test sensitivity. These methods are outlined as:

Method A - A maximum amplitude signal was obtained from the center or mid-thickness reference hole by positioning the transmitter search unit while the receiver search unit was held stationary directly above the hole. The instrument gain control was adjusted to set the peak signal amplitude at 80% full scale deflection (FSD). An electronic gate was set to accept ultrasonic indications from a discrete time interval. The recording system was adjusted to record signals with an amplitude of 30% FSD or greater.

Method B - This method was identical to Method A with this exception: A decade decibel (dB) attenuator was placed in the coaxial cable connecting the receiver search unit and the instrument. The instrument gain was set for a peak signal amplitude of 80% FSD with 20 dB attenuation in the receiver line. Method B is more desirable because test sensitivity can be changed by known increments (dB) with respect to one reference point or hole size. Method B was developed during the program and was used for the remainder of the program.

The preliminary Basic Delta tests were conducted at 5.0 MHz using 0.375 inch diameter search units. This combination was employed to establish a basis for comparison of search unit combinations. Weld panels containing known defects such as gross lack of fusion and lack of penetration were used to evaluate the Basic Delta configurations.

A- 2/64" diam. Flat Bottom Hole
B- 3/64" diam. Flat Bottom Hole
C- 5/64" diam. Flat Bottom Hole



Delta Reference Block

Figure No. 9

2.2 Duo Delta Configuration

This configuration is a variation from the Basic Delta. The major change is the addition of a second transmitter search unit positioned perpendicular to the weld seam and on the opposite side from the first transmitter search unit. This configuration of the Delta is shown in Figure No. 7. The transmitter search units were matched for ultrasonic energy output; therefore, unequal ultrasonic signal response from the same defect was minimized. Test sensitivity for this test sequence was set according to Method A. Setup procedure for this configuration was identical to that used for the Basic Delta; however, each transmitter search unit had to be positioned individually. The sound path for each transmitter search unit had to be equal in order for the redirected energy from each transmitter to be accepted in the same time interval. Two transmitted shear beams propagating into the weld zone from opposite sides prevent large defects from masking smaller ones. This concept is illustrated in Figure No. 10.

All Duo-Delta scan recordings were made at 5.0 MHz. Search units for this test sequence ranged from 0.250 inch to 0.750 inch in diameter. The welds inspected contained lack of fusion and lack of penetration.

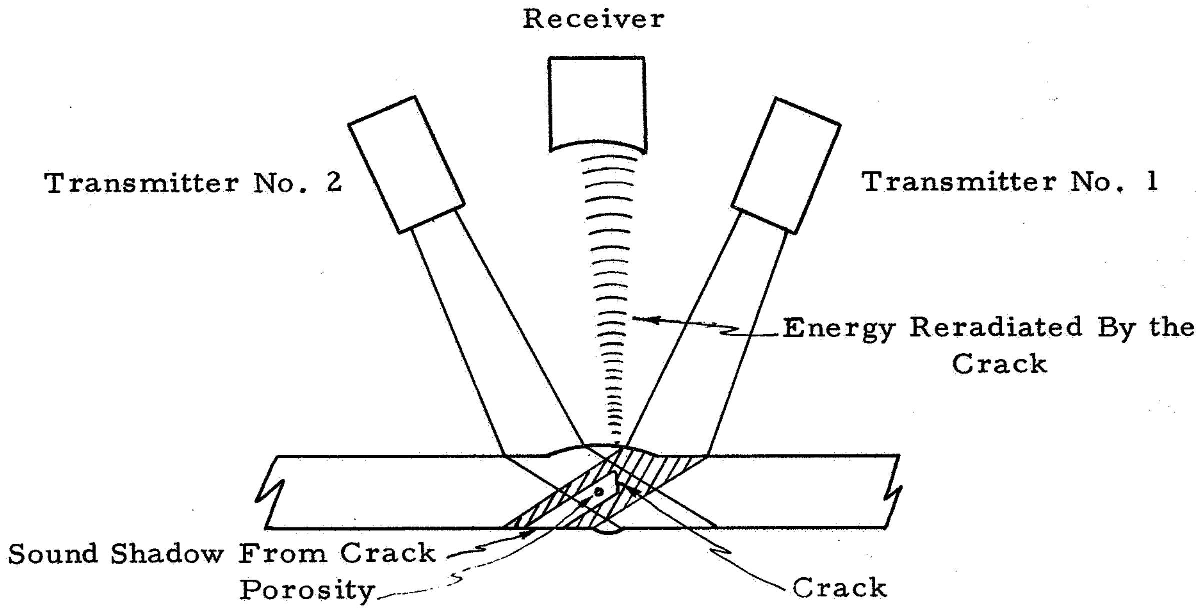
2.3 Transmitter Array Delta Configuration

A special fixture was manufactured to position transmitter search units in a circle at 90° intervals around a single receiver search unit. This fixture is shown in Figure No. 8. This fixture used a fixed 25° incident angle (α). Four 5.0 MHz, 0.500 inch diameter transmitter search units were used in this test. The setup procedure for this test was identical to that for the Duo-Delta. Each transmitter search unit was positioned individually and the water paths adjusted to maintain the proper sound travel time. An electronic matching network was used to achieve an equal ultrasonic energy output from all four transmitters.

2.4 Delta Modifications for Reducing Weld Noise

Erratic noise from the weld crown was a problem in the early phases of this study. The weld crown had various degrees of weld crown buildup, ranging from flush to approximately 0.120 inch above the base metal. Apparently, the welding schedule followed for producing defective welds also tended to produce elevated weld crowns. The sample production weldments received from MSFC did not have the elevated weld crowns.

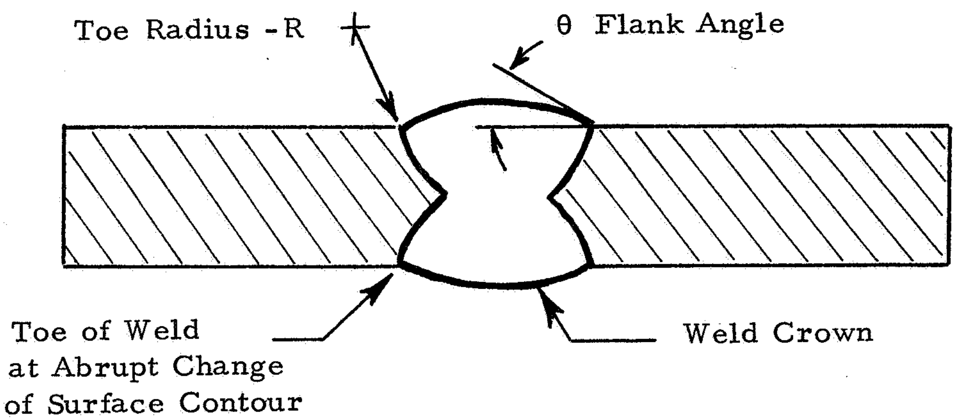
Elimination of weld noise was approached from two directions: (1) the Delta configuration was modified to reduce the nose, and (2) the weld was modified to reduce the noise. The first step in both approaches was to identify the problem and the cause. The cause was isolated to the weld configuration. See sketch in Figure 11. Spurious noise originated at the abrupt surface change where the base metal and the weld crown meet.



Transmitter No. 2 fills the sound shadow behind the crack which otherwise would cause the porosity to be mashed. This method enhances definition of closely grouped defects.

Dual Transmitter/Single Receiver Delta Configuration

Figure No. 10



Weld Crown Configuration

Figure No. 11

The level of the noise was directly proportional to the flank angle and indirectly proportional to the toe radius. An abrupt surface change presented an interface to the transmitted shear beam and the result was a defect type ultrasonic indication.

Refined techniques for positioning the electronic gate helped to reduce the weld noise; however, the gating techniques could not be refined to a point where noise was eliminated for 0.500 inch weld panels and thinner. Physical masking of the weld crown and the receiver search unit reduced the noise but a sensitivity loss accompanied this modification.

The production weldments had a small flank angle and a large toe radius. These weld panels were not noisy because of the gradual transition from base metal to weld crown. An investigation was conducted to determine the extent of weld crown which must be removed to eliminate the noise. These tests were performed in the following sequence:

(1) Top weld bead only, removed in 0.020" increments.
(2) Bottom weld bead only, removed in 0.020" increments.
(3) Both weld beads blended into the parent metal. (This operation was an attempt to duplicate the desired toe radius and flank angle.)

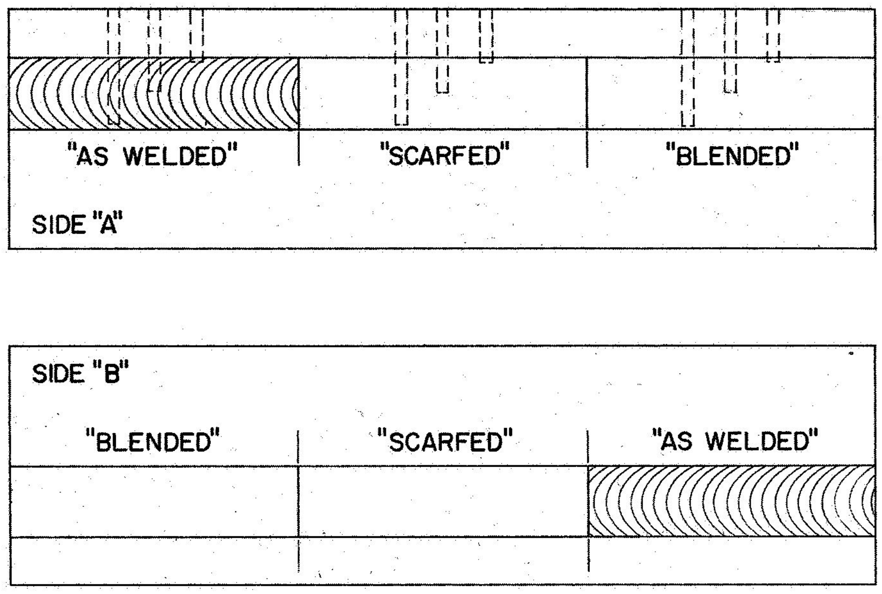
Flat bottomed holes were drilled parallel to the panel surface with the hole ends terminating in the weld zone at the center and both edges. See Figure No. 12 for test hole location in the weld panel.

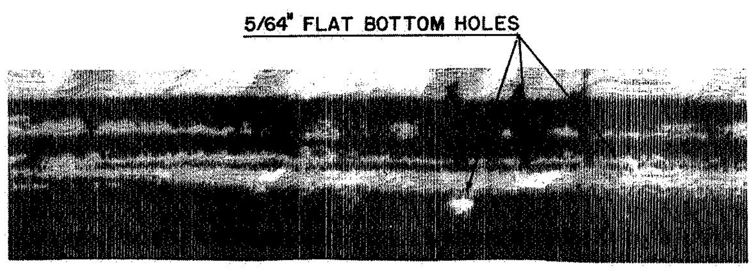
3.0 Test Results

3.1 Basic Delta Configuration

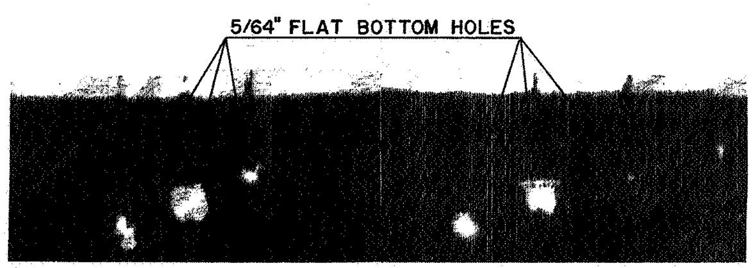
Basic Delta scans were made for weld panels with defective welds and welds containing no defects. The defective welds contained lack of penetration, lack of fusion, porosity and microfissuring discontinuities. Results are shown in Figures No. 13, 16, 18, and 25. These ultrasonic tests were made at 5.0 MHz with a 0.500 inch diameter, flat, 5.0 MHz transmitter search unit and a 0.750 inch diameter, sharp focus 5.0 MHz receiver search unit. This search unit combination was used for all weld thicknesses between 3/16" and 1". The operating parameters were selected from Table No. 2 of the Appendix.

All Basic Delta scan recordings were made full length of each panel so a direct correlation could be established with the radiographic records. A Delta reference standard was used for each test. A Delta scan recording of the standard was made prior to scanning each weld panel. The Delta scan of the standard provided a reference for evaluating the test results. Following the Delta tests, representative weld panels were selected for destructive analysis to determine the actual defect content.





"AS WELDED"



"SCARFED" "BLENDED"

WELD PANEL CONFIGURATION FOR WELD CROWN NOISE STUDY AND DELTA SCAN RESULTS

FIGURE NO. 12

These welds were cut into lengths of 0.62", ground, polished, etched, and examined for weld flaws. Micro and macro-photographs were made of the defective weld structure. These photographs are shown in Figure No. 14 - 17, 19 - 24, 26, 27. Destructive test results for each weld sample are included on the pages immediately following the respective Delta scan recordings.

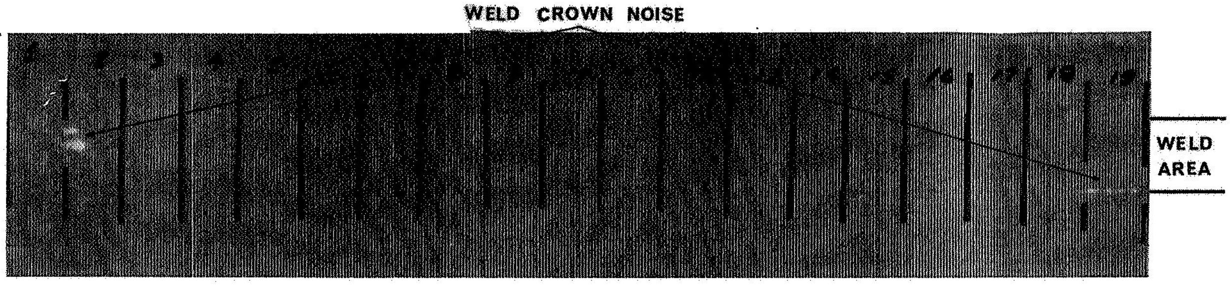
3.1.1 Discussion of Results

The Basic Delta scan recording and the corresponding radiograph of weld panel MR 58 are shown in Figure No. 13A. This weld panel is the good weld example. Close correlation of the test results was achieved for the Delta and radiographic inspection techniques. Tests showed the weld to be free of defect indications. This weld panel was inspected in the as-welded condition. Two instances of weld crown noise were recorded on the Delta scan recording for panel MR 58. These noise indications are identified in Figure No. 13A. Destructive analysis proved the weld to be free of defects.

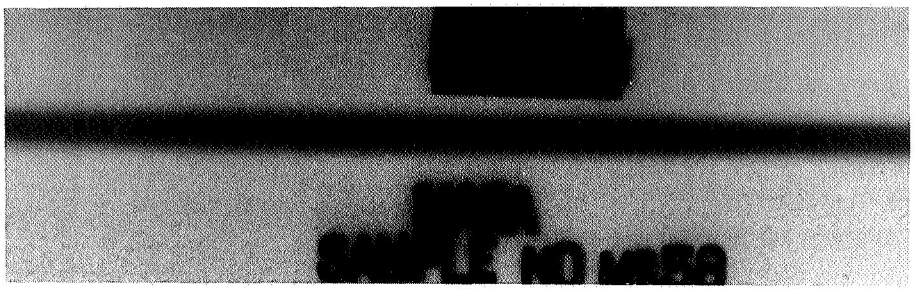
The Delta scan and radiograph of panel 92102 in the as-welded condition, containing a tight lack of penetration condition, are shown in Figure No. 13B. This Delta recording indicated a defect condition along the entire length of the weldment; however, only one line type defect indication was detected in the radiograph. The radiographic indication was interpreted as lack of penetration in sections No. 2 and 3; no other LOP indications were noted on the radiograph. Weld crown noise was recorded along the outside edge of the weld zone, but such indications had no significance when the weld was evaluated in the as-welded condition. No weld blending tests were made on panel 92102 prior to destructive analysis.

Four metallurgical sections were removed from panel 92102 and the lack of penetration condition was confirmed for all sections. Micro and macro-photographs of the defect condition are shown in Figures No. 14 and 15. (Images in the micro-photos are reversed because of the camera-microscope optic system.) These photographs show a tight lack of penetration with a vertical width of approximately 0.070 inches. This LOP condition was continuous through all metallurgical sections of this 7/16" thick weldment.

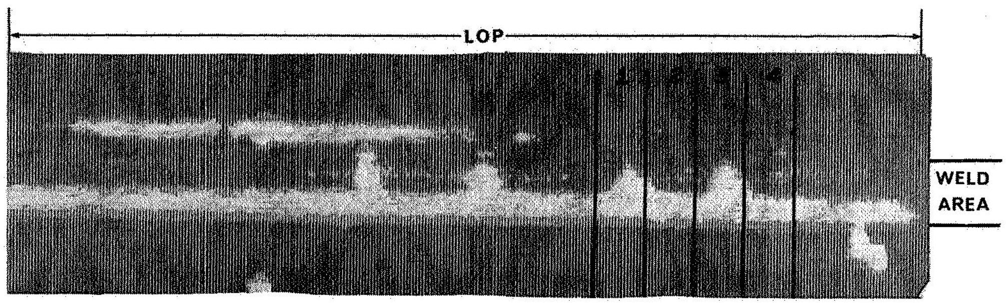
Another example of LOP detected with the Basic Delta Technique is illustrated in Figure No. 16. Weld panel 92107, 1.0 inch thick was radiographed and the LOP condition was not detected. The Delta scan clearly shows the defect condition on the right side of the weld sample (see Figure No. 16). In Section No. 3, the LOP indication was reduced in size, but the indication was still evident. This LOP condition was located in all three metallurgical specimens, one of which is shown in Figure No. 17. Both edges of the unfused weld joint are in intimate contact, a most difficult flaw condition to consistently detect by radiographic examination.



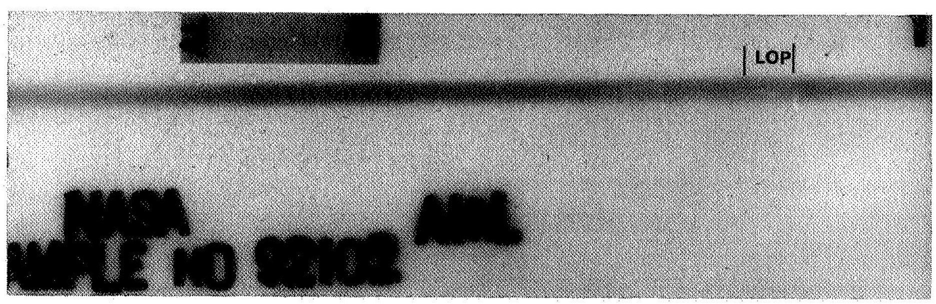
DELTA SCAN RECORDING



RADIOGRAPH
PANEL MR 58



DELTA SCAN RECORDING



RADIOGRAPH
PANEL 92102

BASIC DELTA SCAN RECORDINGS AND RADIOGRAPHS OF WELD PANELS MR 58 AND 92102

FIGURE NO. 13

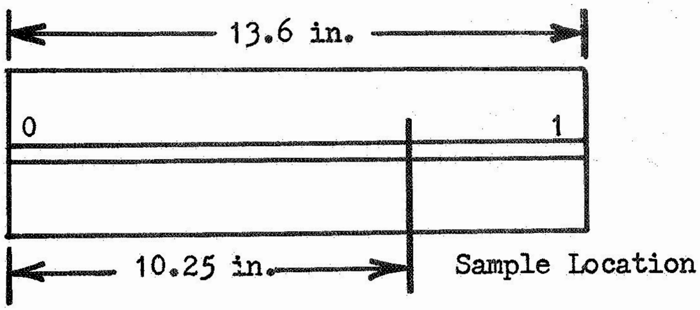
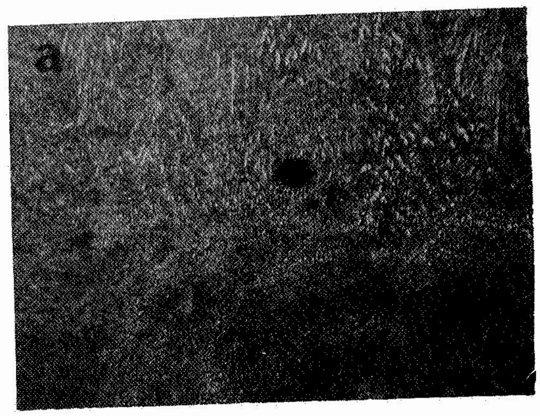
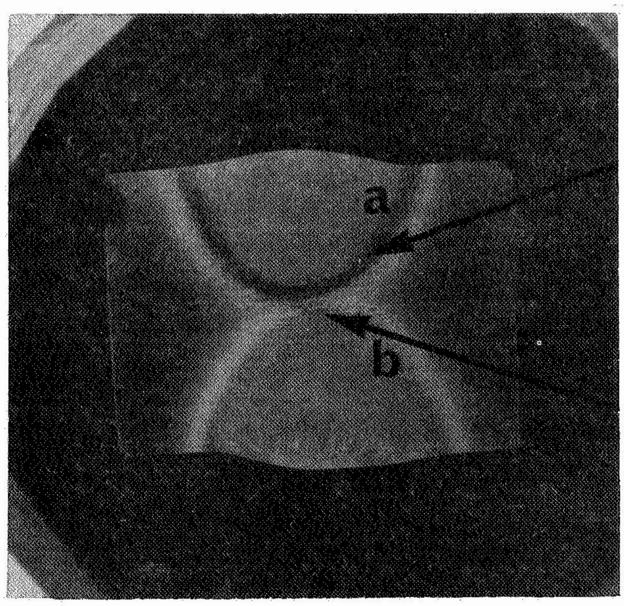


PLATE NO. 92102
SECTION NO. 1/0-1
CUT NO. Face cut



50 X, Keller's Etch



2¼ X, Keller's Etch

50 X, Keller's Etch

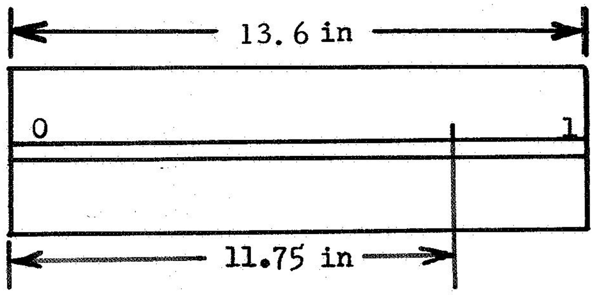
DEFECT DESCRIPTION

Micrograph B shows the lack of weld penetration in the root area.
Micrograph A illustrates small porosity located above the root area.

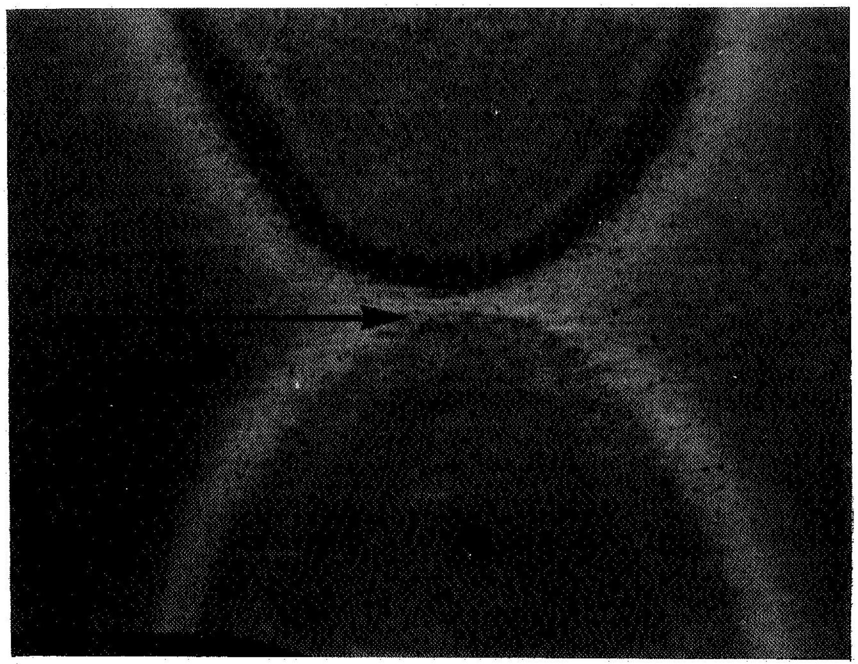
Destructive Analysis of Panel 92102

Figure No. 14

PLATE NO. 92102
SECTION NO. 4/0-1
CUT NO. 17



Sample Location



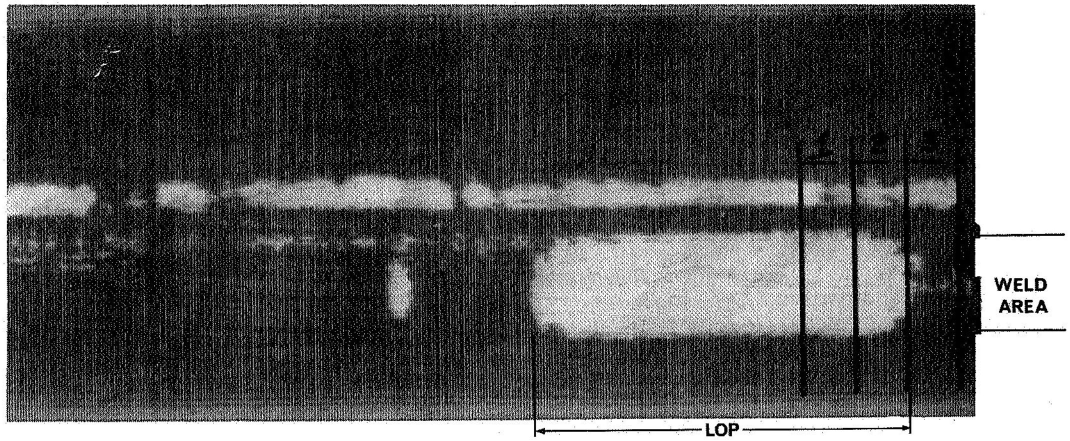
7X, Keller's Etch

DEFECT DESCRIPTION

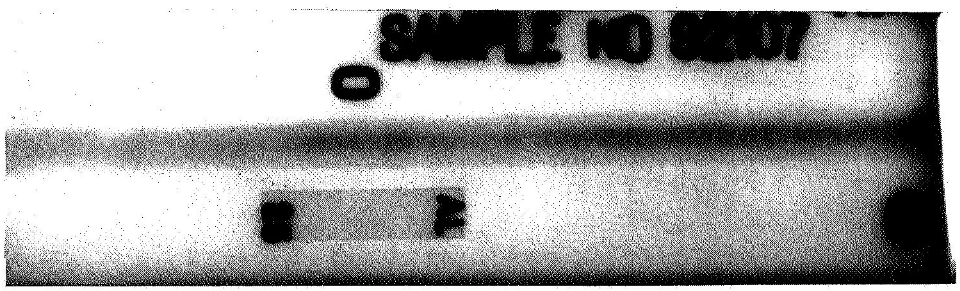
The above macrograph illustrates a 7X enlargement of a lack of weld penetration condition which existed in sample no. 4.

Destructive Analysis of Panel 92102

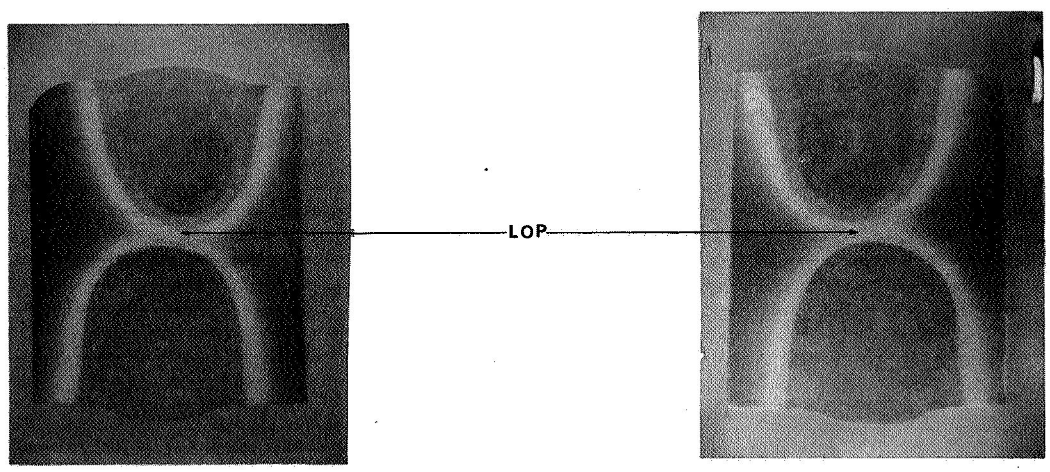
Figure No. 15



DELTA SCAN RECORDING



RADIOGRAPH



SECTION 1

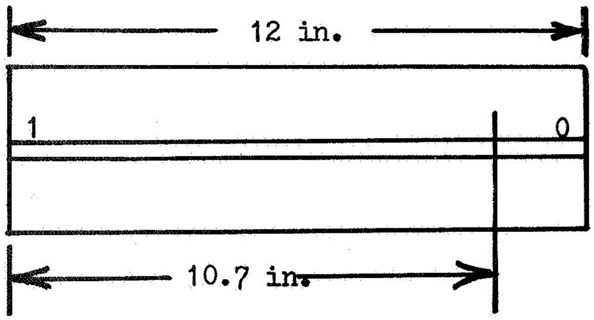
SECTION 2

MACROPHOTOGRAPHS

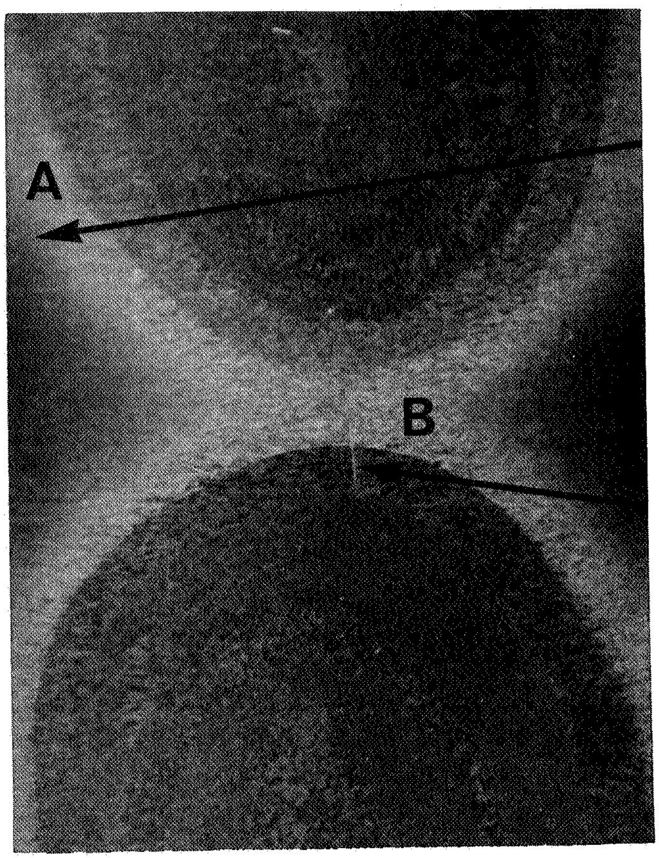
NONDESTRUCTIVE AND DESTRUCTIVE ANALYSIS
OF PANEL 92107

FIGURE NO. 16

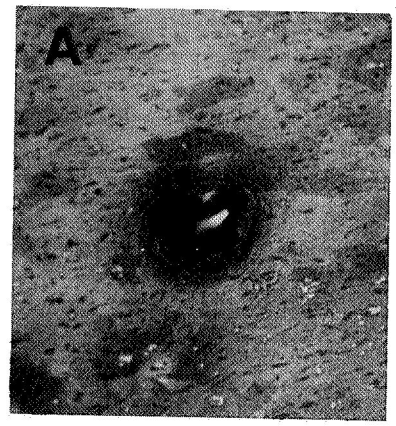
PLATE NO. 92107
SECTION NO. 2/1-0
CUT NO. Face cut



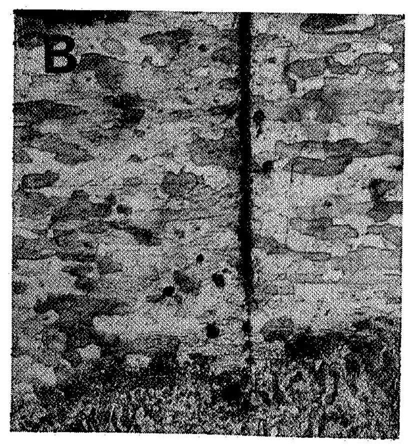
Sample Location



5X, Keller's Etch



100X, Keller's Etch



50X, Keller's Etch

DEFECT DESCRIPTION

Micrograph A shows an inclusion particle found in the base metal adjacent to the weld area. Micrograph B and the macrograph depict the lack of weld penetration condition in Sample No. 2.

Destructive Analysis of Panel 92107

Figure No. 17

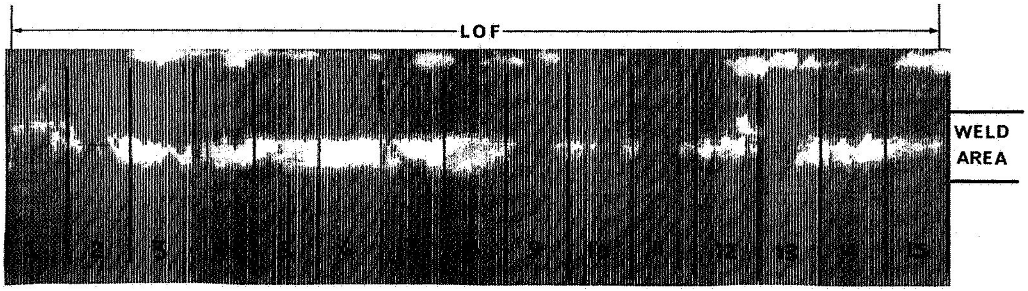
The vertical width of the LOP condition was approximately 0. 160 inches and the defect was continuous along the weldment examined.

Figure No. 18 shows the Delta recording and radiograph of weld panel MR 62 (a 1/2" thick weldment). Both the Delta scan and the radiograph contained full length flaw indications. Destructive analysis of the entire panel revealed a gross lack of fusion (LOF) distributed throughout the weld. These defect conditions are shown in Figures No. 19, 20, and 21. The LOF condition occurred at the edge of the joint between the base metal and the weld deposit. This condition is shown in micrograph B of Figure No. 19. The vertically oriented defect was detected with both Basic Delta and radiographic techniques; however, the second LOF condition was detected with the Delta Technique, only. LOF occurred in the center of the upper weld joint between the bottom of the bead and base metal. See micrograph A in Figure No. 19. This type of LOF was not detected with radiography because the interface lay perpendicular to the X-Ray beam. Figures No. 20 and 21 show additional examples of LOF found in other metallurgical samples from the same weldment. Metallurgical examinations indicated that the LOF conditions in panel MR 62 ranged in size from 0.010 inches to 0. 130 inches in width and extended throughout the total length of weldment.

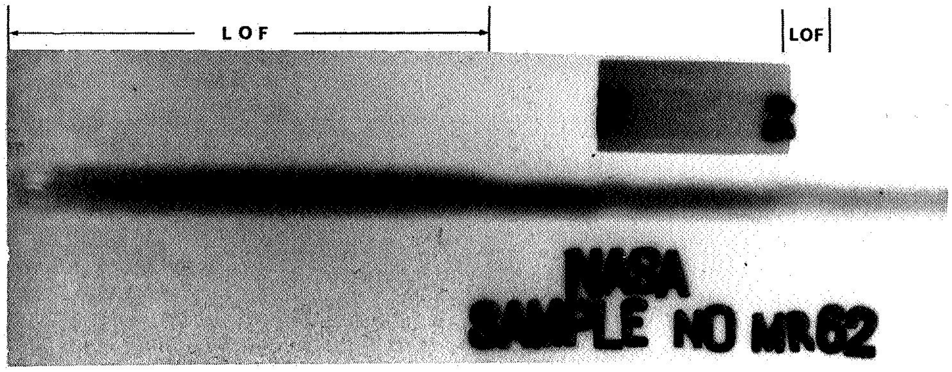
Porosity and intergranular cracking were detected in weld panel 2610000 with the basic Delta Technique. Porosity indications are visible on the Delta recording shown in Figure No. 18. The large indication at the right edge of the Delta scan represented a 0. 250 inch long vertical intergranular crack. This was the most significant cracking condition located during the destructive analysis in this study program. (See Figure No. 24) Isolated porosity greater than 0. 010 inch diameter and chain porosity smaller than 0. 010 inch diameter (micro-porosity) were the major types of porosity found in these aluminum welds. Large bits of isolated porosity occurred in the center region of the welds and were readily detected with both the basic Delta and the radiographic techniques. Micro-porosity (less than 0. 010 inch diameter) occurred in the majority of the weld panels, that were sectioned for metallurgical analysis. The existence of microporosity was not clearly determined by either radiographic nor the basic Delta Techniques.

Photographs of isolated porosity, approximately 0. 060 inches in diameter are illustrated in Figures No. 22 and 23. An example of micro-porosity located at the edge of the fusion zone is shown in micrograph A in Figure No. 24. In some instances this micro-porosity condition was associated with a porosity-like condition in the adjacent aluminum base metal.

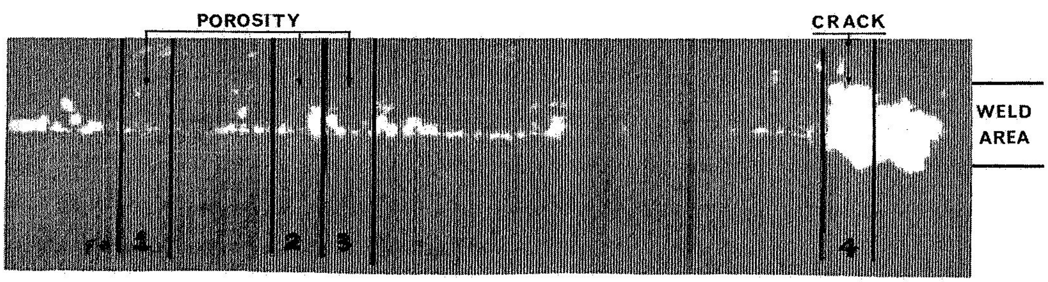
Figure 25 shows the Delta recording and the radiograph of weld panel 191800 which contained LOP and microfissuring. The LOP condition was clearly



DELTA SCAN RECORDING



RADIOGRAPH
PANEL MR 62



DELTA SCAN RECORDING
PANEL 2610000

BASIC DELTA SCAN RECORDINGS OF WELD PANELS
MR 62 AND 2610000

FIGURE NO. 18

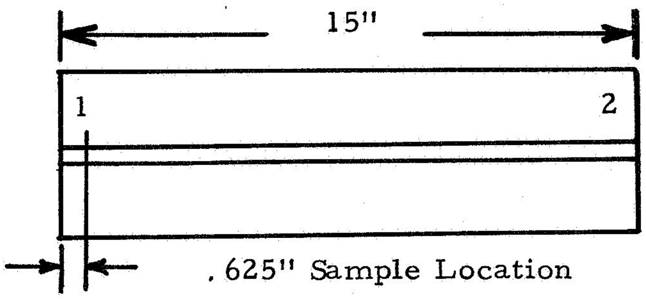
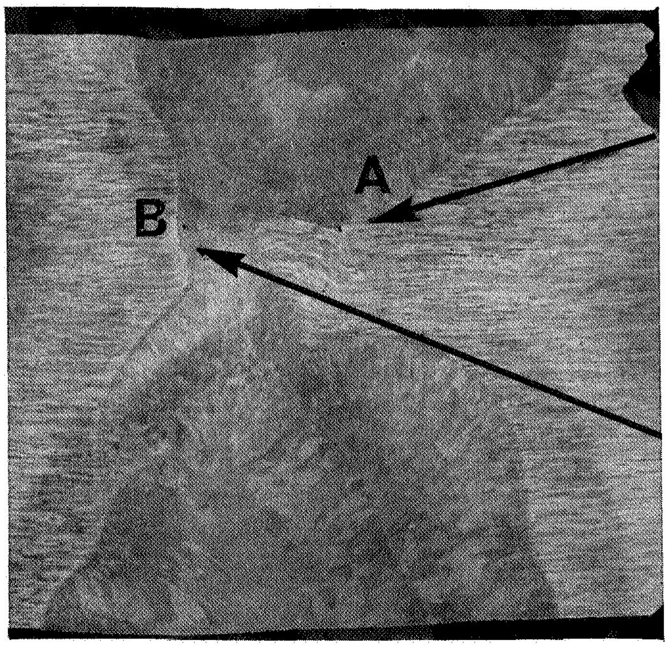
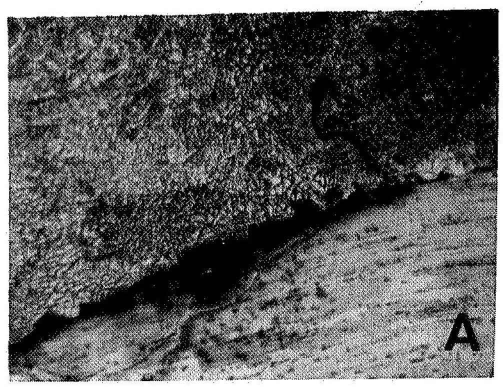


PLATE NO. MR 62
SECTION NO. 2/1-2
CUT NO. Face Cut



6X, Keller's Etch



50X

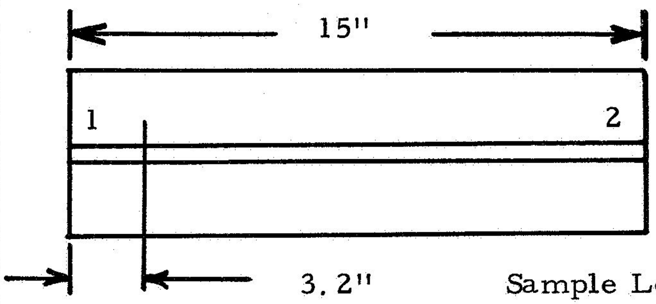
50X

DEFECT DESCRIPTION

Lack of Fusion Condition

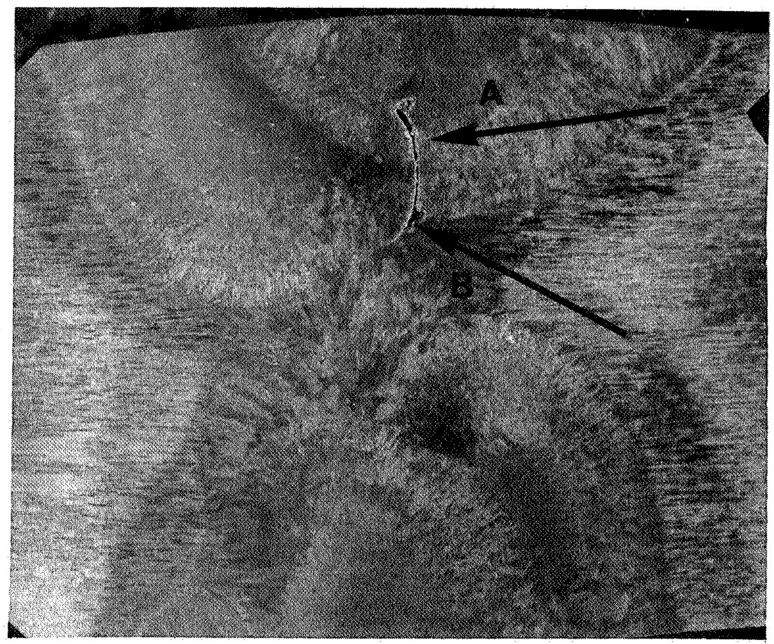
Destructive Analysis of Panel MR 62

Figure No. 19



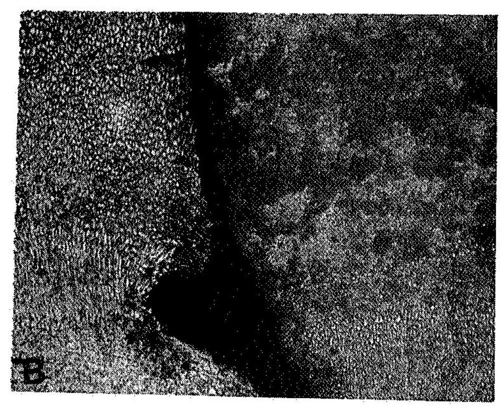
Sample Location

PLATE NO. MR 62
SECTION NO. 6/1-2
CUT NO. Face



6X, Keller's Etch

50X



50X

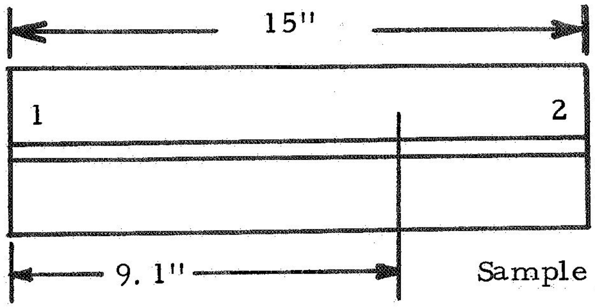
DEFECT DESCRIPTION

Lack of Fusion Condition

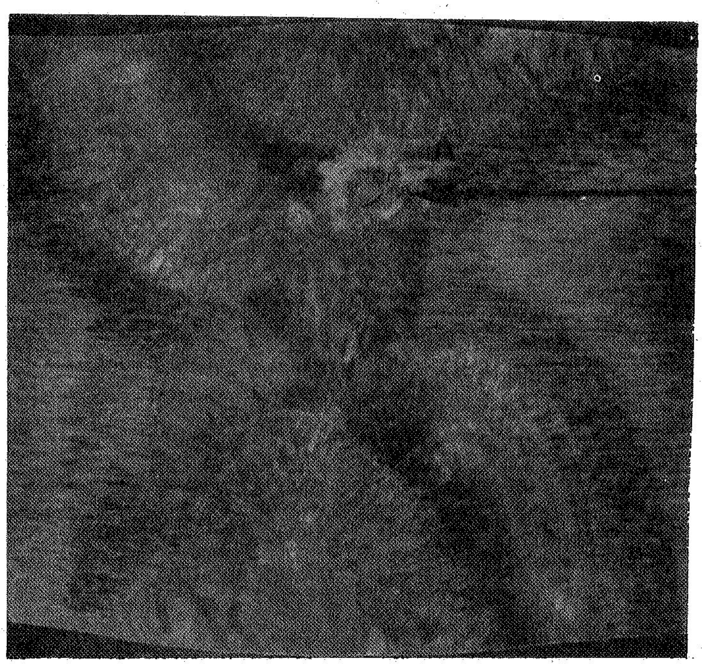
Destructive Analysis of Panel MR 62

Figure No. 20

PLATE NO. MR 62
SECTION NO. 15 /1-2
CUT NO. Face



Sample Location



6X, Keller's Etch

50X

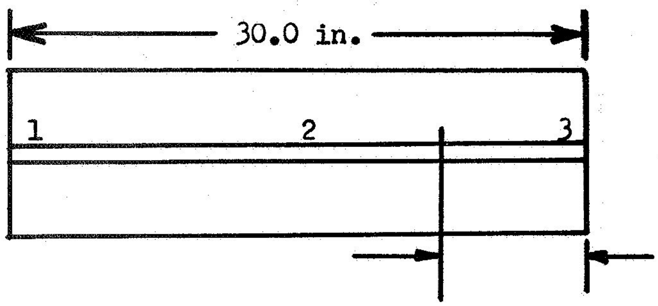
DEFECT DESCRIPTION

Micrograph

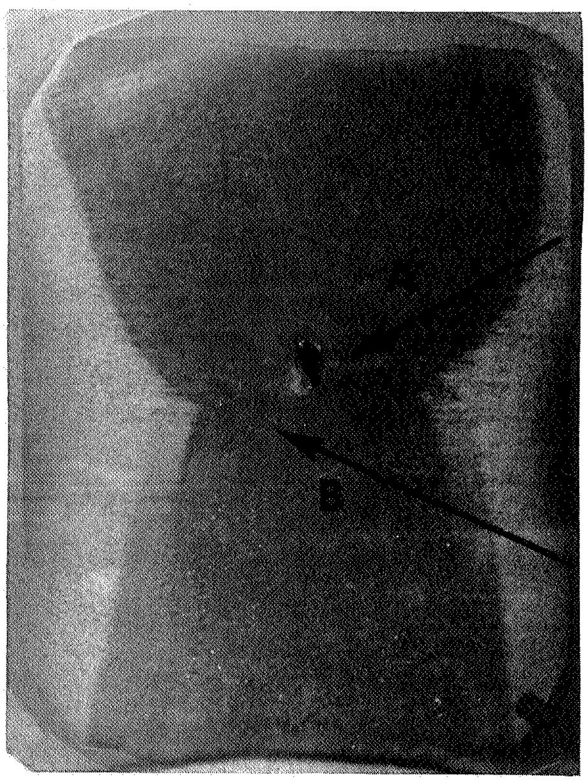
A - Lack of Fusion Condition

Destructive Analysis of Panel MR 62
Figure No. 21

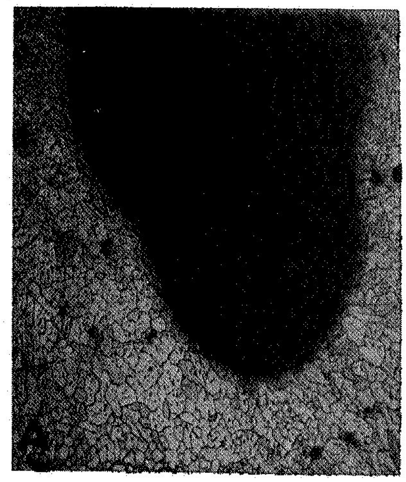
PLATE NO. 2610000
SECTION NO. 1/2-3
CUT NO. 20



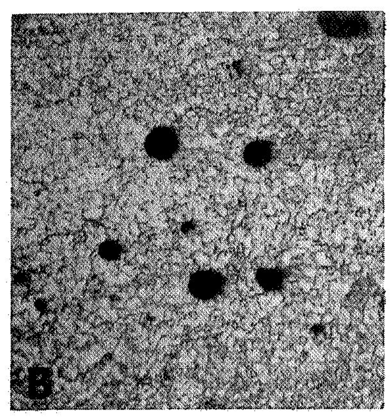
8.7 in. Sample Location



3 3/4X, Keller's Etch



50X, Keller's Etch



50X, Keller's Etch

DEFECT DESCRIPTION

The macrograph and micrograph above illustrates large porosity and micro-porosity existing in sample no. 1.

Destructive Analysis of Panel 2610000

Figure No. 22

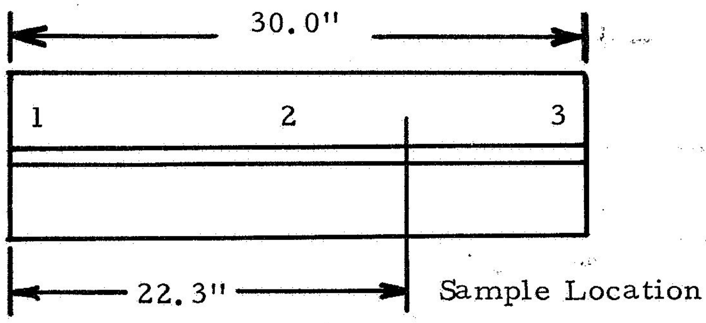
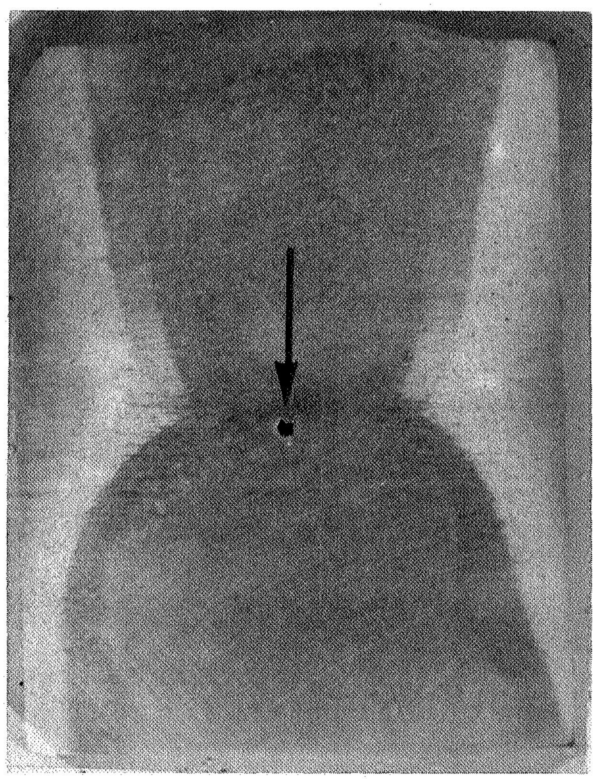
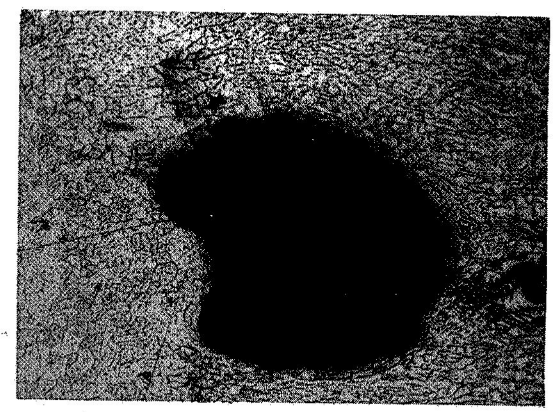


PLATE NO. 2610000
SECTION NO. 2/2-3
CUT NO. 12





3-1/2X Keller's Etch

DEFECT DESCRIPTION

Macrograph - Porosity and microporosity

Micrograph - Enlargement of porosity .024" Diameter

Destructive Analysis of Panel 2610000

Figure No. 23

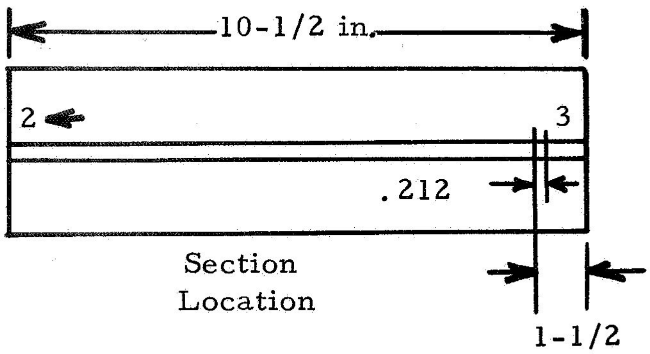
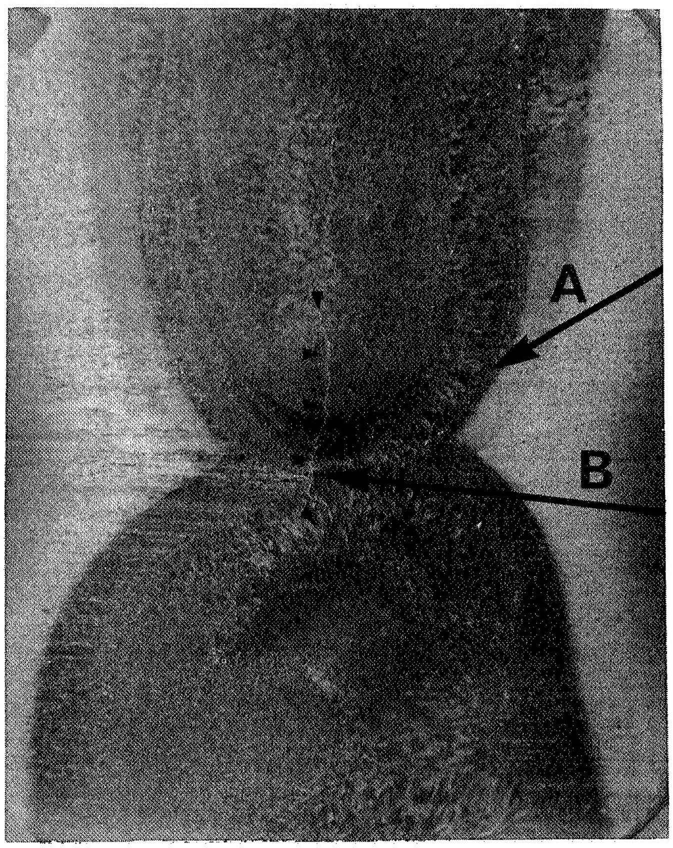
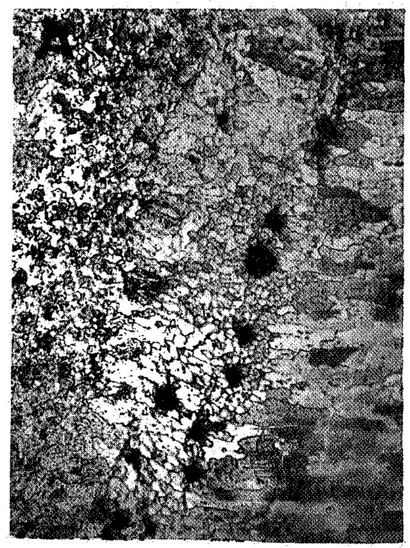


PLATE NO. 2610000
SECTION NO. 4/2-3
CUT NO. 9



4x, Kellers Etch



50x, Kellers Etch

50x, Kellers Etch

DEFECT DESCRIPTION

The above macrograph illustrates an intergranular cracking condition in the root area of the weld. An enlarged view of the 1/4 inch long crack is shown in micrograph B. Chain porosity was noted along the weld fusion zone. Micrograph A illustrates a typical condition.

Destructive Analysis of Panel 2610000

Figure No. 24

indicated at the left edge in both the radiograph and the Delta scan. However, the microfissuring condition shown in Figures No. 26 and 27 was detected only by the Delta Technique. Microfissuring, a shrinkage phenomena that occurred in 3/16" and 1/4" weldments, was oriented parallel to the surface of the weld panels. Defects with this orientation are not readily detected with radiography. The Delta scan recording clearly shows defect indications along the length of the weldment. Destructive analysis of the entire weldment revealed a microfissuring condition near the surface of the weld crown as shown in Figures No. 26 and 27.

3.2 Test Results of the Duo-Delta Configuration

Duo-Delta scan recordings were obtained for 1.0 inch and 0.750 inch thick weld panels in the as-welded condition. Test frequency was 5.0 MHz and the angle of incidence was 24.5° for both transmitter search units. Weldments inspected by the Duo-Delta Technique contained porosity and lack of fusion defects. The Duo-Delta scans were made over complete weld panel sections so comparisons could be made with the radiographic indications. Scanning speed of the Duo-Delta immersion tests was approximately 50 ft/hour, the same rate at which the Basic Delta configuration was operated.

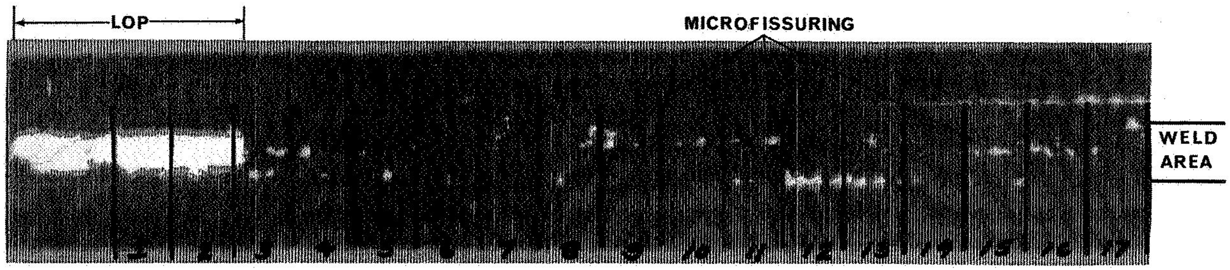
3.2.1 Discussion of Results

Lack of fusion and porosity weld defects were detected by the Duo-Delta Technique. A good correlation was achieved between the radiographic indications and the Duo-Delta scan recordings. However, weld crown noise was recorded at both edges of the weld joint information area in the recording. This erratic noise condition was larger in area than weld crown noise recorded on the Basic Delta scan recordings. In some instances the weld information area on the recording was partially obliterate by the recorded noise indications. This increased interference was attributed to the second transmitter search unit and the interaction of its transmitted ultrasonic beam with the unblended (as-welded) weld crown. The defect indications recorded by the Duo-Delta Technique were larger in area than similar indications recorded by the Basic Delta Technique on the same weld panel.

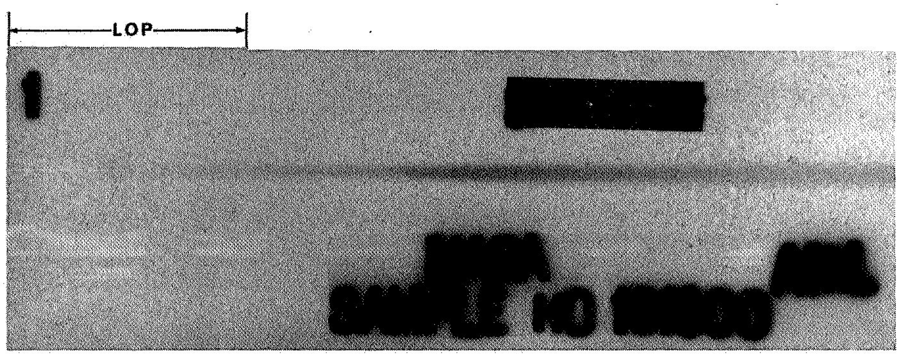
Test results obtained with the Basic Delta and the Duo-Delta were comparable, but there was more weld crown noise. The Basic Delta was selected for eventual use in an ultrasonic wheel because of its smaller size and weight.

3.3 Test Results of Transmitter Array

Transmitter array Delta scan recordings were obtained for 0.075 inch thick weld panels in the as-welded condition containing lack of fusion weld defects.



DELTA SCAN RECORDING

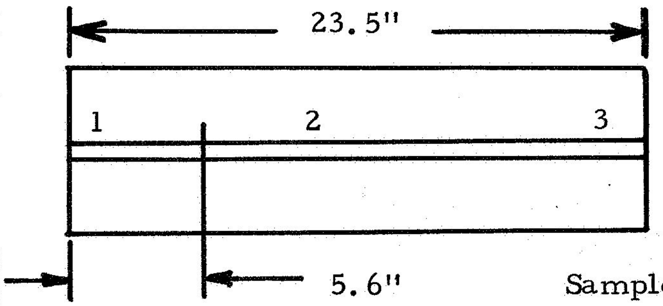


RADIOGRAPH
PANEL 191800

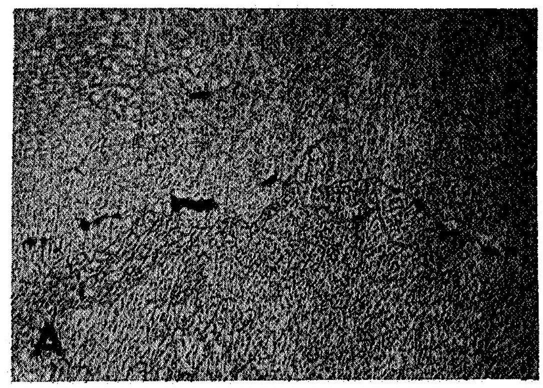
BASIC DELTA SCAN RECORDING AND RADIOGRAPH
OF WELD PANEL 191800

FIGURE NO. 25

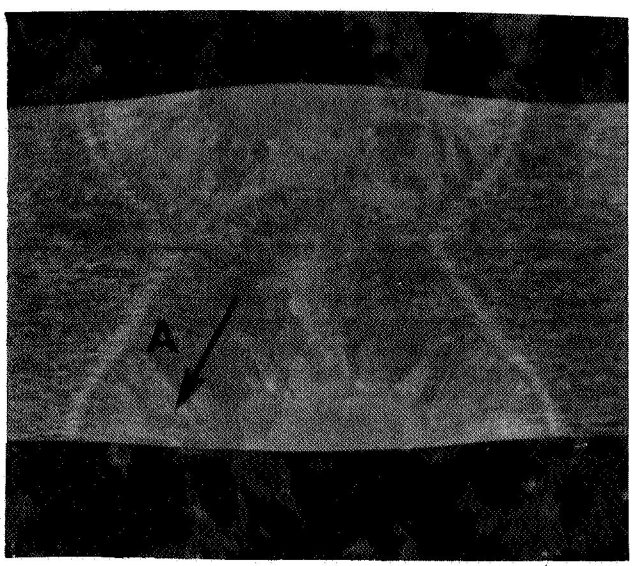
PLATE NO. 191800
SECTION NO. 8/1-2
CUT NO. 2



Sample Location



100X



9-1/2X, Keller's Etch

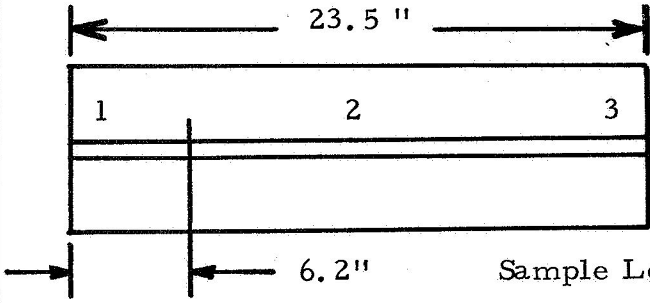
DEFECT DESCRIPTION

Micrograph A - Micro-fissure

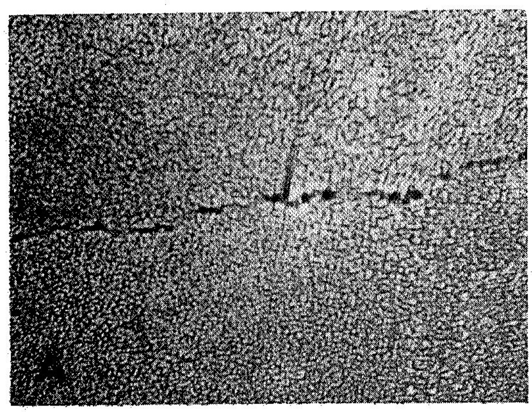
Destructive Analysis of Panel 191800

Figure No. 26

PLATE NO. 191800
SECTION NO. 9/1-2
CUT NO. 2



Sample Location



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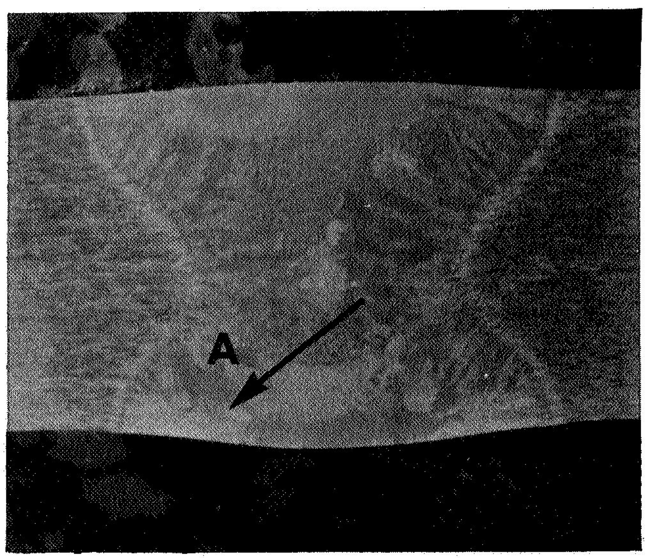


9-1/2X, Keller's Etch

DEFECT DESCRIPTION

Micrograph A - Micro-fissure

Destructive Analysis of Panel 191800

Figure No. 27

The inspections were made at 5.0 MHz using maximum setting for the instrument sensitivity control. Scan speeds were reduced because of the additional weight of the search unit fixture and the increased drag load experienced in the immersion tank.

3.3.1 Discussion of Results

The defect indications on the facsimile recordings obtained with the transmitter array were large and could not be correlated to the radiographic records. Erratic noise from the weld crown was increased by the use of four transmitter search units. The recorded noise indications were continuous along the weld information areas on all facsimile recordings obtained with the Delta transmitter array. In most cases partial or completed obliteration of defect information was experienced. The presence of a weld crown could not be tolerated. This Delta configuration was considered impractical for field application and has no advantages that could be determined. The additional ultrasonic energy was not required for inspection welds 1.0 inch thick and thinner.

3.4 Test Results of Weld Crown Noise

Two Delta scan recordings showing the effects of the weld crown configuration upon the Delta test results are presented in Figure No. 12. In the upper Delta scan recording of the panel in an as-welded condition, only one hole can be clearly seen at the edge of the weld bead. Indications of two holes were obliterated by weld crown noise on the Delta scan recording. The lower Delta scan recording of the same panel shows improved results gained by blending and total removal of the weld crown. Additional test holes were drilled into the weld panel below the blended weld section after the first Delta scan recording was made of the as-welded panel. In this Delta scan recording, all three holes can be clearly seen in the area where the weld crown was completely removed. On the blended side of this Delta scan recording, two holes are readily noted and the third can be seen upon close examination. An increase of instrument sensitivity would have enlarged the image of the third test hole at the edge of the blended weld.

4.0 Summary of Test Results

The performance of the Basic Delta configuration in detecting defects over 256 inches of weld was verified by destructive analysis. Results were obtained for samples in the as-welded condition and for samples with blended weld crowns. A tabulation of these destructive and nondestructive test results are presented in Table No. 1. In Table No. 1, the defects detected

As-Welded Sections	Defect Occurrence in 341 Sections	Number Detected by		Percentage Detected by		Percentage Improvement by Delta
		Delta	X-Ray	Delta	X-Ray	
Lack of Penetration	77	54	28	70	36	94
Lack of Fusion	31	31	27	100	87	15
Porosity > 0.010" Diam.	30	27	24	90	80	13
Porosity < 0.010" Diam.	88	40	28	45	32	41
Cracks	6	5	4	80	66	21
Microfissuring	16	16	2	100	13	670
Blended Weld Sections	Defect Occurrence in 53 Section			%	%	%
Lack of Penetration	5	4	2	80	40	100
Lack of Fusion	22	22	18	100	82	22
Porosity > 0.010" Diam.	5	5	4	100	80	25
Porosity < 0.010" Diam.	19	11	10	58	53	9
Cracks	0					
Microfissuring	2	2	1	100	50	100

Table No. 1

Results of Destructive and Nondestructive Weld Evaluation by radiographic and Basic Delta inspection techniques are compared with the destructive analysis. Percentage values for the level of defect detection achieved is given for both NDT methods. The improvement by radiography and Basic Delta inspection techniques after blending the weld crown is shown by the percentage figures in Table No. 1. In all defect categories listed, the Basic Delta technique outperformed radiography in detecting weld discontinuities before and after blending of the weld crown. As an example from Table No. 1, 77 as-welded samples were found to contain lack of penetration (LOP) when destructively analyzed. The LOP condition was detected in 70% or 54 of these 77 weld samples using the Basic Delta technique. Indications of LOP could be seen in only 36% or 28 of the 77 weld samples using radiographic inspection techniques. This performance by the Basic Delta technique represented an improvement of 94% over radiography in their abilities to detect LOP. Although the number of weld samples destructively analyzed after blending was limited, the increasing level of defect detection could be anticipated. Eighty percent of the lack of penetration (LOP) defects were detected by the Basic Delta technique after weld crown blending, an increase of 100% over the level detected by radiography. The smallest size of LOP recorded on the Delta scan recordings was approximately 0.030 inches wide by 0.060 inches long--it was detected in a 1.0 inch thick weld panel. Most LOP defects were 0.100 inches or greater in length and approximately 0.040 to 0.070 inches wide.

Microfissuring, the shrinkage condition found in the thin weld sections (3/16 and 1/4") was readily detected by the Basic Delta technique. This defect was characterized by a series of shrinkage cavities connected by a microcracking condition (see Figures No. 26 and 27). The shrinkage cavities were approximately 0.002 to 0.005 inches in diameter and were linked by a 0.030 to 0.050 inch long network. Microfissures were oriented with the major interface plane parallel to the weld surface, similar to a lamination type defect found in rolled plate stock.

Porosity pits approximated 0.040 inches in diameter were recorded on the facsimile recordings using the Basic Delta technique. Microporosity pits less than 0.010 inches in diameter were usually clustered or closely linked by microcracks. The Basic Delta technique could detect the microporosity condition when the individual pits were grouped together. However, in a dispersed condition, the microporosity could not be located.

Lack of fusion (LOF) occurred in two distinct forms, an enlarged cavity or a curved plane interface much like a cracking condition. (See Figures No. 19 and 20.) Both forms of the LOF were detected by the Basic Delta technique. In cases where the LOF interface plane was nearly parallel with the weld surface, radiographic techniques could not readily detect the defect. LOF much like LOP, extended throughout a single weld pass which made its detection reliable by the Delta techniques. The LOF condition detected in panel MR 62 were as narrow as 0.025 inches,

III. CONCLUSIONS AND RECOMMENDATIONS

It can be concluded that tight and randomly oriented weld defects such as LOP, LOF, and microfissures can be detected using the Basic Delta Technique. The results of destructive analysis show the Basic Delta Technique to be superior to radiography when both are used to detect LOP, LOF, and microfissures in high strength aluminum butt welds. For the detection of spherical defects such as porosity and foreign inclusions, both radiographic and Basic Delta Techniques achieved near equal levels of detection. Blending the weld crown prior to nondestructive inspection is necessary to obtain a maximum level of detection and reduce weld crown noise on the Delta scan recordings. Indications of small weld defects such as microporosity and the terminal sections of LOP and LOF were more readily apparent on the Delta scan recordings after the weld crown had been blended.

Aluminum welds in the 0. 150 to 1. 0 inch thickness range can be reliably inspected using the Basic Delta Technique. Proper selection of the Delta operating parameters (Table 2 in Appendix) will enable the inspector to test any weld thickness.

Metallic or nonmetallic foreign inclusions were not detected in the weld samples during the destructive analysis. It was possible that any foreign inclusions present could have been dislodged from the weld sample during the polishing operation in the metallurgical laboratory. However, the cavity occupied by the inclusion particle would have been reported as a porosity type defect during destructive analysis.

It is recommended that a Delta search unit configuration be incorporated into a Sperry wheel assembly and used for production weld evaluation at MSFC. A preliminary wheel design has been made incorporating the Basic Delta configuration and is presented in the Appendix of this report. The necessary internal adjustments are provided so the Delta wheel search unit assembly can be used to inspect aluminum welds in the 0. 150 to 1. 0 inch thickness range. By having the adjustment features, no hardware changes will be necessary because of a change in the weld thickness to be inspected. This wheel assembly is compatible with the High Speed Ultrasonic Scanning System now employed at MSFC.

The Basic Delta Technique has been adapted to an experimental hand probe assembly and used to inspect aluminum butt welds. Initial test results indicate that the Basic Delta hand probe assembly can be used to reliably detect LOP, LOF, microfissuring, and porosity. A preliminary design of a similar hand probe has been made incorporating the Basic Delta search unit configuration and is presented in the Appendix of this report. This hand probe can be used with a minimum amount of liquid couplant. It would be useful for post weld repair inspection and in areas where access to the weld joint is limited.

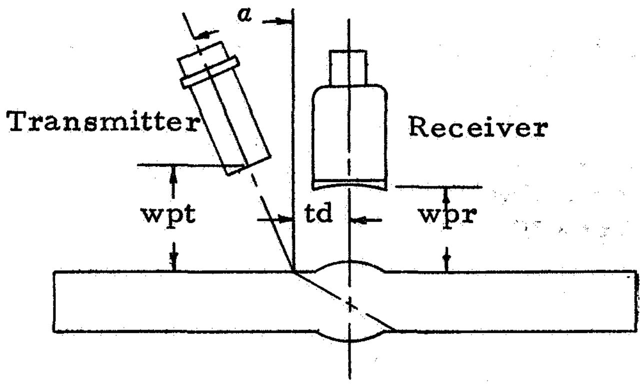
IV. APPENDIX I

A complete list of the flaw detection and associated equipment used in the program is listed below:

Sperry Products, Reflectoscope, Type UM721
Sperry Products, Pulser/Receiver, Type UM, Style 50E533
Sperry Products, Pulser/Receiver, Type UM, Style 50E528
Sperry Products, Special Function Cabinet, Type UM710
Sperry Products, Transigate, Type UM, Style 50C753
Sperry Products, Recording Amplifier, Type STF, Style 50A3159
Alden Electronic and Impulse Facsimile Recorder, Model 311DA
Automation Industries, Inc., Delta Manipulator, Style 57A4082
Automation Industries, Inc., Laboratory Type Immersion Automatic Scanning Tank, Model 57D4294
Automation Industries, Inc., Transmitter Array, -Delta Fixture, Style 57A6048
Automation Industries, Inc., Search Units

Styles:	57A3619	57A2786
	57A3623	57A2802
	57A3625	57A2694
	57A3615	57A2693
	57A3631	

This table lists the various parameters for Delta weld inspection for a given material of a thickness range of 0.187" to 1.00". See sketch to identify the parameters.



td - distance between the receiver axis and the point of incidence of the transmitted beam.

wpr - receiver water path

wpt - transmitter water path

Material: Aluminum
Longitudinal Velocity: 6.37 mm/μsec
Shear Velocity: 3.07 mm/μsec
Density: 2.8 gm/cm^3

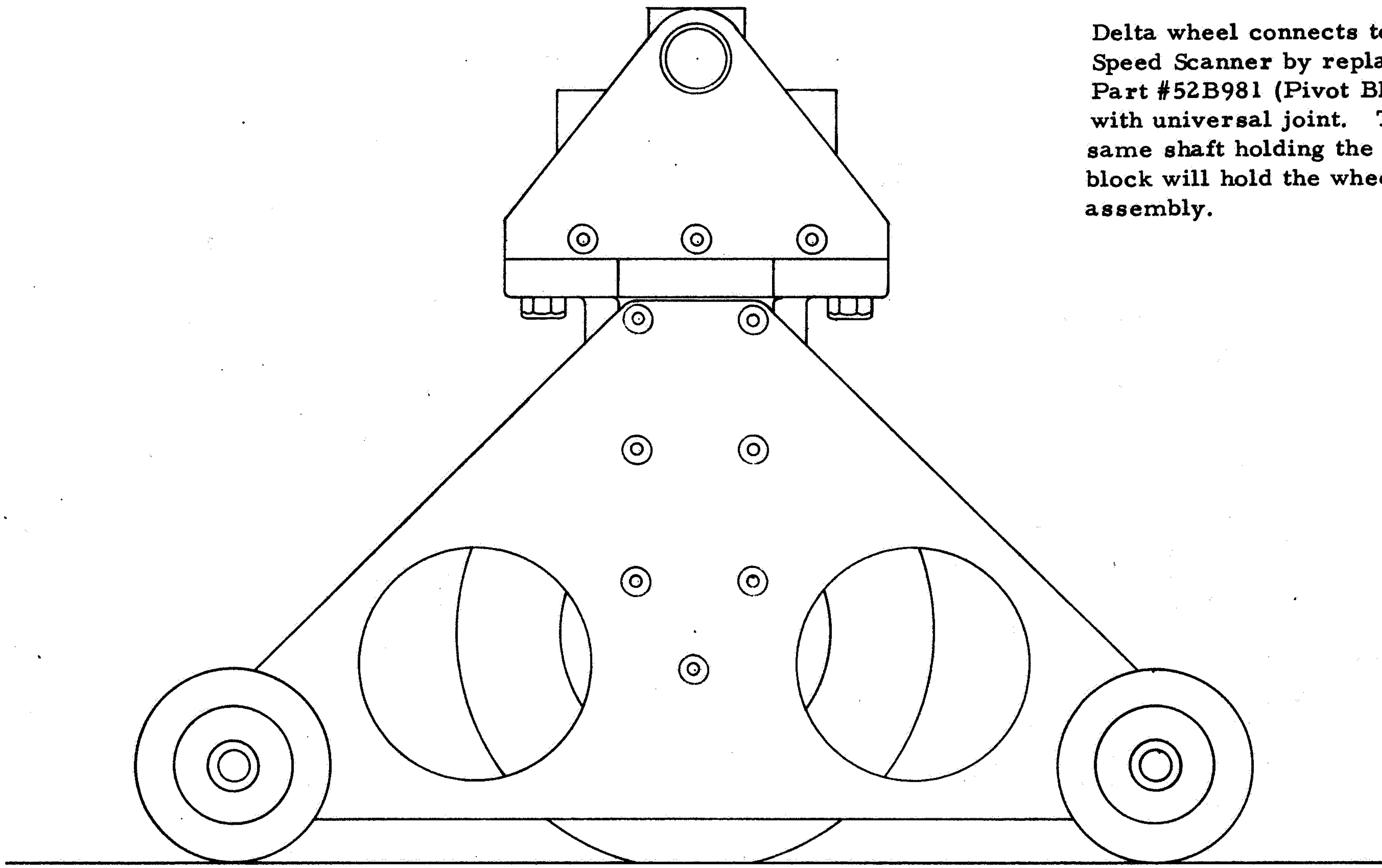
For this material, angle *a* should be 24.5° for optimum results.

Weld Thickness	td	wpr	wpt	Transmitter Search Unit	Receiver Search Unit
.187"	.163"	1.625"	1.375"	0.500" diameter ceramic element with a flat lens.	0.750" diameter lithium sulphate element with a sharp focus lens
.250"	.216"	1.625"	1.375"		
.375"	.325"	1.625"	1.375"		
.438"	.390"	1.625"	1.375"		
.500"	.434"	1.625"	1.375"		
.625"	.542"	1.625"	1.375"		
.750"	.648"	1.625"	1.375"		
1.000"	.865"	1.625"	1.375"		

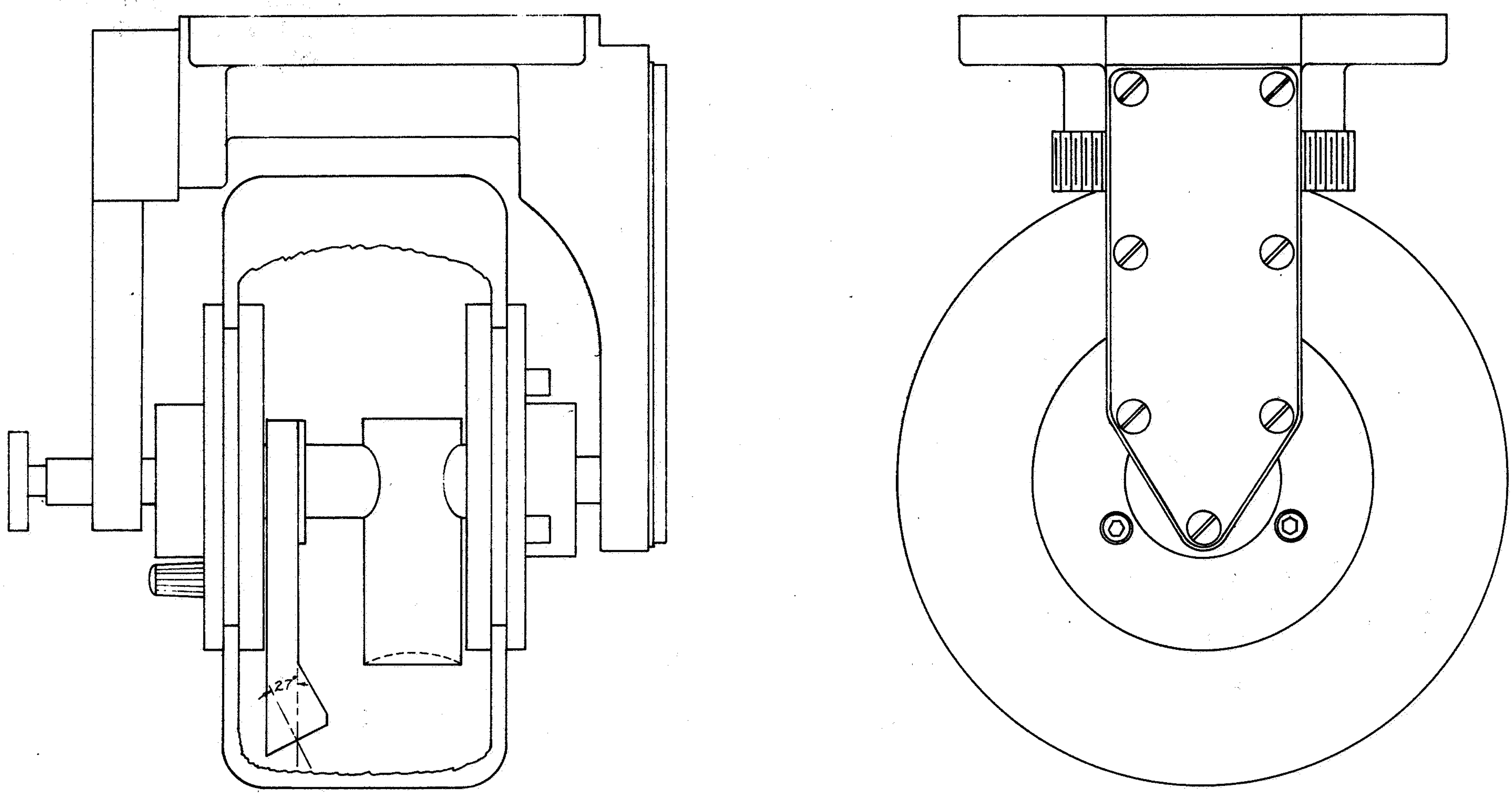
Table No. 2

Delta Parameters for Butt Weld Inspection

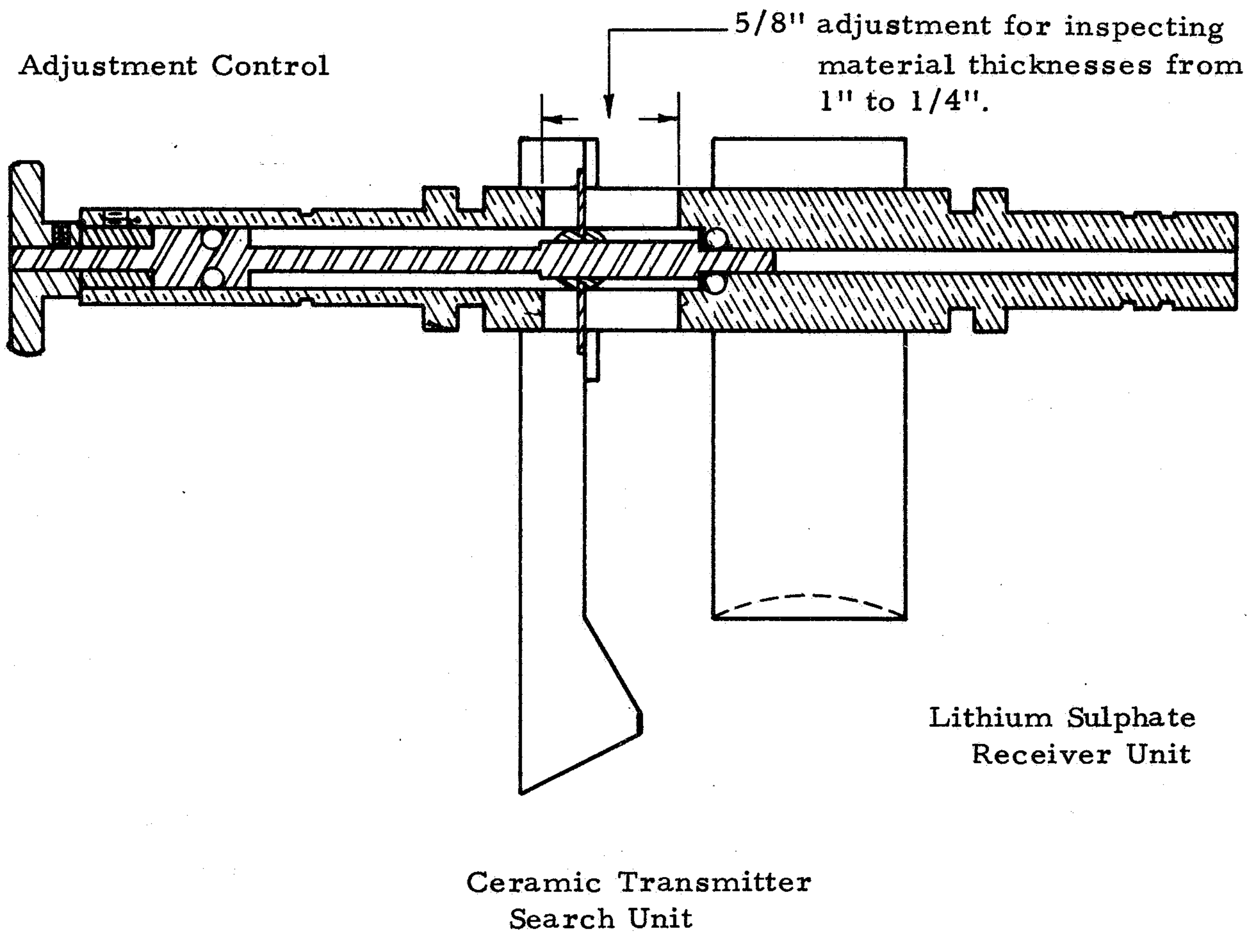
Delta wheel connects to High Speed Scanner by replacing Part #52B981 (Pivot Block) with universal joint. The same shaft holding the pivot block will hold the wheel assembly.



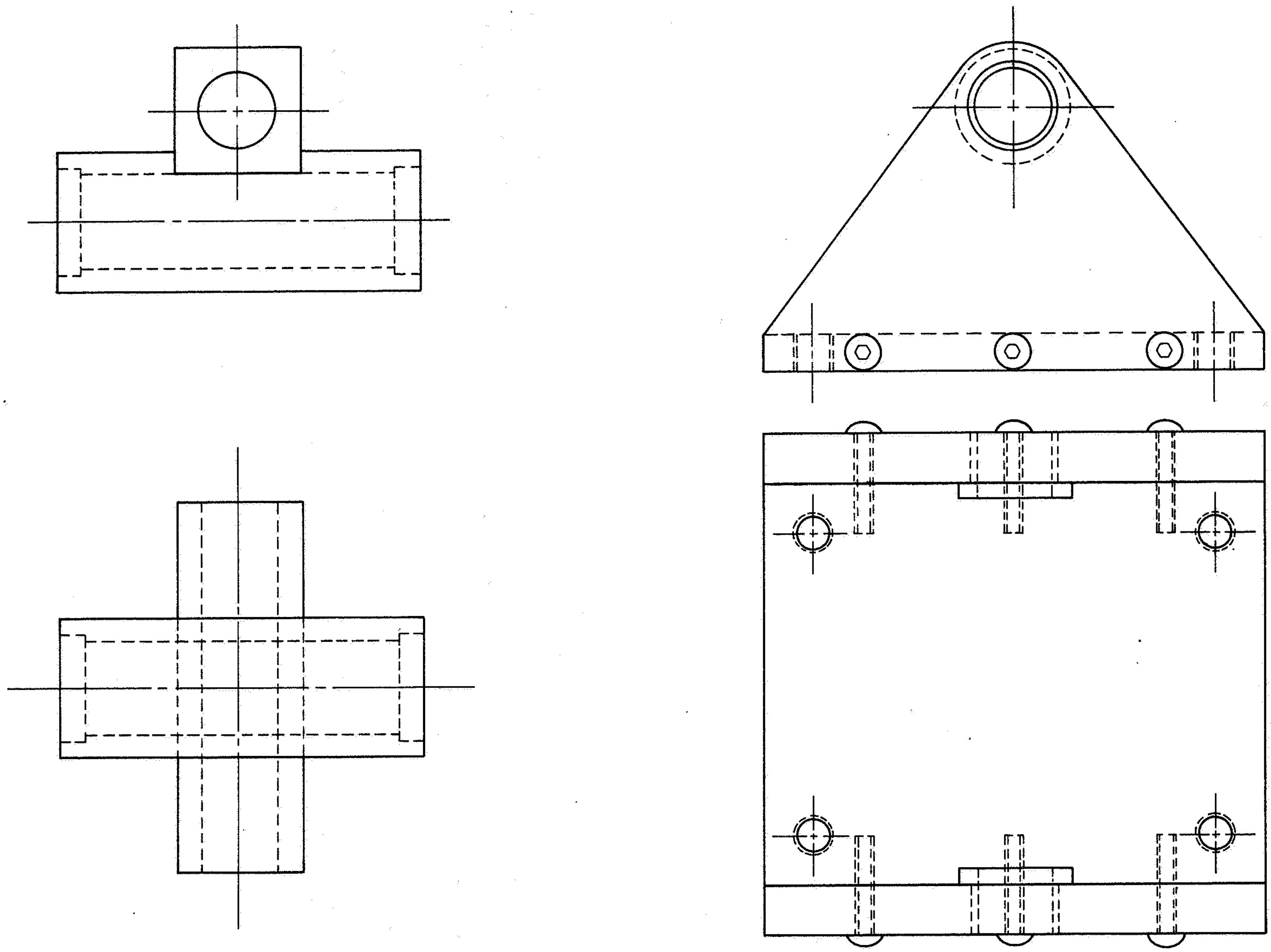
ASSEMBLED WHEEL DELTA



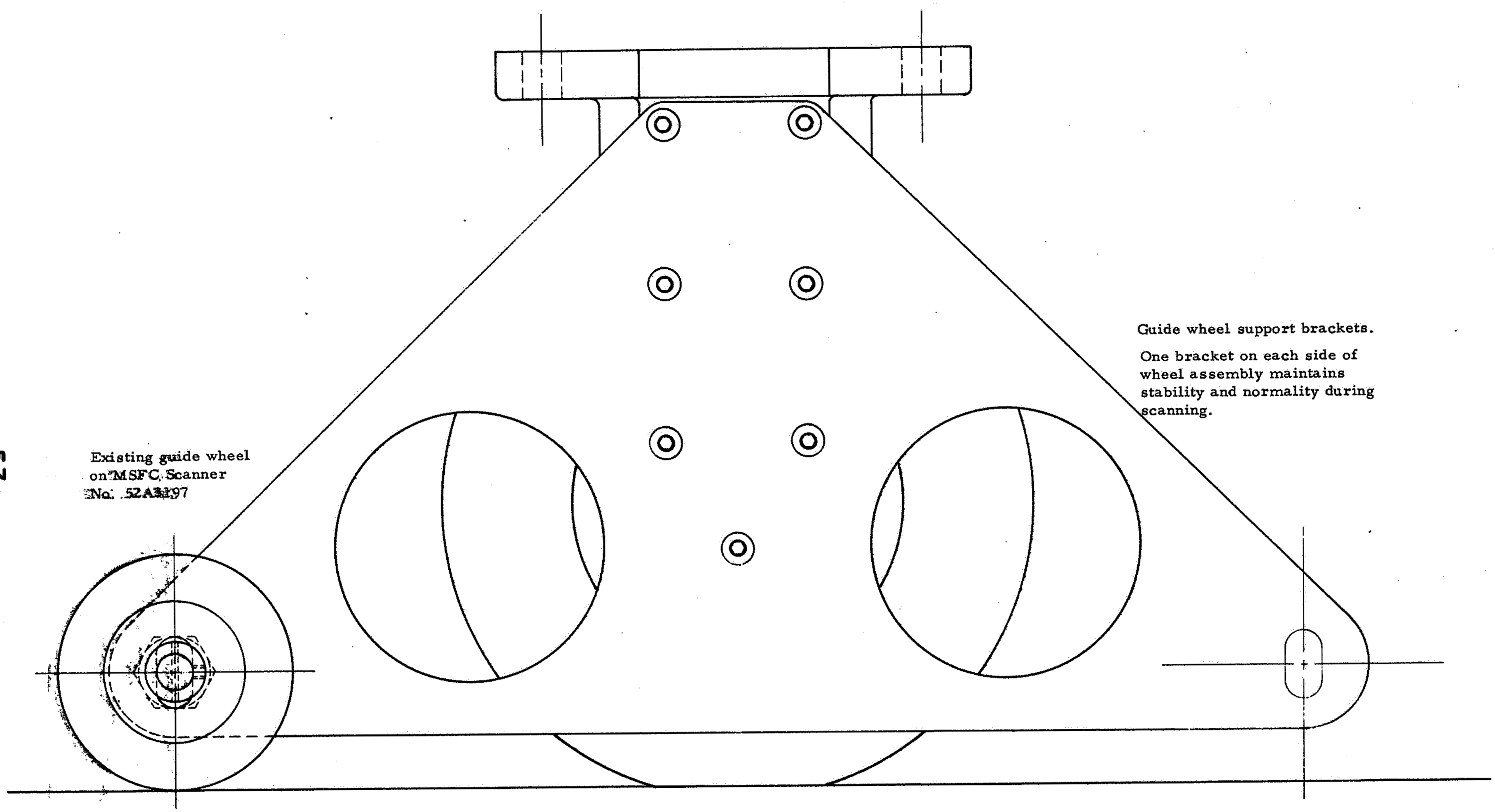
STANDARD 6-1/4" DIAMETER SPERRY WHEEL
SHOWING DELTA MODIFICATION



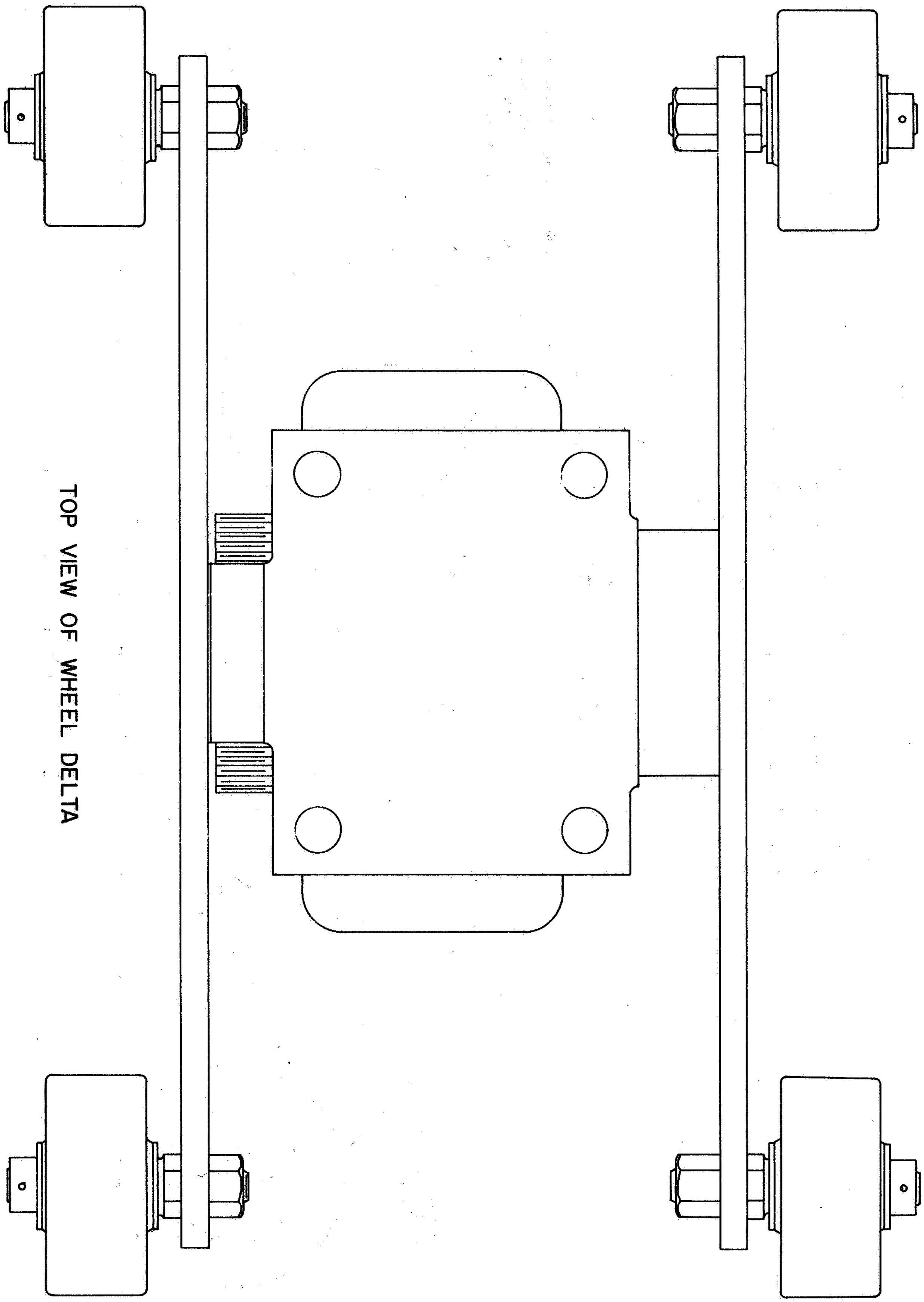
DETAIL OF AXLE MODIFICATION



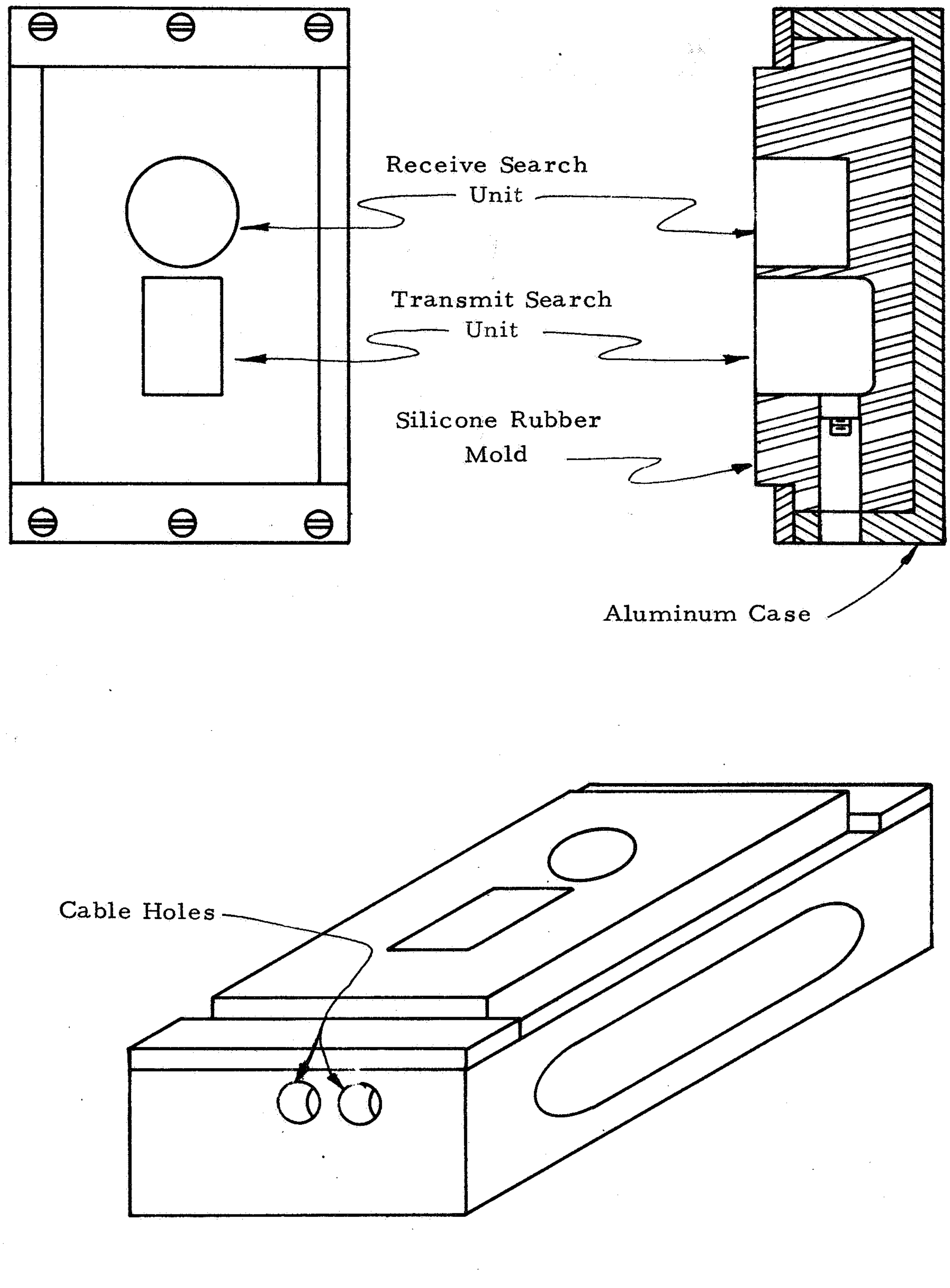
UNIVERSAL JOINT & ADAPTER PLATE



SIDE VIEW OF WHEEL DELTA



TOP VIEW OF WHEEL DELTA



Contact Delta

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