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Inspection of Nuclear Reactor Welding by Acoustic Emission

Prepared by D. W. Prine, T. A. Mathieson, B. S. Filar

GARD, Inc.

Prepared for
U. S. Nuclear Regulatory
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FOREWORD

The work described in this report was performed by GARD, Inc. a subsidiary of GATX Corporation, 7449 N. Natchez Avenue, Niles, Illinois 60648 for the Nuclear Regulatory Commission under Contract NRC-04-74-187. The NRC Technical Representative was Dr. J. Muscara.

The work was performed at GARD in the Nondestructive Testing and Diagnostic Systems Department (W.L. Lichodziejewski, Manager), under D. W. Prine, Principal Investigator, with the assistance of T. A. Mathieson, B. S. Filar and R. A. Groenwald.

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This report is designated Inspection of Nuclear Reactor Welding by Acoustic Emission. Final Report, NUREG/CR-1441. Prior reports in this work are:

Prine,D.W., Clark,R.N., "Inspection of Nuclear Reactor Welding by Acoustic Emission," Final Report - Phase 1, NUREG - 0035-1, 1976.

Prine D.W., "Inspection of Nuclear Reactor Welding by Acoustic Emission," Data Report, NUREG - 0035-2, 1976.

Prine,D.W., Mathieson,T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission," NUREG - 0035-3, 1977.

Prine,D.W., Mathieson,T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission," Final Report, NUREG/CR-0461, 1978.

Prine,D.W., Mathieson,T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission," Progress Report, NUREG/CR-0703, 1979.

These reports are available from the National Technical Information Service.

ABSTRACT

This report is the final report on a two year extension of a previous three year program. This two year program was aimed at extending the capability of in-process acoustic emission monitoring of nuclear fabrication welds from flaw detection and location to flaw characterization in terms of type and size. During this phase a field-hardened system based on design concepts that were developed and tested during the first year was fabricated and the resulting system was successfully tested in a nuclear fabrication shop.

This report contains a detailed description of the microprocessor-based three channel weld monitor in addition to a description of the results of the field test.

TABLE OF CONTENTS

Section | Page

FOREWORD i

ABSTRACT ii

I OBJECTIVE AND SCOPE 1

II INTRODUCTION 2

III SUMMARY OF RESULTS AND CONCLUSIONS 4

IV SYSTEM DESCRIPTION AND OPERATION 7

- 4.1 System Description 8
- 4.2 Stand-Alone operation 15
  - 4.2.1 Clear Operation 15
  - 4.2.2 Run Operation 16
  - 4.2.3 Calibrate Operation 17
  - 4.2.4 Stop Operation 18
  - 4.2.5 Display Operation 19
  - 4.2.6 Miscellaneous Operation 20
- 4.3 Theory of Operation 21

V FIELD TEST 27

- 5.1 Procedure 27
- 5.2 Results 30
- 5.3 Conclusions 41

VI CODE SUPPORT AND DEVELOPMENT 42

- 6.1 Introduction 42
- 6.2 Discussion 42
- 6.3 Results 44

Appendix

A AEWM SCHEMATIC DRAWINGS

List of Figures

Figure 4.1 Acoustic Emission Weld Monitor....................................9
Figure 4.2 Detail, AEWM Front Panel..10
Figure 4.3 Transducer Orientation..12
Figure 4.4a System Block Diagram, Normal Configuration...................22
Figure 4.4b System Block Diagram, Data Acquisition Configuration..........23
Figure 5.1 Exterior Welding Operations.......................................28
Figure 5.2 Interior Welding Operations.......................................28
Figure 5.3 Acoustic Emission Weld Monitor....................................29
Figure 5.4 Transducer Placement on Shell Exterior........................31
Figure 5.5 Transducer Placement on Shell Interior........................31
Figure 5.6 Ocilloscope Display AEWM Locational Capabilities..............33
Figure 5.7 Acoustic Source Location Relative to Manway Weld..............33
Figure 5.8 Ocilloscope Display, Slag Deposit.................................34
Figure 5.9 Photograph of Typical Slag Deposit Area.......................36
Figure 5.10 Ocilloscope Display, Lack of Fusion 37
Figure 5.11 Indicated Lack of Fusion Location Relative to Manway Weld.....37
Figure 5.12 Photograph, Lack of Fusion Area...............................38
Figure 5.13 Ocilloscope Display Slag Inclusion.............................39
Figure 5.14 Indicated Slag Inclusion Location Relative to Manway Weld.....39
Figure 5.15 Photograph of Slag Inclusion...................................40
Figure 5.16 Non Locating Indications...40
Figure 6.1 Summary of AE Weld Monitoring....................................43
Figure 6.2 Piping Calibration Test Summary.................................45
Figure 6.3 Summary of Laboratory Welds (2nd Series)......................47
Figure 6.4 Flaw Detectability for "Laboratory Welds"......................48

Section I

OBJECTIVE AND SCOPE

The objective of this two year program is to extend the capabilities of in-process acoustic emission weld monitoring from flaw detection and location (result of previous three year program) to flaw type and size determination.

To accomplish this objective, the following tasks were defined:

1. Develop flaw identification and sizing software, and test on both taped and live data.
2. Field-harden a breadboard system (which includes the tested software) for use in a nuclear fabrication shop.
3. Test breadboard system in a nuclear fabrication shop.
4. Design and fabricate a computer-based AE weld monitor based on the results of the above tests.
5. Test monitor on both laboratory and shop welding.
6. Provide supporting documentation to aid in code acceptance of in-process AE weld monitoring.

Work in FY 78 concentrated on the first three tasks, while work on the remaining task was accomplished in FY 79.

Section II

INTRODUCTION

Prior to the current program, in a three year effort (1974-77),[1] the feasibility and practicality of using in-process acoustic emission monitoring to detect and locate flaws in nuclear component weldment was proven.

The feasibility was proven by fabricating welds that accurately simulated typical nuclear power plant fabrication under controlled laboratory conditions. Flaws were intentionally introduced during welding, and acoustic emission (AE) data was recorded. Post analysis of the AE data allowed AE signal processing parameters to be optimized. Conventional NDE and metallography were used to confirm flaw presence, and AE results were correlated with these findings. The practicality of applying the technique during production welding was proven by fabricating acoustic emission weld monitors (AEWM's) based on the results of this program and results achieved under parallel efforts under GATX Corporate support. These AEWM's were then applied to typical production welding in nuclear fabrication facilities and the AE results were compared to production NDE.

The successful results of these tests[1] have shown that in-process AE monitoring is a useful new NDE tool, and that in addition to detection and location AE provides:

1 - improved sensitivity (over conventional NDE) to the most serious flaw type (cracks),

2 - reduced perturbation to weld metallurgy by allowing repairs to be made on a single pass basis,

3 - hard copy of weld data on a pass-by-pass basis,

4 - applicability to welds that would be either very difficult or impossible to inspect conventionally because of accessability and/or geometry, and

5 - reduced reliance by operator interpretation because of the electronic signal processing nature of AE monitoring.

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1. Prine, D.W., Mathieson, T.A. "Inspection of Nuclear Reactor Welding by Acoustic Emission," NUREG/CR-0461, 1978.

A great deal of effort has been expended in the area of developing automatic flaw characterization capabilities in conventional NDE methods, since their ability to accurately size and type flaws would greatly expand their utility. This work has had limited success. Because of the intrinsic signal processing nature of AE monitoring, it was felt that AE might be able to perform such characterization. Thus, on the current program (1978-1980) the feasibility of expanding the capability of in-process AE monitoring, from detection and location to flaw characterization, was explored.

In the first year of this program,[2] the feasibility of accomplishing automatic flaw characterization with in-process AE was shown. In the second year adaptive flaw characterization software, based on results of the previous year's effort, was developed, and a microcomputer-based AEWM, incorporating the software, was fabricated. The system was successfully field tested in a nuclear fabrication shop.

This report is the final report on this program and describes the second year's work. It includes a description of the computerized AEWM along with a detailed description of system operation, a description and results of the field test, and a brief summary of program results that are applicable to code and standard development.

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2. Prine, D.W., Mathieson, T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission," NUREG-CR-0703, 1979.

Section III

SUMMARY OF RESULTS AND CONCLUSIONS

A computer-based AEWM was fabricated which can be operated in a stand-alone mode or in conjunction with a terminal and disc system interface. The AEWM can detect, locate and characterize flaws for a varity of different weld applications, including those commonly used in nuclear component fabrication. In the stand alone mode one dimensional location and characterization is obtained from a alphanumeric display on the AEWM itself. Two dimensional planar location of AE indications can be obtained with addition of an x-y oscilliscope.

The AEWM is composed of two basic sections . These sections perform analog operations and computer operations respectively. The analog section preprocesses the acoustic emission signals and provides ringdown counts, frequency activities and locational data. The computer section which consists of three Motorola M 6800 microprocessors, distributes and processes the data into indication types, intensities,and generates the necessary locational displays. The computer section also provides the means for operator interaction with the system and provides either automatic or manual system calibration capabilities. In the stand-alone mode, the monitor is capable of storing up to eight weld passes and sixty four AE flaw indications. The system is capable of automatic operation by means of a weld current sensor that allows the monitor to sense start and stop of a weld pass. The addition of the CRT terminal and disc system allows the AEWM to be used as a AE data logging system where raw data is stored on magnetic discettes.

The AEWM was successfully tested on over 750 feet of weld pass in a manway weld in the upper shell of a nuclear steam generator. The welding was done at the Westinghouse Electric, Water Reactor Division (Tampa, Florida). With the exception of some minor problem with one of the AEWM's modules which was easily repaired by module replacement, the system operated satisfactorily. The use of the AEWM in no way interfered with normal welding procedure. A total of seven indications were detected, located, and characterized by the monitor. Two of these were at 12 db higher than normal sensitivity and were produced by clinging slag in the lower two passes of the second half of the weld. The indications were continuous and roughly outlined the weld on the monitor's two demensional display. They were characterized as slag by the monitor. They were visually confirmed. Weld cleanup removed them. They were considered insignificant, detected only because of higher than normal system gain, but served as a test of system functionality.

The remaining five indications were one slag inclusion and four lack of fusion flaws. The flaws were visually confirmed after AE detection, ground out and repaired on the spot. The slag inclusion was correctly characterized as slag by the AEWM and was the most significant flaw detected. Associated with each flaw characterization, a number from 0 to 9 gives a relative size indication based on average ringdown count for the flaw events. A relative computer-sized magnitude of 3 was seen for the slag inclusion.

The lack of fusion indications was characterized by a mixture of both slag inclusions and cracks. This is consistent with previous AE experience in detection of this flaw type. No other AE indications were obtained and final radiography indicated no repairs.

The test showed that a sophisticated computer-based AE weld monitor can detect, locate, and characterize flaws in nuclear power plant welds during their fabrication. Furthermore, if the monitor is used as a guide for performing repair on the production floor, as it was in this test, expensive and potentially damaging post fabrication repairs can be avoided.

Section IV

SYSTEM DESCRIPTION AND OPERATION

The developed Acoustic Emission Weld Monitor (AEWM) is a microprocessor-controlled system which detects, amplifies, and processes acoustic emission bursts from welds during the welding process. The system is composed of

a. an analog processing section which contains
   1. signal amplifiers and processors,
   2. frequency analysis hardware, and
   3. source locating clocks, and

b. a computer section which contains three microcomputers, each dedicated to processing, in parallel with the other two, one of the tasks of
   1. collecting and disseminating digitized acoustic emission data,
   2. processing this data to determine indication presence location and flaw type classification and relative intensity.
   3. controlling the system via external requests and displaying the results of data collection and processing.

The Acoustic Emission Weld Monitor can be operated in a variety of configurations. The main frame of the monitor, in a stand-alone configuration, can accept up to four transducer inputs and, by appropriate instruction via the front panel push buttons, can display the type classification, relative intensity, and the location of an acoustic indication of weld annomaly. Addition of the x-y oscilloscope to the main frame stand alone configuration enhances the AEWM display repertoire to include a full x,y triangulation of the acoustic source relative to the transducer positions. Further addition of a CRT terminal with keyboard console to the back panel RS232C connector will yield displays of current AEWM status along with x,y triangulation of indications and type classification and relative intensities. Adding a flexible disc drive to this latter configuration will enhance the AEWM function repertoire to include mass storage of digital parameters derived from each acoustic burst. These configurations are usable under the present system software. Modification of that software can create configurations desired by the user. In addition, slight hardware modifications can expand the AEWM transducer acceptance from four up to ninety-five.

4.1 System Description

The Acoustic Emission Weld Monitor is shown in Figure 4.1. The front lower half of the monitor is the analog section (Figure 4.2 .) composed of one locator module in the extreme righthand slot, one frequency analyzer module in the next three rightmost slots, and eight slots for insertion of up to eight interchangeable analog modules. Each analog module has an analog buss connector on its back panel and the following on its front panel:

1.) one insulated BNC transducer connector
2.) two concentric gain selection switches
3.) three LED calibration indicators

The BNC transducer connector is the acoustic emission signal input for the analog module. It also provides 15 volts to power, preamplifiers or line drivers if required for operation. The connector is isolated from the module chassis to eliminate ground loop noise. The gain selection switches change the gain of the analog module in 2 dB steps within a gain span of 40 dB to 80 dB. The outer gain selector is a gain range switch and is designated "heat" for weld heat (or current) input. This range switch changes module gain in 13 dB steps with "low" heat being the most sensitive gain range (for presumably quieter types of welding) and with "high" heat being the least sensitive gain range (for presumably noisier types of welding). The LED calibration indicators provide information on the relative acoustic energy sensed by the module. The red low "out" and high "out" indicators inform, respectively, of acoustic energy underflow and overflow. The green "in" indicator informs that the acoustic energy sensed is typical of acoustic emission emanating from a weld annomaly. Since the sensed energy is gain-dependent, normal operations of the monitor should have gains set so that red low "out" indicators are steadily intermittent during welding.

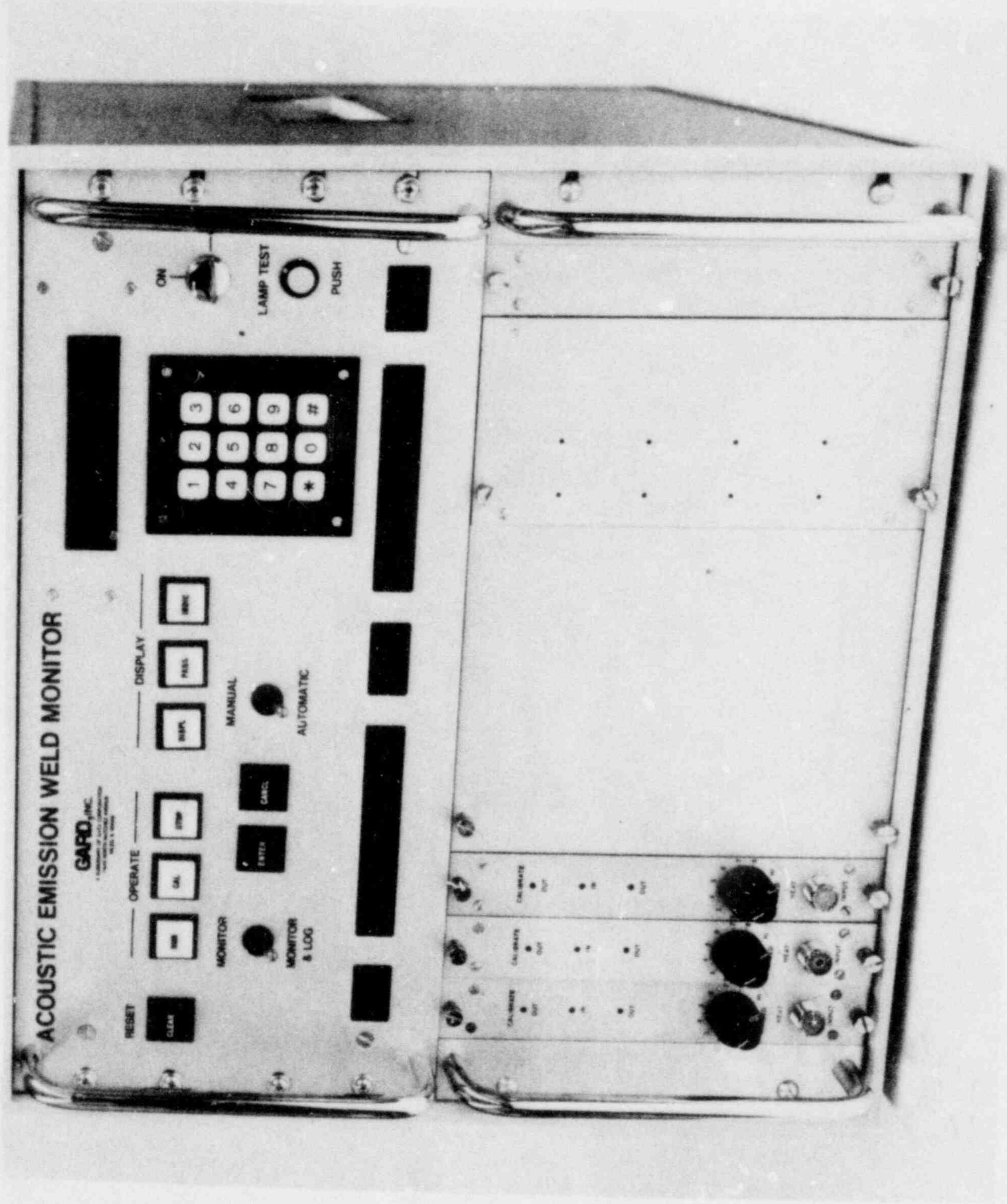

Figure 4.1 ACOUSTIC EMISSION WELD MONITOR

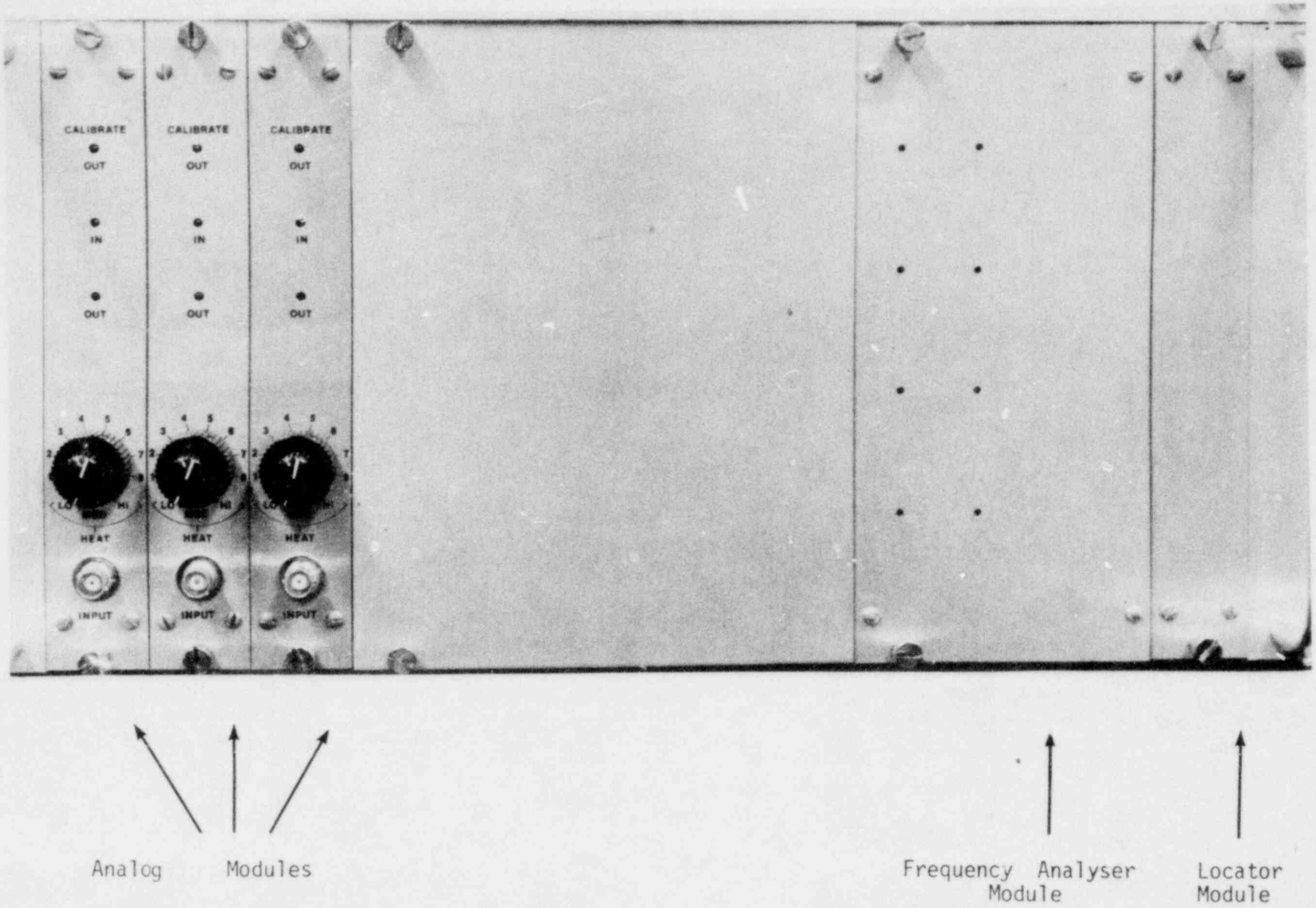

Figure 4.2 DETAIL, AEWM FRONT PANEL

The analog modules supplied with the AEWM are completely interchangeable. The unique individuality of each module , and hence of its connected transducer, is determined by a bit pattern encoded in the multipin receptacle on the analog buss. This coding is such that the analog module in the extreme left slot of the monitor will be identified and sensed by the system's computer as "module 1" and its connected transducer will be designated "transducer 1". Likewise, the analog module in the rightmost available slot (next to the frequency analyzer module) and its connected transducer will be designated, respectively, as "module 8" and "transducer 8". The modules and transducers must be inserted and connected so that the lowest numbers are occupied in a contiguous manner. The order of transducer connections is immaterial to the AEWM, but for the operator's convenience in referring from the monitor display to the actual weld it is recommended that

1. the transducer the operator sees as oriented to his lower left be called transducer 1,
2. the transducer the operator sees as oriented to his lower right be called transducer 2, and
3. all other transducers lie above the line connecting transducers 1 and 2 and to the right of a perpendicular line passing through 1. (See Figure 4.3)

The frequency analyzer module has an analog buss connector on its back panel and eight access holes on its front panel to allow balancing of the rectified outputs of each of eight passive filters. Table 4.1 lists the center frequencies of the eight filters. For proper operation this module must occupy slots 9 to 11 on the analog buss.

The locator module has an analog buss connector on its back panel. This module provides two locating clocks for the triangulation of acoustic emission sources,and also serves as a buss interface between the analog section of CMOS logic and the computer section TTL logic. For this latter function, the locator module must always occupy the rightmost slot (slot 12) of the analog section.

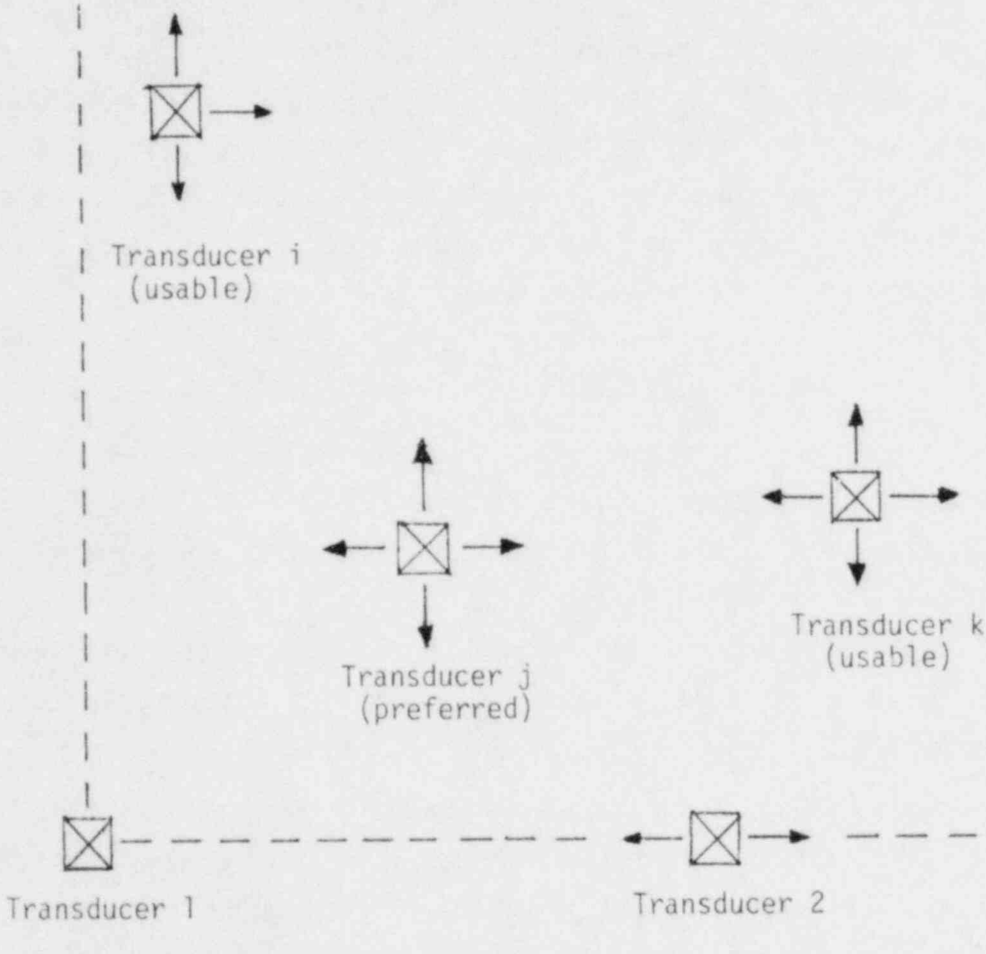

Figure 4.3

TRANSDUCER ORIENTATION

110 kHz	150 kHz	200 kHz	270 kHz
370 kHz	500 kHz	675 kHz	920 kHz

-3dB at ± 30 % of center

Table 4.1

CENTER FREQUENCIES, FREQUENCY ANALYZER MODULE

The front upper half of the AEWM contains the stand-alone controls and display section. This is composed of:

1) a key-lockable on-off switch,
2) a lamp test button,
3) a sixteen-character alphanumeric display,
4) a twelve-entry numeric keypad,
5) nine push-button function keys, and
6) two AEWM state switches.

The on-off switch controls system power and the removable key lock provides security against accidental losses of power. The lamp test button tests the lights associated with the push-button function keys. The alphanumeric display provides 1.) positive feedback of all push-button and keypad entries, 2.) displays of indication locations for each of up to eight weld passes, 3.) displays of indication type classifications and relative intensities, and 4.) system error messages. The numeric keypad is used to enter numbers and separators as part of the AEWM function selection. The keypad character "*" is used as a comma and echoes back a ",".

The push-button function keys serve two purposes. As push buttons, they allow selection of AEWM functions by the entry of simple command statements composed of words associated with the nine keys. As lights, they indicate the current function being processed by the monitor. The state switches are hardware selectors of major AEWM operational states. The "manual/automatic" switch selects between whether start and stop of acoustic emission data acquistion is 1.) the sole responsibility of the operator or 2.) the joint responsibility of the operator and/or a welding current sensor. The "monitor/monitor and log" switch selects whether acoustic emission data will 1.) only be processed or 2.) be processed while a simultaneous mass storage of unprocessed data onto flexible disc is performed.

The back panel of the AEWM contains connectors for:

1) welding current sensor input,
2) outputs to drive an x-y oscilloscope with z-axis modulation,
3) an EIA RS232C interface for teletype or CRT terminal control and display,
4) an ICOM-configured disc system interface, and
5) a line power connector with fuse

A schematic diagram of the system is shown in Appendix A.

4.2 Stand-alone Operation

In this section an extensive description of the possible push-button function commands will be made. Each command statement is set up as a simple sentence composed of words selected from the following vocabulary:

CAL
CANCL
CLEAR
DISPL
ENTER
INDIC
PASS
RUN
STOP

Each command sentence is composed as if one were telling a person of limited intelligence to perform one required operation at a time. In addition, each command sentence if terminated by ENTER starts the required operation or by CANCL erases memory of the entire command sentence. Thus, a request to display the results of monitoring weld pass 3 would be set up by pushing the appropriate front panel keys in the following sentence:

[DISPL] [PASS] ③ [ENTER]

In the following discussion of command sentences and their results, the command sentence format is always composed according to the foregoing rules.

4.2.1 CLEAR Operation

These command statements are used to clear some element or array of computer memory:

[CLEAR] (n) [ENTER] unlocks the software lock of the AEWM, thereby restoring operator control of system function via the front panel push-buttons. The number n must be the same number entered when the operator locked the AEWM (see [STOP] (n) [ENTER]).

[CLEAR] [PASS] (n) [ENTER] clears all the indications detected during the welding of pass n. If no pass number or a pass number in excess of eight is entered, the command will be ignored and the error message "ERROR n" will appear on the alphanumeric display.

[CLEAR] [INDIC] (x) (*) (y) [ENTER] clears the next stored indication at co-ordinates x, y for the pass previously entered as n (see [PASS] (n) [ENTER]). The co-ordinate x is the horizontal displacement of the indication from the left of the pass display and the co-ordinate y is the vertical displacement of the indication from the bottom of the pass display. If there is only one indication at x, y in pass n, then the next stored indication at x, y is that one, and that is the indication that will be cleared. However, it is possible that more than one indication in pass n has the co-ordinates x, y and, if such is the case, the indication cleared will be the one which follows in sequence the indication at x, y currently being displayed (see DISPL INDIC ⓧ ⊛ ⓨ ENTER).

If the front panel alphanumeric display is the only one being used, then the co-ordinate x is directly obtainable from a display of pass n by counting from left to right the number of cells to the desired indication (the leftmost cell is x=0 and the rightmost is x=15. On this display of pass n, the number or letter in the cell is not the co-ordinate y, but the number of indications in memory sharing the same co-ordinate x. The co-ordinate y must be found by explicitly searching through the possible values of y (from y=0 at the "display" bottom to y=15 at the "display" top) for the desired indication. (see DISPL INDIC ⓧ ⊛ ⓨ ENTER). The operator must then take care that once the co-ordinates of the desired indication are found, and if more than one indication share those co-ordinates, he must then cycle around until he is displaying the indication immediately prior to the one he wants cleared. Then he can safely issue the CLEAR INDIC command.

The determination of proper co-ordinates is greatly simplified if an oscilloscope is being used with the AEWM. The oscilloscope picture will be that of the indication at its apparent source relative to the transducers (also shown as squares). Dividing this picture into a sixteen by sixteen grid allows the operator to immediately see the exact or nearly exact x, y required to target the desired indication. If either or both entered indication co-ordinates are in excess of fifteen, the command will be ignored and an error message "ERROR x, y" will appear on the alphanumeric display.

4.2.2 RUN Operation

These command statements are used to indicate some mode of AE data acquisition. RUN PASS ⓝ ENTER starts the acquisition, processing and transfer of acoustic emission data as sensed by any or all transducers connected to the system. If no pass number or a pass number in excess of eight is entered, the command statement is ignored and the error message "ERROR n" appears on the alphanumeric display. If, in an attempt to execute this command, the controlling peripherals microcomputer cannot communicate with the data collecting microcomputer or the data processing microcomputer, the respective error messages "ERROR C" or "ERROR D" will appear on the alphanumeric display and the RUN command will be ignored.

4.2.3 CALibrate Operation

These command statements are used to perform a variety of inter-transducer interval measurements.

CAL ENTER starts the monitor's automatic interval calibration sequence. Each analog module, starting from 1 and proceeding to 8, is directed by the system to drive its transducer sixteen times with a pulse of 60 V peak and 2 usec duration. The system will wait two milliseconds after each such pulse for the resultant acoustic wave to travel through the material and be sensed by one or two other transducers. When the wave is sensed, the time interval between pulse generation and reception is stored as a measure of the interval between the pulsing transducer and the receiving transducer. When no wave is sensed, the fact is noted and, in either case, the pulsing continues until the count of sixteen. The system then summarizes the results, proceeds to the next module in sequence, and repeats the process. After all eight modules are pulsed (128 pulses in all), the system then executes an automatic stop of the calibration (see STOP CAL ENTER).The operator should be aware that the two millisecond interpulse wait period imposes a maximum inter-transducer interval in steel of about 20 feet. He must also take care that all module-to-transducer connections are not interrupted by active elements such as line drivers or pre-amplifiers. The 60 V calibration pulse delivered by the system could impair the operation of such elements.

CAL ⓝ ENTER starts each of the monitor's single-step pulse calibration. This mode is used when preamplifiers or line drivers are needed to boost the acoustic signal strength in the receiving transducers. Only the module designated by the entered number n will deliver sixteen pulses to its connected transducer. By such control of the pulser module, the operator is able to remove the preamplifier or line driver at the transducer before pulse train delivery and is able to replace it after.

When all transducers necessary to sample intervals across the area to be monitored have been pulsed, the operator must then manually terminate this calibration mode (see $\boxed{\text{STOP}}\boxed{\text{CAL}}\boxed{\text{ENTER}}$).

$\boxed{\text{CAL}}$ ⓐ ⊛ ⓝ $\boxed{\text{ENTER}}$ performs each of the monitor's manual loads of inter-transducer intervals. This mode is used when it is impossible to transmit pulsed acoustic emission between transducers across the area to be monitored. The AEWM is currently programmed to assume approximately the shear velocity of sound in steel or aluminum and so the entered number n must be the interval in inches between transducer i and transducer j. The entered number a is composed of two digits, the first being the designation of transducer i and the second being the designation of transducer j. No pulses are generated by any module when this mode is used. When the operator has entered as many intervals as necessary to sample the area to be monitored, he must manually terminate this mode (see $\boxed{\text{STOP}}\boxed{\text{CAL}}\boxed{\text{ENTER}}$).

4.2.4 STOP Operation

These command statements are used to stop some mode of AEWM operations.

$\boxed{\text{STOP}}$ ⓝ $\boxed{\text{ENTER}}$ locks the monitor against any accidental or unauthorized tampering with the push-button keys. Until the system is unlocked (see $\boxed{\text{CLEAR}}$ ⓝ $\boxed{\text{ENTER}}$), all depressions of front panel function keys are ignored and all entries of numerical data are merely echoed on the alphanumeric display. Ongoing operations are not disrupted when the software lock is set, but the system must then be unlocked before the operator can change these operations. The entered number n is solely of the operator's choosing and is effectively the combination of the lock. That is, the same number must be used to unlock the AEWM.

$\boxed{\text{STOP}}\boxed{\text{RUN}}\boxed{\text{ENTER}}$ stops the acquistion, processing, and transfer of acoustic emission data.

$\boxed{\text{STOP}}\boxed{\text{CAL}}\boxed{\text{ENTER}}$ stops single-step pulse or manually loading modes of interval calibration. The AEWM will then 1) organize a table of inter-transducer intervals for future locating of indications, 2) count the number of connected transducers and compute x,y co-ordinates for each transducer, and 3) transmit this information for the purposes of operator interrogation.

For the computation of a series of transducer coordinates that will be convenient for the operator, it is recommended that transducer 1 be set in the lower left of the operator's reference frame, transducer 2 be set in the lower right, and that all other transducers lie beyond the line between transducers 1 and 2 and to the right of transducer 1 (See Figure 4.3).

STOP DISPL ENTER stops displays on the alphanumeric panel and oscilloscope (if connected). This command is independent of the display type (pass, indication, calibration, or error messages).

4.2.5 DISPLay Operation

These command statements are used to display information stored in the peripherals microcomputer memory.

DISPL CAL ENTER shows the position of connected transducers on the oscilloscope output and shows one inter-transducer interval in the following format on the alphanumeric display:

a / n "

where a is a two-digit number, the first digit identifying the pulser transducer and the second digit identifying the receiving transducer

n is the approximate inter-transducer interval in inches assuming the material is aluminum or steel.

Sequential repetitions of this command will cycle through all the stored intervals.

DISPL PASS ⓝ ENTER shows the location of indications detected during weld pass n. The oscilloscope display is a 4096 by 4096 point display of each indication's position relative to the transducer positions. The alphanumeric display is a sixteen-point projection of all indication positions onto the line between transducers 1 and 2. The digit or letter in this display is not the vertical coordinate, but the number of indications sharing the same horizontal coordinate within the resolution of the sixteen-point display. When the number of such indications exceeds nine, letters are used to continue the count with A equal to 10 and Z equal to 35.

$\boxed{\text{DISPL}}$ $\boxed{\text{INDIC}}$ ⓧ ⊛ ⓨ $\boxed{\text{ENTER}}$ shows the type classification and relative intensity of the indication located at x, y relative to the transducers for weld pass n (see $\boxed{\text{PASS}}$ ⓝ $\boxed{\text{ENTER}}$). The coordinate x is the horizontal displacement of the indication from the left of the pass display and the coordinate y is the vertical displacement of the indication from the bottom of the pass display. It may happen that more than one indication in pass n will have the coordinate x, y. When this is the case, sequential repetitions of this command for the same x,y will cycle through all such indications. If only the alphanumeric display is being used, the coordinate x will be directly obtainable from a display of pass n by counting from left to right the number of points to the desired indication (the leftmost point is x = 0, the rightmost is x = 15). The coordinate y, however, must be found by searching through the possible values of y until the desired indication appears. The values of y are limited between y = 0 at the "display" bottom and y = 15 at the "display" top. The determination of proper coordinates is greatly simplified if an oscilloscope display is used. This display will show all indications at their apparent sources relative to the transducer positions (shown as squares). Imposing a sixteen by sixteen grid on the oscilloscope picture allows the operator an immediate measure of the x,y required to target the desired indication.

4.2.6 Miscellaneous Operation

$\boxed{\text{PASS}}$ ⓝ $\boxed{\text{ENTER}}$ allows the operator to change the weld pass number independent of ongoing operations. This must also be done at least once before starting or resetting an automatic mode of operation

$\boxed{\text{PASS}}$ $\boxed{\text{ENTER}}$ allows the operator to ask the AEWM what is the current pass number. The answer appears on the alphanumeric display.

Monitor/Monitor and Log State Selection should be set to Monitor only in the stand-alone configuration. An auxiliary flexible disc system is required to run in the Monitor and Log state.

Manual/Automatic State Selection allows the operator to choose whether he will have sole control of starting and stopping AEWM data acquisition or whether he will share such control with a welding current sensor. With the exception of $\boxed{\text{RUN}}$ $\boxed{\text{PASS}}$ ⓝ $\boxed{\text{ENTER}}$, $\boxed{\text{STOP}}$ $\boxed{\text{RUN}}$ $\boxed{\text{ENTER}}$, and $\boxed{\text{PASS}}$ ⓝ $\boxed{\text{ENTER}}$, all the commands outlined in this section are not controllable by the current sensor. In the Manual AEWM State, the operator is solely responsible for starting and stopping data acquisition and for numbering passes. However, in the Automatic AEWM state, the detection of 0.5 seconds of continuous weld current will start data acquisition and data transfer into the present pass if at least one pass has been explicitly numbered by the operation using the $\boxed{\text{PASS}}$ ⓝ $\boxed{\text{ENTER}}$ command. One minute after the cessation of weld current, data acquisition will be stopped, the pass number advanced, and if less than nine, the AEWM will wait for another weld current. If the advanced pass number is nine, the software automatic start flag is cleared and will not be set until a pass is explicitly numbered by the operator. As long as this flag is clear, the AEWM is effectively out of the Automatic State and will not respond to a welding current command to start data acquisition and data transfer into pass numbers in excess of eight. At any time in the Automatic AEWM State, the operator can intervene and preemptorily start or stop data acquisition.

4.3 Theory of Operation

A functional block diagram of the Acoustic Emission Weld Monitor is shown in Figure 4.4. The AEWM is composed of two basic sections, analog operations and computer operations. The analog section preprocesses the acoustic emission signals into ringdown counts, frequency activities, and locations. The computer section distributes and processes the data into indication types, intensities, and x,y co-ordinates.

The heart of the analog section is the analog signal buss. This is a complex of digital and analog signal lines used for communication between any module on the buss. The locator module on the analog buss, in addition to its other functions of location clocking and calibration pulse generation, serves as the interface between the 12 volt logic of the analog buss and the 5 volt logic of the computer section.

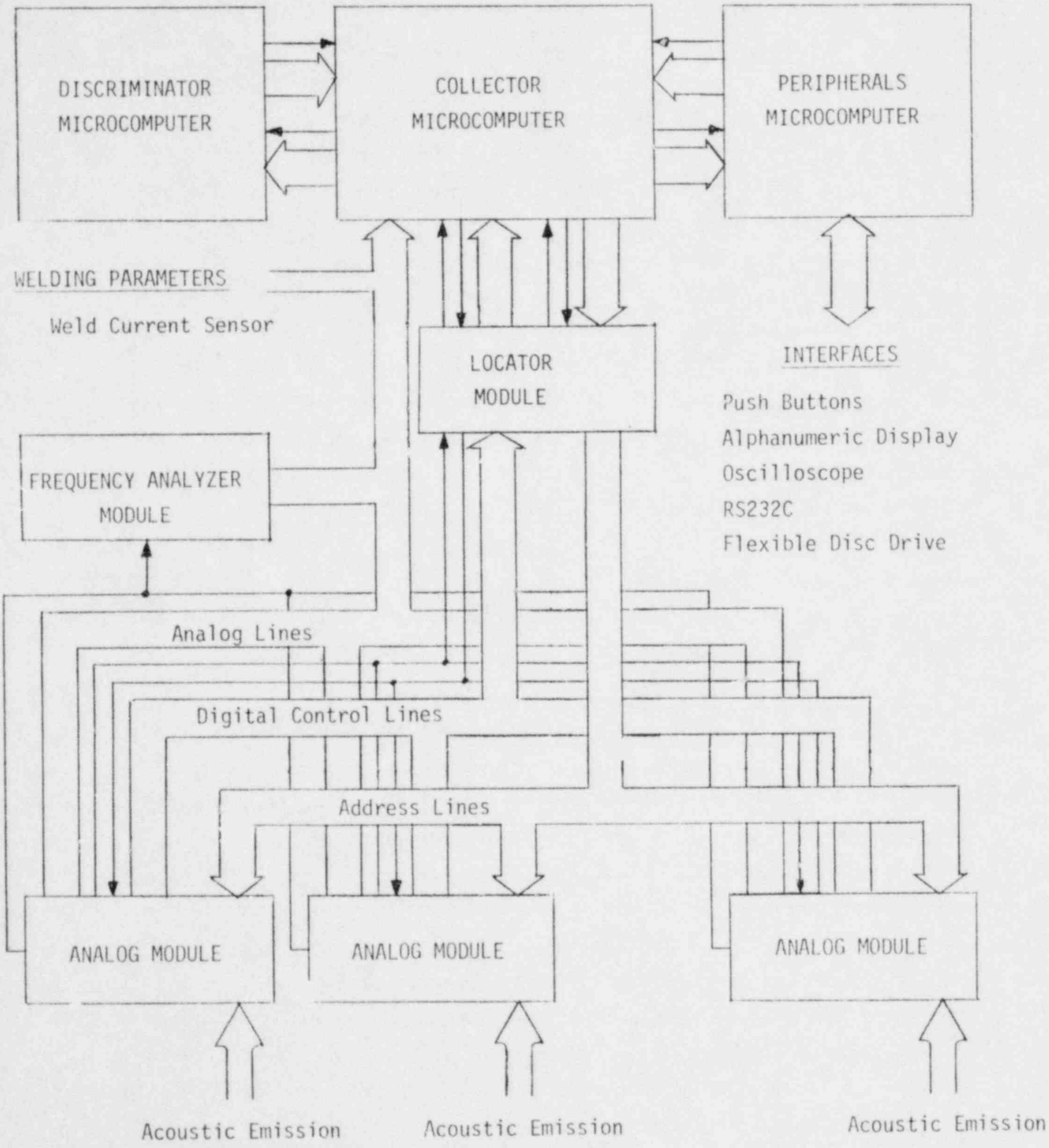

Figure 4.4a SYSTEM BLOCK DIAGRAM, NORMAL CONFIGURATION

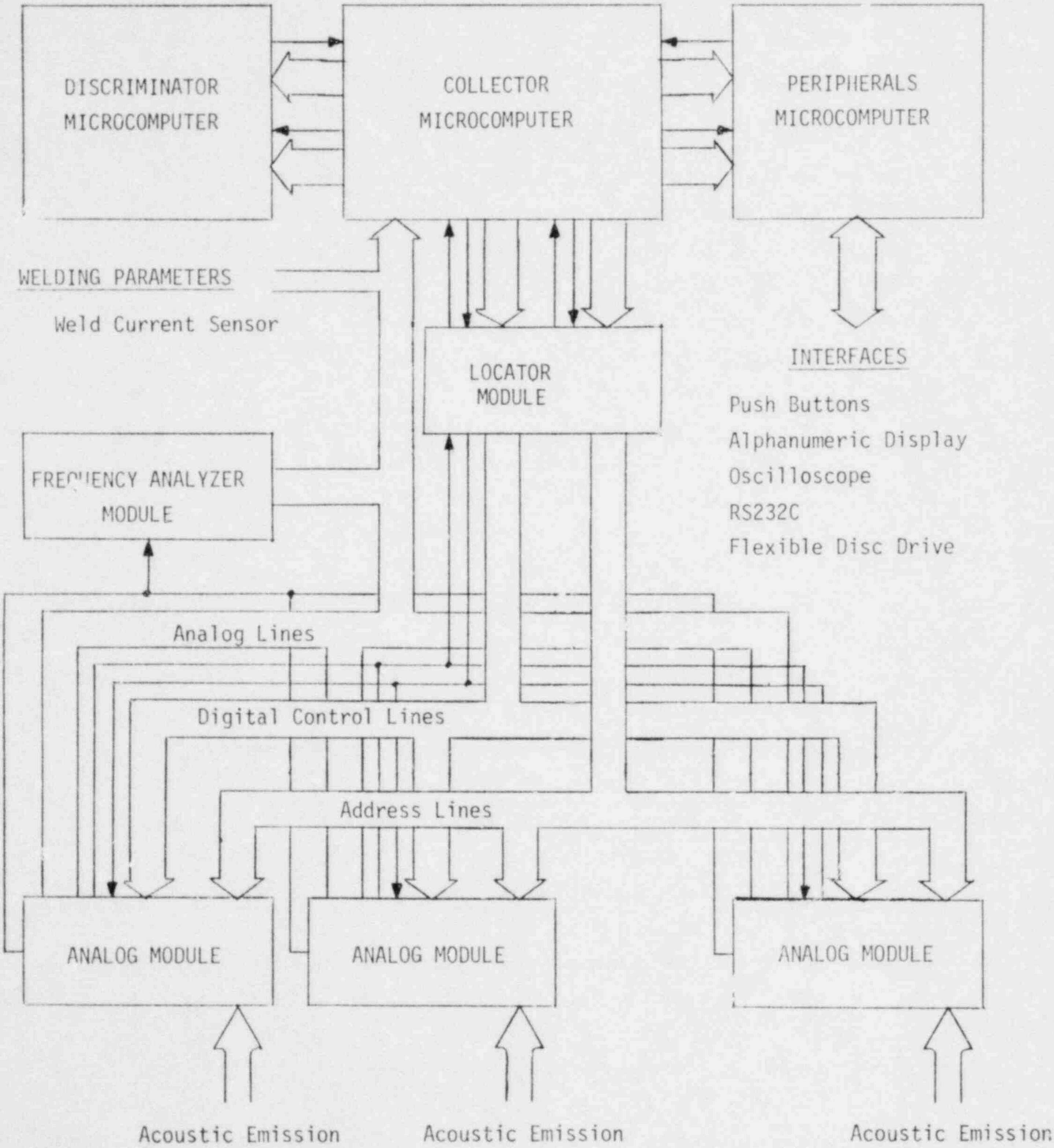

Figure 4.4b SYSTEM BLOCK DIAGRAM, DATA ACQUISITION CONFIGURATION

The computer section is composed of three microcomputers each using elements of the Motorola M6800 microprocessor family. The program for each of the microcomputers is based in EPROM firm ware. The microcomputer that interfaces with the analog buss is termed the "Collector" microcomputer because it is dedicated to the task of collecting, on an interruptable asynchronous basis, preprocessed acoustic emission data from the analog buss. The collector then sends this data to both the "Discriminator" and the "Peripherals" microcomputers. The "Discriminator" processes the data to determine if a weld abnormality indication has occurred and, if so, classifies the indication as to type and relative intensity. Upon termination of processing an indication, the "Discriminator" then uses the "Collector" microcomputer to transfer the processed indication to the "Peripherals" microcomputer for retrieval. The "Peripherals" microcomputer interfaces with all the peripherals used to control the AEWM and store and display the results of weld monitoring. The basic peripherals are the front panel push buttons, keypad, state switches, and alphanumeric display. Provision has been made to add oscilloscopes, current sensors, teletype of CRT terminals, and flexible disc systems to enhance the AEWM's capabilities.

A useful way to describe how the monitor works in detail is to follow the course of acoustic emission event from its source in the weldment to its final disposition in the AEWM. As is typical of sound traveling in a surface, the acoustic emission expands in a circular wave front centered upon its source. One of the AEWM transducers will be the first to be activated by a part of this wave front, and when that signal reaches the connected analog module, the hardware based preprocessing of the signal begins. The signal is amplified by 40 dB and then attenuated by a resistive network controlled by the front panel gain selectors. The signal is then high-pass filtered at 100 kHz and split into two branches. One branch merely amplifies the signal 20 dB and sends it along the analog buss to the frequency analysis module where it is amplified an additional 20 dB. The other branch low-pass filters the signal to 400 kHz, amplifies it 40 dB, compares it with a 1 volt threshold and uses it to drive a counter which computes the ringdown count. The first pulse out of the comparator is also used to start both clocks in the locator module. A short time after passage of the last pulse of the train out of the comparator (usually 7-20 milliseconds), the analog module logic decides the acoustic event is over and initiates an interrupt to the "Collector" microcomputer. During this post-event timeout, other transducers connected to the AEWM have been detecting other parts of the same wave front and their associated analog modules have been processing in a similar manner.

Principle criteria in operation are:

1) The first analog module to receive the acoustic signal is the only one to pass its amplified wave form to the frequency analyzer module,
2) The second analog module to receive a signal stops one of the location clocks started by the first-receiving module,
3) The third analog module to receive a signal stops the other location clock.

By the time the "Collector" microcomputer responds to the interrupt signal, each analog module on the analog buss will have ready for transmission its ringdown count in the form of an analog voltage and a digital bit pattern identifying the order in time in which the expanding wave format crossed its transducer; the frequency module will be holding on eight parallel analog outputs a rectified measure of the frequency colorations of the wave; and the locator module will be ready with two parallel analog voltages representing the counts on its location clocks.

The "Collector" will first interrogate the analog modules to find the time order of acoustic emission reception. It does this by sequencing through all the module addresses using the address lines on the analog buss and strobing each module to force a write of its time order bit pattern to the "Collector" data port. The "Collector" loads the address of each responding module and its reception time order into a time order lookup table and then uses this table to interrogate the responding modules for their respective ringdown count values in the order of their reception. If at least one ringdown count exceeds a set threshold (12 in this monitor), the "Collector" microcomputer proceeds to acquire the eight frequency activities and the two location clocks. It then resets all modules on the analog buss, interrupts both the "Discriminator" and the "Peripherals" microcomputers, and transfers this data package along with the clock time to them. If no ringdown count exceeds the set threshold, the acoustic emission is ignored and the modules on the analog buss are reset.

When acoustic emission data transfers from "Collector" out to Discriminator" and "Peripherals" occur, Figure 4.4 illustrates how the intercomputer interfaces are modified to effect a high-speed handshake-secured transfer. In both the transfer and non-transfer states, the "B" sides of the Collector-Discriminator and Collector-Peripherals interface adapters (PIA's) remain set as outputs on the Collector side and inputs on the Discriminator and Peripherals sides. In the non-transfer state (Figure 4.4a), used for low-speed intercomputer communication, the "A" sides of these PIA's are set as inputs on the Collector side and outputs on the Discriminator and Peripherals sides. However, in the high-speed transfer state (Figure 4.4b), the "A" sides switch so that they are outputs on the Collector side and inputs on the Discriminator and Peripherals sides. The "B" side of each Collector-to-microcomputer PIA is set to automatically pulse line CB2 upon a write operation to the PIA, and the "A" side of each microcomputer Collector PIA is set to automatically pulse line CA2 upon a read operation from that PIA. Thus, by programming the Collector to write to its intercomputer interface in an A, B order and by programming the Discriminator and the Peripherals to read from their Collector interface in a B, A, order the speed of transfer can be enhanced by automatic handshaking and, for the transfer of 20 acoustic emission and weld parameters, will take less than two milliseconds.

Section V

FIELD TEST

5.1 Procedure

The Acoustic Emission Weld Monitor (AEWM) field evaluation tests were performed at the Westinghouse Electric Corporation Water Reactor Division, Tampa, Florida. Acoustic emission was monitored during the welding of a manway port onto a steam generator upper shell section. (Figure 5.1) The welding process was submerged arc and proceeded on a three shift per day basis. The weld was monitored continuously for a period of one week. This period covers the entire welding operation with the exception of the final welding to the built-up areas around the manway on the interior of the shell. A photograph of the welding performed on the interior of the shell can be seen in Figure 5.2. The total amount of weld monitored exceeds 750 feet.

Acoustic emission data was obtained from the alphanumeric display on the AEWM (Figure 5.3) and the oscilloscope display generated from the AEWM. The oscilloscope display presents a two-dimensional representation of acoustic source locations relative to transducer locations. The AEWM alphanumeric display presents these locations of indications as a projection onto the base of the triangle formed by the three transducers (x-axis).

The operator can interrogate the AEWM and determine the y coordinate and a characterization of flaw type and size by means of front panel controls and the alphanumeric display. Flaw indications are shown as either slag inclusions or cracks. Characterization is dependent on the relative frequency content of the acoustic events. Associated with each flaw characterization, a number ranging from 0 to 9 gives a relative size indication determined from the average ringdown count for the flaw events. During the field test, the monitor was used almost exclusively in its automatic mode. In this state, the monitor will detect no acoustic emission until it senses weld current by means of an encircling probe attached to the weld current lead, and will continue monitoring one full minute after weld current is stopped. The location and characterization of indications are then stored in AEWM memory. The memory within the AEWM can contain up to 65 indications per weld for eight weld passes. Previous weld passes can be recalled for analysis during monitoring

Figure 5.1 EXTERIOR WELDING OPERATIONS

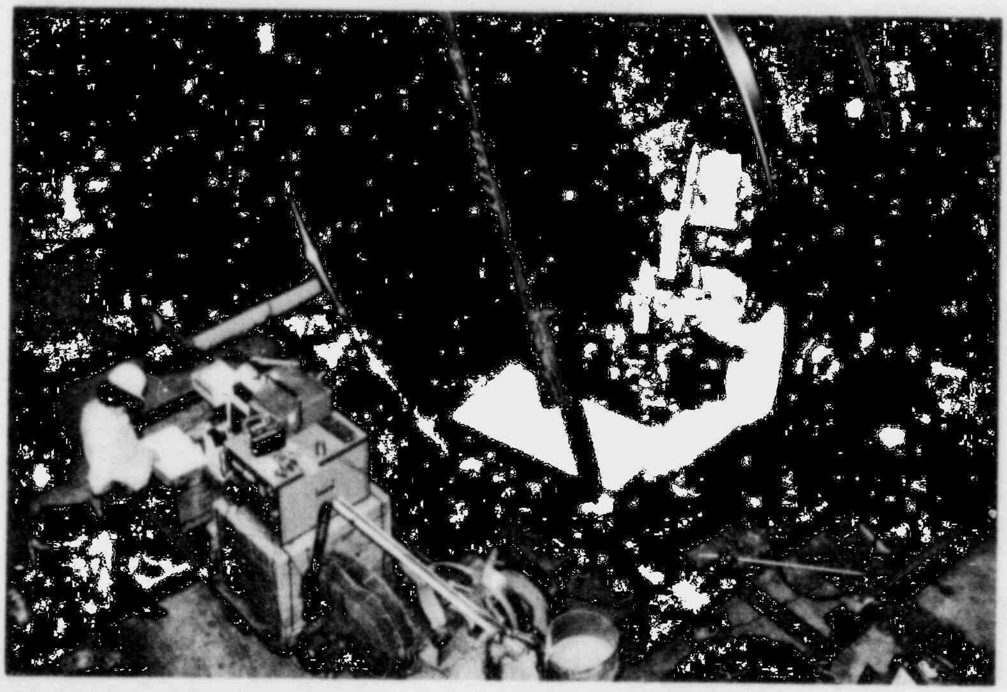

Figure 5.2 INTERIOR WELDING OPERATIONS

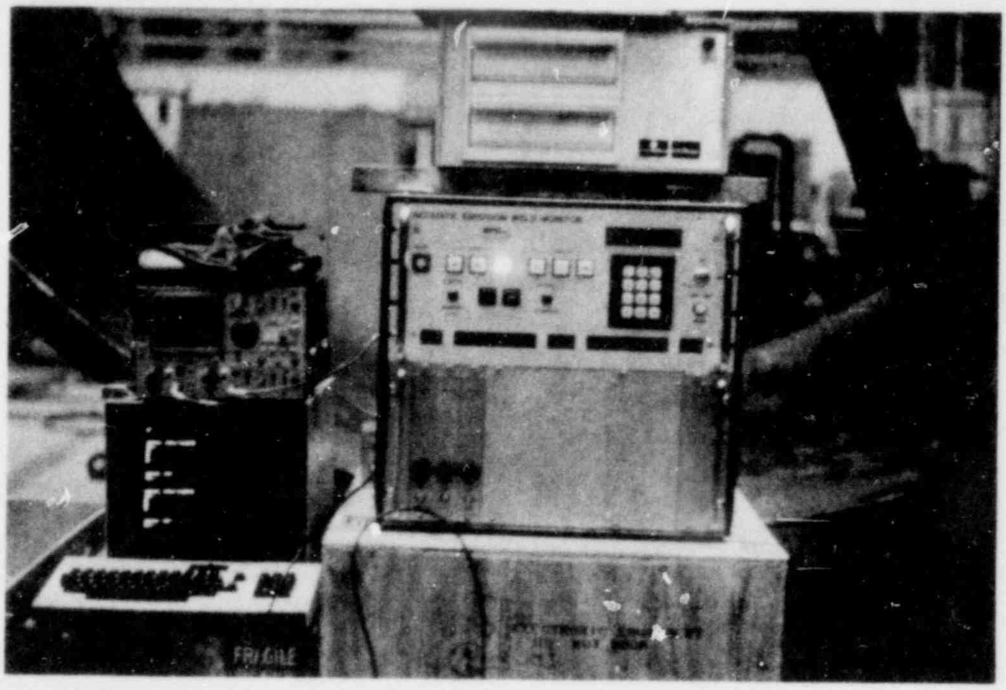

Figure 5.3 ACOUSTIC EMISSION WELD MONITOR

of additional weld passes. During the monitoring of the exterior welding. some difficulty was encountered with the locator module and it was replaced before the interior or root pass welding had begun. No further difficulty with the monitor was experienced. Due to the questionable performance of the locator module during the first portion of the weld, the results of this test are based on the interior or later weld passes. No visual flaws were reported during the exterior welding and no flaws were seen in final radiography.

The manway weld has a circular configuration and the transducers were placed in a triangular orientation enclosing the weld seam. Two transducer types were employed during the tests due to the high temperature encountered from weld preheat. While monitoring the exterior weld passes the temperature of the shell near the transducers appeared to approach 200°F and this required the use of high temperature transducers (Dunegan/Endevco Model D9205M2). Transducer placement on the outside of the shell is seen in Figure 5.4. During the interior welding, the temperature of these areas was considerably less and permitted the use of higher gain low temperature transducers (Dunegan/Endevo Model SM140). Figure 5.5 shows the placement of these transducers on the interior of the shell. High temperature silicone grease was used as a couplant for the transducers. No problems with the transducers or the couplant were encountered during the tests.

Welding operators were encouraged not to alter normal operating procedure during field experimentation. Interference by monitoring personnel was also kept at a minimum. All interruptions in procedure consisted of periodic inspection of transducer couplant and weld bead inspection when an acoustic indication was observed.

5.2 Results

As mentioned previously, these results are based on welding operations performed on the interior of the shell after exterior welding and air arc of original root pass welds. These results are only concerned with what would be considered significant event indications. This excludes isolated single events and includes only those which:

1.) Repeat on different weld passes,
2.) Show large number of indications on a single weld pass, or
3.) Have high relative size indication.

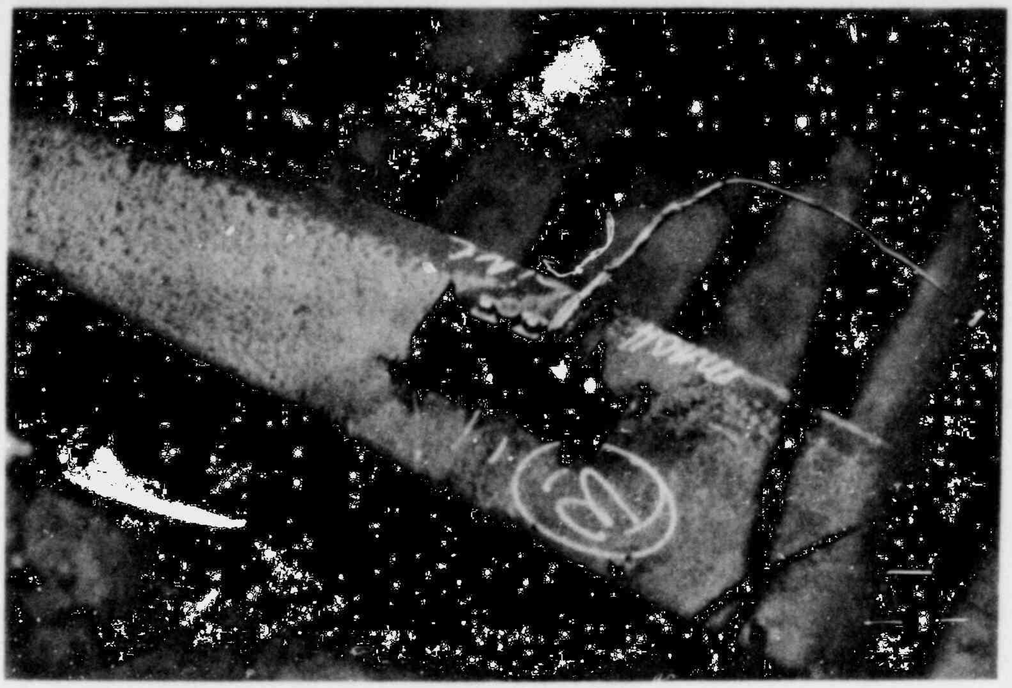

Figure 5.4 TRANSDUCER PLACEMENT ON SHELL EXTERIOR

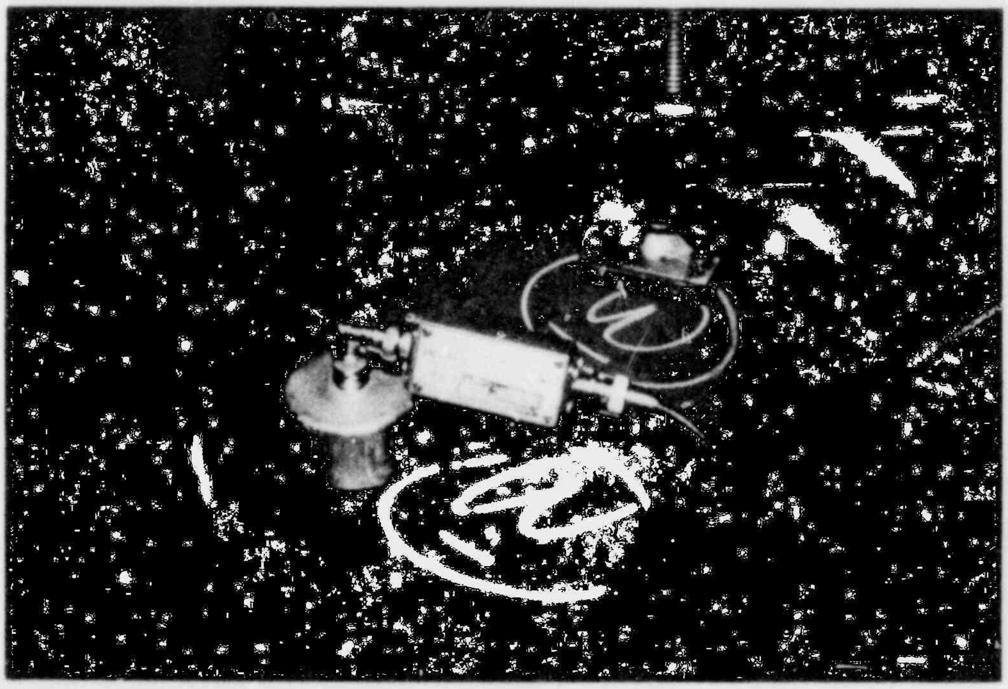

Figure 5.5 TRANSDUCER PLACEMENT ON SHELL INTERIOR

The first two criteria have evolved from experience on over 14,000 feet of weld passes previously monitored during this program. The third criteria has only been available since the inclusion of the computer-based AEWM developed in this program. No indication detected during this test exceeded a computer sized number of 3 which indicates that the majority of indictions probably would not have been serious enough to warrant ASME code rejection.

Location by the AEWM is demonstrated in Figure 5.6. The small squares in the display represent transducer locations and acoustic (mechanical tapping) signals generated around a circular weld seam appear as points. An outline of the weld seam created by these acoustic sources can be seen in the Figure. The source locations are mapped onto a diagram of the manway seam in Figure 5.7. Displacements of AE source locations away from the weld seam are caused by three factors: detection of a low level acoustic event by only two of the three transducers, inaccuracies in the computer locational algorithm, and inaccuracies resulting from threshold crossing measurements. When an event has low enough energy to be detected by only two transducers, it will be located on a line between the transducers, because the third transducer has no locational information. This is responsible for the larger displacements seen in the Figures. For example, the group of four events in the upper left corner of Figures 5.6 and 5.7 were not detected by transducer 2 and clearly lie on a line between transducer 1 and 3. Smaller displacement of events near the weld seam are due to a) the system's use of an electronic threshold for locator timing initiation: different acoustic pulse rise-times cause locational variations, and b) the system's use of a simplified locational algorithm due to computer constraints.

After the exterior welding had been completed, the root passes were removed by air arc and grinding. This region of the weld is traditionally where most repairs are necessitated. The resultant groove at the base of the seam was very narrow and considerable amounts of slag were deposited on the walls of the weld. Figure 5.8 shows the detection of this deposited slag by the AEWM for the initial weld pass at a very high gain setting (72db). Typical gains during monitoring were 60-65 db. An example of a

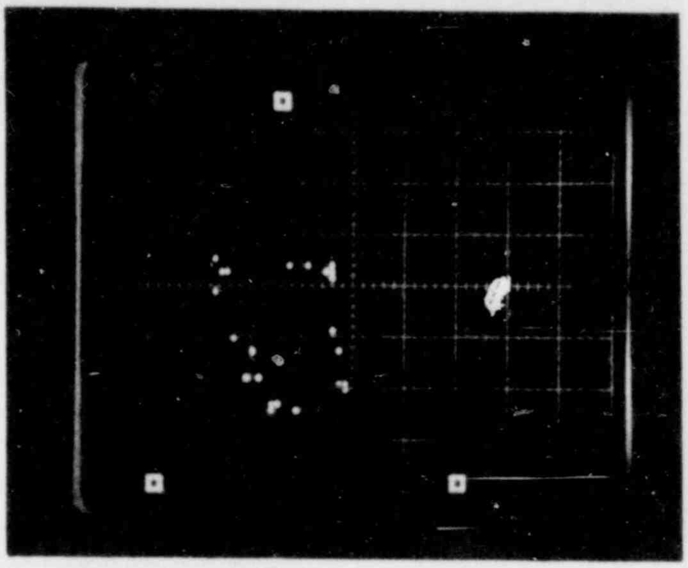

Figure 5.6 OSCILLOSCOPE DISPLAY AEWM LOCATIONAL CAPABILITIES

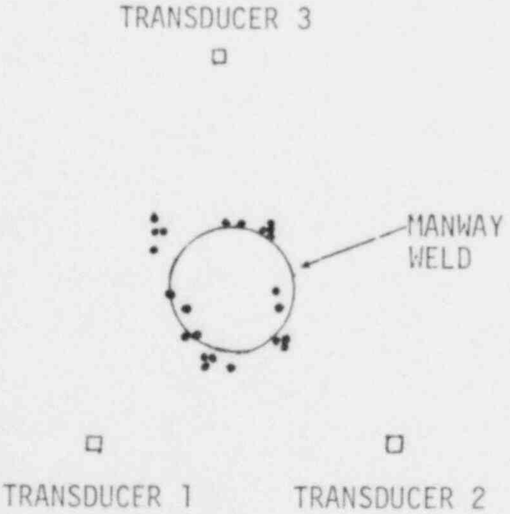

Figure 5.7 ACOUSTIC SOURCE LOCATION RELATIVE TO MANWAY WELD

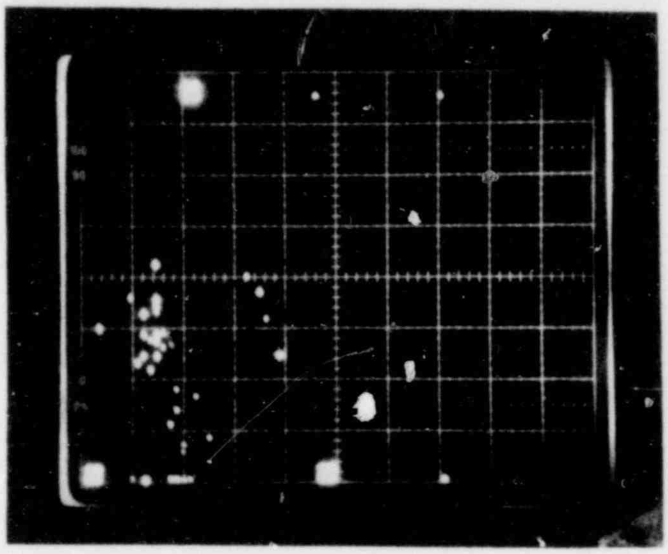

Figure 5.8 OSCILLOSCOPE DISPLAY, SLAG DEPOSIT

typical slag is seen in the photograph of Figure 5.9. The slag was deposited throughout the circumfrential weld pass as was seen by the AEWM. The weld was so acoustically active at this point that the AEWM memory capacity of 64 indications was completely filled.

The AEWM also detected a considerable amount of lack of fusion that occurred for a series of the initial weld passes. An example of this is seen in Figure 5.10. The areas indicated directly correspond to lack of fusion areas on the weld bead. This is illustrated by the diagram of Figure 5.11 and a photograph of one of these areas in Figure 5.12. These areas were immediately ground out, and did not appear on weld radiography. What the AEWM actually detected in the lack of fusion areas was a combination of slag inclusions and cracks which normally occur with this type of defect. This was confirmed by the AEWM which displayed an even distribution of crack and slag indications of varying degrees in the lack of fusion areas.

The earlier portion of interior weld passes also showed a indication of slag inclusion which was confirmed by visual observation. The display for this indication is shown in Figure 5.13. Accompanying this Figure is a diagram of its location (Figure 5.14) and a photograph of the area (Figure 5.15). Since this indication was observed visually, it also was immediately ground out and did not appear on final radiography. The AEWM correctly interpreted this indication as a slag inclusion and showed relative size indication of 3. It should be noted that the characterization level or degree was high relative to other indications observed, and therefore considered significant.

Throughout the monitoring, occasional operator movement and weld clearing operations were detected by the AEWM. However, these indications were usually seen with the monitor set at a high gain and almost all of these indications did not locate anywhere near the area of the weld, if at all. An example of this is seen in Figure 5.16. These indications were seen by the monitor as a combination of cracks and slag inclusions with size indication of 0 or 1 (the lowest characterization level). In the example, all indications were either located in areas outside the display or were not detected by all transducers. The AEWM can only present these indications on the edges of the display as seen in the Figure. Furthermore, if detected by only one transducer, the indication

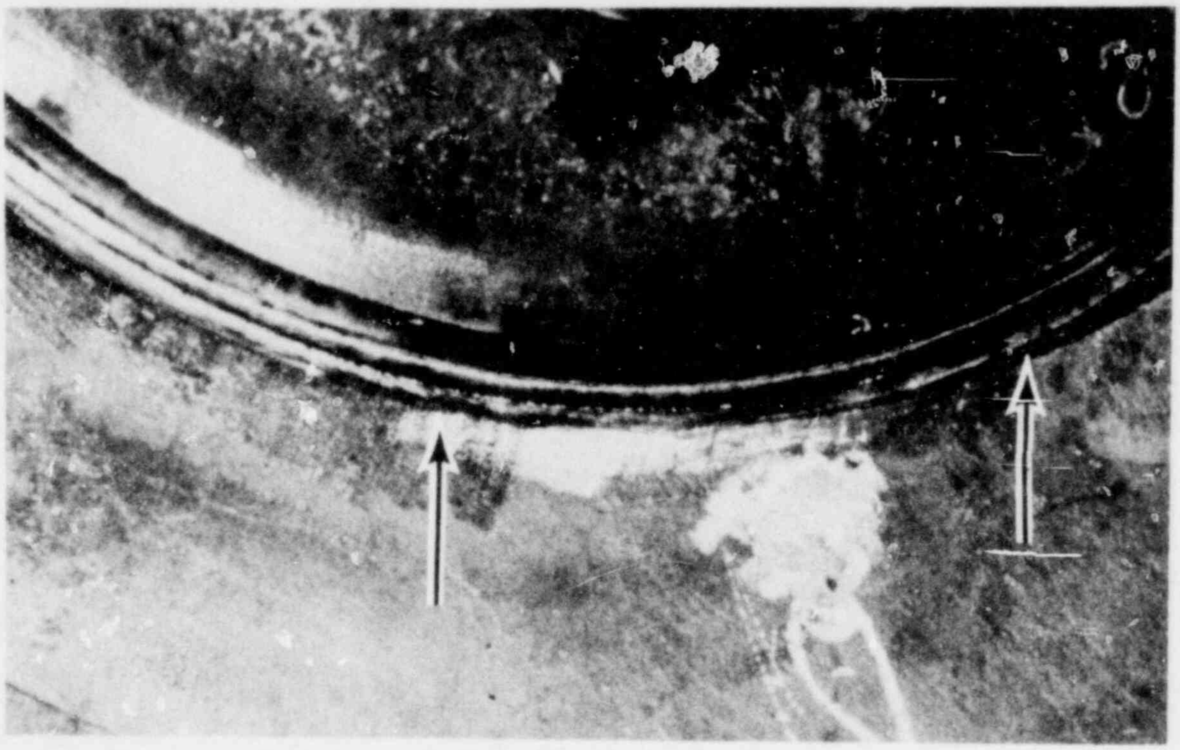

Figure 5.9 PHOTOGRAPH OF TYPICAL SLAG DEPOSIT AREA

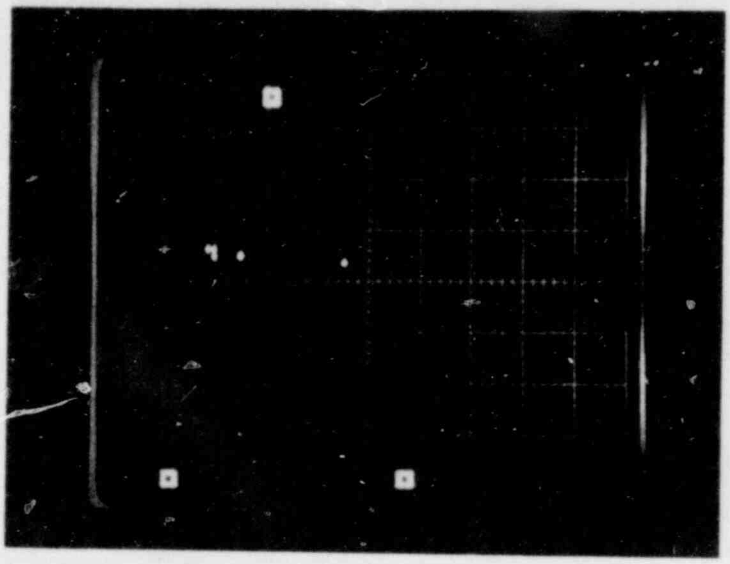

Figure 5.10 OSCILLOSCOPE DISPLAY, LACK OF FUSION

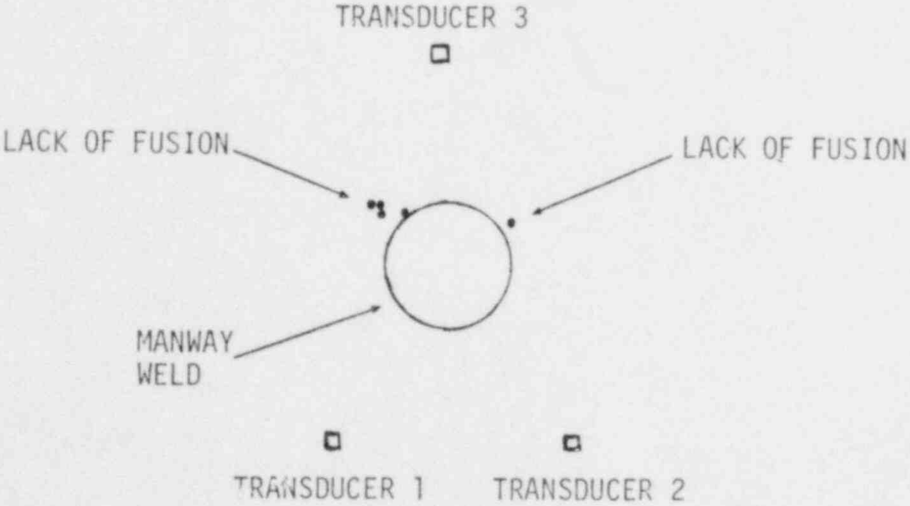

Figure 5.11 INDICATED LACK OF FUSION LOCATION RELATIVE TO MANWAY WELD

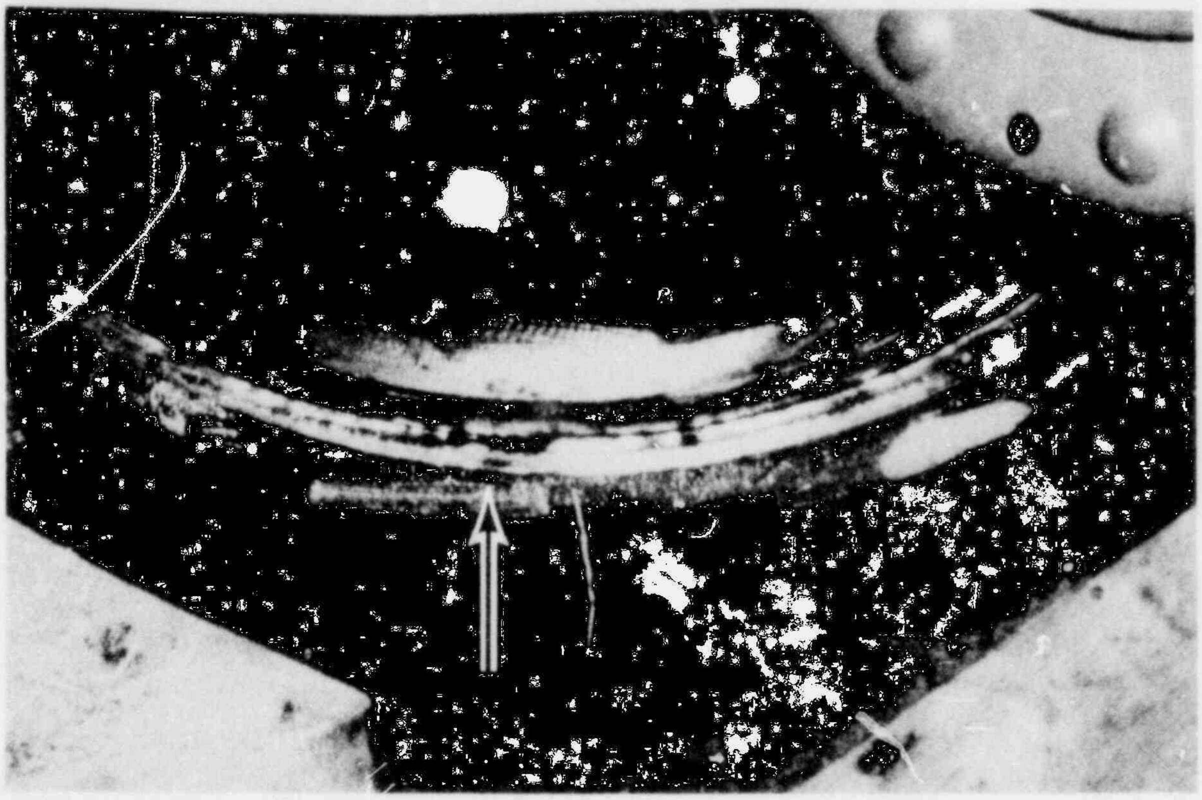

Figure 5.12 PHOTOGRAPH, LACK OF FUSION AREA

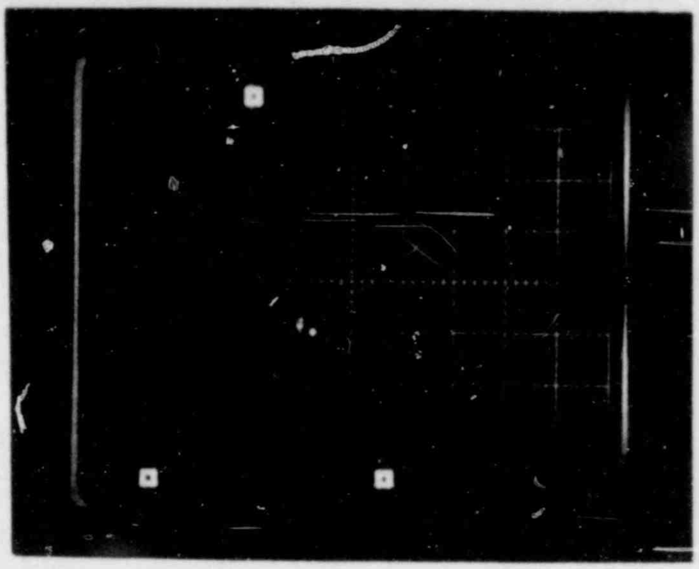

Figure 5.13 OSCILLOSCOPE DISPLAY SLAG INCLUSION

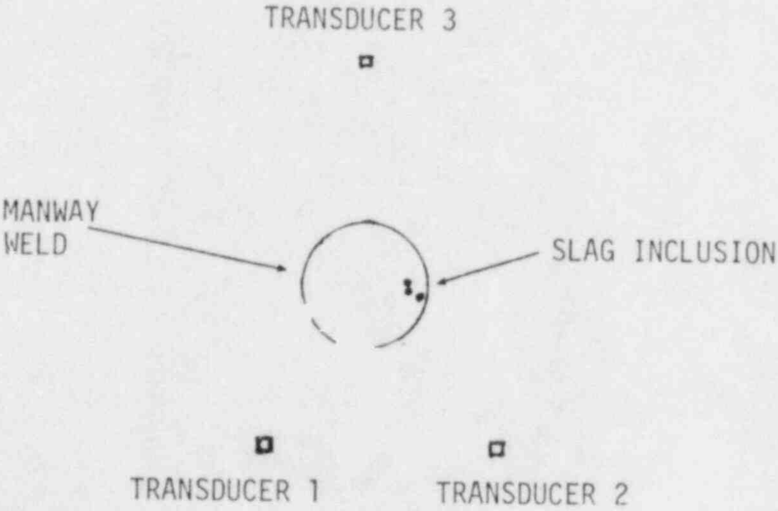

Figure 5.14 INDICATED SLAG INCLUSION LOCATION RELATIVE TO MANWAY WELD

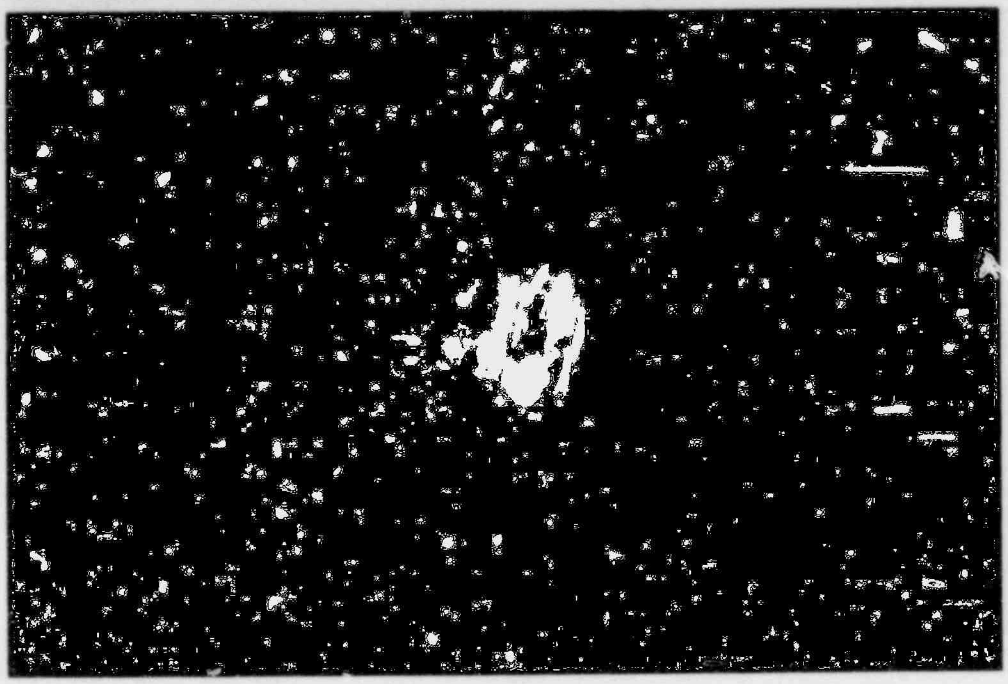

Figure 5.15 PHOTOGRAPH OF SLAG INCLUSION

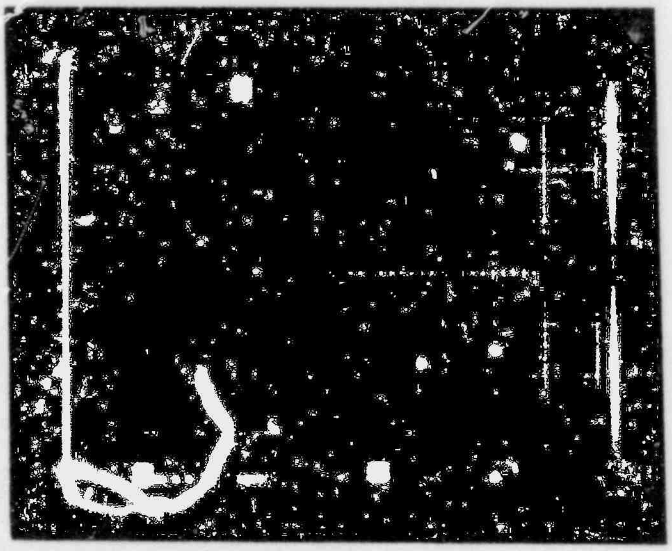

Figure 5.16 NON LOCATING INDICATIONS

will be superimposed over the transducer location. If the indication is only detected by two transducers, it will be displayed somewhere on a line between them. Thus, the locational ability of the monitor is an additional aid in discriminating against background AE.

5.3 Conclusions

During the field evaluation, a total of 750 feet of weld pass was monitored by the AEWM. Indications were seen on seven weld passes which were confirmed visually. The following table summarizes these results.

Flaw Type (Visual Conf.)	Number of Passes Indication Observed	AEWM Type	Characterization Severity	AEWM Sensitivity
Slag Deposit	2	Slag	1	72 dB
Slag Inclusion	1	Slag	3	66 dB
Lack of Fusion	4	Slag/Crack	1	66 dB

Severity is derived from the averaged AE ringdown count for the flaw events. The mix of characterization type for the LOF indications is typical for this flaw type.

Since all AEWM indications were visually confirmed, they were removed immediately and consequently did not appear in weld radiography. This test was the first field test of an AEWM on this program in which the AEWM indications were used as a basis for in-process repair. The fact that the weld passed final ASME code radiography helps confirm the viability of using AE monitoring during welding to avoid the expensive and potentially damaging process of post weld repair.

Section VI

CODE SUPPORT AND DEVELOPMENT

6.1 Introduction

A major goal of this program was to provide data for support of code case development and to apply effort towards gaining code acceptance of in-process acoustic emission monitoring of welds as an NDE method.

A considerable data bank has been developed and it is reported in detail in previous reports published under this program. In this report we include a condensed summary for reference purposes.

As a first step in gaining code acceptance, a document entitled "Recommended Practice for Acoustic Emission Monitoring During Continuous Welding" was written. The document was steered through the ASTM E7.04 subcommittee and as of January 1980 had received full E7 committee approval. The recommended practice will be presented for full ASTM society ballot in April 1980 and after approval will be published in the ASTM standards book. Publication should be sometime during 1980. This document should serve as a starting point for ASME code development. The following sections contain a brief summary of the data developed under this program.

6.2 Discussion

A total of fourteen tests have been conducted under the program. A summary of the tests is included in Figure 6.1. Total footage of weld passes monitored exceeds 14,000 feet. Testing was conducted under laboratory conditions on controlled welds with intentionally induced flaws and in fabrication shops on production nuclear component welding. Confirmation of flaws in the laboratory welds was obtained with radiography, ultrasonics, and metallography. Confirmation of production flaws was provided, primarily, by production radiography. Dye penetrant and visual inspection provided some additional flaw confirmation on some production welds.

The objective of the tests was to show that in-process monitoring of acoustic emission can detect, locate, and characterize typical ASME code rejectable flaws in nuclear component weldments. These objectives are met by the laboratory weld tests while the shop tests, primarily, confirm that the

Weld Methods

1-GTAW, 2-GMAW, 3-SAW, 4-MMAW

Figure 6.1

SUMMARY OF AE WELD MONITORING

TEST	LOCATION	DATE	NUMBER OF WELDS	FEET OF WELD PASS	MATERIAL	WELD METHOD
1. Piping Lab	Southwest Fab. Houston, TX	02-75	20	250	A312T304/A106	1,2,3,4
2. Piping Prod. #1	Southwest Fab. Houston, TX	05-75	18	400	A312T304/A106	1,2,3,4
3. Piping Prod. #2	IIT Grinnell Kernersville, N.C.	06-75	10	340	A106	1,3,4
4. Pressure Vessel Calibration #1	B&W Barberton, OH	11-75	1	500	A508	3
5. Pressure Vessel Calibration #2	CE Chattanooga, TN	02-76	1	260	A533	3
6. Additional Piping Lab. Tests	M&O Products San Luis Obispo, CA	12-76	30	290	A106	1,2,4
7. Pipe Shop Evaluation	G&W Plant #1 Cicero, IL	12-76/ 02-77	80	5800	A105	3
8. Pressure Vessel Prod. #1	B&W Mt. Vernon, IN	01-77	1	680	A508	3
9. Pressure Vessel Prod. #2	Westinghouse Tampa, FL	02-77	1	1800	A533	4
10. Pressure Vessel Prod. #3	Westinghouse Tampa, FL	05-77	3	2000	A533	3
11. Additional Piping Lab. Tests	M&O Products San Luis Obispo, CA	06-77	6	250	A312T304/A106	1,2
12. Additional Pressure Vessel Lab. Tests	GARD, INC. Niles, IL	08-77	15	900	A533	3
13. Production Test "smart" Breadboard	G&W Cicero, IL	06-78	20	400	A106	3
14. Production Test "smart" Monitor	Westinghouse Tampa, FL	01-80	1	750	A533	3

method is practical to apply on the production floor. The shop tests were performed on actual production welds and, therefore, no additional confirmation of flaws beyond normal production NDE (primarily X radiography) was possible.

6.3 Results

Early in the program, a series of laboratory test welds were monitored using relatively simple non-computer based Acoustic Emission (AE) monitoring systems. The system used for Test 1[1] was a simple single channel AE flaw detector. The system used for Tests 4 and 5[2] were a two channel system using the same detection logic as the first system with the addition of source location capability. Both types of systems were laboratory breadboards. These tests served as calibration tests to allow AE monitoring parameters to be optimized so that hardened shop-usable monitor based on these results could be constructed. In Test 1, a total of twenty butt welds simulating typical nuclear pipe fabrication were AE monitored during welding. Data from five of the twenty welds were lost due to equipment problems. Results for the remaining fifteen welds are summarized in Figure 6.2.

These tests show that in-process monitoring AE is an excellent detector of cracking in nuclear pipe welds. In one case (Weld 8), AE detected a severe crack that was missed by ASME code radiography. The crack was later confirmed by metallography.

Tests 4 and 5 served as calibration tests prior to monitoring nuclear pressure vessel production welding. The pressure vessel calibration test consisted of two multipass submerged arc welds in six inch thick pressure vessel steel. One was fabricated in A508 forging steel and one in A533 plate. Standard pressure vessel welding procedure was followed which included preheat and maintenance of interpass temperature between 300^{o}F and 500^{o}F. Two channel AE source location was utilized with these welds along with high temperature transducers and couplant.

A total of six intended flaws were placed in each specimen. The first specimen's intended flaws were two slag inclusions, two undercuts, one void, and a plate with an ELOX slot to simulate a crack. The specimen was intended to be an ultrasonic test block. AE detected all of the intended flaws plus several other indications. Radiography and ultrasonics confirmed all of the

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[1] Prine, D.W., Clark, R.N., "Inspection of Nuclear Reactor Welding by Acoustic Emission," NUREG-0035-1, 1976.

[2] Prine, D.W., "Inspection of Nuclear Reactor Welding by Acoustic Emission," NUREG-0035-2, 1976.

Figure 6.2

PIPING CALIBRATION TEST SUMMARY

WELD	MATERIAL	WELD METHOD	INTENDED FLAWS	CONFIRMATION	AE DETECTION
1	6" A106	GTA/GMA	None	Radiography - No Flaws	None
2	6" A106	GTA/GMA	None	Radiography - No Flaws	None
3	6" A106	GTA/GMA	1 Crack	Radiography - 1 Crack	1 Crack
4	6" A106	GTA/GMA	1 Crack 2 Porosity	Radiography - 1 Crack 2 Porosity	1 Crack
5	6" A106	GTA/GMA	2 Porosity	Radiography - 2 Porosity	None
6	6" 304	GTA/GMA	None	Radiography - No Flaws	None
7	6" 304	GTA/GMA	None	Radiography - No Flaws	None
8	6" 304	GTA/GMA	1 Crack	Metallography - 1 Crack Radiography - No Flaws	1 Crack
9	6" 304	GTA/GMA	1 Crack	Metallography - No Flaws Radiography - No Flaws	None
10	6" 304	GTA/GMA	1 Crack 1 Porosity	Radiography - 1 Crack - 1 Porosity	1 Crack
11	14" A106	GTA/SA	3 Cracks	Radiography - 3 Cracks	3 Cracks
12	14" A106	GTA/SA	1 Crack	Radiography - 1 Crack	1 Crack
13	14" A106	GTA/SA	1 Crack	Radiography - 1 Crack - 1 Incpl.Fusion	1 Crack
14	14" A106	GTA/SA	None	Radiography - No Flaws	None
15	14" A106	GTA/SA	None	Radiography - 1 Excessive Penetration	None

AE indications and the radiographic data indicated slag inclusions associated with all of the indicated flaw areas. The second specimen contained six planned flaws, four cracks and two slag inclusions. All six were easily detected by AE and later confirmed by ultrasonic and radiographic testing.

These tests showed that in-process AE monitoring could accurately detect and locate flaws in welds typical of nuclear pressure vessel fabrication welds. They further showed that slag entrapment, which frequently occurs in conjunction with other flaw types, aids the AE detectability of flaws.

Later in the program, a second series of laboratory test welds were monitored (Tests 6, 11, 12).[3,4] The equipment utilized for these tests was a computer based AE data acquisition and analysis system. This equipment represents a considerable increase in sophistication over that used in earlier tests. These tests were conducted to provide answers to the following questions:

1.) What is the probability that in-process AE monitoring can detect a given flaw type with a minimum of false or unconfirmable AE indications?

2.) If a flaw type can be reliably detected, can the size or severity be related to any AE parameter?

3.) Are there any AE parameters that can be utilized to differentiate between flaw types?

The welds are classified into two categories, piping and pressure vessel welds. The piping welds were fabricated with manual and automatic gas shielded welding processes in carbon and stainless steel. The vessel welds were fabricated with submerged arc welding in A533 pressure vessel steel. A summary of the welds and the flaw population is given in Figure 6.3.

The detection probabilities for the various flaw types is summarized in Figure 6.4.

These probabilities are based on zero overcall or false AE indications. Metallography confirmed two primary mechanisms which produce AE and thus allow detection of flaws in these welds. These mechanisms are cracking of the weld metal and cracking of entrapped slag.

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[3] Prine, D.W., Mathieson, T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission, "NUREG-0035-3, 1977.

[4] Prine, D.W., Mathieson, T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission, "NUREG-CR-0461, 1978.

Figure 6.3

SUMMARY OF LABORATORY WELDS (2nd Series)

FLAW TYPE	NUMBER OF WELDS	NUMBER OF FLAWS
CRACKS		
Piping welds	6	14
Vessel welds	6	20
POROSITY		
Piping welds	16	15
Vessel welds	2	13
INCOMPLETE PENETRATION		
Piping welds	8	8
Vessel welds	14	21
LACK OF FUSION		
Piping welds	6	22
TUNGSTEN INCLUSIONS		
Piping welds	6	4
SLAG INCLUSIONS		
Vessel welds	6	37
TOTAL	70	154

Figure 6.4

FLAW DETECTABILITY FOR "LABORATORY WELDS"

	FLAW DETECTION PROBABILITY	
FLAW TYPE	PIPING WELDS	VESSEL WELDS
CRACKS	100%	100%
POROSITY	5%	80% *
INCOMPLETE PENETRATION	75%	100% *
LACK OF FUSION	0%	not applicable
TUNGSTEN INCLUSIONS	0%	not applicable
SLAG INCLUSIONS	not applicable	100%

* enhanced by slag trapping

A further result of these tests showed that average AE ringdown count for the flaw related AE events was a good indicator of relative flaw size.

These tests (6, 11, 12)[5] further showed that if averaged AE frequency spectra data for flaw related events was compared to average frequency spectrum for background AE signals, cracks could be differentiated from slag inclusions by in-process AE monitoring. Testing of these technique on the laboratory data from Tests 6, 11 and 12 showed that 72% of the time AE could correctly determine the nature of the flaw (slag inclusion or crack).

A total of eight tests were conducted on actual nuclear production welding in nuclear fabrication shops under this program. (Tests 2, 3, 7, 8, 9, 10, 13 and 14).

Tests 2, 3, 8 and 9[1,3] were performed using the non-computer-based laboratory breadboard system. Although no ASME code rejectable flaws were generated during these tests, a total of fourteen AE indications were confirmed by either code radiography, dye penetrant, or visual inspection.

In Test 7[3], 5800 feet of weld passes were monitored on nuclear-grade piping using a simple single channel shop hardened AE monitor. This simple AE system detected 61% of the indications found on production radiography. In this test, AE was correct in detecting a radiographically confirmable indication 70% of the time.

In Test 10[4], approximately 1500 feet of welding was monitored using a shop-hardened two channel AE monitor. The welding was on longitudinal seams in nuclear steam generator shells. A total of six AE indications were generated and all of these were correlated with visual flaws.

Test 13[5] was conducted to confirm the practicality of using a computer-based AE weld monitoring system capable of flaw characterization under typical fabrication shop conditions. The test was done on longitudinal welded seams in nuclear grade piping. The results were positive in that the system operated properly under very severe shop conditions of noise and dirt. The data is somewhat difficult to interpret since the only means of flaw confirmation available was code radiography. Strict agreement between AE and Code radiographic interpretation of flaw nature occurred only 33 percent of the time. A very large

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5. Prine, D.W., Mathieson, T.A., "Inspection of Nuclear Reactor Welding by Acoustic Emission," NUREG/CR-0703, 1979.

number of "tailed" porosity indications were called cracks by the AE system, but since no metallography was possible on these production welds, the correctness of these results could not be absolutely confirmed.

Test 14[6] was conducted on a nuclear steam generator manway weld. The AE monitoring system was a shop hardened three channel computer-based system. A total of seven AE indications were produced. In each case, welding was stopped and the indicated areas were ground out. One AE indication was confirmed to be a slag inclusion and was properly called slag inclusion by the monitor. The remaining AE indications were all confirmed as lack of fusion and were called both slag inclusion and crack on a roughly equal basis by the monitor. This is consistent with our understanding of the mechanism of AE detection for this flaw type. Final radiography on this weld showed it to be free of indications.

This test showed that the application of in-process AE monitoring could be utilized to detect, locate, and characterize flaws in a typical nuclear pressure vessel weld, and that the AE information could be used to direct repairs during welding and thus avoid the expensive and difficult process of repairing welds after completion.

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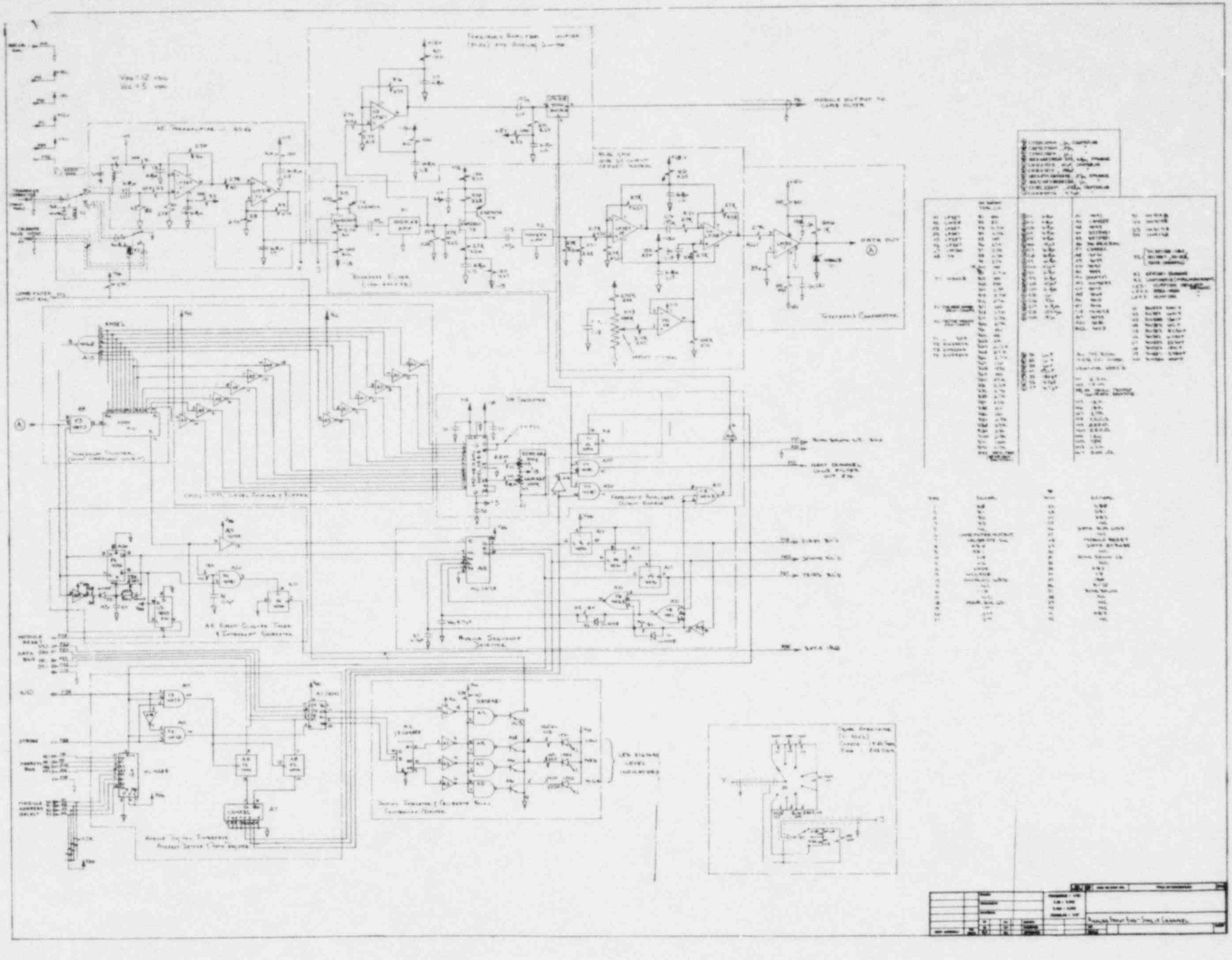
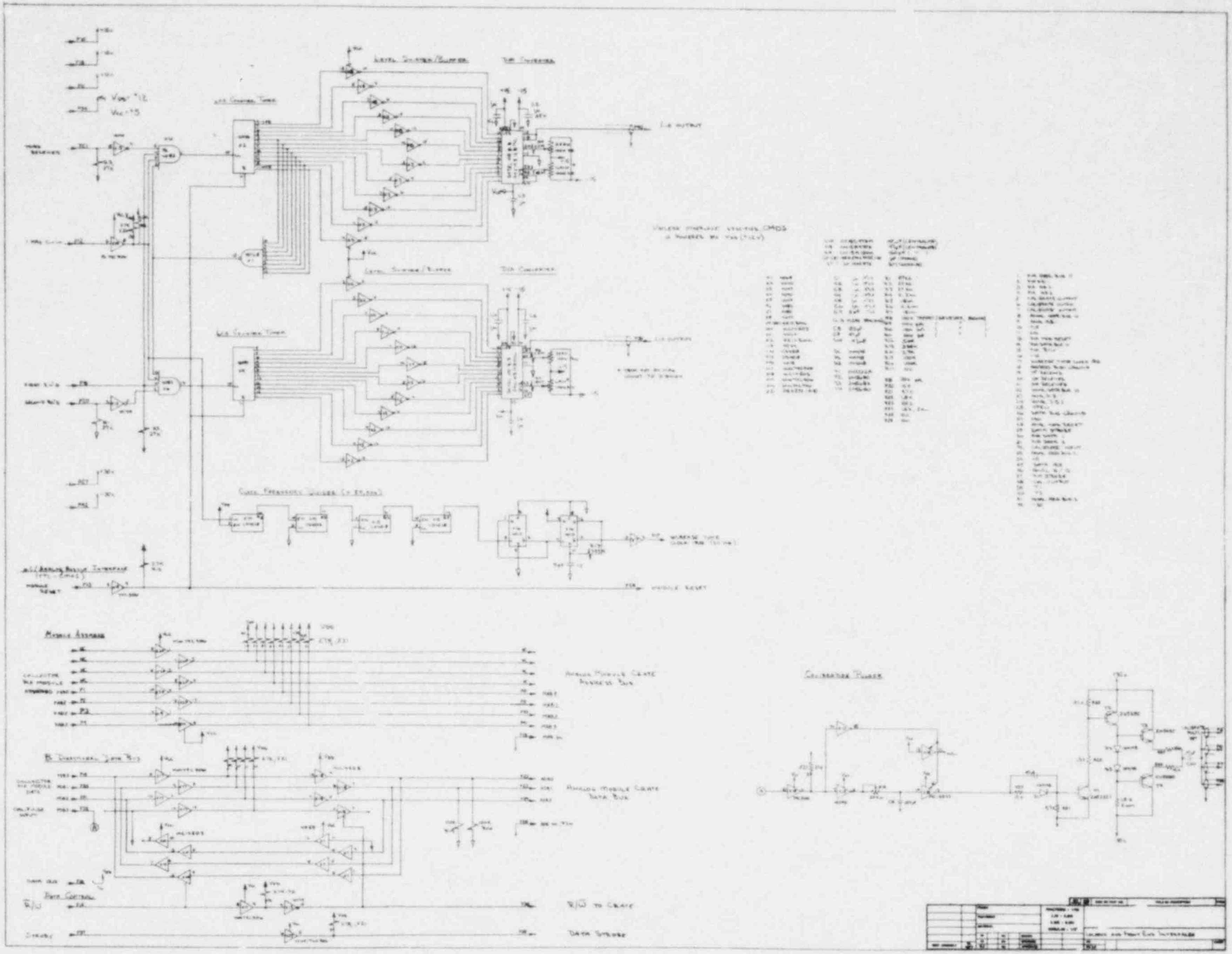
[6] Prine, D.W., et al, "Inspection of Nuclear Reactor Welding by Acoustic Emission," To be Published, 1980.

APPENDIX A

AEWM SCHEMATIC DRAWINGS


Vpp = 12 vdc
Vcc = 5 vdc
MODULE OUTPUT TO CABLE FILTER
DATA OUT
LED SIGNAL LEVEL INDICATORS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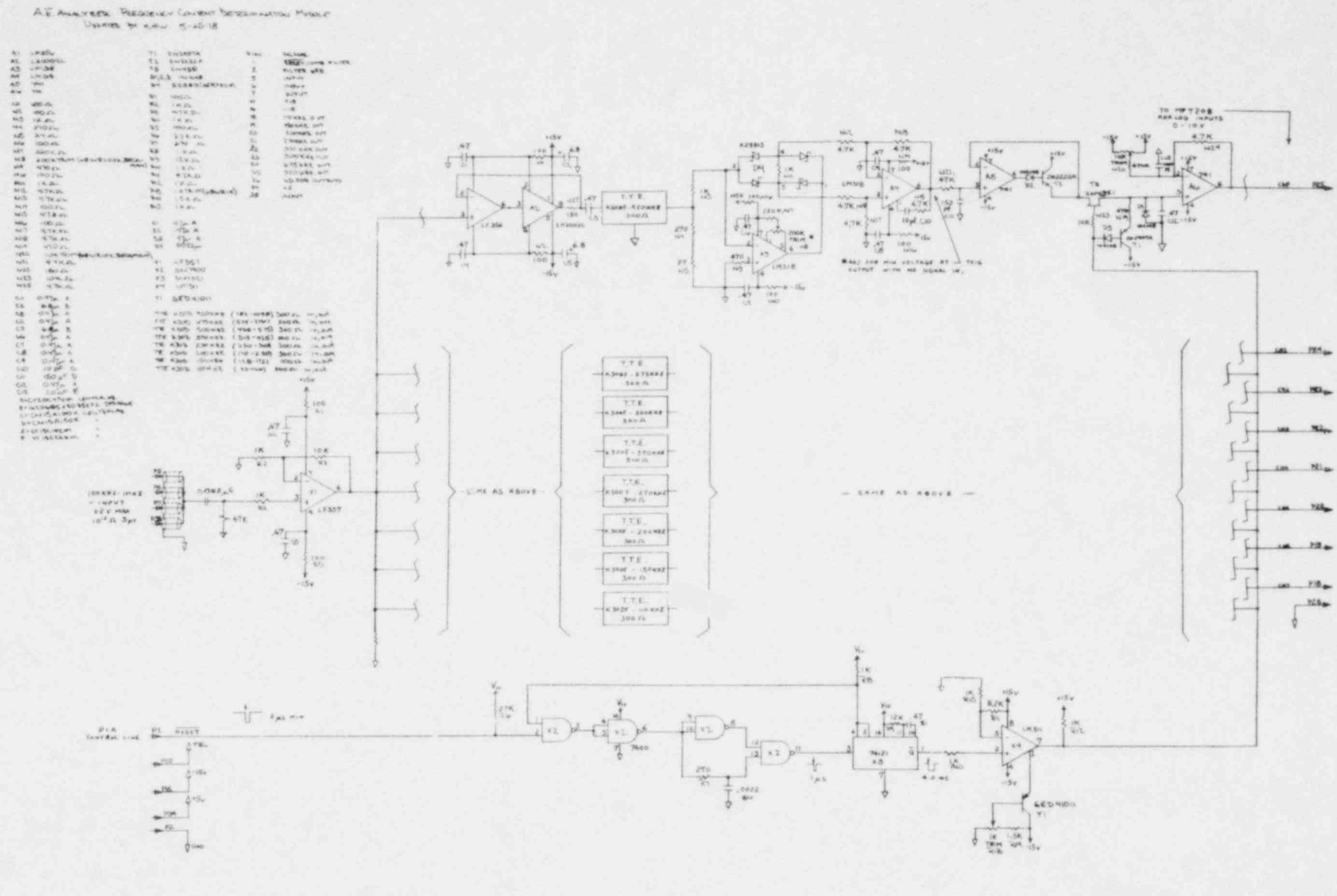
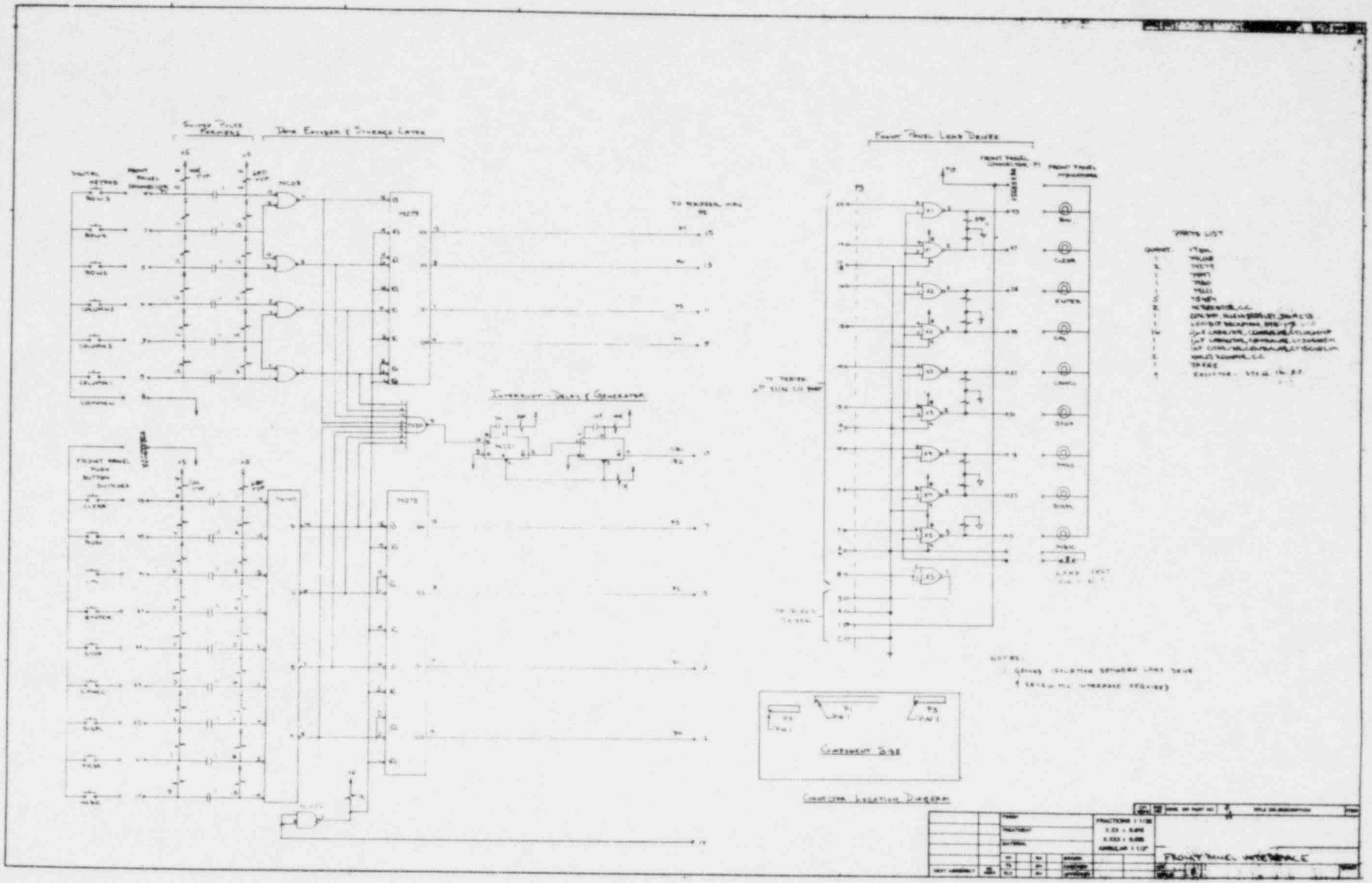
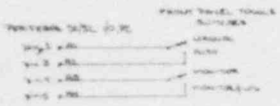
D/A Converter
Vdd = +12
Vcc = +5
Level Shifter/Buffer
D/A Converter
Clock Frequency Divider
Module Reset
Module Address
Analog Module Crate
Address Bus
Bi-Directional Data Bus
Analog Module Crate
Data Bus
Data Control
R/W
Strobe
R/W to Crate
Data Strobe
Calibration Pulser

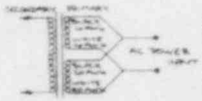


A.E. Analyzer Frequency Content Determination Module
Updated by K.A.W. 5-25-78


Single Pulse Formers
Data Encoder & Storage Latch
Front Panel Lamp Driver
Interrupt - Delay & Generator
DIGITAL KEYPAD
FRONT PANEL CONNECTOR
COMMON
FRONT PANEL PUSH BUTTON SWITCHES
CLEAR
ENTER
STOP
CANCEL
+5
74LS8
74279
TO PERIPHERAL
FRONT PANEL CONNECTOR P1
FRONT PANEL INDICATORS
LAMP TEST
PARTS LIST
QUANT.
ITEM
NOTES:
1. GROUND ISOLATION BETWEEN LAMP DRIVE & [illegible] INTERFACE REQUIRED
P1
P2
P3
PIN 1
Component Side
Connector Location Diagram
FRACTIONS
X.XX
X.XXX
ANGULAR
FINISH
TREATMENT
MATERIAL
NEXT ASSEMBLY
DWG. OR PART NO.
TITLE OR DESCRIPTION
FRONT PANEL INTERFACE



MODIFICATION OF LAMBDA POWER SUPPLY



SHOWN IS THE TRANSFORMER OF THE LAMBDA POWER SUPPLY. MODIFY BY ISOLATING INPUT PRIMARY COILS AND PARALLEL CONNECTIONS PER POWER SUPPLY SCHEMATIC.

MODIFICATION OF MICROPROCESSOR CARD CAGE

ONE CARD CAGE IS MODIFIED TO ACCOMMODATE TWO MICROPROCESSORS (THE COLLECTOR & THE DISCRIMINATOR). THE BUSSES OF THE MICROPROCESSORS MUST BE ISOLATED BY MAKING THE FOLLOWING CUTS, SO THAT THEY MAY OPERATE INDEPENDENTLY.

[illegible]

MODIFICATION OF PERIFERAL D/A BOARD

ADD FOUR 100Ω ¼ WATT RESISTORS IN JUMPER POSITIONS [illegible] AND U20.

MODIFICATION OF COLLECTOR AND DISCRIMINATOR CPU'S

REMOVE CHIPS [illegible]. AT CHIP LOCATIONS [illegible], MAKE THE FOLLOWING JUMPERS:

[illegible]

AT CHIP LOCATIONS [illegible] MAKE THE FOLLOWING JUMPERS:

[illegible]

CUT THE TRACE CONNECTED TO PIN 49 [illegible] AND CONNECT PIN 49 TO PIN 2 OF K2. CONNECT THE WIRE THAT WAS CUT FROM PIN 49 TO GROUND (P1 PIN 50). CONNECT [illegible]

MODIFICATION OF PERIFERAL MPU

CONNECT [illegible]

CUT THE TRACE ON THE BOTTOM OF THE BOARD THAT CONNECTS TO THE PLATED THRU HOLE BENEATH [illegible] AND IS NEXT TO THE LEFT OF PIN 21. CONNECT THAT PLATED THRU HOLE TO [illegible]

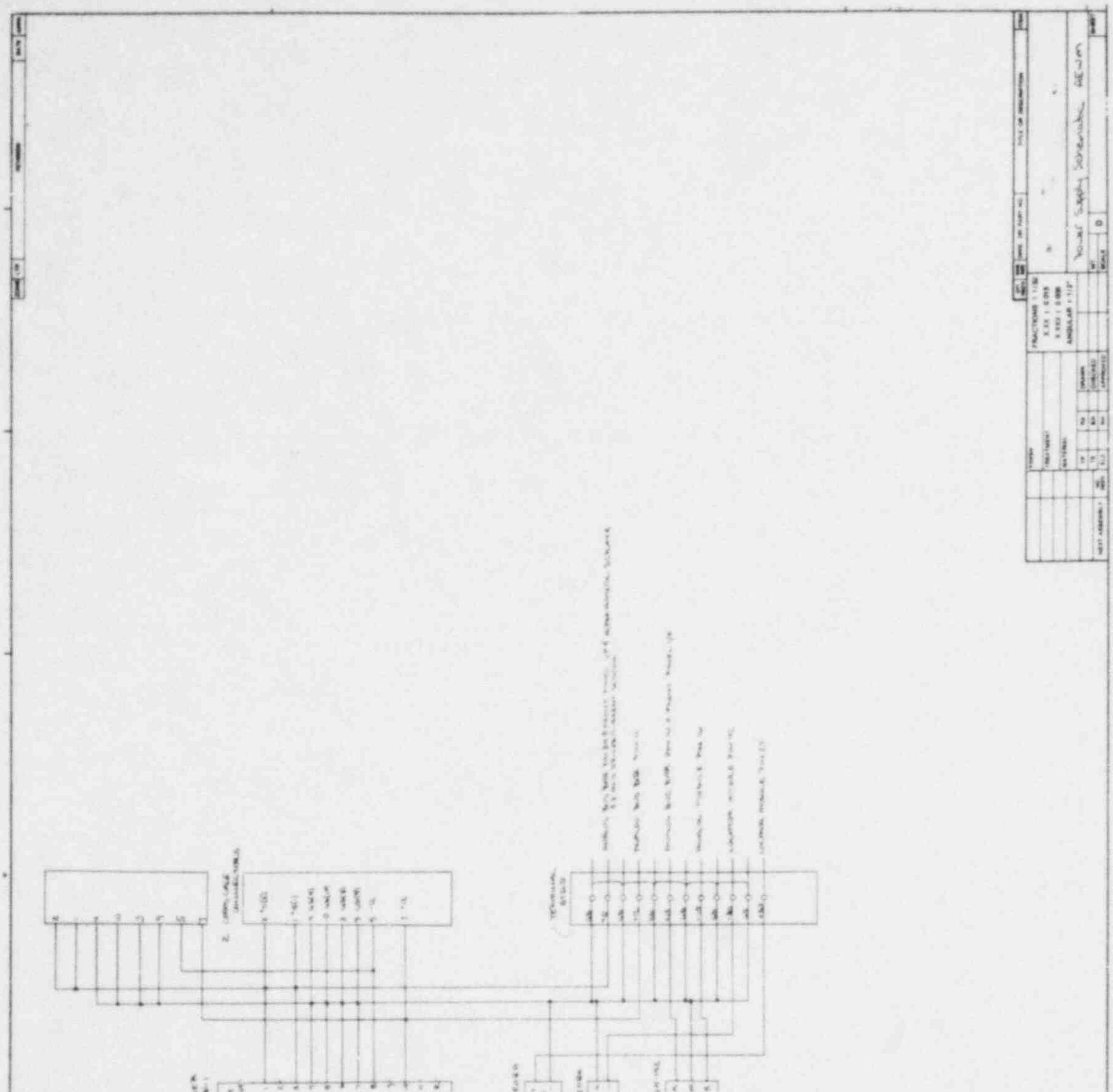
CUT THE TRACES CONNECTING THE RIGHT & LEFT SIDES OF K2 & JUMPER THE TRACES ON RIGHT & LEFT SIDES OF K3.

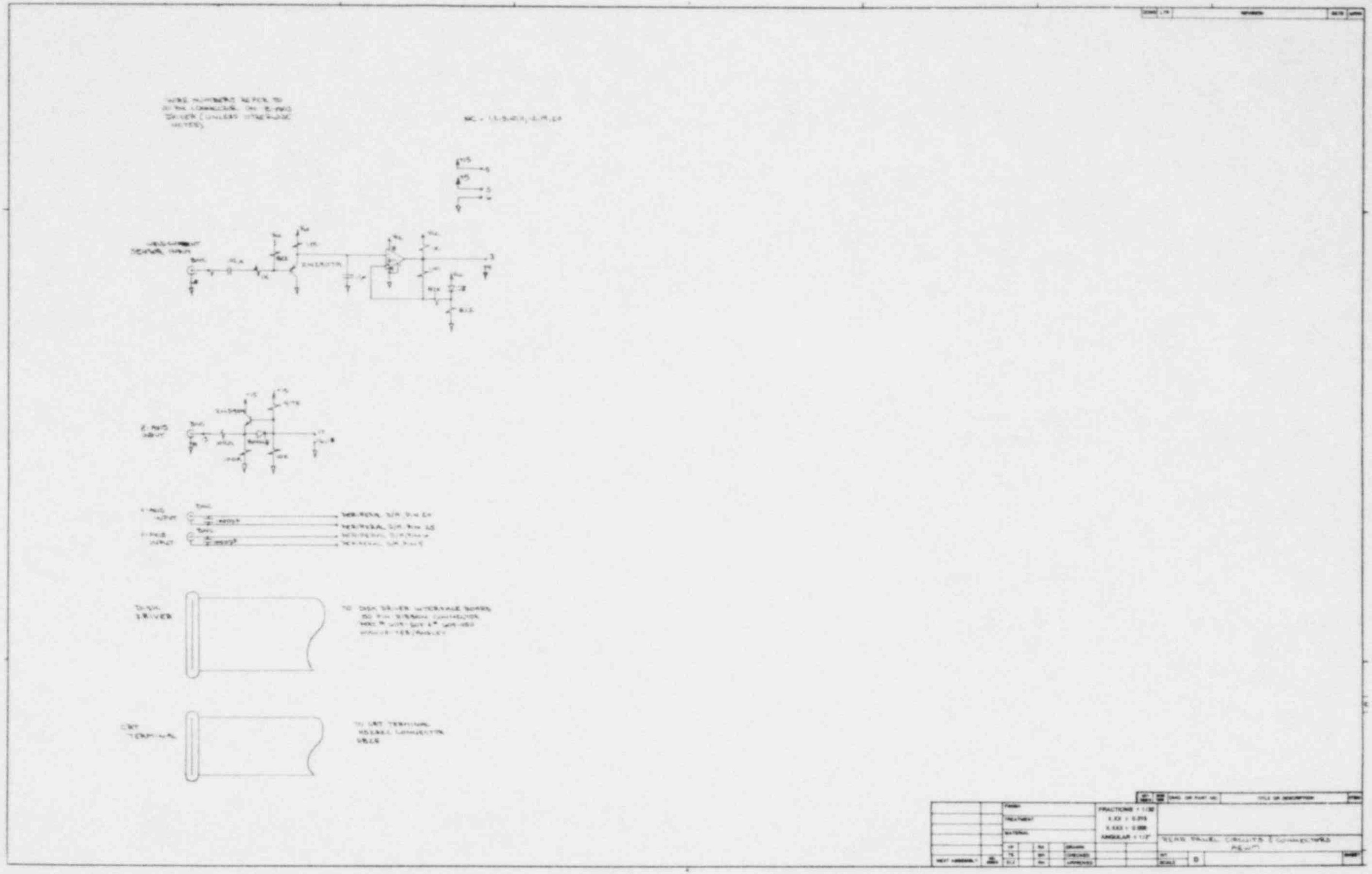
REMOVE EACH LOWER CAPACITOR TO THE RIGHT OF SOCKETS [illegible]

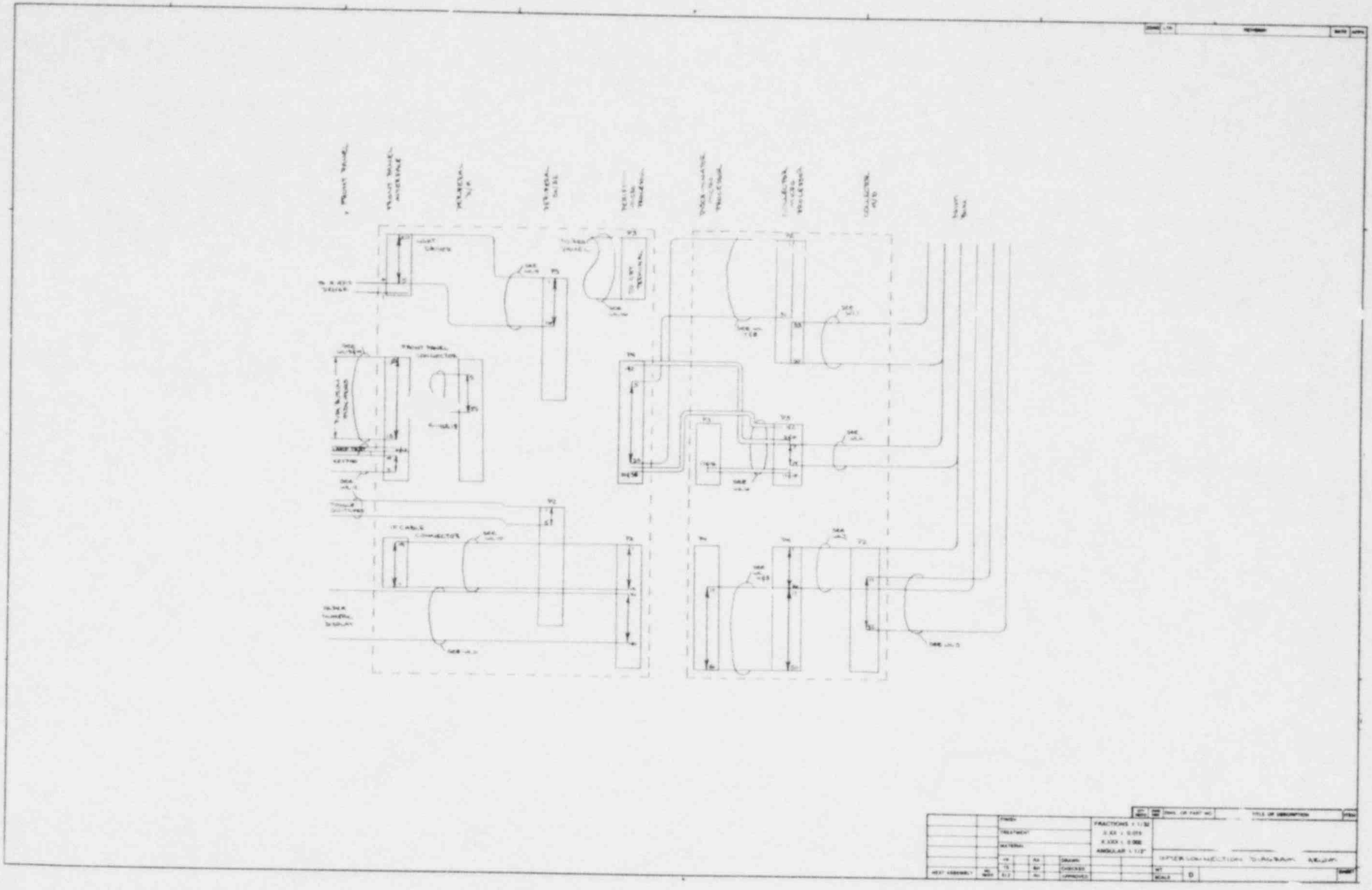
USE [illegible]

FRACTIONS ± 1/32
.XX ± .010
.XXX ± .005
ANGULAR ± 1/2°

DRAWN
CHECKED
APPROVED
SCALE


Power Supply Schematic
FRACTIONS ± 1/32
X.XX ± 0.015
X.XXX ± 0.005
ANGULAR ± 1/2°
TITLE OR DESCRIPTION
FINISH
TREATMENT
MATERIAL
DRAWN
CHECKED
APPROVED
NEXT ASSEMBLY
SCALE
D
TERMINAL STRIP
OUTPUT CONNECTOR
INPUT TERMINAL STRIP
TO FRONT PANEL ON/OFF SWITCH
POWER INPUT 120/240 VAC
FAN


BNC
DISK DRIVER
TO DISK DRIVER INTERFACE BOARD
50 PIN RIBBON CONNECTOR
CRT TERMINAL
TO CRT TERMINAL
+5
FINISH
TREATMENT
MATERIAL
FRACTIONS ± 1/32
ANGULAR ± 1/2°
DRAWN
CHECKED
APPROVED
NEXT ASSEMBLY
SCALE
D
SHEET
DWG. OR PART NO.
TITLE OR DESCRIPTION
REAR PANEL CIRCUITS & CONNECTORS


FRONT PANEL
FRONT PANEL INTERFACE
COLLECTOR A/D
TO CRT TERMINAL
LIGHT DRIVER
FRONT PANEL CONNECTOR
IF CABLE CONNECTOR
FINISH
TREATMENT
MATERIAL
FRACTIONS ± 1/32
X.XX ± 0.015
X.XXX ± 0.005
ANGULAR ± 1/2°
DRAWN
CHECKED
APPROVED
NEXT ASSEMBLY
DWG. OR PART NO.
TITLE OR DESCRIPTION
INTERCONNECTION DIAGRAM
SCALE
D
SHEET

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This report is the final report on a two-year extension of a previous three-year program. This two-year program was aimed at extending the capability of in-process acoustic emission monitoring of nuclear fabrication welds from flaw detection and location to flaw characterization in terms of type and size. During this phase a field-hardened system based on design concepts that were developed and tested during the first year was fabricated and the resulting system was successfully tested in a nuclear fabrication shop.

This report contains a detailed description of the microprocessor-based three channel weld monitor in addition to a description of the results of the field test.

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