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Acoustic Emission Monitoring of Production Armor Plate Welds

Final Report

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The work reported herein is the Phase 2 of a planned 3-Phase program to establish Acoustic Emission (AE) as a means to inspect armor plate welds, to provide a means of overcoming the intrinsic disadvantages of the standard weld inspection techniques of radiography and ultrasonics. The first program phase, completed in October 1979, established the feasibility of using AE for this application by monitoring the laboratory welding of armor plate with the controlled induction of critical flaws. The AE data and radiographic flaw

configuration analysis showed that 78% of all intentional confirmed flaws were detected by AE.

This Phase 2 effort was directed toward the evaluation of AE in a production welding environment by AE monitoring the fabrication welding of heavy armored vehicles. The objectives of this phase were to:

(a) develop a set of flaw discrimination criteria based on AE data that can be used to distinguish between flaw types,

(b) implement these criteria in software form and check them out on recorded AE data,

(c) install the software in a hardened breadboard for use in production monitoring,

(d) perform a field test at an armored vehicle production facility, and

(e) correlate the AE data with production NDE and repair records and assess AE's capability to detect and characterize production weld flaws.

This final report presents (a) the techniques used to establish the discrimination criteria and how these were implemented in software, and (b) the procedures employed in the two weld monitoring field tests, as well as the results of the data analysis correlating AE fault indications with other NDE results. The limited results indicate that AE has the potential to be a valuable NDE tool for production armor welding. Analysis shows that AE detected 79% of the significant radiographic indications. It is recommended that the next program phase be initiated. This Phase should include (a) the fabrication of a minimal AE system, optimized for armor plate monitoring, and (b) its use for extended production monitoring, to increase the monitored database and add confidence to the results already obtained.

ACKNOWLEDGEMENT

This project has been accomplished as part of the U. S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures or prototype equipment (in mechanical, chemical, or nondestructive testing) to insure efficient inspection methods for materiel/material procured or maintained by DARCOM.

SUMMARY

This effort is the second phase of a three phase program to establish Acoustic Emission (AE) as a production NDE tool for armor plate welding processes and for development of a stand-alone monitor system for this purpose. Work in Phase 1, completed in October, 1979, consisted of the generation of laboratory welds in armor plate with the controlled induction of critical flaw types. Recorded acoustic emission was correlated with radiographic ultrasonic and metallographic results. This analysis showed that AE detected intentional flaws.

This phase was directed toward the evaluation of AE when applied to production welding of heavy armored vehicles. In preparation for this task, flaw discrimination criteria were established, based on the data resulting from the Phase 1 effort. These data were refined thru a limited metallographic analysis of some of the laboratory welds to gain a further insight of the nature of natural flaws. We determined that the primary natural flaw appeared to be lack of fusion. Two of the metallographic sections also pointed out that apparent AE overcalls (AE flaw indications with no radiographic confirmation) were not necessarily overcalls but real flaws missed by radiography. This is not surprising in that radiography is quite sensitive to flaw orientation for detection. The flaw discrimination criteria were implemented in software form and checked-out using the AE data gathered in Phase 1. The software was then installed in an available hardened breadborad which could be used for monitoring actual production welds.

After a trial production test to permit familiarization of production procedures, determination of monitor settings, and finding optimal monitoring methods

for this application, the actual production monitoring test was performed. Eleven production welds were monitored. Nineteen significant radiographic indications were identified. Acoustic emission detected fifteen of them. Several application concerns were identified: weld geometry, effects of grinding masking on AE detection, and double weld monitoring. These will have to be addressed before a full-scale production monitor is implemented.

The AE weld monitor in its present form is an effective tool for detecting weld anomalies. AE indications require much less interpretation than other NDE indications. In the short term, if AE is heeded, as was the case with two of the indications called by AE in the production test, flaws can be repaired on the spot, and repairs after radiography can be reduced; further, AE can be used as a guide in looking for indications radiographically or ultrasonically. In the long term, AE might replace other NDE forms.

Second phase goals have been met; acoustic emission has been shown to detect critical flaw types in production armor plate welds. However, there is an insufficient database to assign a high degree of confidence to the results.

We recommend Phase 3 effort be commenced, involving (a) fabricating an AE Weld Monitor designed to monitor armor plate welds,(b)performing a study of the data masking effects of grinding and chipping to see if it might be possible to eliminate the small probability of missing an AE flaw indication because of simultaneous grinding, and (c) a six-month extended field test to provide a larger database for analysis.

PREFACE

This work was performed by GARD, INC., a subsidiary of GATX Corporation, 7449 N. Natchez Avenue, Illinois 60648 for the U. S. Army Tank-Automotive Command under Contract DAAE07-80-C-9113. Army Project Engineer Chester T. Kedzior of TACOM, Warren, Michigan directed the administration of the effort. It was performed at GARD in the contractor's Electronic Systems Department, W. Lichodziejewski, Manager, by R. A. Groenwald, Project Engineer and T. A. Mathieson, Research Engineer with assistance of D. W. Prine, Staff Engineer and J. L. Dobberke, Metallurgist.

The authors gratefully acknowledge the technical assistance provided by the Army Project Engineer and the efforts of J. Elliott, M. Pyhtila and E. Alloway for their assistance in scheduling the production monitoring tests and making the production NDE results available for GARD's use in this program.

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Section 1

INTRODUCTION

Acoustic Emission (AE) techniques are an effective means of accomplishing in-process weld inspection. While not a "perfect" tool, AE does overcome many of the limitations inherent in the standard NDE weld inspection techniques used today, namely radiography and ultrasonics. Being an in-process technique, AE can provide relatively "immediate" results of a weld's integrity. This permits quick corrective action as to the cause of the flaw and reduces repair costs by allowing them to be done on a pass-by-pass basis rather than after the completion of a heavy section weld. Unlike standard NDE techniques, AE is independent of flaw orientation, a critical limitation of both radiography and ultrasonics. Its use of fixed transducers eliminates the scanning process required of ultrasonic testing. The analysis of AE signals with computerized instrumentation minimizes (possibly eliminates) the need for interpretation of inspection data by a qualified operator and can provide for automatic flaw location and characterization as to type and size. The use of AE is not significantly hindered in those cases where the weld geometry renders conventional NDE methods either difficult or impossible to apply.

The advantages cited above have led to the second phase in a three-phase program, which is to determine the feasibility of utilizing acoustic emission to monitor armor plate welds with the ultimate goal of the development of an AE system designed for monitoring the production welding performed in the fabrication of heavy armored vehicles.

1.1 Background

Acoustic emission energy, generated in material under stress, results from such mechanisms as plastic deformation and flaw propagation. Under improper welding conditions, stresses generated by the solidifying weld metal can produce flaws, such as cracks, resulting in the release of acoustic energy. The detection and use of these acoustic signals is the basis for a powerful real-time NDE tool.

GARD began the study of acoustic emission weld monitoring under GATX Corporate sponsorship in 1971 with the goal to improve NDE of welds in the manufacture of railroad tank cars. AE was chosen for study because it is real-time, and real-time in-process inspection has decided advantages over standard after-the-fact NDE methods. During the early phases of this Corporate program, the ability to discriminate between weld flaw related AE, which is random and noise-like, and other welding noises, present in production welding situations, was developed. (Typical non-flaw related AE signals during welding include weld arc noise, slag cracking, and mechanical noises such as grinding, chipping, and part manipulation.)

GARD's efforts continued in 1974 under the sponsorship of the Nuclear Regulatory Commission with a multi-year program to prove the feasibility of applying AE monitoring to the wider range of materials and processes encountered in the fabrication of nuclear power plant components. The correlation of AE data with NDE of both laboratory and production welds clearly demonstrated the viability of using AE to monitor the welding of nuclear components. We developed several stand-alone monitors; one such monitor performed a flaw detection function, while another provided flaw location information as well.

These programs contributed greatly to increasing the understanding of the basic physics of acoustic emission flaw detection in welds. Analysis of a large bank of controlled flaw data, plus production data, led to GARD's development of a "smart" AE monitor that, in addition to the detection and location of flaws, can characterize them as to type and relative size. Three such systems have been fabricated, one for the Nuclear Regulatory Commission, one for the United Kingdom Atomic Energy Authority, and one for the Federal Highway Administration (Department of Transportation). Extensive successful field testing of one of these monitors has been done by GARD personnel and has included:

- o monitoring a steam generator manway weld at Westinghouse, Tampa, FL, (NRC sponsored),
- o simulated low temperature pipeline welding at Battelle, Columbus, OH (AGA sponsored),
- o narrow-gap, thick section hot wire gas tungsten arc welding (GTAW) at Westinghouse, Pittsburg, PA, (DOE sponsored),
- o manual metal arc welding of HY-80 done at GARD's laboratory and NSRDC/Annapolis, MD (Navy sponsored), and
- o thick section (250mm) nuclear steel welding using submerged arc welding (SAW) at GHH Sterkrade, FRG, (NRC sponsored).

Parallel to these efforts, GARD has been developing the AE weld monitoring technology for a U. S. Army application. This report covers the work performed in Phase 2 of a planned 3-Phase TACOM program intended to develop a production oriented "smart" AE Weld Monitor (AEWM) to be applied in monitoring the welding of heavy armored vehicles. The first Phase, begun in October 1978, demonstrated the applicability of AE to armor plate welding. To do this, AE data were collected during the laboratory welding of 14 armor plate welds with controlled induction of critical flaws. Flaw confirmation was accomplished primarily with radiography and supplemented with ultrasonics and metallography, as required. Confirmed flaws were correlated with AE data to predict the accuracy with which AE is able to detect and locate weld flaws as well as discriminate between flaw types. The success of Phase 1, attested by 78% of all confirmed flaws being detected and located, led to the commencement of the second Phase program. Here the AEWM principle was evaluated on production welding of heavy armored vehicles. The subsequent third phase would be directed towards the development, fabrication, and testing of an AEWM system keyed to the unique requirements of armored vehicle production welding.

1.2 Objective and Scope

As cited earlier, the primary goal of this program phase is to evaluate AE's ability to monitor production welding used in the fabrication of heavy armored vehicles. Of particular interest is the determination of how effectively AE techniques can detect, locate and classify critical weld flaws in production. To this end, the following tasks were performed:

a. Using the AE data acquired in Phase 1, the flaw discrimination criteria were optimized for automatic weld flaw recognition.

b. The optimized criteria obtained in (a) above were then implemented in the form of a set of software flaw models. These were first evaluated in a laboratory system, and then installed in a hardened monitor system.

c. The discrimination software was tested using both recorded data from Phase 1 and live laboratory welding.

d. The system was then used to monitor production armor plate welding. Data records of AE flaw indications and production NDE results were gathered for subsequent correlation.

e. An analysis was performed on available data to determine the degree of correlation between AE indicated and NDE confirmed flaws.

The preparatory work of tasks(a) through (c) are covered in Section 2; the remaining tasks of production monitoring and data analysis are covered in Section 3.

Section 2

PREPARATORY WORK FOR PRODUCTION MONITORING

The work performed by GARD in preparation for the production weld monitoring is divided into three categories: (1) the determination of optimal discrimination criteria for automated weld flaw recognition, (2) the implementation of these criteria in software form, and (3) the evaluation of software performance on both recorded and on-line AE data. Each of these tasks will be covered individually in the sections that follow.

2.1 Optimization of Flaw Discrimination Criteria

This task is to determine the unique characteristics of acoustic emission signals from each flaw type to provide discrimination amongst flaw types using AE. The major flaw types for consideration in gas metal arc welding (GMAW) of armor plate are: cracks, lack of fusion (LOF), incomplete penetration (IP), and porosity. To accomplish this task, we analyzed signal characteristics of recorded AE data from confirmed intentional flaws induced during Phase 1 welding. In addition, a limited number of metallographic sections were performed to gain insight into the nature of the detected natural flaw population. This helped to resolve differences between radiography and acoustic emission, explain acoustic signal intensity variations and provide greater understanding of the nature of more probable natural flaws. This, in turn, allowed us greater confidence in the acoustic flaw discrimination criteria established.

Metallographic Analysis

Seven sections were analyzed, each one consisting of an approximate 2-inch length of weld. Each was sliced into 3/16-in. thick sections, as required, to determine the extent and continuity of the flaws in question. Table 1 summarizes the accomplishments of this task. (See TACOM Report No. 12468 for background information in this area.)

The analysis of the laboratory welds fabricated in the first phase of this project revealed a number of occurences where AE indications could not be correlated to radiographic indications. Weld 5, which contained a series of attempts at lack of fusion generation, was the most outstanding example of this situation. To discover why such a high false AE detection rate existed, two sections were cut centered on acoustically active areas, and one section was cut centered on a relatively inactive area.

Section 2 (Figure 1) was cut from a radiographically clear but acoustically active area 33 to 35-in. from the weld start of plate 5. Figure 1 shows several small regions of unfused metal along the lower right wall, agreeing with the observed acoustic persistance of this source in side 2 passes 7 and 11 (Figure 2). Section 1 (Figure 3) was cut from a radiographically clean but acoustically active area 4 to 6 inches from the weld start of plate 5. Figure 3 shows the presence of one unfused region on the upper left bead boundary. This agrees with the acoustic record (Figure 4) in that an indication from this location occurred during the welding of pass 4 of side 1. As a reference, Section 3 (Figure 5) was cut from an acoustically inactive radiographically clear area 10 to 12-in. from the weld start of plate 5. Figure 5 shows nothing but one spherical pore near the weld root. This flaw type is usually acoustically inactive; hence it is not surprising that it went undetected.

From these metallographic examinations, it is seen that the apparent acoustic false detections (as defined by radiography) can be actual flaws oriented so as to be undetectable by radiographic inspection.

Table 1 METALLOGRAPHY/NDT CORRELATIONS

ANALYSIS	SECTION	WELD NO.	LOCATION	RADIOGRAPHIC INDICATION	ACOUSTIC INDICATION	METALLOGRAPHIC
LACK OF CORRELATION	1	5	4" TO 6"	NONE	YES	LOF
	2	5	33" TO 35"	NONE	YES	LOF
	3	5	10" TO 12"	NONE	NO	ISOLATED PORE NEAR ROOT
SIGNAL LEVEL	7	11	23" TO 25"	POROSITY	YES	MICROCRACKING WITH POROSITY
	6	8	23" TO 25"	POROSITY	YES	TAILED POROSITY
FLAW NATURE	4	11	0" TO 4"	PORE STRING	YES	IP, LOF, POROSITY
	5	11	25" TO 27"	NONE	YES	IP, LOF

Figure 1   Lack of Fusion (Section 2)

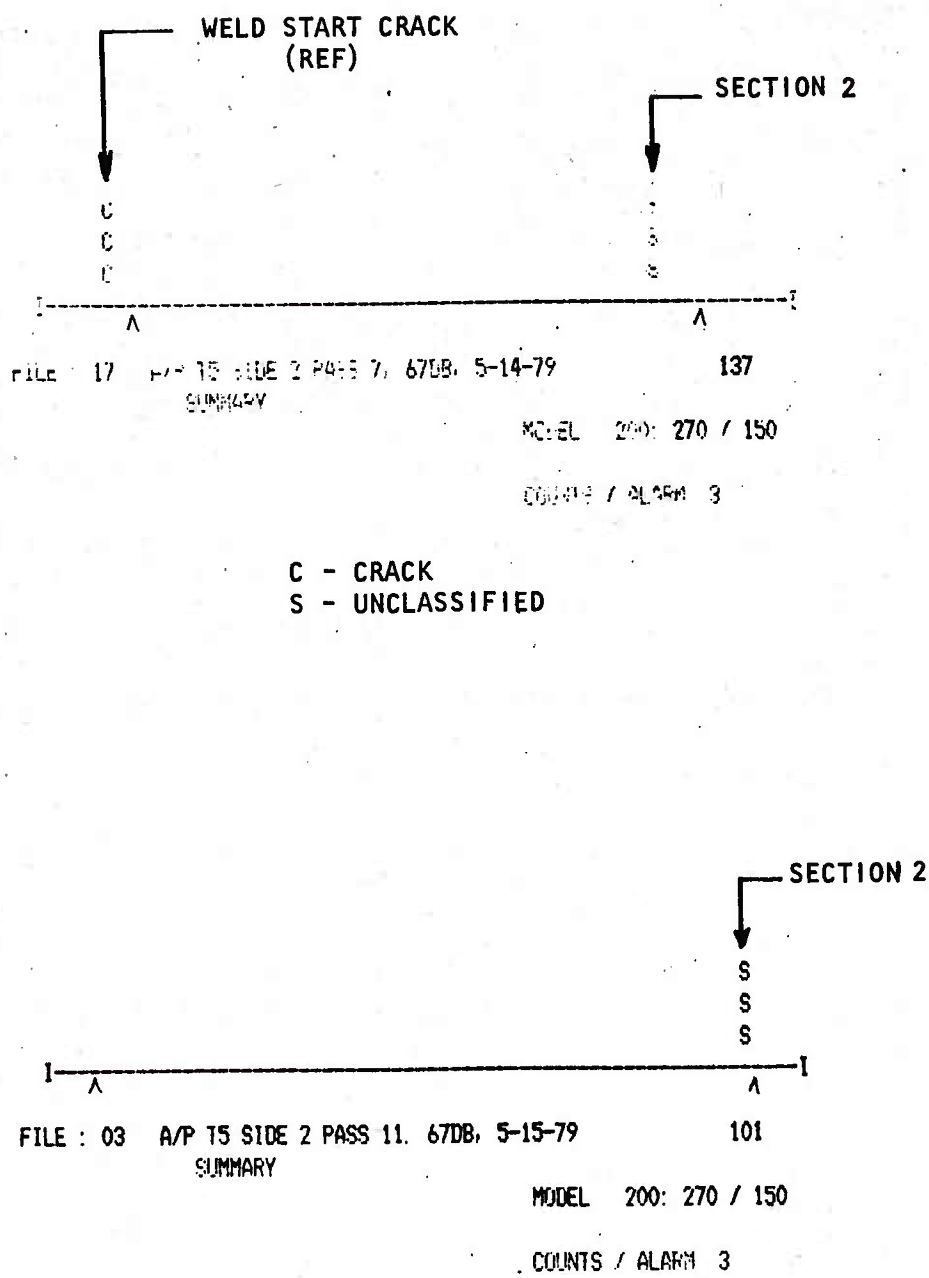


Figure 2 AE Indications (Section 2)

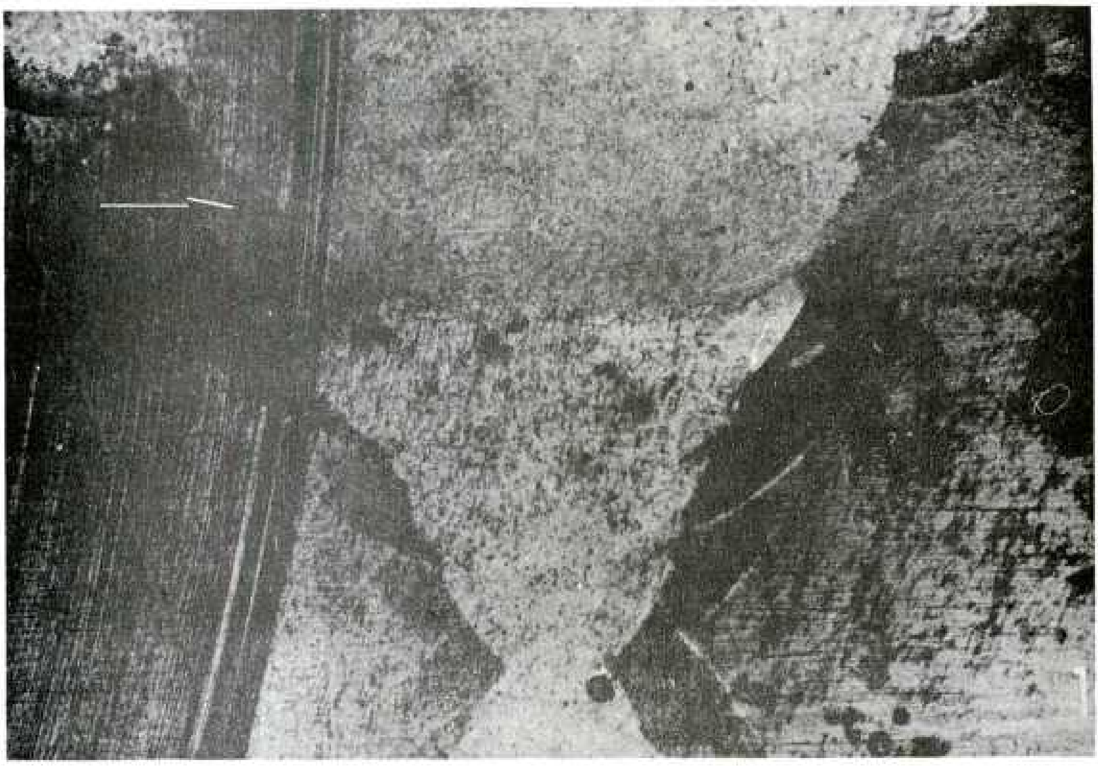
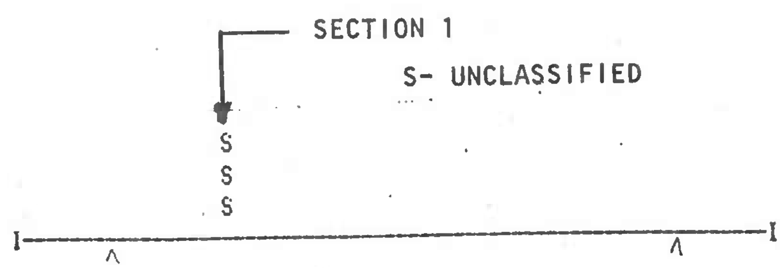


Figure 3 Lack of Fusion (Section 1)



FILE : 12 A/P T5 SIDE 1 PASS 4, 67DB, 5-1-79 107
SUMMARY

MODEL 200: 270 / 150

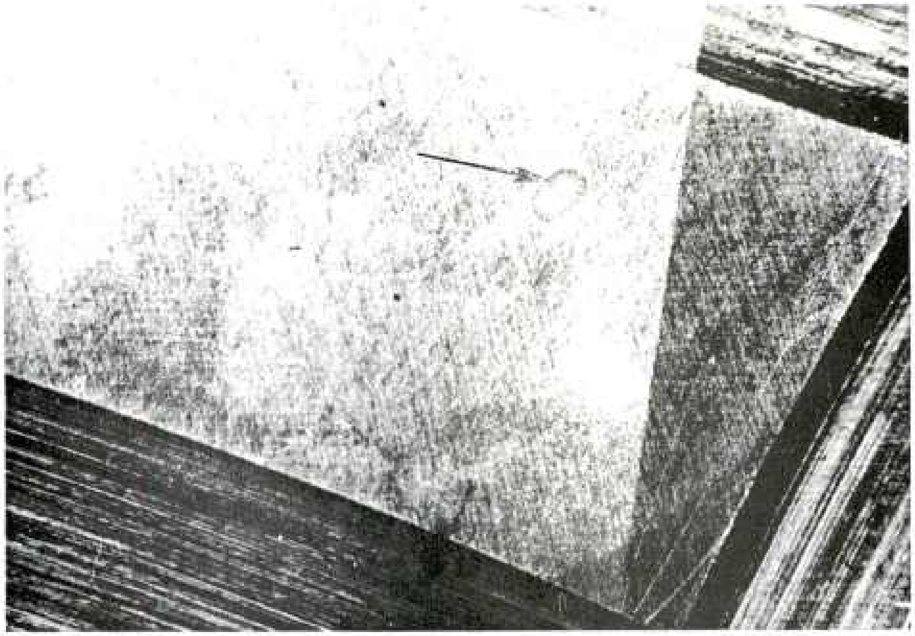
COUNTS / ALARM 3

Figure 4 AE Indications (Section 1)

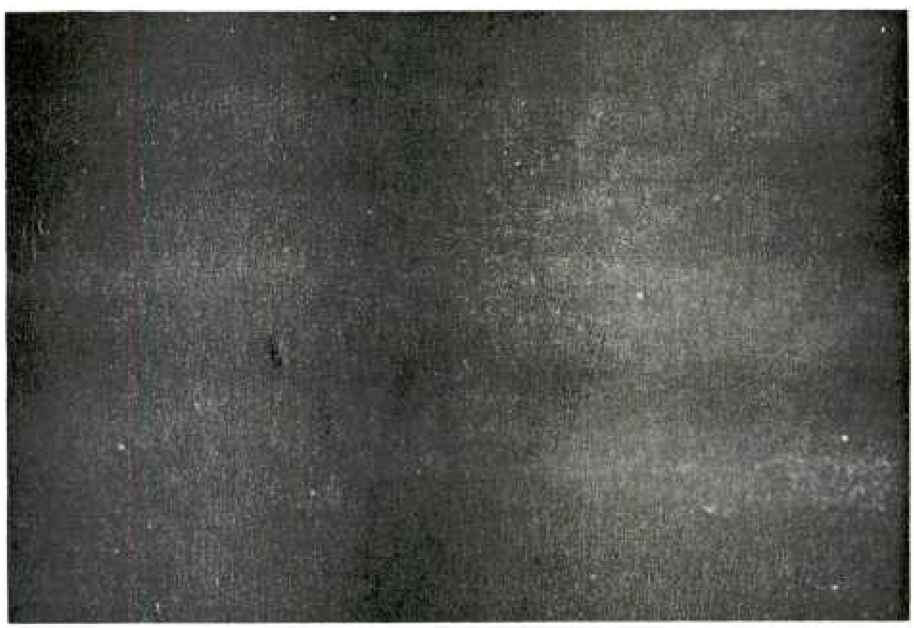
Figure 5 "Flawless"(Section 3)

Another problem from the first phase of the project was presence of acoustic activity at a level greater than the associated radiographic indication implies. In several cases, intended porosity was generated and detected both by AE and radiography. Classically, porosity is not a very acoustically active flaw type and when the radiographic and acoustic densities were compared, the acoustic density appeared to be disproportionately high. An example of this is the section (Section 7) illustrated in Figure 6a, taken 23 to 25-in. from the weld start of plate 11. The corresponding radiograph in Figure 6b shows only a few innocent looking dots. Figure 7 which are metallographs of this porosity area shows an extensive network of microcracks exists, along with porosity. A similar situation occurred during the welding of plate 8. Section 6 was cut to investigate. As Figure 8 shows, the porosity generated had both spherical and linear characteristics with linear or "tailed" type predominating. Thus, it appears when an acoustic indication of high density occurs, sharp stress risers can be in the welded product regardless of the interpretation of the associated radiographic image.

To extend our examination of the true nature of acoustic sources, two more sections, in which acoustic activity was detected but no flaws were intended, were cut from areas in Weld 11: one had radiographic correlation, one did not. Section 4 was cut from the first 4-in. of Weld 11, a region of extremely dense acoustic activity and radiographic indication of a porosity string. Figure 9 is an example of one of the many sections sliced through this region; lack of fusion and incomplete penetration with associated voids appear to be the predominant flaw types. Section 5 was cut from an active acoustic area in which no radiographic indication was observed. However, as Figure 10 shows, incomplete penetration was the apparent acoustic source.

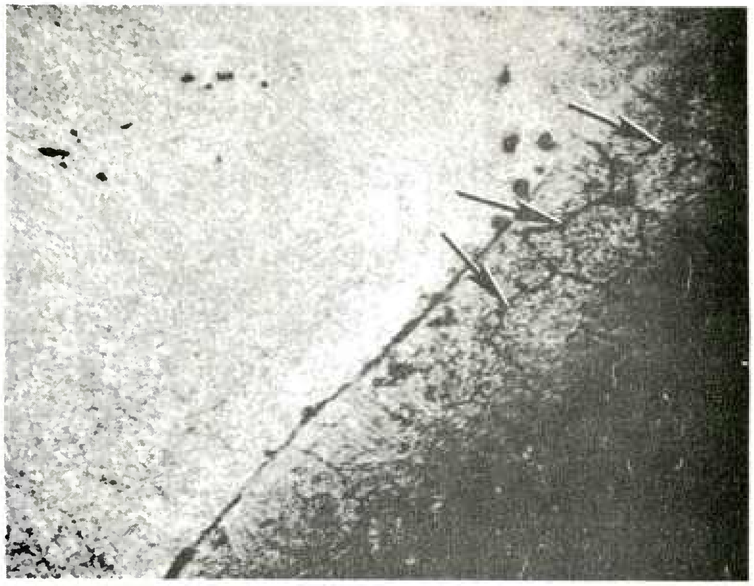


(a) Macrograph



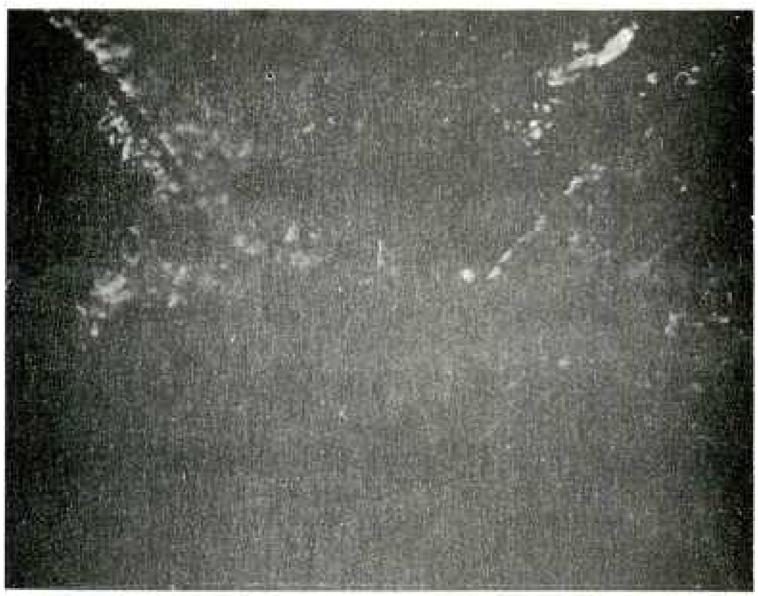
(b) Radiograph

Figure 6 Section 7



(a)

150 X Magnification



(b)

600 X Magnification

Figure 7 Metallographs (Section 7)

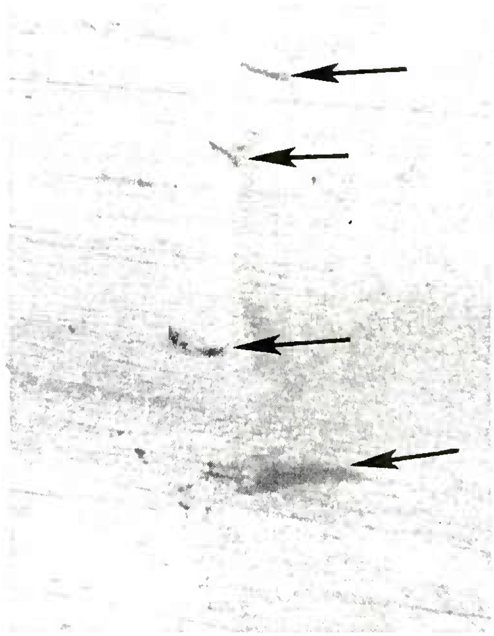


Figure 8 Tailed Pores (Section 6)

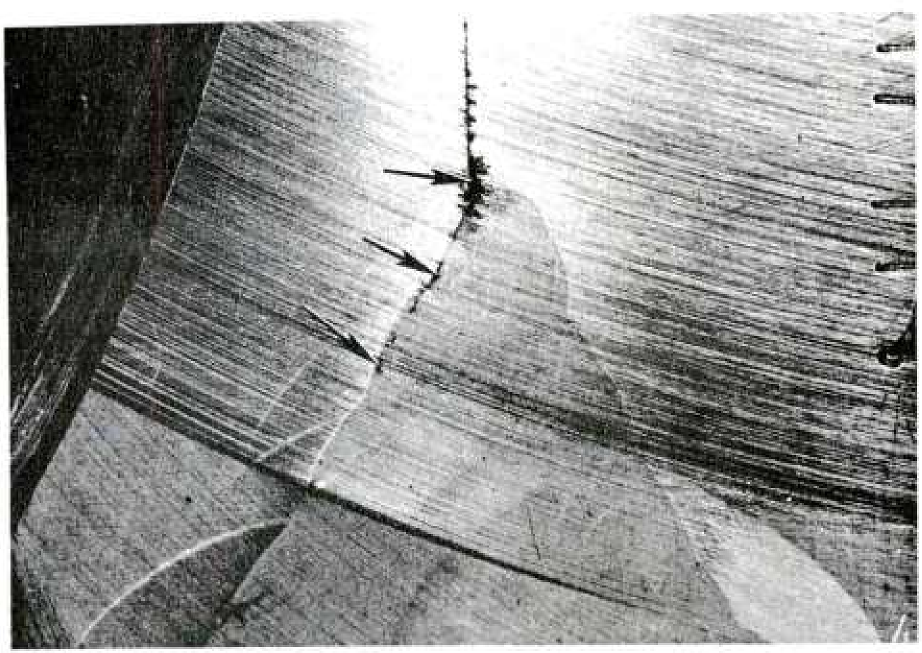


Figure 9 Lack of Fusion, Incomplete Penetration (Section 4)

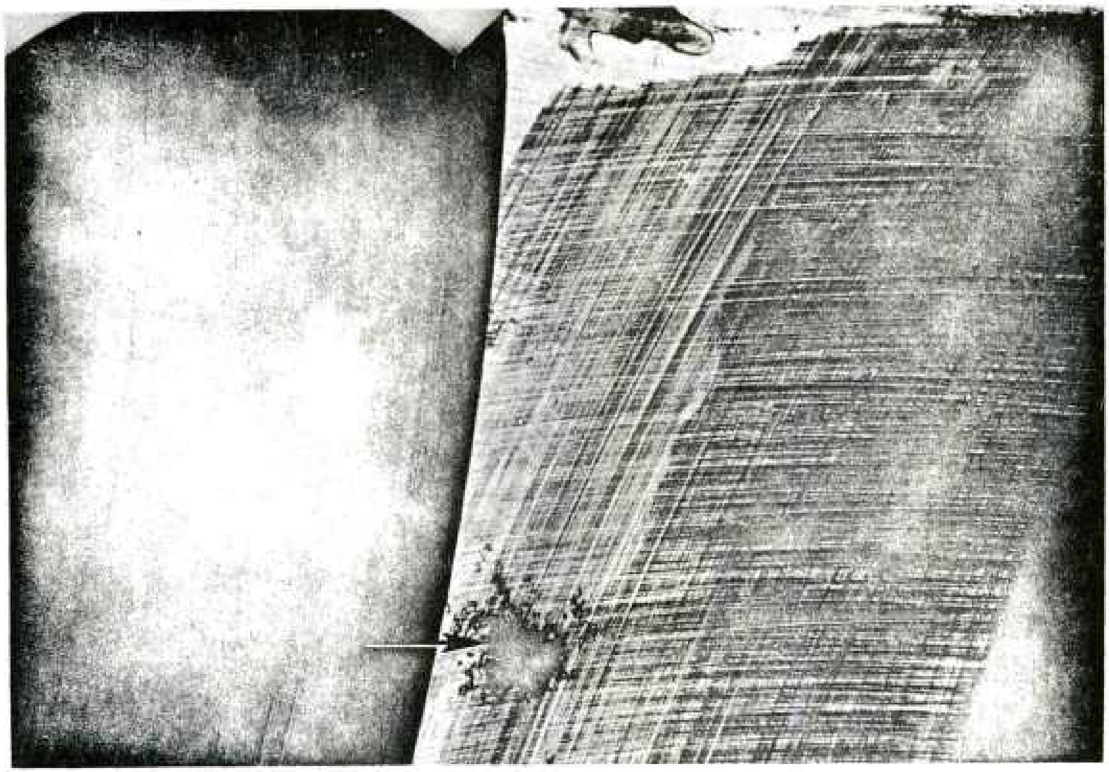


Figure 10 Incomplete Penetration (Section 5)

On the basis of the above sample sections, we conclude that regardless of radiographic detection or interpretation, the acoustic activity observed in our first year database can be associated by metallographic sectioning with some form of cracking in the metal either alone or in conjunction with lack of fusion, incomplete penetration, or linear porosity.

Establishment of Flaw Discrimination Criteria

This task involves a correlation of the AE data characteristics with the radiographically confirmed flaws augumented by the above cited metallographic data. A meticulous examination of the recorded AE data is required.

Statistical analysis of AE parameters was used to spot trends associated with specific flaw types. Early analysis revealed that intended porosity exhibited high emission rates over an extended area of weld length. This was in contrast to the behavior of crack acoustics, which were moderate in rate and localized. Examination of the first year's weld database resulted in a finding of no reliably significant shift in frequency content between intended porosities and the background noise of the weld process itself. However, it was ascertained that a crack creation was signaled by bursts exhibiting a higher-than-background activity near the 270 kHz frequency band. On this basis, the signal characteristics for cracks and porosity were established.

The characterization of lack of fusion and of incomplete penetration required more extended analysis. These flaw types generally presented an acoustic record enhanced in the 270 kHz frequency band, which has already been associated with crack characterization. Metallographic examination showed that when lack of fusion or incomplete penetration was detected acoustically, a sharp crack-like feature was observed extending from the flaw type. Thus, it was not surprising to find that an already proven crack pattern was also asserting its presence upon generation of these flaw types. The problem was then reduced to finding some feature, or features, in addition to 270 kHz enhancement, which could distinguish independent crack growth from those associated with formation of lack of fusion or incomplete penetration.

The characterization problem of incomplete penetration was addressed first. Partial penetration welds were not included in the database for this analysis because they were an intentional incomplete penetration by definition. Incomplete penetration attempted and confirmed in full penetration welds was studied extensively and, in the first year's database, no reliable pattern could be found that would distinguish this type flaw from a crack. As a result, we concluded that the type of flaw interpreted radiographically as an incomplete penetration was in actuality a "crack" that occured in or near the weld root pass. Consequently, an algorithm was devised that took into account weld pass number in addition to crack characterization.

The characterization problem of lack of fusion turned out to be more tractable. Although only one intentional lack of fusion was successfully generated, the first year's database contained many examples of unintentional lack of fusion. A careful study of flaw depth by metallographic section coupled with detailed records of pass placement allowed the extraction of two candidate characterization algorithms for this type flaw. Each appears to detect the lack of fusion at a different point in its history. One algorithm is sensitive to moderate rate of low energy and characterizes lack of fusion by perception of enhanced 270 kHz frequency activity. This scheme seems to detect lack of fusion at the time that it is generated. The other algorithm detects moderate rate of moderate energy and characterizes lack of fusion by perception of enhanced 920 kHz frequency activity. This method detects this flaw type within a few passes after its generation. Faced with a choice of models for incorporation into the weld monitor for production testing, we chose the latter for two reasons. First, a model which detects only at time of flaw generation may yield a large false detection rate when compared to after-the-fact inspection results if flaws so detected are repaired by the weld process itself in subsequent passes. Second, the latter model is more easily integrable into the present AEWM software.

The ultimate result of this preliminary analysis was the flaw discrimination matrix shown in Table 2. As can be seen, cracks, incomplete penetration, and lack of fusion are characterized as localized flaw types with porosity being more extended in space. In addition, porosity is characterized by a higher rate of emission with no specific frequency signature. Cracks, incomplete penetration, and lack of fusion are frequency-characterized; crack and incomplete penetration are resolved by the consideration of the pass number. Since detection is statistical, it is obvious that a category for AE which has the detection characteristics of the non-porosities but no specific frequency characteristics can exist. This is identified in the table as "unclassified".

2.2 Development of Software Flaw Models

The next step, before flaw discrimination by AE could be tested on-line, was the development of software flaw models (i.e., the software implementation

Table 2 FLAW DISCRIMINATION MATRIX

	CRACK	IP	LOF*	POROSITY	UNCLASSIFIED
BURSTS/SEC	3	3	3	5	3
ENERGY RANGE	$100 \le R \le 1000$	$100 \le R \le 1000$	$100 \le R \le 1000$	$100 \le R \le 1000$	$100 \le R \le 1000$
LOCATION SIMILIARITY	0	0 (Pass 1 & 2)	0	2	0
ACTIVE FREQUENCY	270kHz	270kHz	920kHz	NONE	NONE

* An accessory algorithm may be based upon an energy range of $10 \le R \le 100$ and a characteristic frequency of 270 kHz.

of the discrimination matrix determined above). Such a system of models must be compatible with (1) the GARD laboratory system, to allow their evaluation with the data recorded in the Phase 1 effort, and (2) the hardened breadboard monitor available for use in the production testing to follow.

A unique software technique was used which resulted in an n - type model to provide a maximum flexibility in model specification. That is, each flaw type is characterized not so much by the algorithm required for pattern recognition, but by the values of the parameters used in such an algorithm. Therefore, when a computerized system must make a decision on the basis of characterization tests for n possible flaw types, it does not have to execute n different algorithms. It merely executes the same algorithm n times, switching parameter values for each succeeding test. Furthermore, the uniqueness of each set of parameters, as derived above, allows the construction of a sequence of tests which can be used as a series of characterized/not characterized branch points for more efficient test execution. If care is taken to place tests for increasingly severe or sensitive flaw types closer to the start of the test series, then all significant characterizations can be made within a minimum of overall execution time.

The generalized flow chart for this discrimination system is shown in Figure 11 The implementation of this system was first realized on GARD's AE analysis microcomputer system, where it was used to test the workability of the algorithm and the selected parameter values on the Phase 1 database.

Figures 12 to 14 illustrate the results of these tests. The excellent match between detection, characterization, and flaw presence is not surprising because the method was developed through study of this same database.

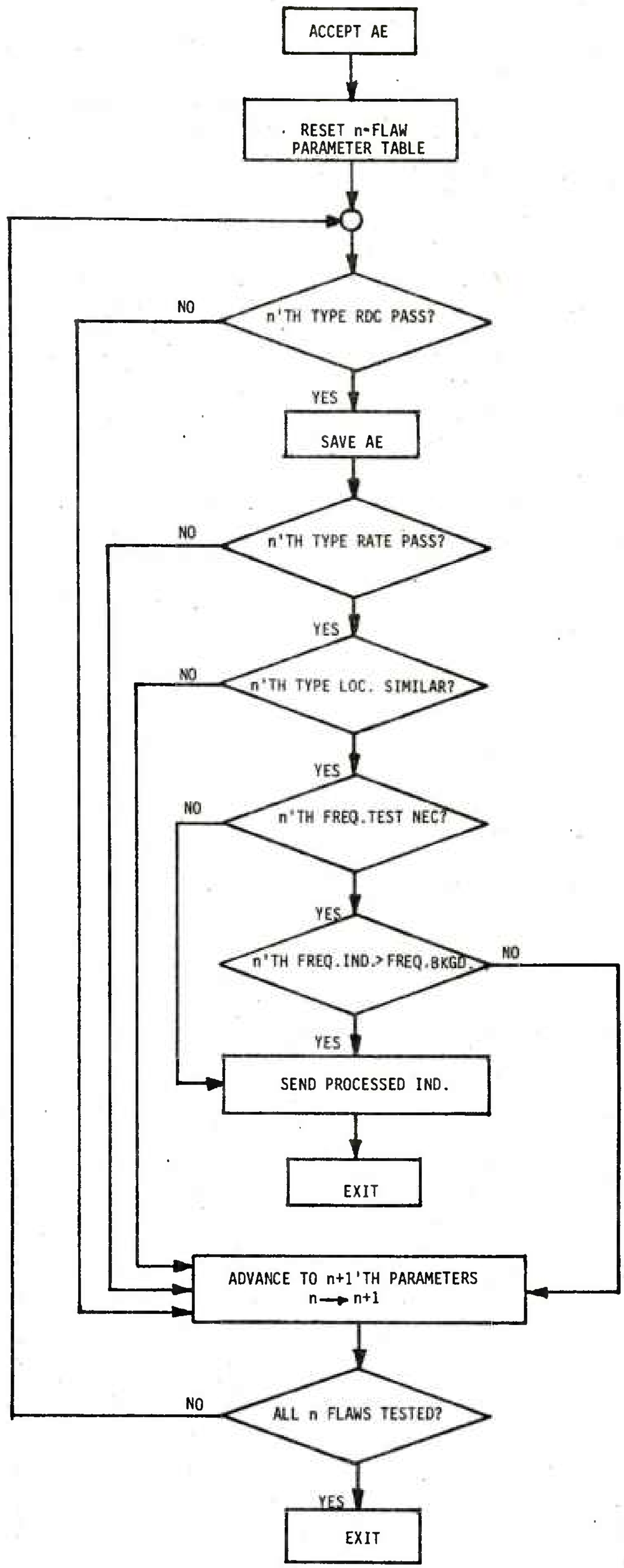


Figure 11 Generalized Discrimination Algorithm

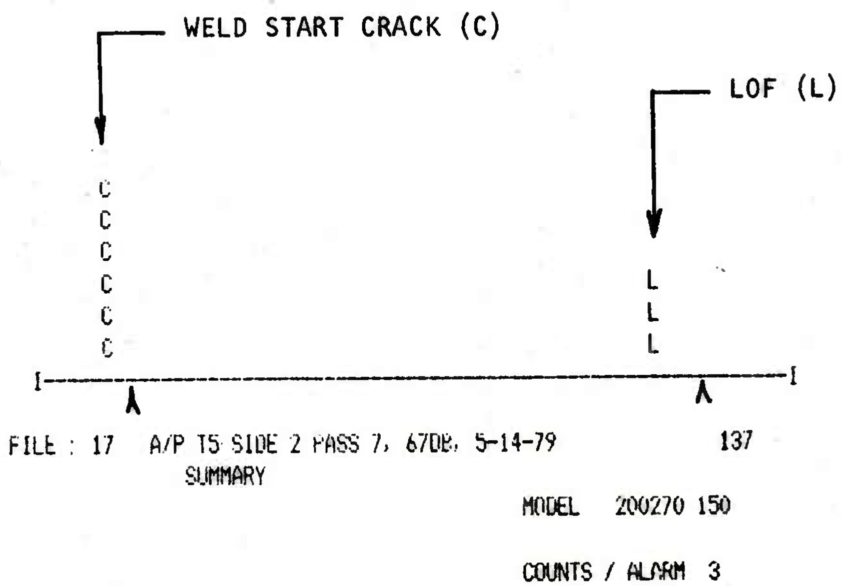


Figure 12 AE Characterization Performance on Indications Associated with Metallography (Section 2)

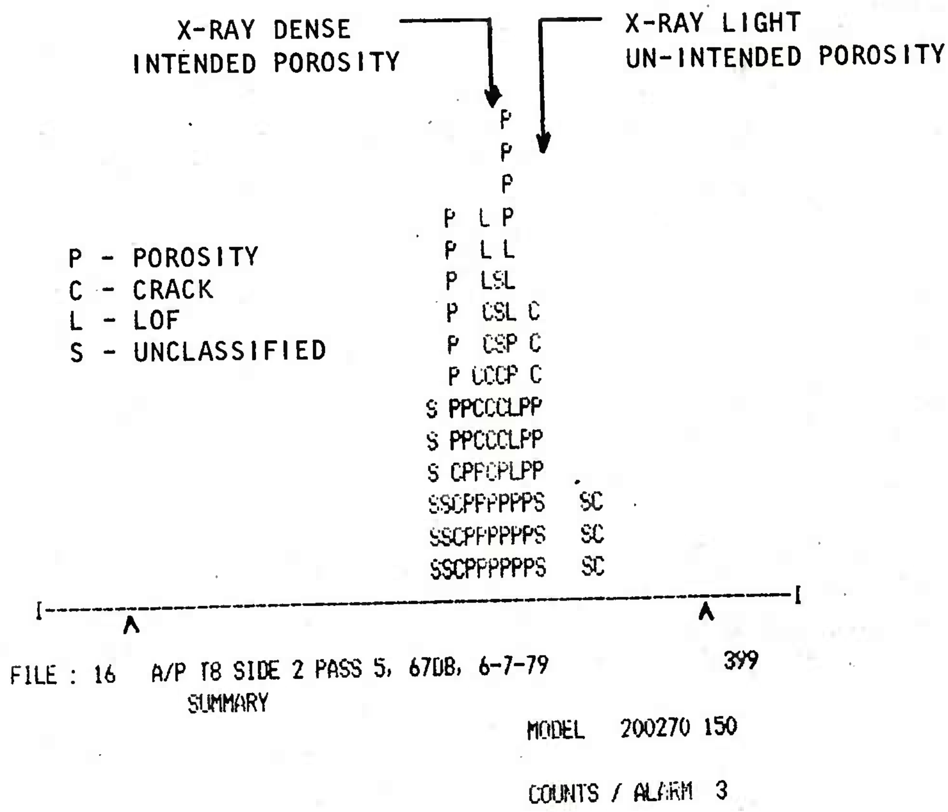


Figure 13 Characterization Performance on Indications Associated with Metallography (Section 6)

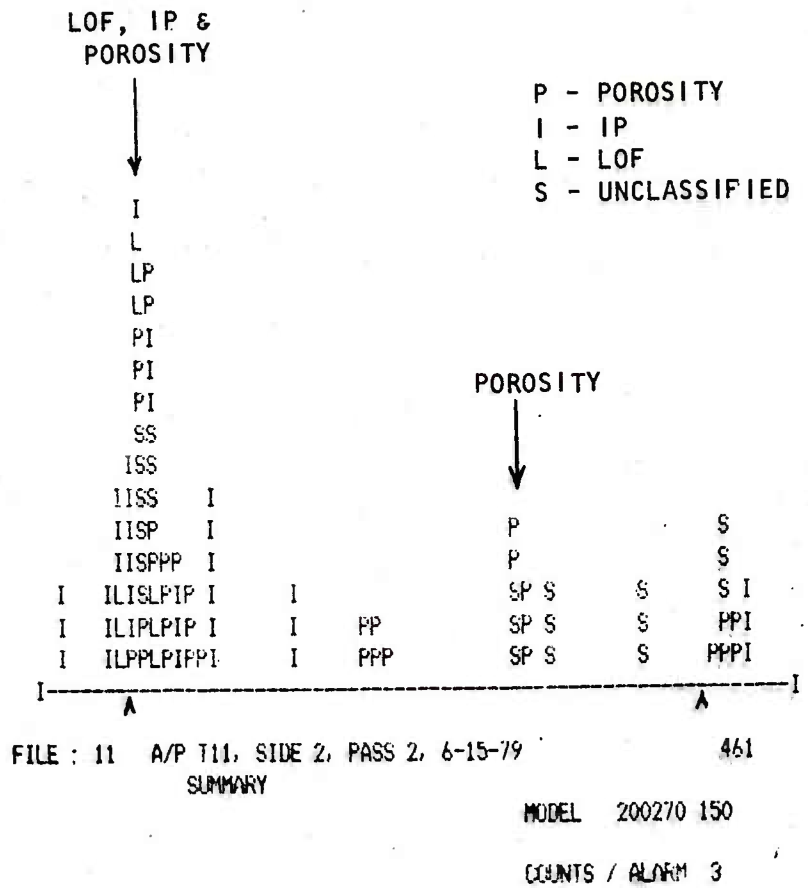


Figure 14 AE Characterization Performance on Indications Associated with Metallography (Sections 4 and 7)

Figure 12 illustrates characterization of a weld start microcrack and a lack of fusion confirmed at 34" from the start of Weld 5. Figure 13 demonstrates performance of the characterization algorithm during pass 5 of the second side of Weld 8 wherein porosity was generated. The indication "S" marks the unclassifiable category. The X-ray confirmed porosity is characterized principally as porosity with some cracks and LOF interspersed. The truths of such a mixed categorization is indicated by Section 6 revealing tailed porosity which may have cracks growing from the "tails". Figure 14 shows more correct classification of porosity and mixtures of LOF, IP, and porosity in Weld 11.

A true test requires new data. Thus the next step was to monitor production welding at an armored vehicle production facility. To prepare for this production-line test, a version of the algorithm was written, programmed, and tested in a GARD-available stand-alone weld monitor.

Section 3

PRODUCTION MONITORING AND DATA CORRELATION

With the tasks described in Section 2 completed, a stand-alone monitor was ready for monitoring the production welding of heavy armored vehicles. The contractually required four-week monitoring period was divided into two trips. A trial production test was performed first. This was followed by data analysis which permitted compensation in the flaw model software (if required), and allowed for adaptation in the data gathering techniques to accommodate any peculiarities in the production welding situation. The second trip involved the actual production weld monitoring, followed by the collection of production NDE test data and its analysis/correlation with the AE records.

3.1 Trial Production Test

The trial production test at a government-specified armored vehicle production facility was intended to provide experience with their welding activities so that GARD could implement efficient transducer placement and meaningful monitoring activity, and to test the reliability and veracity of Monitor performance. One hull was monitored through the three work stations.

Monitoring proceeded with no interruption or delay in the normal flow of weld production. Transducer placement at Work Station 1 was on the top side of the weld, but was on the hull side wall to avoid interference with the welder's movements. Transducer placement on the under side of the plate at Work Stations 2 and 3 accomplished the same thing.

Two repairs occurred during the monitoring on this first trip. One was visually corroborated both by GARD and by production personnel upon detection by the Monitor. The other, revealed by subsequent radiographic inspection, was a dense cluster of transverse cracks, and was not detected by AE because, in retrospect, it was determined that the monitor gain was set too high for monitoring partial penetration root passes. Such welds are acoustically active by nature and this activity masked flaw presence.

One unique aspect of this production situation was the simultaneous welding by two welders on the same assembly. We feel that, with an adequate transducer array, AE data can be adequately isolated as to its source. GARD's current monitor is not configured to provide this discrimination. Another aspect of this production situation which is not as readily soluable is the effect of one worker grinding or chipping while the other is welding. Because of the continuum of acoustic energy that would result and GARD's current signal processing approach to reduce false calls, simultaneous performance of these two production activities "blind" the Monitor in certain cases. This may not pose a serious problem since relatively short grinding intervals coupled with assumed low flaw rates results in a minimal probability of missing flaw-related acoustic activity. Also, serious flaws tend to be active on more than one pass. A more detailed study of this problem will be required if this "blinding" is considered serious.

Data analysis activity after this first trip involved a review of production NDE data and recorded AE data to optimize software and monitoring procedures. It was determined that the only software adjustments required would be an adjustment of the energy window to extremely high levels during root passes. An alternate means to accomplish this would be to reduce monitor gain equivalently during root passes. The latter approach was selected for the second trip in preference to mid-weld software adjustment.

3.2 Production Weld Monitoring

A second trip to the same facility was made to evaluate the AE Weld Monitor, using the above inputs, by correlating AE and radiographic indications on monitored welds.

Most monitoring was done with the system set near 67dB and care taken to assure equivalent response in both signal channels. When root passes of partial penetration welds were monitored, the gain was lowered to 53dB as prescribed by the results of our analysis of first trip data.

3.3 Collection of Production NDE Test Data

Production NDE test data needed to provide a means for evaluating the AE results consisted primarily of applicable radiographs, which the production contractor provided GARD. These, the contractor's radiographic interpretation forms, and photographic documentation of two dye penetrant tests, were the production NDE data used in the analysis below.

3.4 Data Analysis Approach

Radiography

The production contractor's radiographic interpretation forms provide specific sizes for rejectable flaws and general size classifications for non-rejectable flaws. No locational information is provided. To allow an x-ray/AE correlation, GARD performed its own evaluation of the production radiographs to generate flaw type/location/size information. This evaluation was done as follows:

(a) initial film reading was done by a person with 8 years experience reading radiographs;

(b) each radiograph was read carefully on a radiographic viewer;

(c) indications found were drawn, full size, on strip charts which extended the length of the weld;

(d) after initial review of all the strip charts, questionable areas were re-inspected by GARD's Level III Radiographer. His evaluation of these areas was considered final.

The following general rules were applied to flaw identification on the radiographs:

(a) Linear porosity appears on many of the radiographs - along the incomplete penetration line. Based upon the contractor's radiographic interpretation results, this type of flaw is not considered critical - unless a dense area of porosity exists. Thus, non-dense porosity indications were ignored.

(b) Flaws with planar defects provided most of the contractor determined radiographically critical flaws during this test. GARD therefore looked for such flaws in the radiographs (i.e., cracks, tailed pores, lack of fusion, etc.).

(c) Only indications which were large enough to be detectable by production-type reading were identified for the purpose of this evaluation. With magnified viewing, questionable indications can be found in many places on the radiographs, particularly, since these welds had beads on them, and they were not available to resolve whether fine indications might be surface or flaw related.

Acoustic Emission

The basis for the AE correlation with the above x-ray interpretations is the on-line flaw type/size/location information generated by the AE weld monitor. These data are taken from the project log book and the weld log sheets. Both were filled out simultaneously during the test. AE variables which had to be considered during the data analysis were the following:

(a) geometry effects - Welds which were reasonably straight, greater than 32 inches in length, and would allow transducer placement near the weld ends, use the Monitor location presentation directly. There were seven such welds. Two zig-zag welds needed locational correction. In two other cases, the AE data indicated 2 parallel welds (8 feet apart) were being monitored simultaneously. Projection of the far-away weld on the Monitor locational presentation was necessary to allow locational correlation.

(b) AE indication limits - Based upon Phase 1 laboratory work, the Weld Monitor was provided with the ability to identify, locate, and size 4 types of weld indications. A relative measure of acoustic energy released from each flaw is provided as a means of size indication with each flaw characterization.

As shown in the Appendix*, the AE size range encountered in the production data was 0 to 14. A preliminary review of this data showed a size-related AE cutoff would be required (as with radiography above) if a viable measure of correlation between AE and radiography was to be achieved. For the data analysis which follows, these energy-related sizing cutoffs were used for indication acceptance:

CRACKS (C):	2 and above
LACK OF FUSION (L):	2 and above
POROSITY (P):	3 and above
UNCLASSIFIED (U):	3 and above
INCOMPLETE PENETRATION (I):	All unacceptable

* The Appendix to this report provides, for each of the monitored welds, all the AE data plotted against areas with large numbers of x-ray indications.

The first four cutoff limits simply mean some smaller flaw size indications (0, 1, and 2) are ignored during analysis. The fifth cutoff means all incomplete penetration indications were ignored. Since all the welds monitored, but one, were designed as partial penetration welds and the radiographs can not readily quantify the amount of existing partial penetration, any analysis in this area would be fruitless.

3.5 Production Correlation

Eleven production welds were monitored. Two of the welds had dye penetrant verified flaws which were detected by acoustic emission. In Weld 28, a series of reactivating indications commenced during pass 3 and persisted thru pass 6. Nothing could be seen in this area with the un-aided eye, but when dye penetrant was applied, the flaw indication shown in Figure 15 appeared. It was repaired before radiography. In weld 32 during welding of pass 7, a crack indication occurred about 28 inches from the end of the weld, a few seconds after the welder stopped his arc and went to get a hand grinder. He had accidently allowed the weld torch gas cup to contact the weld, creating a rough surface that he intended to smooth before continuing. The mention of the AE crack indication prompted the welder to have an inspector perform a dye penetrant test after grinding. Figure 16 shows the resultant crack network. The welder continued grinding until dye penetrant inspection showed no more evidence of a crack. The welding resumed with no further acoustic indications observed.

The AE/radiography results for the individual eleven welds are presented in Figures 17 to 27. The data analysis approach described in Section 3.4 was used in plotting the indications. (The two dye penetrant indications are included in the Figures.)

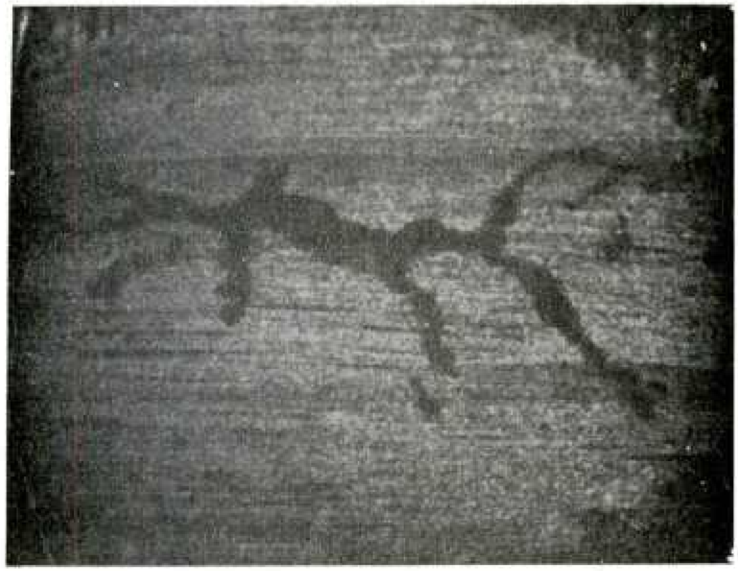


Figure 15 Crack in Weld 28

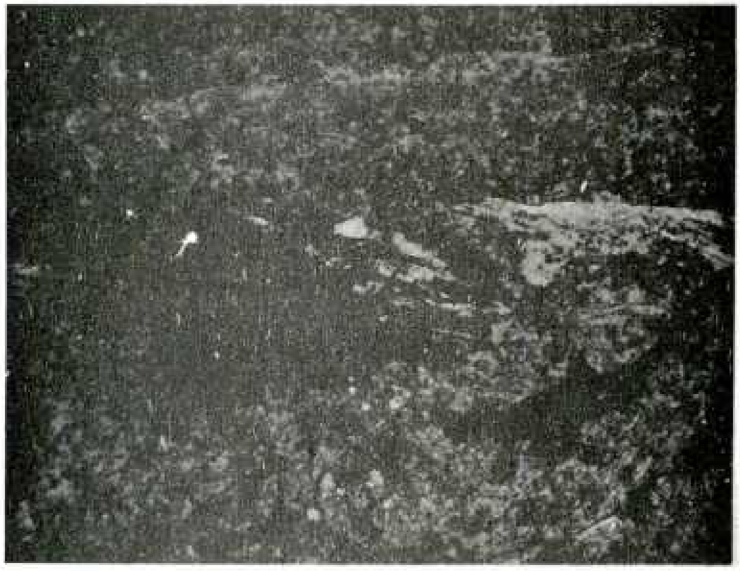


Figure 16 Crack in Weld 32

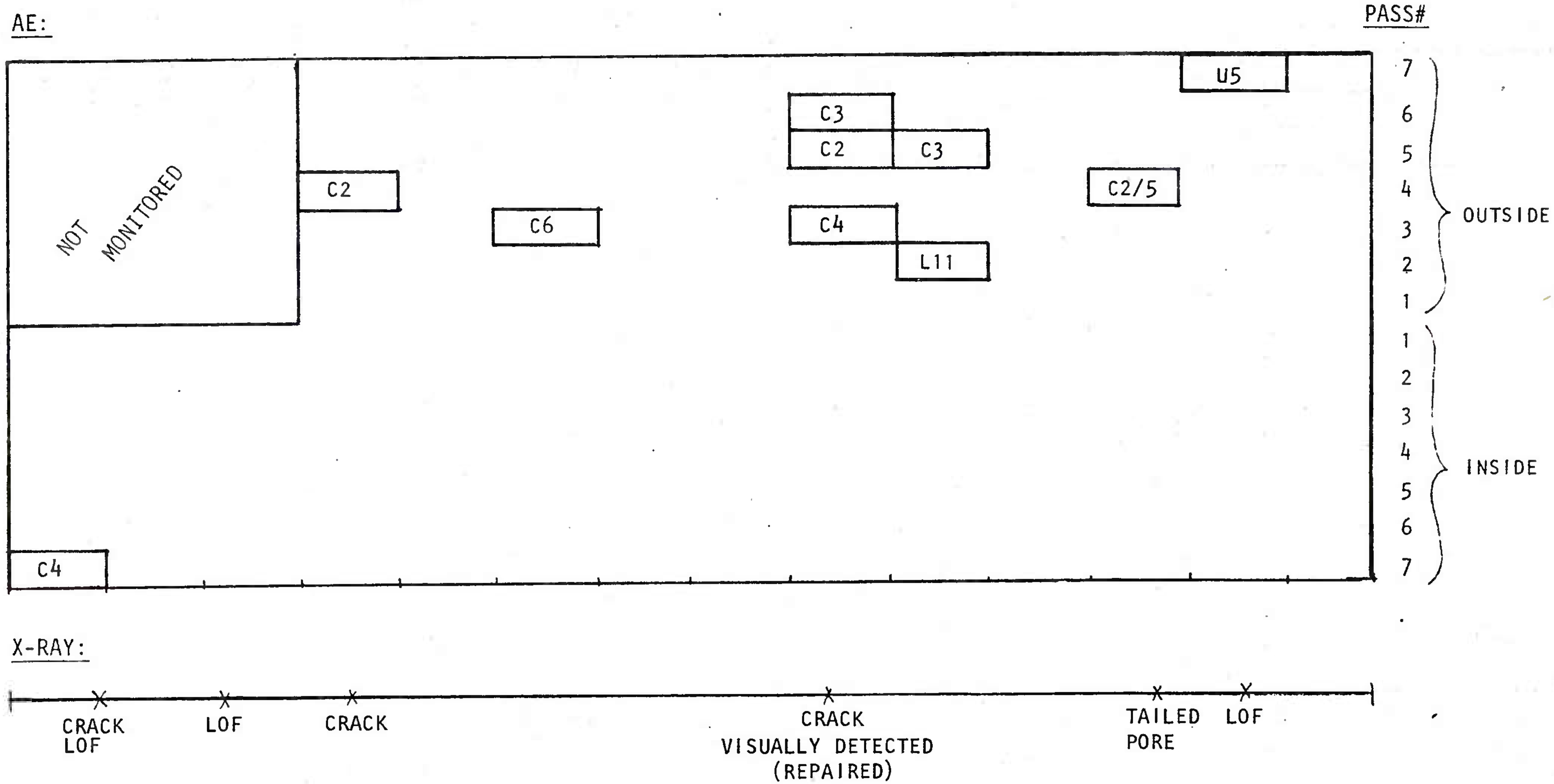


Figure 17 AE vs X-Ray Indications (Weld 28)

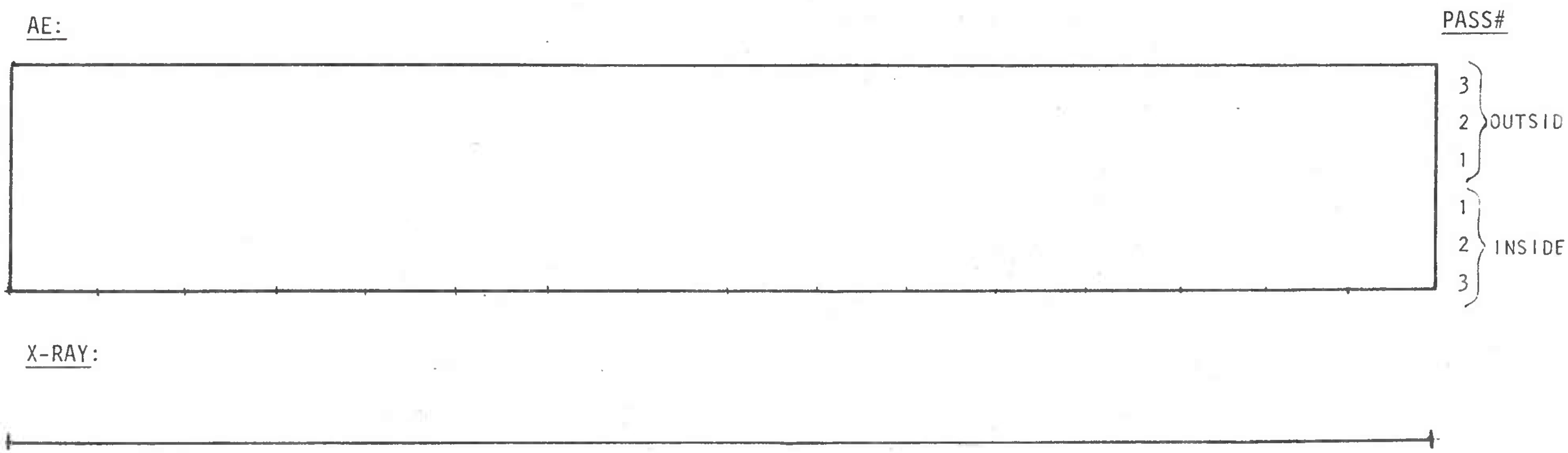


Figure 18 AE vs X-Ray Indications (Weld 30)

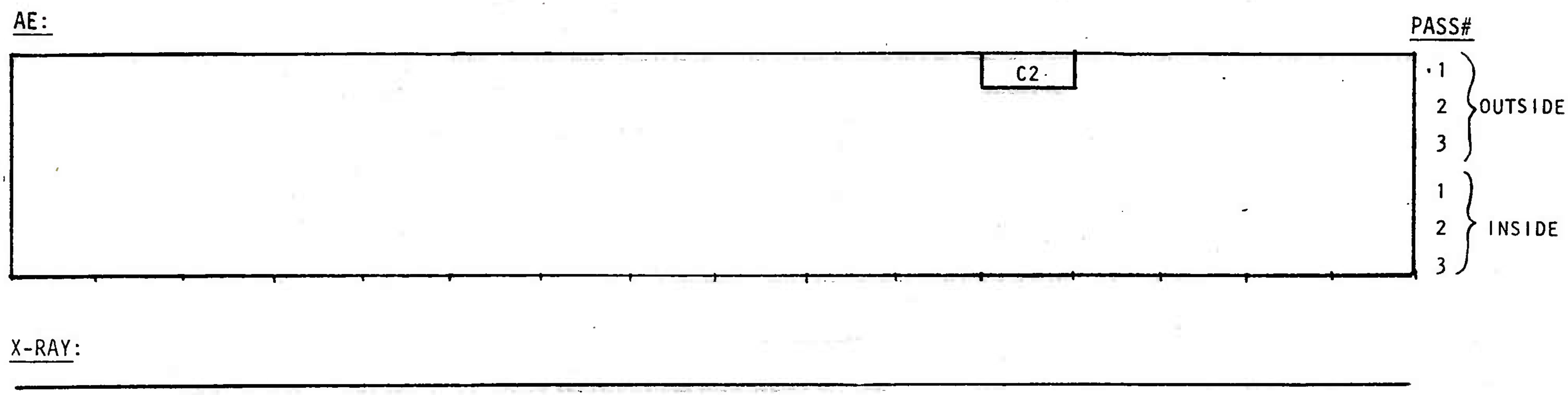


Figure 19 AE vs X-Ray Indications (Weld 31)

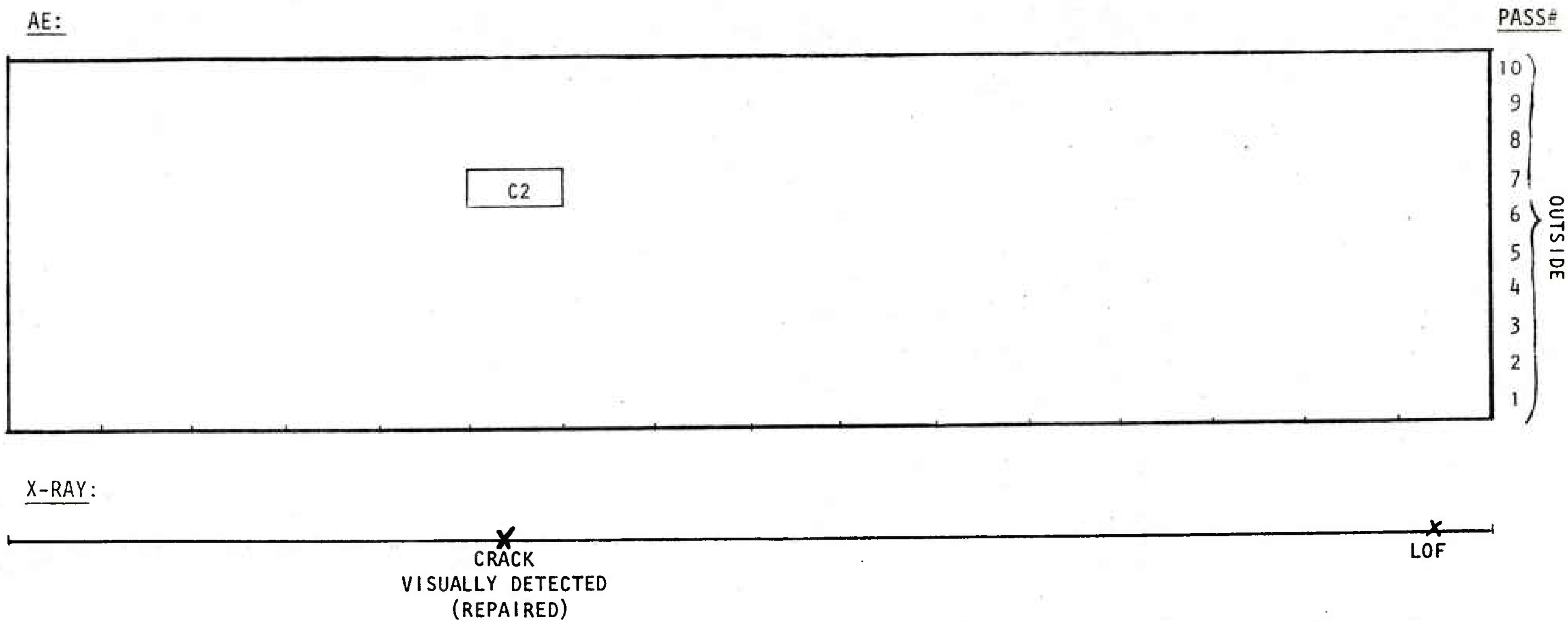


Figure 20 AE vs X-Ray Indications (Weld 32)

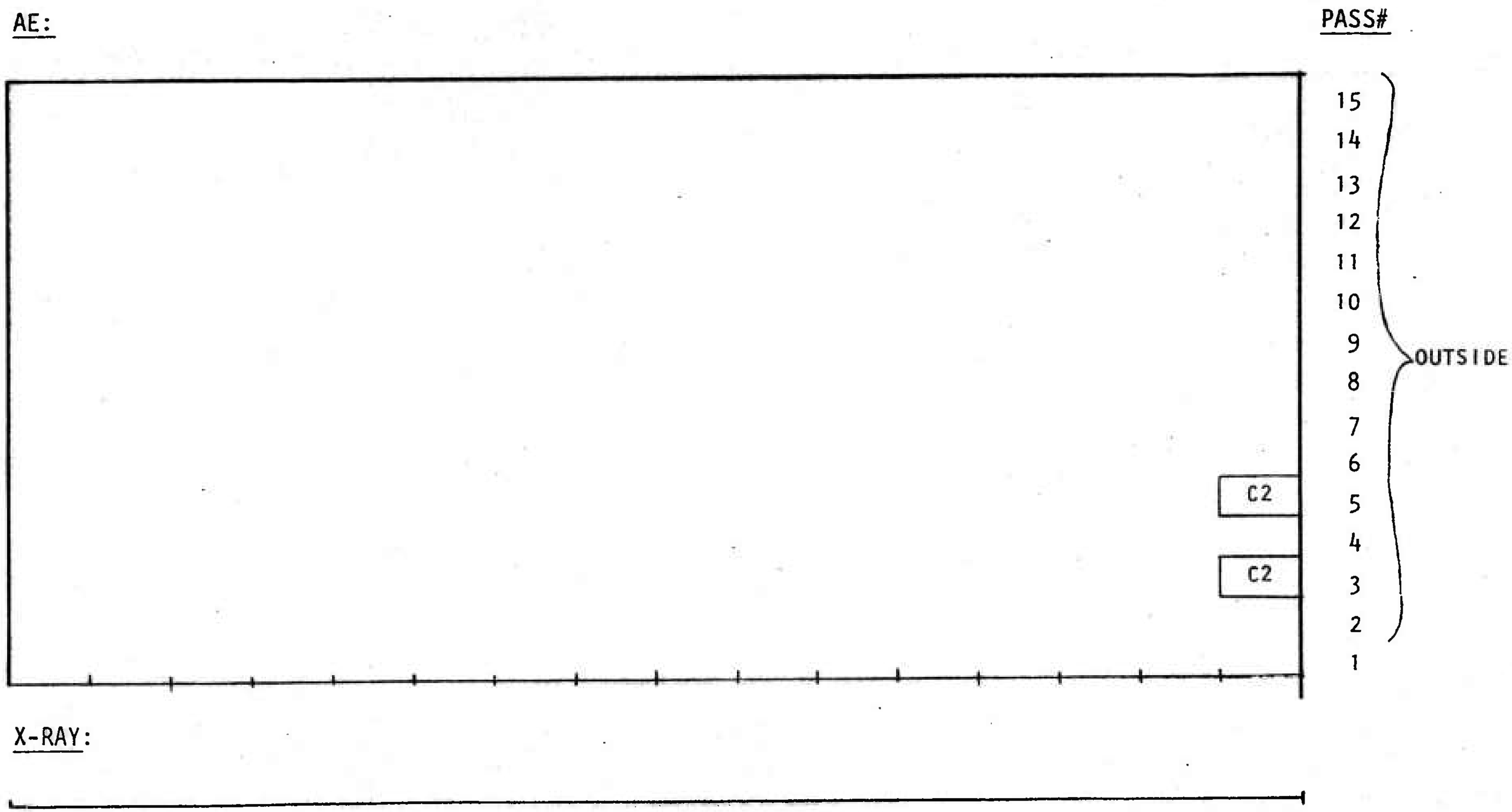


Figure 21 AE vs X-Ray Indications (Weld 33a)

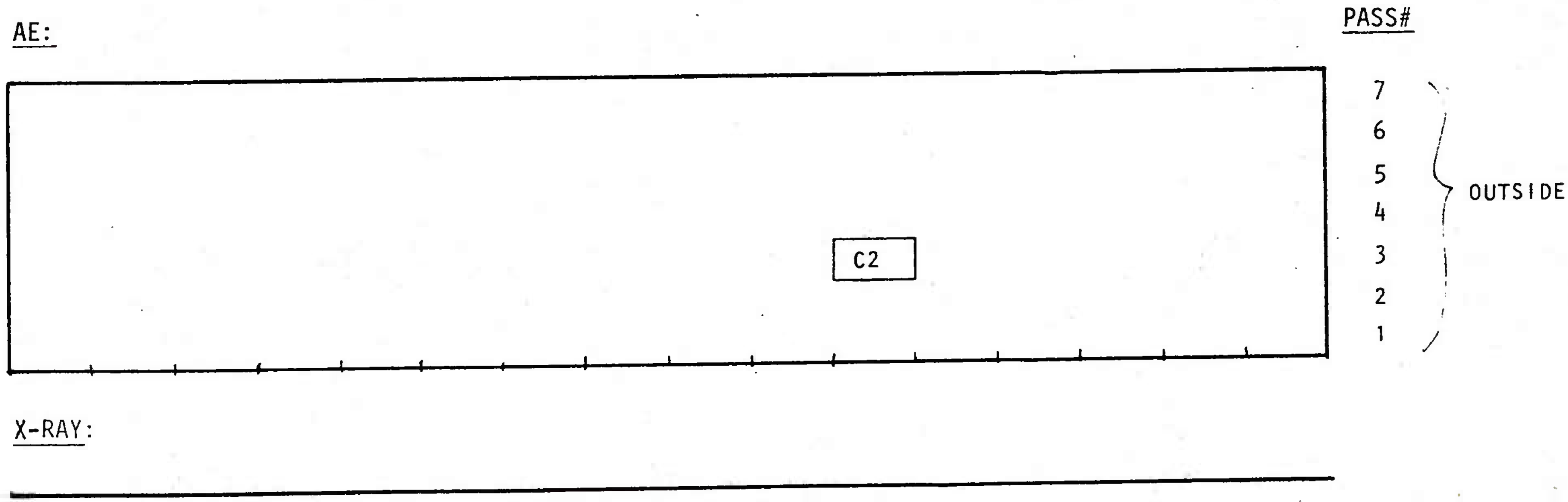


Figure 22 AE vs X-Ray Indications (Weld 33c)

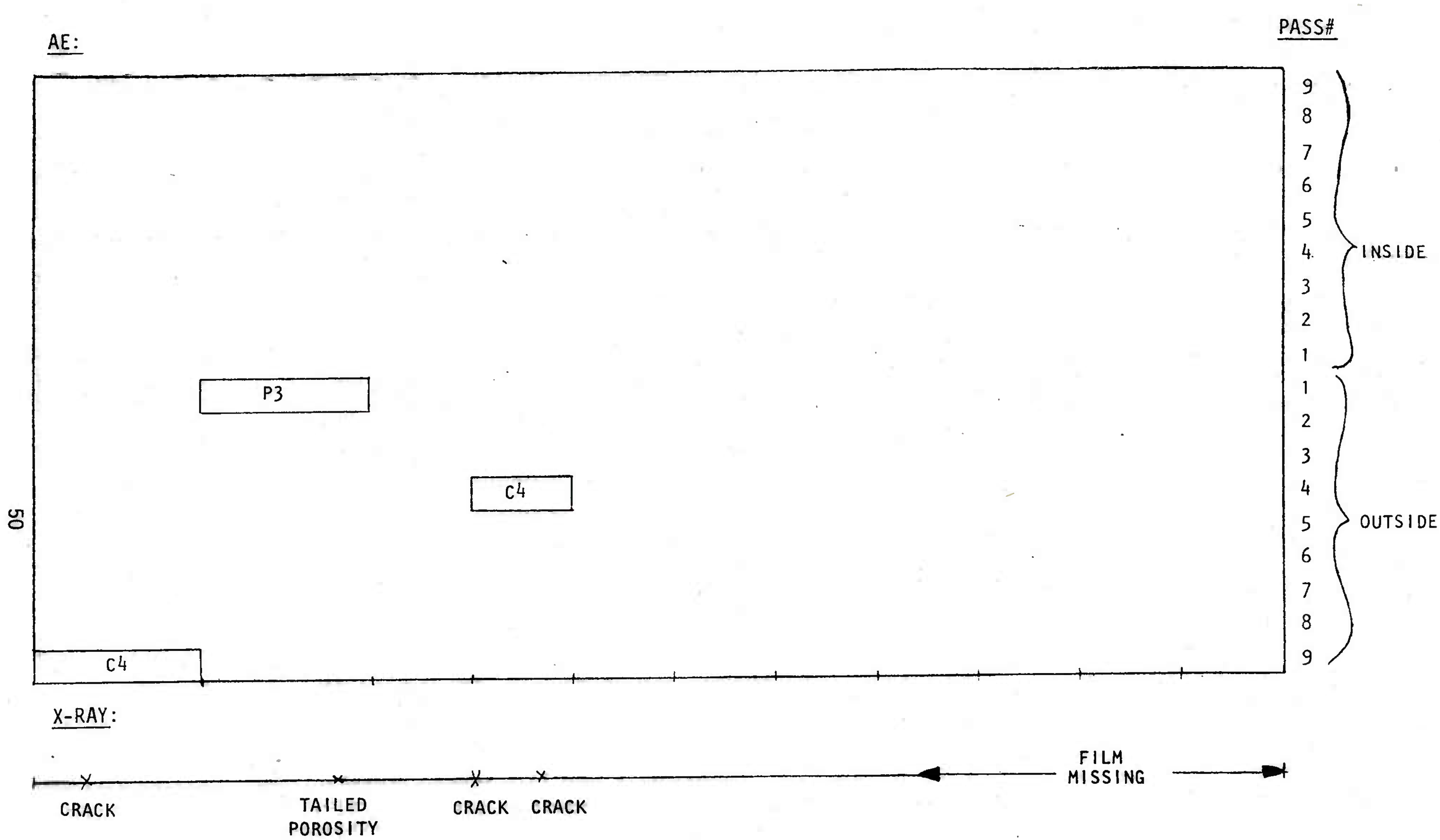


Figure 23 AE vs X-Ray Indications (Weld 34)

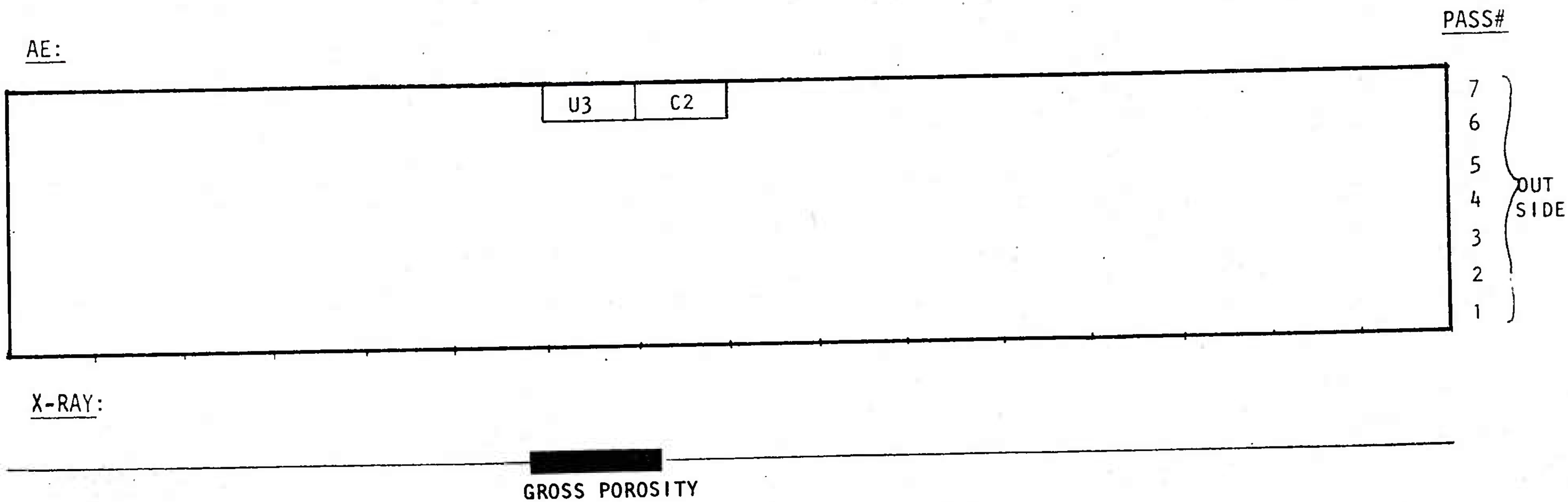


Figure 24 AE vs X-Ray Indications (Weld 41)

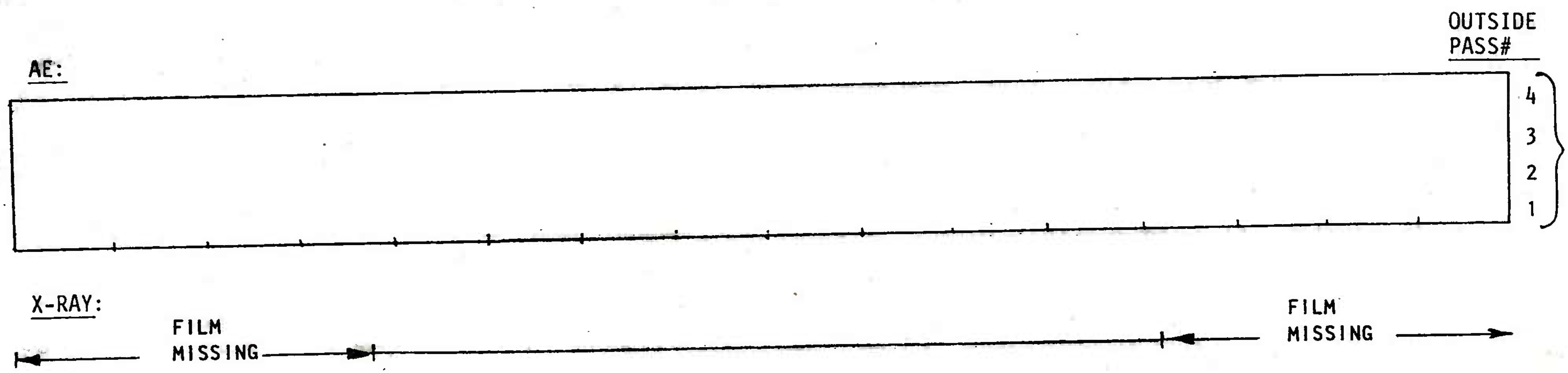


Figure 25   AE vs X-Ray Indications (Weld 42)

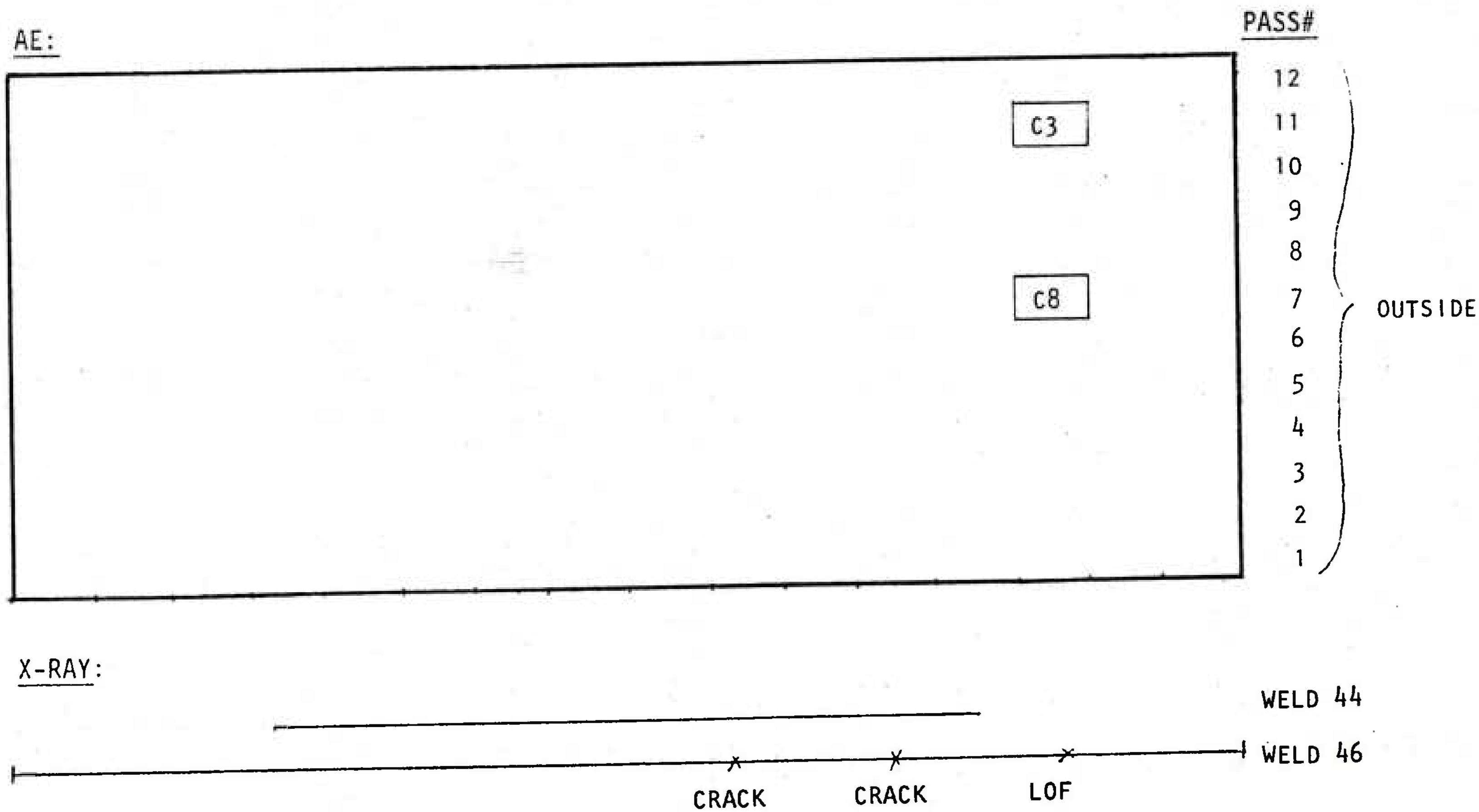


Figure 26 AE vs X-Ray Indications (Weld 46/44)

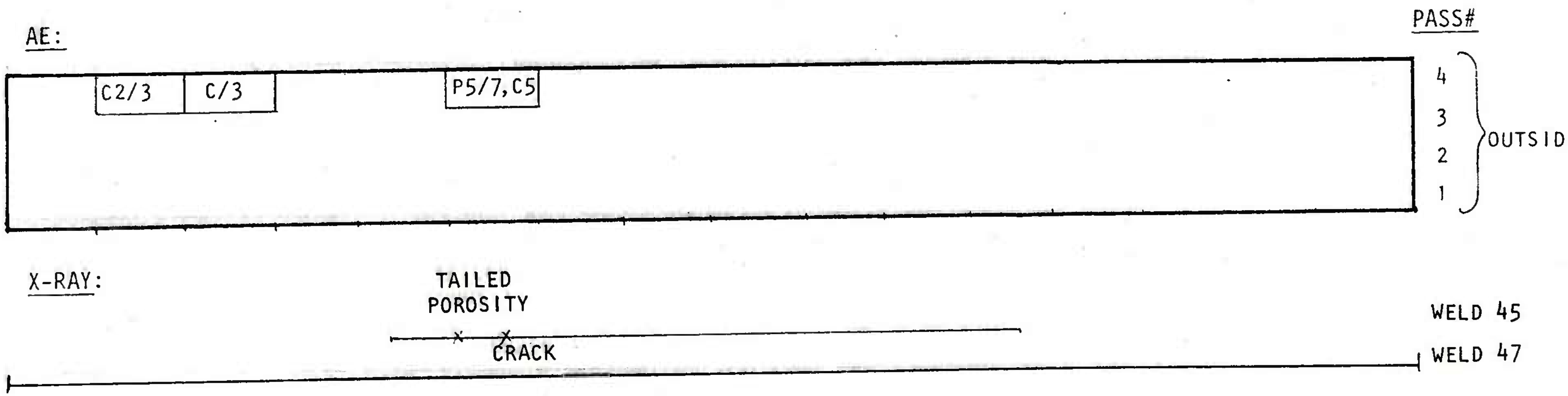


Figure 27 AE vs X-Ray Indications (Welds 47/45)

Flaw Detection

Table 3 provides a summary of Figures 17 to 28, independent of AE flaw characterization. If AE indications exist in places where film is missing, these indications are ignored. AE indications which stack upon each other are treated as reactivating indications (i.e., one flaw), since flaw depth information is not provided by radiography, and any other interpretation is difficult. From the pass numbers in the Figures, it is obvious that not all the inside and outside passes of each weld were monitored. Thus, the percentage of each weld actually monitored is summarized in the table.

The summary shows that 79% of the radiographic indications were detected and located by acoustic emission. This accuracy must be considered from two points of view, (a) missed weld monitoring and (b) data blinding.

Only 67% of the welding was actually monitored. Interestingly enough, the double weld monitoring which occurred on Welds 46/44 contributed 50% of the missed welding, due to their length and number of passes. They also contributed 3 of the 4 missed indications.

It was estimated by GARD personnel that simultaneous grinding on the hull, which caused Monitor blinding during weld monitoring, occurred about 10% of the time. This grinding automatically shuts down the Weld Monitor to avoid the occurrence of false flaw indications. Thus, it can be expected that some AE indications might be lost during the grinding.

If a large enough weld monitoring database was acquired under the above experimental conditions, and flaw occurrance was truly random, a flaw detection accuracy of 50% could be expected from this experiment (assuming Phase 1 detection accuracy of 0.8 for 100% weld monitoring, monitoring 0.7 of the actual

TABLE 3 - FLAW DETECTION DATA

WELD #	AE VS. X-RAY INDICATIONS		POTENTIAL AE OVERCALLS	ESTIMATED % OF WELD MONITORED
28*	5	6	2	90
30	0	0	0	100
31	0	0	1	100
32*	1	2	0	60
33a	0	0	1	50
33c	0	0	1	50
34	4	4	0	100
41	2	2	0	70
42	0	0	0	50
46/44	1	3	0	60
47/45	2	2	2	80
TOTAL	15	19	7	67

* Includes 1 AE indication verified by dye penetrant, repaired and not on radiograph.

welding, and non-blind monitoring time of 0.9: 100x0.8x0.7x0.9). The 79% result is better than this number and probably indicates that flaw occurance is not truly random (i.e., that we monitored the worst parts of the welds).

The data shows an overcall of seven AE indications. This is a 32% rate (100x7/(15+7)). However, only two indications were isolated "low level" events (C2s). One was an isolated high level event (C6). Two had stacked indications (C3/L11 and C2/C2). One had adjacent location cell events (C2/C3 and C3). Based upon the use of radiography as "truth" for this study, and the fact that AE does find flaws undetected by x-ray as established metallographically earlier in this report, some overcall is to be expected. Experience has shown that stacked cell, adjacent cell, and isolated high level events are usually good indicators that a flaw source is present.

Flaw Characterization

The ability of the Weld Monitor to characterize flaws can be analyzed by comparing the confirmed AE indications with their radiographic or visual classifications. Table 3 shows that there were 15 such cases. Table 4 shows the classification comparison.

The table shows that when AE classified a flaw, it was 85% accurate in doing so (11/13). It shows AE was 100% accurate in classifying cracks as cracks. The two mis-classifications were in agreement with our feelings that AE detects flaws when cracks are related to them. It would thus tend to primarily mis-classify flaws as cracks.

Flaw Sizing

AE flaw sizing was evaluated during the Phase 1 effort on this program. An ordering relation between processed energy number and radiographic flaw

TABLE 4 - AE CLASSIFICATION DATA

TOTAL # INDICATIONS	VISUAL AND X-RAY INTERPRETATION	AE CLASSIFICATION		
		CRACK	POROSITY	UNCLASSIFIED
9	CRACK	9	0	0
4	POROSITY	1	2	1
2	LACK OF FUSION	1	0	1

projection can be found, but with much scatter. With the problems of radiographic sizing of flaws an extended evaluation program will be required to fully correlate results for this application. This is beyond the scope of the present planned effort.

The need for an AE Weld Monitor to size flaws is shown by the use of the Monitor's AE sizing limits in the data analysis. The use of these limits enabled a reduction of AE indication of suspect areas from 52 to 15, as can be seen by comparing the AE results in the Appendix with those in the body of the report. This allowed a very respectable AE correlation with radiographic indications. The resultant correlation is thus an indirect measure of the accuracy of the Monitor's approach to sizing.

Section 4

CONCLUSIONS

This program established the applicability of acoustic emission NDE methods to production welding of armor. This applicability was demonstrated by the evaluation of a hardened AE breadboard in monitoring the welding performed in the fabrication of heavy armored vehicles.

In preparation for the production monitoring, a set of flaw models were generated in software using the database generated during the previous program phase. Metallographic analysis of some of these welds was performed under this program to gain further insight into the natural flaw population. This metallography was revealing in that it showed that AE indications in radiographically clean welds were actually caused by weld flaws missed by radiography. A typical flaw missed radiographically was a lack of fusion which substantiates a benefit AE can provide: namely flaw detection independent of flaw orientation.

The production monitoring task was divided into two monitoring periods. The first, a trial production test, established monitor settings and provided a period of time for software/hardware refinements prior to the actual production monitoring task where data collection was to be performed.

Eleven welds were monitored during the production monitoring task. Fifteen out of 19 radiographic/visual flaw indications were detected by acoustic emission using appropriate flaw size data cutoffs. Seven acoustic emission overcalls were generated. An analysis of the amount of welding monitored, blinding time, and flaw detection prediction accuracies from Phase 1, shows that with our small data sample the results are better than expected.

Flaw classification analysis shows AE correctly classified 85% of the correlated AE - radiographic indications. It classified cracks with 100% accuracy. Flaw sizing ability was shown to be invaluable as a sifting mechanism in matching the radiographic indications.

Certain needed hardware/software improvements in GARD's Weld Monitor have become obvious if a production weld monitor is to be developed for this application. They include:

(a) locational accuracy. On the longest welds the current Weld Monitor can only isolate flaws to within a nine inch cell length. A hardware arithmetic board along with appropriate software changes can theoretically reduce this inaccuracy to about half an inch.

(b) hard copy printout. A new data recording scheme is required to provide a permanent production floor copy of the AE data, and locational indication capability compatible with the above improved locational accuracy.

(c) geometry correction. Software location correction is required for some of the weld geometries which need to be monitored. Manual correction estimates as performed in this study are not practical for production.

(d) gain setting. Software gain adjustment for root pass monitoring should be performed to ease the burden on an operator.

(e) double weld monitoring. A guard transducer arrangement must be implemented on the welds which require it (i.e., those which are welded in parallel and could give redundant flaw indications). Whether this could be configured with one pair of transducers on each weld, or with only one set on one weld, needs to be studied.

(f) blinding. Whether this is a serious problem, and whether it can be eliminated by pattern recognition, needs to be addressed.

(g) hardened cabinet. A Weld Monitor for extended production use needs to be configured in a dustproof housing to prevent the shop floor environment from damaging the system.

Section 5

RECOMMENDATIONS

The results of this program demonstrate the potential applicability of AE to armor plate weld monitoring. It is recommended that a Phase 3 effort be initiated, including a 6-month monitoring test, to increase the database, thereby providing greater confidence in the results achieved. The data taking phase of this new effort should be carefully structured so as to address the problems uncovered in the Phase 2 work to insure better correlation potential.

The recommended effort should involve several areas:

(a) fabrication of a minimal Weld Monitor for this application. This entails a 2-channel system in a hardened cabinet with a hard copy data printout. Locational accuracy could remain the same as with the current system. Geometry correction should remain manual. However, pulser excitation along each weld length would be used once (on each weld type) to provide an experimentally-based locational calibration. Double weld monitoring would be verified experimentally by the same pulser; data analysis would recognize any resultant redundancy.

(b) six month field test. This effort involves monitoring production welds for an extended period of time. Any weld monitored must be 100% monitored. Blinding effects must be recorded. Criteria for significant radiographic indication presence must be established with great care, jointly by TACOM, the production contractor, and GARD.

(c) data analysis. The results of the field test monitoring must be accumulated in a meaningful tabular form to indicate the accuracy of the AE monitoring results.

(d) grinding lab test. A short laboratory evaluation of grinding noise signatures should be performed to determine the feasibility of reducing this blinding effect on AE monitoring.

(e) report. The above efforts should be documented along with, if appropriate, design recommendations for an AE Weld Monitoring System which could be used for full-time production-line monitoring in this application.

APPENDIX

DETAILED
AE vs X-RAY INDICATIONS
FOR MONITORED WELDS

Figures show all AE indications generated by the Weld Monitor plotted against weld areas with large numbers of radiographic indications.

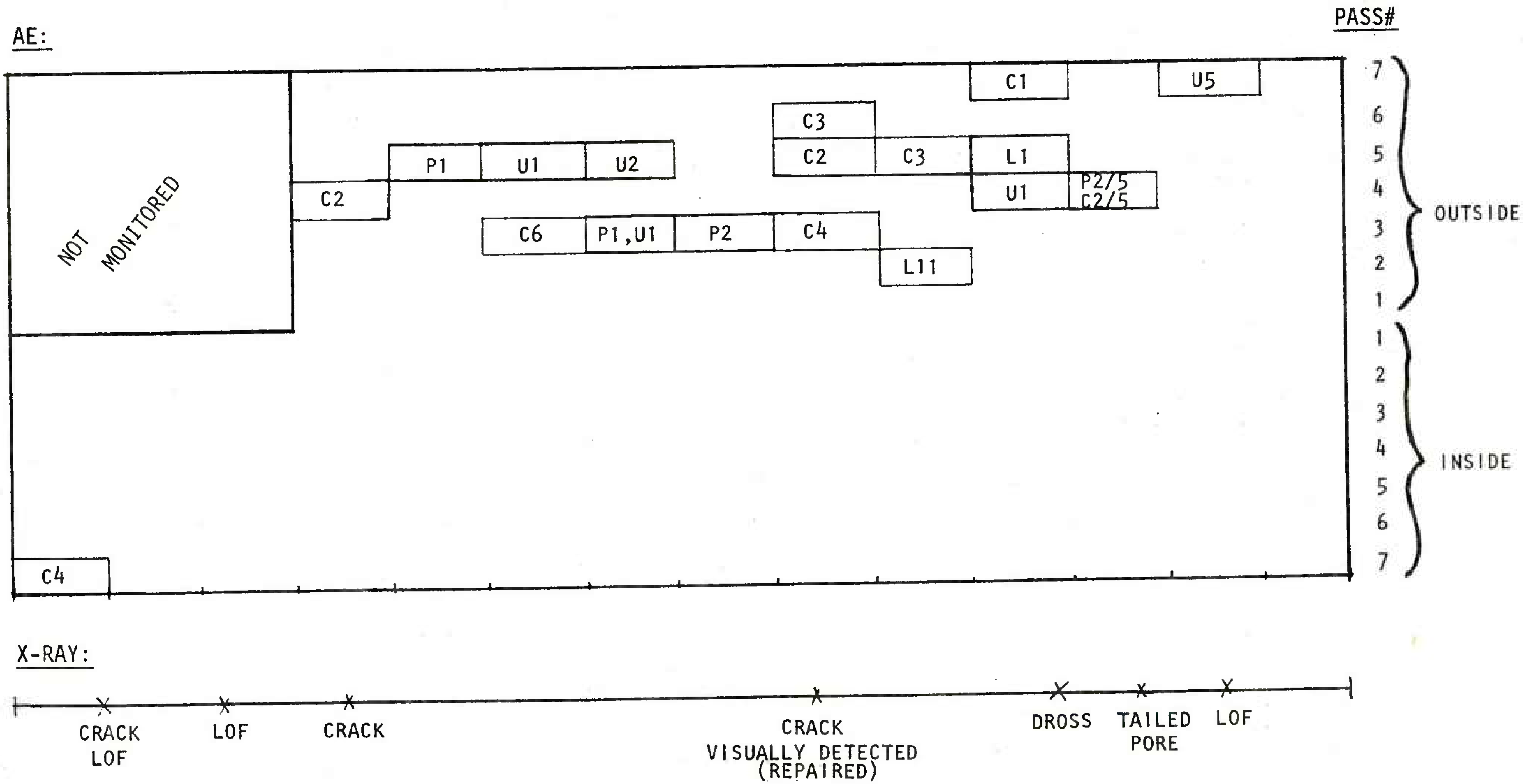


Figure A-1 AE vs X-Ray Indications (Weld 28)

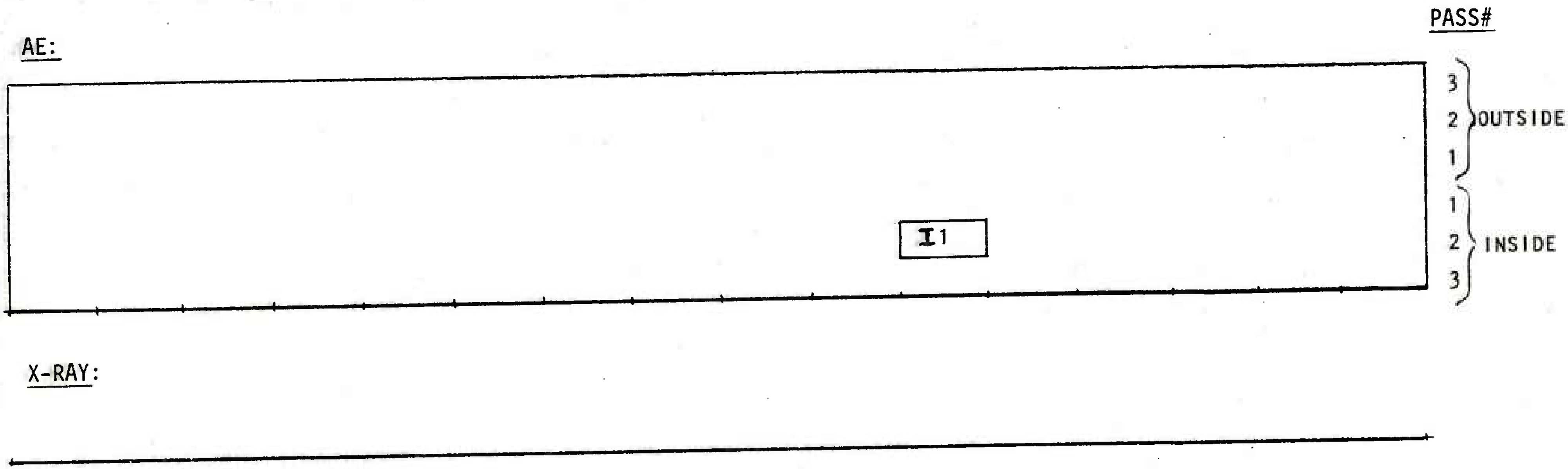


Figure A-2 AE vs X-Ray Indications (Weld 30)

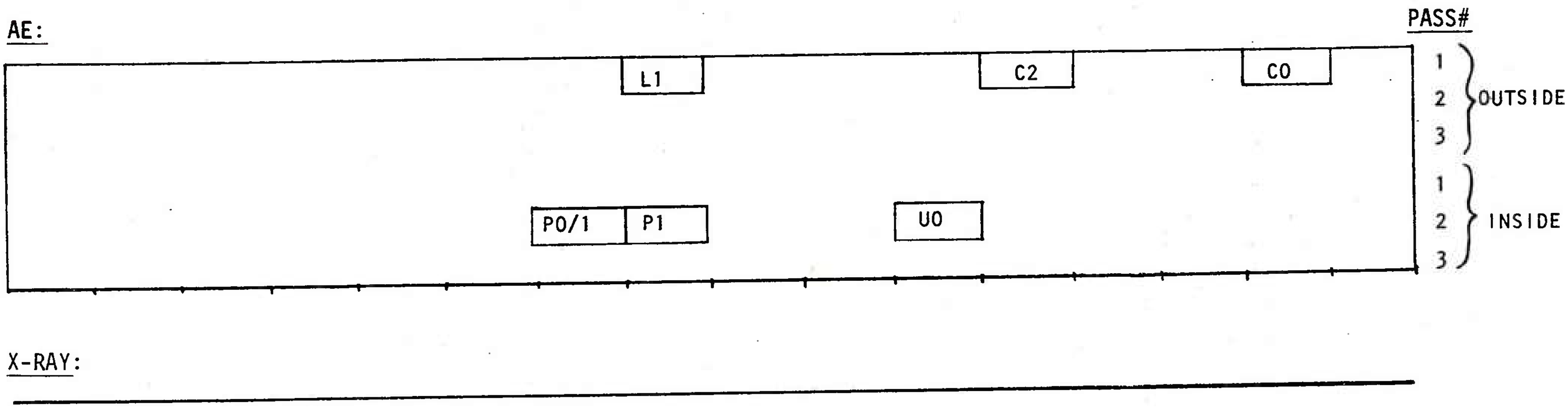


Figure A-3 AE vs X-Ray Indications (Weld 31)

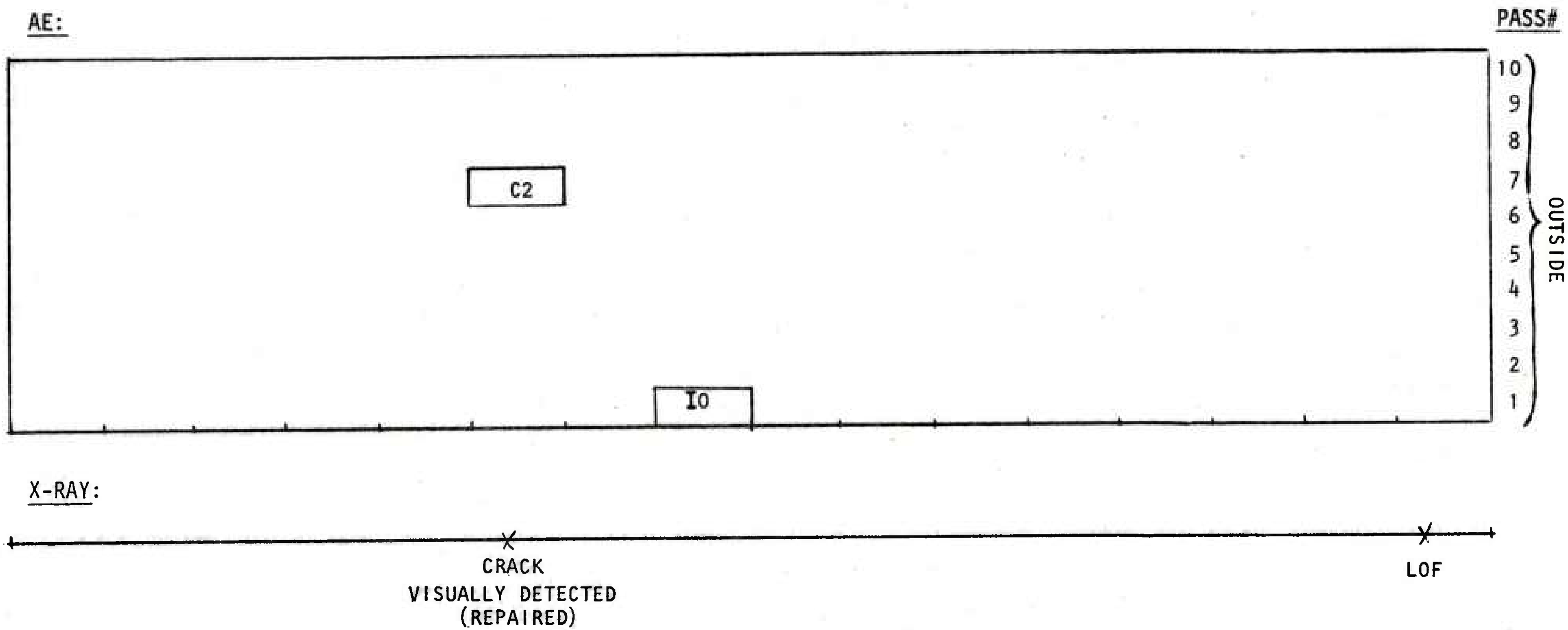


Figure A-4 AE vs X-Ray Indications (Weld 32)

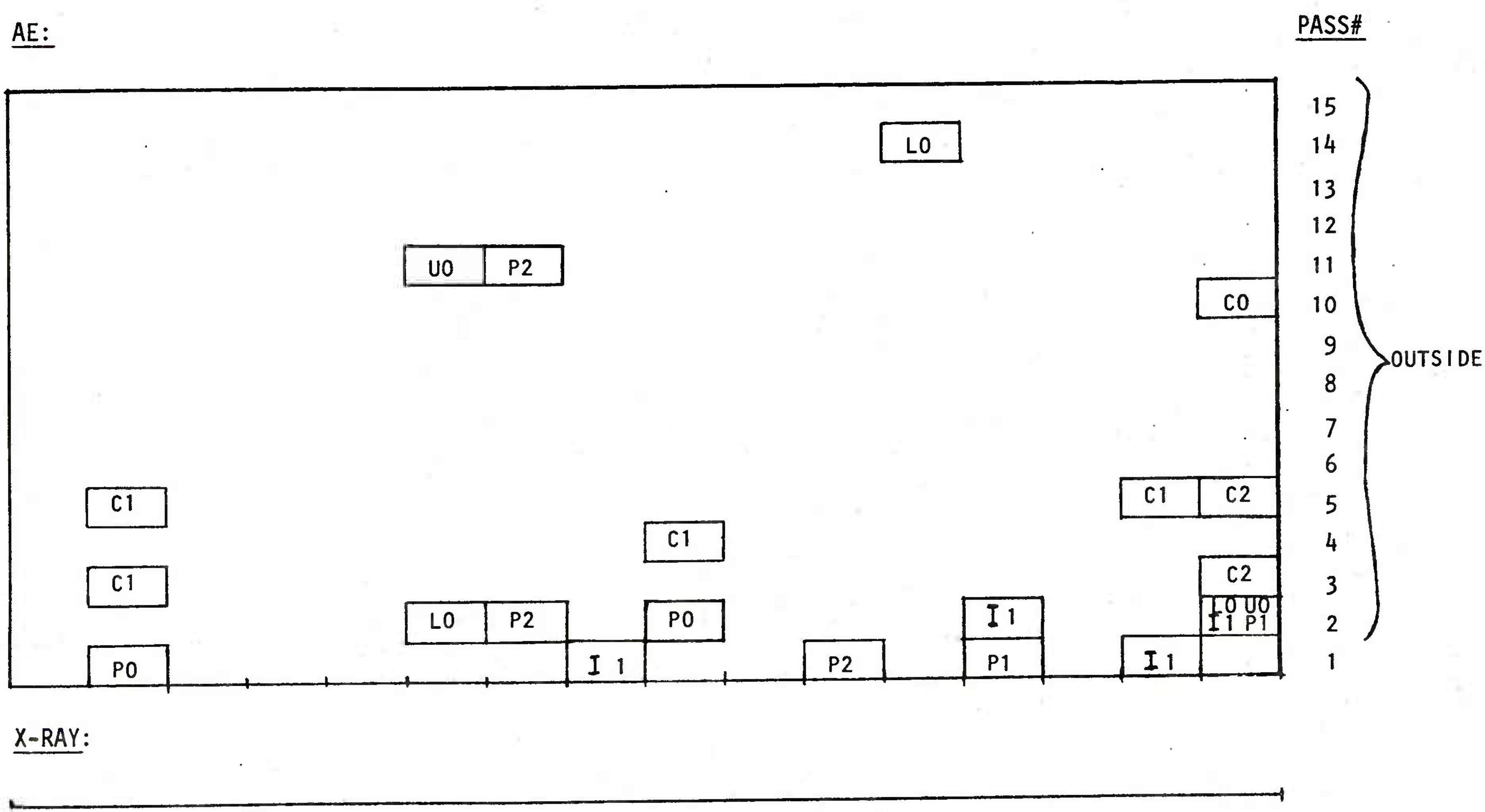


Figure A-5 AE vs X-Ray Indications (Weld 33a)

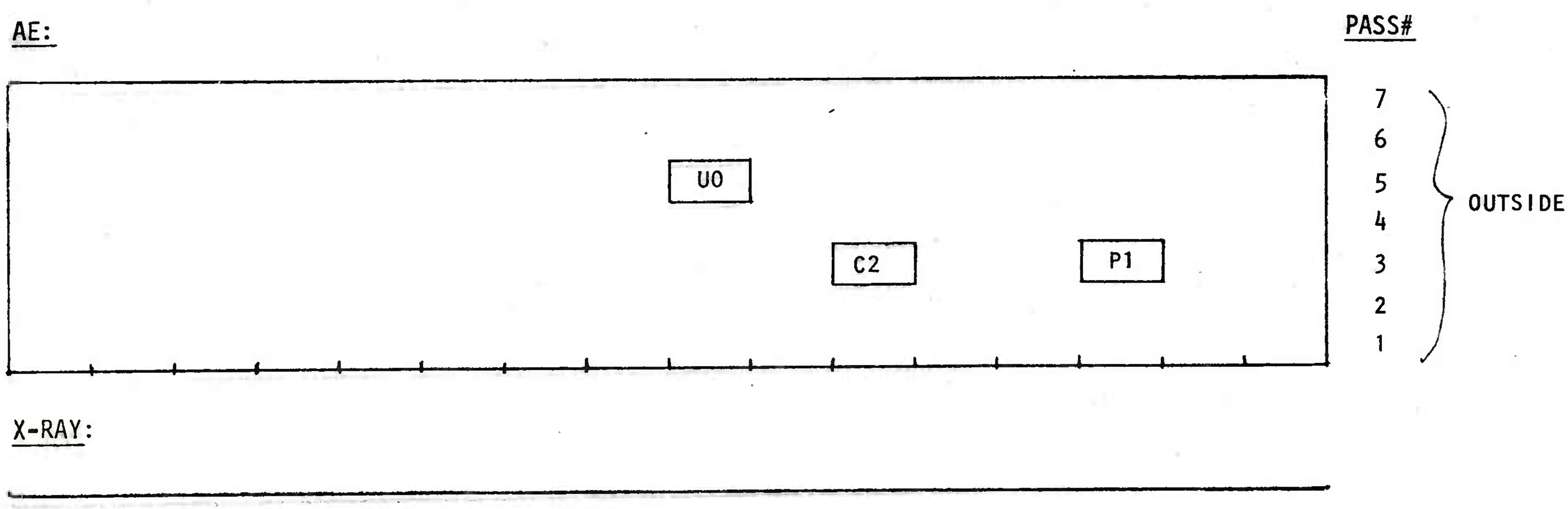


Figure A-6 AE vs X-Ray Indications (Weld 33c)

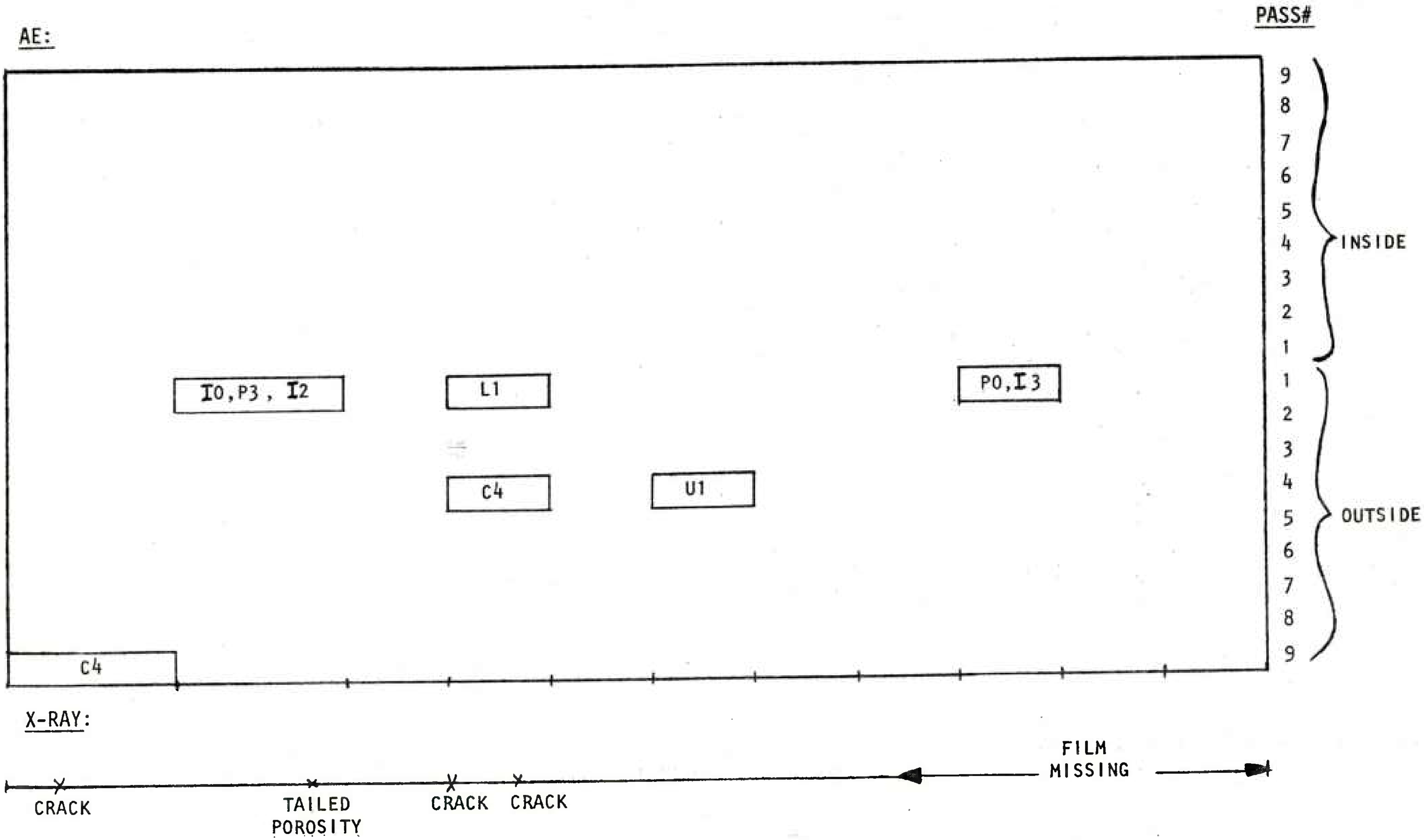


Figure A-7 AE vs X-Ray Indications (Weld 34)

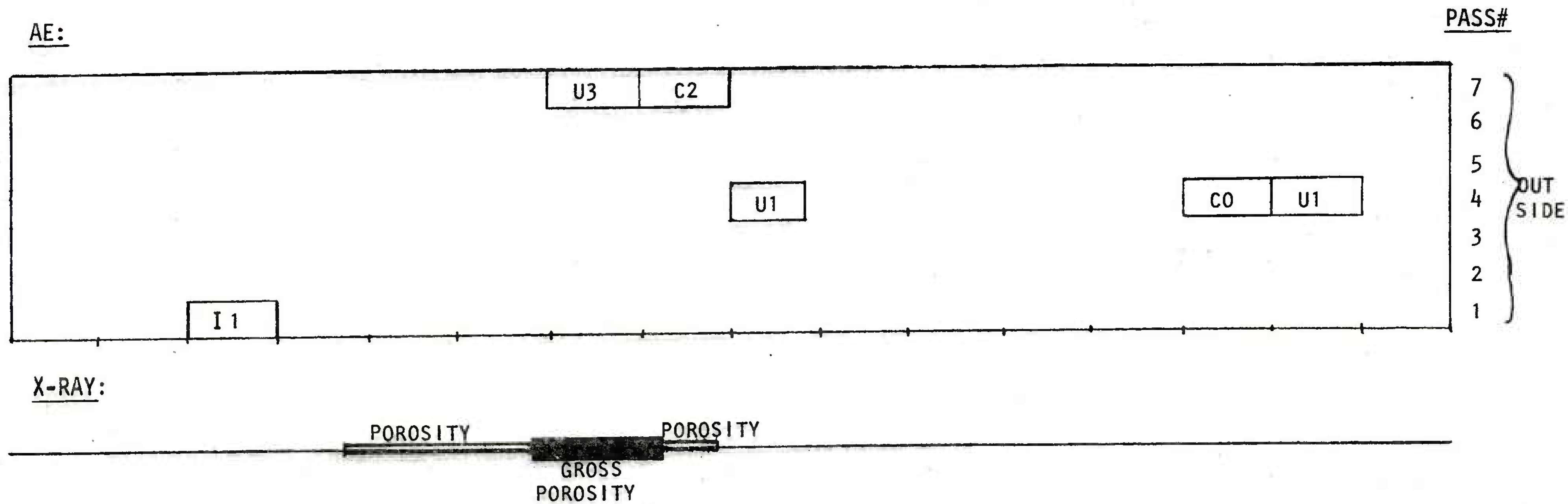


Figure A-8 AE vs X-Ray Indications (Weld 41)

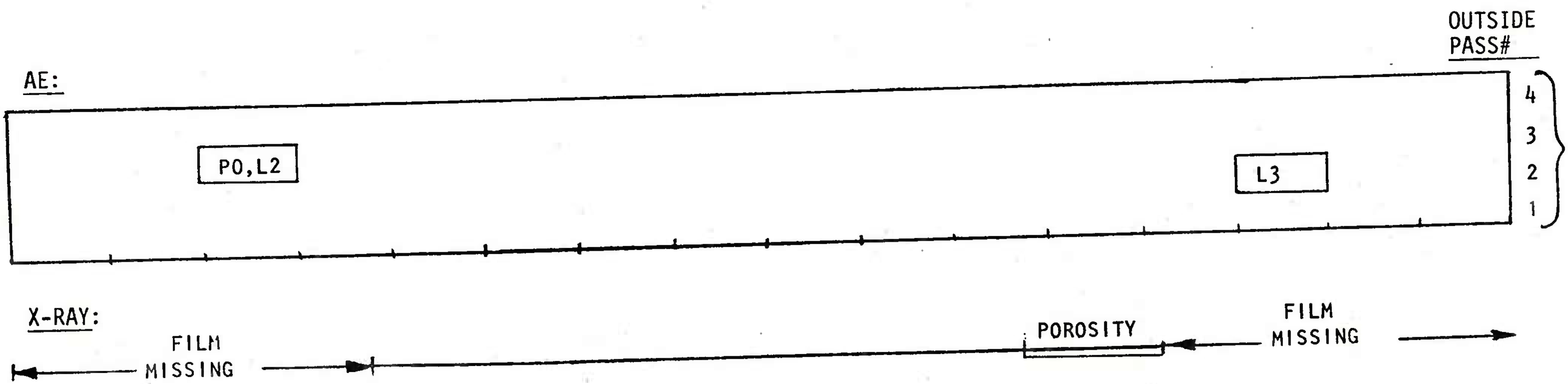


Figure A-9 AE vs X-Ray Indications (Weld 42)

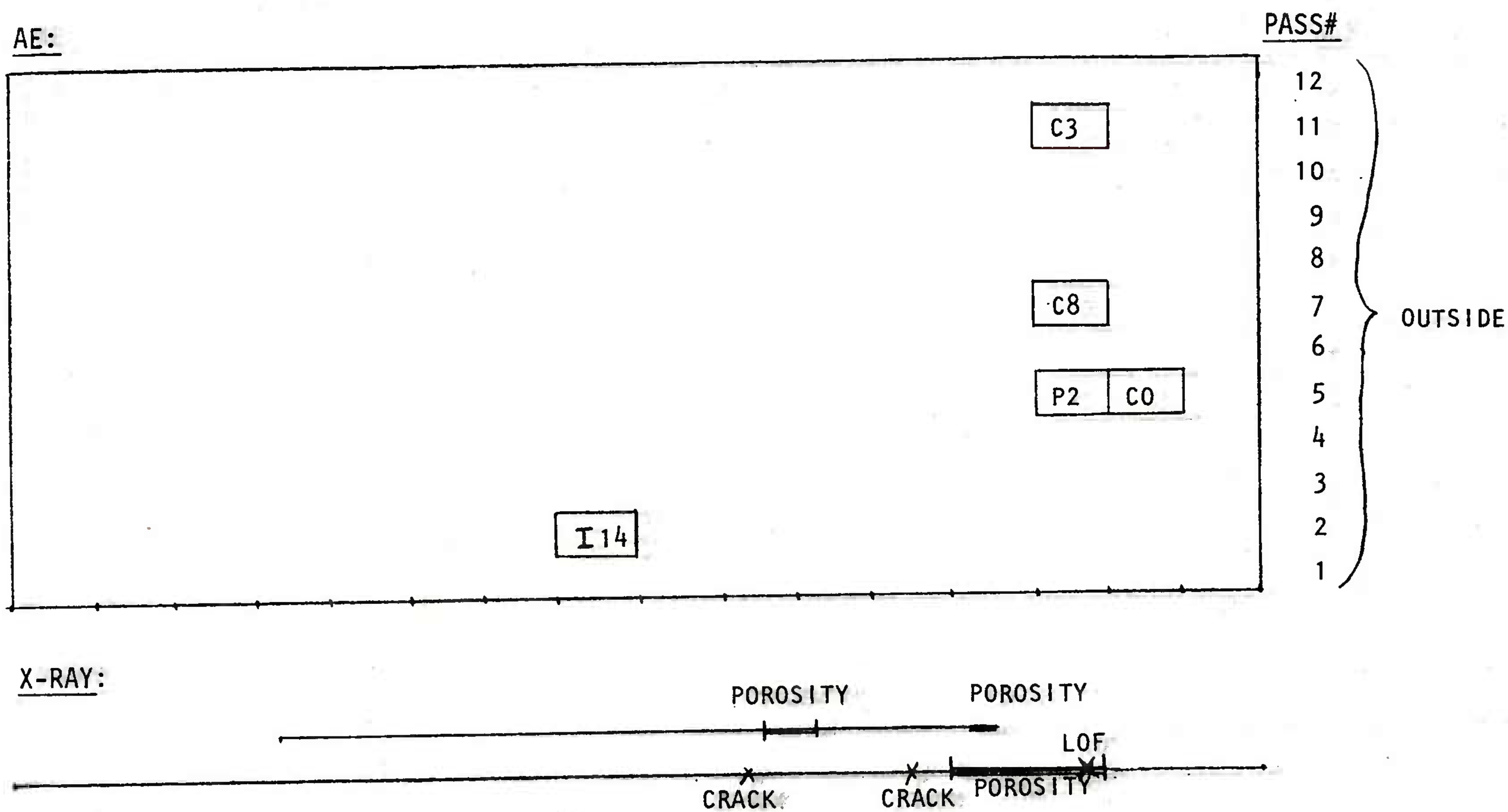


Figure A-10 AE vs X-Ray Indications (Weld 46/44)

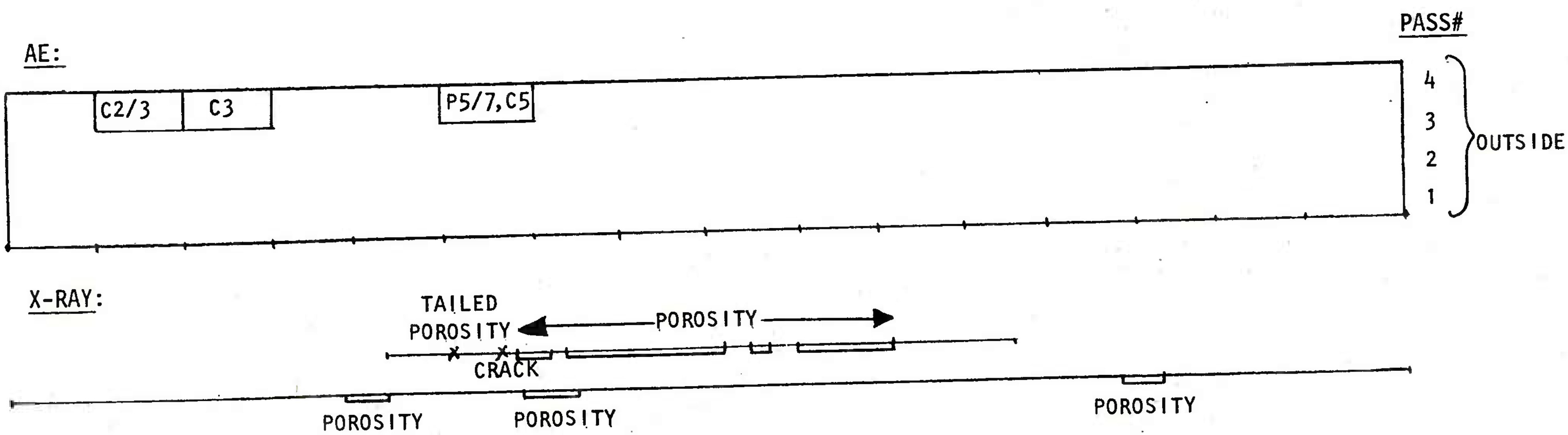


Figure A-11 AE vs X-Ray Indications (Welds 47/45)

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