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Acoustic Emission Weld Monitor System

U.S. ARMY TARADCOM

Data Acquisition and Investigation

Final Report

CONTRACT NO. DAAK 30–78–C–0123

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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.

FOREWORD

The work herein was performed by GARD, INC., a subsidiary of the GATX Corporation, 7449 N. Natchez Avenue, Niles, Illinois 60648 for the U.S. Army Tank-Automotive Research and Development Command under Contract No. DAAK30-78-C-0123. The work was administered under the direction of Army Project Engineer Chester T. Kedzior of TARADCOM Warren, Michigan.

The work covered in this report was performed at GARD in the contractor's NDT Systems group, W. Lichodziejewski, Manager, by R. A. Groenwald, Project Engineer with assistance of D. W. Prine and I. R. Kraska, Senior Engineers and T. A. Mathieson, Research Engineer. The authors gratefully acknowledge the technical assistance provided by the Army Project Engineer and the technical data provided by Messrs Bill Stone, Walt Wulf and Lee Sherman.

This report covers work conducted during the period of October 1978 to September 1979. It was submitted by the authors in October 1979.

ABSTRACT

The standard weld inspection techniques of radiography and ultrasonics have intrinsic disadvantages. The new technology of acoustic emission (AE) has shown an applicability to weld inspection which could overcome such disadvantages. This program is directed at utilizing acoustic emission as a weld monitoring technique on a specific Army welding application.

The reported work is phase 1 of an Army program to develop a microprocessor-based Acoustic Emission Weld Monitor (AEWM) for the purpose of in-process monitoring of armor plate welding. The intended use of this AEWM is to monitor the production welding performed in the fabrication of heavy armored vehicles.

The objectives of this phase are to:

a) perform laboratory MIG welding of armor plate with controlled induction of critical flaws,

b) collect acoustic emission data generated during the welding

c) perform a data analysis to correlate the recorded AE data with flaw presence, and

d) predict the accuracy with which AE is able to detect and locate the weld flaws as well as discriminate between flaw types.

This final report presents (a) the welding procedures used to generate the necessary welds (including flaw induction techniques) and data collection methods and instrumentation used, and (b) the results of the data analysis, correlation, and accuracy predictions of AEWM as it applies to armor plate welding.

In summary, we show that AE is a viable NDE tool for in-process monitoring of armor plate welding. The ability to detect, locate and characterize weld flaws based on AE data is demonstrated.

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Section 1

OBJECTIVE AND SCOPE

The overall objective of this program is to develop improved NDE for heavy armored vehicles through development of an acoustic emission system which can detect, locate and characterize (by size and type) flaws in armor plate welds while the welds are being made.

To accomplish this objective, the following specific tasks were performed as the first phase of a projected three phase program:

a) laboratory MIG welding of armor plate with controlled induction of critical flaws,

b) collection of acoustic emission data generated during the welding,

c) data analysis using GARD's laboratory AE weld monitoring system to correlate the recorded AE data with actual flaw presence, and

d) prediction of the accuracy with which AE is able to detect and locate the weld flaws as well as discriminate between flaw types.

The remaining two phases of the program will be devoted to:

a) the development of acoustic emission flaw software to allow flaw detection and characterization during in-process monitoring of armor plate welding using the MIG process, and

b) the development and fabrication of an in-process AE Weld Monitor using the flaw models generated. This unit is to be delivered to TARADCOM subsequent to heavy armored vehicle production testing.

This report concerns work under phase I of the program.

Section 2

SUMMARY AND CONCLUSIONS

2.1 Summary

Nearly 900 feet of weld passes were generated yielding a total of 32 confirmed flaws as a data base for the subsequent investigation. AE detected 78% of the flaw base with zero overcall and 100% locatability. Variations in AE signals as a function of flaw type were observed during data collection for the flaw types of interest: cracks, porosity, lack of fusion and lack of penetration. An unexpectedly high number of AE signals, as compared with previous experience monitoring submerged arc welding of mild carbon steels, was correlated with a large number of confirmed natural flaws.

2.1.1 AE Weld Monitor Data Collection

During this effort, the armor plate made available by TARADCOM was prepared for welding. This included cutting, grinding and bevel machining to obtain predetermined weld geometries. A total of thirteen multipass welds were fabricated totalling nearly 40 linear feet of weld, which includes nearly 900 feet of weld passes. Controlled flaws were induced at specific locations in 12 of these welds: the 40 flaw induction attempts are distributed according to flaw type as shown in Table 1. The flaw confirmation, accomplished primarily using radiography, showed the existence of the 30, or 75%, of the attempted flaws. Since only one lack of fusion (LOF) was successfully induced, two of the natural LOFs that were locationally isolatable from other flaws were used to broaden the LOF data base.

2.1.2 AE Weld Monitor System Investigation

The work performed during this phase was directed toward the analysis

TABLE 1

FLAW INDUCTION/DETECTION SUMMARY

FLAW TYPE	FLAW ATTEMPTS	FLAWS CONFIRMED	AE DETECTED *		OF FLAWS DETECTED	
			QUANTITY	%	% LOCATED	% DISCRIMINATION
Cracks	19	17	14	82	100	> 90
Porosity	10	8	6	75	100	> 90
Incomplete Penetration	7	4	3	75	≈ 100	> 90
Lack of Fusion	4	1 / 3+	2	67	100	> 90
TOTAL	40	30 / 32+	25	78	100	> 90

Detection Criteria: A minimum of 3 AE events, each within a specific energy band, and all within a 1 second time interval constitutes an alarm condition. Detection/location performed with available GARD hardware/software.

* At 0 overcall

\+ Includes 2 natural LOFs

and correlation of the AE data, using GARD's laboratory AE weld monitoring system, with actual flaw presence and locations as verified by radiographic and/or ultrasonic inspection. As was expected, there was a significant increase in AE activity resulting from flaw induction over the background AE level. These data correlated well with induced flaw location as is shown in Table I. Flaw types, other than cracks, were not always detected on the generating pass, but related crack growth during the welding of subsequent passes would produce AE which could readily be used for flaw detection.

Significant variances were evident in the generated AE data as a function of flaw types. Porosity generation, for example, was characterized by a high AE event rate. Incomplete penetration appeared to have an elevated AE event rate but not nearly to the extent as with porosity. Such variations can be utilized in the development of the needed flaw characterization software.

2.2 Conclusions

The direct applicability of acoustic emission for NDE of armor plate welds has been established during the course of this program. The detection of 78% of the flaw data base strongly supports this applicability. Likewise, the flaw location capability of acoustic emission in armor plate welds is shown to be about 100%. Furthermore, flaw characterization as to type and size appears possible using the differing characteristics of AE signals corresponding to the various critical flaw types. Additionally, the high rate of confirmed natural flaws found in the welds generated during this program indicates that armor plate weld quality is extremely sensitive to welding parameters and processes. The in-process AE technique used in this program will therefore be invaluable to production armor plate welding as it can provide indications of flaw formation at the time of occurrance. This in-process flaw detection technique will permit correction of weld processes and/or parameters, as required, before extensive amount of flawed welds are generated. The result will be improved weld integrity in addition to reduced production cost.

2.2.1 AE Weld Monitor Data Collection

Preliminary analysis during AE data collection showed a marked increase in AE events above the background level when flaws were being induced or when a subsequent weld pass went over an existing flaw. Such an effect is necessary to allow AE to be used for flaw detection. It was also observed that the background AE level was at times significantly greater than that for submerged arc welding of mild steels. The relatively high number of natural flaws shown in the radiographs suggest that a great deal of this AE data can be legitimately traced to natural flaw generation. This is consistent with the higher probability of natural flaw formation in the relatively brittle, high yield steels (in which class armor plate resides) than with the mild carbon steels. The flaws which occurred naturally were equal to about 60% of the quantity of induced flaws.

As shown in Table 1, 75% of the attempts at flaw induction were successful. Lack of fusion, being the most difficult to simulate, was augmented with 2 natural LOFs to broaden the data base for analysis. The two natural LOFs selected for AE analysis were locationally isolatable so that their AE data could also be isolated. A total of 32 flaws were confirmed as present and used for this AE investigation.

The high rate of natural flaws (60% of planned) is about an order of magnitude greater than encountered in mild carbon steel welding. This demonstrates an extreme sensitivity to weld parameters and techniques, which in turn, supports the need of an in-process weld monitoring technique for armor plate welding.

2.2.2 AE Weld Monitor System Investigation

Acoustic emission data collected during this effort was analyzed to find the correlation between AE indicated flaws and actual flaw existence. The AE detectable flaws and the % detection is shown in Table 1. An overall detectability of 78% with 0% overcalls (unconfirmed AE indications) was achieved. It is possible to improve this detectability by relaxing the requirement for detection (i.e., opening the acceptable energy window for AE events, changing the counts necessary for an alarm, or changing the time window in which events must occur). This, however, might result in the generation of overcalls, that is, the indication of un-confirmable flaws.

The location of weld flaws is based on source location of the AE events that are used to detect and characterize that flaw. These events are located using data derived from event time-arrival difference at the two transducers of an AE "locator". GARD normally uses this technique to determine flaw location in welds and used it on this program. All flaws in the data base were radiographically confirmed, and located by AE. From this, and experience on previous AEWM work, a flaw locatability near 100% is predicted.

Crack characterization appears to be possible using the present GARD AE spectral criteria for distinguishing cracks from other flaw types. Alternate means are required to characterize other flaws. Porosity, for example, has rapid event rates which may be used in its characterization. Lack of fusion and incomplete penetration, having only an apparent low level of AE generation, could rely on subsequent pass crack generation for detection. The AE generated during crack formation in armor plate welds was similar to that found with milder carbon steels, where the probability of correctly characterizing a crack exceeded 90%. It is anticipated that this level of accuracy will apply to armor welding. Cracks resulting from incomplete penetration or lack of fusion will normally exist along the entire length of the primary flaw. Thus the length of an AE crack indication could be used to distinguish a local crack from a lack of fusion or incomplete penetration. Pass location information should permit characterizing between lack of fusion and incomplete penetration. Thus, overall characterization accuracy greater than 90% is anticipated.

Section 3

RECOMMENDATIONS

The objective of this work was to demonstrate the viability of AE flaw detection, location, and characterization in armor plate welding. The next phase of the planned effort is to be directed at implementating the detection criteria in software and demonstrating its use in production-type testing.

The results obtained demonstrate the potential of AE as an in-process tool for monitoring armor plate welding. The overall detectability of 78% of radiographically-confirmed, flaw data base is most encouraging. Flaw characterization of primary critical flaw types appears feasible by incorporating acoustic emission event rate into the flaw model criteria currently used by GARD (i.e., spectral discrimination is already used for nuclear weld monitoring). The work performed herein primarily addresses the correlation of AE data with intentional flaws confirmed radiographically. The extreme sensitivity of armor plate to welding parameters resulted in the largest natural flaw population ever encountered in this type of work. Extensive efforts to control weld parameters still resulted in a radiographically - confirmed natural flaw population in excess of 60% of the planned flaw population. A detailed examination of this large natural flaw population was beyond the scope of work of the current effort. Additional investigation into the nature of these existing natural flaws and their corresponding AE data could provide a broader data base through increased flaw population, and additional refinement of flaw characterization models, and therby generate added confirmation of the validity of the report conclusions.

It is recommended that the second phase of the developmental program be initiated based on the favorable results obtained in this data collection/analysis phase. First, that additional metallography and data analysis should be performed on available natural flaws. Then the generated flaw models should be implemented in software using the obtained criteria. After the models have been implemented, they would be tested on the AE data already gathered and stored at GARD, as well as on some production testing on live welds. These, thus proven software flaw models, would then be implemented in the stand-alone monitor to be fabricated in Phase III.

Section 4

INTRODUCTION

Radiography and ultrasonics are the standard NDE techniques used in weld inspection today. Because of the basic principles of physics involved, they have certain limitations in their application. Radiography has very limited sensitivity to planar, crack-like flaws (which are usually critical to the inspected weld performance). Geometry of the inspection sometimes severely restricts radiography application because access to two sides of the weld is required. Ultrasonics is a technique which requires scanning of a weld to inspect it. An extended smooth inspection surface is required to provide constant acoustic input to the weld. A smooth weld crown is required to provide sensitive inspection. Programmed probe manipulation is required to assure detection of randomly oriented flaws. Both techniques require qualified operators to assure inspection success.

Acoustic emission is a technique which uses a "contact microphone" to listen to noises given off by the weld while it is cooling. These noises can tell if a flaw exists in the weld. No scanning is required. Single-sided inspection is possible. Electronics can do the signal interpretation.

In-process acoustic emission weld monitoring can provide:

a) production cost savings and improved weld intergrity by allowing repairs to be performed on a pass by pass basis as the flaws occur rather than after the completion of a heavy section weld,

b) improved sensitivity over conventional NDE methods to the most serious flaw types (i.e., cracks, LOF, etc.),

c) improved reliability over conventional NDE methods for those cases where weld geometry renders normal NDE either difficult or impossible to apply, and

d) improved reliability over conventional NDE methods through reduction of operator dependance by means of automatic flaw characterization as to type and size.

These advantages have led to the work reported herin. It is directed at determining the feasibility of utilizing acoustic emission as weld monitoring technique for armor plate welding.

4.1 Background

Acoustic emission (AE) is the acoustic energy generated in a material under stress. Acoustic emission results from mechanisms such as plastic deformation and flaw propagation. In welding, stress is generated by the shrinking of the molten weld metal as it solidifies and cools. If welding conditions are improper, flaws such as cracks may form during this process and acoustic emission will result. The detection and utilization of these acoustic signals is the basis for a powerful NDE tool.

GARD began a study of acoustic emission weld monitoring under GATX Corporate sponsorship in 1971 with the goal of improved NDE of welds in the manufacture of railroad tank cars. Real time in-process inspection of these welds was desirable for several reasons. A real time in-process inspection tool could be used to warn welders that welding conditions are improper thus allowing the welder to make appropriate adjustments and reduce the overall flaw output and resulting repair costs. Real time in-process inspection allows the flaws to be repaired on the production floor which minimizes material handling and eliminates re-radiography of repaired sections.

The primary problem encountered when applying acoustic emission to in-process weld inspection is that the AE signals are random and noise-like. There are many sources of similar noises present in any typical production welding situation. One must, therefore, develop techniques to suppress the noises which emanate from such sources as the welding arc, slag cracking, and mechanical noises (grinding, chipping, and part manipulation) and allow the AE signals from the weld flaws to be detected. GARD under GATX Corporate sponsorship developed the signal processing techniques and incorporated them in systems applicable to railroad tank car fabrication which primarily consists of submerged arc welding (SAW) of mild carbon steel.

In November of 1974, under the sponsorship of the Nuclear Regulatory Commission, GARD commenced a three-year program aimed at proving feasibility and applying the in-process AE monitoring of welds to the wider range of materials and welding processes encountered in fabrication of nuclear power plant components. The program involved performing a series of calibration welds with intentionally induced flaws while monitoring the AE data and recording it on magnetic tape. The data and subsequent analysis permitted GARD to monitor successfully the various weld types being performed. Several stand-alone monitors were fabricated and evaluated in production welding facilities: one for flaw detection, and one for flaw location. The results of the tests, when compared with normal production NDE, show the effectiveness and practicality of using AE for in-process weld inspection of the four most commonly used weld methods and materials used in nuclear fabrication.

Efforts of this program and our corporate activity contributed greatly to increasing understanding of the basic physics of acoustic emission flaw detection in welds. Analysis of our large bank of controlled flaw data and production data has lead to the development of a "smart" AE monitor that not only can detect flaws during welding but,in addition, supply flaw characterization.

Two such systems are currently being fabricated by GARD: one for the Nuclear Regulatory Commission and one for the United Kingdom Atomic Energy Authority. Also feasibility studies are underway to determine AE weld monitoring applicability for the Department of Energy and Army Corps of Engineers.

This TARADCOM project is similar to the above in that we are utilizing the above GARD developed knowledge to determine AE applicability to a specific Army welding problem.

4.2 Program Plan

The objective of this multi-year program is the development of a stand-alone Acoustic Emission Weld Monitor (AEWM) intended for use for in-process monitoring of MIG-welded armor plate. This production-tested unit will be used by production personnel involved in the welding of armor plate sections for heavy armored vehicles.

The efforts of this first phase of the overall program were directed to the collection and analysis of AE data from armor plate welds. These welds contained intentionally induced flaws of the types which are of critical importance in the fabrication of armor plate welds. The AE data were analyzed to correlate with verified flaws. Flaw verification was accomplished with standard NDE techniques of radiography and ultrasonic testing along with metallography as required. The second and third program phase efforts involve the development of software flaw models for the armor plate welds, and hardware development and fabrication, respectively.

This first phase was divided into two primary tasks: AEWM Data Acquisition and AEWM System Investigation. The first task included an analysis of TARADCOM provided armor plate in terms of chemical composition and acoustic properties, both critical to either the welding and/or AE data collection processes. Subsequent efforts included plate preparation followed by the actual welding and data collection with flaw induction. Also included in this task was the radiographic inspection of all welds. The second task addressed the detailed analysis and correlation of AE data with the confirmed flaws.

The data collected in the first task, coupled with the analysis performed in the second task, determined the flaw types which can reliably be detected and located using AE techniques. The viability of flaw discrimination as to type was also ascertained.

Section 5

ACOUSTIC EMISSION WELD MONITOR SYSTEM DATA ACQUISITION

The work performed by GARD under Task I of this program can be listed in four basic categories: 1) Armor Plate Characteristics and Plate Preparation, 2) Welding Procedures and Parameters, 3) AE Instrumentation System Description, and 4) Radiographic Analysis. Each of these will be individually reported in the sections to follow.

5.1 Armor Plate Characteristics and Plate Preparation

With the goal of in-process weld monitoring of heavy armored vehicles, it was desirable that the welding performed at GARD be closely aligned to that used in armored vehicle production. To this end, a meeting was held early in the program at the facility of an armored vehicle production contractor. This meeting, attended by TARADCOM, AMMRC, contractor, and GARD personnel, enabled GARD to obtain detailed information regarding armor plate characteristics, common weld geometries used, and anticipated weld parameters to be employed in armored vehicle production welding. A discussion of plate characteristics and weld geometry follows; weld parameters will be addressed later.

5.1.1 Armor Plate Characteristics

Successful welding hinges on welding techniques and parameters optimally set for the specific material being welded. Information provided GARD by production contractor personnel provided a starting point to work from, but a detailed evaluation of plate characteristics was needed to insure weld parameters compatible with the provided armor plate would be used. Investigation of acoustic properties was also necessary as these would effect the ability to detect the AE signals being generated by flaw formation.

Chemical Composition

An analysis of the chemical composition of the TARADCOM-furnished armor plate yielded the results shown in Table 2a. Table 2b shows the nominal chemical compositions of three HY steels, namely HY80, HY100, and HY140. As can be seen, the armor plate is similar to HY100 steel, the only significant variation being in carbon content. This armor plate, as well as that specified for heavy armored vehicle fabrication, was procured to Military Specification MIL-A-12560D. This performance specification does not specify actual composition. It does, however, specify the tolerances for the compositions. It is the responsibility of the manufacturer to provide alloy composition which meets performance requirements.

Plate Hardness

Hardness of the armor plate has two effects we need to consider. First, extremely hard steels are difficult to machine, thereby making plate cutting and bevelling time-consuming and expensive. Secondly, hard metals are difficult to weld as a result of their tendency to crack. The surface hardness of the armor plate used in this program was found to be in the 25-30 range on the Rockwell C Scale. The hardness range specified in MIL-A-12560D for two-inch thick armor plate is 269-311 Brinell. Brinell hardness of 269-311 can be correlated to Rockwell C hardness of about 28-34.

Acoustic Properties

Two acoustic properties are of interest in this AE program: the velocity with which acoustic energy travels along the plate, and the rate at which the energy is attenuated as it travels along the plate. The armor plate provided was ideally suited to test for these parameters owing to its 12 ft. x 6 ft. size. The performance of tests in the center of the plate could minimize edge-effects

TABLE 2

CHEMICAL COMPOSITION

Carbon	.27 %
Manganese	.26
Phosphorus	.008
Sulfur	.016
Silicon	.21
Nickel	3.12
Chromium	1.07
Molybdenum	.30
Copper	<.03
Vanadium	<.01
Titanium	<.03
Columbium & Tantalum	.01

A. Analysis of Armor Plate

	HY 80	HY 100	HY 140
Carbon	0.18%	0.20%	0.16%
Maganese	0.10-0.40	0.10-0.40	0.60-0.90
Phosphorus	0.025	0.025	0.015
Sulfur	0.025	0.025	0.015
Silicon	0.15-0.35	0.15-0.35	0.15-0.35
Nickel	2.00-3.25	2.20-3.50	4.75-5.25
Chromium	1.00-1.80	1.00-1.80	0.40-0.70
Molybdenum	0.20-0.60	0.20-0.60	0.30-0.65
Vanadium	———	———	0.05-0.10

B. Composition of Selected HY Steels[1]

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1. From Metal Progress 1978 Databook Mid June, p.55

which introduce reflections and result in extraneous data, thereby making determination of phase velocity and attenuation difficult.

Acoustic tests were performed which used two Dunegan-Endevco SM140A AE transducers. One was connected to a high voltage pulse generator and used as an AE source. It was placed in the center of the plate. The second, used as a receiving transducer, was placed 12 inches from the source. Its output was monitored as the distance between transducers was increased in 12 inch increments. The data showed that the signal attenuation in the plate was 3 db per foot and the phase velocity was 120,000 inches per second. These characteristics are not significantly different from the milder carbon steels monitored by GARD in previous AE programs.

5.1.2 Armor Plate Preparation

The armor plate made available by TARADCOM was a single 2-inch thick plate, 6 feet wide and 12 feet long. Plate preparation began by cutting the plate into 48 pieces, each 3 feet long and 6 inches wide. Preparation continued by Blanchard grinding of the flat surface. This removed the mill scale allowing the plates to be placed flat on the weld table. This also provided a flat, uniform surface to secure the AE transducers. The surfaces to be bevelled were ground to remove the hard, heat-affected surface resulting from the cutting operation. This made the parts more easily machinable and removed the roughness which resulted from flame cutting. The plates were then bevelled to two geometries common to the heavy armored vehicle fabrication, as shown in Figure 1. The primary emphasis in this program is the partial penetration weld. Two-thirds of the plates were machined with the partial penetration bevel. The remainder were full penetration bevels.

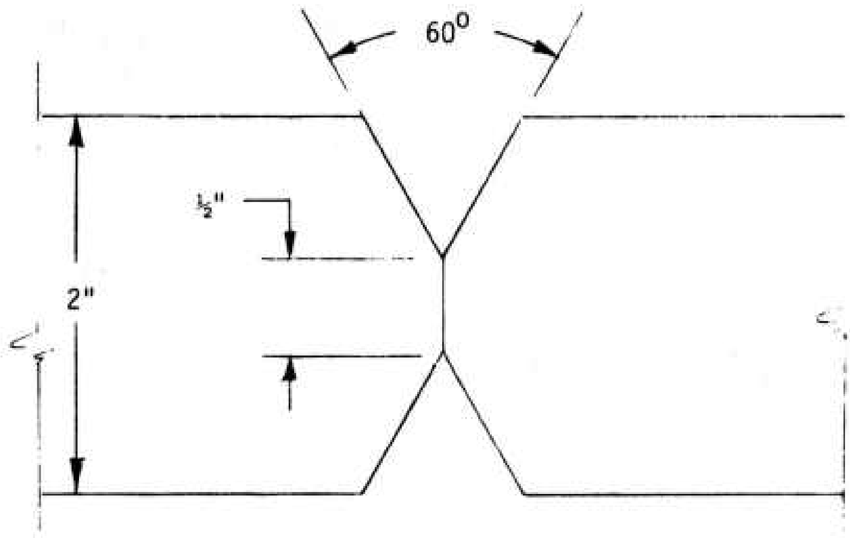


Figure 1a PARTIAL PENETRATION WELD BEVEL

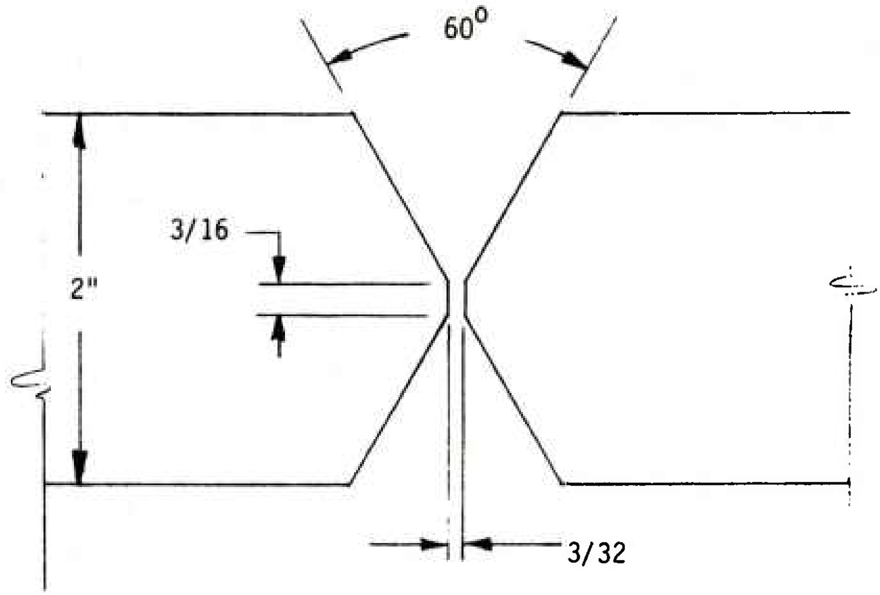


Figure 1b FULL PENETRATION WELD BEVEL

5.2 Welding Procedures and Parameters

To closely simulate armored vehicle fabrication welding, all welding used Metal Inert Gas (MIG) welding process. Guideline welding parameters, obtained from a current armored vehicle production contractor at a meeting early in the program, were adjusted to compensate for differences in material and weld geometries. Some of the parameters, such as electrode voltage, are very critical. They have narrow operating windows for making a satisfactory weld.

5.2.1 Weld Parameters

The weld parameters used are tabulated in Table 3. The preheat and interpass temperature specify a minimum and maximum plate temperature respectively for welding. During the welding and data collection phase of this program, the interpass temperature was typically in the range of 275-300^{0}. The weld current and voltage of the root passes were typically 290 amperes at 21½-22 volts, respectively. As subsequent passes were run, the currents and voltages were raised to 300 - 305 amperes and 23 - 24 volts, respectively. A weld rate of 15 inches per minute was maintained for all welds. Wire feed rate is not a specified parameter but is used to control the weld current. Typically, the wire feed was 200 inches/minute.

5.2.2 Welding Materials

The materials used in the welding process were consistent with those currently used in armored vehicle production. The weld wire used is Linde Type 95. This weld wire will provide a weld with a yield strength of 93,000 to 98,000 psi. This is close to the yield strength of the HY-100 steel (100,000 psi), which the armor plate approximates. The wire diameter used was 1/16 inch. An inert shield gas of argon with 2% oxygen was used.

TABLE 3

WELD PARAMETERS

Preheat Temperature	250^{o}F min.
Interpass Temperature	350^{o}F max.
Weld Current	285-310 amperes
Weld Voltage	21-24 volts
Weld Rate	15 inches/minute
Shield Gas Rate	35-50 ft^3/hr.
Stick Out	1/2 - 5/8 inch

5.2.3 Welding Procedures

The welding procedures used were set up to approximate the techniques used in heavy armored vehicle fabrication as closely as possible. In each case, the two plates to be welded were lined up with weld head travel and secured to the weld table. In the case of partial penetration welds, the plates were butted and clamped together. On full-penetration welds, the plates were spaced with a gap of 3/32 inch between the lands. The plates were tack welded in a 3 inch "runoff tab" zone at each end. The welding started on the side opposite the tack welds.

Preheating the Plates

The minimum preheat temperature was achieved and maintained using two thermostatically controlled 2.5 KW electric heaters placed under the plates, on the weld table. A thermocouple secured to one of the plates provided the feedback to the controller of the heater system allowing the maintenance of the minimum 250^{O}F preheat temperature.

The heaters were energized after the plate had been secured; about 25 minutes were required to raise the plate temperature from 75^{O}F to 250^{O}F. The heater system remained energized during the welding operation. Even though the plate temperature may rise about 20^{O}F as a result of one weld pass, the time between weld passes required for documentation was long enough to permit the temperature to drop below the 250^{O}F level. With the heater controller on, the heaters re-energize, as required, to maintain the minimum allowable temperature.

Weld Pass Patterns

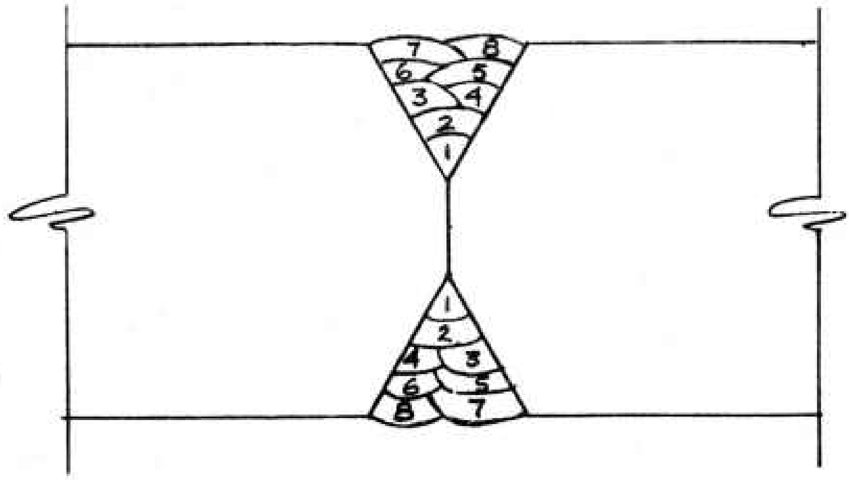
Pass patterns are shown in Figure 2 for each of the two weld configurations employed. Partial penetration welds typically required 8 to 9 passes per side to fill the bevel. The full penetration welds required 14 to 16 passes. The pass maps show the sequence in which the passes were deposited. The sequence was empirically determined during the early welds in the program. Complete fusion with bevelled walls and contiguous weld passes as well as minimizing chance of incomplete penetration were criteria for pass pattern sequence selection.

Back Side Gas Shield

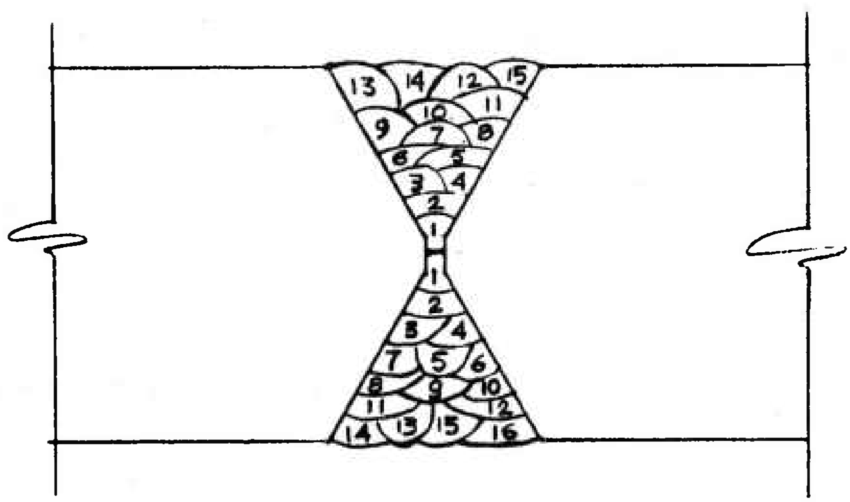
Full penetration welds during MIG process traditionally involve a back-gouging of the first root pass to remove contamination resulting from exposure to normal atmospheric gases. This is done prior to welding the second side root pass. Backgouging was performed in the first full penetration welds performed on this program. Later welds employed a second shield gas source to displace atmospheric gases on the reverse side of the plate. Without the contaminating gases present, backgouging was no longer necessary. Additionally, the carbon deposition resultant from carbon arc backgouging was absent; this reduced the brittleness of the root area, thereby lessening the chance of cracking in the root. The root passes on both sides of these full penetration welds produced much less acoustic emission than those not using the back shield gas.

5.2.4 Flaw Induction Techniques

The controlled induction of critical flaw types is necessary for correlation of AE data with other NDE techniques. The primary flaw types of



Partial Penetration Weld



Full Penetration Weld

Figure 2 WELD PASS PATTERNS

concern in this program are cracks, porosity, incomplete penetration and lack of fusion. Slag inclusion was not addressed since this flaw type is extremely rare in gas shielded welds and seldom reaches serious proportions.

The techniques employed in flaw induction were an extension of those used in previous weld monitoring programs. The injection of copper into the weld puddle is an effective means to induce cracking. Raising the weld voltage while welding over an intentional undercut yields lack of fusion. The same technique when applied to root passes causes incomplete penetration. The technique for generating porosity, unique to MIG welding, involved bubbling the shield gas through water.

5.3 Acoustic Emission Instrumentation System

The acoustic emission instrumentation used in the data acquisition for this program was centered around GARD's Acoustic Emission Weld Monitor System shown in Figure 3. This system is shown in block diagram form in Figure 4. The front end of the system consists of the GARD-developed Acoustic Emission Locator. Originally designed as a stand-alone weld monitor, this system has two transducer inputs and will determine and display the location of all AE events that qualify as potential flaws in terms of energy level and event rate. The internal oscilloscope is used for the display and the unit also provides for self-calibration of transducer spacing permitting the system to be directly applicable to welds of various lengths. In this application, the AEWM locator is used primarily to provide energy and location data for all acoustic emission events received. In this role, it is still active as a stand-alone monitor, providing additional data to verify overall system performance. The microcomputer system is provided with a signal to indicate an AE event has been received along with the location and energy data in digital form from the AEWM locator.

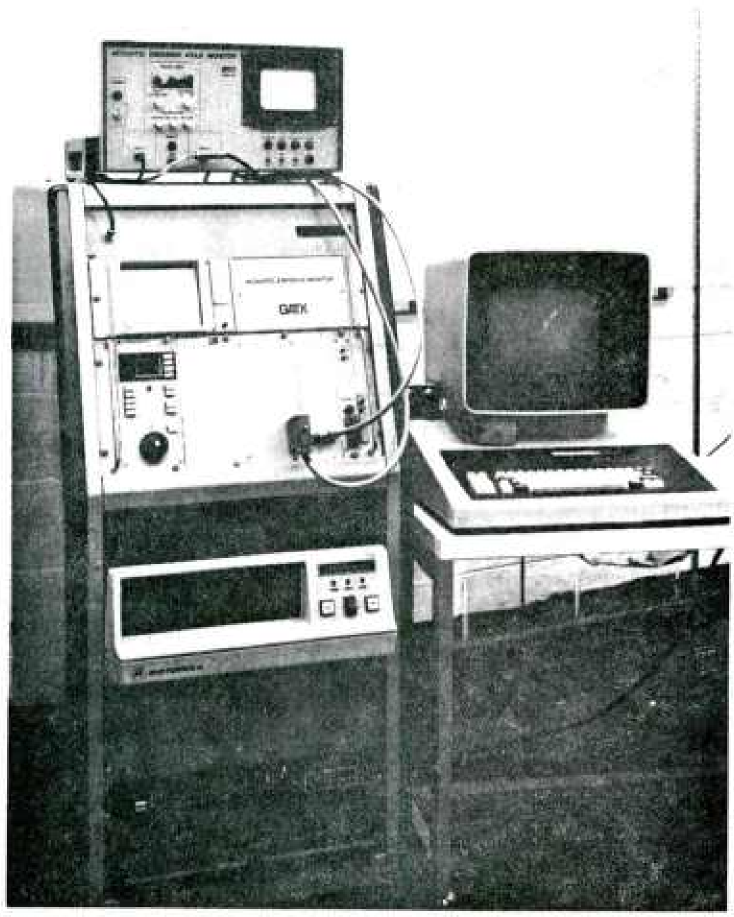


Figure 3 ACOUSTIC EMISSION WELD MONITOR LABORATORY SYSTEM

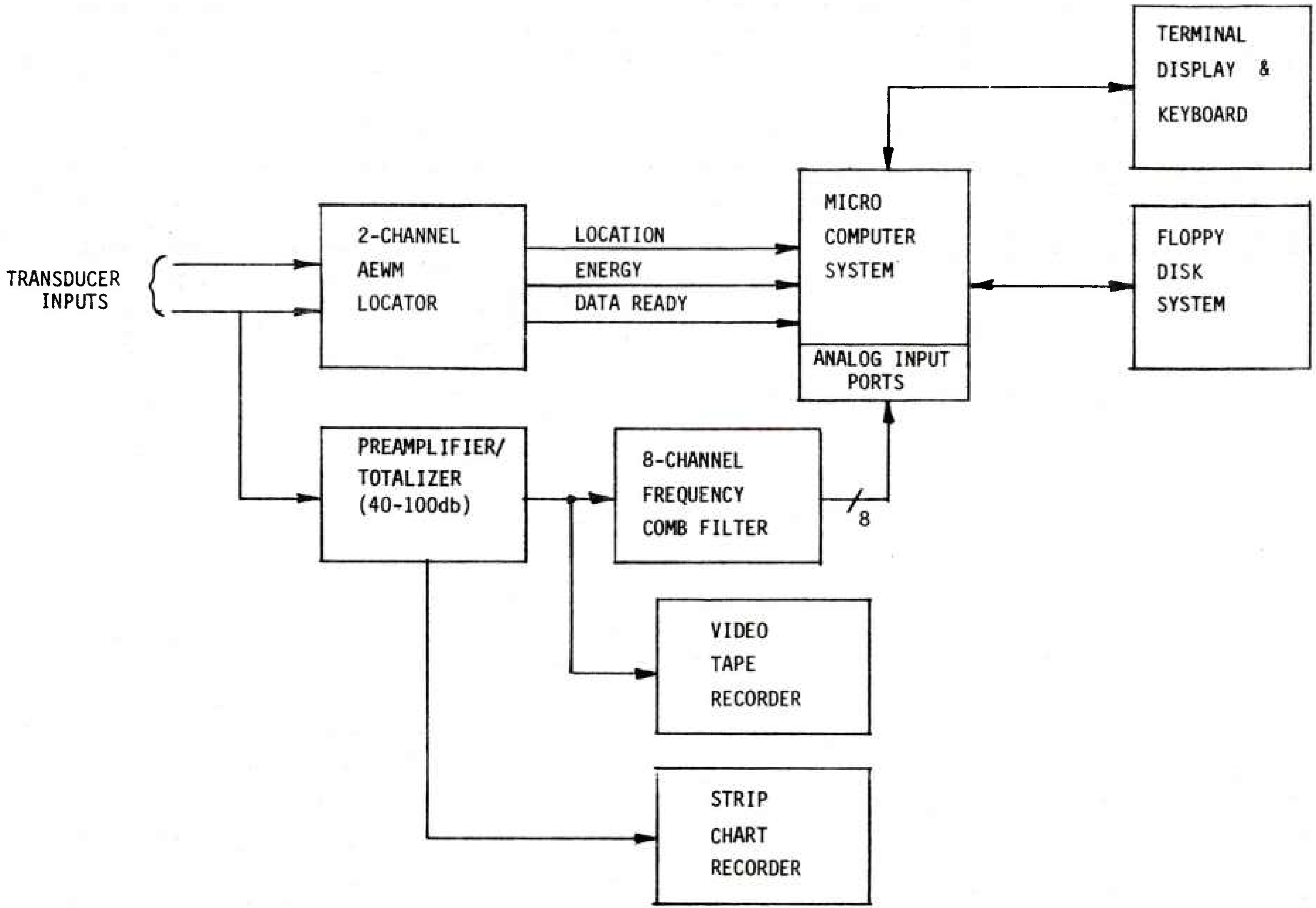


Figure 4 AEWM INSTRUMENTATION (BLOCK DIAGRAM)

Frequency Spectra of AE Events

The frequency spectra of each acoustic event is determined using a comb filter which divides the 100 KHz-1 MHz band into 8 sub-bands. This provides an adequate means for the performance of the flaw characterization accomplished in previous programs. Additional gain required is provided by a Dunegan Endevco 801P Preamplifier and Totalizer Model 301. The latter also provides for an adjustable gain to equalize the GARD frequency comb filter sensitivity with that of the Locator. The comb filter output is a set of 8 DC output voltages corresponding to the peak output of each frequency channel. These are digitized using an A/D converter board which is part of the microcomputer system.

System Control and Data Storage

The overall control of the system is accomplished using CRT display and keyboard terminal. The keyboard provides control over all data collection, recall, and analysis functions provided by the system software. The CRT display is the primary output means for recalling data and data analysis. A Dual Floppy Disk drive is used for the purpose of both loading system software as well as providing for mass storage of pre-processed acoustic emission data. In the normal data collection mode, the location, energy, 8 spectral data channel outputs, the time the event occurred, along with operator-keyed entries are stored for each event. Once stored on disk, the pre-processed data can be recalled, analyzed statistically, or operated upon by one of the flaw characterization models. Review of pre-processed data in both raw and statistical forms can yield new flaw models which can subsequently be evaluated by running the model with the actual stored weld AE data.

In addition to the pre-processed data storage, the raw AE data were recorded using a video tape recorder modified to record continuous wideband data. The bandwidth of standard video tape equipment is compatible with the AE spectra and can be used directly with minimal modification. The recorder output of the Dunegan-Endevco totalizer was also plotted using a strip-chart recorder. This provides a hard-copy of the energy level of AE events as they occur for real time monitoring of overall AE level present. Since AE data continue to be generated after weld stop, the strip chart output also provides information as to the decay rate of AE data subsequent to weld stop.

Transducer Placement

The transducers used in this investigation were of the high temperature type (Dunegan-Endevco Model D9205M2). Operation is permitted at temperatures as high as 1000^{o}F. Weldment temperatures in the 250 to 350^{o}F range make the use of these transducers necessary as more conventional transducers limit maximum temperature to 150-250^{o}F. Two transducers were used, one on each end of the plate. A sample setup is shown in Figure 5.

The transducers were secured on plate using a magnetic hold-down fixture. Electrical isolation between the plate and transducers was accomplished using an alumina disc between transducer and plate and an insulator cap on the hold down fixture. This isolation eliminates leakage of the weld current into the AE equipment. Silicon valve seal couplant was used between the plate-disc and disc-transducer interfaces to provide a reliable acoustic path between the plate and transducer. The couplant is stable to temperatures in excess of 600^{o}F.

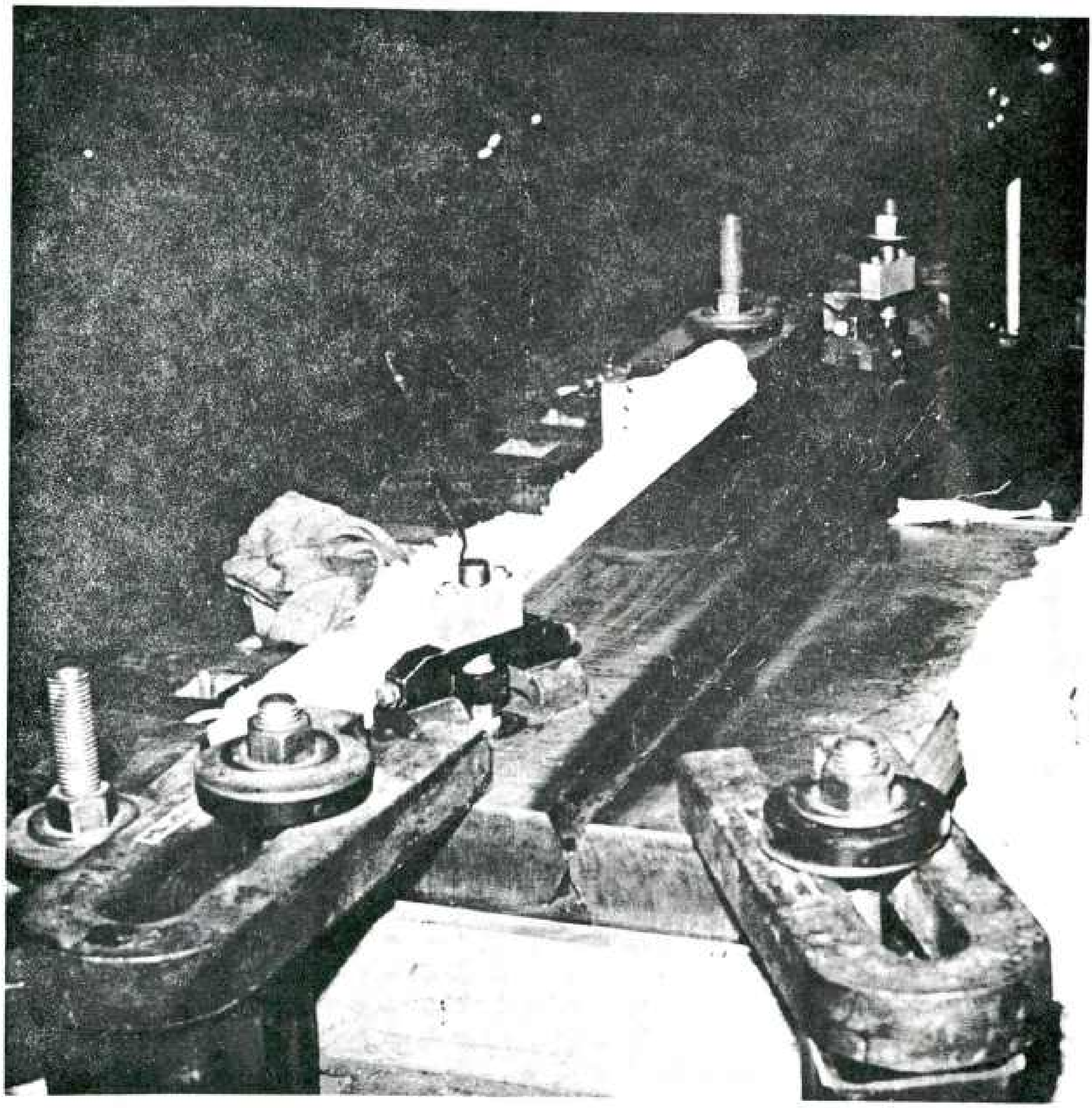


Figure 5 TRANSDUCER PLACEMENT

5.4 Welding Performance

A total of 13 multipass welds were performed under this program totalling 39 linear feet of weld or almost 900 feet of weld passes. All were monitored using the GARD AE instrumentation described in Section 5.3. The first weld was primarily used to refine the weld parameters to the particular armor plate being used for preliminary calibration of AE equipment. With the intent of achieving a controllable welding process, no intentional flaws were induced in this weld.

The remaining 12 welds were used for the purpose of controlled flaw induction. In addition to the recording of all AE data obtained, a record of all flaw generation attempts was made. Each intended flaw was recorded as to weld number and side, pass number, and position along the length of the weld. Radiographic, ultrasonic and/or metallographic inspection was performed, as required, to verify location, type and severity of induced flaws. The verified existence and condition of the induced flaws was correlated with the recorded AE data in subsequent signal analysis efforts.

As weldments were completed, they were submitted for radiography. Radiographs were made with an iridium 192 source. This source is characterized by its softness and is a smaller point than the cobalt sources normally used and therefore provides greater resolution. Double Class I film, while not as sensititive as other films, provided increased contrast or dynamic range allowing detection of a wider range of flaw densities. Double film permits the isolation of film artifacts from flaw indications.

Radiographs of early welds confirmed a natural flaw population suggested by relatively high AE activity generated. Primarily these flaws were cracks and porosity. GARD had been advised that the material may have a natural tendency for cracking. Extra care had to be used to maintain weld parameters favorable to the generation of good welds.

Radiographs of early welds also showed possible lack of fusion. Ultrasonic inspection revealed a consistent response about ½ inch from the center of the plate probably at the weld-bevel interface. This was subsequently confirmed using metallography as shown in Figure 6. This flaw, running a significant portion of the weld length at a consistent location, suggested it might be related to weld pass geometry in addition to weld parameters. This problem was cured by slight modification of the pass map and maintenance of the minimum possible weld voltage to insure penetration and fusion.

AE data obtained in this Task were used in Task 2, System Investigation.

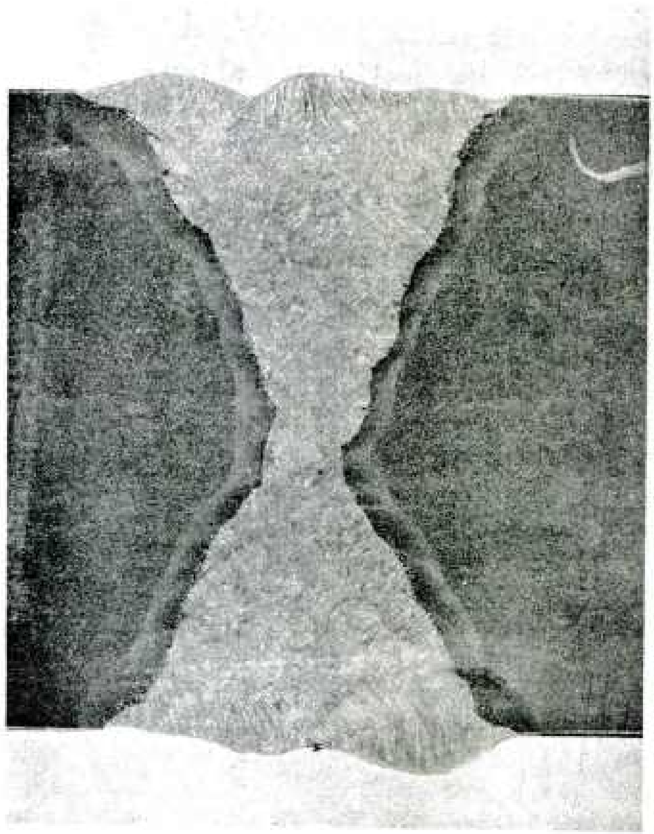


Figure 6 METALLOGRAPHIC SECTION SHOWING
NATURAL LACK OF FUSION

Section 6

ACOUSTIC EMISSION WELD MONITOR SYSTEM INVESTIGATION

The efforts on this task were directed toward the analysis of the data collected in Task 1, and to determine the viability of acoustic emission as an in-process NDE tool for armor plate welding. A detailed inspection of the radiographs of all welds was performed to confirm the existence of the induced flaws. The acoustic emission data were screened to identify the AE characteristics which correlate with the confirmed flaws. These data will be used in the subsequent development of flaw models. An analysis of the correlation between these AE data and flaw presence allows the prediction of the accuracy with which flaw can be detected, located, and ultimately discriminated from other flaw types.

6.1 Flaw Population Confirmation

As cited in the previous section, a total of 13 welds were fabricated during the data collection phase with 12 having intentionally induced flaws. Of the twelve welds with the intentional flaws, the attempted flaw population as a function of flaw type is shown in Table 4. As can be seen, the primary emphasis was placed on the crack flaws in terms of flaw population. This is because cracks have the most significant effect on weld intergrity.

Flaw confirmation was primarily accomplished through the use of radiographic inspection. Positive confirmation of porosity, along with high probability of confirmation of crack, lack of fusion, and incomplete penetration is accomplished in this manner. The high quality radiographs obtained using the iridium source and Class 1 film exceed the 2% density resolution typically required by codes. Radiographic interpretation was performed by Level III NDT personnel.

TABLE 4

ATTEMPTED FLAW POPULATION

Flaw Type	Flawed Welds	Total Induced Flaw Attempts
Crack	6	19
Porosity	3	10
Incomplete Penetration	2	7
Lack of Fusion	1	4

A simple crack found in weld A/PT4 is shown radiographically in Figure 7. A more complex crack network was found in weld A/PT2 as shown in Figure 8. Mild and severe porosity were generated in welds A/PT9 and A/PT8 respectively. Radiographically these flaws appeared as in Figures 9 and 10 respectively. Incomplete penetration flaws were induced in both full and partial penetration welds. These flaws appeared radiographically as shown in Figures 11 and 12 respectively. Radiography of a lack of fusion flaw is shown in Figure 13.

As a result of the radiographic inspection, the actual population of induced flaws was determined and is as shown in Table 5. The table shows that 75% of all flaw attempts were successfully induced and confirmed radiographically. In all cases except lack of fusion, there is an adequate planned flaw population, for the purposes of this AE study, using only those flaws radiographically confirmable. The use of locationally isolatable natural lack of fusion to broaden this particular flaw population will be discussed later.

Both radiography and ultrasonic testing of the weldments show a significant number of natural (or unintended) flaws. They seem to be mostly cracks, porosity and lack of fusion. However, since flaw introduction mechanisms for them are unknown, extensive metallography is required to positively identify their flaw type, in order to allow a meaningful correlation with their corresponding AE data. Such an effort was beyond the scope of the current project and was not performed.

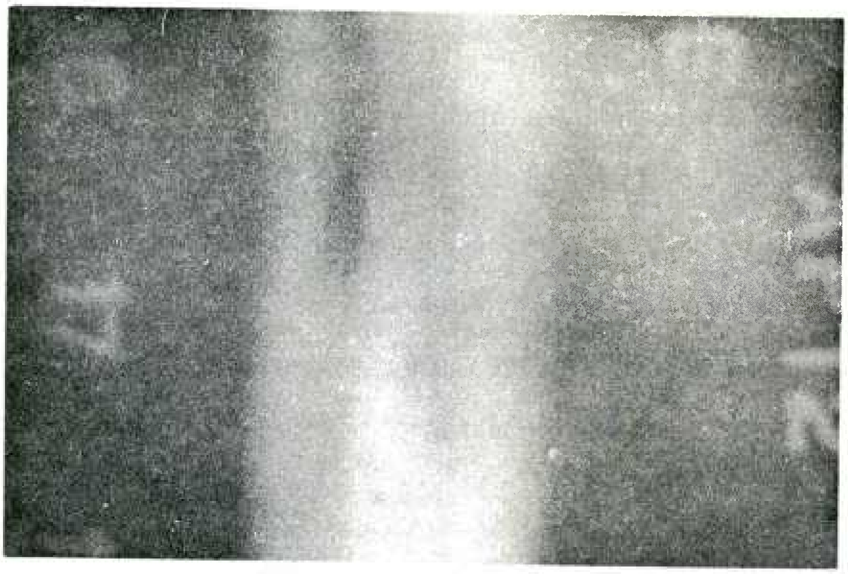


Figure 7 RADIOGRAPHY OF SIMPLE CRACK IN WELD A/PT4

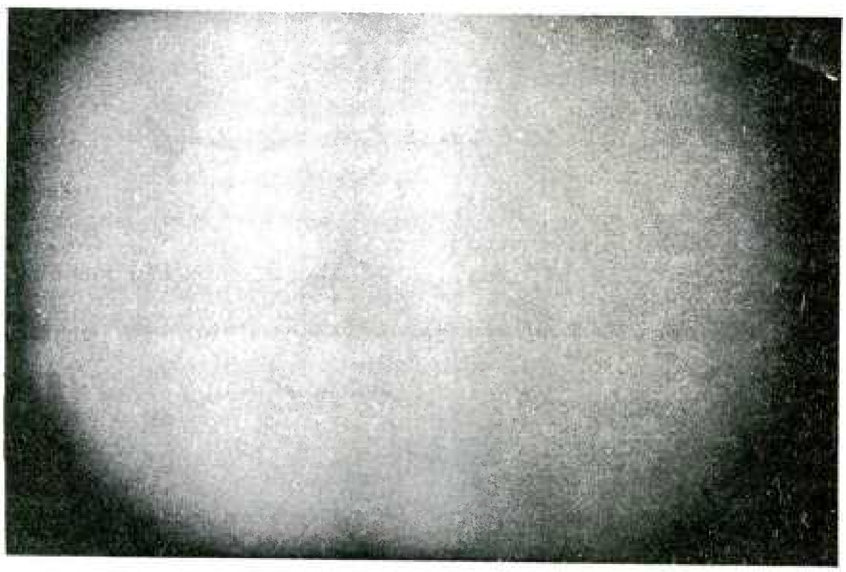


Figure 8 RADIOGRAPHY OF COMPLEX CRACK NETWORK IN WELD A/PT2

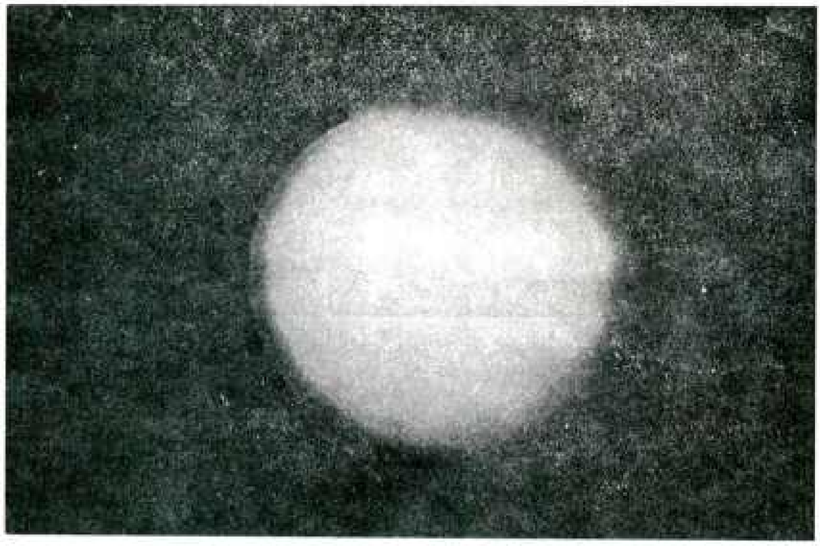


Figure 9 RADIOGRAPHY - MILD POROSITY IN WELD A/PT9

Figure 10 RADIOGRAPHY - COARSE POROSITY IN WELD A/PT8

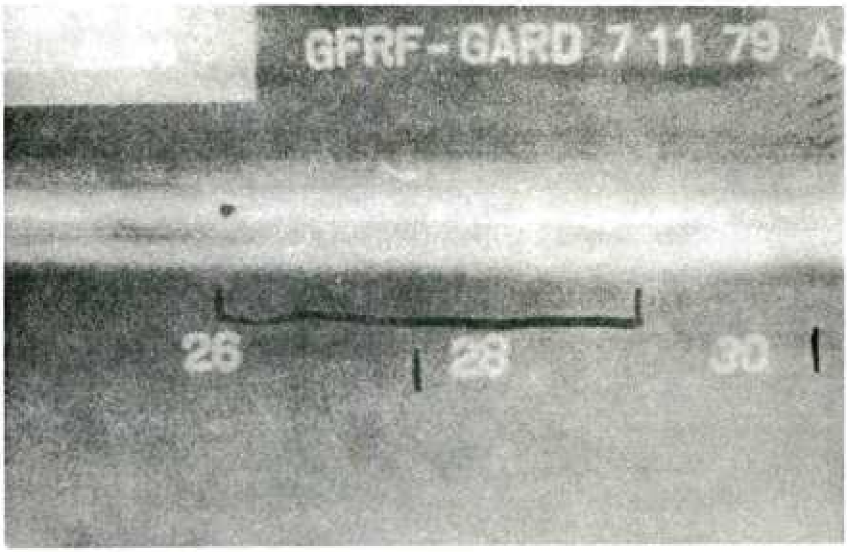


Figure 11 RADIOGRAPHY - INCOMPLETE PENETRATION
FULL PENETRATION WELD A/PT-12

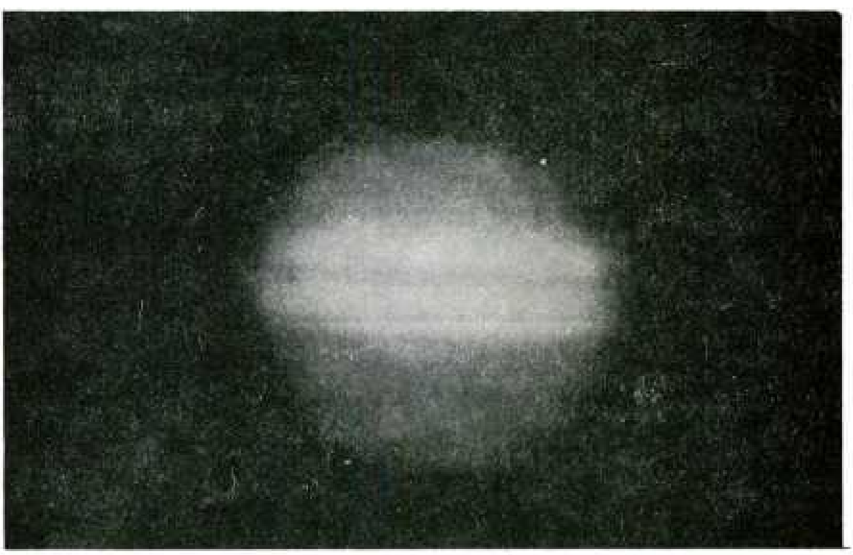


Figure 12 RADIOGRAPHY - INCOMPLETE PENETRATION
PARTIAL PENETRATION WELD A/PT-11

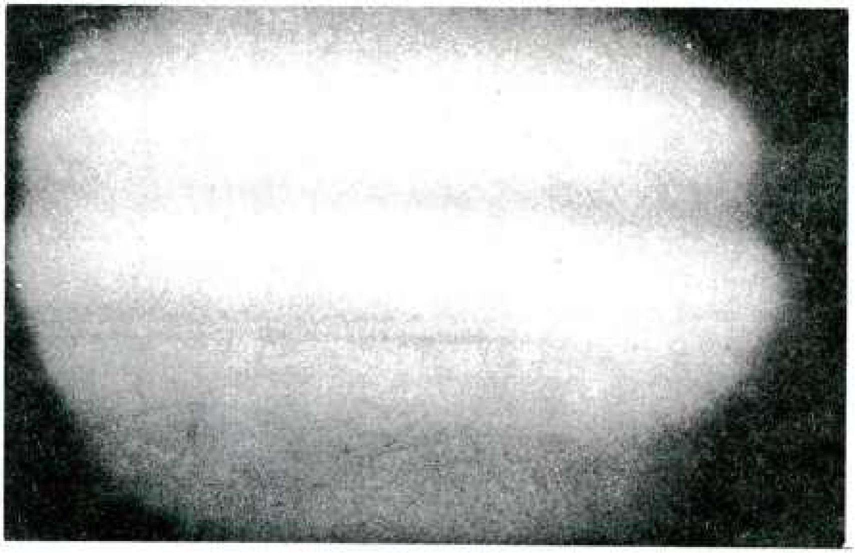


Figure 13 RADIOGRAPHY - LACK OF FUSION IN WELD A/PT5

TABLE 5

VERIFIED INDUCED FLAWS

Flaw Type	Attempted Flaws	Confirmed Flaws
Crack	19	17
Porosity	10	8
Incomplete Penetration	7	4
Lack of Fusion	4	1

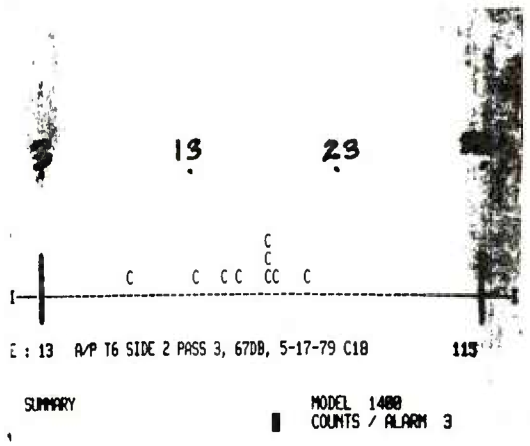
6.2 Correlation of AE Data with Actual Flaw Presence

Correlation of AE data with the actual presence of induced flaws is necessary to determine the viability of acoustic emission as an in-process technique for monitoring armor plate welding processes. The AE data collected during the generation of the thirty flaws cited in Table 5 were analyzed to determine the detectability of the various flaw types using the AE.

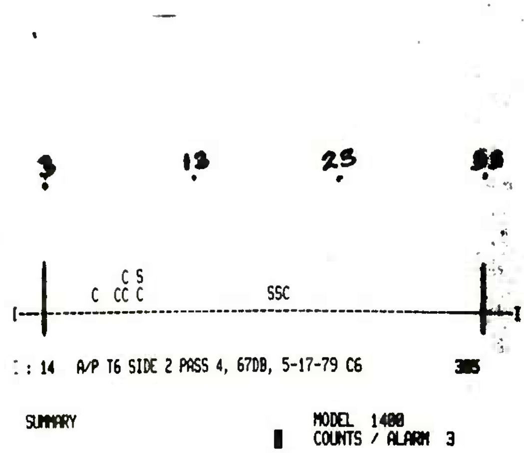
6.2.1 Flaw Detection

GARD's current flaw detection technique (developed from monitoring the submerged arc welding of carbon steel) was used as a starting point and found reasonably effective in detecting flaws in armor plate welding. This method uses three counts per alarm (cpa): i.e., three AE events, each within a specified energy window, occurring within a one-second time interval. With such a detection model, 14 of the 17 induced cracks were clearly detected (82% detection). A cpa = 2 resulted in a 100% detection of cracks. This detection model could result in overcalls (the detection response to non-confirmed flaws). It was not fully investigated.

An example of crack detectability is shown in Figure 14. The cracks induced in side <u>two</u> of this partial penetration weld (A/PT6) were in pass 3: 18 inches into weld, and pass 4: 8 inches into weld. Using a cpa = 3, note the stack-up of detection at about the 18-19 inch point during pass 3, and at the 6 to 9-inch mark on pass 4. Additional AE responses detected during pass 3 are attributed to natural flaw formation as confirmed by radiography. The induced cracks clearly stand out as a stack-up of AE events.



a) CRACK DETECTION AT 18"



b) CRACK DETECTION AT 8"

NOTE

In Figures 14-21, the weld is represented by the horizontal dashed line. Transducer locations, derived from calibration files, are indicated by vertical lines on each weld. Transducers were mounted on opposite sides of the weld, 3" from each end to allow clearance between mounts and weldment clamps. As a result, the actual transducer spacing was 30" and transducer placement corresponds to the 3-inch and 33-inch marks respectively. The 30" spacing varies somewhat in the figures due to gain dependence of the calibration technique used. Location capability outside transducer boundaries is very non-linear in nature. This geometric effect and acoustic edge reflection effect make flaw position indications outside the transducers and location of the plate edge meaningless to the data analysis performed. However, these regions were used entirely for purposes of weld start/stop zones and contained no intentional flaws. The letters stacked up above the line correspond to flaw-related AE events, and between transducers correspond to flaw locations within the weld. The actual letters correspond to flaw characterization techniques developed for nuclear steel welding and may not correctly characterize flaws in armor plate welds.

Figure 14 CRACK DETECTION

Crack growth during subsequent weld passes is also detectable, often times more so than during the original flaw generation. One such example is shown in Figure 14b where the crack induced at 18 inches (Figure 14a) reactivates clearly in the subsequent pass as shown by indications in the center of the figure. An additional example is shown in Figure 15, side one, pass 7 of the same weld, where responses were received both at the 9-14 inch and 21-22 inch marks. These are reactivations of two cracks induced earlier: pass 3 at 12 inches into weld, and pass 4 at 24 inches into weld. Two additional radiographically confirmed flaws were also detected on this pass at the 6 inch and 28 inch points on the weld. As shown, cracks are indeed acoustic sources and can be detected.

Detection of porosity was empirically determined to occur primarily during generation. A minimal amount of AE activity was sensed on subsequent passes. The large quantity of AE data generated during porosity induction may be useful in flaw discrimination. Figure 16 shows the results of AE detection during the generation of two areas of porosity on weld A/PT-14, side 2, pass 4 at 17-24 inches, and side 2, pass 7 at 16-23 inches. A count per alarm of nine was used due to the high rate of AE data. Responses at the beginning of both weld passes are caused by natural flaws.

Incomplete penetration was shown to produce acoustic emission on both generation and successive weld passes. It was found, in this case, that subsequent weld passes were more acoustically active than the pass where the flaw was generated. Since incomplete penetration can only occur in the root pass, it is more likely to be detected in the second pass (that which follows the root). The number of events was typically high, thereby sharing some of the characteristics of the porosity flaws.

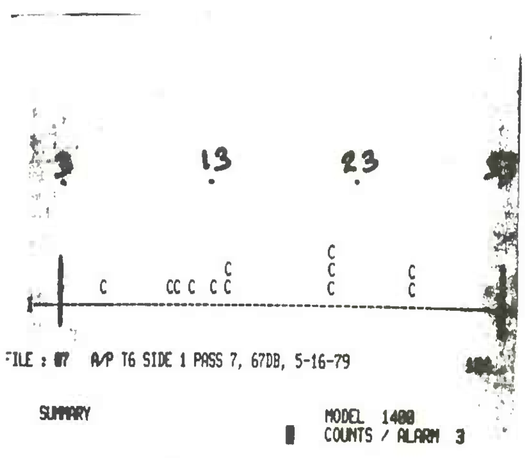
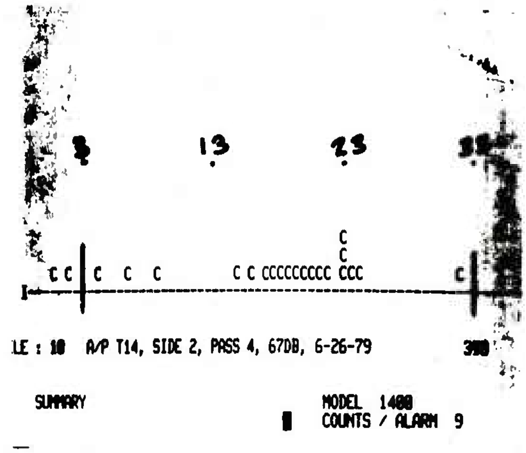
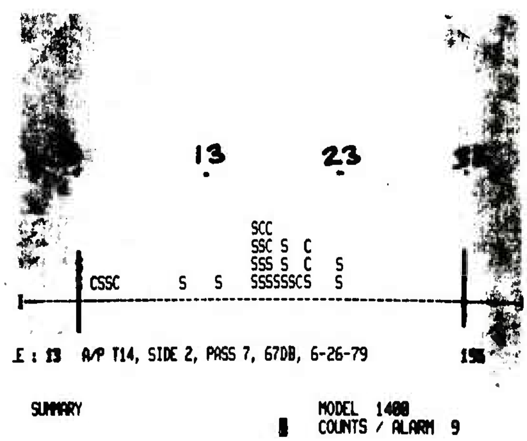


Figure 15 CRACK REACTIVATION DETECTION



a A/PT-14 SIDE 2 PASS 4



b A/PT-14 SIDE 2 PASS 7

Figure 16 POROSITY DETECTION

In the first pass of the partial penetration weld, A/PT-11, an attempt at incomplete penetration flaw induction was made on side one. Per radiography, natural porosity was generated in the start of the weld. The flaw attempt 12 inches into the weld resulted in incomplete penetration. Using a cpa = 9, the high event rate associated with the porosity, produces a response as shown in Figure 17. Note that the incomplete penetration at the 12-inch point is suppressed except for one response. Running the same data, with a cpa = 4, exposes additional incomplete penetration response at the 12-20 inch range as shown on Figure 18. The response from the natural porosity at the weld start has increased as has the background from other natural flaws. However, the activity from the incomplete penetration is still obvious.

The second pass of this weld, using a cpa = 4, shows three significant peaks, one at weld start, one at 9-16 inches and the remaining centered at the 24 inch mark as shown in Figure 19. Reactivation of the pass 1 incomplete penetration (in the 12-20 inch range) at 11-15 inches is indicated. Radiographically confirmed porosity correlates with the AE peaks at the 24 inch mark. AE at the weld start indicates newly generated porosity, possible reactivation of porosity from pass 1, and other confirmed natural flaws generated during weld startup.

Similar results were obtained with the full penetration weld (A/PT-12). One incomplete penetration flaw generated, and confirmed radiographically, was in the side two, root pass, 22-30 inches into the weld. The most significant AE detection from the flaw was in the second, reactivating, pass, shown in Figure 20 (16-30 inches). Again, natural flaws were present in the end of the weld and to a lesser extent during the first half of the weld. These appear radiographically as porosity and produce resultant AE data.

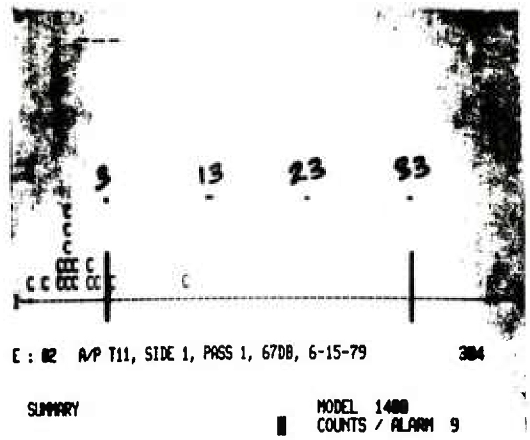


Figure 17 POROSITY DETECTED AT START OF WELD CONTAINING INCOMPLETE PENETRATION

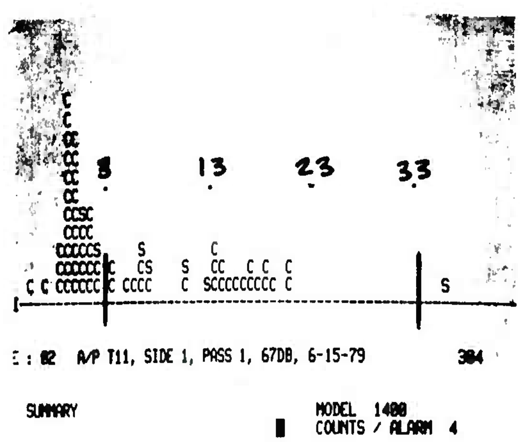


Figure 18 INCOMPLETE PENETRATION DETECTED

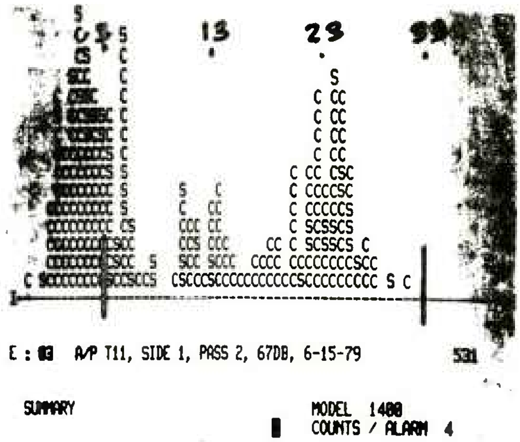


Figure 19 FLAW DETECTION PARTIAL PENETRATION WELD

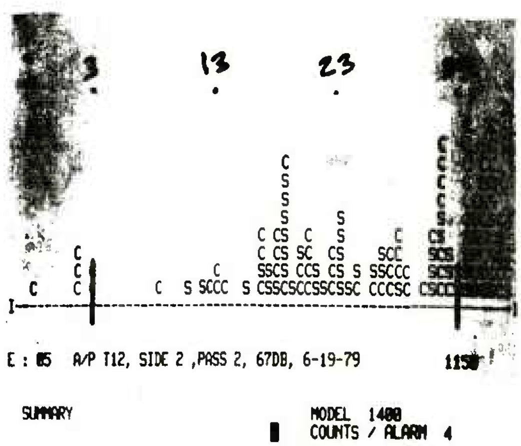


Figure 20 FLAW DETECTION FULL PENETRATION WELD

As cited earlier, only one radiographically confirmed intentional lack of fusion (LOF) was induced. There is, however, a significant population of natural LOFs; ten such natural flaws were apparent radiographically. It was found that LOF generates acoustic emission during both flawing passes and subsequent passes. Natural lack of fusion was most often embedded with other induced flaws. Where the natural LOF is not locationally isolated from the other flaws, data analysis is difficult. Two relatively isolated lack of fusion flaws were located radiographically in weld A/PT4. These were seen by AE in the 29 and 33 inch ranges of side one, pass 8 as shown in Figure 21. The response about 16 inch into the weld is due to the crack intentionally induced on this pass. The 3 inch and the 22 inch indications are additional radiographically confirmed flaws.

A summary of the flaw detectability data is shown on Table 6. The lack of fusion flaw population was augmented to include two natural LOFs, which were locationally isolatable, so as to result in a larger base. It may be possible to improve these probabilities through the incorporation of a newer adaptive data analysis technique now under development for crack identification in other GARD characterization efforts. In this manner, flaw detectability may be improved without sacrificing an increase in overcalls. With the present detection techniques, an average of 78% of the 30 successfully induced flaws (plus 2 natural LOF flaws) were detected with no overcalls.

6.2.2 Flaw Location

Flaw location has been successfully accomplished using GARD's two-channel weld monitor system. With one transducer at each end of the weld,

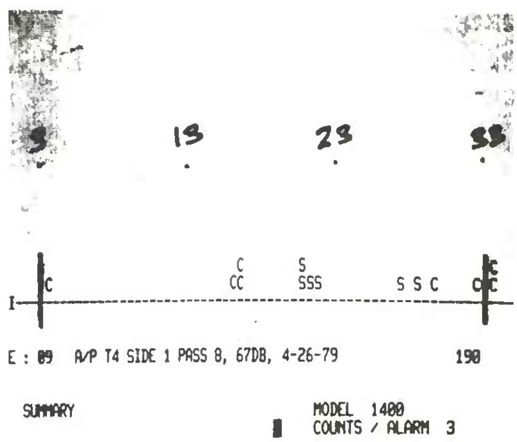


Figure 21 LOF DETECTION

TABLE 6

ESTIMATED AE FLAW DETECTION PROBABILITY

Flaw Type	Confirmed Flaws	AE Detected Flaws	% Detected
Crack	17	14	82
Porosity	8	6	75
Incomplete Penetration	4	3	75
Lack of Fusion	3*	2	67
TOTAL	32	25	78

* The one intentional LOF is augmented by 2 locationally isolatable natural LOFs

the actual location of an acoustic event is determined by the time difference of arrival of the AE signal at each of the two transducers. AE signals associated with weld flaws are of sufficient amplitude to be reliably located. As a result, every AE event has a location assigned to it. The degree of correlation between the actual flaw location and AE location data is indicative of the flaw location ability of AE techniques. The location system has a resolution better than 1% of weld monitored. The fact that all confirmed, intentional flaws were located using the AE data collected during this program supports the conclusion that flaw locatability approaching 100% is feasible. This is consistent with results of previous efforts in AE weld monitoring.

6.2.3 Flaw Characterization

Flaw characterization based on acoustic emission data has been accomplished by GARD for submerged arc welding of nuclear steel. Evaluation of GARD's existing nuclear flaw models was utilized as a starting point in this particular analysis. Early, it was apparent that our crack discrimination technique, based on frequency spectra of the acoustic emission would be useable for this application with minimum modification.

Slag inclusions are not considered as a probable flaw type in MIG welding, or in gas-shielded welding in general. First, all slag material floats on the molten weld metal, regardless of process, and, hence, is unlikely to be trapped. It is a standard procedure in all multi-pass weld situations, to clean the weld surface between passes to remove all oxides and slag. In the case of MIG welding, the minute beads of silica present after a weld pass is several orders of magnitude below the quantity encountered in a submerged arc weld. The resulting probability of a slag inclusion occurring is sufficiently small to justify excluding this flaw type from consideration here.

Porosity is characterized by an unusually high acoustic event rate, typically greater than 9 per second. This high rate can be the primary discriminating factor to characterize porosity flaw types.

Incomplete penetration (IP) and lack of fusion (LOF) do not have direct mechanism for generation of AE. They do form stress risers which, in turn, foster crack formation. It is the crack generation and growth that generate acoustic emission. The cracks formed resulting from these flaw types will, by themselves, be indistinguishable from singular cracks. However, both IP and LOF flaw types are characterized by their length. They are not a point defect characteristic of cracks or crack networks. They are caused by improper weld parameters, weld head positioning or pass patterns, which will more likely exist during the entire weld pass. As a result, these flaw types will commonly occur either continuously or intermittantly, along the entire length of the weld, depending on the severity of the cause. The continuum of crack activity over a finite length of weld can be used to distinguish between a normal isolated crack (or crack network) and an IP/LOF flaw. IP and LOF flaw types may therefore produce similarly characterized AE data. However, by definition an IP flaw is usually associated with a root pass, whereas the LOF is associated with a high level pass. Thus with pass information, characterization between IP and LOF is possible.

It can be seen that criteria for characterization of the pertinent flaw types has been established for armor plate welding. A 90% discrimination level has been estimated for correct flaw characterization. This is based on the data collected which shows:

a) the characterization phenomena are all crack related,

b) porosity has a unique signature (i.e., very high event count), and,

c) the crack signature from this material is very similar to that encountered with our nuclear material (A533) experience.

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Nondestructive Testing
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The standard weld inspection techniques of radiography and ultrasonics have intrinsic disadvantages. The new technology of acoustic emission (AE) has shown an applicability to weld inspection which could overcome such disadvantages. This program is directed at utilizing acoustic emission as a weld monitoring technique on a specific Army welding application.

The reported work is phase 1 of an Army program to develope a microprocessor-

based Acoustic Emission Weld Monitor (AEWM) for the purpose of in-process monitoring of armor plate welding. The intended use of this AEWM is to monitor the production welding performed in the fabrication of heavy armored vehicles.

The objectives of this phase are to:

a) perform laboratory MIG welding of armor plate with controlled induction of critical flaws,
b) collect acoustic emission data generated during the welding,
c) perform a data analysis to correlate the recorded AE data with flaw presence, and
d) predict the accuracy with which AE is able to detect and locate the weld flaws as well as discriminate between flaw types.

This final report presents (a) the welding procedures used to generate the necessary welds (including flaw induction techniques) and data collection methods and instrumentation used, and (b) the results of the data analysis, correlation, and accuracy predictions of AEWM as it applies to armor plate welding.

In summary, we show that AE is a viable NDE tool for in-process monitoring of armor plate welding. The ability to detect, locate and characterize weld flaws based on AE data is demonstrated.