Demonstration and Preliminary Evaluation of the Acoustic Emission Weld Monitor

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DEMONSTRATION AND PRELIMINARY EVALUATION OF THE ACOUSTIC EMISSION WELD MONITOR

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This report describes the demonstration and preliminary evaluation of the microprocessor-based acoustic emission weld monitor (AEWM) developed for the Federal Highway Administration by GARD Inc. of Niles, IL. The equipment was tested successfully on butt welds in several fabrication shops by the Kentucky Transportation Research Program (KTRP). Some problems were encountered in monitoring fillet welds.

The AEWM was demonstrated to personnel from 20 state agencies representing FHWA Regions 1, 3, 4, and 5. The demonstrations were performed at three different fabrication shops in Pennsylvania, Georgia, and Wisconsin.

A preliminary evaluation of the AEWM is included. Also, the summary of a questionnaire sent to the demonstration attendees is included.
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SUMMARY

Work conducted for this study consisted primarily of three phases: 1) preliminary fabrication-shop tests and GARD instruction on the operation of the acoustic emission weld monitor (AEWM), 2) AEWM shop demonstrations, and 3) the follow-up questionnaire survey of the AEWM demonstration attendees. The first phase was to familiarize Kentucky Transportation Research Program (KTRP) personnel with the operation and function of the AEWM. AEWM demonstrations constituted the major objective of the study. The AEWM questionnaire survey was instituted to determine the receptiveness of state highway personnel to the potential employment of the AEWM.

The function of the AEWM and operational weld procedure are described in the second section of the report entitled "Function and Operation of the AEWM."

Two preliminary fabrication-shop tests were conducted at Augusta Iron and Steel Co. of Augusta, Georgia, and High Steel Structures Inc. of Lancaster, Pennsylvania. A limited number of production welding operations were monitored with the AEWM. No flaws were detected during those tests. A few problems were encountered because of the inexperience of KTRP personnel with the AEWM. Those problems were rectified in later work. KTRP personnel also received training in the operation of the AEWM at GARD Inc. headquarters in Niles, Illinois.

Four demonstrations were performed for highway personnel from a total of twenty states in FHWA Regions 1, 3, 4, and 5. The first two demonstrations were held at High Steel Structures Inc. (FHWA Regions 1 and 3). The third demonstration was conducted at Augusta Iron and Steel Co. (FHWA Region 4). The final demonstration was performed at Phoenix Steel Inc. of Eau Claire, Wisconsin (FHWA Region 5).

Each demonstration lasted two days. The morning portion of the first day consisted of classroom instruction on the AE phenomenon and function of the AEWM. The instructors were KTRP and GARD personnel. The afternoon session consisted of deliberate flaw-embedment (cracking) and detection by the AEWM on test plates welded by fabrication-shop personnel. The second day of the shop demonstration consisted of AEWM tests of production welds.

The AEWM demonstrations were successfully performed. Some difficulties were encountered in creating flaws in the test-plate welds. However, the AEWM functioned reliably during those tests. No flaws were detected during monitoring of production welds. A comparison of the AEWM test results with routine nondestructive tests (ultrasound and radiography) was made on one fracture-critical weld for the Maine Department of Transportation. The conventional nondestructive tests confirmed AEWM results (i.e., that the weld contained no rejectable defects).

After the AEWM demonstrations were completed, questionnaires were submitted to 21 of the participants to determine their impressions of the AEWM. Sixteen replies were received and are summarized. All respondents felt the AEWM demonstration was satisfactory. Fifteen felt the equipment functioned suitably. Eleven of the respondents stated that the AEWM would be a useful, cost-effective device for detecting welding flaws in fabrication shops. The main criticism of the AEWM centered on its cost and configuration, not on its function. The
attendees felt the AEWM could best be applied as a quality-control (QC) testing tool. Fourteen respondents felt the AEWM might be useful in other highway applications such as crack detection on in-service bridges.

The KTRP experience with the AEWM was positive. The device consistently detected and accurately located flaws in test welds. In production weld monitoring, the AEWM failed to detect only one small surface-breaking porosity. The AEWM was not subject to excessive false flaw indications. The equipment also showed much potential for QC nondestructive testing, a role not satisfactorily performed by ultrasound or radiography. The AEWM also lends itself well to hardcopy record keeping. Most importantly, the device eliminates the need for operator evaluation of flaws.

The AEWM has several drawbacks in its present configuration: it requires an experienced operator, it is bulky, and it is expensive. KTRP personnel feel the AEWM needs to be reconfigured. To modify those factors, a redesigned AEWM could be made to function simply so the device may be operated by the welding operator. The potential also exists to reduce the complexity and cost of a reconfigured AEWM. Those features would make the device more attractive to fabrication shops.

The production weld data base gathered by KTRP was insufficient to perform an economic analysis of the potential impact of the AEWM. However, the fabrication-shop experiences indicated the AEWM economic impact would depend upon three factors: 1) frequency of weld repair, 2) individual state highway inspection requirements, and 3) shop costs incurred in performing routine QC nondestructive testing. Those costs would vary between fabrication shops and specific fabrication jobs.

KTRP personnel feel that further developmental work and shop experience are necessary before the AEWM becomes an accepted and widely employed nondestructive testing tool. The following steps are recommended:

1. Purchase of necessary accessories for use with the AEWM.
2. Perform additional fabrication-shop tests at one site for a period of 4-6 months, in cooperation with at least two state highway agencies.
3. Conduct laboratory research on use of the AEWM for monitoring fillet-welding operations.
4. Evaluate Tasks 2 and 3 to determine whether continued development would be warranted.
5. If the analysis under Task 4 is positive, reconfigure the AEWM into a more suitable cost-effective shop tool.
6. Interact with state highway agencies to get code modifications that allow use of the AEWM as a QC nondestructive testing tool.
7. Work to achieve widespread acceptance of the AEWM by fabricators, highway agencies, and technical societies and associations.
INTRODUCTION

The GARD acoustic emission weld monitor (AEWM) is a promising nondestructive evaluation tool designed for use in steel bridge fabrication (Figure 1). It possesses the ability to detect flaw formation during the welding operation (in-process). Also, it locates flaws along the weld line, facilitating the use of conventional geometric nondestructive testing (NDT) and weld repair. Due to those features, the weld monitor shows potential for inspection and reduction of repair costs to the fabricator with a subsequent savings to the bridge owner. Also, it has the potential for providing a better final product to the bridge owner.

The AEWM can continuously process large numbers of acoustic emission (AE) events occurring at rates too rapid for an operator to analyze. The microprocessor circuitry also determines when valid flaw activity occurs. The operator is informed of flaw-related events by displays on the AEWM front panel. The unit is also capable of data storage and hard-copy output.

The AEWM is the result of over 10 years of development by GARD INC. In 1980, the Federal Highway Administration (FHWA) contracted with GARD to furnish an AEWM for evaluation and to perform a series of laboratory weld tests using the device. That work was followed by a series of field tests by GARD at three fabrication shops in Illinois and Wisconsin. That contract was completed in 1984 (1). After successful completion of that work, the FHWA elected to have a further evaluation made of the AEWM. To accomplish that evaluation, the FHWA's Office of Implementation issued Task Order No. 8, "In-Process Welding Inspection Using the Acoustic Emission Weld Monitor" to the Kentucky Transportation Cabinet. The study was subcontracted to the University of Kentucky Transportation Research Program (KTRP) in July 1984.

KTRP's experience with acoustic emission dates to the early 1970's when the organization acquired a simple, conventional AE monitor (2, 3). From 1973 to 1976, KTRP personnel conducted a series of weld-monitoring tests using manual shielded-arc welding. It became evident that conventional AE devices were unable to monitor slag-type welding methods "in-process." That was due to the large amount of mechanical noise generated by slag cracking and fretting. The slag noise was sufficient to mask any flaw-related AE activity and greatly limited the utility of the AE equipment. In the late 1970's, the KTRP abandoned AE monitoring of welds.

From 1982 to 1984, KTRP and GARD personnel performed several bridge tests using an AEWM to detect crack propagation on in-service bridges (4, 5). By that time, the ability of the AEWM to function in high-noise environments, based on its unique AE pattern-recognition principle, had been demonstrated. KTRP had obtained an AEWM on loan from GARD prior to work on this evaluation study and was familiar with its "stand-alone" operational mode.

The objectives set for the task order were to

1) demonstrate the acoustic weld monitor on typical welds to state highway personnel from FHWA Regions 1, 3, 4, and 5 at fabrication shops;
1. ACOUSTIC EMISSION WELD MONITOR

A  PUSH-BUTTON FUNCTION KEYS
B  16-CHARACTER ALPHANUMERIC DISPLAY
C  DEFECT INDICATION LAMP

D  CALIBRATION INDICATING LAMPS
E  GAIN ADJUSTMENT SWITCHES
F  AE SIGNAL INPUT CONNECTORS

Figure 1. GARD Acoustic Emission Weld Monitor, Terminal, and Disc Drive.

2. VIDEO TERMINAL

3. FLOPPY-DISC RECORDER
2) monitor production welds and correlate the AEWM data with that of conventional quality-control nondestructive testing (NDT);
3) prepare, disseminate, and summarize a questionnaire on the AEWM to demonstration participants;
4) conduct an economic analysis of the AEWM based on the shop tests; and
5) prepare recommendations regarding the implementation of the AEWM.

FUNCTION AND OPERATION OF THE AEWM

The AEWM subjects consecutive AE events generated by the welding process to a three-step sequential test or AE pattern-recognition filtering program (Figure 2). First, the analog pre-processing circuitry computes the ringdown count (RDC) and time of arrival. Then, the microprocessor portion of the system tests the collected analog information for each event. As the first step in the filtering program, the ring-down count must lie within fixed limits. If this is satisfied, the second filtering step is imposed wherein the AE event must occur within a predetermined minimum event rate with other AE events preceding or following it (which have also passed the ring-down test). The third step determines whether all the events passing the first two filtering tests were located by time-of-arrival from within a tight locational tolerance. All AE event data that fail to pass any one of the tests are discarded. Additionally, the frequency content of each AE event is analyzed using a comb filter. Valid AE events having high-frequency biases are classified as cracks. Other data that satisfy the model are characterized by the AEWM as unclassified defects.

To conduct AE weld monitoring, two Acoustic Emission Technology (AET) 175-L 175 KHz resonant frequency transducers are affixed to the steel plate (Figure 3). Transducers are wired to GARD 0 dB pre-amplifiers, which in turn are connected to analog modules mounted in the AEWM by coaxial cables. The transducers are attached with magnets, which keep them secured to the steel plate. Dow Corning 111 Silicone Grease is used to acoustically couple the transducers to the steel plate. Coupling efficiency and transducer operation are checked by lightly tapping on the steel plate with a screwdriver and checking the indicating lights on the face of AEWM analog modules. The transducers are mounted 6 inches offset of the weld line and 2 inches from the edges of the plate. On the 84-inch wide plate, for instance, the transducers have an 80-inch separation or transducer array spacing.

The AEWM is usually operated in the "stand-alone" mode. Push-button controls on the face of the device are used to input the transducer spacing (for flaw location) and control the weld-monitor operation. The "stand-alone" operation requires that the AEWM operator adjust the system gain (signal amplification) on the two active analog modules and prepare the microprocessors to accept and process AE activity. The gain adjustment is provided by switches on the AEWM analog modules. The gain on each of the two active transducer/pre-amplifier/analog monitor channels is set independently to accommodate for variations in component response and in transducer-test piece coupling efficiency. The amount of gain or signal amplification used is based on previous experimental
Figure 2. AEWM Processing Flow Chart for Flaw Detection.

Figure 3. Schematic of Typical Butt Weld Showing Normal Transducer Placement.
results. Programming and preparation of the system microprocessors require the AEWM operator to conduct a four-step operation, performed by sequentially pressing three or four push buttons mounted on the face of the AEWM in each of the steps.

Once the gain is properly set, it does not need to be readjusted until after the weld is completed and the transducers are moved to another welding operation. Likewise, most of the microprocessor preprogramming does not need to be repeated until the weld pass is completed.

A video terminal is used to visually display the test results and operational sequence. The system gain is set between 40 to 70 dB, depending on the weld length. During the course of this work, it took approximately 10 minutes to place the transducers and prepare the AEWM to monitor in the "stand-alone" mode.

Typically, the welding machine is set to start the weld on run-on tabs tack-welded to the plate. Then, the machine traverses the weld line and completes the welding operation over a set of run-off tabs. Just after the welding arc is struck, the AEWM operator activates the monitoring process while the welding head is still in the run-on tabs.

To insure proper functioning of the AEWM, the operator checks the calibration indicating lights on the face of the AEWM analog modules. The lower red light indicates the low-level AE activity is being received. The upper red light indicates that high-level AE activity is being received. The intermediate green light indicates the AE activity of defect-level intensity is being detected.

During weld monitoring, all three of the indicating lights on the analog modules flicker intermittently as a result of AE activity generated by normal welding operations. Usually, the analog module indicating lights of the transducer nearest the welding head will show the most activity. As the welding operation progresses across the plate, the volume and magnitude of AE activity will shift from the analog module of the transducer near the start of the weld to the module of the transducer near the end of the weld.

If for some reason one analog module does not function or is not receiving a signal from a transducer, the indicating lights on the module will not function. If the signal amplification set on the face of the analog modules is too low, no intermediate or high-level AE activity will be shown by the indicating lamps. If the amplification is too high, the upper-limit indicating light will be the only one that flashes.

At the end of each pass, the AEWM is allowed to monitor the weld for a period of 1 minute. This is done to detect any post-weld AE activity. Thereafter, the monitoring is terminated and the AEWM is reset to monitor the next welding pass. This operation takes about 1 minute to complete. It does not interfere with the welding sequence as the welder is preoccupied for 5-10 minutes between weld passes while chipping slag off the weld, visually inspecting the weld, and re-setting the welding machine for the next pass. Using the "stand-alone" mode to reset the AEWM, the operator must perform a three-step command input on the AEWM panel-mounted push buttons, sequentially pressing three push buttons for each step. The AEWM operator is able to monitor all of the welding operations without interfering with the welding process.
The presence of flaw-related AE activity is shown by a red indicating lamp located on the front panel of the AEWM. The light is activated when the AEWM operator initiates the weld-monitoring process. If the lamp goes off during monitoring, the AEWM has detected AE flaw activity. Also on the face of the AEWM panel is a 16-character alphanumeric LED display lamp. During a test run, if any flaws are detected, their number and approximate location will be shown on the LED display. The operator can interrogate the AEWM using push buttons on the face of the panel to determine whether the defect is crack-related or unclassified (i.e., slag inclusion, lack of fusion, or porosity). A post-monitoring display on the video terminal shows the transducer spacing and the location of any flaw activity between the transducers to within a 1-inch tolerance.

In the "data-recording" mode of operation, the AEWM can store AE test data in the floppy-disc recorder. That data can be recalled and manipulated using a number of processing programs contained in the AEWM microprocessor memory. With those programs, the operator can 1) change the flaw models used by the AEWM, 2) reprocess weld data using revised flaw models, 3) simulate changes in signal gain, 4) analyze AE activity from specific locations and, 5) perform various statistical analyses on prerecorded AE test data.

The test data stored on floppy discs can be replayed through the AEWM and several data manipulations performed. Also, a serial printer can be used to obtain hardcopy printouts of flaw indications, file dumps (display of raw recorded data), and data manipulations.

Operating the AEWM using the "data-recording" mode is more complicated than the "stand-alone" operation. Ten commands ranging from three to sixteen characters must be entered using the video terminal keyboard. Additionally, floppy disc use requires operator attention to several switches and indicating lamps.

Much care must be exercised when operating in the recording mode as incorrect commands or command sequences can cause a "lock-up" between the AEWM and disc drive. Then, both systems will malfunction. When that happens, it takes about 5-10 minutes to sequentially power-down the equipment, remove the floppy disc, sequentially restart the equipment, re-enter the operational commands, load a new floppy disc, start the recording operation, and activate the AEWM.

PRELIMINARY EXPERIENCES WITH THE AEWM

In June 1984, KTRP personnel, using an AEWM on loan from GARD, conducted its first welding tests at the August Iron and Steel Co. in August, Georgia. The objective of that effort was to gain hands-on shop experience with the AEWM.

AE tests were performed on several butt-welds using ASTM A 36 steel plate 84 inches wide (Figure 4). The AEWM detected no flaws in the welds. Several small code-acceptable porosity were observed on the surface of one weld but were not detected by the AEWM. Several I-girder flange-to-web fillet welds also were monitored (Figure 5). However, some difficulties were encountered in monitoring those welds due to the cracking of positioning tack welds as a result of thermal stresses.
Figure 4. Submerged-Arc Welding on Flange-Transition Butt Weld (Augusta Iron & Steel Co., June 1984).

Figure 5. Flange-to-Web Fillet Welding Operation (Augusta Iron & Steel Co., June 1984).
That initial fabrication-shop work provided KTRP personnel with valuable experience in conducting weld-monitoring tests with the AEWM. Unfortunately, due to shop scheduling and steel-plate quality problems, only a limited number of welds were tested.

In August 1984, KTRP personnel travelled to the GARD offices at Niles, Illinois, to pick up the FHWA-owned AEWM and to receive training in the advanced operation of that unit. The FHWA AEWM peripheral equipment included a Pertec dual-drive floppy-disc recorder, a Bee Hive International Micro B video terminal, and two AET 175-L transducers.

KTRP personnel received instruction on complete system operation of the unit in its AEWM/Terminal/Disc configuration or "data-recording" operating mode. This entailed understanding of the interaction of those elements, data processing options, command statements, and statement sequences required for those data-processing options.

GARD performed two weld tests to give KTRP experience operating the AEWM in the "data-recording" mode. In the first test weldment, cracking was induced in the weld by deliberately including copper in the weldment. In the second test, both copper cracking and slag inclusions were induced. In both tests, flaws were generated and successfully detected by the AEWM. Thereafter, KTRP personnel were instructed on post-test analyses of the recorded data.

After training at GARD, KTRP personnel acquired the FHWA AEWM and components for use in this study. During that training, KTRP personnel gained a better understanding of the AEWM operation and the test options available using auxiliary equipment.

In October 1984, KTRP personnel conducted an additional familiarization test of the AEWM at High Steel Structures Inc. in Lancaster, Pennsylvania. As with the Augusta test, this work allowed KTRP personnel to gain additional operating experience with the equipment prior to weld demonstrations.

Both production and "bead-on-plate" test welds were monitored (Figure 6). Some difficulties were experienced with the "bead-on-plate" welds. Those problems were caused by KTRP inexperience with induced copper cracking. Consultation with GARD personnel resolved those difficulties, and satisfactory results were obtained with the appropriate modification in test procedure.

AEWM DEMONSTRATIONS

Four demonstrations of the AEWM were performed by KTRP. Additionally, KTRP contracted for GARD to furnish one engineer to aid with the demonstrations. The demonstration format formulated by the FHWA Office of Implementation, KTRP, and GARD consisted of 1) one-half day of classroom discussion of the AE phenomena and the function of the AEWM, 2) one-half day demonstration of the AEWM detecting deliberately induced weld flaws, and 3) one day of monitoring production welds using the AEWM.

A list of potential state highway demonstration attendees was furnished to KTRP by the FHWA Office of Implementation. A minimum of five names was submitted for each FHWA region. Potential attendees were contacted by KTRP and informed of the demonstrations. Four fabrication shops were contacted and asked to host the demonstrations. One
Figure 6. Butt-Welding Web Plates Using Semiautomatic Submerged-Arc Welding (High Steel Structures, October 1984).
fabricator failed to respond, temporarily delaying the progress of this study. The other fabrication shops agreed to host the demonstrations. As an economy measure, a decision was made to hold two of the demonstrations during one week at a single fabrication shop.

The first demonstration was held at High Steel Structures Inc. on January 8 and 9, 1985. State highway attendees were from FHWA Region 1 -- Vermont, Maine, New York, Connecticut, and New Jersey. Also in attendance were John Hooks and Dennis Quarto from the FHWA Office of Implementation. The second weld demonstration also was held at High Steel on January 10 and 11, 1985. The attendees were from FHWA Region 3 -- Delaware, Pennsylvania, Virginia, and West Virginia. The third AEWM demonstration was held at Augusta Iron and Steel Company, February 27 and 28, 1985. The state highway attendees were from FHWA Region 4 -- Alabama, Georgia, Kentucky, Mississippi, South Carolina, and Tennessee. Jerry McKibben of the FHWA Georgia Division Office and Gerry Schroeder of the FHWA South Carolina Division Office were also in attendance. The final AEWM demonstration was performed at Phoenix Steel Corporation in Eau Claire, Wisconsin, March 27 and 28, 1985. Attendees were from five states in FHWA Region 5 -- Illinois, Indiana, Ohio, Minnesota, and Wisconsin. The names of those in attendance at the AEWM demonstrations are contained in Appendix A.

During each classroom discussion, a representative from the host fabrication shop welcomed demonstration attendees and gave a brief background on their fabrication shop. Thereafter, Theodore Hopwood II of KTRP gave a talk on the AE phenomena and David W. Prine of GARD discussed the AEWM (Figure 7).

During the afternoon portion of the first day, attendees were familiarized with the AEWM (Figures 8-11). Thereafter, the flaw-detection capabilities of the AEWM were demonstrated.

GARD and KTRP decided to use copper cracking for the demonstration of the AEWM flaw-detection capability. While potential problems with controls of weld parameters by a fabricator were foreseen, the ability of the copper crack to be readily visually detected favored its use. Slag embedments often are not superficially visible after the weld has been deposited. It would be difficult to perform follow-up conventional subsurface NDT on partially filled weld grooves. Filling the weld groove after flaw induction was unacceptable, as covering weld passes might "melt-out" defects embedded in previous passes. Also, no facilities were available for destructive sectioning.

The welding operator was given the submerged-arc welding parameters used by GARD for copper cracking. At all of the shops, the welder was not able to duplicate the exact GARD settings due to differences in welding equipment, filler wire, and flux. However, the welding operators selected parameters that would approximate those used by GARD and still produce a suitable weld (Figures 12-14). The test plate was similar to those used by KTRP during schooling at GARD (Figure 15).

The transducers were attached along the weld line 2 inches from the end of the plate (i.e., a 44-inch active transducer spacing). The system gain was set at 58 dB. The weld groove was doped with 3 grams of copper placed in the groove 10-15 inches from one transducer (Figure 16). The AEWM was operated in the "stand-alone" mode. Shortly after the welding head passed over the copper, the defect indicating light went off (Figures 17 and 18). The LED panel revealed flaw indications where the
Figure 7. Discussion of the Acoustic Emission Phenomena at High Steel Structures Inc. (January 1980).

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Figure 18. Shortly after the Weld Is Placed over the Copper, the Defect Indicating Light Goes Out.
copper was located (Figures 19 and 20). Subsequent inspection revealed several copper cracks. A second weld pass produced another flaw indication by the AEWM. Again, cracking was detected in the copper-embedded area (Figure 21).

When the welding operator was able to closely duplicate the GARD copper-crack weld variables, the copper-cracking demonstration worked correctly. However, some problems in creating copper cracks occurred when the weld test variables departed from the GARD values.

Copper cracking requires close control. In the past, KTRP had used copper cracking to prepare ultrasonic defect specimens. However, as was learned, dynamic copper-crack detection by AE monitoring is a more complex task. The welding variables in this operation are critical. The critical test variables are the amount of copper placed in the weld groove, the welding speed, and the size of the molten weld puddle.

No cracking will occur if too little copper is used, the weld speed is too slow, or the weld puddle is too large. Those factors will cause excessive dilution of the copper in the steel and the weld will not crack.

Undetectable copper tearing of the weld will occur if too much copper is present, the weld speed is too fast, or the weld puddle is too small. In this case, too much copper is dissolved in the steel. In the austenitic (high-temperature) phase of the steel, the limited copper solubility in steel will cause migration of copper to the austenitic grain boundaries. The copper phase will tear along grain boundaries in a low-energy fracture that is undetectable by AE testing (while the steel is still austenite). In practical AE production monitoring, this is of no consequence, because the situation is never encountered.

Proper copper-cracking tests require that a minimum critical amount of copper is used. The weld speed and weld bead size must sufficiently dilute the copper to prevent tearing yet not spread the copper along the weld so that no cracking will occur. On cooling below the austenite-to-ferrite transition temperature, the weld metal will crack due to its high carbon equivalent.

The AEWM tests of production butt welds detected no flaw activity during the AEWM demonstrations (Figure 22). A summary of the production shop welds monitored during the preliminary tests and the AEWM demonstrations is contained in Appendix B. Due to shop scheduling, only one or two production welds were monitored during each of the AEWM demonstrations. One AEWM test was verified using both ultrasonic testing and radiography. This was on a fracture-critical web butt weld for the Maine Department of Transportation at High Steel (6). The only problem encountered during that portion of the demonstration was excessively high weld-plate temperatures encountered on relatively narrow flange material tested at Augusta Iron and Steel and Phoenix Steel. That necessitated removal of the transducers before the final weld passes were completed.

AEWM QUESTIONNAIRE RESPONSES

After the AEWM demonstrations were completed, a questionnaire was prepared by KTRP and sent to 21 of the attendees. Sixteen attendees responded. A detailed summary of the questionnaire is contained in Appendix C.
Figure 19. Cracks Located on the Weld at the Position Indicated by the AEWM.

Figure 20. Small Transverse Cracks in Copper-Tinted Portion of the Weld Bead Detected by the AEWM.
Figure 21. AEWM Flaw-Indicating Lamp Goes out during the Second Pass of the Copper-Cracking Weld Test.

Figure 22. AE Monitoring Production Butt Weld during AEWM Demonstration.
All respondents felt the AEWM demonstration was satisfactory. However, several attendees thought that better coordination could have been made with the fabricators to test more production welds.

Despite some problems with the copper-crack demonstrations and some minor equipment problems, 15 of the respondents felt the AEWM functioned suitably. The sixteenth respondent questioned the suitability of the demonstration based on the problems with copper-cracking. Some of the demonstration attendees also wanted to see the AEWM detect other types of defects.

The attendees felt the AEWM had several limitations, most of which related to cost, manpower requirements, and configuration of the device. Some questions also were raised about the durability of the equipment. One attendee stated that the AEWM needed skilled operators and another respondent noted that there was no training school for the AEWM. Several attendees felt that ultrasonic testing and radiography were suitable. Another believed the AEWM in its present configuration might be awkward for testing long fillet welds. Several attendees considered the AE principle of detecting only dynamic flaw activity a drawback.

Eleven attendees felt the AEWM would be a useful, cost-effective device for detecting flaws in fabrication shops. Several respondents believed its use would be limited to shops doing a large amount of heavy welds or full-penetration welds. One respondent noted a potential cost savings on repairs. Of those who felt the AEWM did not have potential for fabrication-shop use, the main drawback centered on the lack of potential cost savings due to the AEWM configuration. Another respondent noted that ultrasonic testing and radiography are the presently accepted NDT code requirements on completed welds.

The attendees felt the AEWM could best be applied as a quality-control (QC) testing tool. One attendee believed it would be useful in shops having high defect-rejection rates. Several respondents felt it might prove useful on fillet welds. Others believed it would be effective for monitoring critical, full-penetration, and/or thick-section welds.

Fourteen respondents also felt the AEWM might be useful in other highway applications. The AEWM might be useful for inspection of in-service bridges for defects or in the evaluation of known discontinuities in those bridges.

When asked for additional comments, one respondent replied that a test should be conducted to show the actual way the unit would be used in a fabrication shop. Another felt that for some weld applications (i.e., cold-cracking) longer monitoring times might be required. One respondent felt the AEWM might eliminate repair of unnecessary or harmless discontinuities not subject to subcritical crack growth. Another attendee wanted a better understanding of the AE behavior of flaws other than cracks. Also, he desired a better understanding of the electronics employed in the AEWM.

KTRP EVALUATION OF THE AEWM

The KTRP experience with the AEWM has been very positive. The device has proven many times that it is capable of detecting and accurately locating flaws in welds. In monitoring over 400 linear feet of
production butt-welds, the AEWM failed to detect only one small porosity in a production weld. Also, a few false flaw indications were experienced with undercuts in welding grooves (which also were experienced by GARD personnel during their earlier shop tests). The AEWM did not detect any other flaws in production welds except for one crater crack in a weld termination, which was to be routinely removed in later fabrication operations. However, it should be noted that KTRP personnel conducted tests at fabrication shops that historically had low weld-rejection rates. In the one comparison of the AEWM with conventional nondestructive testing, the methods correlated well. Also, the ability of the AEWM to produce unambiguous flaw indications and durable, easy-to-interpret hardcopy test records make it ideal for high-production-rate nondestructive testing.

The statistical flaw-detection parameters provided by GARD in the AEWM programming are satisfactory for fabrication shop use. In some cases, the frequency correlation used for flaw classification (crack or unclassified) proved inconclusive. However, since the initial three-step flaw model had been met, the AEWM operator always was alerted that a flaw had been detected. Due to the suitability of the existing programming, the capability of the equipment to perform modified data analyses seems superfluous for routine shop tests.

The linear flaw-location technique will accurately locate flaws within the transducer array to within about ±1 inch. The orientation of a crack within a weld may affect the accuracy of flaw location. However, the AEWM locational accuracy is suitable for conducting follow-up inspections with conventional NDT methods or for performing weld repairs. On long butt welds exceeding 48 inches, the 16-digit LED locational indication is not sufficiently accurate. In testing with the AEWM in the "stand-alone" mode, it is useful to employ a video terminal that will display the more accurate flaw-location information at the end of a weld test. The LED indication is useful for notifying the AEWM operator that a series of flaws has been generated or a flaw has been created that may be related to a specific welding event.

The AEWM has the unique ability to be employed as a QC tool as it can monitor the weld at the lowest level of assembly (during each pass) and detect flaws before successive passes are deposited. QC nondestructive testing can positively impact the cost of fabrication. Quality-assurance (QA) nondestructive testing of the completed weldment serves as a safeguard for both the bridge owner and the motorist. However, QA nondestructive testing may not have a positive impact on the fabrication cost of a bridge. In fact, the opposite may be true. The next bridge he buys from the fabrication shop will be more expensive due to the increased historical fabrication repair costs imposed by that inspection. This does not mean the practice should be eliminated, but its end effect on fabrication costs should be better appreciated by those who employ it.

There are other means of achieving QC "in-process" testing of welds besides the AEWM. Equipment that monitors welding variables such as wire feed and welding amperage are available. However, the creation of a flaw in a weld may or may not be related to those process fluctuations. A flaw may be created by bad steel or flux, for example, and never be detected by a welding-process monitor. Another approach is to use spectroscopy to monitor the weld arc. However, as the bulk of highway
welding employs a solid flux that masks the arc, this approach is not
applicable. It may be possible to use conventional nondestructive
techniques to inspect the weld after each pass. Some research is
presently being done with automated ultrasound. However, even if the
method proved viable, equipment costs would far exceed that of the AEWM.
The only NDT methods presently feasible are the conventional surface
tests — dye-penetrant, magnetic-particle, and eddy-current. All of
those methods would be too laborious and time consuming to prove
economically feasible on a per-weld-pass basis. Only the AEWM offers the
potential for economical QC testing in fabrication shops.

The two common subsurface NDT methods, ultrasonic testing and
radiography, use static geometric flaw evaluation. In that respect, they
are of greater advantage for use in QA testing than the AEWM. Once a
weld is completed and the thermal stresses are alleviated, defect AE
activity will cease in most cases. Thereafter, the weldment must usually
be mechanically stressed to produce defect AE activity. Ultrasonic
testing or radiography do not require mechanical stressing of the weld.
While those methods do not lend well to "in-process" testing, they may
be used to confirm AEWM flaw indications and sizes considered for
repair.

It should be noted that, while AE testing and use of the
conventional NDT methods may be complimentary in their respective QC-QA
roles, the inspection results using those methods may not always
correlate well. The AEWM may miss individual or widely scattered
porosity that would be most easily detected by radiography. Usually, the
type of porosity overlooked by the AEWM may not prove to be troublesome
from a fatigue standpoint in the field. As the AEWM is an "in-process"
test, some of the weld flaws it detects will be eliminated by remelting
during deposition of subsequent weld passes. The AEWM will also
occasionally detect slag trapped in undercut weld beads that are removed
by chipping or rewelding. However, those occurrences will be infrequent.
AEWM flaw indication locations can be recorded and those areas subjected
to careful follow-up conventional QC or QA nondestructive testing. GARD
has found that the AEWM is very good at detecting planar weld flaws such
as cracks and lack of fusion. Those flaws are the most difficult to
detect with conventional NDT methods and pose the greatest risk to
structural integrity.

If properly applied, the AEWM can be incorporated with conventional
NDT methods into a QC-QA program that is effective not only in detecting
flaws but also in reducing production costs. However, inspection
personnel involved must take advantage of the complimentary aspects of
those NDT methods rather than to focus on their differences.

The AEWM in its present configuration is a multipurpose NDT test
device that may be used for both production monitoring and research.
Although operation of the equipment in the "stand-alone" mode is fairly
simple, great care must be used by the operator to successfully perform
weld tests. Incorrect use of the equipment usually will result in
undercalls (missed flaws). As the testing is "in-process," the operator
must have the equipment properly connected, adjusted, coupled,
calibrated, and programmed before the welding operation is initiated.
Otherwise, he will miss the test and will be unable to determine whether
the weld pass contained a defect.
When the equipment is run in the "data-recording" mode, the AEWM operator must perform many additional programming steps and be alert to additional potential "lock-up" problems. KTRP experience with the AEWM operated in the "data-recording" mode indicates that, while this mode is useful for research, it may be too troublesome for normal production monitoring.

The operator also needs to have some experience with the AE phenomena and be aware of potential noise sources, such as several shop personnel working on the same weldment. He also needs to be familiar with potential electrical problems such as grounding of the transducer to the test piece.

Coordination between the welder and the AEWM operator has never been a significant problem during a weld test. The only delays experienced occurred when KTRP personnel were not informed of an impending welding operation and had to delay the welder for a few minutes to set up the test.

In its present configuration, the AEWM requires a full-time operator while the testing is in progress. However, GARD experience indicates that this is no more costly than follow-up inspection using ultrasonic testing or radiography.

The most important feature of the AEWM is that the operator does not have to evaluate flaw indications. The AEWM microprocessors perform that task internally, removing an important variable from the inspection process. The AEWM operator does not need exceptional vision or psychomotor skills to accurately detect defects. Also, the AEWM is not subject to worker fatigue. The importance of those features is exemplified by the amount of research in progress attempting to remove the equipment operator from flaw evaluation in many forms of nondestructive testing by using computers.

Despite the many advantages of the AEWM, in its present configuration it has some drawbacks that need to be overcome before it is widely employed. One of those relates to code acceptance by state highway agencies. As one demonstration attendee noted, only ultrasonic testing and radiography are specified for subsurface inspection of welds. The main codes governing nondestructive testing of welds are contained in the American Welding Society "Structural Welding Code - D.1.1," the American Association of State Highway and Transportation Officials Standard Specifications for Highway Bridges, and the added specifications of each highway authority (which differ widely). If a bridge member is deemed fracture-critical, additional codes and specifications are applicable. Also, among highway authorities, there is no uniformity as to what NDT method(s) is to be applied.

Fabrication shops usually are required to perform QC nondestructive testing of completed weldments; this is followed by QA nondestructive testing conducted by the highway authority. It should be noted that most of the present QC testing performed by the fabricators are actually QA nondestructive tests using ultrasound, radiography, magnetic particle, or dye penetrants of a completed weld that are later duplicated by the highway authority.

Fortunately, the limiting factor in this somewhat jumbled situation is that a relatively few large fabrication shops nationwide produce most of the welded plate-steel bridge members. That presents both a benefit and a problem as far as AEWM deployment is concerned. If a large
fabrication shop has the AEWM for QC nondestructive testing, it may use the equipment to the benefit of many highway agencies. But, most highway agencies serviced by the fabrication shop must accept the AEWM for QC testing for it to be economically beneficial to the shop.

A second pertinent question the demonstration attendees had about the AEWM concerned its purchase cost and operating expense. Presently, an AEWM costs about $40,000. While this is considerably more expensive than a conventional portable ultrasonic tester, it is less expensive than some of the computer-enhanced ultrasonic test devices (including the time-of-flight device presently being investigated for the National Cooperative Highway Research Program by the Welding Institute). Also, it is difficult to make comparison between test-equipment costs since the AEWM is a true production QC tool and ultrasonic devices are not.

Other cost-related limitations of the present AEWM are the requirement for an equipment operator while the welding operation is in progress and the need for one AEWM at each critical weld station. For a large fabrication shop, four or five AEWMs might be required as well as an equivalent number of operators. The obvious expense would make widespread use of the AEWM impractical.

Several demonstration attendees were emphatic about the need for a NDT tool to inspect fillet welds. This was reflected in the responses to the questionnaire. As previously noted, the present AEWM would be awkward for inspecting long fillet welds. The present effective transducer spacing is limited to about 20 feet. Therefore, the transducers would need to be reset several times for girder flange-to-web fillet welds. The problem, however, may be overcome through research on the subject. If the AEWM can be made to reliably monitor fillet welds, that would render the device a much more useful shop tool.

A review of the attendees' comments seems to suggest that the AEWM, in its present configuration, would be most useful for monitoring heavy welds where follow-up conventional NDT would result in expensive repairs. However, while that may be true to a certain extent, it limits the application of the AEWM. The bulk of bridge fabrication shop welding is on plates less than 4-inches thick. While application of the device on that type of welding might be the easiest to justify, it certainly would not lead to widespread use of the AEWM.

While the attendees' opinions provide some impetus for further investigation of the AEWM, their exposure was too brief for them to determine the potential of the equipment. This somewhat affects their evaluations. Also, KTRP personnel feel that an equal or greater amount of exposure of the AEWM must be made to fabricators, who would probably be the purchasers and users of the equipment.

The AEWM in its present configuration has several operational drawbacks. As a result of its ubiquitous design, the present device has a complexity of operation that is unwarranted for routine AE production-shop work. Also, this ubiquity combined with dated electronics make the AEWM complex, bulky, and expensive. Those factors limit its present potential for widespread fabrication shop use. There is a compelling need to reconfigure the equipment to make it more attractive to fabrication-shop owners. GARD personnel have stated that a redesign of the present system would yield a smaller, less-complex, easier-to-operate, and less-expensive AEWM.
The main long-term expense involved in the present AEWM is not the equipment but the need for an attending operator. With some engineering effort, the equipment may be simplified to the point that it could be operated by relatively unskilled personnel. The microprocessors in the unit already perform flaw evaluation and location. It would not be unreasonable to use some of their present capacity allotted for data manipulation purposes to make the device more user-friendly (i.e., easier to understand and operate).

Although KTRP faced a varying number of weld-monitoring tasks in the different fabrication shops, in a short time, the testing at any specific location became routine. This allowed for routine equipment adjustment that could be mastered by personnel unskilled in AE testing.

If the AEWM is reconfigured into a simpler device, the welder becomes the obvious AEWM operator. That eliminates the greatest potential long-term expense to the fabrication shop, the full-time AEWM operator. Even in high-production fabrication shops, the welder is not so occupied as to prevent him from placing several transducers on the weldment, coding in a weld identification code on push buttons, pressing four or five sequential operational controls on a simpler AEWM, occasionally monitoring the AEWM (visually or audibly during welding), and removing the transducers once the weld is completed. Other test variables such as system gain could be preprogrammed for a work station by shop QC personnel more familiar with its operation. The welder would not have to adjust those settings. Even the existing AEWM has control interlocks that provide for the automatic starting and stopping of the monitoring process keyed by a signal from the welding machine. The present AEWM also has a self-calibrating mode that can eliminate the need for a pulser. Routinely, that device is used to inject an ultrasonic pulse into the weldment. The pulse is detected by the AEWM. That device is used to ascertain proper AEWM test setup. In the self-calibration mode, one transducer rings while the other one passively receives the ultrasonic signal. Then, the procedure is reversed. The operation calibrates transducer spacing, ensures system function and transducer coupling, and determines the suitability of the AE system gain. That feature was not utilized in the KTRP tests as the FHWA preamplifiers will not permit self-calibration.

KTRP personnel have consistently noted that welders take a strong interest in the AEWM output when they discover it functions well. When told the device is meant to verify that their work is satisfactory, welders willingly accept AEWM results. That indicates there would be little resistance by the welders to impose self-monitoring using the device. Also, KTRP experience indicates the use of the AEWM provides a real incentive for the welding operator to do his best.

If the AEWM is to be operated by the welder, further steps will be needed to simplify the unit. Also, several types of AEWMs may be required, including a model for groove welds and short fillet welds and another model for long fillet welds. Data output from the fabrication shop AEWM may be stored in a data retrieval system or may be directly fed into a master computer. The data would not only appraise the fabrication shop staff of the quality of the welds, but would also keep the production management abreast of the progress of shop welding operations. The hardcopy records of the quality-control tests could be maintained in digital form for easy retrieval and review. For example,
shop managers could quickly and easily use a microcomputer to ascertain the defect or rework rate for the plant, the welder, the work station, or a particular job. The data could be readily furnished to highway authorities to determine fabrication-shop performance. Infrequent but recurring problem areas could be easily pinpointed and remedied. Also, manpower required to perform those tasks would be minimal.

One demonstration attendee noted that the AEWM did not seem to be sufficiently trouble-free or damage-resistant for fabrication-shop use. That has not been the experience of KTRP personnel. The AEWM has been subjected to fairly rough handling on bridges, in transit, and in the fabrication shop. The only problems have been with occasional operator mistakes and with damage to the accessory components (i.e., the transducers, the coaxial cables, and the transducer lead wires).

The cables used in the AEWM demonstrations are rubber-coated RG 58 coaxial cable. Occasionally, the cable insulation will be burned when contacted by hot slag. More commonly, the BNC cable connectors will be damaged by rough handling. That treatment can be anticipated as normal usage. Stronger, heat-resistant cable should be selected for routine fabrication-shop testing. Also, a more rugged connector should be employed for that environment.

Lead wires connecting the preamplifiers to the transducers also should be changed. Those wires are presently RG 174 coaxial cable with BNC connectors on one end and more delicate LEMO connectors on the other. RG 174 cable is very light duty and often breaks at the connector. The LEMO connector is another very weak link and KTRP has had to repair at least three LEMO connections. Unfortunately, the LEMO units are required to attach the lead wires to the AET 175-L transducers.

The AET 175-L transducers can withstand normal rough handling. However, the maximum service temperature of those units is limited to about 250-300°F. Thereafter, the internal piezoelectric crystal may become debonded from the wear plate and the transducer may be ruined. KTRP lost one of its transducers to overheating during the AEWM demonstrations. While higher-temperature transducers are available, it is doubtful that they possess the good voltage-response characteristic of the AET units. Selection of different transducers will require testing to determine new AE system gains for common tests.

ECONOMIC IMPACT OF THE AEWM

During the KTRP fabrication-shop tests with the AEWM, no flaws were detected that required repairs. Only one weld-monitoring was compared with conventional NDT methods. The data base was insufficient to perform an economic analysis of the AEWM based on repair savings. In part, this was due to the need for KTRP personnel to concentrate on familiarizing themselves with the AEWM. Also, the fabrication shops had fixed work patterns and schedules that precluded large-scale testing or NDT comparisons while KTRP personnel were present. The fabrication shops also tended to have very low defect-rejection rates. One shop had a butt-weld rejection rate of less than one percent for all projects fabricated for one state. Those shops had good reputations for quality control.
Other fabrication shops having greater probability for defect detection could have been selected. However, KTRP did not want to become involved in controversial situations at this early stage. Also, both KTRP and GARD believed better cooperation would be provided by fabrication shops having low defect rates.

From discussions with highway and fabrication-shop personnel, it was determined that the typical butt-weld rejection rate was five percent or less in the fabrication shops visited. In other shops, a higher rate might be anticipated. Also, it is probable that the defect frequency may vary depending on a number of factors including base material, welding materials, equipment problems, welder error, and weld design. Since it is likely that the frequency of occurrence of defects will either be high for a short-term or very infrequent, the chances of detecting a flaw during any one inspection trip are very small.

Repair costs will also vary due to the stage of completion of the weldment at the time of repair, the type of repair required, and the amount of reinspection and documentation imposed for the repair. Those costs will vary between fabrication shops and jobs (as highway agency repair requirements will vary). Also to be considered are weldments that must be discarded due to faulty welds or poor base metal. The amount of fabrication work done on those items prior to scrapping is also a real cost to the fabricator.

To gain sufficient insight into potential cost savings to a fabricator, based on savings due to reduced cost of repairs, long-term AEWM monitoring is necessary. Also, the calculated savings will only apply to that specific fabricator. Fabricators having low defect-rejection rates will probably save less than those having higher defect rates.

If a situation is examined more closely, the effect of reduced defect-rejection costs due to the AEWM may prove insignificant compared to operational savings that may be achieved by the fabricator. Regardless of the defect-rejection rate at a fabrication shop, highway agencies still impose a requirement for QC inspection. Since the AEWM is a true QC tool having a low cost per test, fabricated items could be properly inspected at the most economical level of production (i.e., the individual weld pass).

There are several major routine costs in QC nondestructive testing. The most obvious of those is the cost of performing tests. If conventional NDT methods such as ultrasound or radiography are used, a QC technician is required to perform the tests and record data. However, another major cost is entailed in handling the completed weldment prior to inspection.

Depending upon the fabrication shop involved and the NDT method(s) employed, a certain amount of time is consumed by other personnel in accessing or turning the weldment for ultrasonic testing or moving it to another area for radiography. In several shops visited, the completed welds remained in work stations while being subjected to QC ultrasonic testing. This idled the welder and rendered the work station unproductive while the NDT work was being performed. Also, a certain amount of time is consumed in coordinating the welding operation and the follow-up inspection.

As presently envisioned, the reconfigured AEWM would eliminate most of the conventional NDT work and the expense of the NDT inspector. This
would result in a savings to the fabricator over the life of the AEWM. Secondly, since the AEWM is a real-time test device, once a defect-free weldment is completed, the AEWM may be moved to its next level of production. This would eliminate lost productivity by the welder and would minimize material-handling costs. Also, if desired, the AEWM could be used to perform 100-percent weld monitoring on details where specifications require only partial testing.

Since the AEWM can test the welds in real-time at the most basic fabrication level, the production flow can be maintained and many bottlenecks due to weld defects and major repairs can be minimized. Those costs are difficult to determine even in long-term tests. However, those costs along with inspection and repair costs are incurred by the fabricator and are reflected in his pricing of subsequent work.

The AEWM also may yield direct cost savings to highway agencies. Once they gain confidence in the use of the AEWM, it is likely they can reduce the level of shop inspection. Presently, some states have expensive contracts with testing firms who supply inspectors. With greater assurance of proper quality control, due to the use of the AEWM, those inspectors would not need to scrutinize every facet of the fabrication-shop operation. Also, AEWM records may be reviewed more rapidly than conventional NDT records, thereby occupying less of an inspector's time. Production problems may be detected quickly and problem areas resolved with a minimum of involvement by a shop inspector.

The cost savings realized by the fabricator and, in turn, by the highway agency depend on the extent the agency will allow the fabricator to employ the AEWM. If the agency will allow the welder to automatically repair areas where flaws were detected by the AEWM, a greater cost savings will accrue. Also, some codes and specifications presently require a percentage of compression welds to be subject to QA nondestructive testing. If the highway authority will accept the AEWM results, another cost savings would result. It is not suggested that QA nondestructive testing of tension welds be supplanted by the AEWM. However, if long-term use of the AEWM provides greater confidence of weld quality, some other cost savings in QA testing might be implemented by highway agencies.

Another intriguing possibility is for highway agencies to impose the use of the AEWM on fabrication shops that experience unacceptably high defect-rejection rates. A contract NDT firm could be employed to enter the shop with an AEWM and monitor production welds until the shop's defect-rejection rate fell to a tolerable level. One demonstration attendee felt the AEWM might be useful in shops having nominal technical expertise. Typically, those would be shops that would have high defect rates. Usually, such shops would not acquire an AEWM of their own volition, nor would they necessarily support a unit.

RECOMMENDATIONS

While the work conducted by KTRP indicates a potential benefit in the use of the AEWM, more extensive shop testing must be performed. This is due to several reasons:
1. To sample a significant number of defects in any fabrication shop requires a large initial number of welds be monitored, especially at fabrication shops having low defect rates.

2. To correlate AEWM results with conventional QC and QA nondestructive testing requires extended use of the AEWM in the fabrication shop.

3. Close cooperation will be required between AEWM personnel and the fabrication shop to accurately determine potential cost savings (both of repair and operational costs).

4. To obtain acceptance of the AEWM by a fabrication shop for initial adoption of the device, the FHWA will need sufficient long-term use data and first-hand shop experience with the unit.

5. At least two highway agencies that have continuous ongoing fabrication work at the shop should participate to determine if the AEWM will be utilized in subsequent welding operations.

6. More experience is necessary to determine how to properly reconfigure and utilize the AEWM.

It will be necessary to build a considerable AEWM history to promote a nationwide adoption of the device by fabrication shops and gain acceptance by highway agencies.

Laboratory and field research should be conducted on the use of the AEWM for inspecting flange-to-web fillet welds for girders. Both partial- and full-penetration welds should be studied. If necessary, fabrication-shop practice may need to be revised.

Once that work is complete, the AEWM should be evaluated thoroughly to determine if all factors point to continued development. If this is the case, then the AEWM should be reconfigured and placed in a shop having practical "hands-on" use by the fabricator. Also, several participating states must modify their codes to economically justify use of AEWM by the fabricator.

Concurrent with that work, the FHWA should interact with the governing associations and technical societies to encourage acceptance of proven AE systems for weld monitoring. Also, the FHWA should urge states to accept AE testing in their specifications.

The following future tasks are proposed:

1. Acquire the following accessories for the AEWM:
   a. a suitable AE pulser for calibration,
   b. a dot-matrix printer for hardcopy output,
   c. at least three conventional transducers,
   d. at least three high-temperature transducers,
   e. a spare analog module,
   f. two bi-directional preamplifiers, and
   g. spare coaxial cables.

2. Select a fabrication shop willing to accept the presence of the AEWM for a period of 4 to 6 months. Contact and coordinate shop testing with a minimum of two highway agencies having ongoing work in that fabrication shop during the test period. Conduct AEWM tests and correlate results with conventional nondestructive testing. Familiarize the highway agencies with the AEWM and the test results. Determine the shop repair rate and potential AEWM cost savings to the fabricator.

3. Conduct fillet-weld tests with the AEWM and modify the unit, as required, to allow its employment for such tests.
4. Evaluate Tasks 2 and 3 and determine if continued work is worthwhile.

5. If the analysis of Task 4 is positive, reconfigure the AEWM to a suitable cost-effective shop tool.

6. Interact with willing highway agencies to get code modifications that would permit use of the AEWM for QC nondestructive testing. Furnish one or more reconfigured AEWM units to the fabrication shop. Train shop personnel to use the AEWM(s) and provide long-term technical support for the shop. Monitor application of the AEWM on a production basis.

7. Work with the FHWA to achieve more widespread acceptance of the AEWM by fabricators, highway agencies, and technical associations and societies.

CONCLUSIONS

The AEWM may have the potential to provide greater cost savings than originally anticipated. However, the practical deployment of the device will probably not occur within a short time. Historically, there is a long period of gestation before new NDT methods are widely adopted. Ultrasonic testing had been applied for some 20 years by the aircraft industry before it was applied on welded bridges.

As the AEWM is a QC tool, it will be adopted by fabricators because they want to benefit from its use, not because it is forced upon them by specifications or codes. Also, it must be widely accepted by highway agencies and technical associations. The present lack of general agreement by highway authorities on the relative merits of ultrasonic testing and radiography indicates that considerable effort will be needed to achieve acceptance.

REFERENCES


APPENDIX A
PERSONNEL ATTENDING AEWM DEMONSTRATIONS

FHWA Region 1, January 8-9, 1985
High Steel Structures, Inc., Lancaster, Pennsylvania

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<thead>
<tr>
<th>NAME</th>
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<td>Allan Couch</td>
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<td>Inspector</td>
<td>Maryland State Highway Administration</td>
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<td>Krishna Verma</td>
<td>Welding Engineer, Bridge Division</td>
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<td>Jeff Callahan</td>
<td>Senior Engineer</td>
<td>New Jersey Department of Transportation</td>
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<td>Carline Lutyuski</td>
<td>Metallurgist</td>
<td>Connecticut Department of Transportation</td>
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<td>Dennis Quarto</td>
<td>Engineer, Office of Impl.</td>
<td>Federal Highway Administration</td>
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<tr>
<td>John Hooks</td>
<td>Manager, Office of Impl.</td>
<td>Federal Highway Administration</td>
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FHWA Region 3, January 10-11, 1985
High Steel Structures Inc., Lancaster, Pennsylvania

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<tr>
<th>NAME</th>
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<td>John Fleek</td>
<td>Materials Engineer</td>
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<tr>
<td>Don McKensie</td>
<td>Inspector</td>
<td>TEI Corporation</td>
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FHWA Region 4, February 27-28, 1985
Augusta Iron and Steel Co., Augusta, Georgia

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<tr>
<th>NAME</th>
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David Gaines*  Branch Manager, Construction  Kentucky Department of Highways
Homer Voiles*  Chief Structural Steel Inspector  Alabama Department of Transportation
Huen Croft*  NDT Supervisor  Georgia Department of Transportation
Earl Brewer*  Chief Bridge Designer  Mississippi State Highway Department
Tim Ray*  Concrete and Steel Engineer  South Carolina Department of Highways and Public Transportation
Jerry McKibbon  Engineer, Georgia Division  Federal Highway Administration
Gerry Schroeder  Engineer, South Carolina Division  Federal Highway Administration
John McGrady  Engineering Manager  Soil & Material Test Co.

FHWA Region 5, March 27-28, 1985
Phoenix Steel Inc., Eau Claire, Wisconsin

Lloyd Welker*  Asst. Structural Steel Engineer  Ohio Department of Transportation
Jim Wavering*  Engineer of Fabrication  Illinois Department of Transportation
Ray Kellerman*  Structural Metal Inspector  Minnesota Department of Transportation
Greg Paddock  Structural Metal Inspector  Minnesota Department of Transportation
Emmet Camp  Mechanical Engineer  Tennessee Valley Authority
Gary Wood  Supervisor of Shop Inspection  Wisconsin Department of Transportation
Cliss Hotchkiss  Bridge Inspector  Wisconsin Department of Transportation
Don Leonard*  Construction Field Engineer  Indiana Department of Highways
Bill Ashton  Production Manager  Egger Steel Co.
Fred Hiebichuk  Q. C. Foreman  Egger Steel Co.
Lyle R. Johnson  V. P. & Manager  Egger Steel Co.
Lowell Larson  Shop Superintendent  Egger Steel Co.

* Official AEWM demonstration attendee
## APPENDIX B

### FABRICATION-SHOP WELDS MONITORED USING THE AEWM

<table>
<thead>
<tr>
<th>SHOP</th>
<th>DATE</th>
<th>WELD TYPE</th>
<th>MATERIAL</th>
<th>PLATE THICKNESS</th>
<th>WELD LENGTH</th>
<th>WELD DESCRIPTION</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augusta</td>
<td>Jun 84</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>2 in.-1 1/4 in.</td>
<td>84 in.</td>
<td>Flange Transition</td>
<td>3</td>
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<tr>
<td>Augusta</td>
<td>Jun 84</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>2 in.-1 in.</td>
<td>572 in.*</td>
<td>Flange-to-Web</td>
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<td>High Steel</td>
<td>Oct 84</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>2 1/2 in.-1 1/2 in.</td>
<td>18 in.</td>
<td>Flange Transition</td>
<td>1</td>
</tr>
<tr>
<td>High Steel</td>
<td>Oct 84</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>3/4 in.</td>
<td>116 in.</td>
<td>Web Splice</td>
<td>1</td>
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<td>High Steel</td>
<td>Oct 84</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>7/8 in.</td>
<td>112 in.</td>
<td>Web Splice</td>
<td>3</td>
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<tr>
<td>High Steel</td>
<td>Jan 85</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>1 in.</td>
<td>113 in.</td>
<td>Web Splice</td>
<td>1</td>
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<tr>
<td>High Steel</td>
<td>Jan 85</td>
<td>Butt Weld</td>
<td>ASTM A 36</td>
<td>3/4 in.</td>
<td>116 in.</td>
<td>Web Splice</td>
<td>1</td>
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<td>High Steel</td>
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<td>ASTM A 441</td>
<td>11/16 in.</td>
<td>100 in.</td>
<td>Web Splice</td>
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<td>High Steel</td>
<td>Jan 85</td>
<td>Butt Weld</td>
<td>ASTM A 572</td>
<td>3/4 in.</td>
<td>118 in.</td>
<td>Web Splice</td>
<td>1</td>
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<td>High Steel</td>
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<td>Butt Weld</td>
<td>ASTM A 572</td>
<td>5/8 in.</td>
<td>110 in.</td>
<td>Web Splice</td>
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<td>Augusta</td>
<td>Feb 85</td>
<td>Butt Weld</td>
<td>ASTM A 588</td>
<td>2 1/2 in.-1 1/2 in.</td>
<td>42 in.</td>
<td>Flange Transition</td>
<td>1</td>
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<tr>
<td>Phoenix</td>
<td>Mar 85</td>
<td>Butt Weld</td>
<td>ASTM A 572</td>
<td>2 in.-1 3/8 in.</td>
<td>16 in.</td>
<td>Flange Transition</td>
<td>2</td>
</tr>
</tbody>
</table>

* Length of transducer array

** AEWM tests results verified by ultrasonic testing and radiography
APPENDIX C

SUMMARY OF AEWM ATTENDEE SURVEY

1. Did the demonstrators adequately explain the acoustic emission phenomena and the function of the AEWM?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes (1)</td>
<td>16</td>
</tr>
<tr>
<td>no</td>
<td>0</td>
</tr>
</tbody>
</table>

Comments:
(1) An advance explanation handout would have been helpful.

2. Were the visual aides adequate and relevant to the presentation?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes (1, 2)</td>
<td>16</td>
</tr>
<tr>
<td>no</td>
<td>0</td>
</tr>
</tbody>
</table>

Comments:
(1) More slides showing details of set-up possibilities as well as more "action" slides would be helpful. An exaggerated schematic of instrumentation and receptors would be helpful.
(2) Have a better supply of markers.

3. Were the shop demonstrations sufficient for understanding of the AEWM function and test routine?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes (1, 2)</td>
<td>15</td>
</tr>
<tr>
<td>no (3)</td>
<td>1</td>
</tr>
</tbody>
</table>

Comments:
(1) The induced flaw produced the promised citing on the monitor, exactly where the copper was placed.
(2) Step-by-step considerations, description, and explanation without shop noise would have been a desirable preparation.
(3) Longer weld test with hardcopy of readings.

4. Were all your questions satisfactorily answered by the demonstrators?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>16</td>
</tr>
<tr>
<td>no</td>
<td>0</td>
</tr>
</tbody>
</table>

5. (a) Was the entire AEWM demonstration satisfactory?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
</table>
yes (1, 2, 3)

Comments:
(1) A bit confused due to the shop schedule.
(2) The demonstration could have been coordinated better with the shop so that more welds could be tested.
(3) Hands-on application by the students is not practical because understanding the "set-up" sequence of the unit is not possible without training and experience.

(b) What suggestions would you have for improving future AEWM demonstrations?
(1) Closer liaison with shop people.
(2) Reduce demonstration to a single day.
(3) Do demonstrations of other flaws.
(4) Have on-site confirmation of flaws spotted using another NDT device.
(5) Monitor other than butt-weld configurations.
(6) Perform the shop demonstration in a less congested and noisy area.
(7) Demonstrate on full-penetration web-to-flange welds.
(8) Model examples for porosity and slag in shop demonstration.
(9) Prepare a mock-up of the machine and explain the setup and calibration prior to going into the noisy fabrication shop.
(10) The monitor needed to be closer to the welded plate.

6. Did the AEWM function as described by the demonstrators?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
<tbody>
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<td>15</td>
</tr>
<tr>
<td>no (4)</td>
<td>1</td>
</tr>
</tbody>
</table>

Comments:
(1) Does GARD take into account that the only pause to change a lead wire was considered acceptable and do they furnish the extra wires with the initial purchase?
(2) Arrange the demonstration with stick welding where the welder could probably intentionally create slag, cracks, and porosity and then see what levels of AE were emitted.
(3) The demonstrators had some minor difficulties making a "bad" weld with cracks to demonstrate the AEWM.
(4) Copper cracks may not be the best signal-producing crack for the demonstration. Maybe a better cracking signal could be a hard-surfacing bead without preheat, such as EFe5-A, B, or C and then weld over the hard-surfacing bead.

7. Describe what you feel are limitations of the AEWM.

(1) The flange-to-web welds for welded beams and the cover plate-to-flange welds on rolled beams are the welds that need to be covered more adequately. Presently AEWM is awkward for long welds.
(2) Cost justification.
(3) Need of energy release to indicate a flaw.
(4) The AEWM is not useful for routine welds in bridge fabrication. The standard methods of inspection (RT & UT) work well.
(5) No calibration standard.
(6) No training program.
(7) In large shops, the distance between work stations that may need monitoring could cause a problem.
(8) Not sturdy enough for shop work.
(9) Will not monitor enough weld stations.
(10) Transducers too heat sensitive.
(11) (AEWM) size, present configuration.
(12) Operator must be highly skilled.
(13) Monitoring transducer is time-consuming.

8. Do you feel that the AEWM would be a useful and/or cost-savings device for detecting welding defects in fabrication-shop welding operations?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
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<td>11</td>
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<td>no (7-9)</td>
<td>5</td>
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</table>

Comments:
(1) Mostly for a production tool in shops with many heavy plate butt welds.
(2) On full-penetration welds -- to catch flaws before they are incorporated into the final weld.
(3) For use by fabrication shops, AEWM appears to have cost-saving potential.
(4) Depends on the fabricator.
(5) Joint repairs could be done more quickly.
(6) Could be useful to the fabricator in detecting defects as they occur, and the welder could repair immediately.
(7) Not for bridge fabricators, RT and/or UT is required on the completed weld.
(8) Most fabrication shops need multiple sensors and more than one unit to adequately monitor the welding sequence at various work stations. Cost savings would not outweigh the initial cost of the equipment.
(9) Would be cost-effective only on a thicker plate. All a fabricator has to sell is time and labor. Therefore AEWM would have to monitor more stations and needs some sort of warning to the welder so he would not have to go to the machine after each weld pass.

9. How do you feel the AEWM would be best applied in fabrication shops?

(1) As a production tool for heavy plate weldments and monitoring welds now being inspected with magnetic-particle method.
(2) "In-line" quality control used directly by welding operator. (Best for shops with high error rate; probably the shops with low management expertise.)
(3) As demonstrated.
(4) On full-penetration welds.
(5) As a process-control monitoring system plantwide.
(6) In monitoring web-flange fillet welds that cannot be thoroughly checked by other current NDT methods.
(7) Monitor critical multipass welds such as flange splices.
(8) By immediately locating flaws.
(9) With in-progress visual testing (or magnetic-particle testing) on heavy thickness complete-penetration welds.
(10) In-house quality control.
(11) Used in addition to (conventional) nondestructive testing.
(12) Apply the testing to very critical weld joints like those on tension members of fracture-critical structures.
(13) Only on very thin sections.

10. Do you feel the AEWM would be useful in other highway applications?

<table>
<thead>
<tr>
<th>Response</th>
<th>No. of Respondents</th>
</tr>
</thead>
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<td>0</td>
</tr>
<tr>
<td>no opinion</td>
<td>2</td>
</tr>
</tbody>
</table>

Comments:
(1) To monitor for fatigue cracks.
(2) To aid in bridge-condition surveys.
(3) If affordable.
(4) To monitor known discontinuities, whole segments of bridges.
(5) Field monitoring of cracked structures as part of an in-depth structural inspection.