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DOE REPORT NO. ~~GOO 4592-1~~

SEMI-ANNUAL REPORT

Investigation into
Continuous Acoustic Emission Monitoring
of BWR Components

John W. McElroy
June 2, 1980

This work was performed under contract to
the Philadelphia Electric Company by the
U. S. Department of Energy
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SECTION 1

SUMMARY

A program to evaluate the capabilities of continuous, on-line acoustic emission (AE) monitoring as applied to reactor pressure boundary components has been ongoing at the Philadelphia Electric Company's Peach Bottom Nuclear Generating Station Unit 3 since April 1977. This report covers the work accomplished during the eight month period from October 1, 1977 through June 1, 1978. During this time, Peach Bottom Unit 3 was operational for the first six months and was shutdown for a refueling outage for the last two months. During the operational period, AE monitoring continued utilizing the installed instrumentation. During the refueling outage, removal, recalibration, refurbishment, and reinstallation of all the instrumentation used in the program was performed. Technical improvements were also incorporated into the monitoring instrumentation during this outage. This report discusses the data gathered, analyses performed, and the overall results and recommendations developed based on the first year of continuous monitoring.

The following are some of the highlights of this reporting period:

- The coupling efficiency and thereby, the sensitivity of the sensors has been found not to vary significantly with time.
- 5600 AE events were accepted showing several localized areas of concern.
- Five main steam safety relief valves suspected of leakage based on AE data were replaced during a maintenance outage.

- The guard sensors used to establish monitoring region boundaries performed satisfactorily.
- Computer programs which simplified data presentation and thereby, facilitate the rapid identification of areas of concern were developed and implemented.
- A leak in the recirculation system of the plant was clearly indicated and located by the AE system.
- Several plant operating procedures have been critically reviewed based on AE data accumulated during the accomplishment of the respective actions.
- Many problems in installation, operation, and diagnosis of the instrumentation have been identified and solutions have been developed.
- Correlation between AE results and the results from alternate inservice inspection techniques has been initiated.

SECTION 2

INTRODUCTION

The research effort is a continuation and expansion of a previous program sponsored by the U. S. Department of Energy (DOE) at the Peach Bottom Nuclear Generating Station Unit 3 under the DOE Contract EN-77-C-02-4087. The previous program began October 1, 1976 and extended through September 30, 1977 and involved the design and installation of the acoustic emission (AE) surveillance system and operation of this system from April through September 1977. The current contract (DOE EN-78-C-02-4592) began October 1, 1977 and extended through February 28, 1979. The scope of this effort was to continue monitoring activities, to expand system capabilities, to inspect and repair system instrumentation and to begin correlation between AE data and the results of inservice inspections on each of the components monitored. The objective of the entire experimental study is to evaluate the feasibility of routine implementation of AE surveillance of crack propagation and leak detection as applied to nuclear reactor pressure boundary components. The overall goal of this effort is to demonstrate techniques that are capable of reducing the need for manual maintenance and safety inspections as well as improve component reliability. The expected benefits from a successful demonstration and utilization of these techniques is an increase in the availability of light-water reactor systems and a reduction in the radiation exposure to plant workers.

The results of the first year of this program (October 1976 to October 1977) are contained in DOE Report No. COO-4087-001 entitled, "An Experimental Study of Advanced Continuous Acoustic Emission Monitoring of BWR Components." This report was issued in December 1978 and is available through the National Technical Information Service in Oak Ridge, Tennessee. During the period of October 1976

to October 1977, AE sensors, vibration transducers, thermocouples, and AE calibration devices were installed on four plant components: a segment of the recirculation bypass line, a segment of the core spray line, and two of the reactor feedwater nozzles. During the first year some problems were experienced with the reliability of sensors and calibration devices. However, it was possible to conduct discrete-event AE monitoring on both passive components (recirculation bypass and core spray lines) and active components (feedwater nozzles) having substantial background noise. Some AE event clusters were observed in various locations on all four components. However, it was concluded that no major indications of flaw growth had been observed in these components during the five and half months ending September 28, 1977.

The conclusion, based on the first year of this program, was that on-line AE monitoring in an operating nuclear power station was feasible, especially for selected regions of certain components. However, additional data and correlations with results of other inspections were needed in order to formulate guidelines for pursuing routine implementation for surveillance of light-water reactor components. Furthermore, improvements were required in the reliability of sensors, cables, and associated accessories, which will be expected to operate continuously in a radiation environment at 300°C for many years and formats for data presentation and interpretation would have to be simplified so that a plant operator can review results of the AE monitoring and confidently relate them to component structural conditions.

The program was expanded in October 1977 to include monitoring of an additional core spray line and the eleven main steam relief valves. Monitoring of the original four components was also continued through this period. Investigations will continue to be conducted to detect and diagnose acoustic emission originating from thermal cycle fatigue and stress corrosion cracking (and other stimuli) on the piping lines and feedwater nozzles, as well as acoustic emission originating from leaks in the safety relief valves.

The program is currently divided into the following six tasks:

1. Continuation of On-Line Monitoring Effort to Refueling Outage
2. Refueling Outage Inspections and Installation
3. Main Steam Safety Relief Valve Exploratory Testing
4. Expanded On-Line Monitoring Effort
5. Data Analysis and Documentation
6. Refueling Outage Correlations

The objectives, method of accomplishment, and results of each of these tasks are discussed in detail in the balance of this report.

SECTION 3

OBJECTIVE

The chief objective of this program is to assess the feasibility of routine implementation of AE surveillance of crack propagation and leak detection as a technique to assist in reducing the radiation exposure to plant workers and for increasing the availability of light-water reactor systems. The successful development and utilization of AE surveillance could result in:

- The reduction and minimization of manual inservice inspection (ISI) requirements.
- The alteration or minimization of operating practices that have a deteriorating effect on plant systems and components.
- The scheduling of maintenance on deteriorated components during planned maintenance outages rather than during unanticipated forced outages.
- The reduction in manpower radiation exposure and outage time by localizing areas of components requiring repair or inspection prior to containment entry.

The proposed objective is being accomplished through the successful completion of the following six tasks:

Task 1 - Continuation of On-Line Monitoring Effort (October 1, 1977 - April 1, 1978)

AE monitoring was conducted on the "N4A" and "N4E" feedwater nozzles, the "B" core spray line, and the "B" recirculation bypass line. Data was collected, processed, and analyzed in a manner which allowed for correlation with inservice inspection (ISI) results and plant operating procedures. This task represents a continuation of the monitoring which was conducted under the previous DOE contract.

Task 2 - Refueling Outage Inspections and Installations (April 1, 1978 - May 18, 1978)

During the refueling outage all existing sensors and preamplifiers were removed from the reactor system and recalibrated using a standard procedure to determine deterioration characteristics due to the operating environment. Failed sensors were replaced and the systems (sensors, calibration selenoids, vibration sensors, and thermocouples) were reinstalled on the "N4A" and "N4E" feedwater nozzles, the "A" and "B" core spray lines, and "B" recirculation bypass line. Additionally, a sensor and a thermocouple were installed on all 11 main steam safety relief valves.

ISI results were obtained during the refueling outage so that correlation with AE results could be accomplished.

Task 3 - Main Steam Safety Relief Valve Exploratory Testing

During each refueling outage, tests shall be performed on every main steam safety relief valve to optimize sensor sensitivity to pilot stem leakage in the valve. These tests consist of inspecting the valve for indications of leakage at Wyle Laboratories and comparing the measured leakage to predictions of leakage made during plant operation. This task has not been performed at the time of this report.

Task 4 - Expanded On-Line Monitoring Effort

AE monitoring is performed on two feedwater nozzles, two core spray lines, and one recirculation bypass line on Peach Bottom Unit 3. This monitoring consists of recording the pertinent real-time data for data reduction. The data set consists of AE characteristics (event number, location, oscillation count, peak voltage), component parameters (temperature, vibration amplitude, vibration frequency), and plant parameters (total core flow, total feedwater flow).

Task 5 - Data Analysis and Documentation

Data reduction programs are required to optimize use of the available real-time data. The data must be correlated in a rapid and reliable manner with information concerning plant operations and other local component parameters. This data is reviewed bi-weekly to identify trends in the acoustic activity. Procedures are developed to document and standardize the performance of any routine operation associated with the conduct of the monitoring program; for example, procedure are written for the routine calibration of the acoustic sensors.

Task 6 - Refueling Outage Correlations

Correlation shall be made of all acoustic emission sources located during this monitoring effort to the nondestructive examination, ISI, scheduled during scheduled refueling outages. Correlation shall also be made between the leak rates of the main steam safety relief valve as determined by the AE data to the leak rates measured during recalibration testing of the valves.

SECTION 4

BACKGROUND

4.1 Core Spray Lines and Recirculation Bypass Lines

Austenitic stainless steel is used extensively in light-water reactor components. For these components, the failure rates have been extremely low. General Electric's "Task Force for the Investigation of Cause of Cracking in Austenitic Stainless Steel Piping" concluded "that while their effect on unavailability can be significant." Since the time of that statement in 1975, pipe cracks have continued to occur at low rates on recirculation bypass lines, core spray lines, and CRD return lines affecting unavailability accordingly. Each of these components have experienced cracking at the Peach Bottom sites to some degree. It has been documented⁽¹⁾ that this type of cracking can cause outages lasting between three to four weeks. By monitoring these components with acoustic emission, the occurrence of crack growth may be detected. If AE only occurs during specific plant maneuvers, then the possibility may exist to alter those operations and maybe reduce the incidence of cracking. Also, by evaluating the quantity and quality of AE activity, specified inspections and required maintenance can be forecasted or eliminated prior to major outages.

(1) H. H. Klepfer, et al, "Investigation of Cause of Cracking in Austenitic Stainless Steel Piping," General Electric NEDO 21000, July 1975

4.2 Feedwater Nozzles

There are six feedwater nozzles in each unit at Peach Bottom. These nozzles are the entry ports for the water supply for the reactor vessel. The inlet temperature on the water supply is 85°F. The temperature is increased during operation through the use of five stage heaters. When the turbine trips off line for any reason, the five heaters are bypassed and the 85°F water reaches the feedwater nozzle region. The feedwater pump is a high capacity single speed demand pump. This means that when the turbine has tripped there is no demand for steam and the reactor pressure quickly increases and the pump stops. At this time, the reactor water (500°F) flows into the feedwater. Then when enough steam has gone to the condenser and the reactor pressure has gone down the demand for water starts the pump. The pump delivers 85°F water to the nozzle region. The pump is a high capacity pump and increases reactor pressure rapidly and then shuts off due to lack of demand. As before, reactor water (500°F) enters the nozzle region. This cycling continues until the heat removal systems have removed enough heat so that there is no demand for the feedwater pumps. This thermal cycling has had fatigue effects on the feedwater nozzle structure. The inner blend radius weld on some nozzle regions has experienced thermal cycle fatigue cracking in the heat affected zone. Presently, the inner blend radius welds of all feedwater nozzles are being thoroughly inspected during scheduled inservice inspections at the time of the refueling outage. The inspections include a mechanized ultrasonic examination performed on the outside of the feedwater nozzle and a liquid dipenetrant examination performed on the inside--directly on the inner blend radius weld and its heat affected zone. These inspections require a large amount of inspectron time in high radiation areas. This results in excessive accumulated radiation exposure to qualified inspectors. The inspectrons also increase the outage time experienced by the plant.

4.2 Feedwater Nozzles (Cont'd.)

By monitoring the feedwater nozzle using continuous on-line acoustic emission techniques, it may be possible to eliminate the inspection of the feedwater nozzle. If it can be shown that the AE from thermal cycle fatigue cracking can be detected during plant operation, then the absence of AE should indicate sufficient evidence to waive the inspection requirement. This may develop by inspecting first the most "acoustically active" nozzle and if this nozzle was found free of defects there would be no reason to inspect other nozzles. Having this capability should reduce accumulated radiation exposure to the quality inspectors and increase the plant availability by reducing outage time.

4.3 Main Steam Safety Relief Valves

A commonly-used safety/relief valve in BWR plants is a pilot-operated type, having a two stage valve section and a main valve section. A schematic of the valve is shown in Fig. 1. In operation, the pilot stage is held closed by the internal pressure acting over the pilot stage seat area. As the pressure increases, bellows expansion reduces the abutment gap between the stem and disc yoke. When the stem abuts against the yoke, further pressure increase lifts the disc from its seat, admitting steam to the operating piston of the second stage, causing it to open. This vents the chamber over the main valve piston to the downstream side of the valve, thus creating a pressure differential across the main valve piston and the valve opens.

The pilot-disc seat is vulnerable to deteriorating processes which lead to increasing leakage across the seat into the chamber of the second stage. A small leak has no immediate major bad effect, because the pilot valve discharge line can accommodate the flow without substantial pressure buildup. However, as a small leak grows, the second-stage pressure increases until, upon reaching a critical value, the second-stage disc opens; even though the pilot disc was not lifted. The resulting plant outage is usually four or five

4.3 Main Steam Safety Relief Valves (Cont'd.)

days long. Since valve malfunction does not occur until a leak worsens to that critical leak rate, early detection of leakage can allow corrective measures to be scheduled, thereby reducing the loss of plant availability. A review of on-line leak detection methods for reactor systems indicated that AE monitoring has the greatest potential for providing desirable features not found in other methods. These features include high sensitivity in the noise environment and the advantage of a potential for determining leakage rate.

SECTION 5

SYSTEM DESCRIPTION

5.1 Discrete AE Monitoring System

The equipment utilized in the conduct of this program is essentially identical to that reported in DOE Report No. COO-4087-1. In summary, the equipment consists of sensors, amplifiers, processing and display instruments, and associated cabling. Figure 5 shows a block diagram of the system. The sensors are 500 kHz resonant AE sensors. A typical calibration curve is shown in Figure 6. The preamplifiers are broad band 40 dB gain voltage amplifiers. The solenoids used for calibration are specially designed high-temperature impact devices. The vibration sensors are 30 kHz resonant accelerometers. An MSCD (Multi-Sensor Comprehensive Data) system is used for data processing and display. Appendix 1 is the vendor's description of the MSCD system.

The AE sensors are clamped onto the reactor components, dry-coupled, with a stainless steel clamp. Figure 7 shows the installation of the sensors on the recirculation bypass line which typifies all installations. The signal from the sensor is amplified 40 dB by the preamplifier and routed through containment penetration to the plant control room where the AE console is located. The signal is further amplified to approximately 78 dB and filtered in band-width 400-800 kHz. In addition to the features described in Appendix 1, the MSCD system has some special features which were adopted especially for this program. First is the inclusion of the parametric signal conditioner that provides inputs for the temperature, vibration amplitude, vibration frequency, and plant total core flow on each of the components monitored. This enables those parameters that may influence the generation of acoustic emission

5.1 Discrete AE Monitoring System (Cont'd.)

to be recorded with the AE event. Second is the development of a remote impact calibrator which is used to evaluate the coupling coefficient of the sensors. The impact calibrator's purpose is to assure the performance of all sensors and monitor the deterioration of sensor sensitivity. Third is the development of specific software to reduce data in a variety of methods. All parameters recorded can be plotted one against another while keeping other parameters constant. This will permit a wide scope of reduction processes available. Lastly is the inclusion of the real-time clock which will enable coordination between plant operations and the acoustic emission monitoring.

Figure 2 shows various areas of the recirculation bypass line installation. Figure 3 shows various areas of the core spray lines installations. Figure 4 shows various areas of the feedwater nozzles installations.

5.2 Valve Leakage Monitoring System

There have been many steam relief valve failures on BWR's throughout industry. These failures are due to excessive leakage through the valve. The failure takes the unit off the line for several days at a great cost. The leakage in the valves is located at the pilot stem in the actuator stage of the relief valve. If the valve were operating properly, over-pressurization in the main steam line would lift the pilot stem, pressurizing a second stage in the valve. Once pressure in the second stage reaches a critical level it opens the valve. If there is a leak across the pilot stem into the second stage pressure will build up in that second stage until the valve blows down, even though there had been no over-pressurization in the main steam line. However, there is a bleed off from that second stage to ambient (drain), such that in order for pressure to build up in the second stage, the leakage rate must be greater than the bleed off rate. This increases the time between the initiation of a leak to improper blowdown. This time may be on the order to months. Therefore, if leakage can be detected with acoustic techniques,

5.2 Valve Leakage Monitoring System (Cont'd.)

preventive maintenance can be scheduled to replace the valve, thereby increasing plant availability.

Preliminary tests sponsored by the Philadelphia Electric Company have been performed at Wyle Laboratories in Huntsville, Alabama. Using sensors with a resonance of 200 kHz, the pilot stem leakage was clearly indicated at 5-8 kHz.

Philadelphia Electric has been utilizing a valve surveillance instrument specially designed for use in this leak detection program. The basic components of the proposed instrument are a multiplexer, signal conditioner, microprocessor and display(s). The system is shown in block diagram in Figure 8.

The multiplexer can accept up to 32 parallel inputs, each typically being the voltage output from a Piezoelectric acoustic detector on a valve. Each signal enters the signal conditioner in turn (rate selectable). The conditioner consists of an amplifier, a programmable filter and an interface to the microprocessor. The microprocessor will be programmed to accept special language commands from the terminal display. Through its use, the sampling procedure and data display modes can be varied.

The operator-oriented dedicated display will constantly present updated displays of the data. The following example demonstrates one possibility for the automatic mode:

Example: Using a narrow bandwidth of 7-9 kHz, each channel is sampled once a minute and a running average of rms and variance is compiled for an hour. The resulting two numbers (rms and variance) are entered into the past 50 hours of history. Each channel is sequentially displayed for ten seconds, unless the alert level has been exceeded. In that case, the channel will remain displayed and an alarm light will flash until an acknowledgment button is pressed. The sequential dis-

5.2 Valve Leakage Monitoring System (Cont'd.)

play will then continue. The freezing of the display does not influence the sampling tasks of the microprocessor. The memory is circular, that is, from zero time, the 51st data set replaces the first data set. A sample of an "alerted display" is depicted in Figure 9, where the recent history has stabilized above the alert level within normal variance.

The system will also permit further analysis of the situation by the research engineer. For example, each channel could be sampled in two bandwidths, one being a broadband background monitor. Through command, the background noise could be compared with the chosen leak-detection bandwidth. In this way, confidence in interpretation is enhanced. This part of the system utilizes existing peripheral instruments, interfaced to the microprocessor through a switch, so that their use on the AEM program is not affected. The predominant features for the research engineer's use are:

- Ability to use sequential sampling bandwidths, controlled by the microprocessor.
- Ease of changing sampling interval and sampling time.
- Ability to write descriptive notes on screen for hard copy records.
- Other forms of flexibility provided by special language and microprocessor.

Figure 15 shows a typical sensor installation on the main steam safety relief valves for leakage monitoring.

SECTION 6

TEST DATA

6.1 Continuation of On-Line Monitoring Effort (October 1, 1977 - March 22, 1978)

AE data was accumulated on the BWR components throughout the period of October 1, 1977 to March 22, 1978. During this time, approximately 5600 events were accepted as valid by the AE system. An additional 31,900 events were rejected. (Rejection was based on criteria that established invalid arrivals or erroneous electrical transients.) The major portion of the accepted events occurred on the recirculation bypass line. The remainder were randomly scattered about the different components corresponding to the same locations as discussed in DOE Report No. COO-4087-3 section on results.

The most outstanding series of events monitored during this period (October 1, 1977 - March 22, 1978) was accumulated between February 23, 1978 and March 3, 1978 on the recirculation bypass line (RB). Starting at about noontime on February 23, 1978, the threshold on guard sensor number RB 1 was consistently being exceeded. No investigation into this condition took place at this time due to the fact that it was a guard sensor. At approximately 1100 hrs on February 24, 1978, active sensor number RB 3 began exceeding the threshold with 600 mv p-p (3.75 S/N) bursts. At 1400 hrs, the same day active sensor number 1 began exceeding the threshold also with bursts of 400 mv p-p (2.66 S/N). During the 48-hour period (February 23, 1978 - February 24, 1978), 2765 events were accumulated. Figure 10 shows the rate of occurrence versus elapsed time for this period. The leak indication is readily observable. With these indications the following were the conclusions:

- Guard sensor No. RB 1 appeared to be sensing a leak.
- The active sensors are sensing transients indicative of rotating machinery impacting.

On March 5, 1978, Unit 3 was shutdown due to excessive leakage in the drywell. Upon inspection, our predictions were confirmed. The "B" Recirculation Discharge Pump (MO53) had a substantial leak and the "B" Recirculation Cross Connect Valve had a minor leak which stopped when the valve was back-seated. When the unit returned to operation, there were no indications as were previously observed.

As a result of the MSSRV monitoring system data taken during February 1978, five relief valves were removed during a convenient maintenance outage. The valves were discovered to have indications of leakage varying from 10 psi - 100 psi second stage pressure. Figure 11 shows the comparison of the existing spectrums between the leaking valves and the non-leaking valves. It is evident from Figure 11 that the leaking valves had clear evidence of valve leakage with the increased response in the frequency range 5-8 kHz. The valves that replaced these five had been recently rebuilt and did not leak. When the plant went back into operation the leak indications were gone. The five valves removed were decontaminated and sent to Wyle Laboratories for further investigation and recertification. Only one of these valves was scheduled to be tested as received and the other four were immediately rebuilt when received at Wyle.

The valve which was scheduled for testing as-received had a mating surface irregularity caused by an over-torqued bolt. The valve was disassembled and machined and recertification testing replaced the as-received testing. During the recertification testing pilot stem leakage was present approximately 100 psi below the set pressure on the valve.

Through February and March the monitoring system was 100% operational. There were no further indications of leakage in any of the 11 main steam safety relief valves. Figure 12 shows the typical display in which the detection of leakage is observed. Figure 12 is the weekly plot of the acoustic activity

occurring in the valve. Valve 5 has been steadily increasing for over five days. Presently confirmation of leakage is done by performing spectrum analysis as shown in Figure 11.

6.2 Refueling Outage Inspections and Installations (April - May 1978)

6.2.1 Inspections

Preparation was made to have a detailed ultrasonic and radiographic inspection of the areas involved in this program incorporated into the normal inservice inspection program scheduled for this refueling outage. This included resolution examination of all "insignificant indications" ($<100\%$ DAC). This was partially performed. The abnormally high radiation levels on the components in question negated a complete resolution examination (recording all indications $>20\%$ DAC). All the monitored components were inspected. Figure 13 compiles the results of the ultrasonic inspections. There were no recordable indications on the recirculation bypass line during both the 1977 and 1978 inservice inspection. Two geometric reflectors (insignificant) had been detected during the 1977 Feedwater "A" nozzle mechanized inspection with no corresponding examinations in the 1978 inspection. There were nine insignificant indications on various scans on the 1977 Feedwater "E" nozzle inspection. One of these was a 1/10-inch long slag-like indication at 36° nozzle azimuth at subsurface intersection of nozzle boss and vessel outside surface under the nozzle to vessel blend radius weld. The 1978 inspection of the Feedwater "E" nozzle revealed 20 insignificant indications.

Due to the high level of radiation on the components during the 1978 inspection any indication less than 100% DAC did not receive any additional resolution as was originally requested. This was done to prohibit excessive manpower radiation exposure which might have jeopardized the completion of the required inspection work. The 1979 inspections may incorporate a higher level of indication resolution due to the fact radiation levels may not be as high.

6.2.1 Inspections (Cont'd.)

The core spray lines had been repaired during the 1977 refueling outage. The inspection performed after the repair showed no recordable indications on either line. In 1978, 43 insignificant indications were located on the core spray "B" loop. Four of these indications were found on the pipe-to-elbow weld number 23. The remaining 39 were found on the reducer-to-pipe weld number 26.

The 1979 refueling outage is scheduled to accommodate a large amount of maintenance which will extend the outage to four-six months long. If this should occur, there is a good chance that detailed resolution of the insignificant indications can be obtained at that time.

From the final report covering the first year of this program, "It is concluded that no major AE indication of stress corrosion cracking (or thermal fatigue cracking) was observed in these components during the five and a half months ending on September 28, 1977." The monitoring results from the October 1977 through April 1978 period also did not indicate any sources of major stress corrosion cracking or thermal cycle fatigue cracking. The inservice inspection confirms these results. No significant indications were found on any of these components.

Figure 14 shows the activity distribution around the "B" core spray weld number 26. This activity was accumulated during load and heat reduction operations of the plant and is representative of insignificant activity. This reduction operation is a critical time for acoustic emission during stress corrosion cracking. Thirty-nine insignificant indications were located at that weld during UT inspection. Repetition of this behavior during future plant operations will be considered particularly important and emphasis will be placed on these areas during the succeeding inservice inspection.

6.2.2 Calibrations

As part of the refueling outage, all of the incontainment instruments were removed, recalibrated, refurbished, and reinstalled. Calibrations were performed to evaluate the degradation of sensitivity the various channels experienced in the reactor operating environment. Secondary calibrations were performed after all channels were upgraded and refurbished. Finally a tertiary calibration was performed on the channels after they were installed. This remote tertiary calibration is being performed once a week throughout the operating cycle until the next refueling outage. This will enable an understanding of the sensitivity fluctuations in an operating environment. A channel consists of the mounting structure, sensor, cable preamplifier and transmission line. Each item was calibrated separately and then as a unit.

All AE sensors used during plant operation had sufficient degradation that the average sensitivity was down 30 dB from original calibrations. The degradation was found to be a result of over temperature instead of over radiation. Based on the fact that sensitivity was down, all sensors were replaced.

The performance of approximately 60 sensors and 60 preamplifiers were assured by using present ASTM recommended practices (in ballot). In addition, the entire electronic instrumentation system was checked using the proposed ASTM recommended practice (see Appendix 2).

SECTION 7

PLANS

No work to date has been accomplished on Tasks 3 through 6. Progress has begun to have these tasks completed by the end of the contract.

Plans have been made to monitor channel sensitivity versus plant operating time very closely. Data will be accumulated continuously on all components throughout this operating cycle. Data will be reduced generally at the completion of each data disc. Data will be reduced extensively once a month. Accurate plant parameters will be included in the data set, such as component temperature, vibration amplitude, vibration frequency, feedwater flow and total core flow. This will enable more profitable data reduction processes. Alarms have been set to notify the technical staff of the research program that a concentrated amount of activity has occurred and that its source should be investigated.

The next outage of Peach Bottom Unit 3 is scheduled for September 1979. At this time, further investigations will take place to identify the sources of detected acoustic emission and to determine the overall performance of the acoustic emission instrumentation.

Figure 1 - Main Steam Safety Relief Valve Schematic

mirror insulation (covers sensors)

calibration
solenoid

AE sensor

vibration sensor

Figure 2 - Recirculation Bypass Line Installation

"A" Core Spray

AE sensor

Preamplifier
Housing

mirror insulation

"B" Core Spray

Figure 3 - Core Spray Lines

Feedwater N4A & N4E Nozzles

Figure 4 - Feedwater Nozzles

CALIBRATION RECORD

Acoustic Emission Sensor
Manufacturer: Trodyne Corp.
Model No.: 7537A-500K REV B
Serial No.: 2572
Capacitance: 120 PF
Nominal Frequency: 500 kHz

Figure 6 - Typical Sensor Calibration Record

Figure 7 - Recirculation Bypass Line Installation

FIGURE 8 MAIN STEAM SAFETY RELIEF VALVE LEAKAGE MONITORING SYSTEM BLOCK DIAGRAM

Figure 9 - Example of Operator-Oriented Display, Showing an Increasing rms Signal, Which Has Stabilized Above the Alert Level

Figure 10 - Recirculation Bypass; Rate of Occurrence vs Elapsed Time

Figure 11

PECO VALVE LEAK MONITOR
VALVE #02 BANDWIDTH B 14-DEC-78 13:09:18
REPLOTTED HOURLY

FIGURE 12
RATIO PLOT USED TO DETECT
LEAKAGE

Figure 13 - Ultrasonic Inspections

Recirc. Bypass	January 1977			April 1978		
	No Recordable Indications	Insignificant Indications (0-100% DAC)	Geometric Reflections	No Recordable Indications	Insignificant Indications (0-100% DAC)	Geometric Reflections
<u>Weld 8 Visual</u>	x			x		
0° Lam Scan	x			x		
45° Scan	x			x		
45° T Scan	x			x		
60° Scan	x			x		
<u>Weld 9 Visual</u>	x			x		
0° Lam Scan	x			x		
45° Scan	x			x		
45° T Scan	x			x		
60° Scan	x			x		
Feedwater "A"						
Mechanized						
21° RC	x			x		
0° Lam Scan	x			NP		
0° Weld Scan			2	NP		
45° Scan	x			NP		
60° Scan	x			NP		
Feedwater "E"						
Mechanized						
21° RC		5			20	3
0° Lam Scan	x			x		
0° Weld Scan		*		NP		
45° Scan		2		x		
60° Scan		1		x		

- Not Performed

1/10" long slag-like indication at 36° nozzle azimuth at subsurface intersection of nozzle boss and vessel outside surface under the nozzle to vessel blend radius weld (2" metal path).

Figure 13 - Ultrasonic Inspections (Cont'd.)

January 1977				April 1978		
Core Spray "B"	No Recordable Indications	Insignificant Indications (0-100% DAC)	Geometric Reflections	No Recordable Indications	Insignificant Indications (0-100% DAC)	Geometric Reflections
<u>Weld 23 Visual</u>	x			x		
0° Lam Scan	x			x		
45° T Scan	x			x		
45° Scan	x				1	
60° Scan	x				3	
<u>Weld 24 R</u>						
Radiograph	x			x		
<u>Weld 25 R</u>						
Radiograph	x			x		
<u>Weld 26 Visual</u>						
0° Lam Scan	x			x		
45° T Scan	x			x		
45° Scan	x				11	5
50° Scan	x				18	2
Core Spray "A"						
<u>Weld 23 Visual</u>						
0° Lam Scan	x			x		
45° T Scan	x			x		
45° Scan	x				1	
60° Scan	x				3	
<u>Weld 24 R</u>						
Radiograph	x			x		
<u>Weld 25 R</u>						
Radiograph	x			x		
<u>Weld 26 Visual</u>	x			x		

Core Spray "B"

Activity Distribution
PB20 File

Figure 14 - Source Location Core Spray "B"

Figure 15 - Main Steam Safety Relief Valves Installation

APPENDIX 1

Multi-Sensor Comprehensive Data System

TRODYNE
CORPORATION

Tomorrow's Concepts Today

MSCD ACOUSTIC EMISSION

Multi-Sensor Comprehensive Data System

TYPICAL ARRANGEMENT OF AN MSCD "STANDARD" VERSION.

OUTSTANDING FEATURES OF THE MSCD SYSTEM

- ★ OPERATION NOT RESTRICTED BY STRUCTURAL GEOMETRY.
- ★ SENSOR ARRAY PATTERNS DETERMINED BY APPLICATION REQUIREMENTS AND NOT BY SYSTEM CONSTRAINTS.
- ★ OPTIMUM DATA REDUCTION DUE TO UNIQUE DISCRIMINATION TECHNIQUES.
- ★ DATA GENERATION AND DATA TRANSFER DECISIONS PERFORMED BY AE INSTRUMENTATION (MICROSECONDS) NOT BY MINICOMPUTER (MILLISECONDS).
- ★ COMPLETE AE DATA SET ACCUMULATED FOR EACH EVENT.
- ★ PRIORITY INTERRUPT FEATURE ASSURES PREFERENCE OF REAL-TIME DATA TRANSFER AMONG ALL OPERATIONS.
- ★ DISC OPERATION FOR HIGH SPEED MASS DATA STORAGE.
- ★ CAPABLE OF GENERATING TRADITIONAL AE FUNCTIONS WITHOUT SPECIALIZED HARDWARE.
- ★ UNLIMITED INPUT CHANNEL EXPANSION.
- ★ LOW EXPANSION COSTS.

The Multi-Sensor Comprehensive Data (MSCD) System represents a significant expansion of acoustic emission measurement capabilities. The demand for its development originated from the nuclear and conventional power industries and from the chemical processing industry with the need of applying acoustic emission techniques to large structures. The multitude of various forms and shapes represented by these structures require system operation not only with many channels but also with flexibility and adaptability to any structural geometry. Because of the quantity of data that was involved in larger or more complicated structures, a complete re-evaluation of system concepts was necessary. This new system concept affected the areas of data acquisition, storage and presentation of results. Heretofore, conventional systems measured unrelated parameters, generated by specialized hardware and presented by considerable and costly duplication of output devices. It was obvious that a consolidation of the numerous AE parameters and hardware functions were required. Recognizing the need for a comprehensive data system for acoustic emission instrumentation, the MSCD system was developed.

The fundamental design criteria are as follows:

- i. No limitation regarding the number of sensors employed by the system.
- ii. System operation to be independent of structural geometry.
- iii. Operation to be independent of any specific sensor arrangement.
- iv. Sensors to be capable of performing measuring, control and discrimination functions simultaneously.

FUNCTIONAL DESCRIPTION. Briefly, the MSCD measures the magnitude of acoustic emission events in a structure as a function of their location, the time of their occurrence and several circumstantial parameters (e.g. stress, strain, temperature, etc.) Furthermore, the system processes all the derived acoustic emission parameters, instantaneously presents the data in selected functional relationships and stores the full compliment of processed data for off-line analysis.

Each input channel consists of a sensor, preamplifier and amplifier. Six channels feed the amplified and filtered signals into the detector module. The detected signals from 12 channels are fed into the multi-sensor processor. By adding a data system expander to the processor, the system can be expanded by an additional 12 channels. By adding additional detector and expander modules, the system can be expanded without any system limitations.

The sensors are not assigned rigidly into groups or arrays. Moreover, they do not have to cover a contiguous area on the structure. Peripheral or internal boundaries can be arbitrarily employed. The group of sensors which actually performs the single measurement is determined by the signal itself. The three nearest sensors register the first, second and third arrivals. At the time of the third arrival, all measured parameters are digitally encoded in primary storage registers. These parameters are: arrival time differences, sensor identity codes in the sequence of arrivals, the peak voltage of the analog signal envelope, the event number, elapsed time and the parametric quantities. The oscillation count is an exception requiring a much longer time to accumulate; however, its use is optional and not necessary.

The integrity and correctness of the measurement is protected by advanced methods in the system. The instantaneous state of acoustic excitation of a large structure can be very complicated. The probability of nearly simultaneous or overlapping source signals and their secondary effects is increased by the magnitude of the structure. Acoustic emission measurements, on the other hand, are meaningful only if they are related to single and discrete events. The identification of measurable events and the protection of the measurement are assured by the following:

- i. The time required for a measurement is kept to a minimum. This reduces adverse effects that are caused by nearly simultaneous or overlapping source signals.
- ii. A "Programmable Exclusion Logic" circuitry sequentially excludes the unnecessary sensors for the time of the measurement. The first arrival sensor causes its own exclusion and the exclusion of all the other sensors which cannot form a legitimate arrival sequence with the first.
- iii. A "Sensor Activity Detection" feature constantly monitors the status of all sensors in the system. It determines the instantaneous time when the structure is in a favorable state for the next measurement. The system is reset at this point.
- iv. In applications where a region of a structure is to be AE examined, the active sensor arrangements can be protected against signals that originate outside of the region. If any one of the boundary guard sensors detects a first arrival, the programmable exclusion logic circuitry activates an abort function and the instrumentation will abandon the particular measurement.

In agreement with the design philosophy of the Multi-Sensor Comprehensive Data System, the acoustic emission hardware gathers all the measurable independent acoustic emission parameters into a set of storage registers. A data set is identified by the event sequence number and consists of arrival time differences, sensor identity codes, arrival sequence, peak amplitude, parametric value and instantaneous elapsed time. This set of data is immediately transferred to a buffer area of the data processing hardware. The data set is then processed to generate the derived acoustic emission parameters. These are grouped into the following categories:

- i. Linear or logarithmic rate of events, peak amplitudes and oscillation count with time as the independent parameter.
- ii. Count event ratio and amplitude distribution with a selected number of events as the independent variable.
- iii. Accumulation of rate of events and peak amplitudes with location coordinates as the independent variable. For the MSCD System, two new parameters are defined, the magnitude distribution and the activity distribution functions. The magnitude distribution function is generated by the summation of peak signal amplitudes (or oscillation counts) for each source individually and then the operation is extended to all sources on the entire structure. A similar operation leads to the activity distribution function.

DATA PRESENTATION. Most applications require that selected processed data be presented instantaneously to the operator. Other parameters, on the other hand, can wait or are meaningful only after the real-time test. The most popular real-time output device is a CRT screen with the capability of presenting both graphic and alpha-numeric information. The most frequently desired real-time information is the graphic display of locations of the sources, referenced to a mapped representation of the structure and of histograms showing the accumulation of peak amplitudes as a function of locations on the structure.

In order to maintain a permanent record of the entire test or measurement and to make the data available for post-test analysis, the processed data sets are stored in mass storage.

The real-time data presentation and the mass storage immediately determine the nature of the necessary computer peripheral devices. The real-time display is done through a storage type CRT terminal device. In most instances, it is combined with a Hard Copy Unit which can produce a permanent record of the content

of the screen at any desired moment of the test. The terminal part serves as operator communication with the data processing equipment. The mass storage is usually a floppy disc or a rigid disc system or, in smaller systems, it can be punched paper tape.

The full capability of the MSCD System can only be utilized if the proper data presentation and storage devices are available to the system. Therefore, several levels of sophistication in peripheral equipment are offered in terms of processing speed, data storage capacity and software operating systems.

SOFTWARE. As a consequence of the most popular hardware configuration, four groups of software are provided with Multi-Sensor Data Systems. These are:

- i. **Real-Time Multi-Sensor Data System Programs.** These control the data gathering from the acoustic emission equipment, the testing of the data sets for validity, the data set processing, storing the data sets in mass storage, generation of the data presentation functions, servicing of the output peripherals, measurement of propagation velocity and the performing of system self-test functions. The source programs in this category are written in assembly language or FORTRAN II and processed through Hewlett-Packard Basic Control System or Disc Operating System or Dicom Floppy Disc Operating System.
- ii. **Off-Line Analytical Programs.** The collection of programs in this series provides post-test analysis, data reduction and reporting capability. The processed data sets will be taken from mass storage and individual parameters will be lifted off and combined in required associations and presented through the selected output device as a print-out or graph. These source programs are written in assembly language or in FORTRAN II.
- iii. **Standard Software.** These include operating and programming systems, data handling, testing and programming aids.
- iv. **Configured Software.** The more important programming systems are also supplied in configured form.

HARDWARE. The MSCD System is divided into two sections, Data Acquisition and Data Processing. The acquisition section includes Acoustic Emission detection, filtering, amplification and data accumulation functions. The data processing section transfers the data into the buffer memory and controls the recording, computational and data presentation functions.

Several versions of the MSCD system are available, offering the widest selection of AE functions and several levels of sophistication in peripheral equipment in terms of processing speed, data storage capacity and software operating systems. For less complex requirements, there is a "Starter" version, which at very nominal cost can be expanded to a "Standard" version and still further expanded to a "Full-Line" version. There is no difference among all versions with respect to the Data Acquisition (AE) Section. There is only a difference in the number of input channels, which is selected in accordance with program requirements. Therefore, the "Starter" version may consist of the Data Acquisition Section with less than twelve input channels plus the very minimum of data presentation peripherals. Obviously, whenever peripherals are added, the full potential of the MSCD system is increasingly realized.

The "Standard" version normally consists of twelve or more input channels and is capable of handling

large data volumes and complicated sensor arrangements for larger and more complex structures.

Further expansion of mass memory and the addition of high speed printing capability lead to the MSCD "Full-Line" version, offering the utmost in convenience and speed of operation. The "Full-Line" version represents the complete capability for utilizing the potentials inherent in the Data Acquisition (AE) Section.

For special requirements, "Custom" versions can be made available.

In addition to an extensive software library, Trodyne's Computation and Programming Group can develop software for special requirements.

For further information of the Trodyne MSCD System, write to the attention of Marketing Manager and request a detailed MSCD Technical Description.

TYPICAL SPACE SAVING ARRANGEMENT OF AN MSCD "STANDARD" VERSION IN ONE CABINET.

TYPICAL ARRANGEMENT OF AN MSCD "FULL-LINE" VERSION.

TRODYNE

CORPORATION • 39 INDUSTRIAL AVENUE • TETERBORO, NEW JERSEY 07608 • 201 288-4400

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APPENDIX 2

"Recommended Practice for Measuring the Limits of Specified AE Instrumentation"

August 22, 1978

E07.03.04

RECOMMENDED PRACTICE FOR MEASURING THE LIMITS OF
SPECIFIED ACOUSTIC EMISSION INSTRUMENTATION

1.0 GENERAL

1.1 Purpose

- 1.1.1 This recommended practice is intended for use as a guide in testing and measuring specific operating characteristics of specified acoustic emission electronic components or units.
- 1.1.2 Where the manufacturer of the specified component or unit provides testing and measuring details in an operating and maintenance manual, the manufacturer's methods shall prevail over the suggested methods described in this document.
- 1.1.3 Difficult or questionable system measurements shall be referred to qualified electronics personnel working in well equipped instrumentation standards laboratories.
- 1.1.4 The methods set forth in this document are not intended to be either exclusive or exhaustive. The user of this document assumes the full responsibility for both the techniques used for and the results of all specified measurements.
- 1.1.5 The methods (techniques) used for testing and measuring the components or units of an acoustic emission system, and the results of such testing and measuring shall be documented and defensible and in accord with currently accepted

standards in the industry. Documentation shall consist of photographs, charts or graphs, calculations, and tabulations where applicable.

1.2 Specified components

1.2.1 The specific acoustic emission electronic components or units shall include the sensor(s), preamplifier(s), filter(s), power amplifier(s), line drive amplifier(s), threshold and counting instrumentation, and signal transmission lines.

1.2.2 The sensitivity calibration and transfer characteristics of sensors are excluded from this document.

1.3 Required measurements

1.3.1 Tests and measurements shall be performed to determine the limits of acoustic emission system bandwidth, system gain, system dynamic range, system threshold of detection, system dead time, system noise, and system precision in emission counting.

1.3.2 Where acoustic emission test results depend upon the reproduced accuracy of the temporal, spatial, or spectral histories, additional measurements of system parameters shall be performed to determine the specific limits of system performance. Examples of such measurements may include amplifier slew rate, gate window width and position, and spectral analysis.

1.3.3 Tests and measurements shall be performed to determine the loss in sensor sensitivity resulting from the coupling of a transmission line and preamplifier to the sensor. The transmission line and preamplifier shall be the same as that used for the acoustic emission tests without substitution.

2.0 Applicable Documents

- 2.1 ASTM E610-77, "Standard Definition of Terms Relating to Acoustic Emission."
- 2.2 ASTM E_____, (Calibration of Open Circuit Sensitivity of Acoustic Emission Sensors).
- 2.3 Manufacturer's Operating and Maintenance Manuals pertinent to the specific system or component.

3.0 Definitions

- 3.1 Voltage Threshold: A voltage level on an electronic comparator such that signals with amplitudes larger than this level will be recognized. The voltage threshold may be user adjustable or design fixed or automatic floating.
- 3.2 System Dead Time: The interval following an acoustic emission event during which a system is incapable of repeating a specified performance. The system dead time is comprised of the overload recovery time and the rearm delay time.
- 3.3 Overload Recovery Time: The interval following an acoustic emission event in which the amplitude exceeded the linear operating range

over a measurable time period causing incorrect operating bias voltage/current within the system or component.

- 3.4 Rearm Delay Time: The interval where the system or component is incapable of accepting new information following a detected acoustic emission event. The rearm delay may be variable or fixed.
- 3.5 Dynamic Range: The ratio of the specified maximum signal level capability of a system or component to its noise level. The maximum signal level must be specified: for example, signal distortion, overheating, damage, etc. Where the maximum signal level is specified by signal distortion, the distortion level shall be given as a percent total harmonic distortion.
- 3.6 Signal Overload Point: For any specified setting of the amplifier gain controls, and with an input signal increasing from any level within the linear operating range of the amplifier, that input signal amplitude at which the ratio of output to the input first differs by 3dB from the ratio of output to input observed within the linear operating range.

NOTE: This is an amplitude rather than a distortion criteria.

4.0 Test Apparatus

- 4.1 The basic test instruments required for measuring the operating characteristics of an acoustic emission system shall include:
 - 4.1.1 Variable sine wave generator
 - 4.1.2 RMS voltmeter

4.1.3 Oscilloscope

4.1.4 Attenuator variable in decibels

4.1.5 Phase meter

4.1.6 Tone burst generator

4.2 Additional test instruments shall be used for more specialized measurements of acoustic emission systems or components. Some of the recommended test instruments shall include:

4.2.1 Variable function generator

4.2.2 Time interval meter

4.2.3 Frequency meter, or counter

4.2.4 Random noise generator

4.2.5 Spectrum analyzer

4.2.6 D.C. voltmeter

4.2.7 Tone burst generator

4.2.8 Variable pulse generator

5.0 The Acoustic Emission System

5.1 The Acoustic Emission Sensor

5.1.1 An acoustic emission sensor is an electro-acoustic transducer which converts stress wave energy into electrical energy the wave form in this conversion remaining substantially unaltered.

5.1.2 A transformer or amplifier, or acoustic wave guide, if combined with the sensor in such way that the readily accessible terminals include these components shall be

considered part of the sensor and the term "sensor" shall apply to the combination.

5.1.3 Sensors may be designed with different active elements including magnetostrictive, electromagnetic, eddy current, capacitive, piezoresistive, piezoelectric, photoacoustic or acoustoelectric devices.

5.1.4 The most frequently used sensor is the piezoelectric type contained within a conductive housing. The active face is often fitted with a nonconductive, machinable wear plate or shoe. An electrical connector mounted to the housing completes the sensor.

5.2 The Acoustic Emission Preamplifier

5.2.1 The acoustic emission preamplifier is the first amplifier following the sensor. The preamplifier may be battery operated or power may be supplied by the secondary amplifier, or powered directly from the power mains. The preamplifier is defined as the first stage of amplification with the major function of converting the sensor impedance to an impedance suitable for driving long signal transmission lines and additional electronic components or units.

5.2.2 The input impedance of a preamplifier forms the load for the sensor. The proper magnitude and phase angle of the input impedance is governed by the sensor requirements. Inductive sensors may require relatively low impedance loads.

Capacitive sensors generally require high impedance loads.

The low impedance loads depend upon current (or power) drive, and the high impedance loads depend upon voltage (or charge) drive. Because the most used sensor is a piezoceramic device, the preamplifier input impedance is moderately high.

5.2.3 The output impedance of acoustic emission preamplifiers is low, usually about 50 ohms. This low impedance is required for the purpose of driving long transmission lines and reducing the susceptibility to coupled noise currents.

5.2.4 The acoustic emission preamplifier may include filters and input/output line transformers. Filters are often employed to reject undesirable signals for the purpose of avoiding potentially overdriven stages within the preamplifier and succeeding components, or units. Transformers are used for matching impedances between the source and its load. Transformers are also used for matching balanced to unbalanced transmission systems.

5.3 The Acoustic Emission Secondary Amplifier

5.3.1 The secondary amplifier provides the final, required system amplification. This amplifier must supply sufficient signal power to supply a combination of additional components or units such as: oscilloscope, voltmeter, counters, and recorders. For this reason, the secondary amplifier is often

called a power amplifier.

- 5.3.2 The secondary amplifier may also include signal processing circuits such as an rms voltage converter, and an event counting circuit. Additional bandpass filtering is often employed in this amplifier.
- 5.3.3 The input impedance of the secondary amplifier shall provide the required load impedance for the preceding component. The preceding component is usually the preamplifier, but may be a bandpass filter.
- 5.3.4 The secondary amplifier shall be used within its stated nominal operating range. The amplifier shall complement the operating characteristics of the preceding component.

5.4 Wave Filter (Filter)

- 5.4.1 A wave filter separates waves on the basis of their frequency. It introduces relatively small insertion loss to waves in one or more frequency bands and relatively large insertion loss to waves of other frequencies.
- 5.4.2 Filters may be active or passive. Active filters require electrical power. Passive filters require no electrical power.
- 5.4.3 The most frequently used filter is the bandpass filter. A bandpass filter is a wave filter that has a single transmission band extending from a lower cutoff frequency greater than zero to a finite upper cutoff frequency. The

amplitude of the cutoff frequency shall be 3dB less than the passband center frequency unless otherwise specified.

5.4.4 The filter shall not limit the specified signal overload point of the preceeding component or unit.

5.4.5 A.C. coupled amplifiers and preamplifiers limit the bandwidth by circuit design, although these components may not admit to having a designed wave filter. Typical bandwidths may extend from a low of .004 to 100 kHz, to a high of 300 to 4000 kHz for these components.

5.5 Transmission Lines

5.5.1 A transmission line is defined as a wave guide consisting of two or more conductors. Transmission lines are characterized according to their configuration and use. The most frequently used transmission lines for conducting acoustic emission signal currents are the coaxial (coax) lines, followed by the shielded pair of wires, triaxial lines, and the shielded multiconductor.

5.5.2 Transmission lines have unique characteristics. The electrical currents flow through the lines at a fixed velocity less than the speed of light in a vacuum. This value is called the "velocity factor" and is stated in terms of percent of the speed of light. Transmission lines have impedance to current flow. This impedance is defined as the "characteristic impedance". The impedance presented to a

signal current depends upon the termination of the line, the characteristic impedance, and the signal wavelength with respect to the line length.

5.5.3 The length of the transmission line may have a direct effect on the signal currents delivered to the load. One of the less innocuous effects of a line is the distributed capacitance. Capacitive shunting of piezoelectric elements and capacitive sensors will attenuate the signal by voltage or charge division independent of frequency.

5.5.4 The choice of transmission line and the termination of this line shall be governed by the specified load and service requirements of the component or unit to which it is attached. Line reflections of signals are considered insignificant compared with acoustic reflections within test structures.

5.6 Line Drive Amplifiers

5.6.1 Where extremely long transmission lines must be used, line drive amplifiers are frequently used. The line drive amplifier is an impedance conversion device with a unity gain. Line drive amplifiers are used to supply sufficient signal current to drive several hundreds of meters of transmission line.

5.6.2 The output impedance of a line drive amplifier shall be the same impedance as the transmission line that it drives, and

the transmission line shall terminate in its characteristic impedance for maximum power transfer.

- 5.6.3 The dynamic range, signal overload point, and spectral response of the line drive amplifier shall be equal to or greater than those of the preceding component or unit unless otherwise specifically stated in report documentation.

5.7 Threshold Counting Instrumentation

- 5.7.1 Threshold counting is one of the most frequently used signal processing techniques for acoustic emission. This technique requires the signal amplitude to exceed a threshold voltage or comparator level to be recognized and recorded. Counting is often performed in two ways: rate and summation counting. The accuracy of rate counting depends upon the accuracy of a comparator clock frequency. The precision of rate and summation counting depend upon the stability of the threshold level and frequency selectivity.
- 5.7.2 The threshold level shall be specified as fixed, manually variable, and/or automatic floating depending upon the design and user application.
- 5.7.3 Tests and measurements shall be performed to determine the threshold level, frequency sensitivity, and time constants for signal detection and recovery. Permanent records shall be maintained and made available for inspection on the results of these tests and measurements.

5.7.4 Tests and measurements shall be performed to establish the accuracy and precision of the comparator clock used in rate counting. These records shall be made available for inspection and maintained on file.

6.0 Tests and Measurements

6.1 Preamplifier Input Impedance

6.1.1 The preamplifier input impedance shall be documented as the nominal input impedance. The preferred expression of input impedance shall be a stated value of resistance shunted by a stated value of capacitance.

6.1.2 Where inductive coupling is used, the input impedance shall be documented in either the polar or rectangular form of its equivalent impedance as a function of frequency over the designed bandwidth of the preamplifier.

6.1.3 Where charge amplifiers are used for acoustic emission amplification, the manufacturers specification shall suffice to describe the input impedance for direct coupled piezoelectric generators. Any modification of the input impedance and the precise change of that impedance shall be documented.

6.2 Input Transmission Lines

6.2.1 The transmission line, coupling the piezoelectric/capacitive sensor to the preamplifier, together with the transmission line couplings shall be measured with a suitable bridge to

determine the line capacitance.

- 6.2.2 The line capacitance shall be documented and added to the preamplifier capacitance. The sum of line capacitance and preamplifier input capacitance shall be documented as the sensor load capacitance.
 - 6.2.3 Where the sensor to preamplifier cable is used for also supplying a voltage to the sensor the cross coupling between the signal lines and power supply lines shall be documented. This documentation may be waived where proof exists that the coupling will not affect the acoustic emission signal with system gains up to 100 dBV.
 - 6.2.4 The influence of the transmission line and preamplifier impedance on the sensor open circuit sensitivity shall be documented regardless of the sensor, transmission line, and preamplifier type or design.
- 6.3 System Bandwidth
- 6.3.1 The system bandwidth shall be measured to a minimum of one full octave beyond each of the nominal cutoff frequencies.
 - 6.3.2 The bandwidth shall include all contiguous frequencies with amplitude variations limited to $\pm 3\text{dB}$. Systems which include signal processing of amplitude as a function of frequency shall have bandwidth amplitude variations limited to $\pm 1.5\text{ dB}$.
 - 6.3.3 The System, shown in Fig. 1, shall include the preamplifier wave filters, secondary amplifier, and interconnecting

cables. All measurements and tests shall be documented.

6.3.4 With the system connected as in Fig. 1 and the sine wave oscillator set well within the system's specified dynamic range, the bandwidth may be measured to the nominal cutoff frequencies. The oscillator is maintained at a fixed amplitude and the frequency is swept through the bandwidth limits. The secondary amplifier, or final filter, output is monitored with an rms voltmeter. Values of amplitude are logged for each of several frequencies within and beyond the nominal cutoff frequencies. The logged values are plotted on suitable chart paper. The amplitude scale may be converted to decibels with each major division equal to 0.5 dB. The frequency scale may be plotted either linearly or logarithmically.

6.4 System Gain

- 6.4.1 The system gain in decibels is the sum of the sensor sensitivity rating in decibels, the electronic amplification in decibels, and the sensor coupling factor in decibels.
- 6.4.2 The electronic amplification is comprised of the preamplifier gain, the secondary amplifier gain and the wave filters insertion gains or losses.
- 6.4.3 Piezoelectric and capacitor sensors are rated in decibels referred to one volt per pascal. All other sensors are rated

in decibels referred to one milliwatt per pascal and the rating impedance shall conform with ANSI S1.1, 7.24 as shown in Fig. 2. The units shall be 0 dBV per Pa, and 0 dBm per Pa, respectively for the one volt reference, and one milliwatt reference.

- 6.4.4 The electronic amplification may be measured with the system shown in Fig. 1. The sine wave oscillator is set to the geometric mean of the nominal bandwidth of the system.

$$f_M = (f_L f_H)^{1/2} \quad \text{Where:}$$

f_M = Mean frequency
 f_L = Nominal lower cutoff
 f_H = Nominal upper cutoff

The oscillator amplitude is set well within the system's dynamic range to avoid the signal overload point.

With the voltmeter at V_{osc} set the oscillator amplitude to one volt. The attenuator is set for a value greater than the anticipated electronic amplification. Next, move the voltmeter to V_{out} . The attenuator is now adjusted until the voltmeter again reads one volt. The electronic amplification is equal to the new setting on the attenuator.

NOTE: If the input impedance of the preamplifier is not equal to the required load impedance of the attenuator, proper compensation shall be made.

6.4.5 This system gain measurement is known as the "Insertion Voltage, Gain Measurement." The root-mean-square (rms) open circuit voltage of a sensor at a given single frequency is the calibrating rms voltage necessary to produce the same deflection on the indicator connected to the output terminals of the sensor amplifier as that produced by the stress wave pressure at that frequency activating the sensor in the absence of the calibrating voltage. The open circuit voltage of a sensor is determined by the following method: the two accessible electrical terminals of a sensor on which stress wave pressure is acting can be regarded as the terminals of a generator having an internal electrical impedance connected in series with an electromotive force. The electromotive force which is equal to the open circuit voltage is measured by connecting a low impedance source of known and adjustable voltage, called the calibrating voltage, in series with the sensor and an amplifier-indicator system. The calibrating voltage is adjusted until the same effect is produced as is produced by the open circuit voltage generated by a given stress wave pressure acting on the sensor element in the absence of the calibrating voltage. The open circuit voltage is then equal in magnitude to the calibrating voltage. The connection of the known calibrating voltage source to the sensor adds an accessible electrical terminal to the sensor

and calibrating voltage system. The new terminal is at ground potential (see Fig. 3) and serves as a shield to fix the impedance between the terminals of the sensor.

- 6.4.6 The electrical transfer function displaying amplitude as a function of frequency may be accomplished through the use of a sweep generator synchronized with a spectrum analyzer. The known calibrating voltage source is replaced with the sweep generator. The indicator on the amplifier output terminals is replaced with a spectrum analyzer. The spectrum will display the sensor resonances, if any, and the behavior of the wave filters, and the system gain as a function of frequency. Replacing the sensor with a short circuit effectively places the sweep generator across the amplifier input terminals. The difference in amplitude observed before and after removing the sensor will permit a calculation of the sensor coupling coefficient as a function of frequency.

NOTE: The system components or units shall not be substituted for those components or units actually used for in service acoustic emission tests.

6.5 System Dynamic Range

- 6.5.1 The criteria used for establishing dynamic range shall be documented as either the signal overload point (Section 3.6), or the one percent total harmonic distortion point (Section 3.5), referenced to the system noise amplitude. In addition,

dynamic range relating to system damage may also be documented. The total harmonic distortion criteria shall be used for signal processing involving spectrum analysis. All other signal processing may be performed with the signal overload point criteria.

6.5.2 The dynamic range may be measured as

$$\text{Dynamic Range} = 20 \log_{10} \left(\frac{\text{maximum peak to peak}^* \text{ output}^*}{\text{peak to peak noise output}} \right) \text{ dB}$$

*At the signal overload point, Section 3.6. Adequate peak to peak measurements may be performed with a wide bandwidth oscilloscope. The time base should be set for 5. ms per cm, and the oscilloscope vertical amplifier should be calibrated for the amplitudes required.

6.5.3 The system electronic noise may be measured with the system assembled as in Fig. with the sensor connected (sine wave oscillator disconnected). The peak to peak voltage is measured at the system output (V_{out}). NOTE: The electronic noise is sensor dependent, and the noise measurement assumes no external excitation of the sensor.

6.5.4 The signal overload point is measured by replacing the sensor with a sine wave oscillator as shown in Fig. 1. The frequency is set for the geometric mean frequency of the system. The oscillator amplitude is fixed at one volt peak to peak monitored at V_{osc} . The attenuator is adjusted to

increase the signal level to the preamplifier until a further one decibel signal increase will not produce a corresponding increase at the system output (V_{out}) as measured with an oscilloscope. A one decibel change is equivalent to approximately 12% voltage amplitude change.

- 6.5.5 Should the peak amplitude of acoustic emission events exceed the dynamic range, several deleterious effects may be produced among which are clipping, saturation, and overload recovery time related phenomena. The system gain should be adjusted to limit these effects to an absolute minimum and to increase the reliability of the data.

6.6 Overload Recovery Time

- 6.6.1 The overload recovery time results from insufficient dynamic range. The time required to recover from an acoustic emission event whose amplitude exceeds the dynamic range depends on the amplifier and system design and the magnitude of the event.
- 6.6.2 The recovery time may be measured with an oscilloscope and a tone burst generator. The tone burst generator replaces the oscillator shown in Fig. 1 and the oscilloscope is connected to V_{out} . The tone burst generator is set between the geometric mean frequency and the nominal lower cutoff frequency. The duration of the tone burst is set for the duration expected from the acoustic emission events. Unless

otherwise restricted and stated, the amplitude shall be set for ten times the signal overload point. The tone burst shall have a repetition time in excess of the system recovery time such that system recovery shall occur in less time than the next tone burst would occur. The oscilloscope shall record the signal at V_{out} such that the residual feed through from the tone burst generator may be observed following the tone burst and system overload recovery. This residual should be less than one percent of the tone burst amplitude. The system overload recovery time shall be the time from the end of the tone burst to when the residual feed through appears.

6.7 System Dead Time

6.7.1 The system dead time is dependent on the signal processing instrumentation. This dead time may be variable or fixed depending on the system design for handling the routing of the input and output data processing. The dead time also includes the overload recovery time whose measurement is given in Section 6.6.

6.7.2 The measurement of data input/output delay depends upon the system design following the secondary amplifier. This delay shall be documented where the delay exceeds 20 microseconds.

6.8 Threshold Level (Threshold of Detection)

6.8.1 Various acoustic emission signal processing instruments rely

upon the signal exceeding a comparator voltage level. This level may be fixed, adjustable, or floating and fixed, or floating and adjustable. The floating threshold may be called automatic threshold. Signal recognition does not occur until the threshold is exceeded.

6.8.2 The nonautomatic threshold level may be measured with the system assembled as shown in Fig. 1 and the signal processors attached to the point V_{out} . The signal processors are frequently digital electronic counters that may be part of the secondary amplifier or independent components or units connected externally to the amplifier. Increasing the oscillator amplitude will result in an increasing signal level at V_{out} . The counters will begin count at some level. This level may be measured with an oscilloscope connected to V_{out} . Many counters and other signal processors utilizing threshold detection are frequency sensitive. Therefore, the threshold level should be measured over the system bandwidth.

6.8.3 The automatic threshold cannot be measured with a continuous wave generator. The tone burst generator provides an adjustable duration burst on and off times that may be used to establish the threshold level in the same technique that is used in Section 6.8.2.

6.9 Wave Shaping

6.9.1 Acoustic emission systems often contain electrical circuits that modify the applied waveform through a predictable and expected process. Such circuits are defined as wave shaping circuits. Wave shaping circuits include delayed action circuits, integrators, and differentiators. These circuits are often found in systems with floating threshold and event counters. The number and function of wave shaping circuits likely to be found in acoustic emission systems are too numerous to be listed within this recommended practice.

6.9.2 The characteristics of wave shaping circuits of interest shall include rise time, duration, and fall time. The measurement of these characteristics depend upon the circuit design. The manufacturer shall provide the temporal data and the methods of test and measurement of this data in the operating and maintenance manual supplied with the component or unit. See also section 6.3.

6.10 Counting

6.10.1 Counters fall into two categories: Summation counters and rate counters. Counters that tally signals for fixed repetitive periods of time during an acoustic emission test are known as rate counters. The tallied signals may be a count of acoustic emission signals, or loading cycles, or amplitude levels.

6.10.2 Counters are designed to accept signals which exceed a

comparator threshold level. Upon counting to some maximum total count, the counter will simultaneously reset to zero count and continue another upward excursion of count. The counters are manually resettable to zero count and may include an electrical circuit permitting the counter to be reset by a periodic electrical signal. The periodic signal is often called a clock signal. The clock transforms a summation counter into a rate counter.

- 6.10.3 The precision of count depends upon the relationship of signal frequency and threshold level. The accuracy of rate counters additionally depends upon the accuracy of the clock signal.
- 6.10.4 The counting function of the system may be assured by using a tone burst generator set as follows: 1) The amplitude shall be well above the threshold level, but well within the dynamic range of the system; 2) The tone burst frequency shall be within the system nominal bandpass; 3) The tone burst duration shall be at least one cycle, but fewer cycles than would cause the automatic threshold to take effect; 4) The tone burst repetition rate shall be adjusted for a period that does not cause the automatic threshold to interfere with the count function. The counting accuracy is assured by comparing the emission count with the tone burst count.

NOTE: A continuous sine wave signal is appropriate for tests and measurements of non-automatic threshold levels.

7.0 Noise

7.1 Definition of Noise and Their Sources

7.1.1 Noise, by definition, is any unwanted disturbance within a useful frequency band, such as undesired electric waves in a transmission channel or device. Noise may be erratic, intermittent, or statistically random. Noise is further defined as acoustic noise or electric noise to avoid ambiguity. This section is concerned with identifiable and controllable noise sources.

7.1.2 Acoustic noise is detected by the sensor as a pressure wave. This noise may be generated by reactive agents in contact with a subject specimen during an acoustic emission test, or by loading fixture noise, or by fluid noise. Fluid noise may be generated by control orifice size and fluid flow velocity forming an effective Helmholtz resonator or a Gulton whistle. The signals generated by leaks may or may not be considered artifact noise depending on the application of the acoustic emission technique or system. Thermal emission shall become relevant when either the specimen or sensor is subjected to temperature changes. Thermal emission is often generated by material phase change, material geometry change, and the pyroelectric effect of some sensors. Many other sources of acoustic noise exist, but are not identified here for the reason of brevity.

7.1.3 Electrical noise is noise coupled to the acoustic emission system by electrical conduction or radiation. The preponderance of electrical noise is synchronized to the power mains frequency. Electrical noise may contain the largest number of high amplitude harmonics of any signal detected. Electrical noise may also be stable and continuous, or random in amplitude and repetition rate. Ground loops are often a problem at one work area, but may not be a problem at an adjacent work area. Radio transmitters may be another source of intermittent noise. Radio transmitters may include the traditional voice transmission units, or such sources as electrical motors, and fluorescent lamps, and resistance welding.

7.1.4 Noise may be introduced to the amplifier from noise impulses on the power mains voltage, through inadequately filtered power supplies. This noise is usually identifiable from the "normal" electronic noise. The characteristics include random impulse or burst signals, short duration, very fast rise time compared with acoustic emission signals, and intermittent occurrence. A series of several low pass power mains filters will often attenuate this noise to an acceptable level.

7.2 Electronic Component Noise

7.2.1 There are several sources of noise in electronic circuits. In practice, the noise figure of an amplifier is usually

determined by the first, or input, stage of the amplifier. This is because noise introduced by other succeeding circuits of the system will undergo less amplification, and so will be relatively unimportant in the system as long as the amplification of the first stage is at least moderate.

7.3 Noise Measurements

- 7.3.1 Electronic noise is a characteristic of the gain and bandwidth. Amplifier noise shall be documented as: Noise Density. The noise density of an amplifier is a measure of the rms noise voltage at the terminated output, divided by the square root nominal bandwidth, divided by the amplifier gain expressed as a multiplier.
- 7.3.2 The amplifier input impedance is the governing noise source. Therefore, the amplifier input shall be terminated with a suitable impedance during noise tests and measurements. A suitable impedance shall consist of either the component or unit normally used to drive the amplifier, or a lumped impedance equivalent to the output impedance of the component or unit normally used to drive the amplifier.
- 7.3.3 The thermal agitation noise in amplifiers is generated in the resistive elements. When two or more resistances are in parallel, the thermal agitation noise is that corresponding to the resultant resistance. When a resistance is shunted by a capacitance, the thermal agitation noise voltage is

decreased. This fact explains why the preamplifier noise voltage is decreased when a piezoelectric sensor is connected to the amplifier input. The piezoelectric sensor and signal cable are each excellent capacitors.

- 7.3.4 The data acquired from an acoustic emission test shall be further tested for validity only when the artifact noise sources have been identified and attenuated from the test records. All such artifact noise sources shall be documented as to the effective reduction, and residual interference to the acoustic emission test.

APPENDIX A

Measurement of Input Impedance

Refer to Figure ., and note that the amplifier input voltage (V_2) is not easily measured. A technique is needed which does not require its measurement.

If the attenuator setting is large enough so that V_{osc} is independent of the load on the attenuator, then the amplifier input impedance may be found for a particular frequency from the formula below, which requires only measurements on the amplifier output. By putting two different values of Z into the circuit, and measuring the amplifier output voltage and phase for each case (use the oscillator as reference phase), the amplifier input impedance can be calculated. Let Z_1 be zero and amplifier output be $\underline{V}_{01}$. Then let Z_1 be an arbitrary value greater than zero, and the corresponding amplifier output be $\underline{V}_{02}$. The amplifier input impedance is then:

$$Z_A = \frac{\underline{V}_{02}(R_s + Z) - \underline{V}_{01}R_s}{\underline{V}_{01} - \underline{V}_{02}} \angle \pm \theta = R_A \pm jX_A$$

Note that for an accurate measurement the difference $\underline{V}_{01} - \underline{V}_{02}$ should be made large. The phase angle is the voltage measured across Z_A with respect to the voltage across R_1 .

In the case where Z_A is purely resistive, let Z be purely resistive also, and increase its value from zero until the output voltage decreases by one-half. The input resistance of the amplifier is then simply:

$$R_A = \frac{\frac{1}{2}V_{01}(R_s + R_1) - V_{01}R_s}{V_{01} - \frac{1}{2}V_{01}} = R_1 - R_s$$

Where $Z_A = R_A$

and $Z_1 = R_1$

Figure 1

Fig. 1

7.24 Microphone Rating G_M . The system rating of a microphone is 10 times the logarithm to the base 10 of the quotient of the ratio of the nominal electric power available from the microphone to the reference power divided by the ratio squared of the free-field sound pressure to the reference pressure.

The standard symbol is G_M . Thus the microphone system rating is given by

$$G_M = 10 \log_{10} \left(\left[(E^2/4R_{MR})/P_0 \right] / (p/p_0)^2 \right)$$

where

E = open-circuit voltage in volts generated by the microphone

p = free-field sound pressure of a plane progressive wave existing at the microphone location prior to the introduction of the microphone into the sound field

$20 \log_{10}(E/p)$ = response to a plane progressive sound wave whose direction of propagation has a specified orientation with respect to the principal axis of the microphone

P_0 = reference power

p_0 = reference pressure

R_{MR} = microphone rating resistance.
This resistance is to be taken from the following table:

Magnitude of Nominal Microphone Impedance at 100 cps and 20 C	Rating Impedance
19 to 75 ohms	38 ohms
75 to 300 ohms	150 ohms
300 to 1,200 ohms	600 ohms
1,200 to 4,500 ohms	2,400 ohms
4,500 to 20,000 ohms	9,500 ohms
20,000 to 80,000 ohms	40,000 ohms
80,000 ohms or more	100,000 ohms

Note 1: If $P_0 = 1 \text{ w}$, $p_0 = 1 \text{ microbar}$, and E/p is in units of volts per microbar, for practical application the defining equation becomes

$$G_M = [20 \log_{10} (E/p) - 10 \log_{10} 4R_{MR}]$$

and the unit of G_M is the decibel re 1 w per microbar squared.

Note 2: If $P_0 = 0.001 \text{ w}$, $p_0 = 0.0002 \text{ microbar}$, and E/p is in units of volts per microbar, for practical application

$$G_M = [20 \log_{10}(E/p) - 10 \log_{10} 4R_{MR} - 44]$$

and the unit of G_M is the decibel re 0.001 w per (0.0002 microbar) squared.

Fig. 2

INSERTION CALIBRATION BOX

Fig. 3

INSERTION CALIBRATION BOX

Fig. 3