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ACOUSTIC MONITORING SYSTEMS TESTS
AT INDIAN POINT UNIT 1

FINAL REPORT
(WCAP-9650)

J. R. Smith
G. V. Rao
J. Craig

December 1979

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PREPARED FOR THE

U. S. DEPARTMENT OF ENERGY
DIVISION OF NUCLEAR POWER DEVELOPMENT
UNDER CONTRACT EY-76-C-02-2974

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ABSTRACT

This report describes the results of a program to test acoustic monitoring systems on Indian Point Unit No. 1 under actual plant operating conditions, less the reactor core. The two types of systems evaluated were the monitoring of acoustic emissions generated by growing flaws and the monitoring of acoustic signals from leaks.

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SECTION 1

INTRODUCTION AND SUMMARY

1.1 BACKGROUND

Acoustic monitoring is becoming a valuable inservice inspection technique for evaluation of the structural integrity of pressure vessels and other pressure retaining components, and is expected to be especially useful in commercial nuclear power reactors. Substantial benefits can be realized in nuclear plants by increasing their availability and reducing worker radiation exposures. Both of these benefits can be realized through surveillance systems, such as acoustic monitoring, by reducing unscheduled downtime through the early detection of abnormalities, by allowing improved maintenance scheduling, and by replacing, eliminating, or reducing the frequency and duration of current manual safety and maintenance inspections.

The two types of acoustic monitoring evaluated under the program were the monitoring of acoustic emissions generated by growing flaws and the monitoring of acoustic signals from leaks.

1.1.1 Acoustic Emission Monitoring

Acoustic signals are generated when material undergoes deformation under the influence of mechanical stress. Their origin can be traced back to the fundamental microdeformation processes^[1] such as slip, twinning, and dislocation motion occurring within the individual grains and the grain boundaries that make up the material. The signals are sharp, broadband pulses with a frequency spectrum from audio range to above 50 MHz.

Theoretical predictions and laboratory investigations suggest that acoustic emission from an active flaw bears a direct relationship with the fracture mechanics parameters characterizing the significance of the flaw. The exact nature of the relationship, however, is controlled by the details of plasticity within the crack-tip plastic zone. The results of laboratory studies demonstrate that both acoustic emission total counts and counts per load cycle bear a direct power law relationship with ΔK , the crack driving force, under fatigue loading conditions.

1. J. J. Carter, "Stress Wave Metallography," J. Australian Inst. Metals. Vol. 19, No. 1, pp. 74-87 (March 1974).

In large structures, such as reactor pressure vessels, regions of acoustic emission activity can be located through the use of a moderate number of transducers and some relatively sophisticated system electronics, generally including a minicomputer. The signal processing equipment must measure the relative arrival times of acoustic emission pulses at the sensor sites, and use that information to perform a triangulation operation. Further signal processing can then be included, as desired, to evaluate signal characteristics or grade the activity levels of various source regions.

1.1.2 Leak Monitoring

Leak detection on a reactor is feasible because metal-borne acoustic signals are generated when pressurized water escapes through a metal boundary. These signals can be easily detected using piezoelectric transducers attached to the surface of the various components. For these acoustic signals, the source of energy is the fluctuation in the flow momentum of the fluid. In general, the signal from a leak is wideband and continuous, very much like random noise. With proper selection of frequency passband, detection at a distance can be quite good, while background noise is minimized. An acoustic leak monitoring system is sensitive, response time is fast, and a leak source can be located through processing of the relative strength of its signal at different transducer positions by making use of the signal's attenuation with distance from the source.

The program was carried out in two phases.

1.2 PHASE 1 TEST OBJECTIVES

Phase 1 was designed as an introductory test of acoustic emission and leak monitoring on the reactor so that most of the required installation work could be performed, the monitoring system could be tested under plant operating conditions, and the inevitable bugs could be worked out to ensure the feasibility of proceeding to more extensive Phase 2 tests. Specific objectives of Phase 1 were as follows.

- To verify proper monitoring system operation
- To measure reactor acoustic background noise for all operating conditions
- To investigate reactor vessel acoustic emission generation during heatup
- To test for observability of acoustic emission from two types of fatigue samples at operating temperature
- To conduct preliminary leak detection tests

1.3 PHASE 2 TEST OBJECTIVES

Phase 2 was designed to yield the quantitative data needed to demonstrate the practicability of an online leak monitoring system and to further the development of acoustic emission (flaw growth) monitoring as an online inservice technique. The specific objectives of the Phase 2 test program were as follows.

- To establish the detection of acoustic signals from the initiation and growth of cracks in reactor vessel steel under plant operation conditions
- To evaluate the influence of acoustic signal propagation and attenuation characteristics of the reactor vessel on the crack growth location and characterization capabilities of acoustic monitoring under PWR environment
- To evaluate the influence of crack orientation (with respect to the rolling direction of the pressure vessel steel) on acoustic signal generation
- To evaluate the feasibility of online monitoring of flaw severity by acoustic monitoring, under plant conditions
- To determine the masking effects of pump and flow noise on the leak signals by measuring signal characteristics during operation from leaks in both high-background-noise (cold leg) and low-background-noise (hot leg) areas
- To determine the range of detectability of acoustic signal versus leak rate in both high- and low-background noise areas, calculate the loop attenuation function with distance and investigate any deviations from the expected attenuation, and determine the minimum leak rate magnitudes necessary to meet various possible system detection and location operability requirements
- To compare the acoustic signals emitted from cracked pipe leaks with those emitted from valve leaks for equivalent leak rates. (Recent laboratory results have shown cracked pipe leak signals to be approximately an order of magnitude greater than the signals from orifice-type leaks.)
- To determine the detectability of a second leak in the presence of a pre-existing, but stable, first leak

1.4 SUMMARY OF ACCOMPLISHMENTS

The major accomplishments of Phase 1 were^[1] as follows.

- Dry-couplant attachment of sensors, and placement of all signal amplification outside of containment (150-250 meters away), was achieved without undue sensitivity or electrical noise problems

1. J. R. Smith, M. B. Olex, J. Craig, "Acoustic Monitoring Systems Tests at Indian Point Unit 1, Phase 1 Test Report," (COO-2974-1), WCAP-9324, May 1978.

- The modified pressurization technique during startup, which employed the primary coolant pumps to accomplish heatup but employed the pressurizer for pressurization with pumps off, was quite successful for eliminating all flow noise and thereby facilitating acoustic emission monitoring during most of the pressure increase
- Background noise was measured under a variety of plant conditions; the levels were not excessive at higher pressures and should allow monitoring during normal operation
- During plant startup in Phase 1, several small leaks which occurred in the plant system were detected only by the acoustic monitoring system

Phase 2 was a successful test of both acoustic emission (flaw growth) and leak detection monitoring under conditions equivalent to plant operation. The major accomplishments of this phase were as follows.

- In acoustic emission monitoring
 - (1) The acoustic signals from the growth of cracks under fluctuating loads in reactor vessel steel were successfully detected under PWR conditions without regard to the orientation of the flaw
 - (2) Online location of an active flaw at the pressure boundary was shown to be feasible under plant conditions
 - (3) Significant changes in acoustic emissions were detected with the variation in crack severity. The acoustic emission data collected during stable crack growth region indicate that counts per load cycle and peak count rate during load cycle are viable parameters for the characterization of flaw severity
- In acoustic leak monitoring
 - (1) Small, measured leaks from three different locations around a reactor coolant loop were easily detected, even on the high-noise cold leg
 - (2) Detection of small leaks at a distance was excellent, and the capability was demonstrated for determining leak location based on signal attenuation
 - (3) Both high and low frequency sensors were used in the tests. High frequency sensors were shown to be generally superior for leak detection use, while the low frequency sensors positively identified a minor interference source on the hot leg to be a loose part impacting in the steam generator inlet plenum.

Due to consistent crack clogging, it was not possible to obtain a comparison of signals from cracked pipe leaks with signals from valve leaks.

SECTION 2

THE MONITORING SYSTEM

Key elements in the acoustic monitoring of a nuclear reactor are the sensors, which must be reliable in the high-temperature, high-radiation environment, and which generally must be mounted without the usual ultrasonic couplant grease. In the test at Indian Point Unit 1, the radiation and atmospheric pressure levels were very low, but for normal reactor operation the environment could be 288°C (550°F) at the reactor surface, over 200 r/hr radiation, the containment atmosphere might range up to 100 percent relative humidity, and 5.2 bars (75 psia) pressure (during a containment pressurization test).

Figure 2.1. illustrates the severe environment acoustic emission transducer (sensor) used in this program. It detects acoustic signals by means of a high temperature piezoceramic, and contains an integral electrical matching network designed to be loaded by a 95 ohm non-resonant transmission line. With this construction, the amplifier or preamplifier may be placed as far as 200 m from the transducer. The other end of the transmission line is terminated by the necessary matching impedance in parallel with the stepup transformer of a low-noise amplifier stage.

To couple the sensors to the reactor, a moderate force is supplied by a compression spring in each mounting fixture. The sound-sensitive contact surface of a sensor is less than 3 mm (1/8 in.) in diameter, so that the spring force actually applies a large pressure to the contact face. A dry-mounted sensor is not as sensitive as one coupled by viscous grease; however, the reduction in sensitivity is nominally only a factor of three (9.5 db), which is acceptable in many cases.

Because no welding or machining operations are generally permitted on nuclear pressure vessels, the mounting fixtures for the sensors were magnetically attached to the carbon steel reactor vessel and steam generators. On the stainless-steel main coolant piping, the mounts were attached with stainless-steel bands. Altogether, a total of 25 acoustic emission sensors were employed in Phase 2: 14 on the reactor vessel, 9 on one coolant loop, and 2 on a second coolant loop. Details of their locations and attachment techniques appear in later sections.

Figure 2.1. Acoustic Emission Sensor

The original test plan for Phase 1 called for the amplifiers and other electronics to be located inside the reactor containment on the operating deck, which would have required cabling of about 50 m (150 ft) to each sensor. However, because of the difficulties associated with the radiation exposure and the possibility of equipment contamination, a decision was made to keep all electronics outside containment. Cable lengths to the sensors therefore increased to between 150 and 210 m (480 to 700 ft). Cable runs were made continuous from sensors to amplifiers, however, and no noisy containment penetrations had to be traversed, since the cables were run through the open air lock. It was then possible to successfully place all amplification outside containment, in the motor-generator-set room, together with the other equipment.

Figure 2.2. illustrates the relative frequency response characteristics of a typical sensor, plotted together with the response of a very-wideband reference. Test programs several years ago were responsible for establishing the midband frequency at 500 kHz in order to get the sensitive range above most of the mechanical background noise, but still stay below the frequencies where attenuation of the metals becomes large. In absolute terms, the sensitivity of the sensor at 500 kHz is roughly -90 db referred to 1 volt per microbar.

The operation of the remainder of the acoustic monitoring system is indicated in the block diagram of figure 2.3. The system is designed for online operation; that is, acoustic emission events are located, counted, and displayed as they occur, and the background rms acoustic noise levels are monitored continuously. Operation of the system is as follows.

- Acoustic information is received by sensors whose electrical output signals are transmitted over long lengths of RG-22 B/U or RG-111 A/U twinax cable to the high-gain amplifiers. Each sensor channel is connected to one amplifier/discriminator module which amplifies the signal by 83 db to 103 db and filters it to the 300 kHz-to-700 kHz range. Emission activity is detected by a discriminator circuit which triggers a pulse whenever the output voltage exceeds a certain adjustable threshold.
- The discriminator pulses are used both to define time differences for emission source location computations and to define individual acoustic emission events. The time-difference counters for the various sensor zones are incorporated in the triangulation modules, while each totalizer module contains counters to measure the total number of events detected by each channel. Information from these two modules is processed by a PDP-11 minicomputer, which performs the source location determination, drives a CRT display, and stores source and count data on a cassette for later review and time history analysis.

Figure 2.2. Acoustic Emission Transducer Sensitivity Calibration

Figure 2.3. Block Diagram of the Acoustic Monitoring System

- The system uses what is called a "look-up table" acoustic emission source location technique. Time difference information is precomputed on a larger computer and simply stored in the online computer's memory. The structure being monitored is therefore divided into a large number of resolution elements, but there is no problem selecting element sizes comparable to the maximum accuracy obtainable because of wall thickness and wave propagation considerations. In fact, the computer algorithm used has a number of strong advantages: the program for operation in real time is much simpler, but more importantly, much faster than a direct computation technique; it is possible to monitor structures of varying geometry (e.g., spherical, cylindrical, conical, and combinations) without any loss of accuracy, while allowing the sensors to be placed in almost any configuration (i.e., no special zone pattern); and a significant degree of validation testing can be done on the incoming time-difference information.
- To detect and locate the sources of leak signals, the amplifier outputs are monitored directly for their rms acoustic noise levels by either a true rms voltmeter or a special microprocessor-based module. The microprocessor module first determines if an increase in the noise level on one or more channels is abnormal, based on past variations, and then locates the position of the detected leak by exploiting the known attenuation characteristics of the reactor system.

A photo of the acoustic monitoring system equipment used at Indian Point Unit 1 is shown in figure 2.4. Appendix A gives additional information on the major components of the system.

Figure 2.4. Acoustic Monitoring System

SECTION 3

CRACK GROWTH DETECTION AND LOCATION

3.1 GENERAL

A total of four fracture mechanics specimens, fabricated from a reactor vessel nozzle cutout (A533-B, Class I plate material), and welded integral with the vessel closure head were employed for the acoustic monitoring tests.

Two of these were notched cantilever beam specimens (figure 3.1. and appendix B) fabricated so that their crack propagation directions were parallel and perpendicular respectively to the nozzle shell rolling direction. The location of the test specimens within the nozzle cutout and their orientation in relation to the rolling direction is illustrated in figure 3.2. As shown in the figure 3.2. cantilever 1 is machined from Plate B while cantilever 2 is machined from Plate A. The other two specimens employed for crack growth monitoring tests are the two-inch thick WOL specimens (figure 3.3.) taken from 1/4 T location of the nozzle cutout section. A complete listing of the history of the plate material including chemistry, heat treatment, and mechanical properties is given in appendix B.

All the specimens were mounted on the vessel closure head lifting lugs by fillet welding and were fatigue cycled (Mode I loading) to examine the acoustic emission behavior of the cracks (figure 3.3.). Details of the specimen geometry and head lug-to-specimen joints are illustrated in appendix B.

Figure 3.4. illustrates the top view of the vessel closure head with the four specimens in the weld-mounted position on the head lugs.

Detection of acoustic signals from the specimens was achieved by an array of five transducers suitably located on the vessel head. Figure 3.5. shows the positioning of the transducers. Following the installation of the transducers, a relative check of their sensitivities was performed by injecting acoustic emission signals through each of the sensors in turn, while receiving the signals through the other four channels.

In addition to the monitoring of flaw growth in test specimens, the acoustic emission testing also included monitoring of acoustic emissions from the reactor vessel during plant heatup. A modified plant heatup method was employed to gain maximum signal-to-noise ratio. The results are considered in later sections.

Figure 3.2. Location and Orientation of the Two Cantilever Beam Specimens Fabricated From a Reactor Vessel Nozzle Cutout

RELATIVE DIMENSIONS

$$\begin{aligned} W &= 2.55B \\ a &= 1.0B \\ H &= 1.24B \\ B &= 0.70B \\ W_1 &= 3.20B \\ T &= 0.625B \end{aligned}$$

**WOL TYPE COMPACT FRACTURE TOUGHNESS SPECIMEN
(RELATIVE DIMENSIONS IN TERMS OF THICKNESS B)**

a crack length (in.) at the time of onset of crack instability

B specimen thickness (in.)

W specimen width (center line of loading to back edge)

Figure 3.3. Specimen Geometry and K-Calibration Curve for WOL Type Compact Tension Specimen

- A: BASE METAL WOL
- B: WELD HAZ WOL
- C: BASE METAL CANTILEVER NO. 1
- D: BASE METAL CANTILEVER NO. 2

Figure 3.4. Top View of the Closure Head Showing Locations of Various Test Specimens

Figure 3.5. Indian Point Unit 1 Reactor Top Head

3.2 SPECIMEN LOADING CONSIDERATIONS

All the specimens were tension-tension cyclic loaded with remotely controlled hydraulic units. The hydraulic loading unit was directly mounted on the WOL specimen so that the loading plunger made direct contact with the lower face of the specimen; while for the cantilever specimen, the plunger unit was placed on the operating deck directly above the specimen and the loading was transmitted through a rigid bar link system. The hydraulic load control units for both the specimens were placed on the operating deck. The units, however, could be actuated from the instrumentation room outside the containment, where the electronics of the acoustic emission monitoring system were situated.

A photographic display of the overview of the vessel top head as seen from the operating deck is shown in figure 3.6. while closeup views of the loading setups for WOL and cantilever specimens are illustrated in figures 3.7. and 3.8. Figure 3.9. is a view of the hydraulic loading and control systems located on the operating deck.

Loading of the specimens was maintained so that a starting ΔK of about $17.58 \text{ MPa} \sqrt{\text{m}}$ ($16 \text{ ksi} \sqrt{\text{in.}}$) was imposed on the crack at an R value ($P_{\text{max}}/P_{\text{min}}$) of 0.1, where ΔK is the stress intensity factor range defined as the difference between the maximum and minimum values of crack-tip stress intensity factor, K. The strains at the crack tip were monitored initially during loading by employing strain gage rosettes mounted on either side of the specimens at the crack front locations. This was to ensure that the loading was axially symmetric, and Mode I type of loading was applied at the crack front. Figures 3.1. and 3.2. illustrate the specimen geometry and K-calibration curves under a given loading, for cantilever and WOL specimens, respectively.

3.3 REACTOR VESSEL ACOUSTIC EMISSION MONITORING

Monitoring of the reactor pressure vessel for acoustic emissions during plant heatup was conducted by employing a modified heatup procedure that would greatly increase the available signal-to-noise ratio. The test procedure was similar to the one employed in the Phase 1 program with the exception that a liquid couplant was employed to couple the transducers to the vessel surface for increased sensitivity of detection. The testing was carried out by employing a total of 14 sensors mounted on the reactor vessel. The locations of those on the main shell were dictated by accessibility, as only the top flange and a small area on the bottom were open and reachable. A total of eight sensors were placed on the flange, as a linear array of six with two slightly offset, while one sensor was placed on the bottom. The top head of the reactor was completely open, however; five sensors were placed there in a convenient pattern. These sensors were spaced as far apart as possible but kept on line-of-sight with each other for ease of pulser testing. A sketch of the reactor vessel showing sensor locations is shown in figure 3.10.

Figure 3.6. Vessel Head as Seen From the Operating Deck

Figure 3.7. Loading Setup for the WOL Specimen Showing the Positions of Crack Opening Gage, Lug-Mounted Transducer, and the TV Camera

Figure 3.8. Loading Setup for the Cantilever Specimen Showing the Positions of Clip Gage (Crack Opening Gage), AE Transducer and the TV Camera

Figure 3.9. Hydraulic Plunger Unit (Front) Employed for the Loading of the Cantilever Specimen. Also Shown are the Hydraulic Pump (Shown on the Left) and the Load Control (Shown on the Right) Units.

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Figure 3.10. Indian Point Unit 1 Reactor Vessel

The heatup procedure was begun by turning the four primary coolant pumps of the two available coolant loops to provide about 5 Mw of frictional heating power. Primary system temperature and pressure were allowed to gradually increase until conditions of 213°C (415°F) and 41 bars (600 psig) were reached. As had been expected, the general noise levels at this point were still rather large (see figure 4.11.).

The primary coolant pumps were turned off at that point, and the pressurization continued by means of the pressurizer alone. The reactor vessel could then be monitored for acoustic emission generation during most of the pressure escalation without any interference from flow noise. The 480 kw pressurizer heater banks were able to pressurize the system to 103 bars (1500 psig) in about two hours, with little drop in temperature. An approximate plot of the temperature-pressure heatup curve that was followed in this test is illustrated in figure 3.11. The solid curves in the figure define the heatup bandwidth limits which must not be exceeded.

Very little acoustic emission activity was observed from the reactor vessel during this pressurization. The results are very similar to the Phase 1 testing even though a liquid couplant was employed in Phase 2 testing for increased sensitivity of detection.

3.4 FATIGUE SPECIMEN AND TEST PROCEDURE AND DATA COLLECTION

The details of the acoustic emission monitoring system utilized for the source location of cracks are dealt with in a separate section of this report. Acoustic emission signal parameters were online monitored for each of the specimens from channels closest to the specimen of interest. Specifically, acoustic emission counts per load cycle and peak count rate during load cycle were continuously monitored during stable crack growth while the signal amplitudes were visually monitored on a four-channel storage oscilloscope. The decision on the monitoring of counts per cycle and count rate was based on the results of a laboratory development program^[1] jointly sponsored by the Empire State Electric Energy Research Corporation (ESEERCO) and Westinghouse which demonstrated that both these parameters bear a direct power law relationship with ΔK , the crack driving force. During selected periods of active crack growth, raw acoustic emission signals were also recorded on tape for off-line data analysis.

Acoustic monitoring of the fatigue crack growth was conducted on each of the specimens successively, as follows.

- All through the test period, the crack length in each of the specimens was monitored in two ways:

1. G. V. Rao, "Development of Acoustic Emission Interpretational Techniques for Pressure Boundary Integrity Monitoring," WCAP-9462, 1979.

Figure 3.11. Primary Coolant System Heatup Procedure for Indian Point Unit 1

- (1) By monitoring the output of a precalibrated crack opening displacement gage (clip gage) mounted on the opening face of the specimen, and
 - (2) By monitoring the vernier reading viewed through a remote TV camera on a scale mounted along the crack length on the side of the specimen.
- Acoustic emission counts per load cycle and peak count rate during load cycle as a function of crack length were carefully monitored during the stable crack growth region. Changes in the peak amplitude of signals were closely followed by visual examination of channel outputs on the oscilloscope.
- Care was taken to see if crack initiation and growth could be detected, in the earlier stages of loading, by acoustic monitoring.
- The output of the clip gage and acoustic emission data were simultaneously recorded so that an online, one-to-one correlation could be made.
- Acoustic emission data from at least two channels (one close to the crack and one on the vessel head, away from the crack) were closely followed for characterization purposes during crack growth monitoring, while the output from at least three channels was utilized for the source location purposes.

The instrumentation utilized in the monitoring of acoustic emission signal parameters during crack growth is shown in figure 3.12.

3.5 WOL SPECIMEN TEST RESULTS

Acoustic emission signals were clearly detected by all of the five head channels during crack growth. In the earlier stages of loading, crack initiation was accompanied by low amplitude bursts shown in figure 3.13. As the crack length increased, the signal amplitude increased resulting in higher acoustic emission counts per cycle. As the crack length exceeded 1.2 inches, some of the acoustic emission signal peaks were clipped, indicating saturation of the amplifier.

Figure 3.14. shows the oscilloscope traces of acoustic emission signals detected at two different crack lengths and the corresponding TV monitor display pictures of the WOL specimen. TV monitor display of progressively growing cracks at three different load cycles is illustrated in figure 3.15. Test data on counts per load cycle and crack length at various load cycles are tabulated in table 3.1. A graphical plot of these results is also illustrated in figure 3.16.

Figure 3.12. Instrumentation Setup Utilized for the Acoustic Monitoring of the Growth in the Cantilever and WOL Specimens

Figure 3.13. AE Signals Generated During Crack Initiation in the WOL Specimen

Crack Length $\approx$ 10 Inches (TV Monitor)

Crack Length at 14 Inches

Figure 3-14. Oscilloscope Traces of AE Signals (Bottom Row) Recorded at Two Different Crack Lengths (Shown on TV Monitor Display Pictures in the Top Row) for the WOL Specimens

← Crack at 136,000 Load Cycles
(2/5/79 11:45 am)

← Crack at 148,000 Load Cycles
(2/5/79 3:00 pm)

↓ Crack at 156,000 Load Cycles
(2/5/79 6:00 pm)

Figure 3.15. TV Monitor Displays of Growing Crack in the WOL Specimen Shown After Various Load Cycles

TABLE 3.1
TEST DATA FROM WOL SPECIMEN

Load Cycles x 10 ³ (n)	Crack Length (Inches) (a)	AE Counts Per Cycle (dN/dn)	Peak AE Count During Load Cycle (dN/dt)
0.0	0.375	128.0	---
28.8	---	---	0.9
36.0	---	90.0	1.05
68.4	1.125	160.0	1.1
79.2	1.187	100.0	1.4
88.2	1.25	105.0	1.8
96.3	---	106.5	1.78
108.0	1.25	174.0	---
126.0	---	134.0	2.2
133.2	1.43	---	2.4
147.6	1.65	142.0	2.0
156.4	1.75	177.0	3.0

Figure 3.16. AE Counts per Load Cycle, Peak AE Count Rate During Load Cycle and Crack Length Plotted as a Function of Load Cycles for the WOL Specimen

The source location for the crack growth in the WOL specimen was quite successful since all five channels on the vessel head clearly detected signals from crack growth. Figures 3.17. and 3.18. show the top view display of the triangulation of crack signals at two different times of active flaw growth in the WOL specimen. The side view (elevation) is shown in figure 3.19.

3.6 CANTILEVER SPECIMEN TEST RESULTS

Stable crack growth region in a cantilever specimen is quite limited and, for this reason, the duration of acoustic signal generation and its detection was relatively small prior to rupture of the specimen. Signals from the cantilever were generally lower in amplitude and longer in duration, perhaps due to the longer signal path which also contained two weld interfaces. Source location was successfully achieved only during intermittent periods of time when the signals were strong enough to be detected by three or more transducers. Figure 3.20. shows the display of the source location for both cantilever and WOL specimens, during a period when both specimens were simultaneously loaded. The corresponding TV monitor display of the crack length in the cantilever specimen is shown in figure 3.21. The shorter range of stable crack growth region and poor image resolution of the crack-tip region have made it difficult to closely monitor the crack growth data from the cantilever specimen. The counts-per-load-cycle are observed to be significantly lower as compared to the WOL specimen under similar loading conditions.

3.7 EVALUATION OF RESULTS

The results obtained from the acoustic monitoring of crack growth in both WOL and cantilever specimens clearly demonstrate that detection of crack growth under plant conditions is quite feasible, and that source location can be successfully achieved by suitably locating sensors. Evaluating the signal path in choosing sensor locations could be a significant factor to ensure successful source locations, as was demonstrated by signals from cantilever specimens.

Test data from the WOL specimen provided extremely useful information both during initial and final stages of flaw growth. The larger stable crack growth region in the WOL (as compared to the cantilever) specimen certainly made it possible to collect enough quantitative data so that feasibility for the detection and location of signals from the crack source as well as characterization of crack growth can be established. The data suggest that detection of crack growth at incipient stages is quite feasible under plant operating conditions. This can be clearly seen in figures 3.13. and 3.14. The signal strengths are adequate to achieve successful online source location. This is clearly illustrated in figures 3.17. through 3.20. The successful location of the two crack sources (WOL and cantilever

Figure 3.17. Source Location Display for WOL Specimen

TRIANGULATION ON
SIGNALS FROM CRACK
GROWTH IN WOL SPECIMEN

Figure 3.18. Source Location Display for the WOL Specimen

TRIANGULATION ON SIGNALS
FROM CRACK GROWTH
CANTILEVER SPECIMEN

VESSEL SIDE VIEW

Figure 3.19. Vessel Side View Source Location Display for Cantilever Specimen

Figure 3.20. Source Location Display During Crack Growth in Cantilever and WOL Specimens

Figure 3.21. TV Monitor Display of Growing Crack in the Cantilever Specimen (Crack Length 0.875 Inches)

specimens) when they were activated simultaneously (shown in figure 3.20.) provides a positive confirmation that detection of simultaneous multiple sources in neighboring zones should not pose a significant problem. The quantitative information on acoustic emission counts per load cycle, peak count rate during load cycle, and crack length (table 3.1 and figure 3.16.) shows that the parameters bear a direct relationship with the crack growth severity. The test data illustrated graphically in figure 3.16. shows that both counts per cycle and peak count rate during cycle progressively increases with the crack length and load cycles in agreement with the laboratory-established test results.^[1] Examination of the test data suggests that peak count rate during a load cycle (transient) could be a more meaningful parameter to measure crack severity.

1. G. V. Rao, "Development of Acoustic Emission Interpretational Techniques for Pressure Boundary Integrity Monitoring Final Report," ESEERCO - Westinghouse EP6-2 Report, WCAP-9462, August 1979.

SECTION 4

LEAK DETECTION TESTS

4.1 GENERAL

The leak detection tests of Phase 2 were similar in nature to those that had been conducted in Phase 1, but were quantitative and much more extensive. Basically, the experiment entailed welding onto one primary coolant loop three leak source devices, together with the instrumenting of that loop with acoustic emission (AE) sensors and accelerometers. Upon heatup of the reactor to operating conditions and energizing of the artificial leaks, the resulting acoustic signals could be correlated with leak rates and source positions. To give a complete picture of the efficacy of the AE instrumentation the related measurements of background noise characteristics, response of the lower frequency accelerometers to the leaks, and the effects of pressure and temperature on the signal were also needed.

A schematic diagram of the primary coolant loop that was used in the experiment is illustrated in figure 4.1. Because this reactor was a very early power plant design, the coolant loops are quite different from those of later generation plants. The steam generators on this plant are both horizontal and U-shaped, with a completely separate steam drum; there are two primary coolant pumps (the canned motor type with the motor rotor immersed in the primary coolant) operating in parallel in each loop; and the reactor vessel inlet piping enters the vessel at the bottom rather than the top.

As shown on the diagram, a total of nine AE sensors and four accelerometers were used to monitor the loop: four AE sensors and two accelerometers on the reactor vessel outlet piping or hot leg, and five AE sensors and two accelerometers on the reactor vessel inlet piping, or cold leg. The three attachment points of the leak sources are also shown: one was attached to the cold leg, one to the hot leg, and one to the steam generator inlet plenum.

The locations of the leak sources were determined partly by experimental considerations and partly by feasibility. Since the reactor, though shutdown, could eventually be put back into service, no modifications could be made on the major piping. There were a number of small pipes connecting to the main piping which could be modified on the far side of isolation valves, but since system sensitivity determination was an important part of the

Figure 4.1. Acoustic Sensor Locations: Loop 12

experiment, the leak sources had to be as close to the main piping as possible. And, of course, at least one leak source had to be on the high-noise area of the cold leg, near the primary coolant pumps. Careful examination of the primary coolant system yielded finally what were by far the best three sites for leak source attachment — sites which had conveniently-sized (small), thick-wall piping connected to the main loop piping with only very short distances to isolation valves.

For the cold leg leak source, attachment was made to the drain line off of the bypass line around the cold leg loop isolation valve, and this source is illustrated in figure 4.2. The large main coolant pipe is hidden behind insulation, as is the bypass line, but basically a tee-connector next to the main coolant pipe splits into the bypass line and a drain line. The 2.5 cm (1 in.) Schedule 160 drain line exits from under the insulation after a short distance, and at that point the manually operated isolation valve can be seen. Immediately following the valve is where the drain line was cut to allow insertion of the leak source.

The cold leg leak source itself was composed of two sections. One section contained a 2.5 cm (1 in.) solenoid valve for fully-opened/fully-closed operation, while the other section contained a variable-opening air-operated valve in a 1 cm (0.5 inch) pipe. Both sections exhausted into a 100 liter (30 gallon) size steel drum, where leakage would be condensed and collected for measurement.

The leak source therefore possessed two modes of operation: the solenoid valve could be opened and then a leak created by manually opening the isolation valve as required, or the isolation valve could be opened wide (with the solenoid valve closed) and a leak created by control of the air-operated valve. Putting the leak point at the isolation valve had the advantage of relatively close proximity to the main coolant pipe, while the air-operated valve had the advantage of remote controllability.

The hot leg leak source, illustrated in figure 4.3., was quite similar to the cold leg leak source. In this case, the drain line on the hot leg loop isolation valve bypass contained two manual valves rather than one, and the leak source apparatus contained an extra pipe section. The extra section was a pipe containing a fatigue-generated crack which was to be used for comparison of the acoustic signals from a crack leak source versus those from the valve leaks.

The third leak source was also attached to the hot leg side of the loop, but onto the steam generator inlet plenum vent pipe, roughly 4 m (12 ft) from the other hot leg leak source. This source is illustrated in figure 4.4. Attached immediately following the vent line shutoff valve, that leak source contained two sections, one of which had a manually-operated needle valve and the other a piece of cracked pipe. Further detailed information on this and the other leak sources, condenser data, and loop piping dimensions are provided in appendix C.

Figure 4.2. Cold Leg Leak Source

Figure 4.3. Hot Leg Leak Source

Near the bottom of figure 4.4. can be seen AE sensor channel 20, which was magnetically mounted to the carbon steel steam generator head. This sensor and channel 22 were the only loop sensors to be magnetically mounted, since the piping was type 304 stainless steel and required clamp-on type mounts. Figure 4.5. illustrates a typical pipe-mounted sensor installation, in this case AE sensor channel 19 and accelerometer A19, both mounted close to the steam generator.

In no case was ultrasonic couplant material used at the interface between a loop sensor and the piping. Past experience has indicated that such materials either would not be permitted on stainless steel piping, due to the presence of chlorides or other contaminants in the materials, or else such materials themselves normally degrade over time. At each sensor location the pipe surface was cleaned and smoothed, but then acoustic coupling was made by pressure contact alone.

4.2 CALIBRATION

Following installation of the AE sensors, a calibration operation was performed to verify their sensitivities for use in leak detection and location. Especially with only pressure contact coupling of the sensors to the pipe surfaces, significant variations in coupling efficiency were expected. Past experience had shown that the difference in sensitivity between the most sensitive sensor and the least sensitive sensor under these conditions could be as large a factor as ten-to-one. This is in direct contrast to the case when ultrasonic couplant grease is used at the interface, for it not only improves the nominal sensitivity of the sensor by a factor of three but also reduces the most sensitive to least sensitive sensor difference to perhaps a factor of two-to-one.

The calibration operation was carried out by placing another transducer at a fixed distance from each sensor, approximately 10 cm (4 inches), coupling it to the pipe by high-viscosity ultrasonic couplant grease, driving it with a known level of random noise, and measuring the rms output voltage from the receiving sensor. This operation was performed with each of two types of driven sensor: first a flat response, low sensitivity lithium sulfate driver, and then a standard AE sensor driver for comparison. While the flat response transmitter should provide a more reliable calibration, general transmission/reception at a distance such as leak simulation must be done with AE sensors because of their much greater output.

Figure 4.4. Steam Generator Leak Source

Figure 4.5. AE Sensor Channel 19 and Accelerometer A19,
Near Steam Generator Inlet

The data from this experiment are presented in figure 4.6. Agreement between the two types of driver is not bad for the cold leg sensors (channels 22-26), but there definitely is some mismatch on the hot leg sensors. Relative sensitivities of all of the AE sensors do appear to be quite reasonable, though. Those channels which indicated lower sensitivity tended to be on pipe sections with relatively poor surface conditions, while the highest sensitivity sensor was on a quite smooth, bright finished pipe section.

No attempt was made to resolve the differences between the two measurements. Although simple in principle, calibration turned out to be one of the most difficult problems of the test. The reason for this was not primarily the acoustics, though, but rather the ionizing radiation. Because the calibration operation required an experimenter to be in extremely close proximity to the main coolant pipe for several minutes at each sensor location, even for the quick technique performed here, the radiation exposure rapidly accumulated and could not be afforded if the whole test program was to be completed. A more rigorous calibration using an acoustic transducer transmitter would actually require a standard transmitter/receiver pair and proper surface preparation to guarantee the coupling of the transmitter. But in the radiation environment encountered, such a technique becomes much less feasible. What might be a useful method, requiring much less time and possibly no surface preparation, would be to use an air or gas jet impinging on the pipe as a random noise signal source, as some experimenters have reported.

4.3 LEAK SIMULATION TESTS

As noted in the calibration section, the ultrasonic transducers (sensors) used in this test are efficient and sensitive enough that they can be used not only for receiving, but also for generating acoustic signals.

For example, when dealing with acoustic emission crack growth detection much of the monitoring system checkout involves driving transducers with sharp voltage spikes. By detecting the propagated acoustic bursts, the transit time, sonic velocity, or distance can be measured, together with attenuation and the accuracy of the AE source triangulation function. On stainless steel piping, transmission characteristics are usually too poor to propagate a burst acoustic signal any appreciable distance, but a continuous input which allows superposition of multipath acoustic signals at the receiving sensors can quite easily be monitored.

Great care must be taken in the case of continuous transmission, though, to avoid any electrical noise injection into the receiving sensor electronics. While the received signals from pulse transmission can be discriminated from electrical noise by the propagation delay, that is not possible for continuous signals. It was, in fact, necessary to take the signal

Figure 4.6. Loop 12 AE Sensor Relative Sensitivities

generating equipment inside containment, close to the drive point, to do such transmission in this test program, because most sensor cabling ran the distance between containment and the monitoring system in a tight bundle. Crosstalk was not overpowering, but was definitely significant for signals strong enough to be detected 10m (30 ft) away.

A basic desire in leak simulation testing, of course, is to have the signals injected into the pipe be representative of the signals that would result from an actual leak. If such is the case, the overall piping system can be easily characterized and the response to leaks at various locations can be much more accurately predicted. Past experience has many times indicated that a good continuous drive signal to use for leak simulation is gaussian white (random) noise. Actual leaks from many different types of sources have been shown to have an essentially flat frequency spectrum in the band of interest here (300-700 kHz), and the acoustic wave propagation from a point-source, surface-mounted transducer has been shown to be very similar to signal propagation from a leak.

In this test leak signals were simulated from each of the three leak source locations while the reactor was still at cold conditions, following the calibration experiments, to allow later comparison against the actual leak signals. An AE sensor was mounted successively on the 2.5 cm (1 inch) diameter piping of each leak source device, coupled to the surface with water-soluble ultrasonic couplant, and driven with the signal from a wideband random noise generator fed through a 50 db power amplifier (ENI Model 240L). The results are shown in figures 4.7. through 4.10.

Figure 4.7. illustrates the raw signal data from the leak simulation performed at the cold leg leak source. Three signal input levels: 10 mv, 30 mv, and 60 mv. rms, were used for this and all other leak simulations. The quiescent background level shown was roughly equal at all sensors, since it was only the basic electronic noise present with amplifier gains of 103 db. The relative responses at different distances can readily be seen from the shape of the plots. Note that the sensor closest to the signal source did not quite give the largest output. When the output values are adjusted based on the calibrated sensitivities of the sensors, however, as shown in figure 4.8., the shape of the curves changes significantly, since two cold leg sensors were so much more sensitive than the others. The adjusted curves indicate the source position quite well.

Similar data for leak simulation at the hot leg leak source and the steam generator leak source as monitored by the hot leg sensors are shown in figures 4.9. and 4.10. In each case, the source position is clearly indicated by the maxima and shapes of the data curves. Only the raw signal data is illustrated for these sensors, though, since their calibration data was somewhat ambiguous. All three source simulations should also be directly comparable against each other here, since the same drive sensor was used at each location together with viscous grease coupling.

Figure 4.7. Leak Simulation at Cold Leg Leak Source —
Raw Signal Data. Amplifier Gains All Set to 103 db

Figure 4.8. Leak Simulation at Cold Leg Leak Source — Data Adjusted for Relative Sensitivities

Figure 4.9. Leak Simulation at Hot Leg Leak Source — Raw Signal Data. Amplifier Gains All 103 db

Figure 4.10. Leak Simulation at Steam Generator Leak
Source — Raw Signal Data

4.4 BACKGROUND NOISE MEASUREMENTS

Mechanical background noise, which can play an important role in almost any on-line acoustic monitoring setup, is usually the main factor in sensitivity limitations and various other problems, especially if it changes over time and operating conditions. Experience has shown that the primary coolant pumps are by far the major noise sources on the reactor coolant system, and the resulting background noise is very much a function of the temperature and pressure of the water. In this test, therefore, the levels of background noise were monitored closely from the beginning of plant heatup right on through plant cooldown.

Figure 4.11. illustrates the background noise measurements that were made during the plant heatup, as the reactor was brought from room temperature and 17 bars (250 psig) pressure to over 200°C (400°F) and the operating pressure of 105.9 bars (1535 psig). The measurements shown agree in general with previous measurements on other plants. At first pump turnon, the noise levels on the cold leg were tremendous. As temperature and pressure gradually increased, however, the noise levels steadily fell. At 218°C (425°F) and 33.1 bars (480 psig), the noise levels were only about one-twentieth of their original four-pump values. As pressure was further increased to 105.9 bars (1535 psig), at essentially constant temperature, the noise levels decreased again by roughly a factor of five to yield total noise levels that were only a hundredth of their original four-pump values.

On this reactor these factors only held for the cold leg sensors, though. Since both the steam generator and cold-leg/reactor-vessel acoustic paths were extremely long (as compared with later model reactors), the hot leg sensors saw only a fraction of the noise levels of the cold leg. At operating conditions, the hot leg noise was almost down to the electronic background.

A second interesting result obtained from the noise measurements was the variation in noise level with the number of operating coolant pumps. Each primary loop had two coolant pumps that normally operated in parallel. In startup or shutdown sequences, however, it was always found that the noise decreased significantly when both pumps in a loop were energized rather than just one. These data are illustrated in figure 4.12., which shows the result of operating Loop 12 in three different ways: with just pump 121, just pump 122, and with both pumps together. Noise levels from pump 122 alone were really abnormally high, which may have been related to the bearing overheating problem that it had during the test. The problem was severe enough that the pump could only be run for short periods. Even so, with both pumps running, the background noise was still less than with either pump alone.

Figure 4.11. Background Noise During Plant Heatup, All Four Primary Coolant Pumps On (Except Pump 121 Curve). Output Values Adjusted to be Equivalent to 103 db Amplifier Gain

Figure 4.12. Background Noise Versus Pump Operation at Operating Conditions. Amplifier Gains 103 db

During the Phase 2 test, it was also possible to study more directly than in any previous tests the behavior of background noise as a function of temperature and pressure. The reactor cooldown at the end of the test was divided into two stages: first, the temperature was maintained constant at 232°C (450°F) while the pressure was decreased from 107 bars (1550 psig) to 45.5 bars (660 psig), and then the pressure was held constant at 45.5 bars while the temperature was decreased to 193°C (380°F). The results of this program are shown in figure 4.13. Over the entire cold leg the background noise approximately doubled for each 30 bar (450 psi) decrease in pressure, and also doubled for the separate 39°C (70°F) decrease in temperature. The pressure and temperature decreases could not be continued further due to reactor cooldown bandwidth limitations (the allowed operating conditions), but these data are surprisingly consistent with the low pressure/low temperature data from the plant heatup. Extrapolating and assuming 156°C (280°F) further decrease in temperature, or four more noise doublings, and another 30 bar (450 psi) decrease, or one doubling, the single pump background noise at cold conditions should have been in the neighborhood of 256 times the operating condition noise, and it was.

4.5 LOOSE PART DETECTION

As noted previously, in the Phase 2 test wideband accelerometers were mounted on the loop piping in addition to the AE sensors, primarily to determine their relative value for leak detection. However, early in the test the value of accelerometers became readily apparent in a different sense. During Phase 1 the AE sensors on the hot leg, especially those near the steam generator, had observed many burst-type emission signals which sometimes interfered with rms noise measurements. The bursts had long decay times, like mechanically generated noise, but their cause could not easily be determined since no noise was audible. With the accelerometers also monitoring the piping, though, the cause was immediately found, namely, metal impacts occurring inside the steam generator inlet plenum, probably from a loose part.

Typical signal data from the impacts is illustrated in figure 4.14., which shows the responses of accelerometers A17 and A19. That the signal source was near A19 can be determined from the higher amplitudes, sharper leading edges, and earlier arrival times of the signals at that channel.

To compare the accelerometer response against that of an AE sensor, examine figure 4.15. This figure shows accelerometer A19 response and the nearby AE sensor channel 19 response to the same impacts. The signal-to-noise ratio was quite clearly better on the accelerometer channel. If the ratio of peak-to-peak signal to peak-to-peak noise is measured, the accelerometer performed at least three times better. And of course the total signal energy relative to background is much, much greater for the accelerometer. Unfortunately, that same sensitivity to metal impacts was sufficient to completely disrupt the background noise data, and the sensitivity to leaks in cases such as this would be greatly degraded.

Figure 4.13. Background Noise Versus Pressure and Temperature, Three Pump Operation (Pumps 121,131,132). Amplifier Gains All 103 db or Equivalent

A17 (1v = 3g)

A19 (1v = 10g)

Figure 4.14. Comparison of Accelerometer A17 and A19 Responses to Metal Impacts in the Steam Generator Inlet Plenum Near A19

Channel 19

A19

Channel 19

A19

Figure 4.15. Comparison of AE Sensor Channel 19 Response to Accelerometer A19 Response to Metal Impacts. Channel 19 and A19 at Same Pipe Location

4.6 PRIMARY WATER LEAK TESTS

With all of the preliminary measurements completed, the Phase 2 tests employing actual primary water leaks could get underway. The leak source devices described in section 4.1 were to be operated as had been done originally in Phase 1, but this time with more source points and measurement of leak rates.

The first leak source to be operated was the one on the cold leg (see figure 4.2.), situated in the main coolant pipe section with the highest background noise of anywhere on the reactor. In addition, only one of the two Loop 12 primary coolant pumps was operated to ensure maximum noise conditions. The leak source was operated by opening the straight-through solenoid valve and then crack-opening the manual isolation valve to obtain a leak. The results from this test are shown in figure 4.16. for three different leak rates. The signals from the 4-11 liter/min (1-3 gpm) leaks are just about an order of magnitude above the background noise for most channels, with the exception of channel 22, which was on the steam generator on the opposite side of the coolant pumps, where good response was not necessarily expected. These results may be compared against the leak simulation results discussed earlier. Again, the outputs from channels 25 and 26 appear rather large due to the sensitivity of those channels. When adjusted for the approximate relative sensitivities of the sensors, the signal data appear as in figure 4.17.

It should also be mentioned that the 4-11 liter/min (1-3 gpm) leaks used here were definitely small leaks. For 232°C (450°F) water in the reactor, leakage to atmosphere meant that the exhaust would be a mixture of hot water and saturated steam, but the steam would only represent about 20 percent of the total. A 4 liter/min (1 gpm) leak rate therefore does not imply a large volumetric flow of gas.

A further test was performed with the cold leg leak source by closing the solenoid valve, opening the manual isolation valve, and then opening the air-operated remote-control valve to create the leak, moving the leak point several feet away from the main coolant pipe onto 1/2-inch piping. The results of this test are illustrated in figure 4.18., and are rather disappointing, as the increase in signal level over background was very small. The exact reasons for such a discrepancy can only be speculated upon at this time, although the reduction to the small (1 cm or 1/2 inch) pipe is the most likely cause. With the pipe diameter and wall thickness reduced by about half, the pipe was no longer "thick-wall" to a 500k Hz acoustic wave. In addition, the step thickness change at the 1"-to-1/2" reducer would act to reduce signal transmission. The 1/2-inch pipe was not originally desired but was used as a last resort due to the high cost and long delivery time of 1-inch-diameter, thick-wall, remote-control valves.

The next set of leak tests performed employed the hot leg leak source (see figure 4.3.) on its low-background-noise piping. Initial data from this source for a leak point at the closest manual valve to the main coolant pipe is illustrated in figure 4.19. The leak rates of 2-14 liters/min (0.5 to 3.6 gpm) were easily detectable, and the graphs look very much like the data obtained with electronic simulation.

Figure 4.16. Reactor Cold Leg Leak Detection — Raw Signal Data. Amplifier Gains 103 db.

Figure 4.17. Reactor Cold Leg Leak Detection — Data Adjusted for Approximate Relative Sensitivities of Sensors

Figure 4.18. Cold Leg Leak Source Air-Operated Valve Leak on 1/2-inch Pipe

Figure 4.19. Hot Leg Leak Source, First Leak Trials

A similar set of tests were tried several days later to examine repeatability. Those data are illustrated in figure 4.20. The figure shows that the leak signals were indeed in the same range as before, but the magnitudes did not correspond directly to the leak rates. The signal from the 2 liter/min (0.5 gpm) was almost identical to that from the 11 liter/min (3 gpm) leak. The figure also shows the results of testing with the air-operated valve. Once again, as for the cold leg leak source, the distant valve on the small (1 cm or 1/2 inch) pipe yielded poor signals.

The hot leg leak source contained a third pipe section consisting of a cracked pipe leak also. However, this section turned out to be inoperable. The problem encountered was the extremely high sediment content of the primary water, which clogged the crack and sealed off the leak. Several cracked pipe sections were welded into the system over the course of the test program, but all suffered the same fate, on both the hot leg leak source and the steam generator leak source.

Good data were obtained for the valve leak portion of the steam generator leak source, though, and these data are illustrated in figure 4.21. For this source the leak point was the needle valve approximately 1 meter (3 ft) from the vent, and for this valve with 2.5 cm (1 inch) thick-wall piping up to it the results were much better than for the small air-operated valves. Although the source did not produce the large signals of the other close-in leaks, it was clearly detectable.

As mentioned previously, accelerometers were also used to monitor the coolant system, and they showed their value in detecting metal impacts in the steam generator. The data obtained from the accelerometers during operation of the three leak sources are given in table 4.1. Data in the table were generated by taking the outputs from the signal conditioners, filtering them to the range of 4 kHz to 20 kHz, and extracting the rms values. In general, the results would have to be considered disappointing, though not unexpected. The data indicate that an accelerometer needed to be rather close to detect the leak, with much less increase in output than with the AE sensors. The primary difficulty was the instability of the background noise, since mechanical noise sources put most of its energy into the low frequency band, as with the metal impacts, for example. It was always difficult to get a good idea of just what a nominal background noise level was.

One further leak detection test was performed during the cooldown stage of the program. Because the reactor pressure was decreased from 106.9 bars to 45.5 bars (1550 to 660 psig) while maintaining constant temperature, the change in leak signals with pressure could be evaluated. This experiment was conducted with the hot leg leak source and used approximately the same leak rate each time. The data are illustrated in figure 4.22., and show that as pressure is decreased the leak signals decrease greatly. This result agrees well with typical laboratory figures.

Figure 4.20. Hot Leg Leak Source, Second Leak Trials

Figure 4.21. Steam Generator Leak Source, Needle Valve

TABLE 4.1
ACCELEROMETER DATA

COLD LEG LEAK SOURCE							
Channel	Full Scale (g)	Background	Leak and Background (mv _{rms})				
			3.75 lpm	7.5 lpm	10.4 lpm	Air-operated 3.75 lpm	Air-operated 16.7 lpm
A23	10	22.5	30	38	84	27	24
A25	3	100	121	128	116	102	100
HOT LEG LEAK SOURCE							
Channel	Full Scale (g)	Background	Leak and Background (mv _{rms})				
			1.9 lpm	8.3 lpm	13.6 lpm	Air-operated 2.9 lpm	Air-operated 6.3 lpm
A17	1	16	22	24	24	23	21
A19	0.3	24	26	43	38	26	32
STEAM GENERATOR LEAK SOURCE							
Channel	Full Scale (g)	Background	Leak and Background (mv _{rms})				
			1.5 lpm	4.5 lpm	9.5 lpm		
A17	1	37	37	37	37		
A19	0.3	71	70	70	72

Figure 4.22. Hot Leg Leak Source Signals Versus Pressure for Similar Leak Rates. Amplifier Gains All 103 db

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 ACOUSTIC EMISSION MONITORING

The Acoustic Emission (AE) monitoring conducted with the vessel head specimens was quite successful. Results from both the cantilever and WOL specimens demonstrated that detection of crack growth in reactor vessel steel (A533B) under plant conditions is feasible and the signals are large enough to permit source location. The results further showed that detection of simultaneous multiple sources in neighboring zones should not pose a major problem. The grading of the individual sources should, however, be based on separately channeling and processing AE signals from localized sources by the use of a suitably designed AE system such as the one shown in figure 5.1.^[1]

The overall test results also showed that both "AE counts per load cycle" and "peak AE count rate during a load cycle" exhibit a direct relationship with crack growth. This is significant in that it is consistent with laboratory results obtained under the Acoustic Emission Interpretational Techniques Development Program jointly supported by the Empire State Electric Research Corporation (ESEERCO) and Westinghouse. That program, which utilized results from several fatigue crack growth monitoring tests, established that "counts per load cycle" bears a direct power law relationship to the crack driving force, ΔK .

Although the accomplishments of this program have shown the practicality of AE technology, commercialization of the technology for reactor pressure vessel integrity monitoring will require further work in several areas.

While the modified plant heatup technique developed under this program could prove quite useful in enhancing the "visibility" of true AE signals during the critical pressurization period, detection of AE signals from potential flaws activated by plant transients under normal operating conditions needs to be demonstrated. Detectability of AE signals during plant transients is crucial for AE monitoring of vessel integrity since the growth of an existing defect to a

1. G. V. Rao, "Development of Acoustic Emission Interpretational Techniques for Pressure Boundary Integrity Monitoring Final Report," ESEERCO-Westinghouse EP6-2 Report, WCAP-9462, August 1979.

Figure 5.1. Block Diagram of a Conceptual Design of the Vessel Integrity Monitoring System

critical size under the influence of reactor operating transients forms the fundamental basis for reactor vessel life prediction methodology using the fracture mechanics approach. A listing of typical design transients is shown in table 5.1.

To provide increased assurance of AE monitoring capability and to evaluate flaw characterization methodology over a range of safety margins (corresponding to various flaw sizes), acoustic monitored pressurization tests of an intermediate size vessel implanted with a number of flaws ranging from subcritical to critical size would be highly desirable.

With respect to complete volumetric AE monitoring, lack of accessibility to the vessel shell is a problem that needs to be addressed. While AE signals propagated fairly well over the distances of the reactor vessel head, it is not reasonable to assume good propagation over distances of 10 m (30 ft) or more. Any AE monitoring of the complete vessel will have to address the issue of placing sensors or acoustic wave guides at reasonably spaced intervals over the entire vessel surface. At the present time, the most promising use of AE monitoring is the monitoring of limited critical areas such as the reactor inlet and outlet nozzles and steam generator feedwater piping.

5.2 ACOUSTIC LEAK MONITORING

In this program, a variety of small leaks on the primary system were easily and rapidly detected by the acoustic system, even at large distances on high background noise piping. Attenuation of the acoustic signals with distance was large enough to provide good source location, but not so large as to hinder detection.

A number of other characteristics related to leak detection capability were also measurable in this program: background noise as a function of temperature and pressure, leak signals as a function of system pressure, the similarity of leak signals to electronically simulated signals, and the capability for leak detection in the presence of loose part impacts. None of the possible interferences was severe enough to destroy the sensitivity of the acoustic leak monitoring system, and the sensitivity of the system was shown to be extremely high under typical conditions as compared to more conventional forms of detection such as humidity, sump level, water inventory, and condensate collection.

Actual quantification of leak rates based on acoustic signals is, however, a subject requiring further work if the leak rate from an unknown type of leak at a random location is to be determined. Leak orifice shape, transmission medium, temperature, and pressure are all significant factors in this regard, and a certain degree of nonrepeatability was encountered in

TABLE 5.1
TYPICAL REACTOR DESIGN TRANSIENTS^[9]

Normal Conditions	Occurrences
Heatup and cooldown at 100°F/h Unit loading and unloading at 5% of full power/min Step load increase and decrease of 10% of full power Large step load decrease with steam dump Steady state fluctuations	200 (each) 18,400 (each) 2,000 (each) 200 10 ⁶
Upset Conditions Loss of load, without immediate turbine or reactor trip Loss of flow (partial loss of flow, one pump only) Reactor trip from full power	80 80 400
Test Conditions Turbine roll test Hydrostatic test conditions Preoperational (cold) Hydro Test Postoperational (hot) Hydro Test	10 5 40

this program. It should be possible, however, based on laboratory experience or simply empirical tests, to develop approximate formulas to relate acoustic signals with leak rates; at least for the monitoring of specific components or critical areas where the expected site or type of leakage is known.

The sum total of laboratory and plant test experience to date — this program, previous test programs, and investigations by others — has essentially proven the feasibility of acoustic leak detection systems to a level of confidence where acceptance in the marketplace has begun. Systems have already been applied to the detection of leakage in important reactor components including the detection of opening/closing/leaking of pressurizer relief valves, and the monitoring of feedwater lines for both crack growth and through-wall leakage.

5.3 SUMMARY

This program demonstrated the feasibility and potential of acoustic technology for monitoring reactor pressure boundary integrity. Limited applications of this technology are being made and, with additional work in the various areas discussed above, broader applications will become possible.

APPENDIX A

ACOUSTIC MONITORING EQUIPMENT

The following is a listing of equipment used in the acoustic monitoring tests.

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ACOUSTIC MONITORING EQUIPMENT (see figure 2.4.)

Left Rack (top to bottom)

- DEC cassette tape unit
- Tektronix 4010 CRT terminal
- DEC PDP-11/10 minicomputer
- DEC RX01 floppy disk unit

Left Center Rack

- ENI 50 db power amplifier 10 kHz — 10 MHz
- Rockland 1042 dual hi/lo filter, 48 db/octave
- Unholz-Dickie 1112 signal conditioners (for accelerometers)
- Sangamo Sabre III tape recorder (14-track, 2 MHz at 120 ips)

Right Center Rack

- Westinghouse AE simulator (for triangulation)
- Westinghouse AE amplifiers (83-103 db gain, filtered 300-700 kHz)
- Westinghouse matrix switches (for triangulation zone setup)
- Westinghouse triangulation modules (contain Δt counters)

Right Rack

- HP 3403C true-rms voltmeter
- Wavetek 144 function generator
- Tektronix 7313 oscilloscope with 7A18 vertical amps and 7B53A horizontal amps
- CCTV monitor
- Leak source remote valve controls
- Crack source remote controls
- DC power supply
- Tektronix 4610 hard copy unit

APPENDIX B
CRACK GROWTH SAMPLE DATA

These figures and tables show the specimen types used and the material history.

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B.3

Figure B.1. Details of "Specimen-Heading Joint" for the Mounting of Cantilever Specimen

Figure B.2. Specimen Geometry and Mounting Details of 2T WOL Specimen

TABLE B-1
REACTOR PRESSURE VESSEL STEEL PLATE HISTORY AND
PROPERTIES FOR A533 GRADE B CLASS I PLATE MATERIAL

Plate	Heat No.	Mill Chemical Analysis, wt %							
		C	Mn	P	S	Si	Ni	43	Cu
A	A9406-2	.24	1.35	.010	.020	.27	.61	.55	
B	A9406-1	.25	1.37	.010	.020	.27	.61	.55	.13

Heat Treatment

- (1) Austenitize 1650°F/1 hr per inch thickness and WQ
- (2) Temper 1225°F/3/4 hr per inch thickness
- (3) Stress Relief 1150°F/20 hrs; Heat and Cool at ~ 100°F/hr

RmT Tensile Properties

Plate	YS, ksi	UTS, ksi	Elong. in 2"	% RA
A	62.9	86.3	26.0	64.4
	64.1	86.6	26.0	63.7
B	66.8	84.7	28.0	64.6
	60.9	84.0	28.0	64.1

APPENDIX C
LEAK SOURCE AND CONDENSER DATA

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BILL OF MATERIAL								
ITEM	NOTE	PART NAME	DRAWING & GR OR IT.	MATERIAL	REQ. PER GROUP			
					01	02	03	04
01		1"-90° ELBOW 3000#		304 S/S	3			
02		1"-SCH 160 PIPE		304 S/S	AS REQ			
03		1" TEE 3000#		304 S/S	1			
04	A	1" SOLENOID VALVE		304 S/S	1			
05		1/2" x 1" REDUCER 3000#		304 S/S	1			
06		1/2" SCH 160 PIPE		304 S/S	AS REQ			
07	B	1/2" AIR VALVE		304 S/S	1			
08		1/2" 90° ELBOW 3000#		304 S/S	1			

NOTES:

A - B.O. FR. ATKOMATIC, INDIANAPOLIS, IND., 46201.
No. MPSS-VPI-8404-22-S

B - B.O. FR. EQUIPMENT AND CONTROLS, INC. PGH, PA.
RESEARCH CONTROL VALVE, TYPE 75.

NOTES:

1 - ALL WELDS TO BE .25 FILLET PER PS82148PF
AND 821272V WITH 125/

2 - DYE PENETPANT PER 595139, LEVEL B.

Figure C.1. IPP-P2 Cold Leg Leak Source

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BILL OF MATERIAL									
ITEM	NOTE	PART NAME	DRAWING & GR OR IT.	MATERIAL	REQ. PER GROUP				
					01	02	03	04	
01		1" COUPLING 6000#		304 S/S	1				
02		1" SCH 160 PIPE		304 S/S	AS REQ				
03		1" CROSS 6000#		304 S/S	1				
04		1" 90° ELBOW 6000#		304 S/S	2				
05	A	1" SOLENOID VALVE		304 S/S	2				
06		1" ELBOW 3000#		304 S/S	1				
07		1" x 2" REDUCER 3000#		304 S/S	1				
08		2" SCH 160 PIPE		304 S/S	AS REQ				
09		2" END CAP 3000#		304 S/S	1				
10		1/2" x 1" REDUCER 6000#		304 S/S	1				
11		1/2" SCH 160 PIPE		304 S/S	AS REQ				
12	B	1/2" AIR VALVE		304 S/S	1				
13		1/2" 90° ELBOW 3000#		304 S/S	1				

NOTES:

A - B.O. FR. ATKOMATIC, INDIANAPOLIS, IND., 46201.
No. HPSS-VP1-8404-225.

B - B.O. FR. EQUIPMENT AND CONTROLS, INC., PGH, PA.
RESEARCH CONTROL VALVE, TYPE 75.

NOTES:

1. ALL WELDS TO BE .25 FILLET, PER PS82146PF AND
821272V WITH 125/

2. DYE PENETRANT, PER 595139, LEVEL 8.

Figure C.2. IPP-P2 Hot Leg Leak Source

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BILL OF MATERIAL									
ITEM	NOTE	PART NAME	DRAWING & GR OR IT.	MATERIAL	REQ. PER GRUP				
					01	02	03	04	
01		1" 3000# COUPLING		304 S/S	1				
02		1" SCH 160 PIPE		304 S/S	AR				
03		1" 3000# TEE		A182/304	1				
04	A	1" SOLENOID VALVE		304 S/S	2				
05	B	1" NEEDLE VALVE		316 S/S	1				
06		1" 3000# ELBOW		304 S/S	4				
07		2" x 1" 3000# S.W. REDUCER		A182/304	1				
08		2" SCH160 PIPE		A312/304	AR				
09		2" 3000# END CAP		A182	1				
10	C	1" 6000# Y-STRAINER		304 S/S	1				

NOTES:

A - B.O. FR. ATKOMATIC, INDIANAPOLIS, IND., 46201.
#HPSS-VPI-8004-225.

B - S.D. FR. WILLIAMS AND CO., INC., PGH., PA., 15233
#1B74-1-SWE

C - B.J. FR. PIPING SPECIALISTS, FARMINGDALE, NY, 11735
#855 S/S FILTER.

NOTES:

1. ALL WELDS TO BE .25 FILLET, PER PS 82148PF & 82127ZV
WITH 125°

2. DYE PENETRANT, PER 595139, LEVEL B.

Figure C.3. IPP-P2 Steam Generator Leak Source

Figure C.3. IPP-P2 Steam Generator Leak Source

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Figure C.4. Sketch of Condenser Arrangement for Cold Leg Leak Source
(9/8/78 - IPP-1 - Phase-2) Scale: 1/10

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C.10

Figure C.5. Condenser Assembly for Hot Leg Leak Source

Figure C.6. Sketch of Condenser Arrangement for Steam Generator Leak Source
(9/8/78 - IPP-1 - Phase 2) Scale: 1/10

APPENDIX D
LOOP DIMENSIONS

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Figure D.1. Loop 12 Dimensions (in Meters, with Feet Shown in Parentheses)