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Acoustic Emission System Calibration at Watts Bar Unit 1 Nuclear Reactor

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Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
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ABSTRACT

An acoustic emission system has been installed on TVA's Watts Bar Unit 1 reactor to monitor selected areas of the pressure boundary during cold hydrostatic testing, hot functional testing, and ultimately, during reactor startup and operation. This is part of a cooperative effort between TVA and NRC Research to test and demonstrate AE technology. This technology has been developed under an NRC Research program to validate the application of AE techniques for continuous, on-line monitoring of reactor pressure boundaries to detect cracking. This report discusses the performance of and results from a special calibration test of the AE system using simulated AE signals to evaluate the accuracy of signal source location by the system.

EXECUTIVE SUMMARY

A major research program devoted to validating acoustic emission (AE) technology for continuous, in-service monitoring of nuclear reactor pressure boundaries to detect cracking is being performed at the Pacific Northwest Laboratory. The program is sponsored by the U.S. Nuclear Regulatory Commission, Office of Research (NRC-RES) with support from the Tennessee Valley Authority (TVA).

Much of the technology demonstration has been performed at the TVA Watts Bar Unit 1 Nuclear Power Plant. Selected areas of the reactor pressure boundary have been AE monitored during cold hydrostatic and hot functional testing of the reactor system with significant benefit to the AE technology. A third set of tests performed to evaluate the signal source location capability of the installed AE system is the subject of this report. Ultimately, the installed AE system will be used to monitor the same parts of the reactor system during startup and operation of the reactor.

It is important to evaluate the signal source location capability of the AE system on a reactor because of the large wall thickness used in pressure boundary components. AE signal source location algorithms available today for practical application locate in two dimensions. Many reactor components have a wall thickness of 8 to 12 inches or more. With a third dimension of this magnitude, there is a need to evaluate the accuracy of the two-dimensional source location. The Watts Bar Unit 1 vessel, being completely empty, offered an opportunity to evaluate the source location function using simulated AE signals injected on the inside of the vessel and nozzles.

Signal attenuation by the vessel cladding at the clad-to-vessel interface in the 400 to 500 kHz frequency range being used to monitor for AE precluded use of the normal pencil lead break signal source to inject signals at the inside of the vessel and nozzles. In real application of AE monitoring, this problem would not be present because one would be seeking to detect signals originating in the ferritic vessel wall. An electronic pulser with a transducer was used to inject acoustic signals at known points around the inside of the #2 inlet nozzle and on the inside surface of the vessel.

Signal source location for signals injected on the ID of the #2 inlet nozzle was accurate to the projected signal input location generally within 3 to 5 inches in the circumferential direction. In the front-to-rear direction, the location was accurate to within 5 to 7 inches for signals originating within the region under the AE sensor array, but this accuracy deteriorated progressively as the source point moved farther outside of the AE sensor array. There are methods of overcoming the front-to-rear location inaccuracy with additional sensors; however, since the signals are being detected and the radial location is accurate, it may be difficult to justify the additional hardware for the increase in source localization efficiency.

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ACOUSTIC EMISSION SYSTEM CALIBRATION[a] AT WATTS BAR UNIT 1 NUCLEAR REACTOR

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1.0 INTRODUCTION

A program titled "Acoustic Emission/Flaw Relationships for In-Service Monitoring of LWRs" devoted to validation of acoustic emission (AE) technology for continuous, in-service surveillance of reactor pressure boundaries to detect cracking is in progress at the Pacific Northwest Laboratory [1]. This program is sponsored by the U.S. Nuclear Regulatory Commission, Office of Research with support from the Tennessee Valley Authority (TVA). The program is in the final phase of demonstrating developed technology on a nuclear power plant(s).

A significant part of the technology demonstration on a reactor power plant is taking place at the TVA Watts Bar Unit 1 Nuclear Power Plant. Selected areas of the pressure boundary are being monitored with an installed AE system. This has been or will be applied during:

- cold hydrostatic testing,
- hot functional testing, and
- reactor startup and power operation.

Monitoring cold hydrostatic testing and hot functional testing has been completed and the results reported [2,3]. This report concerns the results obtained from utilizing an opportunity to perform AE system calibration as an intermediate step between hot functional testing and reactor startup. With the reactor startup delayed, there has been a period of time wherein the vessel has been completely empty. This offered an unusual opportunity to enter the vessel and inject simulated AE signals at selected locations to calibrate the source location accuracy of the AE system. Such a calibration is important because the algorithms available at this time for practical application to AE monitoring on a reactor locate in two dimensions (X and Y) on the surface of the structure containing the AE sensors. On components where the wall thickness is relatively small, such as 2 to 3 inches on piping, this is not a serious concern. Considering, however, the circumstance of AE sensors mounted on the outer surface of a reactor vessel or nozzle sensing a growing crack at the inner surface of the structure which may have an 8- to 12-inch wall thickness, there is obviously a sizeable third (Z) dimension involved. The question being addressed is, "Does the two-dimensional source location operating on the outer surface of a heavy wall structure provide an acceptable indication of the location of the AE source?".

(a) Work supported by the U.S. Nuclear Regulatory Commission and the Tennessee Valley Authority under Contract DE-AC06-76RLO 1830; FIN. B2088 and B2905; NRC Contact: Dr. J. Muscara; TVA Contact: C. Cantrell.

2.0 AREAS MONITORED

Locations being monitored on the Watts Bar pressure system are shown in Figure 1. They consist of:

- Inlet Nozzle #2
- The safety injection line near its connection to the loop 2 cold leg
- A section of the reactor pressure vessel bounded at the top by the No. 2 inlet and outlet nozzles and at the bottom by two sensors installed near the bottom end closure-to-shell weld directly below the No. 2 inlet and outlet nozzles.

In this calibration work, the No. 2 inlet nozzle is of primary importance. This is the component where maximum wall thickness and geometric complexity is encountered. The vessel wall is second in interest; the wall thickness is large, but it is a simple plate geometry and the AE monitoring array is quite large relative to the wall thickness. The safety injection line is of limited interest. It was instrumented originally to provide an area where a fracture specimen could be installed to test detection of real crack growth AE signals in the presence of full coolant flow noise conditions during hot functional testing. (It was demonstrated that these signals could be detected [3].)

3.0 TEST APPROACH

The general approach used was to check the installed AE sensing system for suitable performance and then proceed with the assessment of AE system response to acoustic signals injected on the inside wall of the vessel and #2 inlet nozzle. A prototypic AE monitor/analyzer instrument developed under the NRC program was transported to Watts Bar, installed in cabinets provided earlier for the instrument in the auxiliary instrument room, and connected to the AE sensors.

3.1 INSTRUMENTATION

Sixteen AE sensors with associated preamplifiers and cabling were permanently installed on the Watts Bar Unit 1 reactor in the locations shown in Figure 1 in 1983 in preparation for AE monitoring during hot functional testing of the reactor system. Sensors installed earlier to monitor cold hydrostatic testing were removed after the test to avoid interference with continuing construction activities. Following hot functional testing, the sensor subsystem was left in place. The same sensor subsystem was used for the current calibration work. Details of the installation and characterization of the AE sensor subsystem are given in the report on hot functional testing [3] and will not be repeated here. The sensitivity of the sensors was tested by breaking 0.5-mm, 2H pencil leads against the outer surface of the reactor components in the vicinity of the sensors (access to the component surface near the end of the waveguides was precluded by mirror insulation). Sensor sensitivity tests showed that all sensors but one were functional even after residing on the reactor for four years unattended. Fortunately, this one faulty sensor did not interfere with achieving the objective of the test. Two AE sensor arrays are installed on the #2 inlet nozzle - one is a cylindrical array to monitor the total nozzle which would be used in normal AE monitoring during reactor operation, and the other which contains the faulty sensor is a special quad array to focus on a limited area of the nozzle where AE source indications clustered during the cold hydrostatic test and hot functional testing. The preamplifier housed at the end of the waveguide for one of the sensors in the quad array was not functional. The fact that 15 out of 16 sensors and associated preamplifiers installed four years ago are functioning is significant, since these sensors were in place during hot functional testing and subsequent high-temperature tests.

A prototypic AE monitor instrument designed for long-term monitoring (Figures 2 and 3) was developed for the NRC AE program. One of the features of this instrument is the use of digital tape cartridges with 67 Mbyte capacity for mass data storage. These cartridge units, which overcome the limitations of disk units for long-term service, have been tested in application over about three years and found to be very reliable. The prototype measures signal peak time, signal amplitude, signal duration, event count, and difference in time of signal arrival at the sensors in an array for source location, rms signal level for leak detection, plus clock time, and up to 12 parametric values (reactor system operating characteristics such as coolant temperature and pressure, power level, etc.). These basic values are digitized and recorded on tape cartridge for reference plus simultaneously passing them to an analysis

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The prototypic instrument was separated into the individual modules and shipped to Watts Bar where it was installed in two cabinets provided earlier for the purpose. These cabinets in the Auxiliary Instrument Room are part of the original plan for AE monitoring at Watts Bar Unit 1. Signal leads from all of the AE sensors are routed to these cabinets.

3.2 AE SIMULATION

Acoustic signals were injected into the nozzle and vessel wall using an electronic pulser and an ultrasonic transducer. Normally the signals would have been generated by breaking pencil leads against the structure surface; but due to the signal attenuation at the AE monitoring frequency (400 to 500 kHz) caused by the vessel cladding and the cladding-to-vessel interface on the inside of the vessel and nozzle, the signal was frequently not detected at all four sensors in an array. This was not an unexpected problem. It had been observed previously in tests on an uninstalled reactor vessel [4]. Signals from the pencil lead breaks injected directly into the ferritic vessel wall were readily detected at a distance of 10 to 15 feet. The electronic pulser approach is not as desirable because it does not produce the clean impulse or delta function type signal input as does the lead break. This, in turn, degrades source location accuracy. The alternate would have been to perform the test at much lower frequencies (100 to 150 kHz) where the lead break input would probably have penetrated the vessel cladding with sufficient signal strength. This was rejected because it was not representative of the monitoring frequency necessary for on-line reactor AE monitoring, and because it would have required significant modification of the installed AE monitoring instrumentation to function at the lower frequencies.

Both the electronic pulser and the transducer were fabricated at PNL. The pulser produces a square-wave output with voltage selectable at 100, 200, or 300 volts and pulse width selectable at 0.05, 0.1, 0.2, or 0.5 μsec. The 300-volt/0.5-μsec. combination was used in the testing. The characteristics of the input signal are shown in Figure 4. The pulse out of the pulser, the waveform of the transmitted signal, the response of a tuned waveguide AE sensor and a broadband sensor to the transmitted signal, and the frequency content of both signals are shown. This characterization was performed at PNL using a steel calibration block.

At the #2 inlet nozzle, acoustic signals were input on the inside vessel wall near the nozzle-to-shell weld, on the inner radius of the nozzle, and at 10 inches and 31 inch into the nozzle referenced to the vessel wall ID. Ten pulses minimum were input at 0°, 90°, 180°, and 270° around each of the input lines. Circumferential position follows the convention of looking at the nozzle from the outside with 0° at the top, 90° on the right at the horizontal mid-plane, 180° at the bottom, and 270° on the left at the horizontal mid-plane. Refer to Figure 5 for a graphic description of these input points.

On the inside wall of the vessel, acoustic signals were input at 44, 104, and 128 inches below the horizontal centerline of the nozzles and on vertical lines at 113° and 157° circumferential position which correspond approximately to the vertical centerline of the #2 inlet nozzle and the #2 outlet nozzle, respectively (see Figure 6).

Signals were injected on the outside wall of the vessel near the shell-to-bottom head weld at the 113° and 157° circumferential positions as shown in Figure 6.

All data was recorded on digital tape cartridge for analysis. A problem in the software for the analysis section of the AE monitor system precluded analysis of the data on site. This problem has been corrected.

The AE sensors, preamplifiers, and cabling remain in place on the reactor. The AE monitor system was returned to PNL, since it appears that startup of Watts Bar is some time away.

4.0 TEST RESULTS

The test data has been analyzed at PNL from the digital tape record using the analysis section of the prototypic AE monitor system. The system was designed to operate in this mode to cover situations where some problem may be experienced with the analysis computer during monitoring.

Figures 7 through 22 are the AE source location maps used for interpreting the source location capability for the four sensor arrays. A calibrated transmitter was used for sending acoustic pulses into the vessel wall. Location of events are indicated by the position of the letters A through E on the chart. The symbol key for each map identifies the range of events represented by the corresponding letter. This range is calculated by taking the maximum number of events and dividing by five.

4.1 PERFORMANCE OF #2 INLET NOZZLE AE ARRAY

Figures 7 through 10 give the signal source location results from acoustic signal inputs at 31 inches into the nozzle referenced to the inside wall line of the vessel. This places the signal sources within the front-to-rear boundaries of the AE sensor array on the nozzle. The signal source location indications are very good in the nozzle circumferential direction. In the front-to-rear direction, there is scatter in all cases but the indications generally are within 6 inches of the correct plane. The greatest error occurs at the 90° position. Considering the aspect ratio of the array (11-3/4 inch wide by 176 inch circumference), it is reasonable that the greatest scatter would be in the direction of the smallest dimension (front-to-rear).

Data from signal inputs along a circumferential line on the nozzle ID 10 inches into the nozzle referenced to the vessel ID wall (see Figure 5) are given in Figures 11 through 14. The plane of these inputs is about 9 inches outside of the cylindrical AE sensor array on the nozzle barrel. The source location results are similar to those for the 31-inch input line discussed above. The circumferential location indications are very good, and the front-to-rear location shows scatter. The front-to-rear locations are generally within 8 inches of the correct plane. Again, the 90° location shows the poorest performance.

Signal source location indications derived from signal inputs on the inside radius of the nozzle where it blends into the vessel ID (see Figure 5) are given in Figure 15 through 18. The plane of these inputs is about 13 inches outside of the cylindrical AE sensor array on the nozzle barrel. Similar information for inputs on the inside wall of the vessel about 7 inches outside of the nozzle bore are shown in Figures 19 through 22. These points are about 15 inches outside of the cylindrical AE sensor array on the nozzle barrel. In both sets of data, it is evident that the source is located quite accurately in the circumferential direction, but the front-to-rear source location is significantly in error.

Summarizing the results obtained from testing the nozzle array, the signals were detected and the source was located accurately in the circumferential direction. As the signal source point moved farther outside of the AE sensor array on the outside surface of the nozzle, the accuracy of the front-to-rear source location progressively deteriorated. The availability of a vessel surface monitoring array that covered the region around the nozzle-to-vessel juncture should improve the accuracy of source location for signals originating at the nozzle ID radius and nearby vessel wall when used in conjunction with the array on the nozzle barrel. From a practical standpoint, the fact that all of the signals were located accurately in the circumferential direction is of major importance to follow up verification inspection using ultrasonics.

A factor which leads to some unavoidable error, particularly with monitoring a nozzle, is the variation in effective wave propagation speed to different sensors in the array. With the cylindrical AE sensor array wrapped around the nozzle barrel, regardless of the location of the source in the nozzle, some sensors will receive the signal by straight line while others will receive the signal by reflection from the nozzle walls. This requires using an "average" propagation velocity somewhat higher than shear-wave velocity for calculation of source location. Another approach to minimize or eliminate this factor would be to use a more recently developed AE sensor array that would divide the nozzle circumference into four to six segments and treat each segment as an independent element. Thus, for any source point around the nozzle, there would be at least one array where all sensors in the array would have a straight line view of the source. This approach would require twice as many sensors with associated electronics and cabling to monitor each nozzle. Considering that the signals are being detected and are being located accurately in the circumferential direction, adopting the more expensive array before more field experience is gained in monitoring for real AE on an operating reactor may be questionable.

4.2 PERFORMANCE OF THE VESSEL WALL ARRAY

Injecting signals on the inside of the vessel wall did not produce usable data. The previously discussed signal attenuation in the vessel cladding and at the clad-to-vessel interface resulted in signals that were too weak to be detected by all four sensors in the monitoring array. This array is quite large (70 inches x 260 inches). The results flag an operating mode of the prototypic AE monitor system that needs to be modified. Presently, the system requires that a signal be detected by all four sensors before the signal will be accepted and its associated parameters recorded. The fact that a sensor detected a signal is noted and is logged into a record of total number of "hits" for each sensor. During the test, many of the acoustic signals input to the vessel wall triggered two or three of the array sensors, but they were not recorded. Data from two or three sensors is sufficient to perform some level of signal source determination even though it may not be optimum. The four sensor hit requirement will be made optional. There are cases when it is desirable to use this requirement to minimize recording extraneous information.

These results should not create concern about the capability of detecting AE from crack growth in the belt-line region of the vessel with an AE sensor array such as that on the Watts Bar Unit 1 vessel. It has been demonstrated in the intermediate scale vessel (ZB-1) tests performed in Germany [5] and in tests performed on an uninstalled reactor vessel at Hanford [4] that AE signals originating in the ferritic vessel wall can definitely be detected at a distance of at least 12 feet using pressure-coupled waveguide AE sensors of the type installed on the Watts Bar vessel. Of the two locations tested (the inlet nozzle and the vessel wall), calibration of the source location on the vessel wall is less critical because it is a simple plate geometry and the AE sensor array dimensions are large relative to the thickness of the vessel wall which would support expectation of definitive source location results.

4.3 CORRELATION WITH EARLIER SOURCE LOCATION DATA

During AE monitoring of cold hydrostatic testing [2] and hot functional testing [3] at Watts Bar Unit 1, there was spontaneous AE detected from the #2 inlet nozzle which clustered near the vessel wall at about 270° circumferential location on the nozzle. This is discussed on page 13 of Ref. 2 and on page 21 of Ref. 3. The source location results obtained at the #2 inlet nozzle during the current testing provide some support to the plausibility of the tentative conclusion that the clustered data originated from a slag inclusion mid-wall in the nozzle-to-vessel weld which had been identified in radiographic examination of the weld. The location of the signal source indications in the previous tests would indicate that the signals originated at a nearby point in the plane of the nozzle OD or at a point on the nozzle ID at about 270° and 16 to 20 inches into the nozzle by the convention shown in Figure 5.

5.0 CONCLUSIONS

The conclusion reached from this test is that two-dimensional AE source location supports an effective application of AE monitoring to in-service surveillance of reactor components even on very thick wall, geometrically complicated components such as nozzles. The planar signal source location shows an accuracy of about ±5 inches in the circumferential direction with a signal path length through the nozzle wall of about 15 to 80 inches to reach all sensors in the array. Recognizing that current AE methods may not provide accurate location determination in the front-to-rear direction on a nozzle and do not provide location definition in the "Z" or thickness direction, they do provide for detection of crack growth and localization of the flaw location. In instances where the use of AE is to monitor a known flaw indication for evidence of crack growth, the location definition could be made much more definitive by calibration to the specific location if the need for such accuracy could be justified.

Development of a practical three-dimensional AE source location method is an area of AE technology that should receive research attention to maximize the benefits from continuous in-service AE monitoring of thick wall pressure systems.

6.0 REFERENCES

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4. Ibid, pp. 18-19.

5. Hutton, P. H., R. J. Kurtz, R. A. Pappas, J. F. Dawson, L. S. Dake, and J. R. Skorpik. 1985. Acoustic Emission Results Obtained from Testing the ZB-1 Intermediate Scale Pressure Vessel, NUREG/CR-3915. Pacific Northwest Laboratory, Richland, Washington.

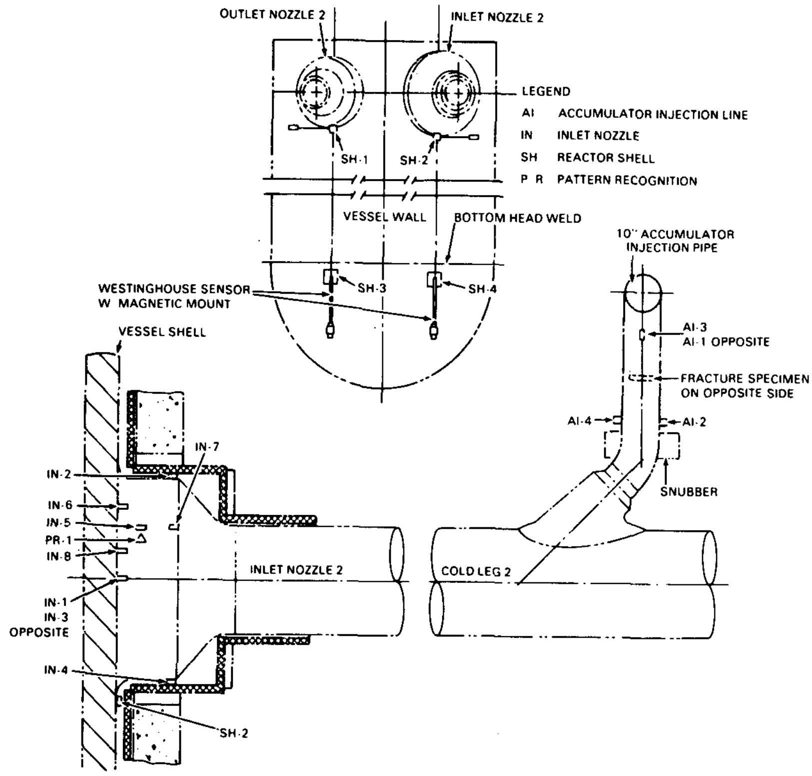


FIGURE 1. AE Sensor Locations - Watts Bar Unit 1 Nuclear Plant

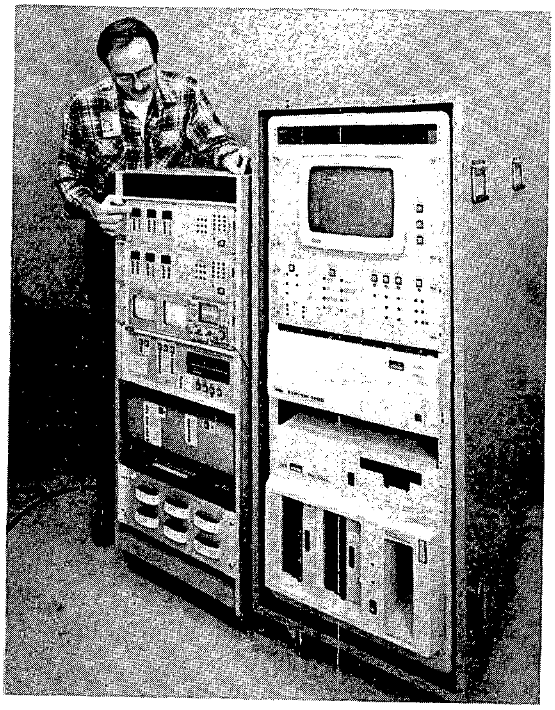


FIGURE 2. Prototypic AE Instrument for Inservice Reactor Monitoring

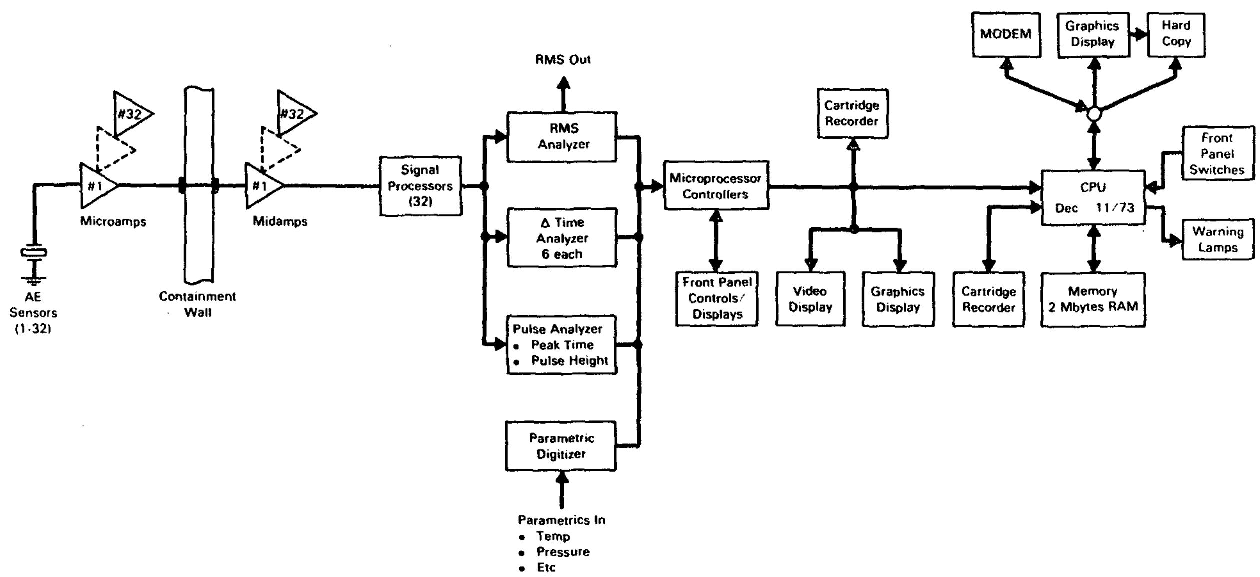
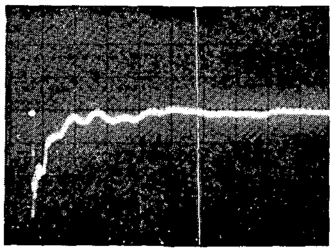
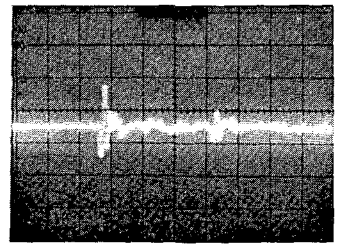


FIGURE 3. Block Diagram of Watts Bar AE Monitor System Functions

Input Signal

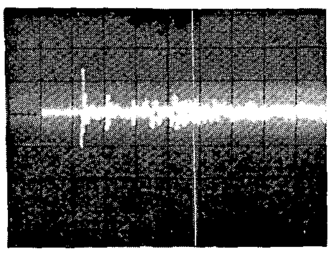


Pulse out of signal generator

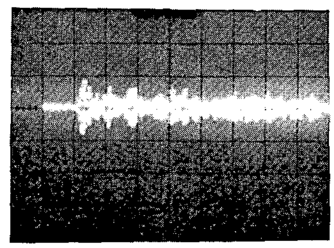


Signal received by the AE sensors through plate

Signal Out of Sensor

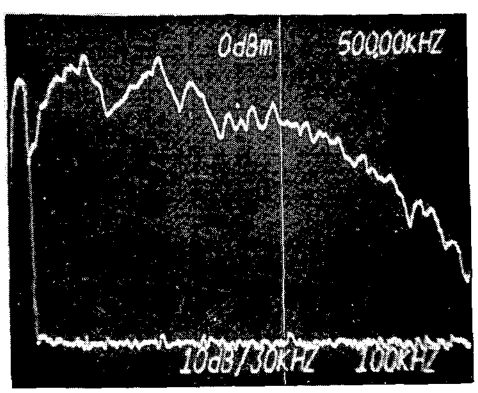


Broadband sensor (20 V. full scale)

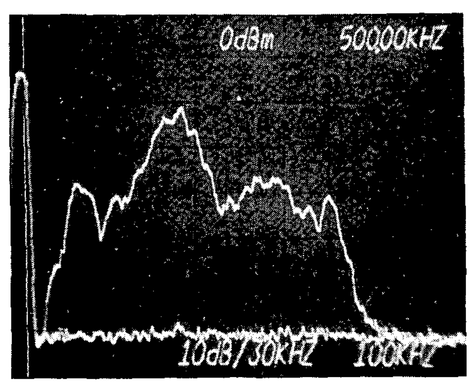


375 kHz tuned waveguided (2 V. full scale

Spectral Content of Signal



From broadband sensor



From 375 kHz waveguide

FIGURE 4. Characterization of AE Simulation Signals

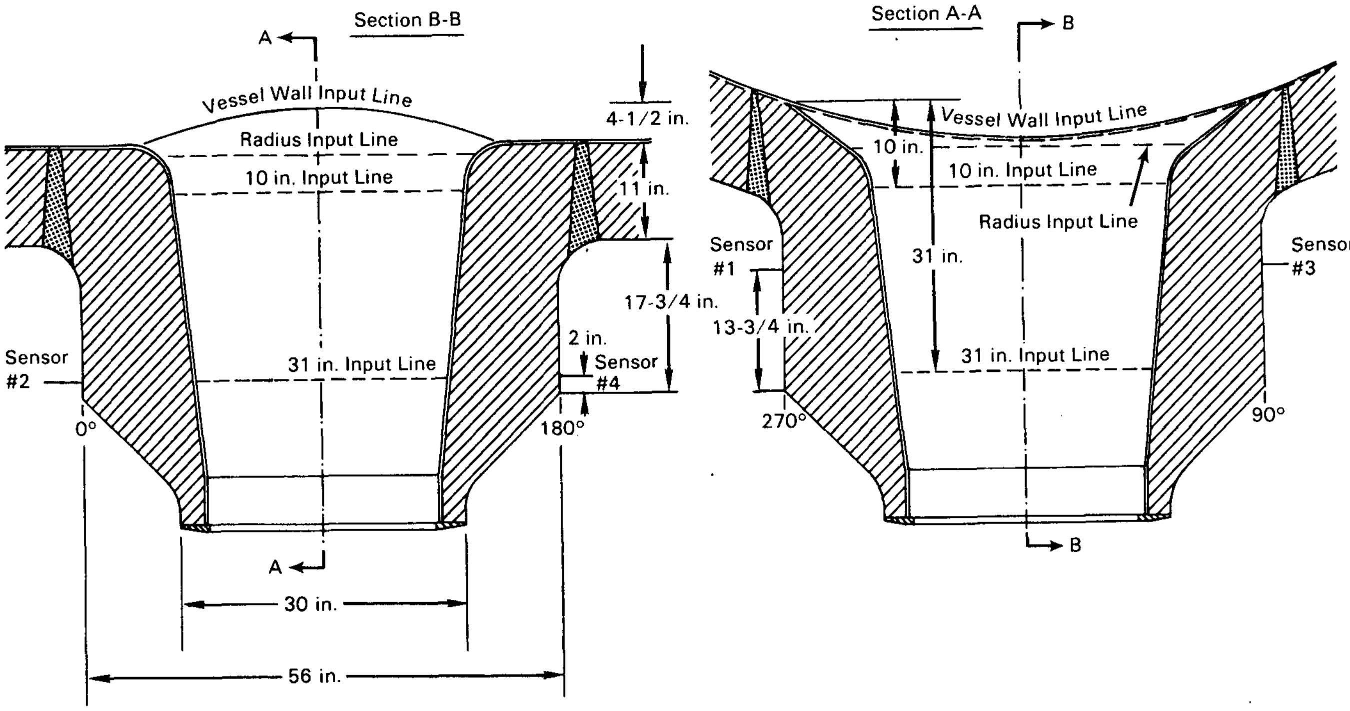


FIGURE 5. Location of Acoustic Signal Inputs on the #2 Inlet Nozzle - Watts Bar Unit 1

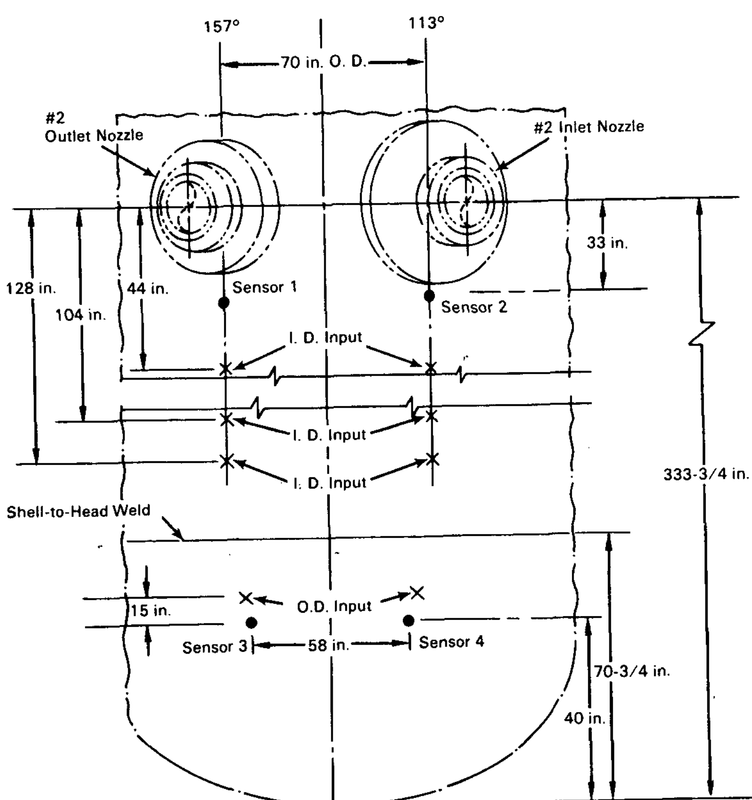


FIGURE 6. Location of Acoustic Signal Inputs on the Vessel Wall - Watts Bar Unit 1

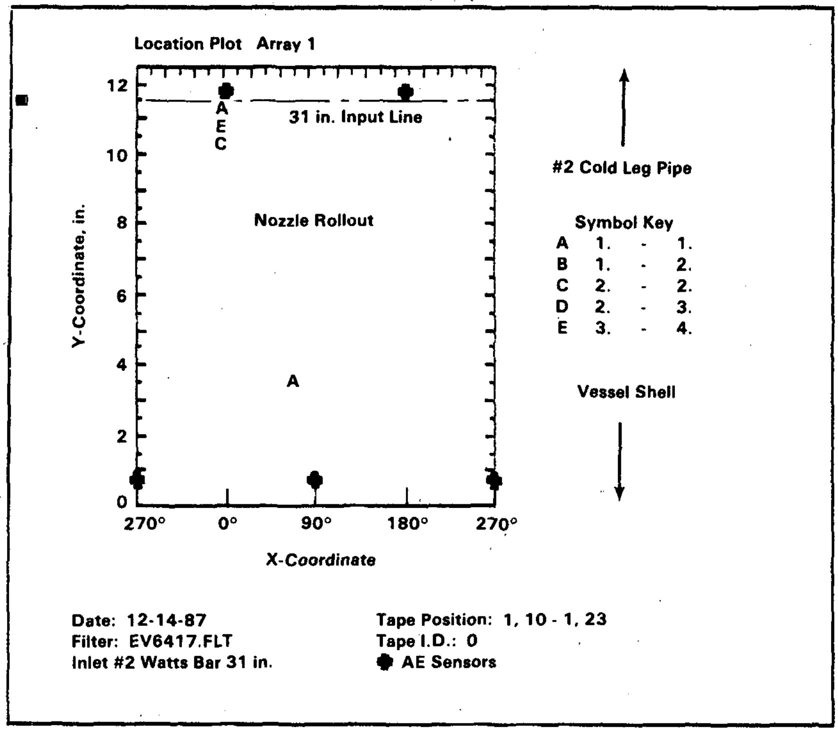


FIGURE 7. Source Location Indications from Inputs at 0° on the 31" Input Line - #2 Inlet Nozzle

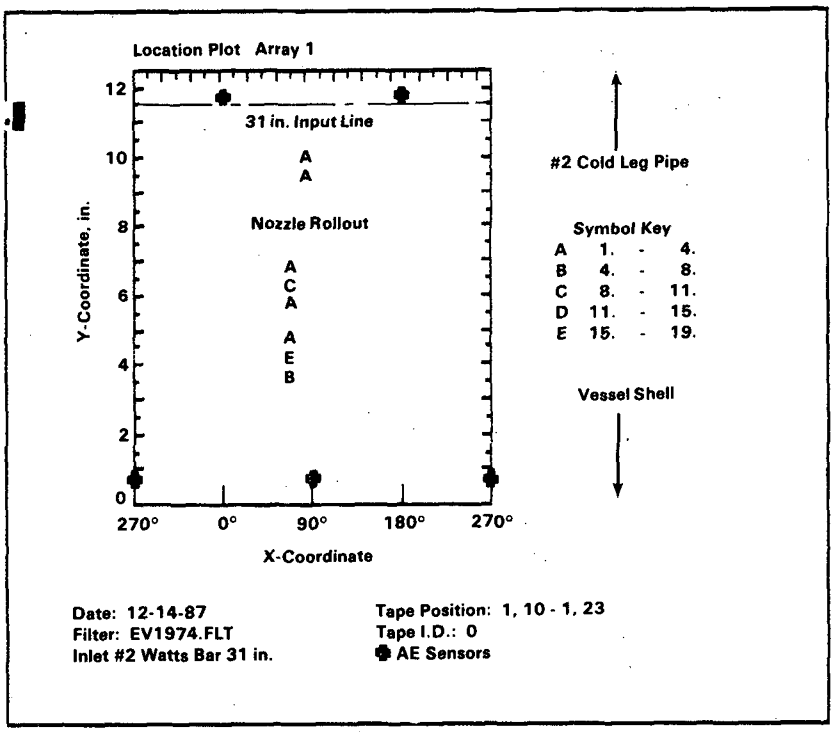


FIGURE 8. Source Location Indications from Inputs at 90° on the 31" Input Line - #2 Inlet Nozzle

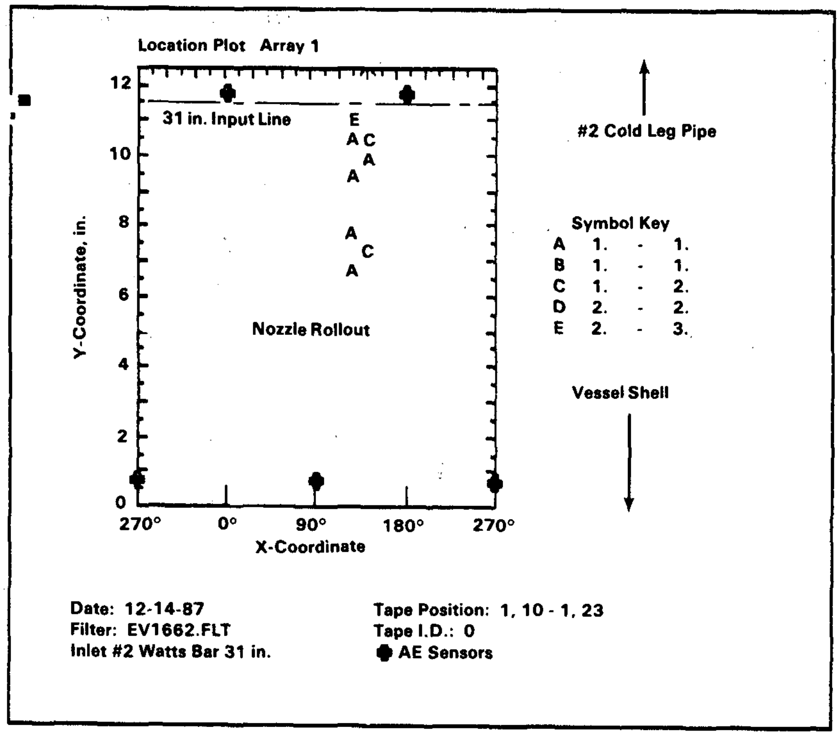


FIGURE 9. Source Location Indications from Inputs at 180° on the 31" Input Line - #2 Inlet Nozzle

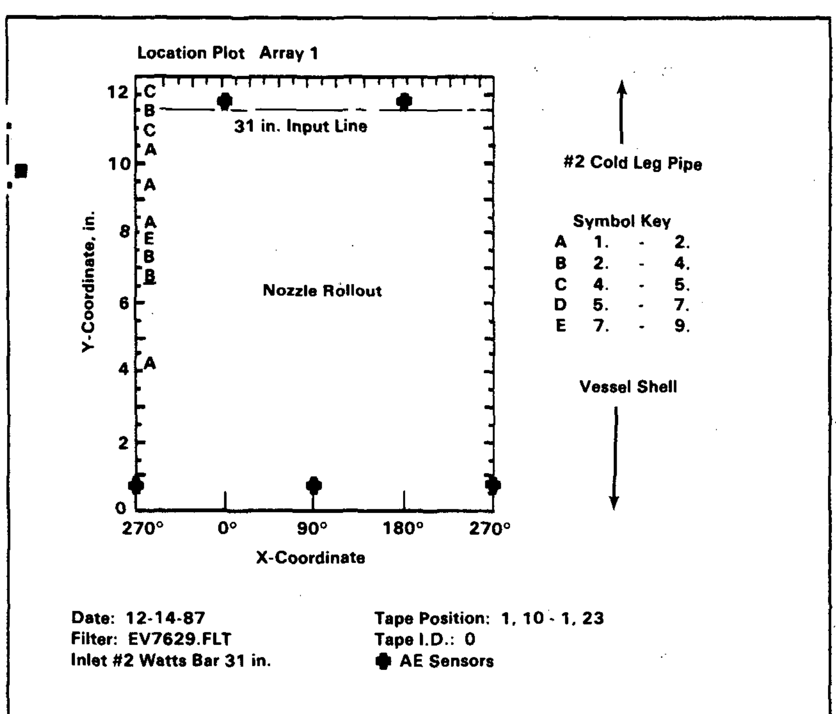


FIGURE 10. Source Location Indications from Inputs at 270° on the 31" Input Line - #2 Inlet Nozzle

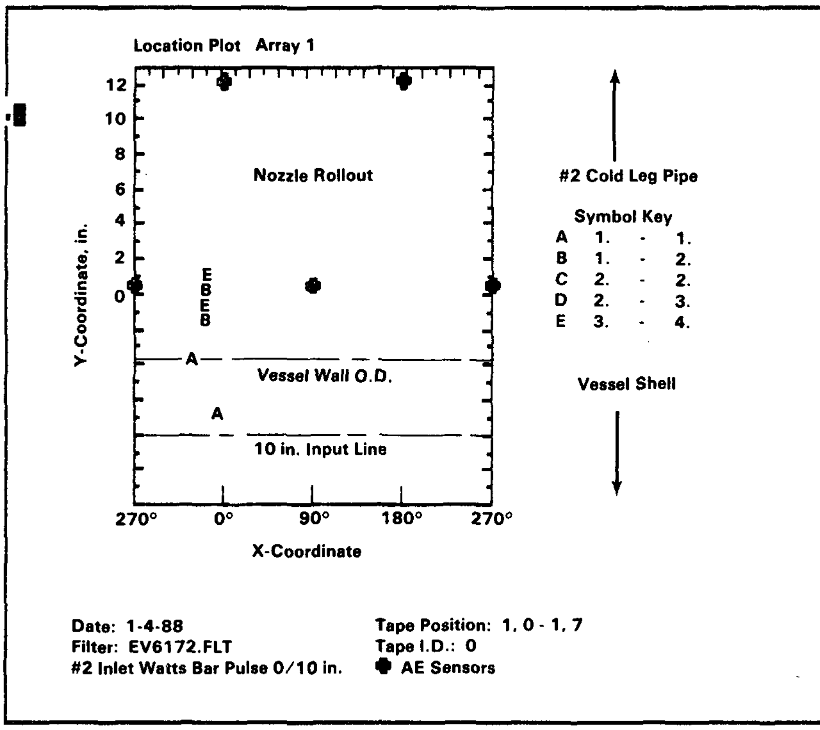


FIGURE 11. Source Location Indications from Inputs at 0° on the 10" Input Line - #2 Inlet Nozzle

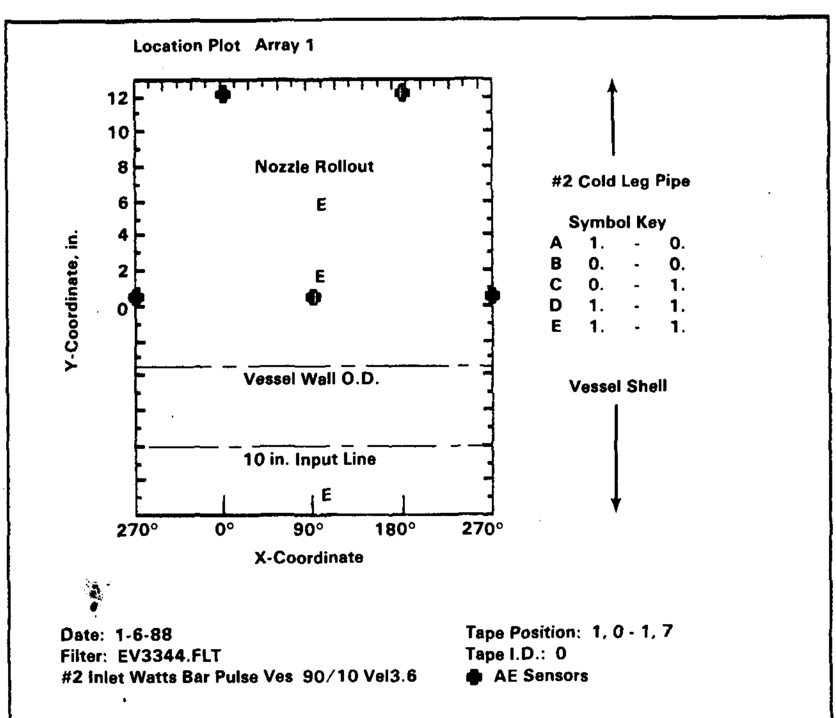


FIGURE 12. Source Location Indications from Inputs at 90° on the 10" Input Line - #2 Inlet Nozzle

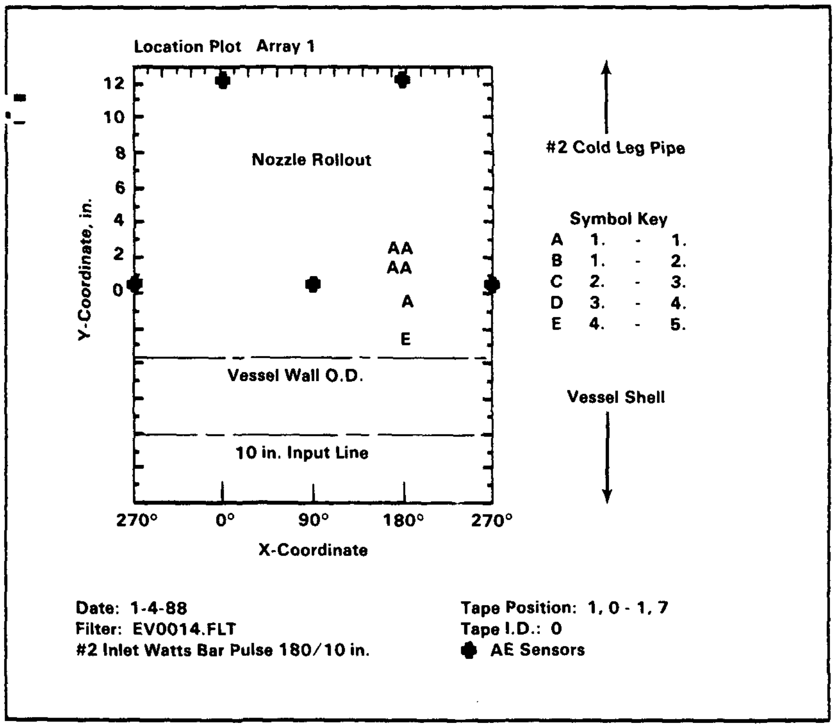


FIGURE 13. Source Location Indications from Inputs at 180° on the 10" Input Line - #2 Inlet Nozzle

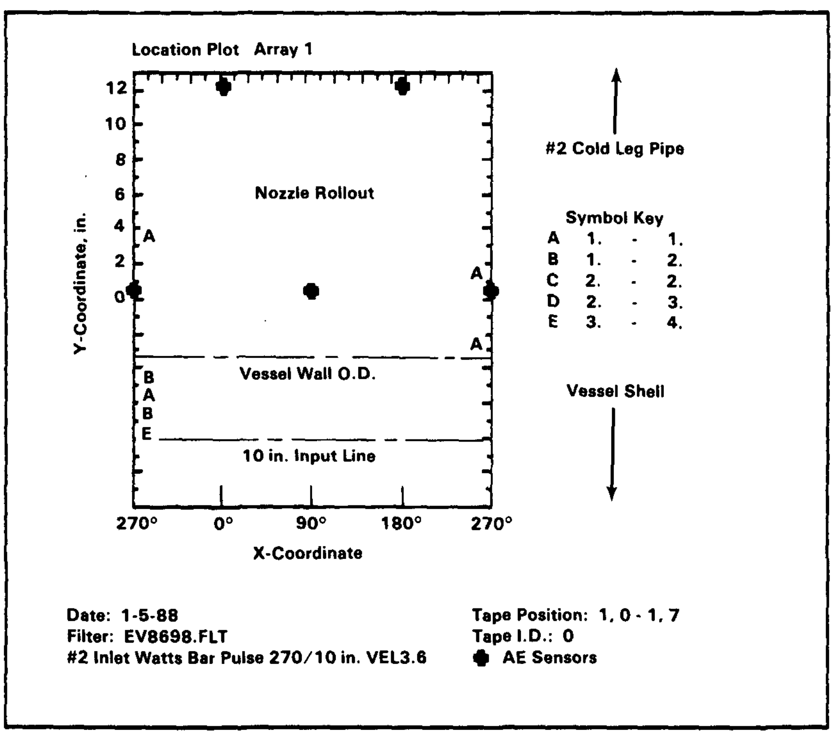


FIGURE 14. Source Location Indications from Inputs at 270° on the 10" Input Line - #2 Inlet Nozzle

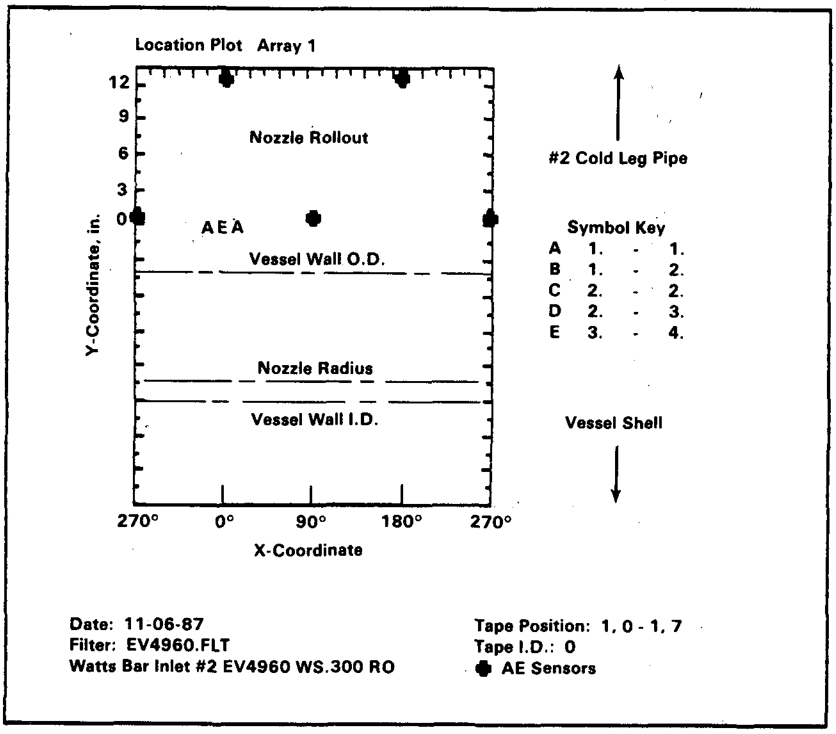


FIGURE 15. Source Location Indications from Inputs at 0° on the Inside Radius - #2 Inlet Nozzle

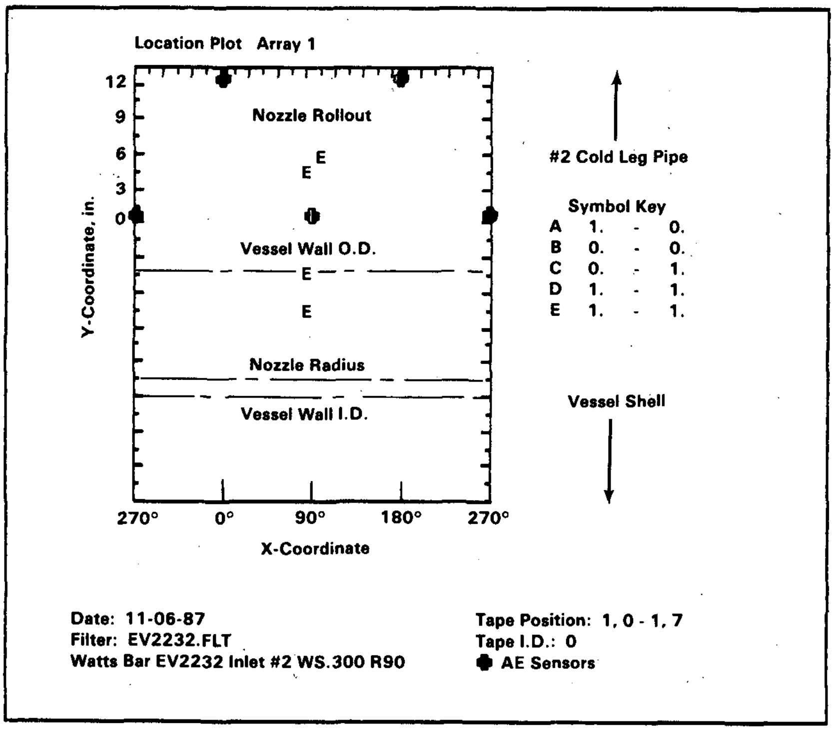


FIGURE 16. Source Location Indications from Inputs at 90° on the Inside Radius - #2 Inlet Nozzle

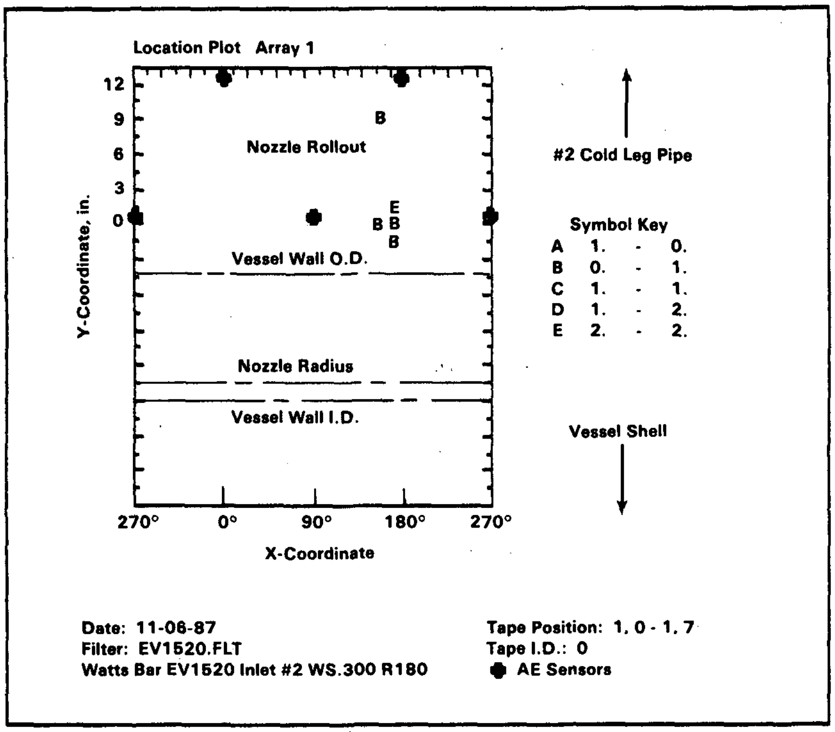


FIGURE 17. Source Location Indications from Inputs at 180° on the Inside Radius - #2 Inlet Nozzle

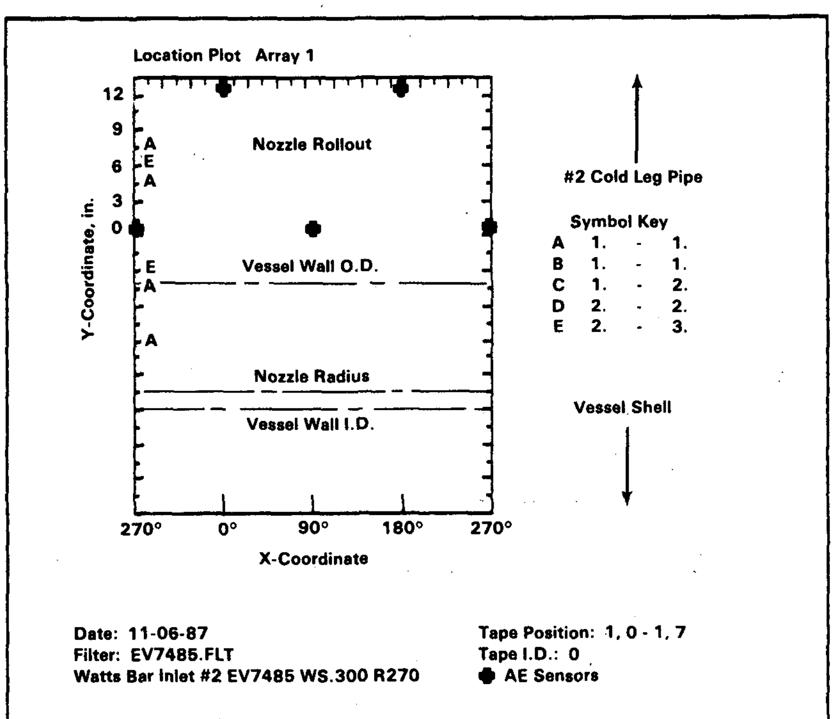


FIGURE 18. Source Location Indications from Inputs at 270° on the Inside Radius - #2 Inlet Nozzle

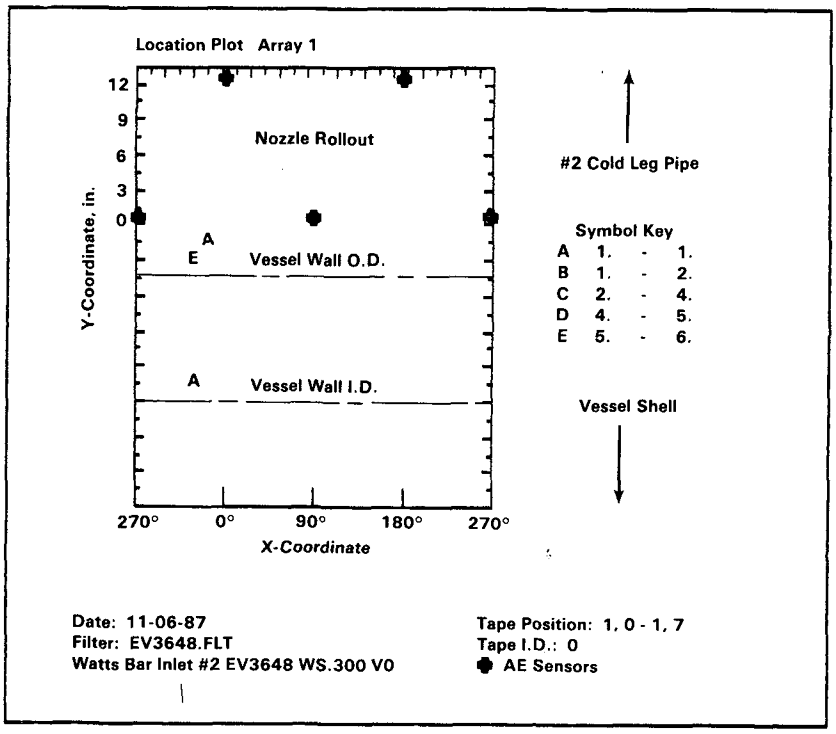


FIGURE 19. Source Location Indications from Inputs at 0° on the Vessel Wall Near #2 Inlet Nozzle

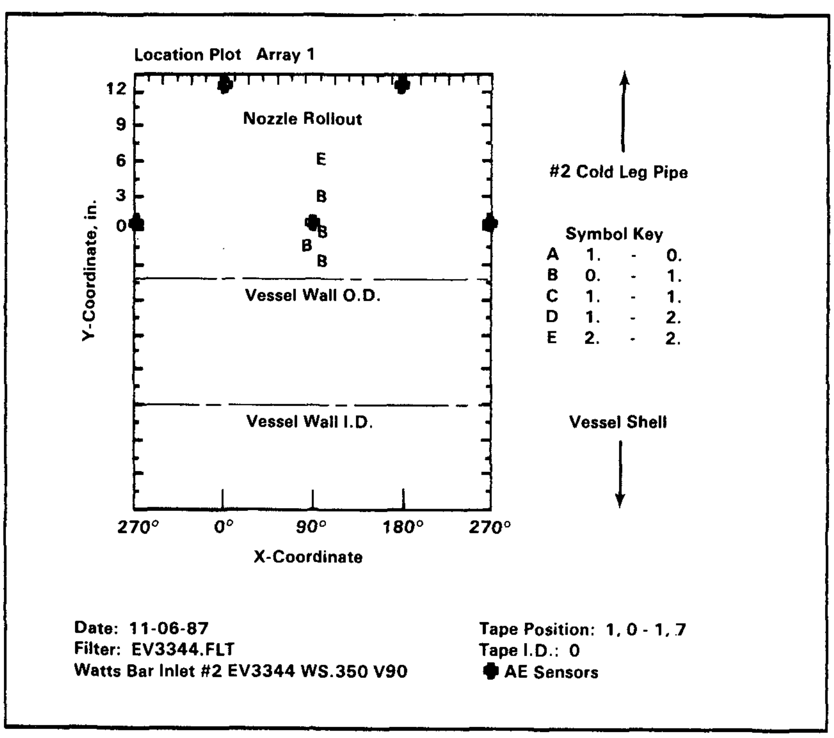


FIGURE 20. Source Location Indications from Inputs at 90° on the Vessel Wall Near #2 Inlet Nozzle

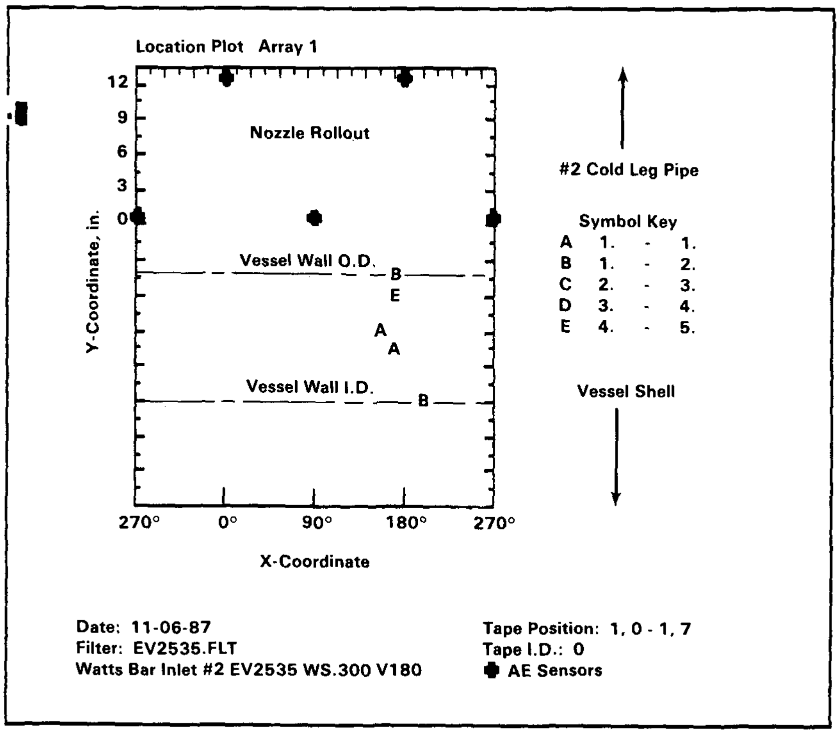


FIGURE 21. Source Location Indications from Inputs at 180° on the Vessel Wall Near #2 Inlet Nozzle

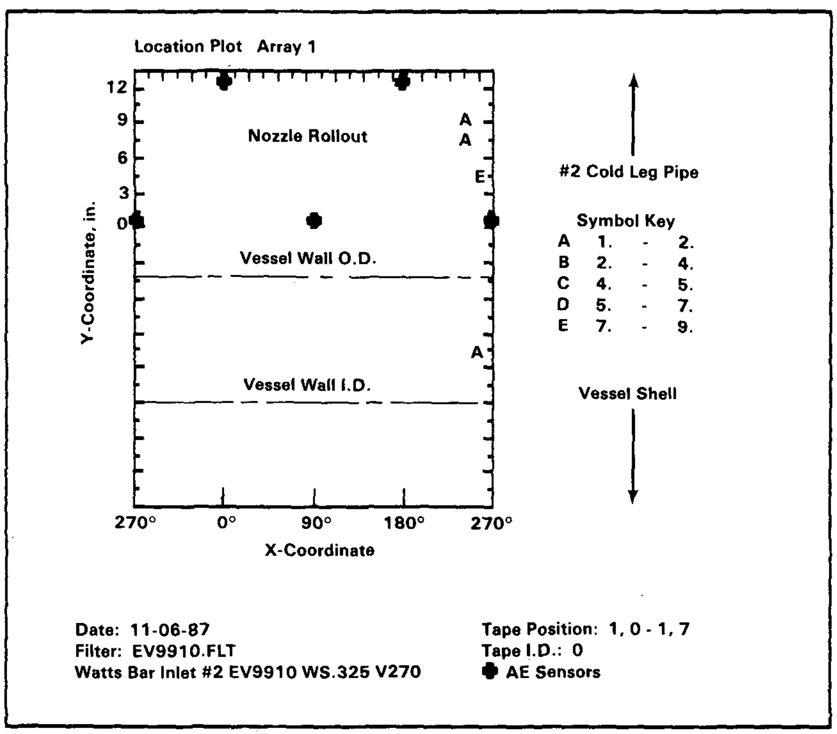


FIGURE 22. Source Location Indications from Inputs at 270° on the Vessel Wall Near #2 Inlet Nozzle

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13. ABSTRACT (200 words or less)

An acoustic emission system has been installed on TVA's Watts Bar Unit 1 reactor to monitor selected areas of the pressure boundary during cold hydrostatic testing, hot functional testing, and ultimately, during reactor startup and operation. The work is part of a cooperative effort between TVA and NRC Research to test and demonstrate AE technology. This technology has been developed under an NRC Research program to validate the application of AE techniques for continuous, on-line monitoring of reactor pressure boundaries to detect cracking. The performance of and results from a special calibration test of the AE system using simulated AE signals to evaluate the accuracy of signal source location by the system is discussed in this report.

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