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Vols. 3, 4

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

Quarterly Report
April 1984 - September 1984

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

Pacific Northwest Laboratory
Operated by
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Manuscript Completed: December 1984
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Office of Nuclear Regulatory Research
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ABSTRACT

Technical progress toward continuous acoustic emission monitoring of nuclear reactor pressure boundaries for flaw detection is described for the period April-September 1984. A draft report of ZB-1 vessel test results was completed. Growth of machined flaws was detected by AE during both 65°C and 285°C testing. A key result was clear detection of a natural crack in a fabrication weld by AE. Crack growth rates estimated from AE data compared well with measured crack growth rates for the machined defects. In service hydro test monitoring gave mixed results. Questionable vessel integrity as denoted by continued AE at pressure hold is readily detectable. With low overpressure (1.15 x operating pressure), flaws as deep as 70% through-wall did not produce significant AE. With higher overpressure (1.4 x operating pressure), flaws produced identifying AE. An engineering prototype AE monitor system has been completed for use in operational monitoring at Watts Bar Unit 1 reactor. A modified approach to crack growth AE signal identification is producing about 95% correct determinations on recorded waveforms from the ZB-1 vessel test. A report on results from AE monitoring hot functional testing at Watts Bar Unit 1 has been published.

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FIGURES

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

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

SUMMARY

Initial analysis of all data from the ZB-1 intermediate scale vessel test has been completed and a draft report prepared. AE from growth of the machined flaws was consistently detected during both low temperature (65°C) and high temperature (285°C) testing. Crack growth rates estimated from AE data compared well with measured crack growth rates from machined defects. A major result was detection and identification of an unexpected crack in a vessel fabrication weld. Fracture surfaces associated with the various flaws are being examined at both PNL and MPA, Stuttgart.

Hydro test results from the ZB-1 vessel test indicated that large flaws ($\geq$80% through-wall) could be detected during a 1.15 x operating pressure hydro test. Smaller flaws will probably not be detected.

An engineering prototype AE monitor has been completed and is being tested. It will be installed at Watts Bar, Unit 1 reactor.

Tests to characterize AE from IGSCC are in process.

A modified approach to crack growth AE signal identification by pattern recognition is giving about 95% correct identification using acoustic signals recorded during the ZB-1 vessel test.

NUREG/CR-3693 describing results from AE monitoring hot functional at Watts Bar, Unit 1 reactor has been published.

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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 evaluate the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries on a continuous basis using acoustic emission (AE). 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.

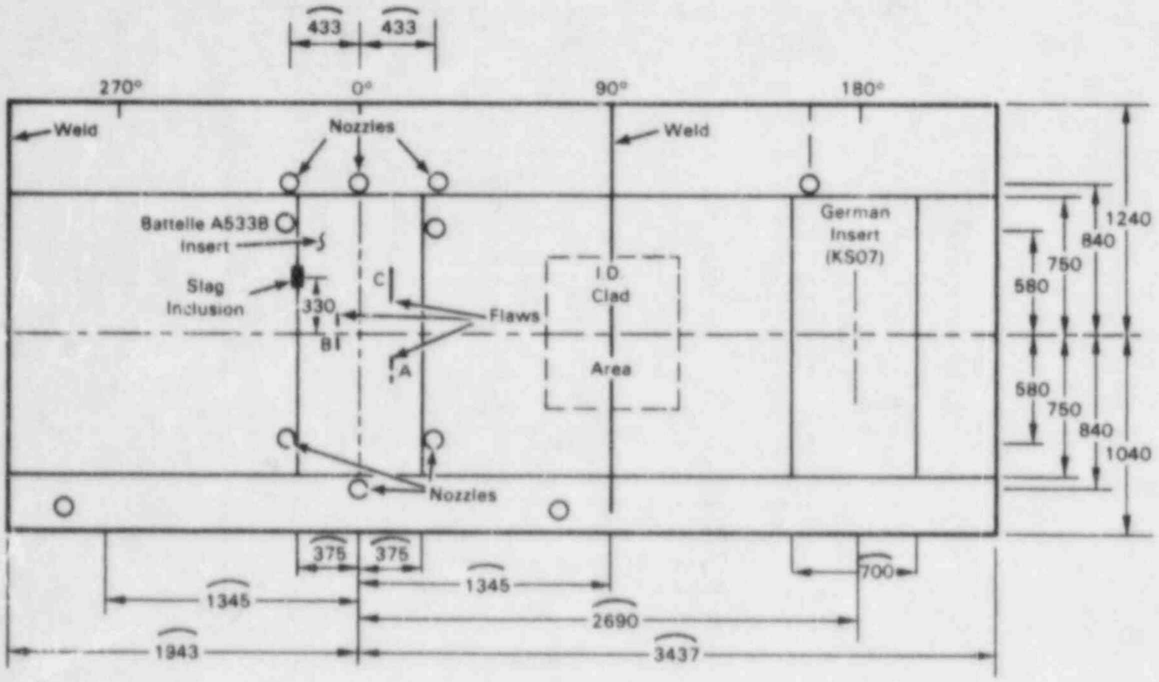
TECHNICAL PROGRESS

Technical progress for the report period is treated under the following topics:

- Off-Reactor Vessel Test
- Reactor Monitoring
- AE Signal Pattern Recognition
- Stress Corrosion Cracking Tests

OFF-REACTOR VESSEL TEST

The off-reactor vessel test, designated ZB-1, was performed in Mannheim, West Germany in cooperation with the Materialpruefungsanstalt (MPA) laboratory and Grosskraftwerk Mannheim (GKM) utility company. The test was completed in late September 1983 after one year total duration. To aid the reader in keeping the discussion in context, Figure 1 summarizes the test vessel arrangement. This shows the various features (A533B insert with machined precracked flaws, slag inclusion, ID clad areas, and the insert of degraded German steel) of the test vessel which are of primary importance.



Note:

1) Illustration is a Roll-Out of Vessel Cylinder
2) Dimensions in Millimeters

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

A draft report has been completed on results from the test. Results from the various phases of the test are summarized here to provide an overview.

AE Monitoring at 65°C (150°F)

AE from growth of the machined flaws A, B, and C was detected by both a sensor array on the A533 insert and by an array monitoring the entire vessel cylinder (Figure 2). The crack growth AE assumed characteristics of high amplitude relative to laboratory test data and of occurring at or near peak load. The AE data rate was power-law related to the actual crack growth rate as determined by crack opening displacement and fracture surface measurements. This is discussed further under AE/Flaw Growth Interpretation.

Flow noise simulation had little affect on AE detection with sensors tuned to about 400 kHz, however, low frequency (150 kHz) sensors were completely saturated. These results are consistent with subsequent results obtained on TVA's Watts Bar Unit 1 nuclear reactor.

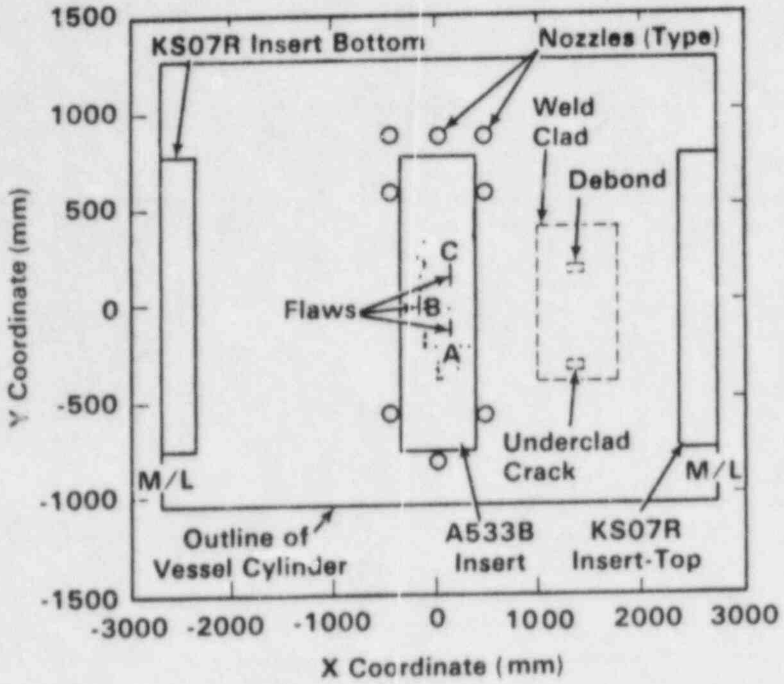


Figure 2. AE Source Locations - Step 5, Array 2, ZB-1 Vessel Test.

Noise from a manhole cover assembly was an intermittent problem throughout the low temperature testing. Generally, this noise could be eliminated by filtering with parametrics (load position and signal amplitude). This, however, underscores the need for real time AE identification by pattern recognition to isolate crack growth AE. Generally, parametrics such as load position in particular will be of little use in a reactor monitoring situation.

There was some evidence of AE activity from the KS07R insert weld during the final step of low temperature testing. The indications were not, however, sufficient to draw attention to the weld at the time.

AE Monitoring at 285°C (550°F)

The major feature of the high temperature testing phase was detection and identification of an unanticipated crack in the KS07R insert weld. AE from growth of the machined flaws A, B and C was also detected. Figure 3 illustrates AE distribution during the middle phase of cyclic testing. During the third and final phase of cyclic testing, AE from the weld crack became so intense that it overshadowed other sources. Figure 4 shows the weld crack at the end of the test.

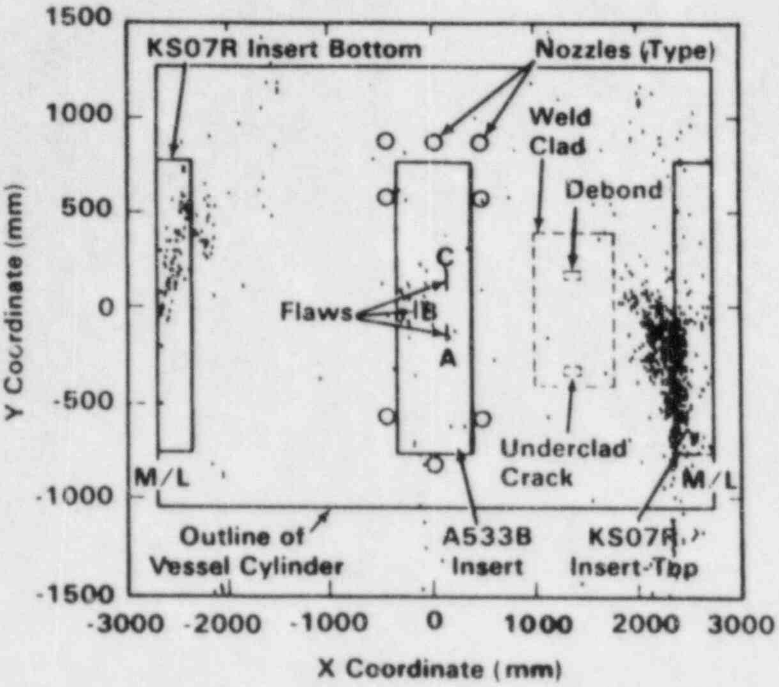


Figure 3. AE Source Locations, Step 9, Array 3 (65-80 L.P.), ZB-1.

AE signals from crack growth were detectable at distances of at least ten feet by pressure coupled wave guide AE sensors.

There was some evidence of a crack growth rate influence on detection of AE from crack growth. An external machined flaw which grew only about 0.17 inches in depth during the entire test produced very little detected AE. The estimated crack growth rate determined from COD data ranged from 0.04 to 0.3 microinches per second. Two internal machined flaws which grew 1.9 and 2.3 inches respectively unquestionably produced detectable AE throughout the test. The estimated crack growth rates ranged from 0.4 to 2.6 microinches per second. This is a potentially important result from this test.

AE/Flaw Growth Interpretation

Flaw growth characteristics for the machined flaws and the KS07R weld cracking have been determined from NDE, crack-opening-displacement and fractographic measurements. This information was used to establish crack growth rates for comparison with predictions derived from the AE/flaw severity relationship (see Figure 5). A test of the relationship using data from the machined flaws (Flaws A, B, and C) indicates that the relationship tended to under predict the crack growth rate at 65°C test temperatures. This was not expected but may not

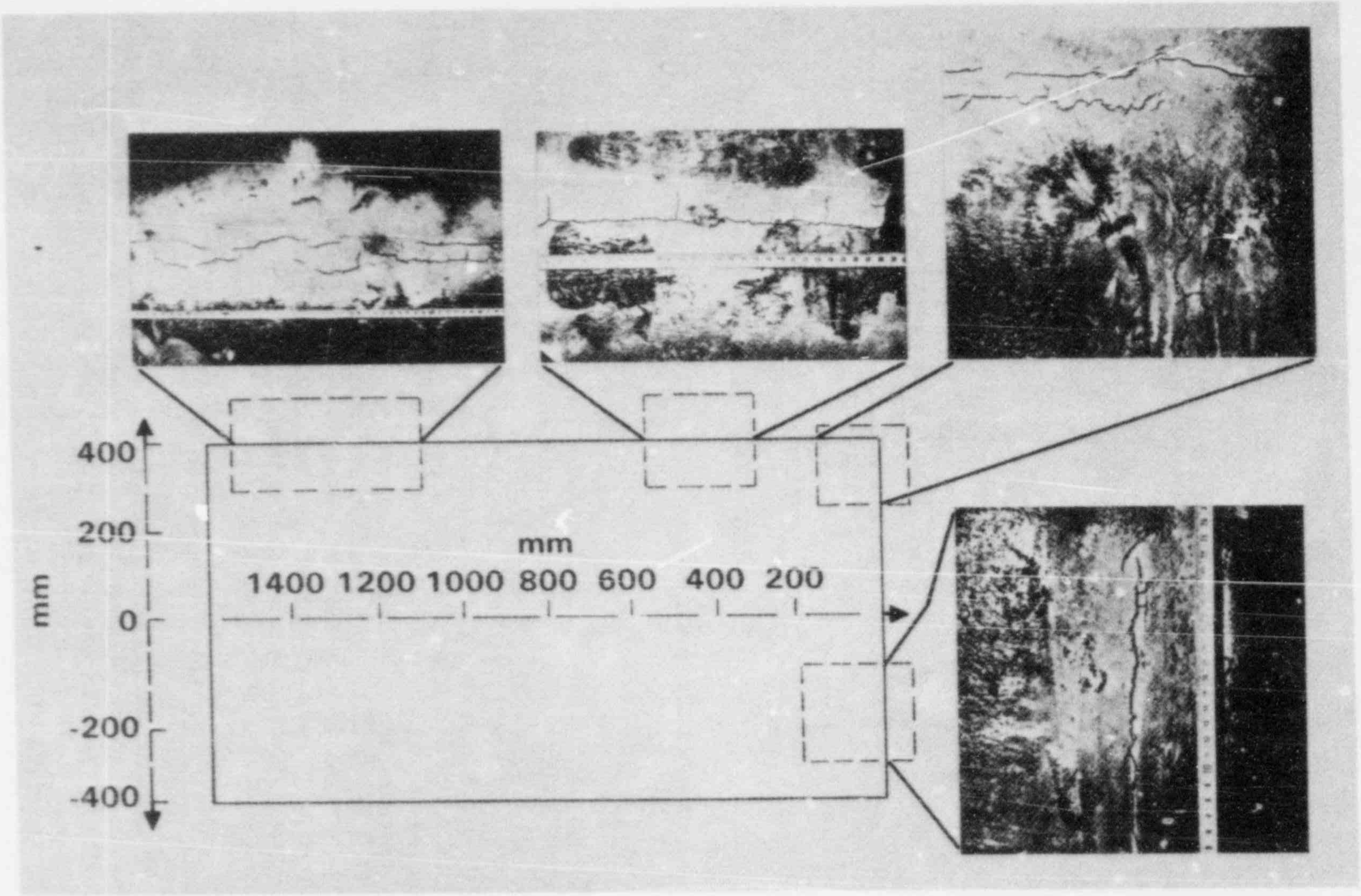


Figure 4. KS07R Insert Weld Crack, ZB-1 Vessel Test.

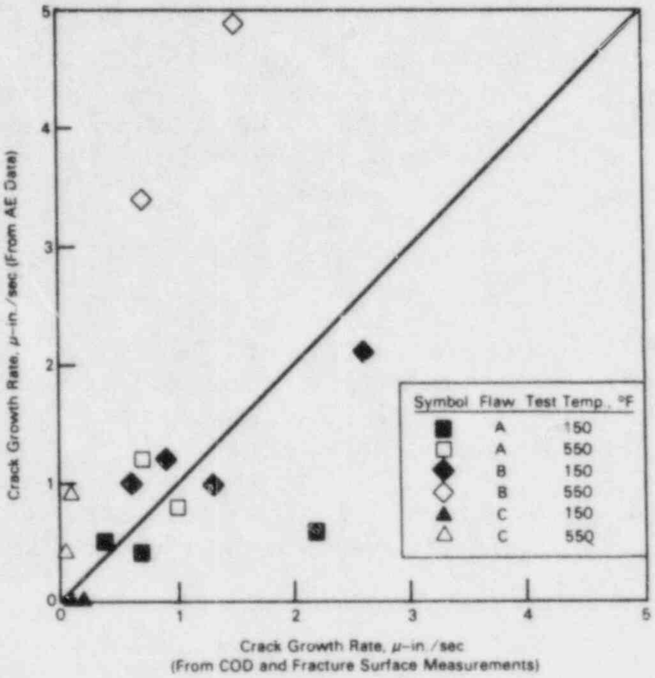


Figure 5. Evaluation of the AE/Flaw Severity Relationship, ZB-1 Vessel Test.

seriously affect the application of the relationship on an operating reactor. When the relationship was applied to data taken at 285°C, the crack growth rate was generally over predicted, as was expected since the relationship is derived from a lower bound limit of laboratory test data. The range of predicted crack growth rate was within the normal variation observed during laboratory testing.

A test of the relationship on the weld cracking in the KS07R replacement patch was attempted and showed a significant over prediction of the crack growth rate. The magnitude of the over prediction was beyond our expectations based upon the laboratory data. Basically, this resulted from the very high rate of AE from the weld crack. There are several possible explanations for the very high AE activity level. First, the material chemistry of the KS07R weldment is undoubtedly different from A533B steel. Impurity levels are known to be largely responsible for the AE activity in high-strength-low-alloy steels and so material chemistry may be an important factor in the production of AE from this weldment. Secondly, differences in heat treat conditions may be responsible for the emissiveness of this material. The cracking tended to originate in the HAZ of the weldment which was not stress relieved. The weld HAZ may have been somewhat more brittle than the surrounding material due to lack of stress relief thereby giving rise to greater amounts of AE. Lastly, the flaw geometry in the KS07R weldment was extremely complex as shown in Figure 4. Many surfaces were available to produce corrosion and rubbing types of AE. The accumulated length of the flaw which provided many sites for AE production (crack growth, rubbing, and oxide film cracking) is difficult to accurately determine.

Hydrostatic Test Results

There were five hydrostatic tests performed as part of the ZB-1 test. The objective was to evaluate the effectiveness of AE monitoring during inservice hydrostatic tests to detect flaws. The results obtained do not necessarily relate the the effectiveness of AE for flaw detection during preservice hydrotests. Flaw size and amount of over-pressure (maximum hydro pressure vs. operating pressure) are key variables. The hydro tests performed were:

- Step 1 - 1.00 x Operating Pressure
- Step 4 - 1.02 x Operating Pressure
- Step 7 - 1.04 x Operating Pressure
- Step 10 - 1.15 x Operating Pressure
- Step 13 - 1.36 x Operating Pressure

The AE results from the hydro tests performed in the course of the ZB-1 test lead to the following conclusions:

- In the context of the pretest hydro of the ZB-1 vessel, AE was sensitive to two unique flaw conditions. In the first part of Step 1, KS07 degraded material which was subsequently replaced because of concern over possible failure produced an abundance of AE even before reaching the 1.0 x operating pressure level (Figure 6). In the second part of Step 1, after the degraded insert was replaced, the KS07R weld crack which appears to have initiated during welding is estimated to have been only about 5 mm deep (4% through-wall); however, the AE from the 1.0 x operating pressure hydro showed some indications of the crack (Figure 7). The machined defects did not show up in Step 1 probably because they had been previously stressed in precracking.

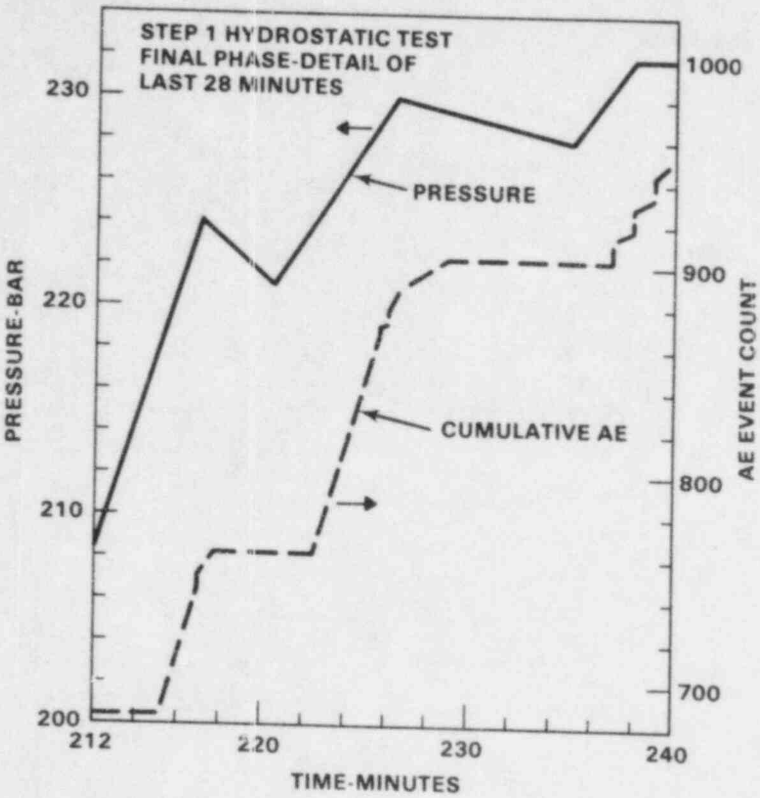


Figure 6. AE (KS07C Insert) and Pressure Versus Time, Last 28 Minutes of Phase 1, Step 1 Hydro, ZB-1 Vessel Test.

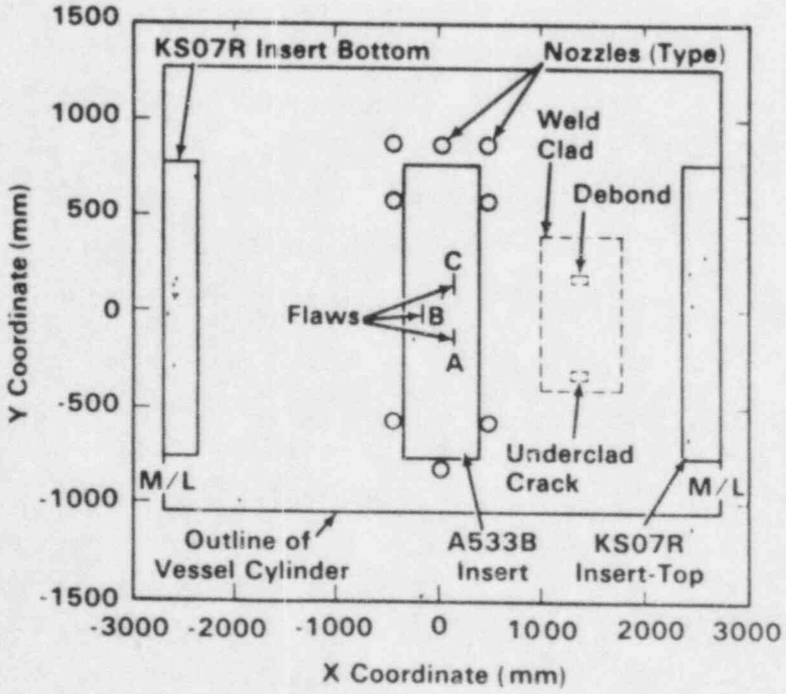


Figure 7. AE Source Indications - Phase 2, Step 1 Hydro, ZB-1 Vessel Test.

- The hydro results raise a question as to the effectiveness of AE monitoring during inservice hydrostatic testing to 1.15 x operating pressure. Steps 4, 7 and 10 (1.02, 1.04 and 1.15 x operating pressure respectively) produced no noteable indications from the known flaws. In Step 13 (1.36 x operating pressure) AE was identified with Flaw B starting at about 1.1 x operating pressure (Figure 8); however, flaw B was 80% through-wall at this point. This is a questionable degree of resolution for early detection of flaws.

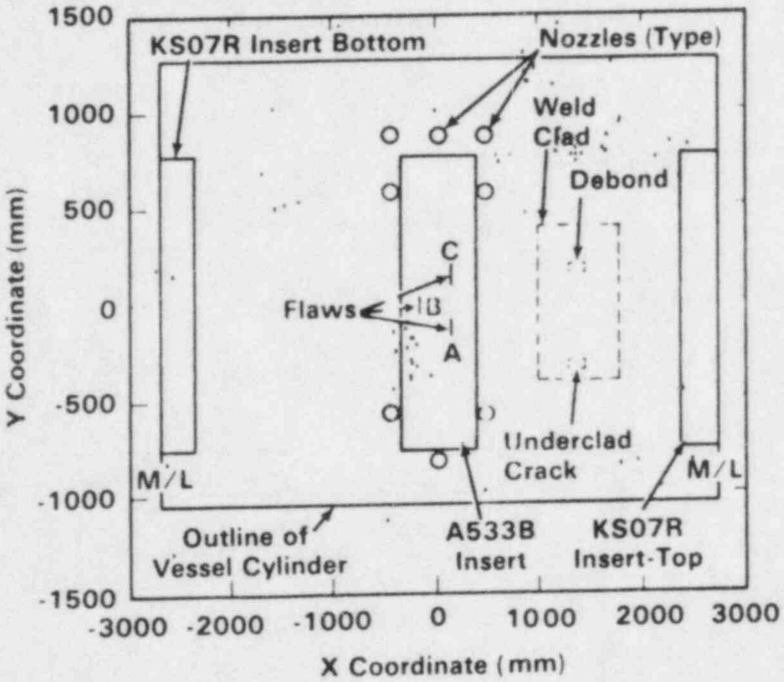


Figure 8. AE Source Locations, Part 2, Step 13, ZB-1 Vessel Test.

- With higher overpressure (about 1.4 x operating pressure or greater), it appears that AE does provide a reasonable degree of flaw detection resolution. In Step 13, the KS07R weld crack as well as the machined flaws produced AE at about 1.3 overpressure. Referring to Figure 9, the areas labeled 3 and 4 are related to the weld crack and the area labeled 2 is from the machined flaws. Areas 1 and 5 are known artificts from movement of steel bands around the vessel. In this plot of AE source locations, there are a number of scattered indications, the source of which have not been identified at this time. They may be due to the

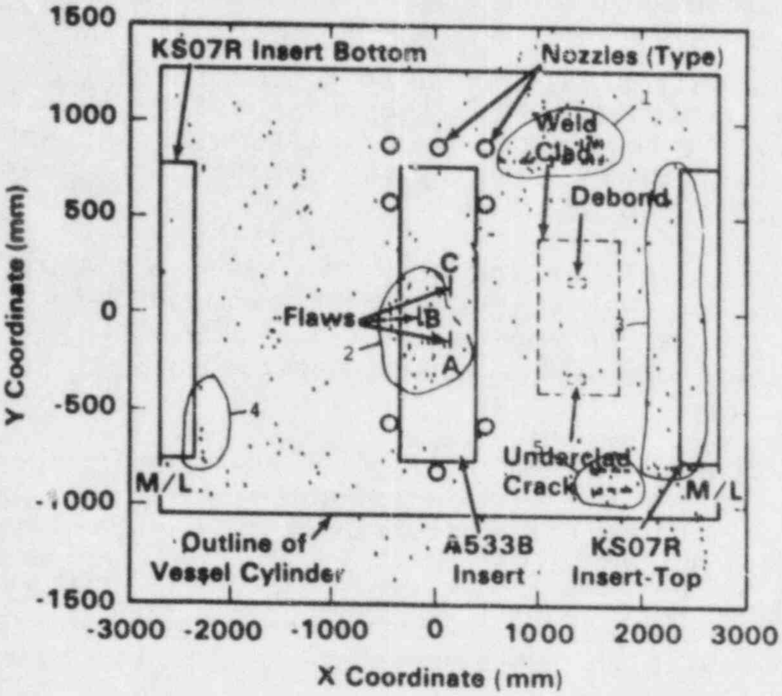


Figure 9. AE Source Locations, Array 3, Step 13, Total, ZB-1 Vessel Test.

whole vessel being in a stress range not previously experienced during the test. It was indicated by NDI and by examination of trepan samples from the weld area that the weld crack depth ranged from 10 to 40 mm (8 to 30% through-wall) at this time and as stated above, Flaw B was 80% through-wall. The higher overpressure logically improves the flaw size resolution of AE monitoring during hydro.

In summary, AE monitoring during in-service hydros would detect a possible failure condition or a major flaw; however, detection of small flaws particularly in a 1.15 over pressure hydro is questionable. It must be emphasized that these conclusions do not apply to preservice tests where the structure has not been previously stressed to a significant level. Resolution of flaw detection by AE should be much better in that case.

We expect to finalize the report on ZB-1 vessel test results for publication in December 1984.

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 were 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 during that period. A topical report, NUREG/CR-3693 describing the AE results from hot functional monitoring was published June 1984.

Work focused on completing an engineering prototype AE monitor system for use in operational monitoring at Watts Bar Unit 1. The AE monitor system used in the ZB-1 vessel test performed with very limited problems during the one year duration of the test and has continued in use on laboratory tests since that time. An engineering prototype system design has been developed based on the ZB-1 experience. The instrument concept is shown in Figure 10.

The acquisition subsystem, which receives data from the sensors, is composed of 24 channels divided into six arrays. Arrays may be composed of 1, 2, 3, or 4 channels. Each channel has a maximum electronic amplification of 90 dB, which can be reduced with channel attenuators in 1 dB steps by 14 dB. A 20

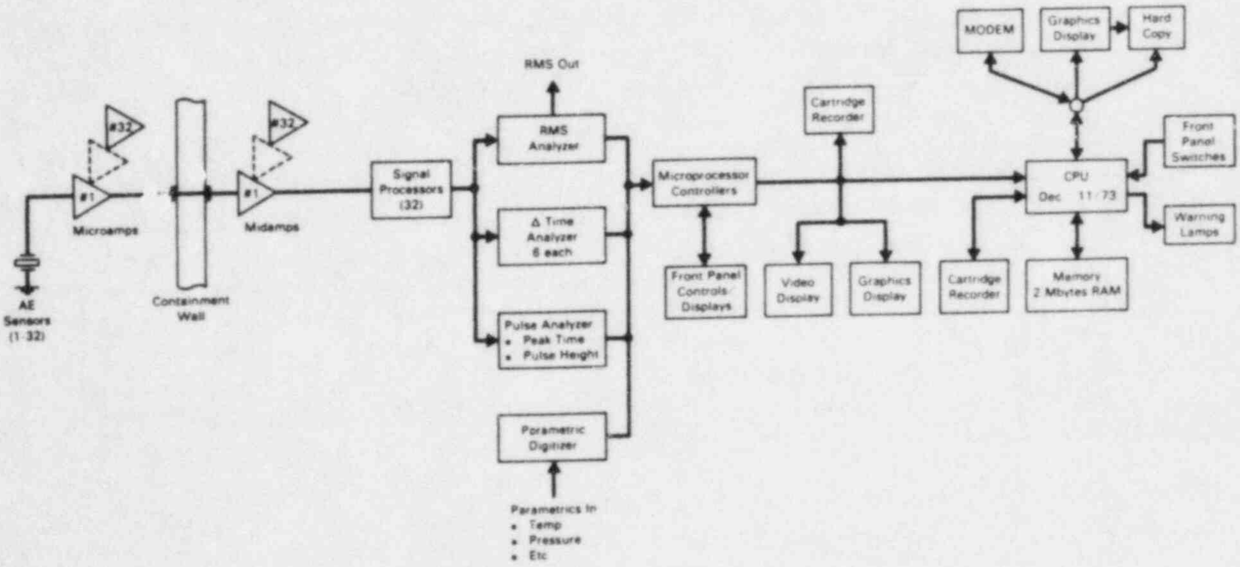


Figure 10. Engineering Prototype AE Monitor System Functional Diagram.

dB microamp is used in close vicinity of the sensor to provide sensor impedance matching and cable driving. All amplifier stages are linear.

Data collected from each array consists primarily of 1) delta-times, 2) RMS, 3) peak time, 4) pulse height, and 5) sensor hits. Delta-times are used for source location and are measured with 1 microsecond resolution. RMS is measured on each channel for leak detection analysis. Peak time and pulse height are measured only on one channel of each array. Sensor hit totals are used to determine both sensor functional condition and signal propagation affects.

All data is recorded on a 67 Mbyte cartridge tape for long term storage. The data is also passed on a high speed buss to the DEC 11/73 for real-time analysis.

The system is operated on a menu approach wherein a video display shows function choices to the operator and a keyboard lets the operator enter his choice. Once a choice is made, a series of questions and prompts follow for operator guidance.

Data analysis is performed in a separate subsystem which is designed to maximize speed and information accessibility with a minimum of operator intervention. It operates in both an on-line mode with data directly from the data acquisition subsystem or in an off-line mode receiving data from cartridge tape.

High processing speeds are attained with the use of DEC's 15 MHz, 32-bit J-11 CPU and over 2 Mbytes of RAM memory. System software resides in battery backed nonvolatile memory eliminating the need for the slower mechanically based mass storage devices.

The analysis subsystem allows easy access to information for personnel not experienced in the details of acoustic emission monitoring techniques and instrumentation. Front panel lamps and gauges serve to direct the operator to monitoring conditions and to instrument conditions such as data storage device full or hardcopy paper empty. Information concerning acoustic activity is presented in the form of graphic displays on a CRT screen. the selection of display type, reactor area of interest, and information screening is accomplished through the use of front panel switches. With minimal training, the operator can characterize acoustic activity according to its location, rate, and characteristics (amplitude, rise time, and pattern recognition classificaiton).

Several automated features are integral to the analysis subsystem to facilitate unattended operation. Periodically, hard copies of a select group of principle displays are generated by the system. A modem can be used for remote system access. A 67 Mbyte cartridge tape unit used for off-line analysis also serves as a backup read-time data storage device when the primary storage device in the acquistion system has been filled. The data processing rate is about 150 events per second maximum. Data rate can be reduced by several variables such as the size of the sensor array, the length of time that a high data rate is sustained, and buffer capacity.

The instrument system hardware is illustrated in Figure 11. The modules will be installed in existing racks at Watts Bar, Unit 1. The system is currently undergoing extensive functional testing in the laboratory.

Fuel loading at Watts Bar, Unit 1 has been delayed until March 1, 1985.

AE SIGNAL PATTERN RECOGNITION

One of the key elements of this program is to develop a method of separating AE signals produced by crack growth from acoustic signals produced by innocuous sources. The original approach taken was to use signal processing techniques to generate features related to spectral content of the signals. These features provided a reduced set of information that described characteristics of the waveform of interest. Analysis of waveforms recorded on the ZB-1 test showed that the method was not effective in separating crack growth AE from noise.

In the course of reassessing the problem, visual examination of recorded waveforms showed evidence of a consistent three-pulse signal pattern present in practically all waveforms originating near known and suspected regions of crack growth (Figure 12). It was determined experimentally that the three pulses are wave modes, traveling at different group velocities, and that separation of these wave modes takes place in the waveguide as a response to a high frequency, short duration input pulse - i.e., an AE signal. Incorporation of this feature into a pattern recognition approach has resulted in correct classification rates of about 95% when applied to recorded waveforms from the ZB-1 vessel test.

Current emphasis is on incorporating the pattern recognition technique into the engineering prototype system to perform analysis on acoustic signals as they are received.

STRESS CORROSION CRACKING TESTS

Stress corrosion cracking tests to characterize the asso-

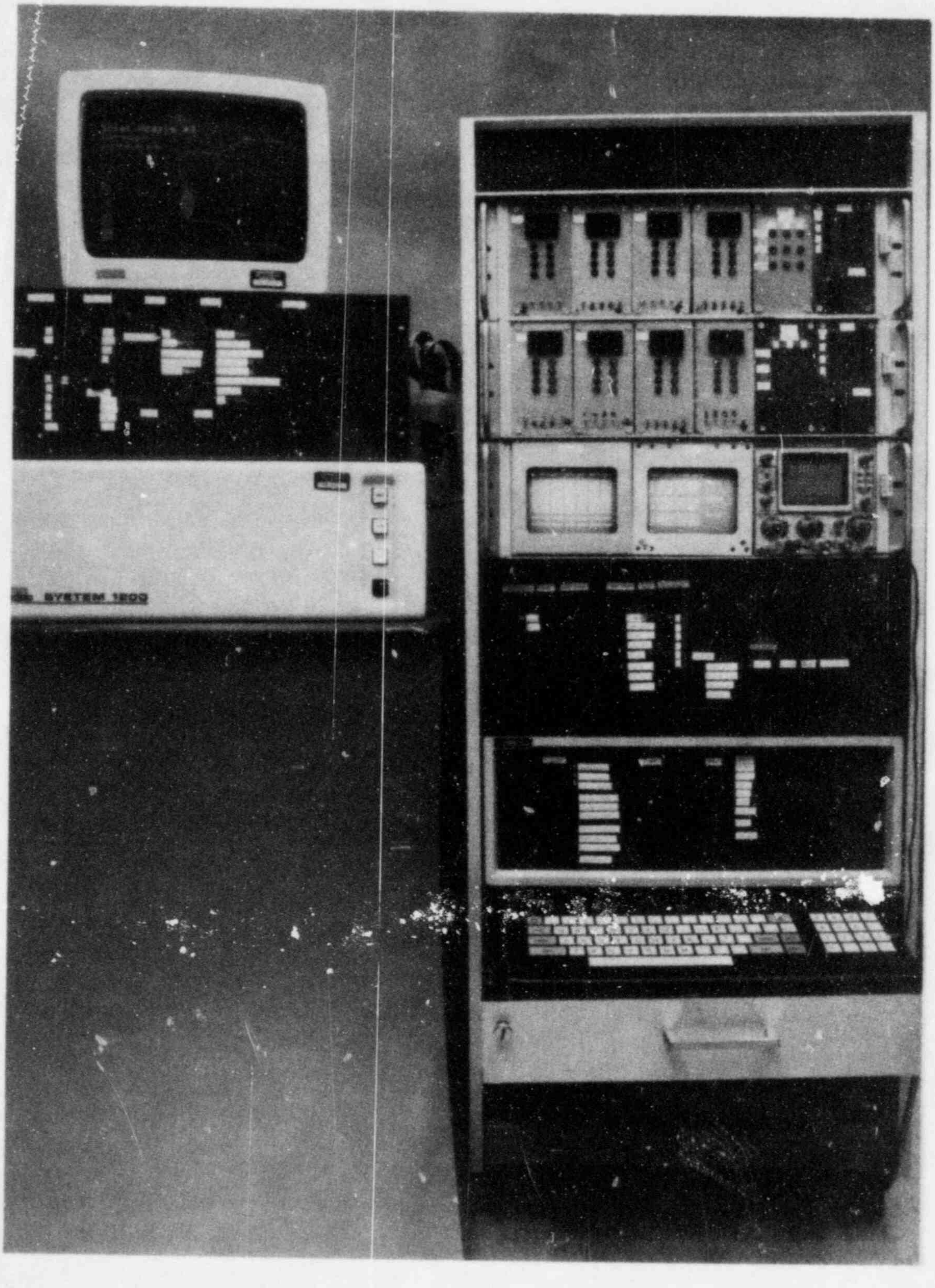


Figure 11. Engineering Prototype AE Monitor System for Watts Bar, Unit 1 Reactor.

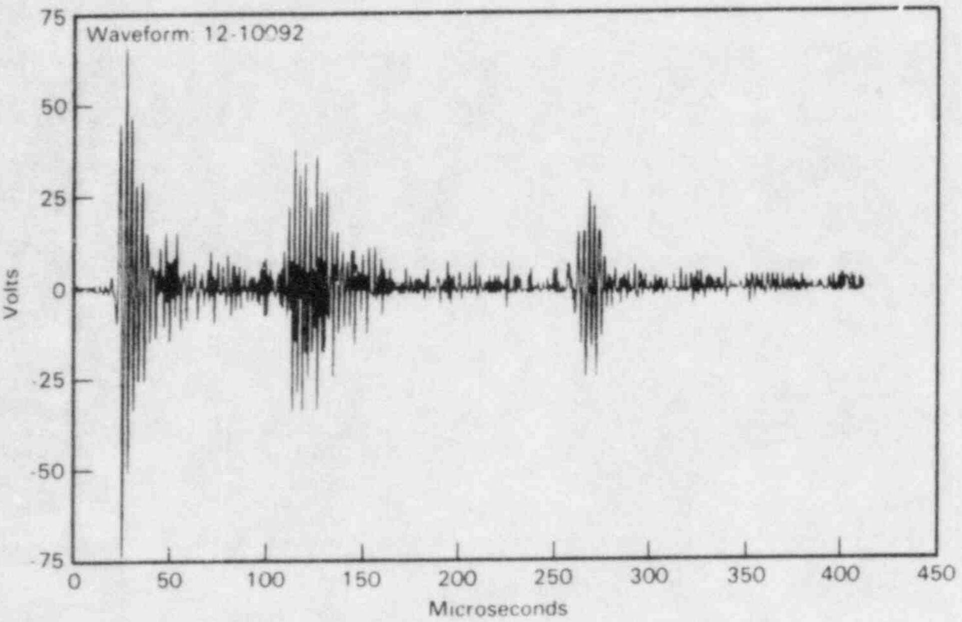


Figure 12. Three Pulse Response of Waveguide Sensor to AE Signal.

ciated AE are in process using two 4 inch Sch. 80, Type 304 stainless steel pipe specimens. Figure 13 shows the test assembly with the specimen clevis pinned to the load cell and bottom mounted hydraulic cylinder. The upper flange connects the specimen to the alignment bearing and the hot water loop.

Before applying axial test loads, the water loop was heated to 550°F at a pressure of 1350 psig, demonstrating its ability to hold required temperature and pressure within tolerances. It was necessary to wrap the load cells with water cooled coils to keep them within operating specifications.

AE sensors were attached to each specimen with accompanying data recording instrumentation. A four sensor cylindircal array is used on each specimen to provide point source location. A fifth sensor is used on each specimen for signal waveform recording.

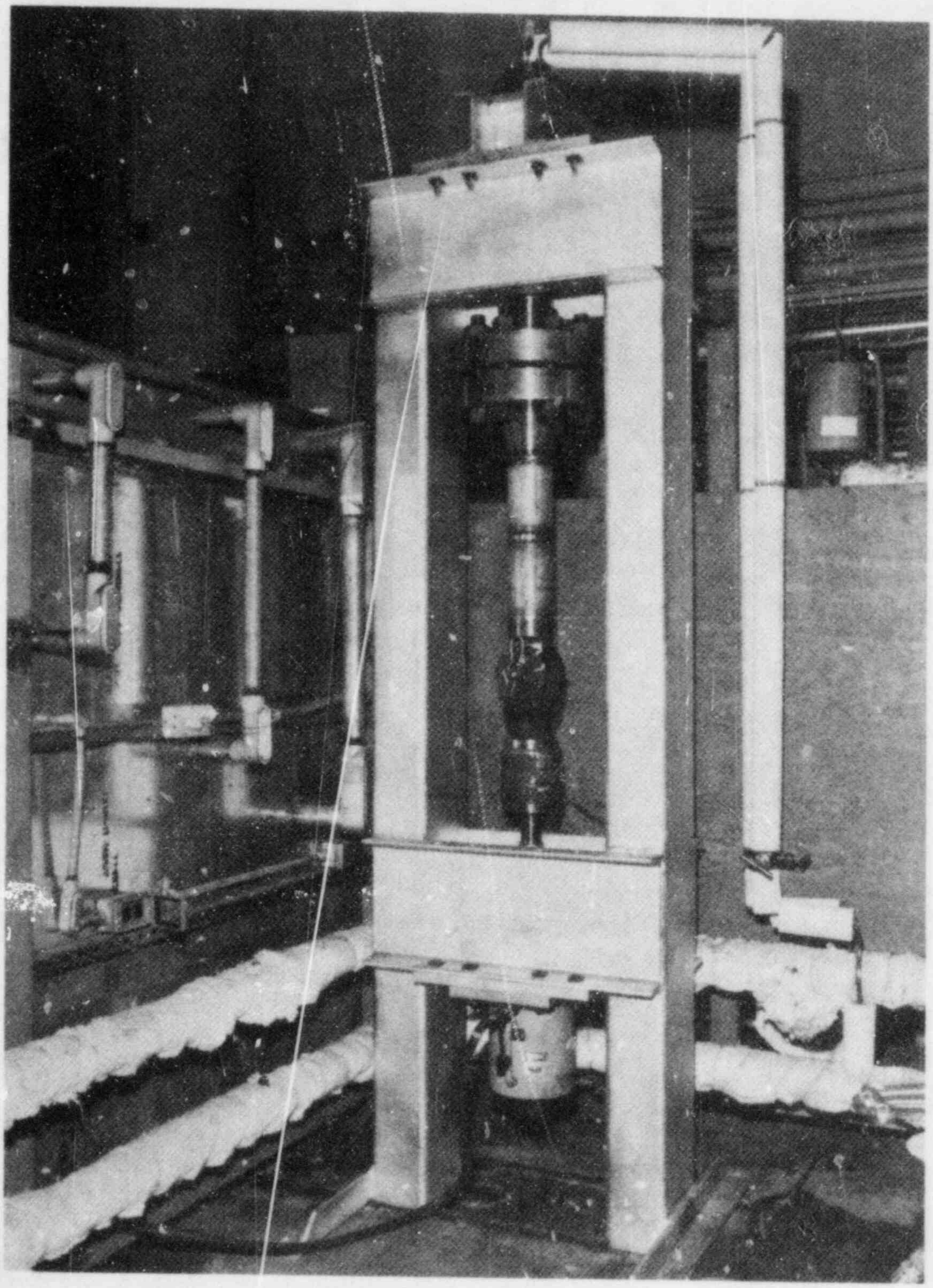


Figure 13. IGSCC Test Specimen Mounted in Test Stand.

Water loop chemistry is:

Parameter	Source Water	Loop Water
pH	5.54	5.74
conductivity (mho)	1.76	3.02
O_2 mg/l	6.03	4.88
Cl^- mg/l	<0.02	0.12
$SO_4^=$ mg/l	0.03	<0.02

Axial loads at temperature were applied on July 9, 1984. Loading conditions were:

	Axial Stress, ksi		
Test Specimen	Externally Applied	Water Pressure	Cyclic Frequency
1	13.5	4.5	1/day
2	5.5	4.5	1/week

There is no evidence of cracking in either specimen yet.

REPORTS

NUREG/CR-3693, "Acoustic Emission Monitoring of Hot Functional Testing, Watts Bar Unit 1 Nuclear Reactor," was published June, 1984.

FUTURE WORK

- Publish NUREG document on ZB-1 vessel test results.
- Review ZB-1 vessel test results with German participants.
- Complete testing of the engineering prototype AE system.
- Install equipment on Watts Bar, Unit 1 reactor for operational AE monitoring.

- Continue AE characterization of IGSCC.
- Submit a complete standard to ASTM for continuous AE monitoring of pressure systems.

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16. ABSTRACT *(200 words or less)*

Technical progress toward continuous acoustic emission monitoring of nuclear reactor pressure boundaries for flaw detection is described for the period April-September 1984. A draft report of ZB-1 vessel test results was completed. Growth of machined flaws was detected by AE during both 65°C and 285°C testing. AE data was generally proportional to crack growth. A key result was clear detection of a natural crack in a fabrication weld by AE. Crack growth rates estimated from AE data compared well with measured crack growth rates. In service hydro test monitoring gave mixed results. Impending failure conditions are readily detectable. However, with low overpressure (1.15 x operating pressure), flaws as deep as 70% through-wall did not produce significant AE. With higher overpressure (1.4 x operating pressure), flaws produced identifying AE. An engineering prototype AE monitor system has been completed for use in operational monitoring at Watts Bar Unit 1 reactor. A modified approach to crack growth AE signal identification is producing about 95% correct determinations on recorded waveforms from the ZB-1 vessel test. A report on results from AE monitoring hot functional testing at Watts Bar Unit 1 has been published.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS
Acoustic emission monitoring of reactor pressure boundaries for flaw detection.

17b. IDENTIFIERS OPEN-ENDED TERMS
acoustic emission, AE, reactor pressure boundaries, continuous monitoring, flaw detection

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