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WELD FLAW DETECTION EVALUATION UTILIZING ULTRASONICS AND RADIOGRAPHY

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NASA

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ABSTRACT

This report presents the results of a research program evaluating ultrasonics in the detection of aluminum butt weld flaws common to Saturn V S-IC Stage welds. Comparisons were made with radiographic test results on the same welds. Flaws investigated were lack of penetration, lack of fusion, porosity, slag inclusions, and a brief investigation of weld bead interference. The advantages of ultrasonics over radiography, except in the case of porosity, were demonstrated. The use of ultrasonics in support of radiography is recommended.

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DEFINITION OF TERMS

BOUNCE SHOT - An angle beam reflection technique in which the shear wave beam is bounced off the bottom surface of the test plate and then up to the weld; particularly useful for testing crowned welds.

COUPLANT - A material, usually a liquid, placed between the probe and the test surface to provide continuity of ultrasonic energy transmission into the structure. Water, oil, and glycerine are common couplants.

DIRECT SHOT - An angle beam reflection technique in which the shear waves are transmitted at an angle to the surface, directly to the weld area.

EXTRANEOUS SIGNAL - A pulse, or pip, produced on the instrument screen from any source other than a significant flaw. A "valid" signal is one produced by a significant flaw.

LACK OF FUSION - A two-dimensional discontinuity of infinitesimal thickness lying along the parting line of a weld bead.

LACK OF PENETRATION (LOP) - A two-dimensional weld flaw in which the weld nuggets of two passes on opposite sides fail to penetrate sufficiently so as to overlap each other. This flaw has the following defined dimensions: (Width not normally specified.)

> Width - Distance between mating faces in a square butt weld (usually less than 1 mm or 0.040 inch).
>
> Depth - Distance between nuggets.
>
> Length - Distance measured parallel to the weld pass or bead.

NUGGET - The entire fused area of a single weld pass, but not including the heat-affected zones or fringe area surrounding the nugget.

POROSITY - (Gas Inclusions) pockets (generally spherical) formed in the weld by trapped gas, a three-dimensional flaw.

DEFINITION OF TERMS (Continued)

PROBE - The assembly of transducer, plastic wedge or shoe, container, and cable connection used in ultrasonic scanning. Also see "transducer."

PULSE ECHO - (Reflection) - A technique in which ultrasonic energy is transmitted into a material, bounced off an interface, and received by a transducer, usually the same one that is transmitting. A discontinuity or flaw in the specimen will also send back an echo which can be identified.

SHEAR WAVE - A mode of ultrasonic transmission in which the motion of material particles is perpendicular to the direction of wave propagation. Also called transverse wave.

SHEAR WAVE ANGLE - Angle between the shear wave axis and a normal to the surface.

SKIP DISTANCE - Horizontal distance from center of weld to center of probe when probe is positioned for a full bounce shot to the top of the weld. Trigonometrically it is twice the product of the plate thickness multiplied by the tangent of the shear wave angle.

SLAG INCLUSIONS - Trapped material (non-metallic) produced in arc welding. Generally caused by insufficient cleaning between weld passes, three dimensional flaw.

THROUGH TRANSMISSION - A technique in which ultrasonic energy is transmitted from one transducer and received by another. Flaws, lying along the transmission path, attenuate the signal being received and are thereby detected.

TRANSDUCER - The piezoelectric crystal used in ultrasonic probes; made of quartz, lithium sulphate, barium titanate, or other materials. This term is used quite commonly to mean the same as "probe."

WELD JOINT GAP - Distance between mating faces of a weld joint before welding.

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WELD FLAW DETECTION EVALUATION UTILIZING ULTRASONICS AND RADIOGRAPHY

SUMMARY

A detailed in-house research program was conducted to evaluate use of ultrasonics in the detection of aluminum butt weld flaws. Comparisons were made with radiographic and metallographic test results of the welds. Ultrasonic equipment utilized in this program was the Krautkramer USK-4 Manual Flaw Detector, employing the pulse echo technique. Specific data on the ultrasonic results and comparisons with radiographic results are given below for each of the evaluation phases.

(1) Evaluation of the prepared weld test panels of 2219 T87 aluminum ranging in thickness from 10 mm (0.4 inch) to 25.4 mm (1.0 inch) showed that ultrasonic detection, by the equipment mentioned herein, successfully identified 67 percent of 6060 mm or 239 inches of Lack of Penetration (LOP), whereas radiography detected only 17 percent of this LOP. However, there is a condition of tightly closed LOP cracks (width less than 0.0005 inch) which neither of the two techniques were able to detect. An ultrasonic technique known as "Delta," now being developed by contract NAS8-18009, shows promise of being able to detect larger amounts of this tight LOP than present ultrasonic techniques.

(2) Eleven separate Lack of Fusion (LOF) and slag inclusion flaws in a lox suction fitting weld and a preproduction weld panel, both of 2219 aluminum alloy, were detected ultrasonically, whereas radiography failed to indicate any of these flaws. In another test 50 LOF flaws were detected ultrasonically, with radiography indicating only the larger of these flaws in three areas.

(3) No apparent advantage in ultrasonics over radiography was demonstrated in the detection of porosity. The smallest pore detected ultrasonically was 1.5 mm (0.056 inch) in diameter, whereas radiography disclosed pores as small as 0.4 mm (0.014 inch) diameter.

(4) The ultrasonic technique detected surface cracks as small as 0.5 mm (0.020 inch) long by 0.025 mm (0.001 inch) wide.

(5) Investigation of weld bead interference showed that shaving the bead to a height of 0.5 mm (0.020 inch) or less eliminated ultrasonic signal interference of any consequence. It also demonstrated that extraneous signals from an unshaved bead are capable of obscuring a signal from a serious flaw. Weld bead interference was not considered detrimental to radiography.

SECTION I. INTRODUCTION

Developments in the field of ultrasonics have established its potential as one of the foremost tools for nondestructive testing. It is being used extensively in the testing of structural materials, welds, bonded materials, and other applications. In keeping with this progress, the Quality and Reliability Assurance Laboratory carried out a program to evaluate and apply ultrasonic techniques to the analysis of Saturn V welds. It is acknowledged that radiography is inadequate for detecting certain cracks and crack-type flaws, such as lack of penetration and lack of fusion. Therefore, the major objective of this program was to determine manual ultrasonic test equipment capabilities and limitations and supplement radiography, where applicable,in the testing of welds. This report describes weld evaluation capabilities of the Krautkramer USK-4 Miniature Flaw Detector which was selected because of its capability to inspect Saturn V weld thickness and material, reported accuracy and sensitivity, portability, and reputed reliability.

Radiography was performed in accordance with Quality and Reliability Assurance Laboratory Acceptance Procedures 6-QHSIC-AM-14 and 6-QHSIC-AMS-1005, Rev. A. The completed weld test panels were radiographed with a single exposure of each panel taken normal to the surface through the weld centerline.

The USK-4 instrument is a battery operated, fully transistorized unit with a cathode ray tube display. Figure 1 is a photograph of the unit with a probe and cable connected. It can be operated in either the pulse echo or through-transmission mode in a frequency range of 2 to 6 MHz. Total weight of the unit, including battery, is less than 5 kg (10 pounds).

The evaluation performed with this ultrasonic instrument included a fairly extensive investigation of lack of penetration detection, with lesser efforts being applied to the detection of the other common weld flaws - lack of fusion, porosity, and cracks. Effects of weld bead interference with the ultrasonic testing were also included.

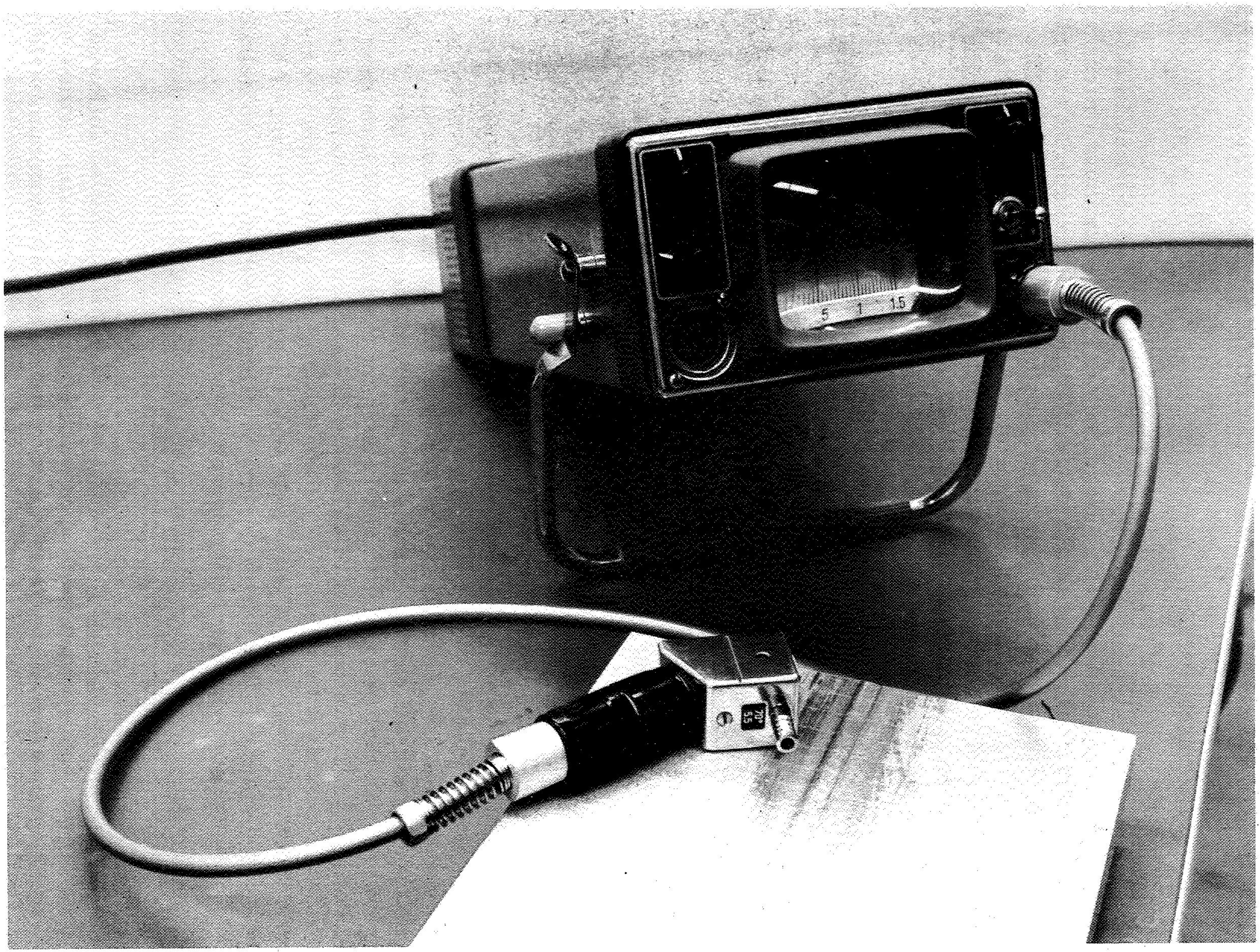


Figure 1. Krautkramer Miniature Flaw Detector

SECTION II. TEST EQUIPMENT AND METHODS

A. TEST EQUIPMENT

1. Radiographic. Production of radiographs taken in this evaluation was accomplished using a Norelco MG 150 X-ray unit, which was standard equipment for Saturn V welds. The unit is designed as a split tank system providing a maximum voltage of 150 kv against ground. The continuous output is 3 kw. Major components of the system consist of a control console, a high voltage generator, high voltage cable, X-ray tube, mobile hydraulic tube support, and a water cooling pump. Operation requires a 220-volt line source.

2. Ultrasonic. The Krautkramer USK-4 Miniature Flaw Detector was selected because of its portability and reputed accuracy over other similar equipment. The normal pulse echo (reflection) method using a single probe was chosen for the testing. Contact probes with both 70 and 80 degree shear wave angle were used.

This Detector operates on either 110 vac or on its built-in battery supply. Operation by battery allows approximately 10 hours of testing between charges. When used in accordance with instructions, battery life in excess of 200 recharges is claimed.

A fluorescent screen picture is obtained on the detector by means of a built-in plastic lens with two-fold magnification. There are four operating controls located adjacent to the screen (figure 2). The zero control moves the trace laterally on the screen, and the gain control, which includes an on-off switch, varies the height of the echo. A test range control is in the upper right hand corner marked as STEEL on the instrument panel. It can be used to calibrate the screen for transmission distance in the test part by expanding or contracting the presentation horizontally. Furthermore, it is a push-pull switch, providing two ranges of transmission distance. The fourth control is a toggle switch used to select the mode of operation - either reflection or through transmission.

B. TEST METHODS

1. Radiographic. Equipment setup and operation followed the general production method for the Norelco MG 150 X-ray unit as described in procedure R-QUAL-AM-112. For the 2219 T87 aluminum weld

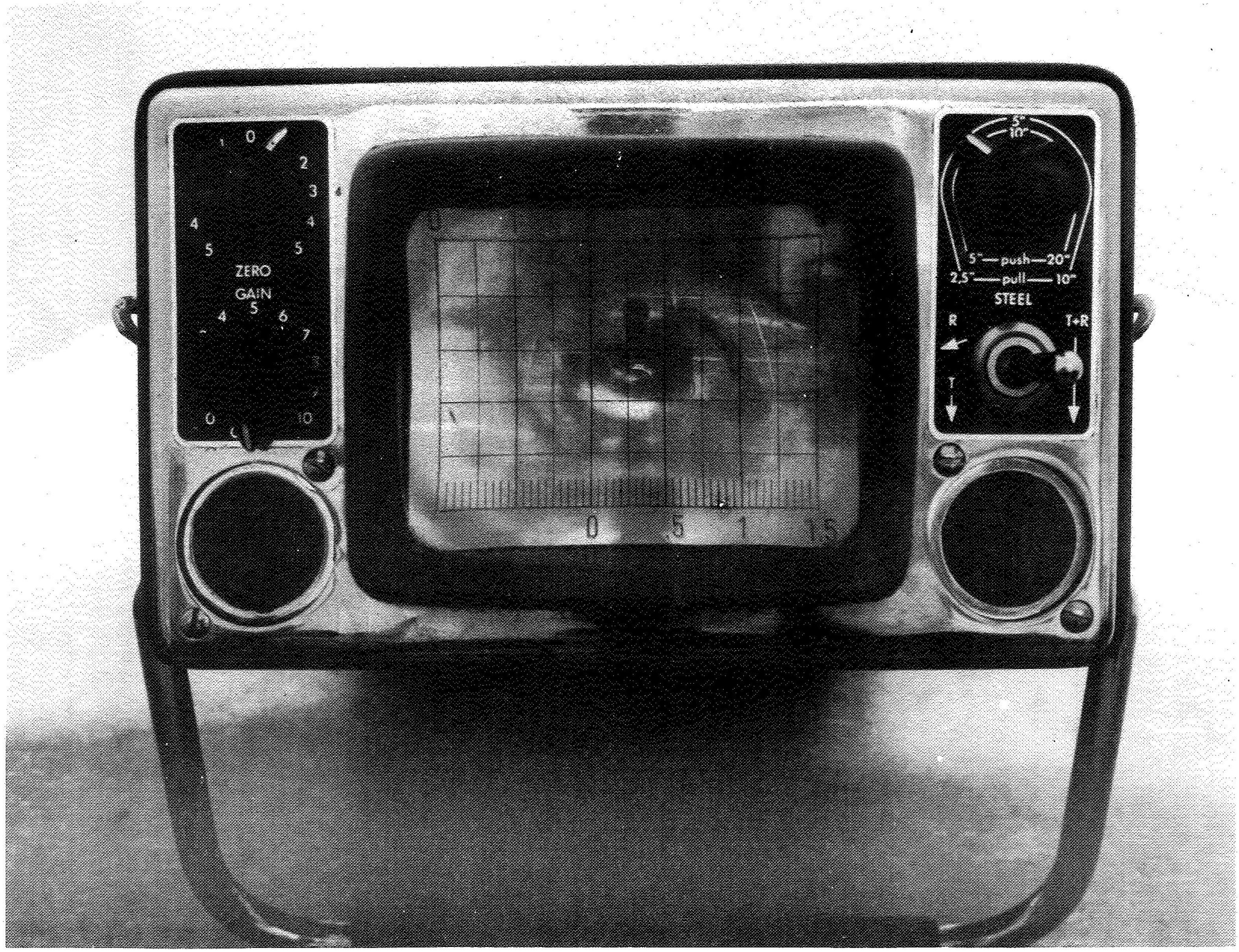


Figure 2. Krautkramer USK-4 Control Panel

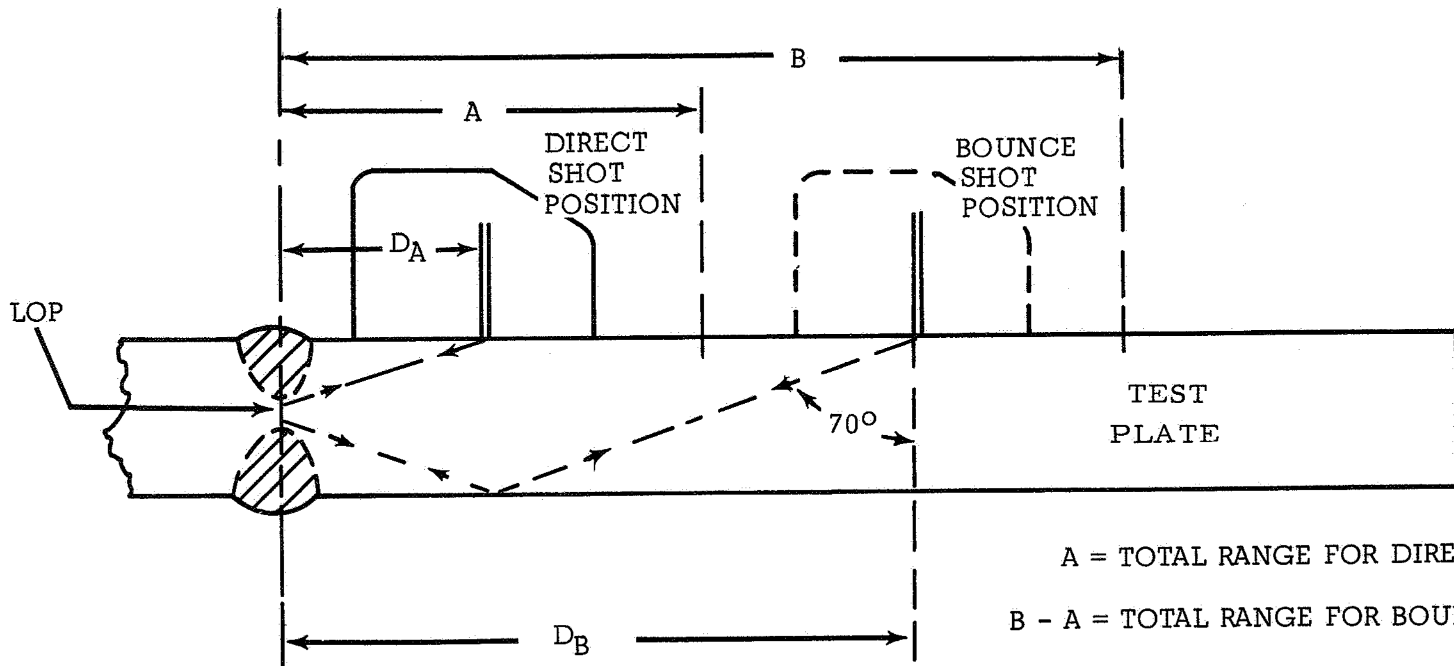
thickness range involved, 10.2 mm (0.4 inch) to 25.4 mm (1.00 inch), the following parameters were employed: power of 75 to 100 kv, time from 1.5 to 3.0 minutes, current range 5 to 15 ma, distance of 36 to 40 inches, and film M ready packs.

2. Ultrasonic.

a. Couplant. A water-soluble oil couplant was used throughout the evaluation. This particular oil was selected because it was ultrasonically adequate, easily removed, and relatively nonflammable.

b. General technique. The pulse echo technique with angle beam probes was employed exclusively in this program. This technique is preferred for manual scanning because it involves less interference with the weld bead and does not require a holding fixture as is needed with multiple probes. Also, geometrically, it views the LOP flaws from a more favorable angle, i.e., normal to the plane of the flaw. The probe transducer transmits longitudinal waves through the couplant film and into the plate at a flat angle, i.e., 70 or 80 degrees depending on the probe used. Shear waves which are created from the longitudinal waves, when the latter enter the plate, are reflected from a defect, such as lack of penetration, picked up by the same probe, and displayed as an identifiable pulse on the cathode ray tube. This transmission can be made directly to the defect via a direct shot, or by bouncing the wave off the opposite plate surface and then to the defect called a "bounce shot." These two forms of transmission are illustrated in figure 3 by probe positions A and B respectively. Both transmission forms were used in this project. A multiple bounce shot, as opposed to a single bounce, is another possibility, but is not recommended because of mode conversion and excessive scattering of the ultrasonic beam, resulting in lack of definition.

Either beam transmission method is satisfactory, providing that the weld or plate geometry does not interfere. For example, referring again to figure 3, as the probe is moved toward the weld the leading edge will strike the weld bead before the ultrasonic beam has traversed the entire weld. This may prohibit the use of direct shots in the thinner plates. On the other hand, as the probe is moved away from the weld, it may, in a production application, encounter plate curvature or surface irregularities which restrict the movement necessary to make a complete bounce shot traverse. Distance of probe movement necessary for a complete traverse can be computed trigonometrically from the plate thickness and probe angle. Relating this required movement to the existing weld geometry would indicate the proper choice of the two methods.



A = TOTAL RANGE FOR DIRECT SHOT

B - A = TOTAL RANGE FOR BOUNCE SHOT

D_A = PROBE DISTANCE FOR DIRECT SHOT FLAW INDICATION

D_B = PROBE DISTANCE FOR BOUNCE SHOT FLAW INDICATION

Figure 3. Angle Beam Detection of a Flaw (LOP)

Thin plates, i.e., those under 12 mm (0.472 inch) thickness, are difficult to scan ultrasonically. First, the thinner the plate the greater the possibility of overlapping and confusion between flaw signals and extraneous signals caused by the weld bead itself. Second, the physical interference between the probe and the bead may prevent a complete weld traverse with either a direct shot or a single bounce shot.

These limitations, caused by physical interference, apply only to the type of probes used in this evaluation, i.e., hard sole, angle beam probes. Listed below are three of the more common probes of this type and plate thicknesses (determined geometrically) that can be traversed by a single bounce shot, i.e., without resorting to double bounce.

Probe No.	Actual Angle (degrees)	Minimum Plate Thickness (mm)	(in.)
WB-70	67	12	0.472
WB-80	74	10	0.394
MWB-70*	70.5	8	0.315

*Miniature 70 degree probe.

The first of the difficulties mentioned above is easily minimized by shaving the weld bead to production specifications as described in paragraph D, section III. The second is not affected by bead shaving, but can be eliminated by complete removal of the weld bead.

In preparation for ultrasonic scanning with the Krautkramer USK-4 detector, two calibration steps are essential. The first involved horizontal adjustment of the cathode ray tube trace so as to represent the bottom and top plate surfaces at the arbitrarily chosen "0" and "1" vertical grid lines, respectively, on the screen. This representation also defines the range within which valid flaw signals will appear, thus enabling the operator to disregard the extraneous and meaningless pulses falling outside these limits. The second step was to adjust the instrument gain setting in a manner that would provide consistent and repeatable sensitivity. These calibration steps are described in Quality and Reliability Assurance Laboratory procedure No. R-QUAL-AM-27.

The following test procedure was used throughout the evaluation, except as otherwise noted. After the instrument was calibrated and the oil couplant placed on the panel, actual scanning of the weld began. Standard practice was to start at one end and scan each 13 mm (1/2 inch) increment along the transverse lines previously laid out. A 6 inch steel scale was butted against the weld bead and held in place so as to guide the probe along a given transverse line perpendicular to the weld. The probe was placed on the plate, against the scale as shown in figure 4, and approximately 80 mm (3 inches) from the weld. It was then guided back and forth through the range of a bounce shot traverse to determine the position that produced a maximum pulse amplitude on the screen. When this position was stabilized, the pulse amplitude, horizontal position on the screen, and distance of the probe from the weld bead were recorded on the log sheet under the heading "Bounce Shot." Only the pulses appearing between the "0" and "1" grid lines on the screen were considered as possible weld flaws. Pulses lying outside these limits are caused by extraneous effects. This distinction was made possible through the previous calibration procedure.

To obtain a direct shot at the same station (transverse line), the probe was moved toward the weld bead until another pulse was found and maximized. This pulse was located to the left of the "0" grid line on the screen with the probe almost touching the weld bead. The above three parameters were again recorded, this time for a direct shot. The straightedge was then moved over 13 mm (1/2 inch) and the next station scanned exactly as before. The process was repeated until the entire length of the panel had been scanned. The panel was then rotated 180 degrees on the table and the procedure repeated from the opposite side of the weld.

C. ANALYTICAL METHODS FOR FLAW VERIFICATION

Several different analytical methods were employed to verify the existence and identity of the various types of flaws detected ultrasonically.

1. Metallographic Analysis. This method was satisfactory for disclosing lack of penetration in such a way that measurement of depth and width were facilitated. Standard practice was to section the test panel along the transverse scanning lines (stations). The resulting samples were polished and etched so as to expose a cross section of the weld corresponding to each scanning station. Polishing was usually concluded with a 600 grit size paper. Either Keller's etch or sodium hydroxide was used for etching. A set of samples treated in this manner is shown in figure 5.

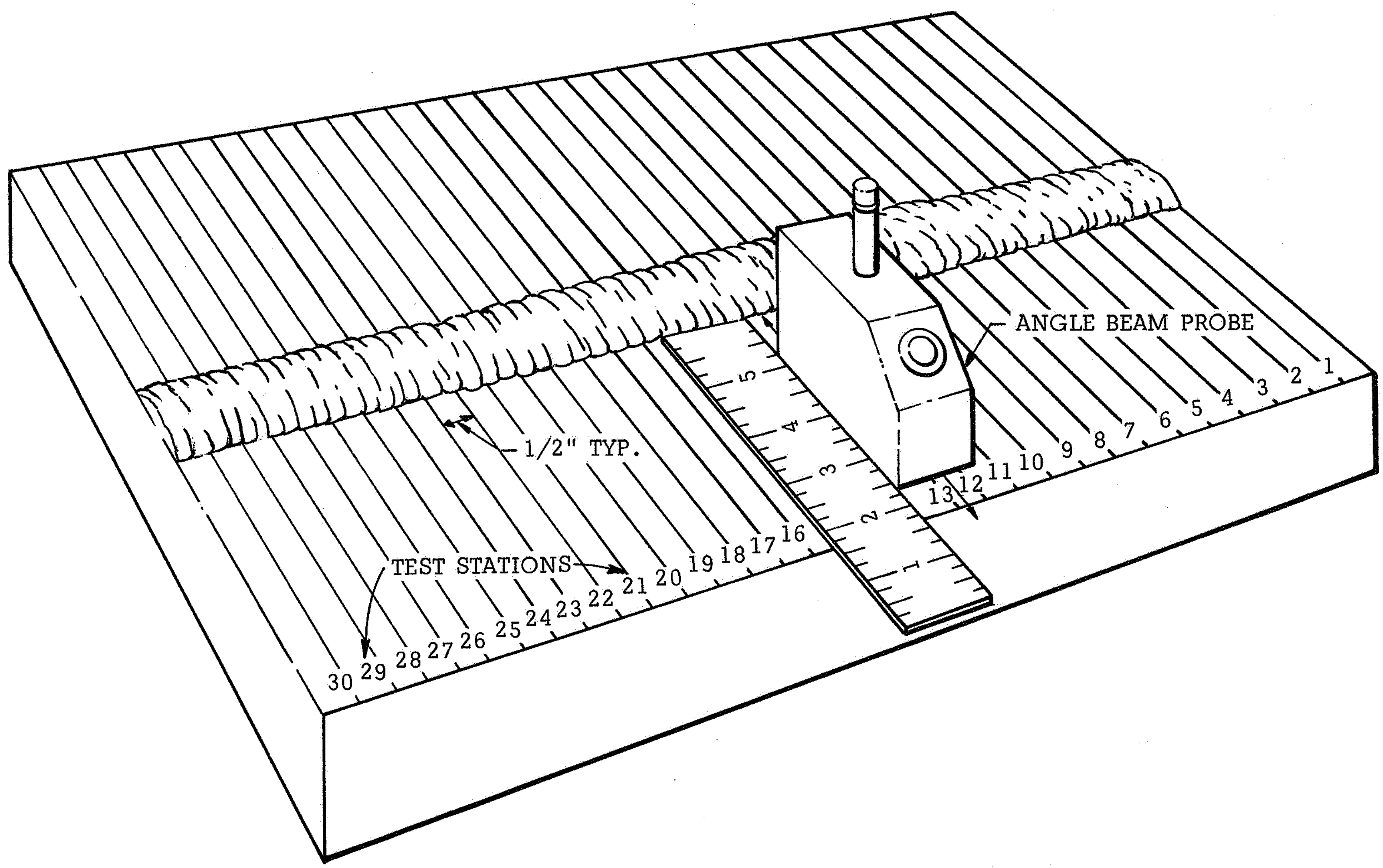


Figure 4. Typical Test Panel Layout

Figure 5. Weld Test Samples Showing Lack of Penetration

2. Tensile Fracturing. It was necessary to resort to tensile fracturing, when metallographic analysis proved inadequate for disclosing the smaller lack of fusion flaws. Tensile fracturing also served to disclose slag inclusions. The procedure in this case was to lay out and cut tensile test specimens to contain the suspected flaws. In every case tried, the specimen fractured through the suspected flaw, thus facilitating measurement of flaw size in two dimensions.

3. Progressive Milling. A third method, used principally for disclosing porosity flaws, is the so-called progressive milling. A milling machine is used to remove thin layers, 0.1 to 1.0 mm (0.005 to 0.040 inch), of material until the flaw is exposed. A light application of etching compound after each milling cut generally enhances the visualization of the flaw. This method provides for three-dimensional measurements, but frequently fails to disclose a thin crack type flaw.

4. Microscopic Examination. Most of the flaw examinations and measurements reported herein were made with the aid of a binocular microscope containing a graduated reticle in the eyepiece. This equipment provided the following ranges of measurement, with typical accuracies also shown:

Range (in.)	Accuracy ± (in.)
0.0002 - 0.001	0.0002
0.001 - 0.010	0.001
0.010 - 0.100	0.005
0.100 - 0.500	0.010

A Cook microscope with a "split image" measuring attachment is claimed to be accurate within 1 micron. Use of this instrument on five lack-of-penetration samples indicated its feasibility. Use of this instrument will provide quite an advantage to future investigations of lack of penetration.

SECTION III. DISCUSSION OF RESULTS

A. LACK OF PENETRATION DETECTION

1. Description. Lack of penetration is defined as a two-dimensional weld flaw in which the weld nuggets of two opposite passes fail to penetrate sufficiently so as to overlap each other. This condition

is not readily detected via radiography and can also be missed by ultrasonics when the gap width between the plates is less than 0.012 mm (0.0005 inch).

2. Approach. The objective of this phase, in addition to evaluating the Krautkramer USK-4 on lack of penetration (LOP) flaws, was to introduce manual ultrasonic testing equipment to supplement radiography. The general approach was to incorporate lack of penetration into a number of weld test panels; radiograph the weld and identify discontinuities; scan the weld ultrasonically and identify the LOP; then finally, section the panels and confirm radiography and ultrasonic findings through metallographic analysis or other suitable means of positive identification.

The scope of the project called for two test panels of each of the following thicknesses: 10 mm (0.4 inch), 15 mm (0.6 inch), 18 mm (0.7 inch), 20 mm (0.8 inch), and 25.4 mm (1.0 inch). Weld length varied from 400 mm (16 inches) to 600 mm (24 inches), dependent only upon the size of material available. The welding current was varied over this length so as to produce a lack of penetration which tapered from approximately 6 mm (0.24 inch) down to zero. All panels were made from 2219-T87 aluminum alloy and butt welded with the standard TIG process using 2319 filler wire and one pass from each side. Welding speed, wire feed, etc., were held constant, and only welding current was varied. These ten panels were welded "flat," with the electrode in a vertical position. The weld beads were not scarfed for the basic testing, only for the bead interference investigation conducted after the basic testing. The scarfing was accomplished in increments within the 0 to 0.020-inch height allowed per production tolerances.

Two special test panels were designed to evaluate the effect of weld joint gap size on the thickness, and therefore, the detectability of an attendant LOP flaw. The first of these had the mating edge of one plate machined to provide weld joint gaps in steps of 0, 0.25, and 1.0 mm depth. Details of this design are shown in figure 6. A second special design featured regular weld plates which were separated, before welding, by 1.0 mm (0.040 inch) aluminum wire spacers. Use of these spacers has been recently incorporated in certain production welds to improve penetration. In initial welds, it has provided the additional benefit of reduced porosity.

The completed weld test panels were radiographed per test methods of paragraph B.1., section II, with a single exposure of each panel taken normal to the surface through the weld centerline. Following the X-ray exposure, the film was processed in accordance with the manufacturer's recommendations. Evaluation of the radiographs were then made to determine that exposure and processing were correct. Density of the radiograph in the weld area was required to be from 2.0 to 2.5 as measured with a densitometer. Interpretation of the radiographs was then performed per MSFC-SPEC-259.

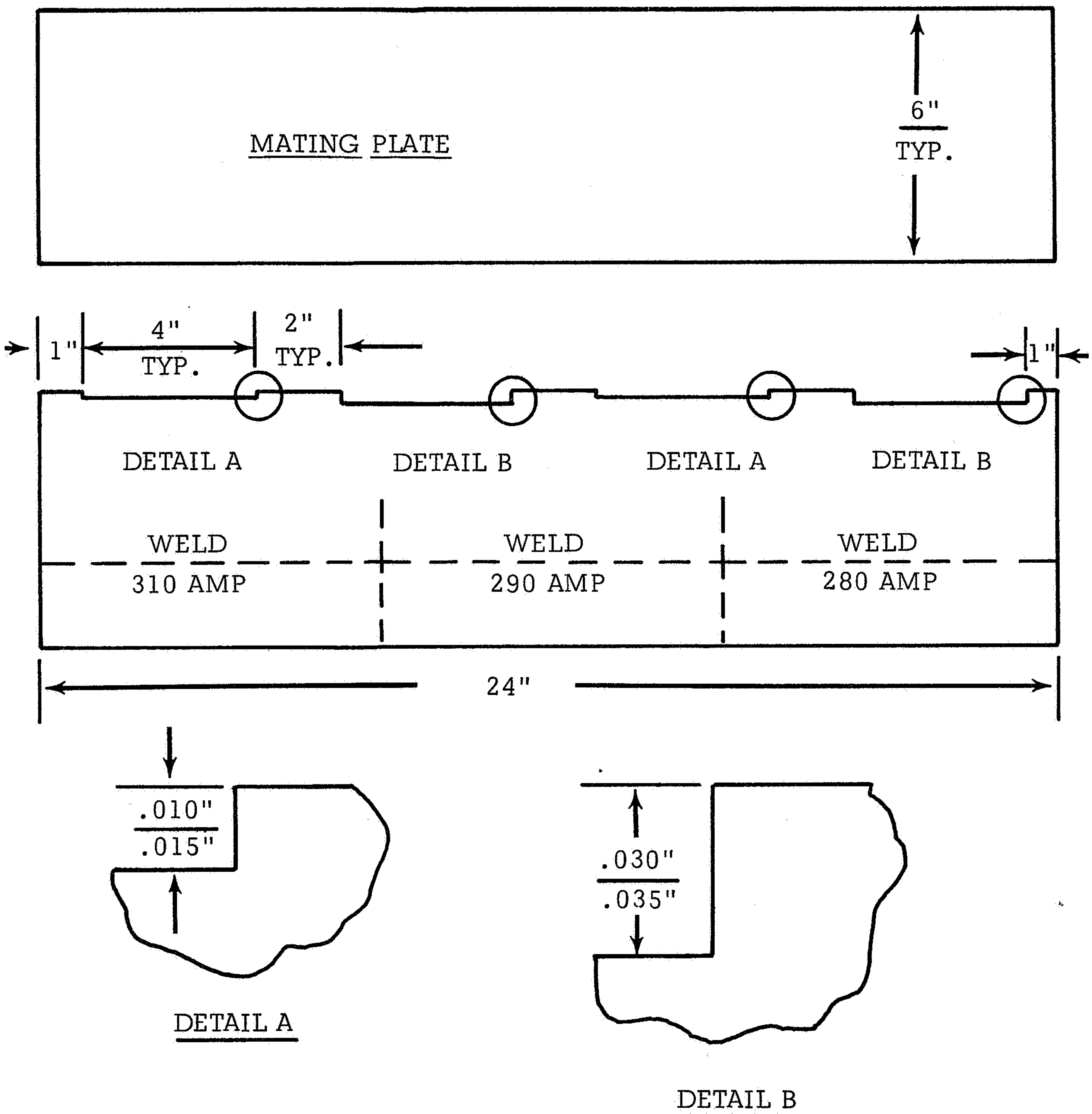


Figure 6. Variable Gap Panel Design

The panels were cleaned thoroughly and polished lightly by hand to smooth out scratches and remove burrs which might produce spurious ultrasonic signals and abrade the contact surface of the probe. One-half inch increments were laid out and numbered consecutively, starting at the end of maximum LOP. At each increment a transverse scanning line was drawn with a pencil or other nonscratching marker. This entire layout is shown in figure 4. This preparation is typical of that used throughout this ultrasonic evaluation.

Scanning was performed in accordance with the ultrasonic test methods described in paragraph B.2., section II, using both direct and bounce shots from each side of the weld, from the top side of the plate only. The 70 degree angle beam transducer was used on all test panels and supplemented on the thinner panels by the 80 degree transducer for purposes of comparison. Signal amplitude and position on the screen as well as transducer position were recorded for each "shot" at each station. The panel was then sectioned to expose a cross section of the weld at each scanning station. The cross sections, or samples, were polished and etched so that the LOP could be seen and measured. Figure 5 shows a typical set of samples after polishing and etching.

3. Results.

a. Standard LOP test panels. A graphic summary of the radiographic and ultrasonic evaluations are contained in figure 7. The bar charts in this figure compare the extent of both radiographic and ultrasonic flaw indication to the extent of penetration actually existing. Each of the fifteen panels tested is represented by a separate bar chart. The length of the bar is proportional to panel length with the consecutive numbers showing the positions or stations (0.5 inch increments) which were scanned and measured. The wedge shaped lines indicate the existence, but not the magnitude, of LOP as measured microscopically. The apex of the wedge is the point where LOP disappeared. The solid line beneath the wedge shows where ultrasonic flaw signals were received. The extent of radiographic detection is shown similarly by the dotted line. The minimum depth of LOP that was detected ultrasonically is printed at the end of the bar. However, in a few cases, the panels were not completely sectioned and this minimum depth was not measured.

By compiling the results of all the bar charts in figure 7, it will be seen that ultrasonic detection, by the equipment described herein, successfully identified 67 percent of all existing LOP, 6060 mm (239 inches) on a

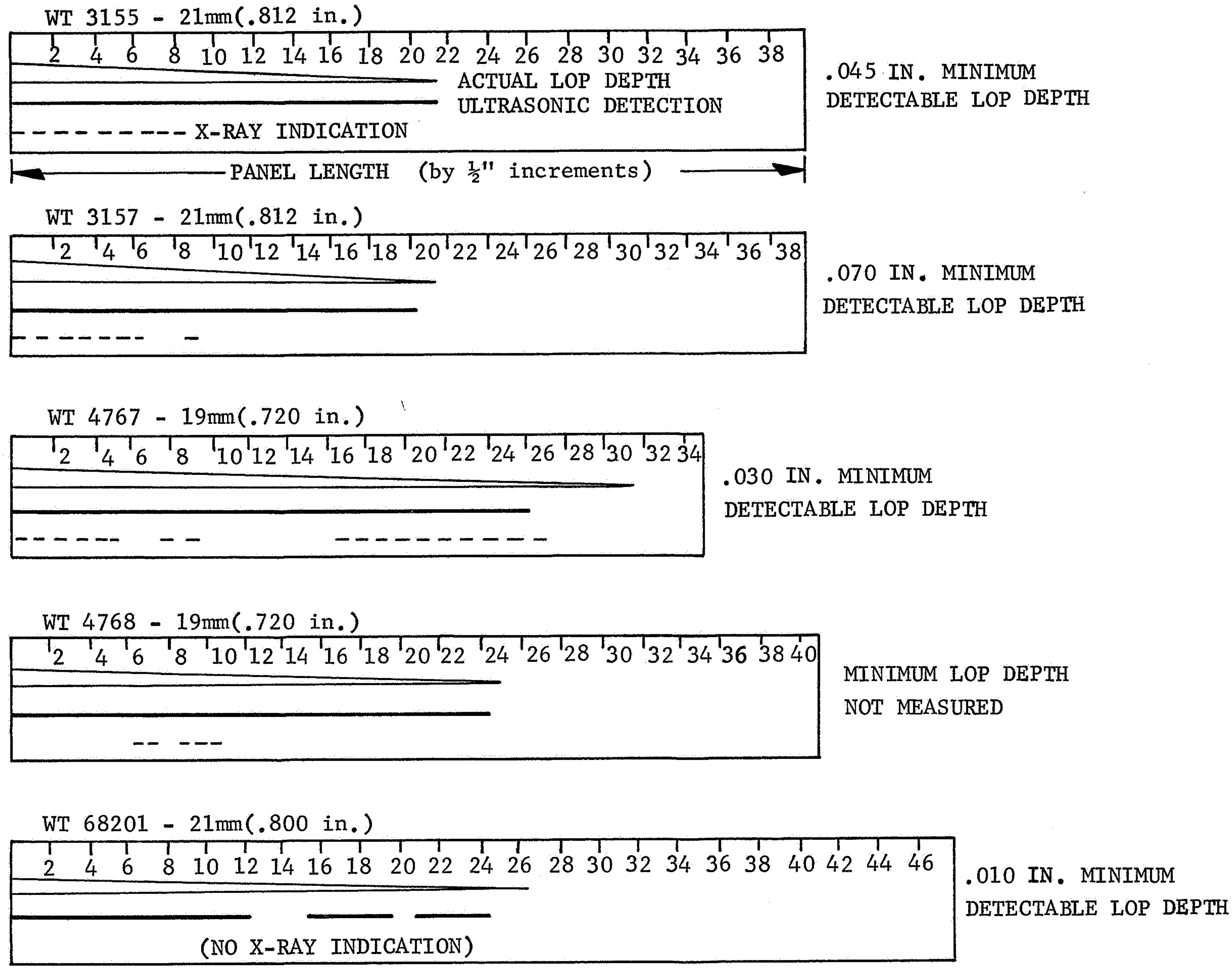


Figure 7. Ultrasonic vs Radiographic Detection Capabilities (Sheet 1 of 3)

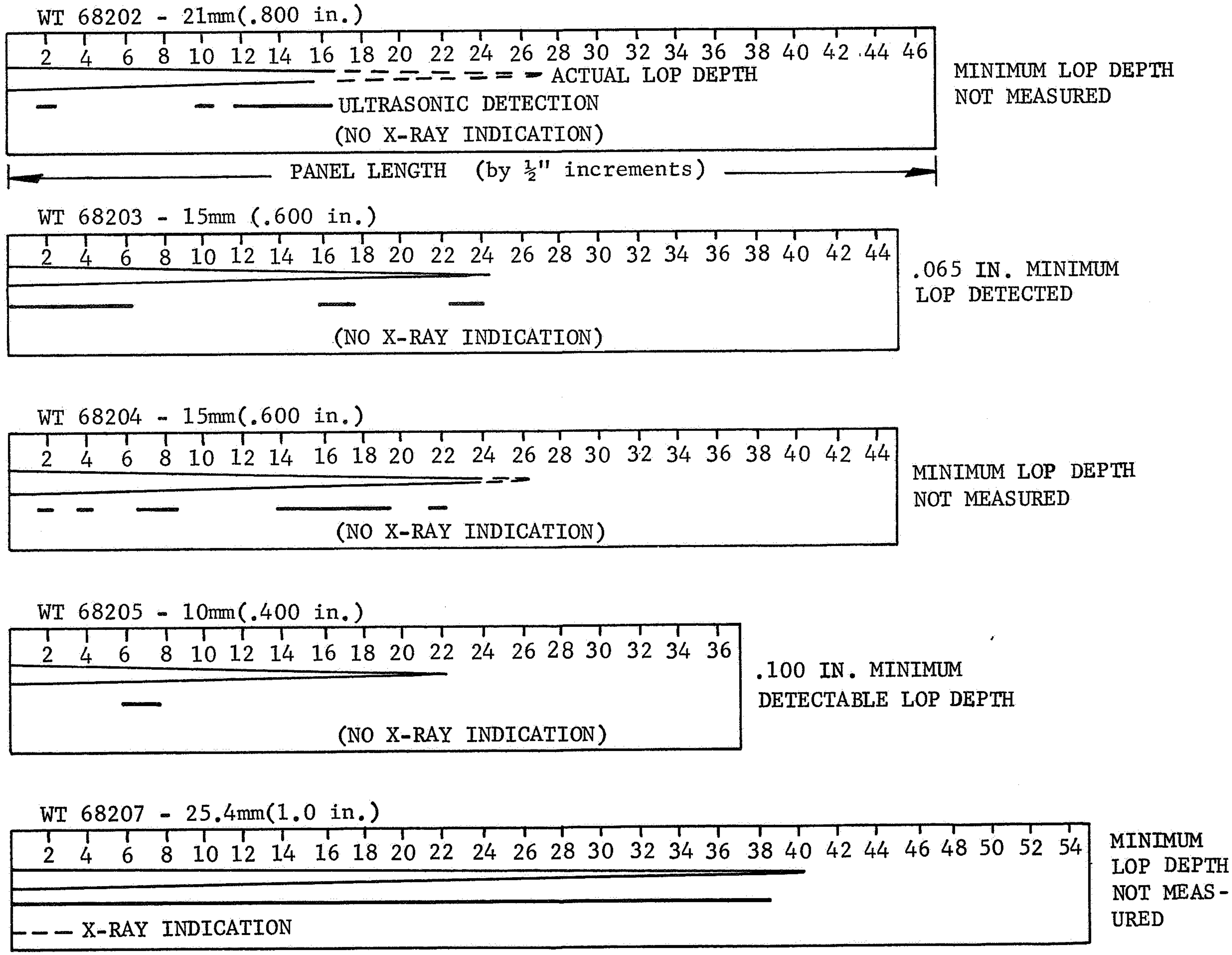


Figure 7. Ultrasonic vs Radiographic Detection Capabilities (Sheet 2 of 3)

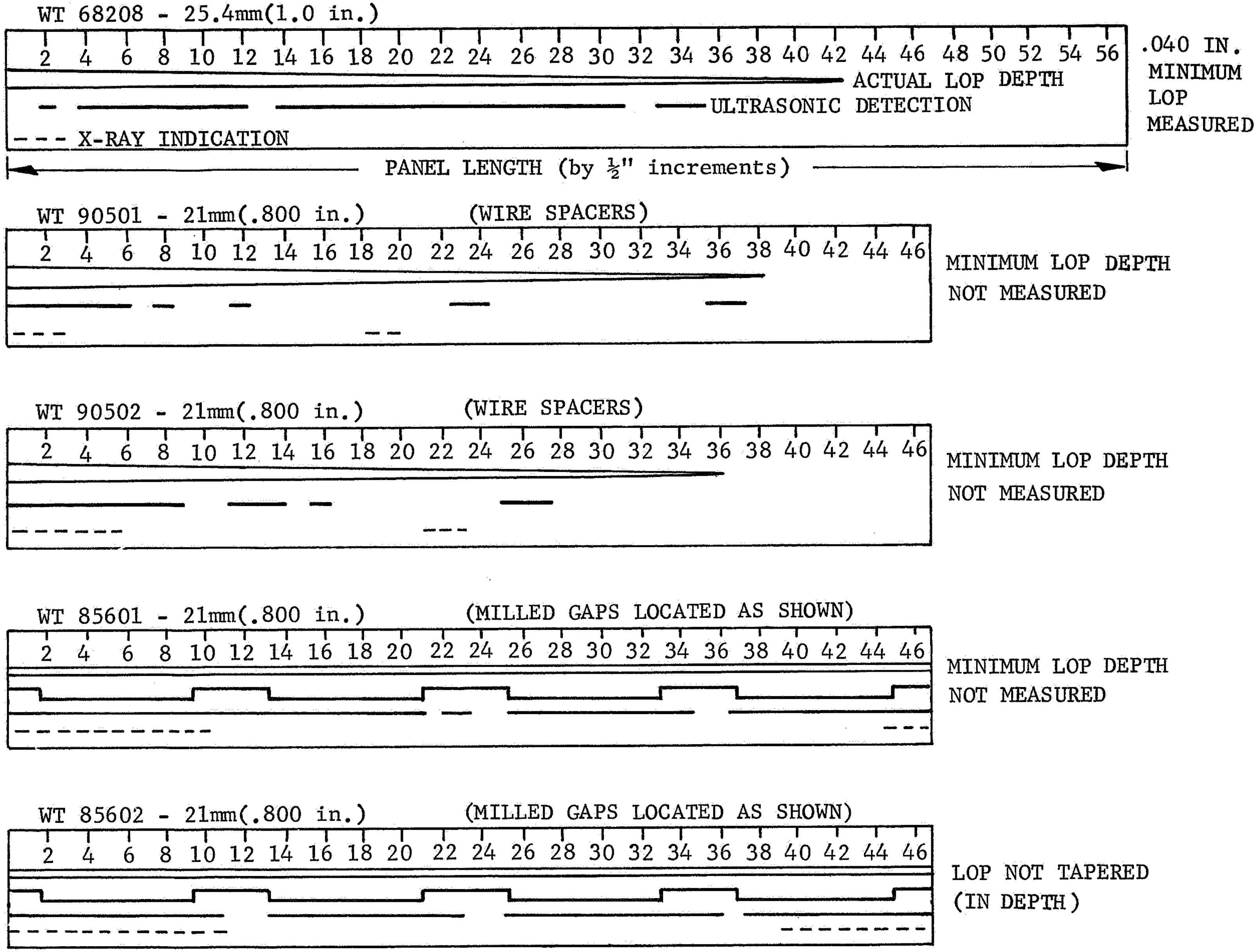


Figure 7. Ultrasonic vs Radiographic Detection Capabilities (Sheet 3 of 3)

lineal basis. The same compilation shows that radiographs detected only 17 percent of the existing LOP. These figures indicate the advantages of the Ultrasonic Krautkramer USK-4 Miniature Flaw Detector in detecting lack of penetration. An LOP detection improvement factor four times greater than the standard radiography methods used herein is indicated for the particular ultrasonic method evaluated by this program.

Several of the bar charts show ultrasonic detection that is intermittent along the panel length. This intermittency, or simply failure of the Krautkramer USK-4 to detect lack of penetration, is concluded to be a direct function of the LOP flaw width. Recognizing this, a phase of the project was directed toward evaluation of this parameter.

b. Variable gap panel. A special panel design featuring a weld joint gap of variable width was conceived to determine the effect of weld gap and LOP flaw width on ultrasonic detection capability. Two panels of this design were made, tested, and analyzed.

Gap widths and ultrasonic results for one of these panels (WT 85602) are shown in figure 8. It should be remembered that "gap width" relates to the preweld geometry only. The abscissa in this figure represents the length of the panel, divided and numbered to show the 13 mm (0.5 inch) incremental stations. The bottom section of the graph is an expanded scale drawing of weld joint geometry for the machined plate. The mating plate had a plane, straight edge. Krautkramer amplitude readings, taken at an instrument gain setting of 2.0, are plotted in the upper portion for both direct shot and bounce shot traverses.

The significant contribution from these data is the remarkable similarity of the amplitude pattern to the weld joint geometry. Note that where a zero gap width existed, essentially no LOP was detected, by radiography or ultrasonic methods, even though it was proved to be present. On the other hand where there was a finite width of either 0.010 inch or 0.030 inch, the LOP was readily detected. The relatively low amplitude readings found at station 30 are unusual, but investigation did not reveal the cause.

Results from these panels lead to the conclusion that there is a minimum preweld gap width of less than 250 microns (0.010 inch), which shrinks during welding to produce an LOP crack width (if LOP is attendant) of less than 2.5 microns (0.0001 inch), which cannot be detected by the pulse echo technique. It should be pointed out that radiography was likewise unable to detect LOP under these conditions. The LOP widths were verified by metallographic dissection and microscopic examination of these panels.

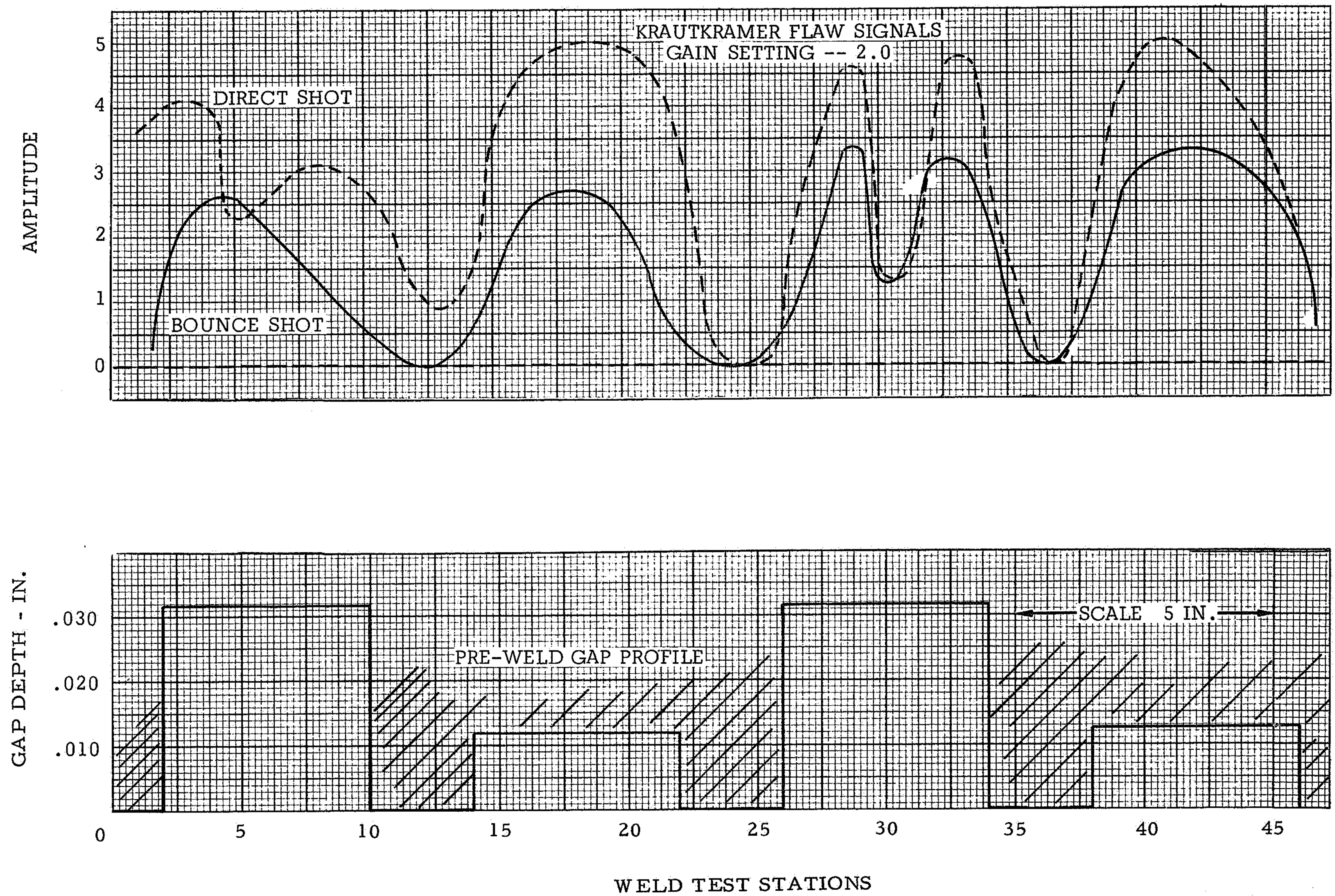


Figure 8. Effect of Gap Width on Ultrasonic Detectability

Since the use of 1 mm (0.040 inch) wire spacers, 150 mm (6 inches) apart, between mating edges had been incorporated in certain production welds, it was decided to include this innovation in the LOP evaluation. It was thought that this gap spacing might result in flaw width (of the coincident LOP) sufficient to ensure detection. However, this was not the result, as very little of the existing LOP was detectable.

4. Conclusions. Based upon existing evidence and experience, it is concluded that ultrasonics approaches complete detection of LOP and exceeds radiographic LOP detection, as shown in this report. The ultrasonics successfully detected 67 percent of all existing LOP, as compared to 17 percent detection by radiography; however, an LOP crack width of less than 2.5 microns (0.0001 inch) cannot normally be detected by the pulse echo technique.

B. LACK OF FUSION DETECTION

1. Description. Lack of fusion is defined as a two-dimensional discontinuity of infinitesimal width lying along the parting line between a weld bead and the parent metal or a previously laid bead. It is caused by insufficient heat or by the presence of foreign material on the fusion face. Lack of fusion is not always detected radiographically and, therefore, requires supplementary inspection techniques.

2. Approach. Several attempts were made to incorporate deliberate and controlled lack of fusion flaws in special weld test panels, but none were successful. However, an S-IC lox suction fitting, rejected because of mismatch, was made available for test purposes. Radiographs of the fitting indicated lack of fusion in three areas. The fitting was divided into two halves, providing material for two separate tests. A third test was made possible by salvaging a preproduction weld panel in which LOF has been found. These welds were of 2219 aluminum and were tested with the weld beads being intact (not scarfed).

a. Lox suction fitting - first test (first half). Radiographs indicated lack of fusion in three areas. The first half of the fitting was scanned with the ultrasonic 70 degree angle beam teansducer by taking separate readings at each of 123 test stations, 0.5 inch apart, around the weld. Signal amplitude, signal screen position, and transducer position were recorded.

The fitting weld was then sectioned into 123 one-half inch specimens which were polished and etched to show the weld in cross section. Each specimen was carefully examined under a 50-power microscope for evidence of flaws.

Ultrasonic flaw signals had been indicated at 83 of the original 123 test stations. However, only eleven of the flaws were disclosed by metallographic analysis due to the limitations of the metallographic and fracturing methods employed. The presence of the remaining 64 "unconfirmed" flaw indications is reasonably certain based upon the analysis of the flaws which were located. No flaws were found in the 40 specimens which had produced no ultrasonic flaw signal. The confirmed flaws ranged in length from 1 mm (0.040 inch) to more than 10 cm (4 inches).

b. Lox suction fitting - second test (second half). Radiographs indicated no discontinuities present. The weld was ultrasonically scanned at stations 13 mm (0.5 inch) apart as before and only five flaws were indicated. These five areas were carfully rescanned and the flaws were pinpointed as to longitudinal location and depth. A tensile test specimen, centered on the suspected flaw, was cut from each area. Metallographic analysis of the five specimens disclosed two of the flaws. The specimens were then ruptured in a tensile test machine. This technique very easily disclosed all five flaws and facilitated measurement of size and location as well as microscopic examination of the flaws. Five additional specimens were cut from flaw-free areas and processed similarly for reference purposes.

The quantitative results of the lox suction fitting second test are summarized in tabular form and discussed in paragraph 3. below. Figure 9 is a macrograph of a typical lack of fusion flaw, looking at the plane of fracture.

c. Preproduction panel - third test. Another opportunity to study the detection of lack of fusion flaws arose with the discovery of flaws in one of the bead interference test panels (No. 35502). (See paragraph D of this section.) After the weld beads had been ground flush, ultrasonic signals were still perceptible. Tensile testing of specimens cut from this panel revealed a small, but nearly continuous LOF flaw through approximately half the length of the weld.

Results of the various methods of inspection used on this panel are summarized in figure 10. The extent of actual flaws as revealed by tensile testing is shown in the lower chart in figure 10. Flaw depths are included

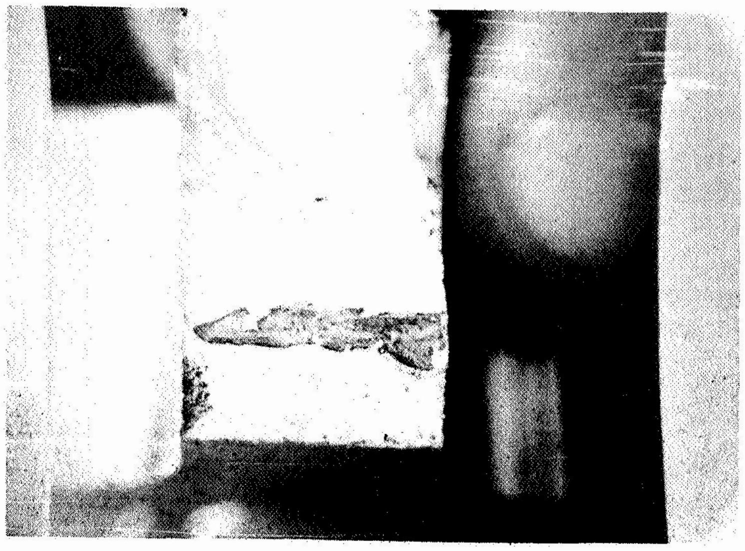


Figure 9. Lack of Fusion Flaw

at several points along the flaw. The flaw was intermittent in occurrence between locations 3 and 4. While the ultrasonic scanning detected the presence of flaws, it failed to reveal this discontinuity. The center chart in figure 10 compares the extent of ultrasonic indication to the extent of actual flaws. It can be seen that better than 90 percent of the flaw length was so indicated. The panel had been sawed into two pieces at location 17 1/2 before scanning. Resulting edge effects precluded any meaningful scanning results adjacent to the cut. This length of weld is represented by broken lines in the figure. The top chart in figure 10 shows all flaw evidence found in radiographs of the weld. The lengths of LOF flaws frequently terminate in a gas pore which appears on the radiograph. They are included in figure 10 because of their close relation to the subject LOF flaws. The extent of radiographic indication is less than 5 percent of the existent flaw length of 279 mm (11.0 inches).

3. <u>Summary of Lack of Fusion Detection.</u> Table 1 is a compilation of the more significant measurements made on the flaws found in the specimens from the second half of the lox suction fitting (second test). They are designated by an AX number. The first four columns compare the ultrasonic location and depth within fitting predictions with actual

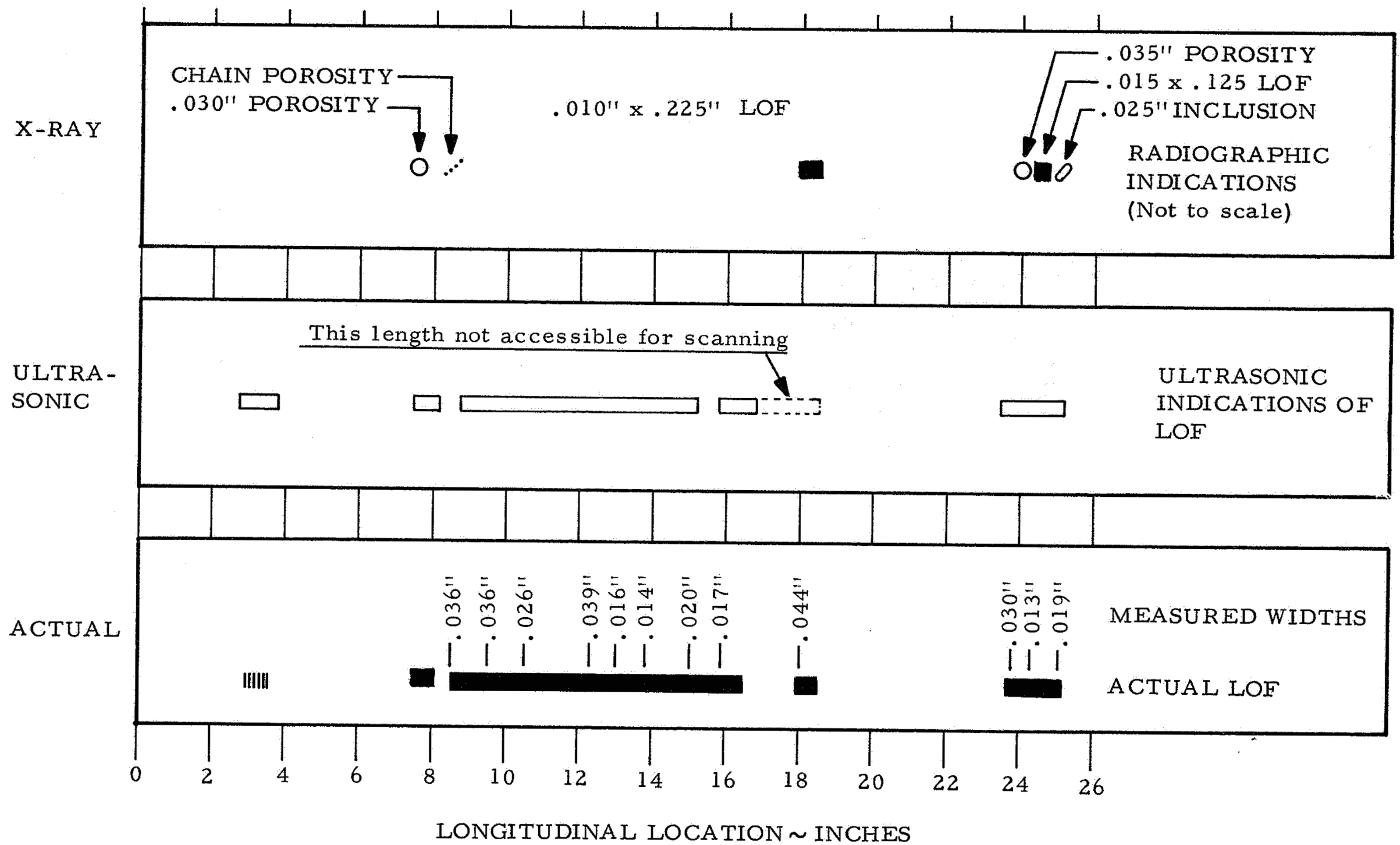


Figure 10. Lack of Fusion in Preproduction Weld Panel

Table 1. Lack of Fusion - Flaw Measurements

Specimen No.	Flaw Location				Actual Flaw Length (in.)
	Longitudinal Location (in.*)		Depth Within Fitting (in.)		
	Ultra	Actual	Ultra	Actual	
AX-135	25.45	25.45	0.5	0.55	0.18
AX-142	29.35	29.30	0.6	0.60	0.33
AX-175	45.4	45.45	0.5	0.60	0.15
AX-178	47.05	47.1	0.5	0.60	0.15
AX-181	48.55	48.6	0.6	0.60	0.50

*Location expressed in inches from reference zero (end of panel).

measurements. Note that in all cases the predictions are accurate within 4 mm (0.16 inch). The more distinct lack of fusion flaws, listed in the top half of the table, were located within 3 mm (0.1 inch).

The Krautkramer ultrasonic detector has shown remarkable performance in finding and locating lack of fusion flaws. Improved techniques, used in the second and third tests, succeeded in confirming all eleven flaws detected by the instrument. On the other hand, there is not a single known lack of fusion flaw which was not detected ultrasonically. However, the possible existence of very small and therefore undetectable flaws has not been disproved. The smallest lack of fusion flaw encountered in these tests was 3 mm (0.1 inch) long. No further evidence is available, from which a minimum detectable flaw size might be inferred.

Radiographs of the three test pieces were used for comparative results. Production X-rays of the lox suction fitting indicated lack of fusion in three separate areas - all within the half of the fitting used in the first test. The extent of radiographic flaw indication was less than that of the USK-4 and was also less than the number of confirmed flaws.

Additional radiographs were taken of the second half of the fitting and repeated examinations of these X-rays failed to disclose any evidence of the five confirmed flaws, or any other lack of fusion.

C. POROSITY DETECTION

1. Description. The study of ultrasonic detection of porosity in welds was made primarily to achieve a complete and comprehensive evaluation of the USK-4 instrument. It does not imply a pressing need for improved test techniques, as was the case with lack of penetration and lack of fusion.

2. Approach. Porosity flaws found in existing weld panels by means of radiography were utilized. Five pores in four separate specimens were scanned, located, and identified. Routine scanning methods did not distinguish between two adjacent flaws found in one of the specimens (BA-32). No attempt was made to search out unknown porosity. However, experience in testing production welds with the Krautkramer Detector indicated no particular problem in this regard. After being scanned, the pores were exposed for actual measurements (microscopic) by progressive milling, i.e., removing successive layers of 0.12 mm (0.005 inch) to 0.24 mm (0.010 inch) thicknesses.

3. Results. The actual measurements and the ultrasonic findings are listed in table 2. The smallest pore detected in this test was 1.5 mm (0.056 inch) in diameter, which is believed to represent very nearly the ultimate capability of the Krautkramer USK-4. In scanning porosity, the transducer was rotated around the pore, always aiming at the pore, and readings were taken at approximately 45 degree intervals. The direction of these readings, identified by compass points, and the maximized amplitude of the flaw signal are included in the table. This is done to illustrate the rule for ultrasonically identifying porosity. The fact that signals are received continuously around the flaw indicates a spherical shape, thus distinguishing it from a two-dimensional or crack-type flaw, which reflects signals only in a direction normal to its plane. Table 2 shows that efforts to determine flaw size ultrasonically were not particularly encouraging. See paragraph F.3. of this section for a more detailed discussion of this subject.

4. Conclusions. It is concluded from these tests that the standard radiographic methods used on this program were generally superior to the Krautkramer USK-4 ultrasonic detection of porosity; at least in welds of 13 mm (0.5 inch) thickness or less. The smallest, clearly identifiable pore found by X-ray was 35 microns (0.014 inch) in diameter. These tests do show that the USK-4 is capable of detecting any porosity of a serious, or rejectable, magnitude in weld thicknesses of 6 mm (0.240 inch) or greater. (Porosity reject level is defined as any diameter greater than T/3, where T equals plate thickness.)

Table 2. Ultrasonic Detection of Porosity

Specimen No.	ACTUAL GEOMETRY			ULTRASONIC RESULTS				
	Location in.	Depth in.	Size in.	Location in.	Depth in.	Size in.	Probe Direction	Maximum Amplitude
BA-32	15-7/8	.180	.105 dia.	15-3/4	.20	.095 dia.	West	4.0
							NW	.8
							SW	4.5
							East	4.5
							SE	3.0
							NE	4.6
BA-32	15-25/32	.280	.092 x .053	Not distinguished from above flaw.				
BA-40	19-8/16	.300	.115 x .063	19-9/16	.175	.060 dia.	West	3.7
							NW	2.8
							SW	1.7
							East	3.0
							SE	1.7
							NE	1.6
BA-45	21-1/2	.400	.153 x .132	21-1/2	.50	.06 dia.	West	6.0
							NW	3.8
							SW	.5
							East	3.8
							SE	2.2
							NE	1.0
BE-3	1.25	.485	.056 dia.	1.31	.4	.06 dia.	Min.	0.5
							Max.	1.0

D. BEAD INTERFERENCE INVESTIGATION

1. Description. Bead interference as related to radiography reveals that visual inspection of welds, film interpretation, experience, and clear detail on film produces little or no problems; therefore, ultrasonic bead interference was the primary investigation conducted.

There are two forms of ultrasonic interference caused by weld beads - physical and signal. Physical interference restricts the movement of the transducer leading to incomplete traverses of a weld area. Signal interference produces extraneous echos on the display screen. These can be quite difficult to distinguish from flaw signals. Obviously, both forms would be eliminated by complete removal of the bead. Since complete removal is not normally permitted, it was desired to evaluate the effect of various increments of removal. The bead height permitted by Saturn V, S-IC current production specifications is zero to 0.5 mm (0.020 inch).

2. Approach. Three welded test panels of different thicknesses, each having weld beads of fairly typical size and shape, were selected. Thicknesses were 6 mm (0.240 inch), 13 mm (0.50 inch), and 20 mm (0.80 inch). The first step was to ultrasonically scan the original weld in 13 mm (0.50 inch) increments, defining and recording all maximum signals. The transducer was moved, normal to the weld, through sufficient range to include direct, bounce, and double bounce shots at the beads. (While the double bounce is occasionally used in the laboratory, it is not recommended in normal operations.) There followed a series of steps in which the beads were progressively shaved, one at a time. In some cases a step consisted only of rounding the corners of a previously shaved bead. After each step of shaving or grinding, the weld was rescanned and data recorded. The final step was completed when both beads were ground flush and the weld scanned for the last time. Signals prevailing at this point were thus confirmed as flaw signals. Occasionally flaws were identified at one step or another during the series, but this usually occurred after the attendant bead interference signal had been reduced by shaving the bead.

3. Results. Figures 11 through 13 illustrate the ultrasonic effects of bead interference from full and partial beads. Successive bead configurations are graphically described across the bottom of the chart. Exact dimensions of each configuration are listed in table 3. The same figures also show typical flaw signals which, as expected, remained reasonably constant throughout the evolution of bead configuration. Some of the flaw signals are depicted by broken lines indicating that the existing signal

REFER TO TABLE 3 FOR BEAD DIMENSIONS

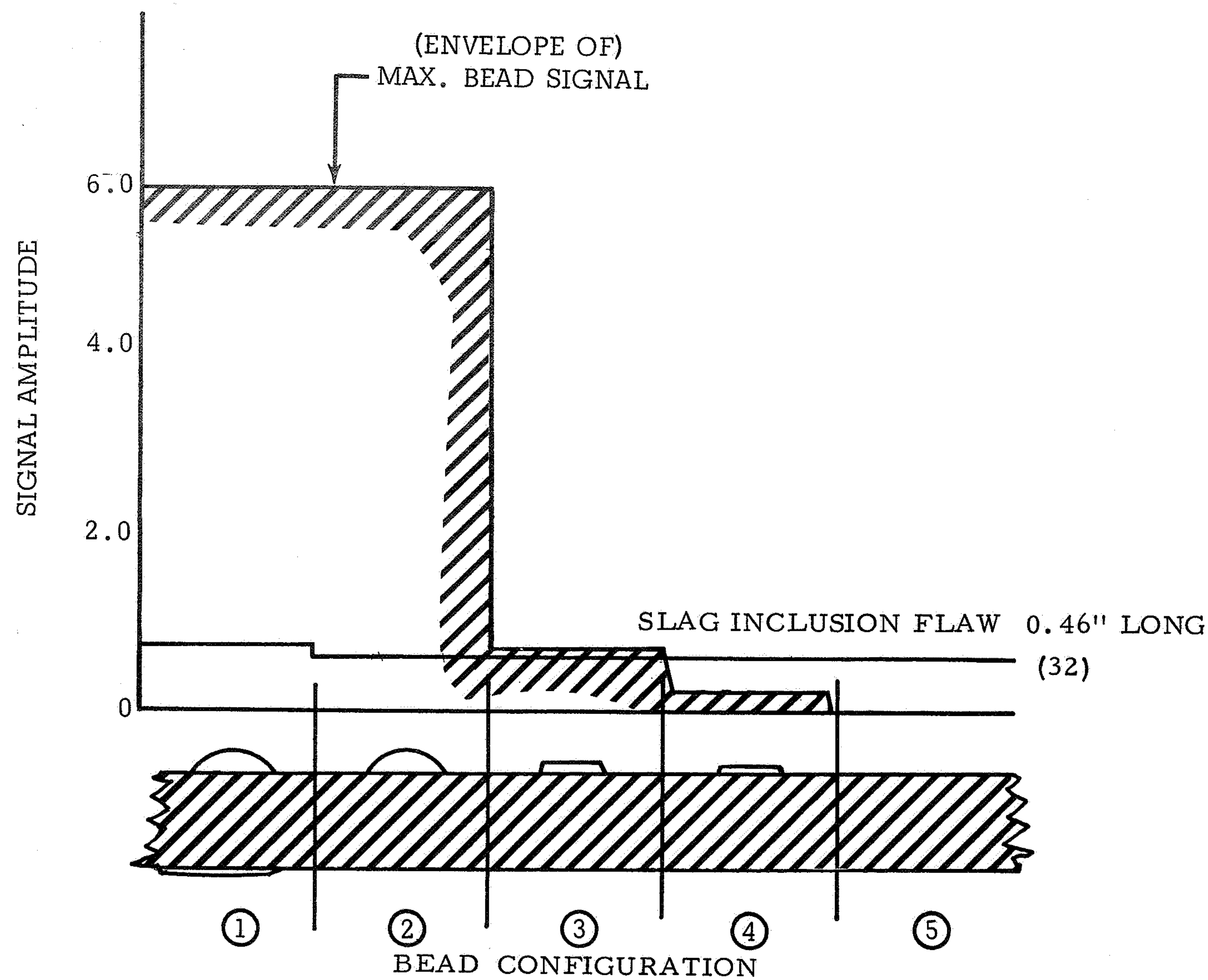


Figure 11. Weld Bead Interference - 0.80 Inch Weld

REFER TO TABLE 3 FOR BEAD DIMENSIONS

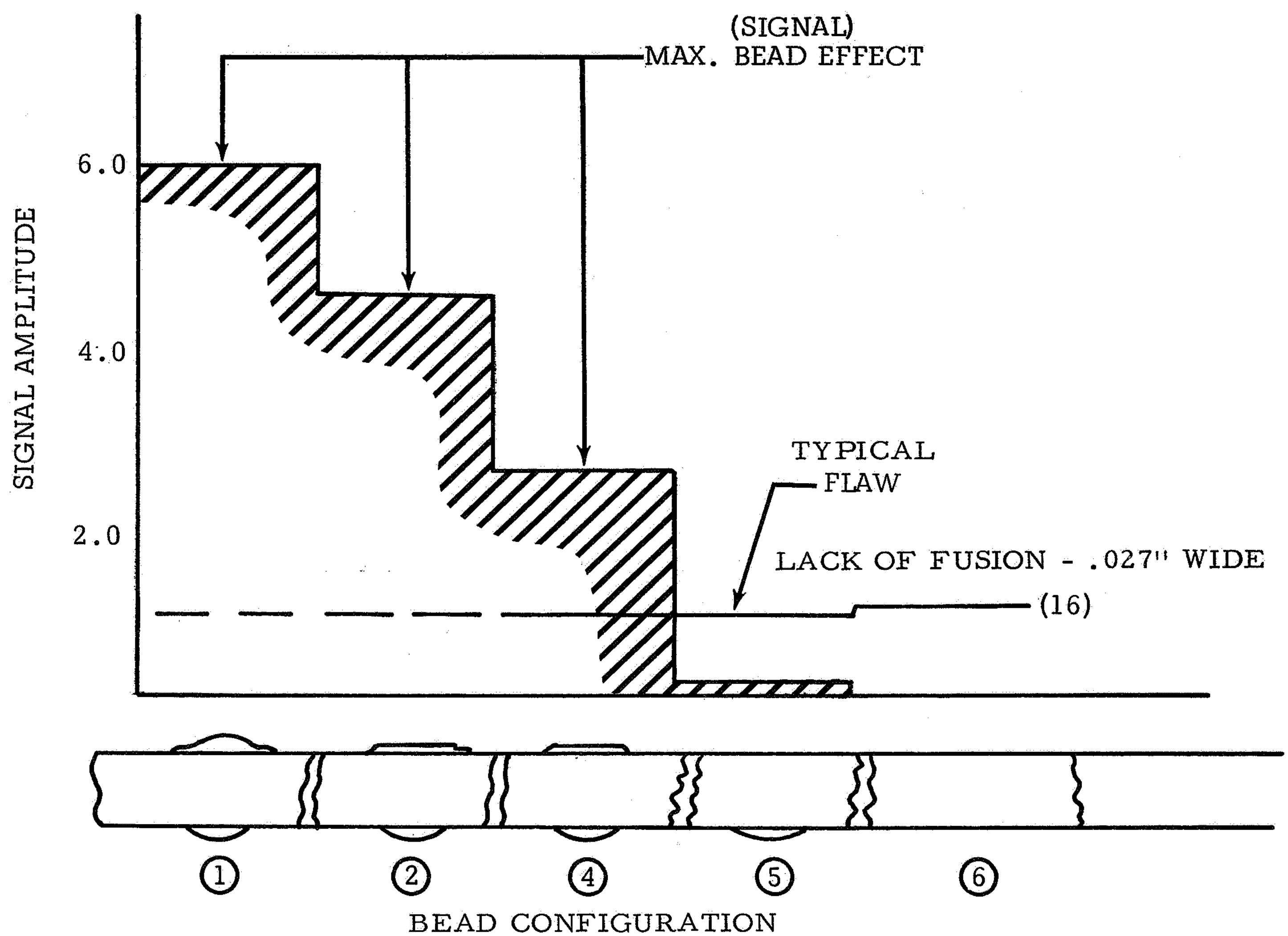


Figure 12. Weld Bead Interference - 0.50 Inch Weld

REFER TO TABLE 3 FOR BEAD DIMENSIONS

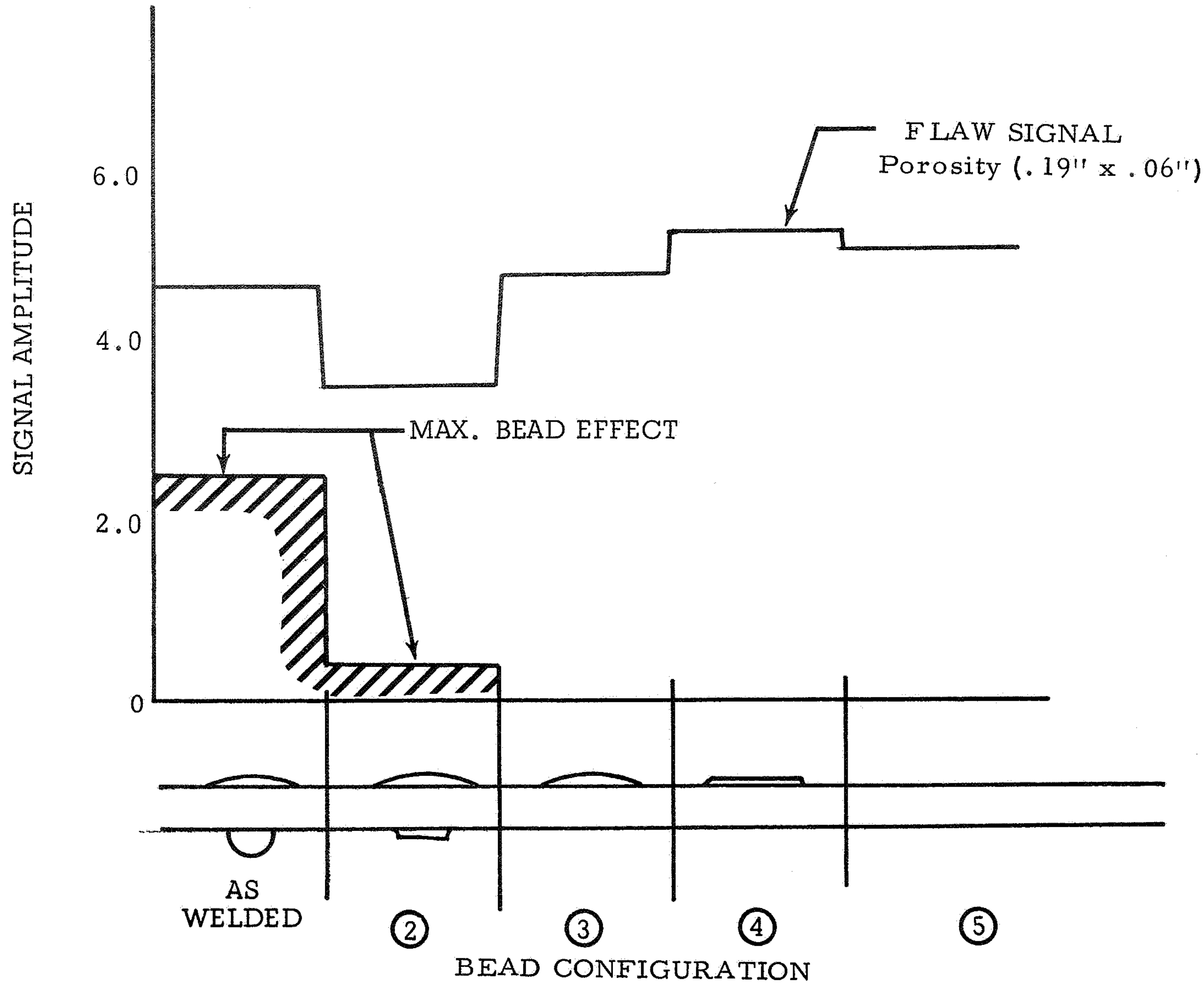


Figure 13. Weld Bead Interference - 0.25 Inch Weld

Table 3. Weld Bead Configuration Dimensions

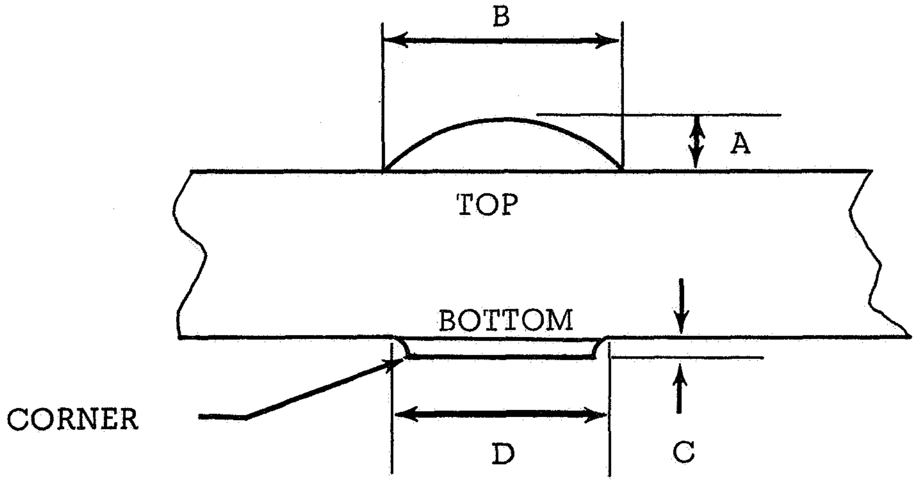


Figure No.	Config. No.	Dimensions A	B	C	D	Corners Top	Bottom
11	1	.082	.350	.040	.750	None	None
	2	.082	.350	0	–	None	None
	3	.025	.350	0	–	Square	None
	4	.012	.350	0	–	Square	None
	5	0	–	0	–	None	None
12	1	.139	.625	.035	.31	None	None
	2	.031	.625	.035	.31	Square	None
	4*	.031	.625	.035	.31	Round	None
	5	0	–	.035	.31	None	None
	6	0	–	0	–	None	None
13	1	.025	.400	.055	.200	None	None
	2	.025	.400	.018	.200	None	Square
	3	.025	.400	0	–	None	None
	4	.010	.400	0	–	Square	None
	5	0	–	0	–	None	None

* Configuration #3 did not apply to entire panel.

could not be, or was not, identified because of the overshadowing effect of bead interference. The bead effects shown in these figures are actually the envelopes of the maximum amplitudes found at any station along the weld for each bead configuration. Figures A-1 through A-3 in the appendix, from which figures 11 through 13 are compiled, show the actual amplitudes observed at several typical stations of the respective panels.

Figure 11 shows the effect of bead interference signals using an 0.80-inch-thick weld. The as-welded bead produced signals of far greater amplitude than the slag inclusion found later in the weld. Complete removal of only the bottom bead did nothing to alleviate the confusion of the interference. However, when the large top bead was shaved to 0.025 inch, nearly all of the interference disappeared. Further degrees of shaving demonstrated further improvement which enabled the rather weak signal from a slag inclusion flaw to be identified.

Figure 12, of a 0.50-inch-thick plate, again shows full scale interference signals from the as-welded bead. It also shows progressive improvement as the larger top bead was shaved. The third step in the evolution was to round the corners of the top bead, which at that point was 0.031-inch high. Rounding the corners, in this case, provided a 40 percent reduction of the interference signal. Since shaving the beads in accordance with production specifications (zero to 0.020-inch high) generally reduced interference to tolerable levels, no further measurements were made of the effect of rounded corners. It can be seen in this figure that the 0.031 inch bead still overshadowed the signal from the 0.027 inch depth of the lack of fusion flaw. This signal is represented by a broken line through the first two configurations to indicate that it was not identified as a flaw until the third configuration.

Figure 13 depicts a 0.25-inch-thick weld panel in which the as-welded bead interference was considerably less. In this case, the signal from a fairly large (0.19 inch by 0.06 inch) gas pore is readily discernible above the limit of the interference signal. However, it was necessary to shave the bottom bead in order to reduce interference below a level that would obscure signals from other significant flaws. It can be seen from configuration 3 that the effect of the small top bead was nil.

Additional ultrasonic testing will be required to evaluate the effect of the several individual parameters which appear to be influential. Parameters thus far recognized are plate thickness; bead height, width, and shape; and interacting effects of both a top and bottom bead.

In order to ensure a reliable weld inspection with ultrasonic scanning, bead signals must be either reduced below a significant level or isolated by screen calibration. The surest method is the former, as discussed above. The second choice is isolation of the signal which theoretically can be done by means of an accurate screen calibration. (See section II, paragraph B. 2.) However, the accuracy of this calibration is seldom sufficient to provide a clear distinction, particularly in thin plate welds.

E. SLAG INCLUSION DETECTION

An opportunity to study the detection of slag inclusions arose with the ultrasonic discovery of such flaws in the weld of one of the bead interference test panels (No. 90102). (See paragraph D of this section.) Six of these flaws were carefully scanned and located, tensile specimens cut out so as to envelop the flaws, and the specimens pulled. Two of the specimens contained two flaws each.

Examination after the specimens were fractured revealed that these flaws were slag inclusions. An example of this slag inclusion flaw is shown in figure 14. The flaw locations and sizes are listed in table 4.

Table 4. Slag Inclusion - Flaw Measurements

Specimen No.	Flaw Location				Actual Flaw Length (in.)
	Longitudinal Location*		Depth Within Specimen (in.)		
	Ultra	Actual	Ultra	Actual	
AZ-40	19.34	19.5	0.56	0.59	0.25
AZ-40	19.9	19.9	0.56	0.56	0.44
AZ-42	20.62	20.75	0.52	0.56	0.46
AZ-44	21.5	21.5	0.48	0.59	0.10
AZ-44	21.7	21.7	0.56	0.56	0.27
AZ-46	23.25	23.12	0.48	0.62	0.12

*Location expressed in inches from reference zero (end of panel).

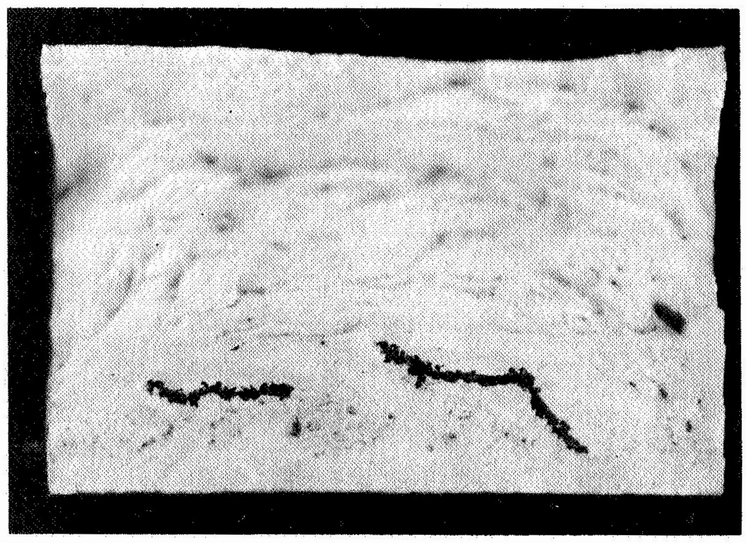


Figure 14. Slag Inclusion

SECTION IV. CONCLUSIONS AND RECOMMENDATIONS

The evaluation has shown that the ultrasonic pulse echo technique has a distinct advantage over radiography in the detection of the major fusion weld flaws, lack of penetration, and lack of fusion. No apparent advantage in ultrasonics over radiography was demonstrated in the detection of porosity. Effects of weld bead on ultrasonic signals were that extraneous signals from an unshaven bead are capable of obscuring a signal from a serious flaw, and that shaving a bead to a height of 0.5 mm (0.020 inch) or less eliminated signal interference. Weld bead interference to radiography was not considered detrimental.

It is recommended that ultrasonics be employed as a supplement to radiography in fusion weld inspection and that all opposite side pass or multi-pass welds from one side be ultrasonically tested for aluminum material in the thickness range of 6 mm (0.240 inch) to 25.4 mm (1.00 inch).

APPENDIX A. METHODS OF INVESTIGATIONS

A. FLAW SIGNAL IDENTIFICATION

There are several "rules-of-thumb," signal characteristics, and simple tests which help to identify and clarify ultrasonic flaw signals. These are not original outputs of this evaluation, but have been practiced, verified, and found applicable.

The first prerequisite for ultrasonic scanning is a knowledge of the weld. Weld geometry must be known to determine the most suitable scanning techniques. Secondly, the history of the weld is helpful in determining the probability of occurrence of a certain type flaw. For example: lack of penetration might be expected in a square butt joint weld made with a single pass from each side; lack of fusion could occur in a weld of multiple passes from one side.

Calibration of the cathode ray tube screen provides the most effective means of distinguishing between valid flaw signals and extraneous weld bead signals. The screen is divided into two discrete zones as described in paragraph B.2., section II. One zone represents the weld thickness for a direct shot and the other for a bounce shot. Screen signals lying just outside these respective zones may generally be attributed to bead interference. Signals lying well outside of the zones are caused by other extraneous sources.

The following test will usually distinguish between two-dimensional flaws, such as lack of penetration, and three-dimensional flaws, such as porosity. The probe is rotated around the flaw, always pointed toward the flaw. If the signal persists throughout the rotation, the flaw is interpreted to be three-dimensional. If the signal appears at only two points, approximately 180 degrees apart, the flaw is interpreted to be two-dimensional with the plane of the flaw oriented perpendicular to a line connecting the two points.

A.S.T.M. specification E164-62T, "Weldments, Ultrasonic Contact Inspection of," dated 1962, for ultrasonic testing describes signal amplitude as a criterion by which to judge the extent of the flaw. With the instrument sensitivity calibrated according to procedures described in paragraph B.2.b, section II, any signal having an amplitude of less than one scale division (20 percent full scale) may be disregarded.

A useful rule-of-thumb is derived from the basic principles of the ultrasonic system. A signal from any source within a weld will move to the left or right on the screen as the transducer is moved toward or away from the weld. Conversely, a signal caused by electrical noise or any other source within the ultrasonic system will not move horizontally as the transducer is moved and therefore should be disregarded.

Another simple and sometimes helpful test is to rub the test surface, in the vicinity of a signal source, with a little fluid couplant. This will produce a fluctuation of amplitude if the source is actually contacted. Of course, if the signal's source lies beneath the surface, its amplitude will not be thus affected. This test is helpful, but not conclusive, in isolating bead interference signals.

B. TRANSDUCER OPTIMIZATION

Some consideration was given throughout this testing to the selection of proper, or preferred, transducer angle to be used in different situations. The following excerpt, from "Ultrasonic Testing of Materials" by the Krautkramer Ultrasonics, Inc., was used as a guide.

> "The choice of the angle used when testing welded seams is governed by the nature of the particular problem. Angle probes with a steep beam angle (less than 70^{o}) are more sensitive than those with a less steep angle. But with a steep angle it is easy for the weld to cause disturbing echos (signals), and with thin sheet the echos are too close to the initial transmitted pulse. Therefore a beam angle as less steep as possible will be chosen, except for thick plates, where a steeper angle will be used on account of the magnitude of the skip distance."

A few comparisons of transducer angle were conducted during this evaluation. In one instance a 60 degree angle beam transducer was able to detect simulated reference cracks, in a surface crack investigation, that could not be found with a 70 degree probe. However, the bead interference problem was quite troublesome.

In the lack of penetration testing, an 80 degree probe was used to supplement the primary 70 degree probe on all panels of 15 mm (0.600 inch) thickness and under. While resolution with the 80 degree probe was somewhat better, it did not disclose any additional flaws. Another comparison of these two probes was made during the bead interference study with more decisive results.

Figure A-1 is a comparison of results with the 70 and 80 degree probes, with and without bead interference, on a 6 mm (0.224 inch) thick plate. The bottom half of this figure shows the difference in bead signal amplitude at several positions along the weld. It shows that the undesirable bead signal is much less with the 80 degree probe. An exception occurred at station 16. However, as proved in the upper graph, the predominant signal source at this station was actually a flaw large enough to out-signal the bead. The upper graph depicts signal amplitudes, after removal of the weld bead, at stations where flaws were found. This shows no difference in sensitivity between the two probes for detecting valid flaws (in this case - porosity).

Each of the comparisons described above corroborates the outline by Krautkramer.

C. FLAW SIZE DETERMINATION

The Krautkramer USK-4 descriptive literature claims that the instrument is capable of approximating flaw size. Accordingly, an attempt was made to define the approximation. Two separate approaches were made, each utilizing a characteristic parameter of ultrasonics. They are signal amplitude and width of the ultrasonic beam.

1. Signal Amplitude. There is, of course, some relation between flaw size and the amplitude of the signal it produces. In the case of round holes or spherical porosity, size can be expressed in terms of diameter to which amplitude bears a linear relation. This is true only to the point where the flaw diameter exceeds that of the transmitted ultrasonic beam. Beyond this point there is little or no increase in amplitude. On the other hand, with two-dimensional flaws, no such straight forward relation was apparent, except in isolated cases. Also, because of limited data, no attempt was made to quantitate any of the relations mentioned above.

2. Ultrasonic Beam Width. Another possibility for making linear measurements lies in the use of the transmitted beam width. The first step was to measure the width of the beam by passing a point source (a small flat bottom hole) across the field of the beam and measuring the distance between appearance and disappearance of the signal. This proved to be approximately 14 mm (0.56 inch) for the standard WN-70 probe. A similar operation produces a dimension of a flaw when the beam width is subtracted from the traversed distance of the flaw. This procedure was

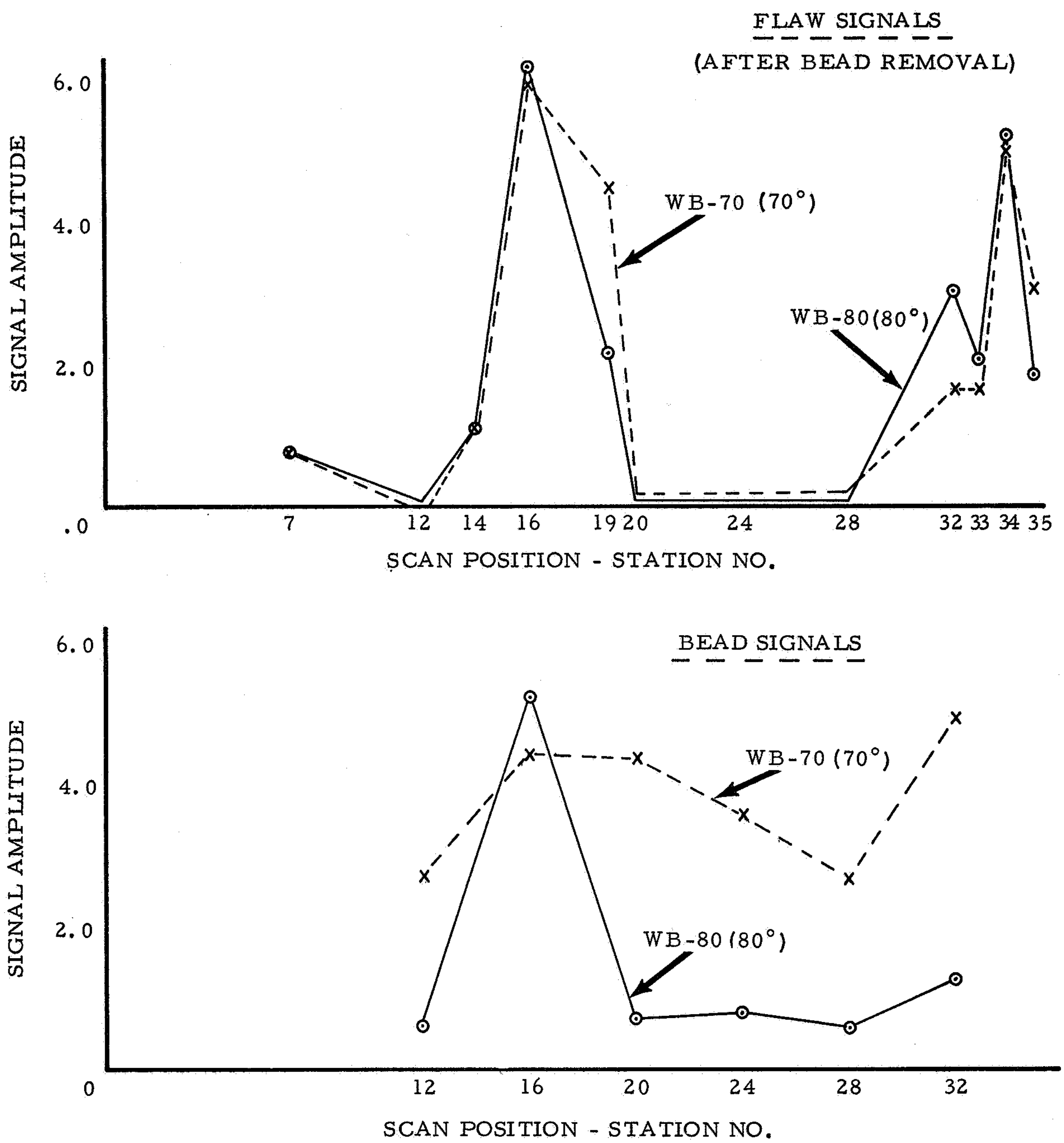


Figure A-1. Probe Comparison, WB-70 vs WB-80 used on a series of varying size round holes and on several porosity flaws. While it appears to be a valid method, the accumulation of tolerances amounts to about 3 mm (0.125 inch) on small three-dimensional flaws. On larger, 13 mm (0.50 inch) diameter, three-dimensional flaws and on all two-dimensional flaws the tolerances are even greater. Nevertheless, it is concluded that the manufacturer is justified in the modest claim that the USK-4 can approximate the size of flaws.

APPENDIX B. BEAD INTERFERENCE EFFECT

Figures B-1 through B-3 are detailed plots of signal amplitude versus bead configuration at a few typical scanning stations along the welds used in the bead interference investigation. They show the reduction of interference signals as the beads are shaved and also the emergence of flaw signals. Simplified versions of these graphs have been included in the text of this report as figures 11 through 13.

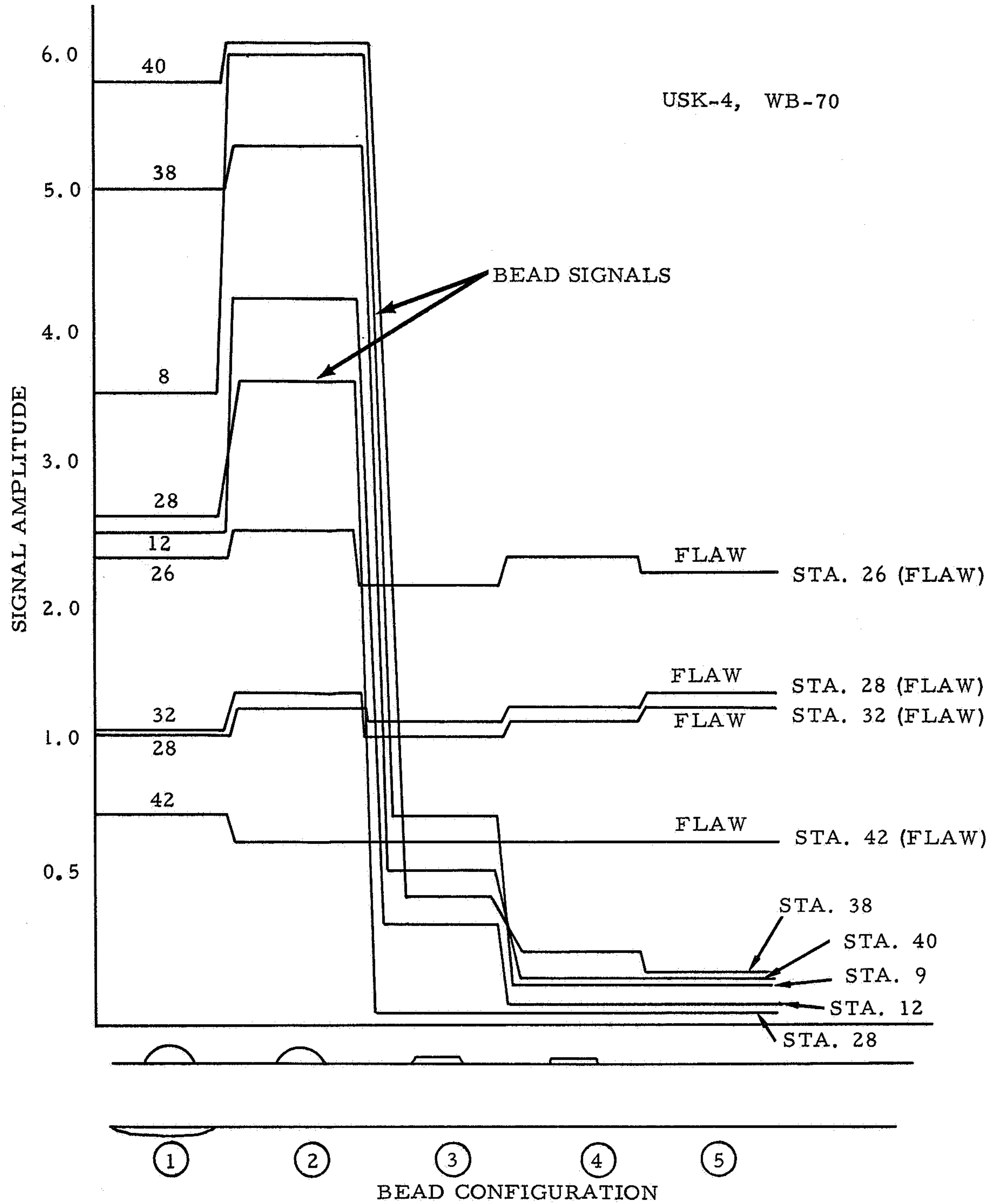


Figure B-1. Weld Bead Interference - 0.80 Inch Weld

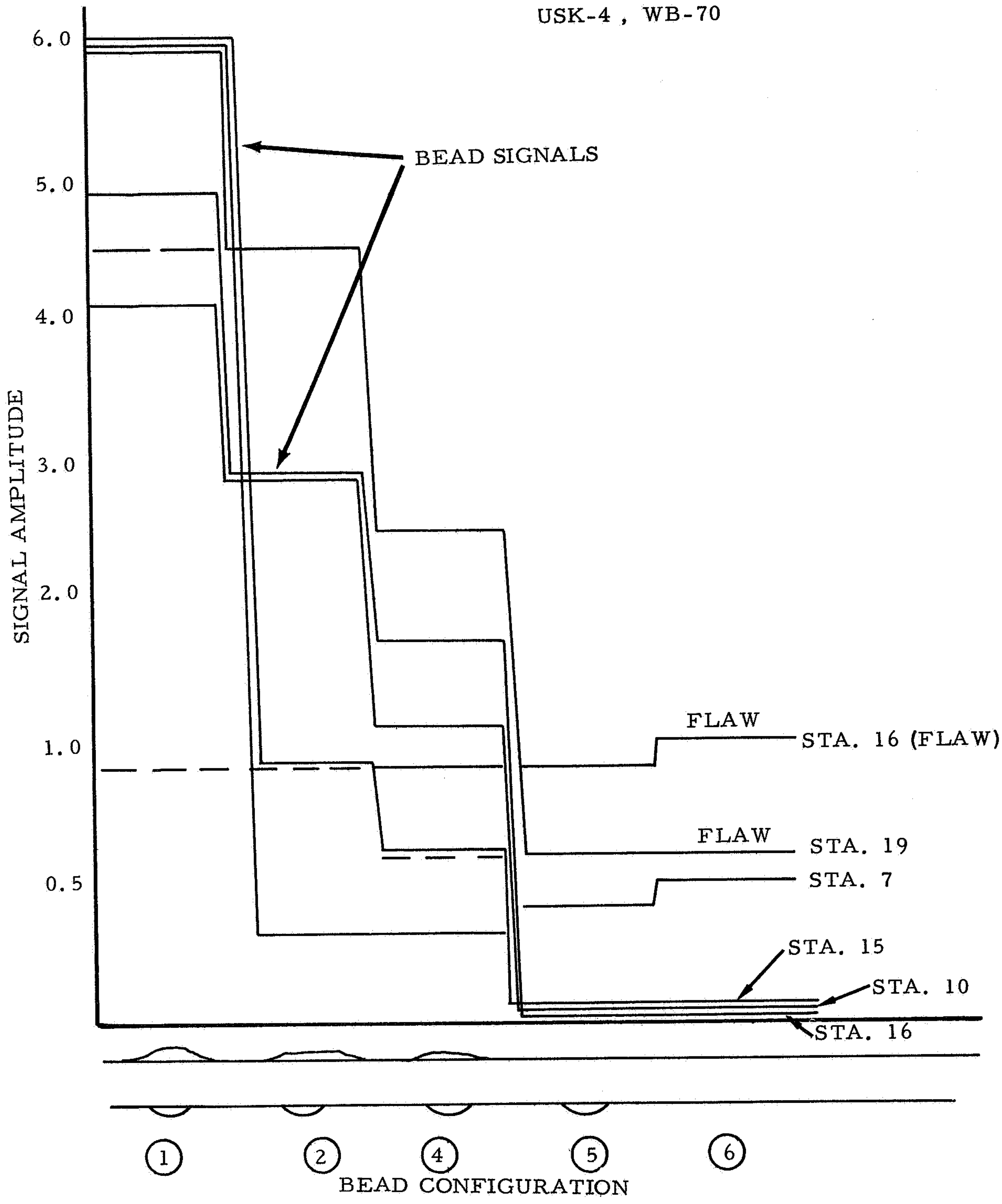


Figure B-2. Weld Bead Interference - 0.50 Inch Weld

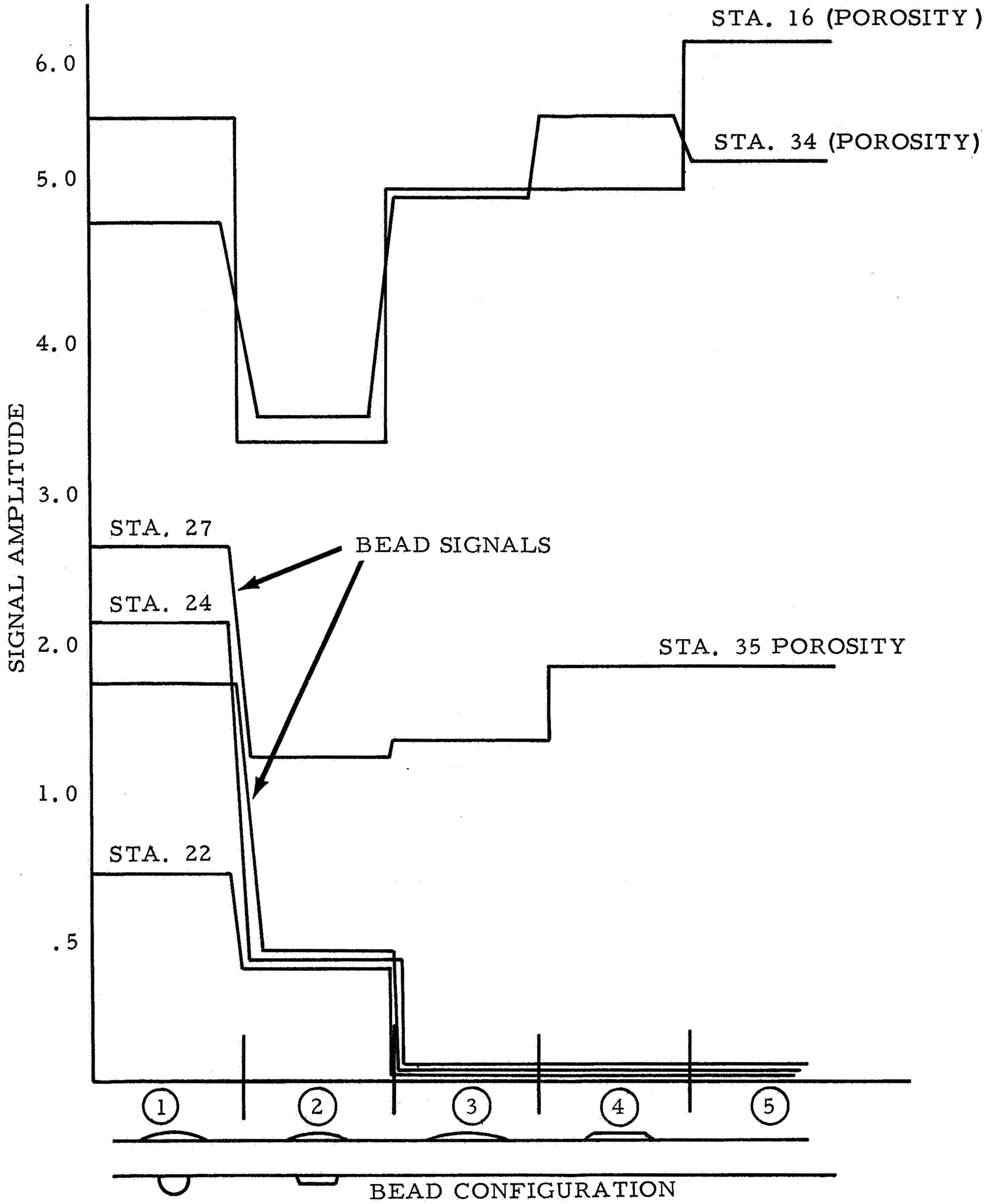


Figure B-3. Weld Bead Interference - 0.25 Inch Weld

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May 10, 1968

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APPROVAL

WELD FLAW DETECTION EVALUATION
UTILIZING ULTRASONICS AND RADIOGRAPHY

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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