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Acoustic Emission/Flaw Relationship for In-Service Monitoring of Nuclear Pressure Vessels

Progress Report
October 1984 - March 1985

Prepared by P. H. Hutton, R. J. Kurtz

Pacific Northwest Laboratory
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P. H. Hutton, R. J. Kurtz

Pacific Northwest Laboratory
Richland, WA 99352

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ABSTRACT

Technical progress in developing continuous acoustic emission (AE) monitoring of nuclear reactor pressure boundaries for flaw detection is discussed in this report. The period covered is October 1, 1984, to April 1, 1985. Topics include final analysis of ZB-1 vessel test data, preparation for continuous AE monitoring of Watts Bar Unit 1 reactor during operation, AE signal pattern recognition development, and development of an ASTM standard for application of continuous AE monitoring to pressure boundaries.

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ACOUSTIC EMISSION/FLAW RELATIONS FOR IN-SERVICE MONITORING OF NUCLEAR PRESSURE VESSELS[a]

P. H. Hutton, Project Manager
R. J. Kurtz, Assistant Project Manager

SUMMARY

Further analysis of data from the ZB-1 vessel test indicates that a stress intensity level of approximately 70-80 ksi$\sqrt{in.}$ will be required to detect existing cracks by AE during an inservice hydrostatic test.

Although the number of AE signals detected by two sensor arrays on the ZB-1 test vessel differed due to location and method of mounting on the vessel, both showed similar crack growth rates using the flaw evaluation relationship.

Results from the ZB-1 vessel test were reviewed with the principal German participants at a workshop in Stuttgart, West Germany.

A report of results obtained from the ZB-1 vessel test has been finalized and submitted for publication as a NUREG report.

The AE sensing system required for operational monitoring at Watts Bar Unit 1 has been installed. Reactor startup is currently expected to take place in late FY-85.

The AE signal pattern recognition approach based on the unique response of a waveguide sensor to AE signals has shown the ability to effectively analyze different sets of data without retraining. This is a significant step in the evolution of a usable pattern recognition technique.

A comment issue of a standard for applying continuous AE monitoring to surveillance of pressure boundaries has been submitted to ASTM.

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[a]Work supported by the U.S. Nuclear Regulatory Commission under Contract DE-AC06-76RLO 1830; FIN. B2088; NRC Contact: Dr. J. Muscara.

INTRODUCTION

The purpose of this Pacific Northwest Laboratory (PNL) program is to develop the application of continuous acoustic emission (AE) surveillance for detecting and analyzing flaw growth in reactor pressure boundaries. Type A533B, Class 1 pressure vessel steel, and SA351-CF-8A cast stainless, Type 304 wrought, and A106 ferritic piping steels are being considered. Objectives of this program are to:

- develop a method to identify crack growth AE signals in the presence of other acoustic signals
- develop a relationship to estimate flaw significance from AE data
- develop an instrument system to implement these techniques
- demonstrate the total concept off-reactor and on-reactor.

TECHNICAL PROGRESS

Technical progress is discussed under the following topics:

- Off-reactor vessel test
- Reactor monitoring
- AE signal pattern recognition
- Codes and standards

OFF-REACTOR VESSEL TEST

Additional analysis has been performed to finalize the report on the ZB-1 vessel test conducted in Mannheim, West Germany. To help keep the discussion in context, Figure 1 summarizes the test vessel arrangement.

Analysis of the stress intensity factor levels for the hydro-test portions of the ZB-1 test matrix has been completed. The table on the following page shows the hydro-tests that were performed.

The stress intensity levels that each flaw experienced during the various hydro-tests are shown in Figure 2. Also shown are the operational stress intensity levels reached just prior to hydro-test. For Step 1, the precracking K-levels are

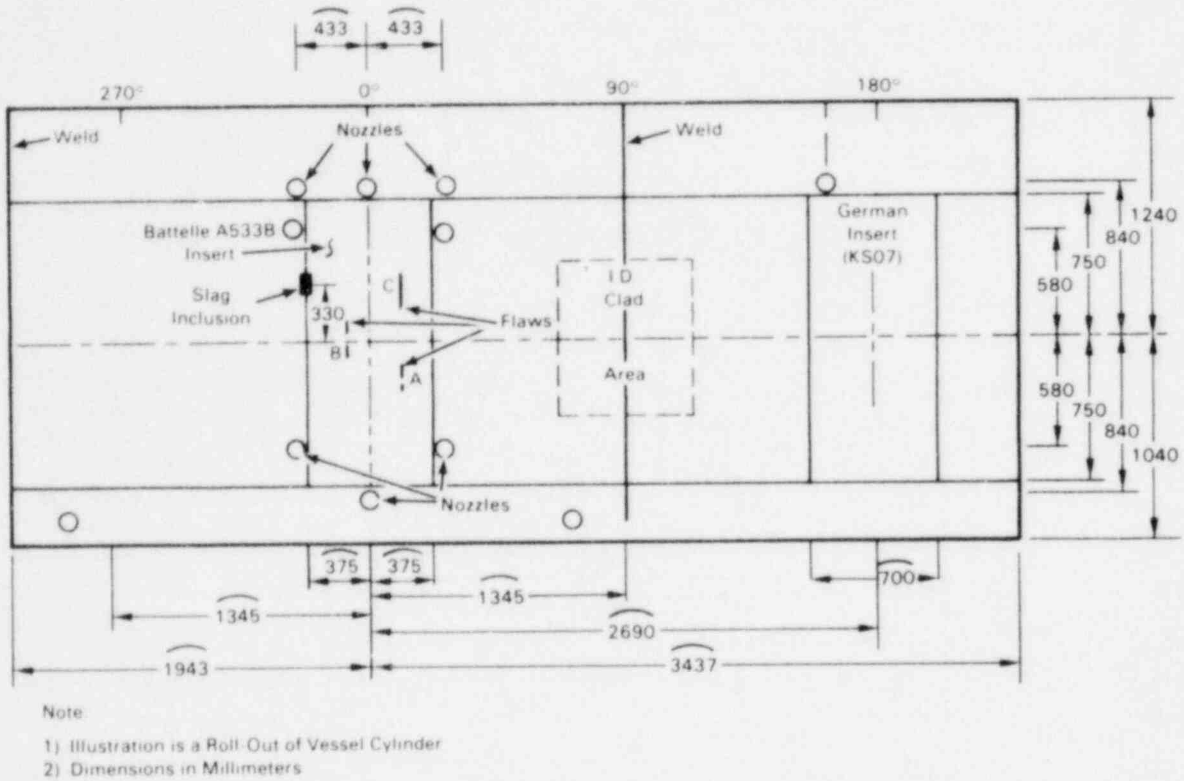

Figure 1. Test Features of the ZB-1 Vessel.

Step	Overpressure, %	Test Temperature, °C
1	0	65
4	2	65
7	4	65
9*	10	240
10	15	65
13	36	65

* This was an unplanned hydro-test that was performed after 2900 cycles of Step 9 were completed. This test was conducted because of concern over vessel integrity.

shown as prior operational loading of the flaws. The amount of over-stressing (in terms of K-levels) is given as the difference between the hydro-test and operational stress intensity factors. Flaw C is not shown for Step 10 because there was no good COD data for Flaw C for Step 10.

The results show that significant over-stressing of each was detected from the flaws during Step 1 (Part 1 only) and

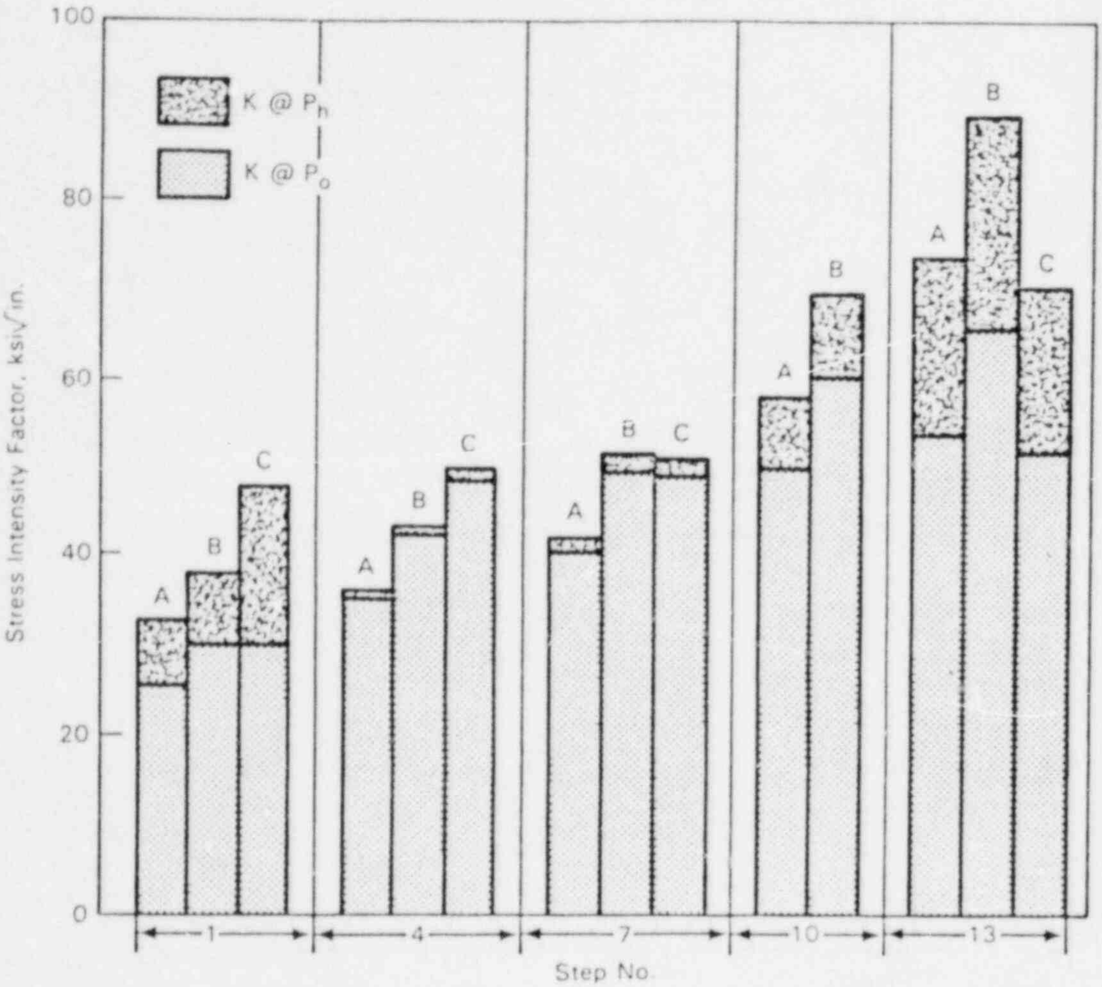

Figure 2. Prior Operational and Hydro-test Stress Intensity Factor Levels for Flaws A, B, and C.

Step 13 (only from Flaw B). AE was not detected during Step 1, Part 2 probably because of the Kaiser Effect. Steps 4 and 7 did not produce much AE because of the very small over-pressure levels. In Step 10 the small amount of AE may have been caused by the limited over-pressure or the influence of the Step 9 hydro-test. Since this test was performed at 240°C, the plastic zone expansion caused by the over-pressure was greater than if the test had been run at 65°C. Thus the five percent difference in over-pressure levels between Step 9 and Step 10 hydro-tests may not have been sufficient to cause AE. During the Step 13 hydro-test, AE was detected from Flaw B, but not Flaws A or C. The results show that the Step 13 over-pressure levels were substantial and they exceeded the K-levels reached during Step 10. Since Flaw B was the only flaw detected during Step 13, this suggests that for inservice hydro-tests, the magnitude of the over-pressure does not completely determine the detectability of a flaw. Perhaps a minimum K-level (about 70 ksi

$\sqrt{in.}$) associated with a substantial over-pressure may be necessary before a flaw can be reliably detected. The KS07R insert weld crack was not clearly detected during hydro until Step 13 (ignoring the Step 1 indications) when the flaw was fairly deep and the applied stress intensity levels were in the 70-80 ksi in. range. It must be emphasized that these results relate to inservice hydrostatic testing. Preservice testing where the vessel has not been previously loaded to service conditions represents a substantially different circumstance.

AE data detected by Arrays 2 and 3 from the machined, precracked flaws (Flaws A, B, and C) installed in the A533B insert was compared. Array 2 was located directly on the A533B insert and coupled to the vessel by drilled and tapped holes to optimize AE detection. Array 3 was positioned to monitor the cylindrical portion of the test vessel and was pressure coupled to the surface to simulate an on-reactor installation. Array 3 sensors were 3 to 10 feet from the growing cracks.

Figure 3 gives the number of AE events detected by each array for the various cyclic loading steps of the test. The results show that Array 2 detected more AE than Array 3. Both arrays failed to detect AE from Flaw C during 65°C testing, but Flaw C grew very slowly throughout the test. This result suggests a threshold crack growth rate for AE detection. During Step 2, Array 3 did not detect AE from any of the flaws, but this is attributable to poor coupling of the sensors to the vessel during this step. Typically, less than 20 events were detected by Array 3 for each phase of the test. This result underscores the need for an effective signal recognition algorithm during the plant operation.

A comparison of the AE event rate (events/second) versus the measured crack growth rate (micro-inches/second) for Arrays 2 and 3 is given in Figure 4. The lines in Figure 4 indicate the lower bound flaw severity relationships extrapolated from laboratory data taken at RT and 285°C. The 65°C ZB-1 data falls at or below the RT lower bound line for both arrays. The data points on the abscissa are instances where no events were detected. As noted above, these instances were associated with low crack growth rate (Flaw C) or inadequate Array 3 sensitivity. The 285°C data generally resides at or above the 285°C lower bound line for both arrays.

Figures 5 and 6 compare the crack growth rates calculated from AE data for Arrays 2 and 3 and the measured crack growth rates. The results for Array 2 have been discussed previously. Array 3 results display reasonably good correlation for the 285°C data and poor correlation for the 65°C data. Again, we know at least part of the problem with Array 3 at 65°C was poor sensor coupling. The data from Arrays 2 and 3 both show the same general trend, but reflect a difference in magnitude

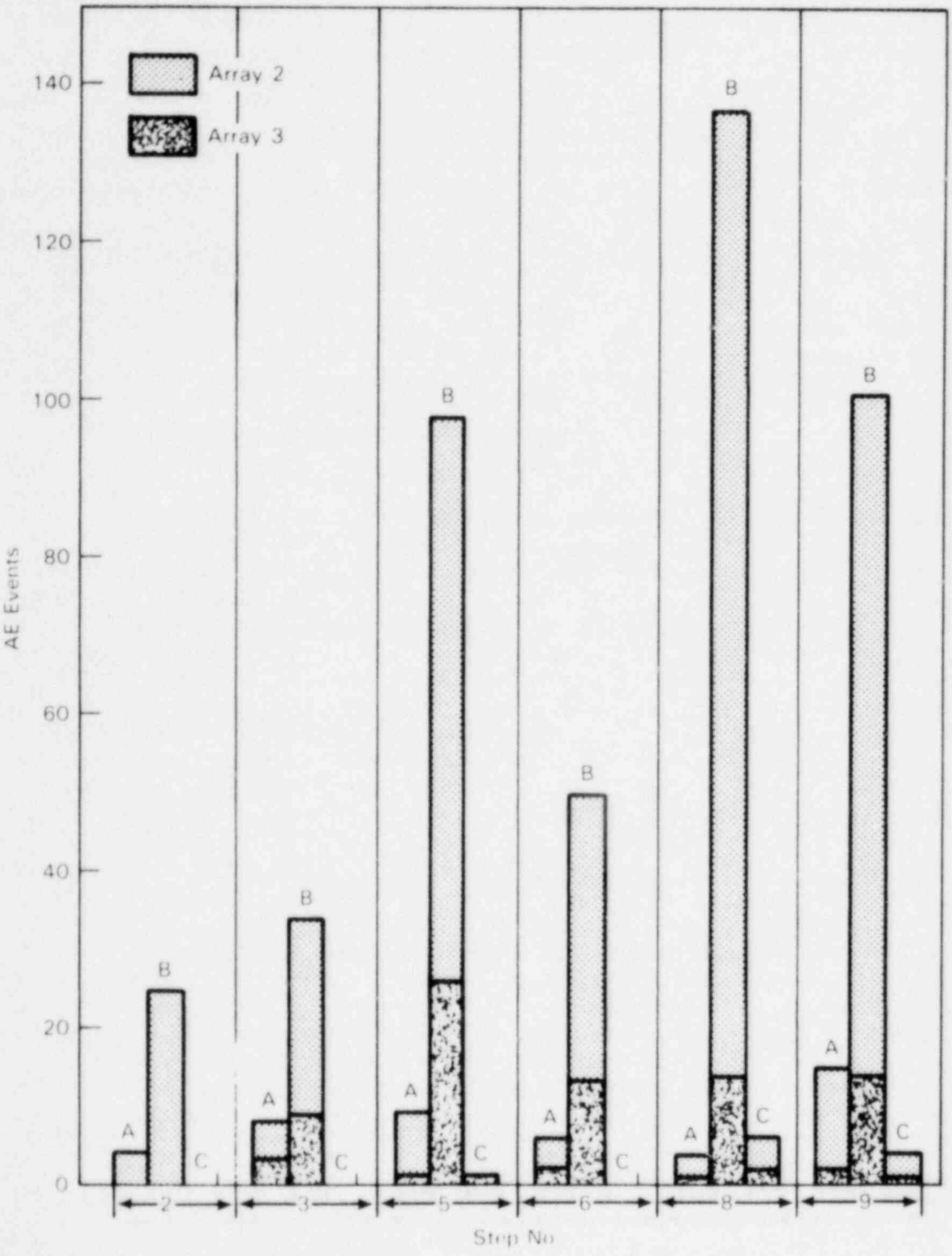

Figure 3. Number of AE Events Detected by Arrays 2 and 3 Versus Cyclic Step.

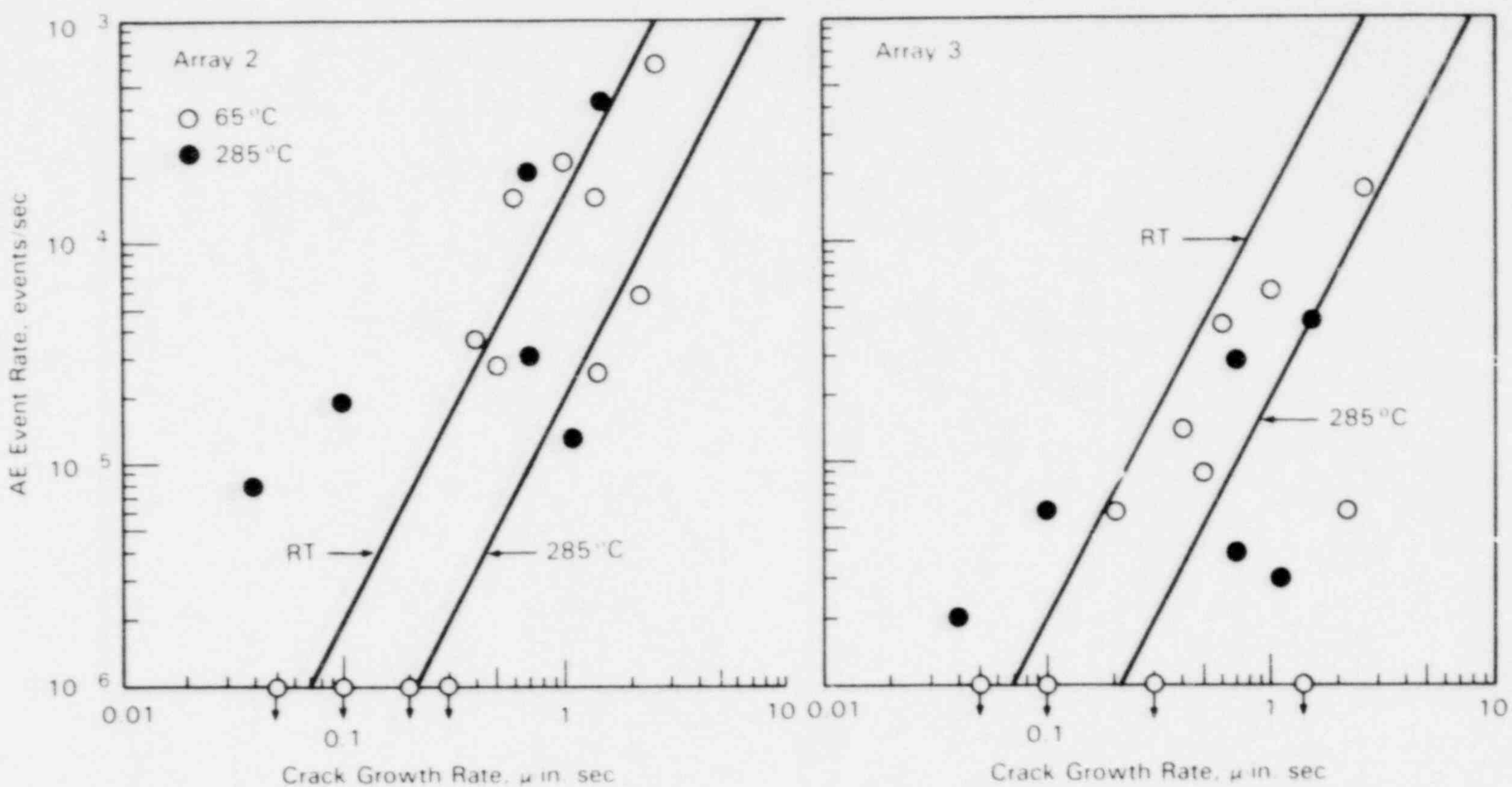

Figure 4. AE Event Rate Versus Fatigue Crack Growth Rate for Arrays 2 and 3.

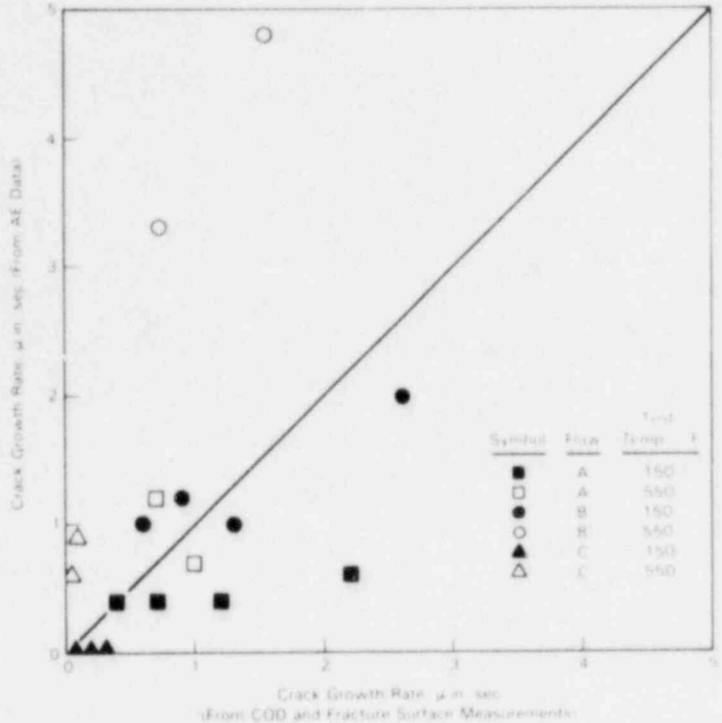

Figure 5. Evaluation of the AE/Flaw Severity Relationship for Array 2 Data.

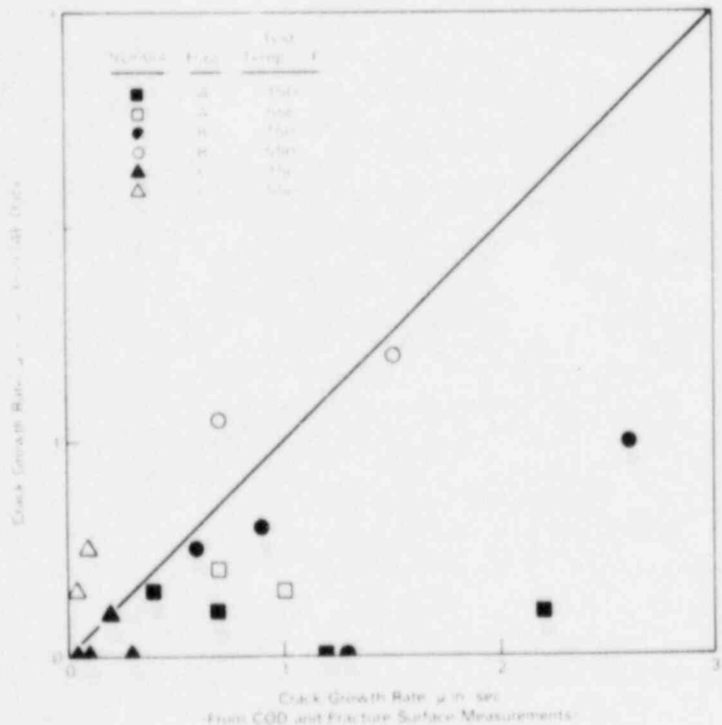

Figure 6. Evaluation of the AE/Flaw Severity Relationship for Array 3 Data.

that depends upon both sensor sensitivity and the relative distance between source and sensor. An important point to note is that even though Array 2 usually detected more AE than Array 3, this did not lead to large discrepancies in the crack growth rate predictions.

Results from the ZB-1 vessel test were reviewed at a workshop held in Stuttgart, West Germany on October 11 and 12, 1984. In addition to NRC and PNL personnel, staff from Kraftwerk Union (KWU), Materialprufungsanstalt (MPA), and Institut Fur Zerstcrungsfreie Profverfahren (Izfp) participated. KWU monitored the low temperature portion of the test in parallel with PNL. In general, the AE results obtained by PNL and KWU for that portion of the test agree quite well.

A report documenting results from the ZB-1 vessel test has been finalized and submitted for publication (NUREG/CR-3915).

REACTOR MONITORING

The Tennessee Valley Authority is cooperating in this program by permitting AE monitoring of selected pressure boundary areas during prestartup testing and during reactor operation at Watts Bar Unit 1. The areas being monitored are the #2 inlet nozzle, the safety injection line adjacent to the #2 cold leg, and a section of the vessel wall. AE monitoring was performed during cold hydrostatic testing in late 1981, and the results are summarized in NUREG/CR-2880. Hot functional testing at Watts Bar Unit 1 was performed in July 1983. The same pressure boundary areas were AE monitored and a topical report, NUREG/CR-3693 describing the AE results from hot functional monitoring was published June 1984.

Work is now focused on preparation for AE monitoring during reactor startup and operation. Installation of AE detection equipment at Watts Bar Unit 1 has been completed. Two sensor arrays on the #2 inlet nozzle, one array on the #2 safety injection line, and one array on the vessel wall are installed. Figures 7, 8, and 9 show sensors on the #2 inlet nozzle. Figure 10 shows sensors on the #2 safety injection line. The method for spring loading the waveguide sensors to provide acoustic coupling to the structure surface is illustrated in Figure 11. An example of the conduit installed by TVA for signal leads inside of containment is given in Figure 12 (these conduits carry the lead wires for sensors on the inlet nozzle). The sensors were calibrated for frequency response and sensitivity using helium jet and pencil lead breaks. Figure 13 gives an example of sensor response to helium jet input. The response shown here is very similar to that of the sensors used effectively on the ZB-1 vessel test to detect crack growth.

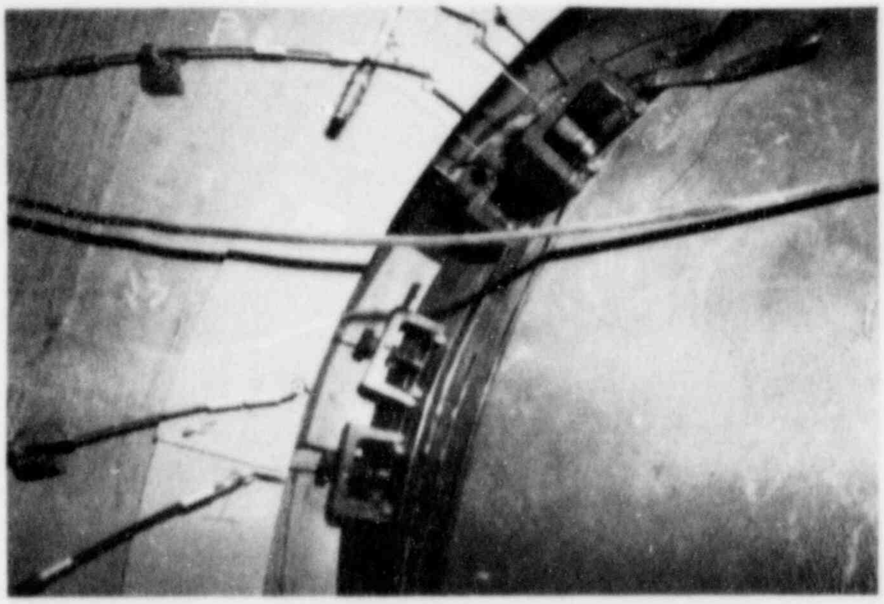

Figure 7. Quad and Cylindrical Array AE Sensors - #2 Inlet Nozzle, Watts Bar Unit 1.

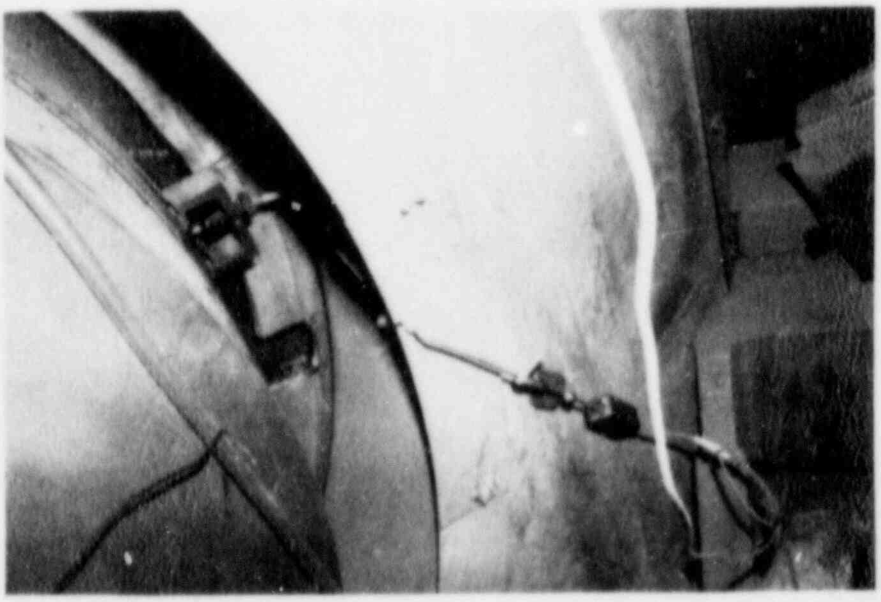

Figure 8. Cylindrical Array AE Sensor - #2 Inlet Nozzle, Watts Bar, Unit 1

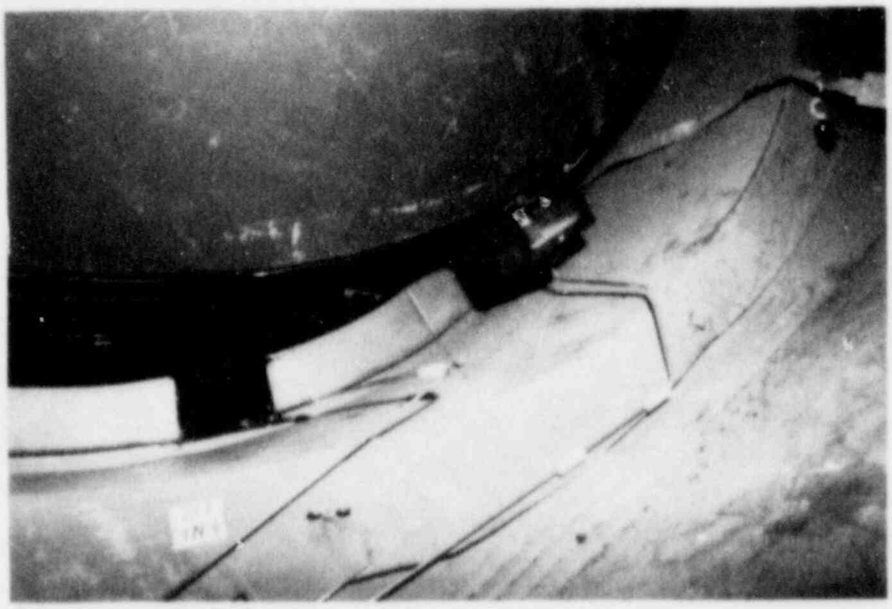

Figure 9. AE Sensor on Vessel Wall Under #2 Inlet Nozzle and Cylindrical Array AE Sensor on #2 Inlet Nozzle, Watts Bar Unit 1.

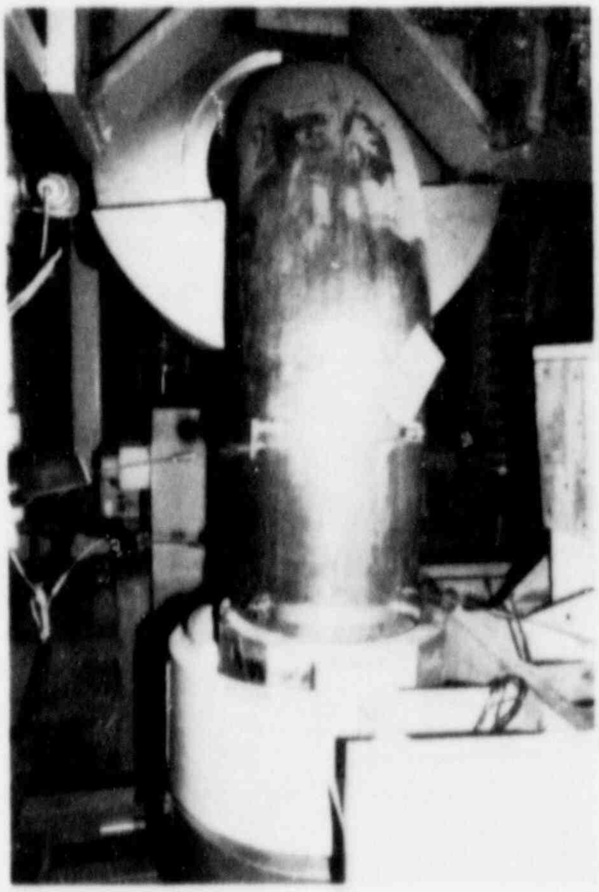

Figure 10. AE Sensors on #2 Safety Injection Line, Watts Bar Unit 1.

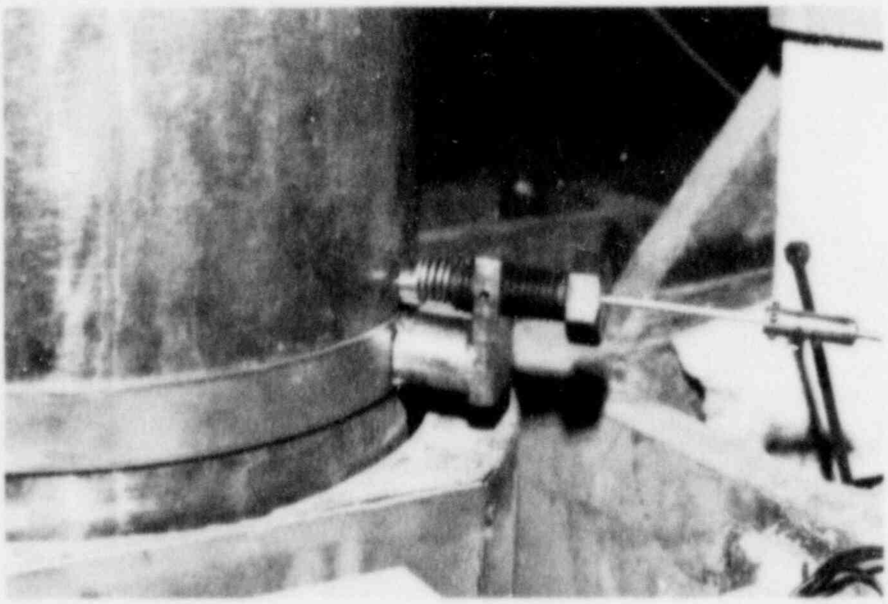

Figure 11. Assembly for Spring Loading Waveguide AE Sensor to Pipe Wall.

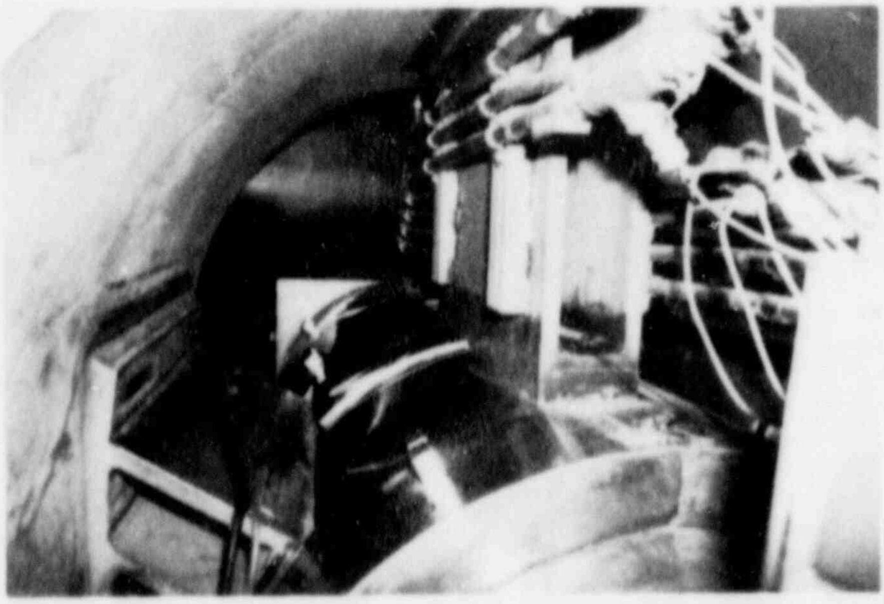

Figure 12. AE Lead Wire Conduits Installed to #2 Inlet Nozzle, Watts Bar Unit 1

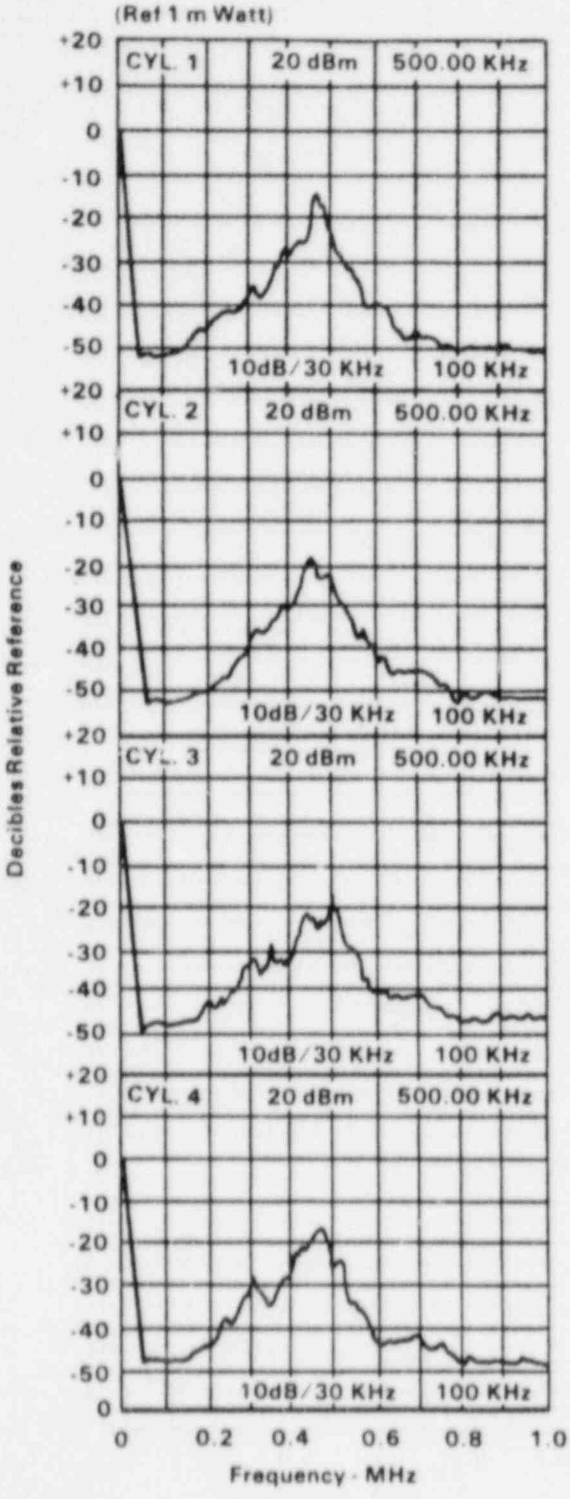

Figure 13. Response Characteristics of Cylindrical Array AE Sensors on #2 Inlet Nozzle - Watts Bar Unit 1.

The AE monitor instrument will be installed and connected to the AE detection equipment near the time for reactor startup (currently estimated to be in the fourth quarter of FY-85). The instrument (Figure 14) is currently undergoing functional testing in the laboratory.

AE SIGNAL PATTERN RECOGNITION

A signal pattern recognition technique based on the three pulse response generated in a waveguide sensor by crack growth AE signals has been tested further. The specific methods developed using data from Step 5 (final cyclic step at 65°C) of the ZB-1 vessel test were applied to waveforms recorded in Step 9 (second cyclic step at 285°C). Out of a sample of 275 waveforms, 273 were correctly classified. Figure 15 shows a source location plot of the unscreened signals. The signals were then screened using pattern recognition and a plot of the source location for the remaining signals is shown in Figure 16. There were a total of [illegible] signals classified as crack growth AE; two each from two nozzles and the remaining eight signals from Flaw B. All are associated with known crack sites. The fact that the method was developed on one set of data and tested on a completely separate set of data is significant. One of the problems with earlier efforts to develop a pattern recognition method was the fact that the algorithms may be effective within one set of data using part as a training set and part as a test set, but they performed poorly on a different set of data without retraining.

STANDARDS AND CODES

A standard titled "Standard Practice for Continuous Monitoring of Pressure Boundaries Using Acoustic Emission-4.04/83-04-01" was submitted to ASTM 07.04.04 at the January 1985 meeting for review and comment. The standard is being revised to include comments and will be submitted for ballot at the June 1985 meeting.

REPORTS

- NUREG/CR-0058, Vol. 4, pg. 362-380, Summary of Detection, Location, and Characterization Capabilities of AE for Continuous Monitoring of Cracks in Reactors. Published January 1985.

- Proceedings of the 7th International Conference on NDE in the Nuclear Industry, Grenoble, France, January 1985, "Acoustic Emission for On-Line Reactor Pressure Boundary Monitoring. Published January 1985.

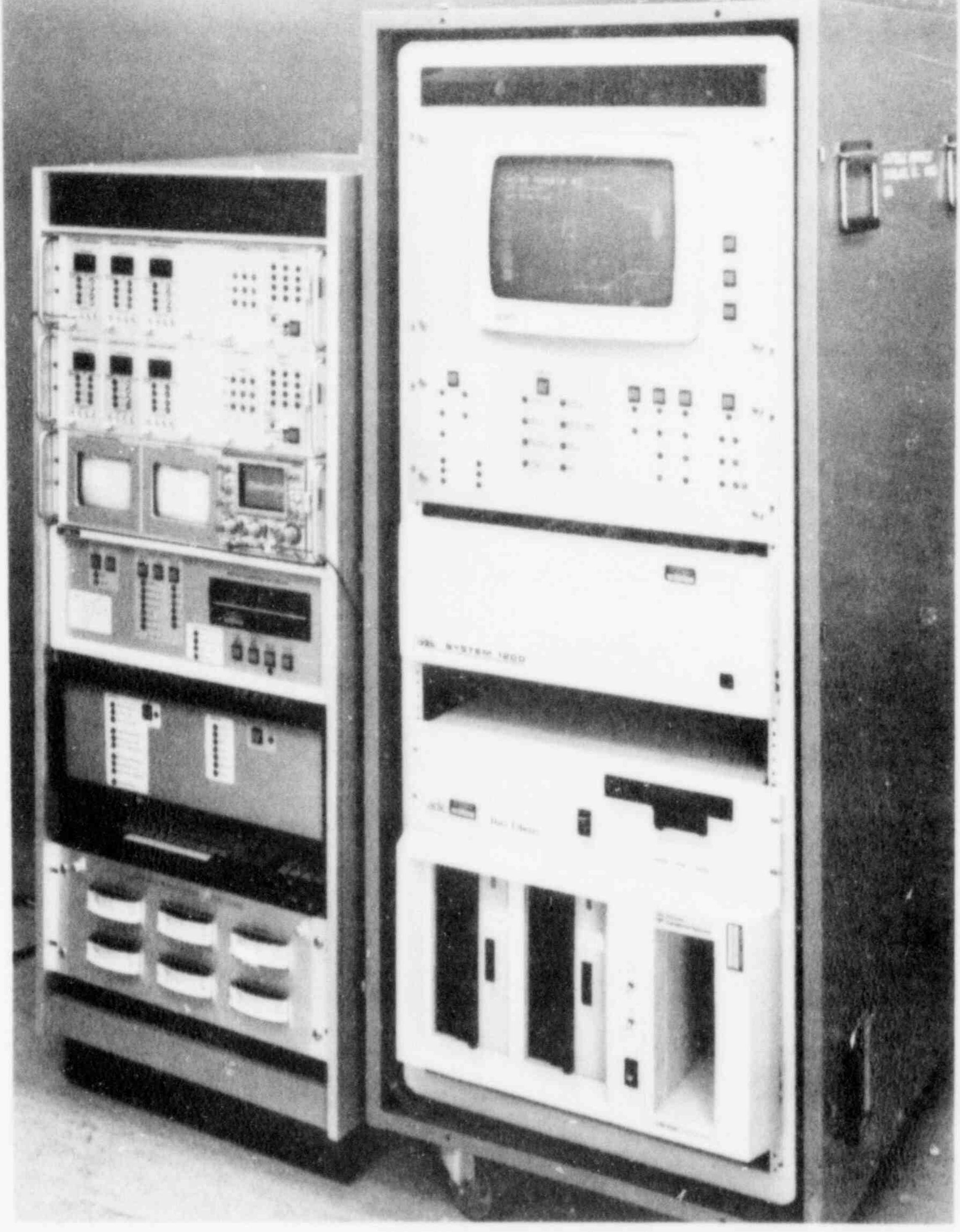

Figure 14. AE Monitor Prototype to be Installed at Watts Bar Unit 1 Reactor.

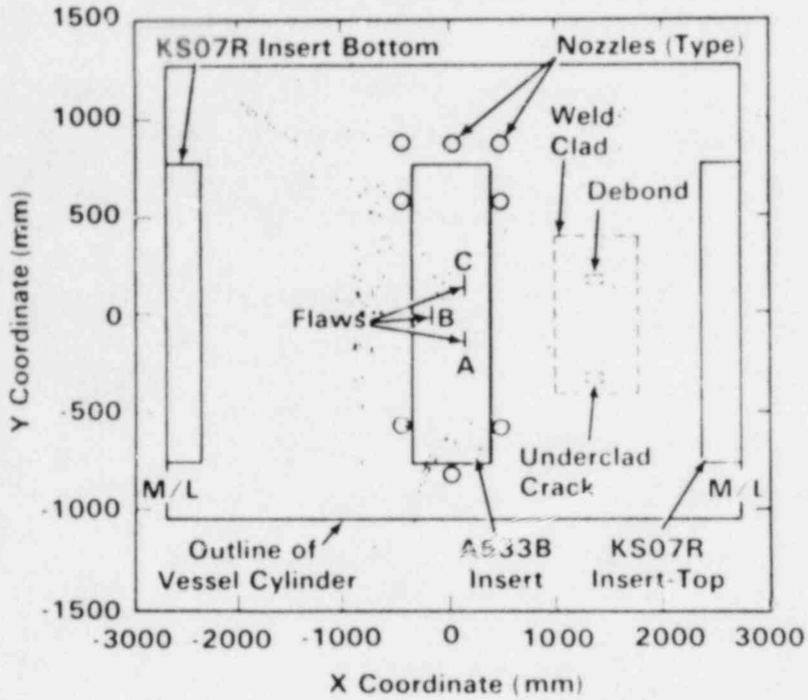

Figure 15. Source Locations for 275 Unscreened Acoustic Signals from Step 9, ZB-1 Vessel Test.

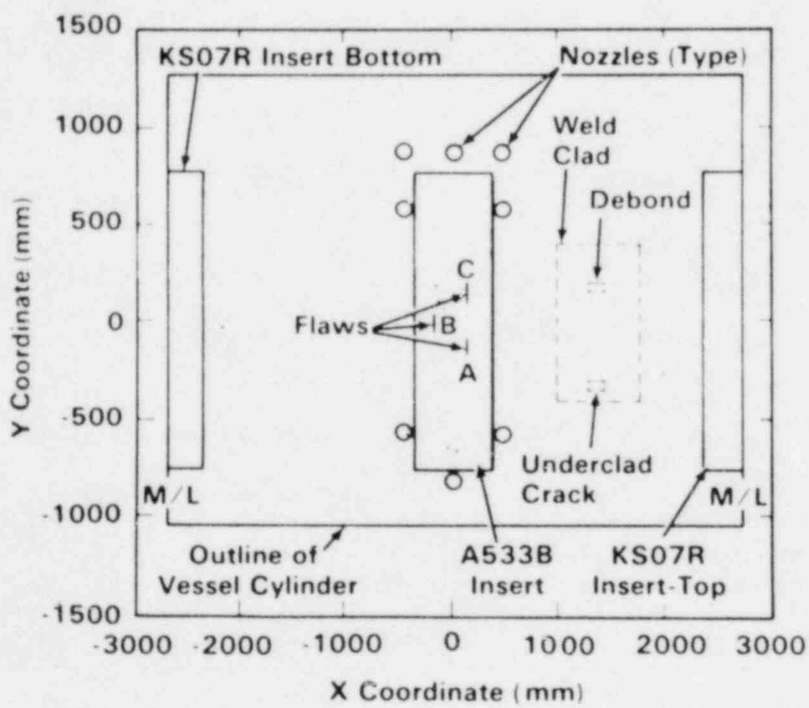

Figure 16. Source Locations for Data Sample in Figure 15 After Screening with Pattern Recognition.

FUTURE WORK

- Start operational AE monitoring at Watts Bar Unit 1 reactor.
- Continue AE characterization of IGSCC.
- Perform laboratory tests to clarify the influence of crack growth rate on detection of cracks by AE.
- Evaluate separation of crack growth AE from oxide cracking AE using pattern recognition techniques.
- Implement AE signal pattern recognition for use on operational monitoring at Watts Bar Unit 1.
- Submit standard for continuous AE monitoring of pressure boundaries to ASTM for balloting.

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