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AEC Research and Development Report

ACOUSTIC EMISSION MONITORING
FOR CONTINUOUS CRACK DETECTION
IN NUCLEAR REACTOR
PRESSURE BOUNDARIES

November 1971

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ACOUSTIC EMISSION MONITORING FOR CONTINUOUS
CRACK DETECTION IN NUCLEAR REACTOR
PRESSURE BOUNDARIES

by

P. H. Hutton
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November 1971

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ABSTRACT

A program to develop application of acoustic emission techniques to reactor system integrity surveillance has been sponsored at Battelle-Northwest by the USAEC, Division of Reactor Development and Technology, from February 1966 to July 1970. This report covers the final portion of the program (January 1969 to July 1970). Full discussion of the first period of the program was previously reported in BNWL-997. Capabilities resulting from this program include use of acoustic emission monitoring to detect and locate flaws in pressure vessels and piping during hydrostatic testing, flaw formation during welding, incipient fatigue failure points in metal structures and stress corrosion cracking in metals. Better definition of the acoustic emission signal and propagation was achieved, as well as development of specialized detection instrumentation and suitable techniques for data analysis (including real-time source location techniques). Two major items required for fulfillment of program objectives were not completed at the close of this program. These are: final resolution of reliable detection of acoustic emission in the presence of operating reactor background noise remains, and development of an interpretive criteria to judge significance of acoustic emission indications. Fourteen technical papers and articles were prepared and presented in open meetings and literature under the auspices of this program.

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INTRODUCTION

Development of the nuclear energy field has incorporated provisions to assure public and private safety which are unequalled in any other industry. There is, however, a continuing interest to enhance this safety assurance. Acoustic emission monitoring has the potential of providing a measure of integrity of a structure such as a reactor pressure system which is unattainable by any other known nondestructive examination technique. A program aimed at such development was in progress at Battelle-Northwest from February 1966 to July 1970. This report details accomplishments during the final period of the program (January 1969 to July 1970).

Acoustic emission is a phenomenon arising from energy released as a solid material undergoes plastic deformation and fracture. Part of this energy is converted to elastic waves which propagate through the material and can be detected at the material surface using high sensitivity sensors. Two outstanding features of acoustic emission as an integrity monitoring device are the ability to detect crack formation or growth at the time it occurs and to accomplish this remotely. Also, simultaneous interrogation of multiple sensors (three or more) provides the necessary information to locate the source of the signals using triangulation.

First basic study of the acoustic emission phenomenon was done in the early 1950's in the United States and Germany.^(1,2) Efforts to develop the potential of acoustic emission for high resolution, nondestructive surveillance of structures and pressure systems to detect growing flaws, however, are of more recent origin. One of the earliest applications of acoustic emission as a true surveillance device was made by Aerojet-General Corporation in 1963.⁽³⁾ In this application acoustic emission was

used as a means of detecting flaw growth during hydrostatic testing of Polaris missile chambers. When a growing flaw was detected in this manner, the chamber would be depressurized in time to avoid failure and permit repair of the faulty area, thus salvaging a chamber which otherwise might have been destroyed in test.

Some of the more significant potential applications of acoustic emission are:

- Continuous surveillance of nuclear reactor primary pressure boundaries to detect and locate active flaws.
- Detection of incipient fatigue failure in aircraft structures.
- Monitoring of weldments for cracking during weld cooling.
- Determining the onset of stress corrosion cracking in susceptible structures.
- Serving as a study tool for investigation of fracture mechanism and material behavior.

Battelle-Northwest has carried on an active research and development program in the area of acoustic emission since early 1966. The major effort has been one sponsored by USAEC's Division of Reactor Development and Technology. This program, in progress from February 1966 to July 1970, was aimed at development of technology and instrumentation required to apply acoustic emission as a reliable continuous integrity monitor for the primary pressure boundaries of nuclear power reactors. Related work was also sponsored by DRDT at the Phillips Petroleum Company's Idaho Test Site, Idaho Falls, Idaho.

In this program, three levels of refinement were visualized in such a system. The first level would detect and locate growing flaws under hydrostatic test conditions, the second would detect and locate growing flaws under on-line reactor operating conditions, and the third would detect, locate, and describe growing flaws under on-line reactor operation conditions. Extending the application of acoustic emission surveillance from

monitoring hydrostatic testing of vessels to continuous monitoring of an operating system such as a nuclear reactor primary coolant system imposes significantly more demanding requirements. Included among these requirements are the necessity for sensors to function for periods of at least 1 1/2 to 2 years in an environment of nuclear radiation and temperature in the 600 to 700°F range, and the ability to distinguish acoustic emission in the presence of intense background noise.

PROGRAM SUMMARY

The following summarizes work conducted during the first part of this program (February 1966 to January 1969) previously reported.⁽⁴⁾

- The acoustic emission signal was established as being a short period transient with the inherent broad spectral distribution.
- High sensitivity PZT-5A piezoelectric sensors with tailored response characteristics were developed for routine use in acoustic emission detection in a temperature environment up to ~500°F (up to ~600°F for short term applications of a few hours).
- Solid state, multichannel acoustic emission detection and analysis instrumentation was developed. This instrumentation provides limited frequency pass band operation selectable in a frequency range from 200 kHz to 2 MHz. It provides a strip chart readout of emission rate, total, and energy. It also provides for storing raw data on magnetic tape for post-test analysis.
- Nuclear reactor background noise analysis was performed on the Dresden I, BWR power reactor. This analysis, plus follow-up laboratory analysis, indicated that acoustic emission detection in the 1 to 2 MHz range would be essentially immune to background noise during start-up and that the monitoring frequency could be dropped to about 600 kHz during equilibrium operation on this reactor.
- Acoustic emission detection was successfully applied to studies of large pipe (24 in. diameter) rupture characteristics, surveillance of known flaws in a test system pressure vessel, detection of flaw formation in welds, and detection of incipient fatigue failure in aluminum, high nickel steel, stainless steel, and reactor grade carbon steel.

In the final portion of the program (January 1969 to July 1970) the following accomplishments were realized:

- Investigation of acoustic emission signal propagation shows a definable relation between material thickness, monitoring frequency, and propagation velocity. Monitoring frequency significantly influences the propagation velocity at which signals are detected due to plate or group wave effects in thin material. Above a defined 'frequency - thickness' ratio, velocity of detected signals tends to normalize at about shear velocity.
- Test information shows that the attenuation of acoustic emission signals in steel at room temperature ranges from about 1 1/4 db/ft at 400 kHz to 3 db/ft at 1.4 MHz.
- Efforts to develop a usable lithium niobate acoustic emission sensor succeeded in determining a particular shear cut of the crystal which provides a satisfactory sensor. Sensitivity is comparable to and linearity is better than that of PZT-5A crystals. Lithium niobate will withstand temperatures two to three times the capability of PZT-5A.
- A simple method of obtaining reproducible relative sensitivity calibration of sensors has been developed using a small air abrasive blast unit to provide a broadband excitation source.
- Limited study of the use of coupling wedges to facilitate use of shear sensors for surface detection of emission signals showed definite promise. The benefits of shear sensors are to provide better propagation mode selectivity and sharper detected signals.
- Efforts to produce a very inexpensive sensor by casting a piezoelectric crystal in a high temperature plastic case were unsatisfactory due to eventual spalling and cracking of the plastic.

- A solid state, variable high pass filter which provides 36 db/octave attenuation was developed to enhance elimination of background noise interference.
- Review of the overall technique for acoustic emission detection and processing for the purpose of minimizing transient noise interference produced an integrated approach to solving this problem.
- A simplified method of source location determination is incorporated into an automatic source location analyzer developed to operate with existing acoustic emission detection equipment.
- Study of acoustic emission produced by the fatigue failure process in metals has resulted in tangible evidence that the nucleation of a macrocrack generates a distinct and consistent feature in the acoustic emission profile.
- Stress rupture tests with high temperature stainless steel showed that slow crack growth produces readily detectable acoustic emission information. A crack area increment of 0.018 in.^2 in 4 hr in one case, and 0.0017 in.^2 in 10 hr in another case showed detectable emission.
- A national "Acoustic Emission Working Group" was formed in November 1967 to promote dissemination of acoustic emission technology. The group is still active to date.
- Fourteen technical papers and articles concerning acoustic emission were presented in open meetings and literature.

Acoustic emission technology and instrumentation has progressed to the stage where it is being applied to detect and locate flaws in pressure vessels and piping undergoing hydrostatic proof testing, and to detection of flaws formed in welds during fabrication and cooling. It is also being used as a tool to study materials and components in the laboratory. In addition, the technique can be used to detect incipient fatigue failure in metals and the onset of stress corrosion cracking.

Two significant items of work essential to attaining the full objective of this program were incomplete at the time the program was terminated. The major item is that of resolving the problem of reliable emission detection in the presence of reactor operational background noise, primarily coolant flow noise. Limited noise data obtained from operating reactors indicates feasibility of on-line monitoring; however, additional noise data for monitor system design and a demonstration of feasibility remain to conclusively solve the problem.

The second item of remaining work is development of an interpretive criteria with which to judge the significance of acoustic emission indications. Only limited and tenuous criteria are available at this time.

A third significant item which received considerable attention under this program appears to have been satisfactorily solved under another acoustic emission monitoring program. This concerns emission detectors capable of long-term operation in a reactor environment of nuclear radiation and temperature in the 600 to 700°F range. Metal wave guides fused to the detection surface appear to satisfactorily solve this problem.

Although there were certainly other contributing factors, it can be stated that in the duration of this program, the acoustic emission flaw detection technique has progressed from a virtually unknown method being examined by about six different laboratories to a technique recognized and being developed world wide for its unique and beneficial capabilities for detecting active flaws in circumstances where no other known method can be applied.

DISCUSSION

The following discussion covers the areas of development during the final period of the program (January 1969 to July 1970).

Most of Battelle-Northwest's acoustic emission study work has been performed on carbon steels--A 212B A 302B, tool steel, HY 80 and mild steel--with a limited amount of work with Types 304 and 316 SS, titanium, aluminum, and zirconium. The reason for concentrating on carbon steels was simply to limit the outside variables while searching for significant acoustic emission parameters.

SIGNAL ANALYSIS

One of the major areas of investigation of the Battelle-Northwest acoustic emission program has been signal analysis and characterization. This investigation, together with development of appropriate detection techniques is felt to be the key to realizing the full potential of acoustic emission as a reliable integrity surveillance tool.

Based partly on study of many hundreds of photographed waveforms of both real and artificial acoustic emission signals, and partly on accepted theory appearing in the literature, it is possible to suggest an acoustic emission propagation model for simple, plate-like structures. From this it is possible to predict approximate propagation velocities for earliest arriving signal components.

Assume that an acoustic emission is a complex disturbance; i.e., it radiates energy of all kinds in all directions and that, furthermore, sometimes there are multiple emissions taking place simultaneously or very closely spaced together in time. In general, however, the acoustic emission takes place as a short time duration burst and thus is considered to be a pulse which originates at a point location and radiates a spherical wave front. It must be understood that bursts are never exactly reproducible. Although they radiate as spherical wave fronts, there may be more compressional energy travelling in a given direction than in some

other direction for emission A; but the same may be true in different directions for emission B, etc. The same would follow for shear energy; i.e., it may radiate in a spherical direction, but a spherical polar plot of energy would be different for each burst.

The concept of a single pulse does not preclude the existence of plate waves (Lamb waves, guided waves). The single pulse can be broken down into its continuous wave spectral components and on this basis it would be possible to predict the existence of various plate wave modes based on the plate or pipe wall thickness and the spectral content of the pulse. Naturally, the spectral distribution and energy levels for each frequency will vary from pulse to pulse, but if a narrow band detection system is used, and if plate thickness is known, then one could feasibly predict the detection of particular plate wave modes.

Knowledge of which modes are apt to be present does not solve the question of "what is propagation velocity?", however, since a wide range of group velocities exists for a given mode in a given plate. Any velocity within the range may be indicated provided a detection system is sensitive to the frequencies associated with the velocities' dispersion range. For example, in a 1/4 in. wall-thickness plate with a detector operating at a bandwidth of 600 kHz to 1.0 MHz, the second symmetrical mode group velocity may vary from about 96,000 to 200,000 in./sec as shown in Figure 1. The first symmetrical mode is probably present in emissions, but for a bandwidth of 600 kHz to 1 MHz in a 1/4 in. wall, the high velocity (low frequency) components are electrically shut out because of the high pass filter (cut off at 600 kHz), and only the low velocity components get through. These low velocity components arrive considerably after the arrival of the 600 kHz components of the second symmetrical wave.

The higher frequency components of the second symmetrical mode arrive at a lower velocity (very close to the velocity of the higher frequency components of the first symmetrical mode which also gets through the filter) so that reinforcement may occur resulting in some high amplitude beat frequencies, probably at about shear wave velocity. The first and second asymmetrical modes may also be present. However, their group velocities

$V_L \approx 230 \text{ to } 236 \times 10^5 \text{ in./sec}$ S1 = FIRST SYMMETRICAL MODE
 V = GROUP VELOCITY S2 = SECOND SYMMETRICAL MODE
 f = FREQUENCY A1 = FIRST ASYMMETRICAL MODE
 t = THICKNESS A2 = SECOND ASYMMETRICAL MODE

FIGURE 1. Approximate Group Velocities Curves for "Plate" Waves in Steel

are lower than the symmetrical modes and they would appear well back in the pulse (long after arrival of the faster components of the second symmetrical mode). A study of the frequency components present in an emission, then would show the lowest frequency of the system bandwidth appearing as the dominant frequency of the first high amplitude arrivals (i.e., occurring after the low amplitude precursor which travels at longitudinal wave velocity). Then, as the slower traveling components start arriving, the spectral content should increase in high frequency components.

A waveform which may depict an example of the described velocity dispersion is seen in Figure 2. The top waveform is a wedge transducer detection of a signal at 6 in. from the source on the 8 1/2 by 1/4 by 120 in. pipe, while the lower waveform shows the same signal at 16 in. Attention is directed to the fundamental frequency content of the earliest arriving components at 16 in., appearing at about 82 to 100 μ sec. Center frequency is about 600 kHz, and propagation velocity is about 195,000 in./sec for the earliest arrival. Further back in the pulse, beginning at about 150 to 160 μ sec, appears a higher frequency component. Center frequency of this component is about 915 kHz, and propagation velocity is about 100 to 107,000 in./sec. Figure 1 shows that for the second symmetrical mode, group velocity will be about 191,000 to 200,000 in./sec for the 600 to 650 kHz components; and group velocity will be about 110,000 to 115,000 in. per sec for the ~915 kHz components. Detection of the second symmetrical mode is thus indicated, the maximum velocity of which is about 200,000 in. per sec at 600 kHz.

By use of the same frequency bandwidth (600 kHz to 1 MHz), and investigation of thin wall material, the first detected arrival will probably be the first symmetrical mode since by going to a thin wall, the wave length - wall thickness relationship is such as to enable excitation and detection of the first symmetrical mode. Again, the fastest components will be the 600 kHz components which travel at about 207,000 in./sec (0.015 in. wall) to 213,000 in./sec (0.0625 in. wall). For a wall thickness of 0.062 in., the 1 MHz components travel at about 177,000 in./sec, whereas for a wall thickness of 0.015 in., the 1 MHz components travel at about 205,000 in./sec.

FIGURE 2. Signal Detection by Wedge Mounted Sensors

As wall thickness goes up (e.g. 1 in.) while frequency bandwidth remains constant (600 kHz to 1 MHz), the lower order modes (first and second symmetrical and asymmetrical) approach a constant velocity, surface wave velocity for the fundamental modes and shear wave velocity for all others. The same would be true for thicknesses such as 4, 7, and 10 in. With wall thickness this large, the pure wave components may be of more importance, i.e., the precursory longitudinal wave or the shear or surface waves. The plate waves that would also be present are probably low amplitude and would arrive at about shear or surface waves velocity. If detection system bandwidth included very low frequencies (20 to 100 kHz), low frequency waves would again be found in plate waves traveling at a range of velocities - some of which would be much faster than shear velocity (e.g., $\sim 207,000$ in./sec for the low frequency components of the first symmetrical mode).

It may be seen that some spectral information may be influenced by plate geometry; thus, a crystal may be mounted to take advantage of a particular mode at a particular frequency whereas another similar crystal may respond to the same mode but at a slightly different frequency. Then again, the frequency - velocity relationship will affect frequency content of a selected portion of a received pulse. At a nearby location, the lows and highs may appear in the same time interval. At a distant location, the lows and highs are separated more from each other and may not appear in the same time interval. In addition, the highs are attenuated more than the lows so that analysis would have to be carried out at a location close to the source.

For now, it appears the best approach for triangulation purposes is to use the plate wave velocity for $\frac{\pi ft}{V_L}$ relationships of less than about three. If this relationship is greater than three, a velocity between shear and surface wave velocity ($\sim 110,000$ in./sec for steel) should be suitably accurate.

Most of the signal attenuation information available is concerned with ultrasonics which does not include the frequency range of primary interest for acoustic emission work. For this reason, emission signal attenuation

versus frequency for steel was investigated. The test specimen was a 5/8 in. thick, Type A 302B carbon steel plate with bend tabs on one end to produce acoustic emission. Sensor groups consisting of a 400 kHz, a 650 kHz, and a 1.2 MHz surface mounted PZT-5 sensors were spaced at 2-ft intervals away from the emission generation point. Figure 3 shows the attenuation curve produced from the data obtained. These data indicate that a 400 kHz sensor will detect a given emission signal with the same voltage output at a distance about two times that for 1.2 MHz sensor.

FIGURE 3. Acoustic Emission Signal Attenuation

SENSOR DEVELOPMENT

A sensor which can withstand extended exposure (1 to 2 years minimum) to reactor pressure system external environment is an obvious essential for continuous, on-line acoustic emission monitoring. This environment involves temperature in the 600 to 700°F range plus nuclear radiation. Lithium niobate piezoelectric material with a Curie point of 1210°C was a candidate

for this application, but it tended to be quite low in sensitivity. Work done in the final quarter of this program produced an "X" shear cut of the crystal which showed sensitivity comparable to that of PZT-5A with much better linearity. This type of sensor has since been used in test work to satisfactorily detect acoustic emission. Figure 4 shows a comparison of the calibration curve for the two types of sensors.

FIGURE 4. Calibration Traces for PZT-5A and LiN603 Sensors Showing Relative Sensitivity and Linearity.

A practical reproducible method of calibrating acoustic emission sensors has been a problem. A technique for calibrating the frequency response and relative sensitivity of sensors has been developed using an air abrasive unit to generate broad spectrum noise in a test block or specimen to which the transducer is bonded. The frequency response curve and relative sensitivity of the transducers are measured with a spectrum analyzer or tunable voltmeter.

The calibration technique was developed using an S. S. White Model F air abrasive unit. This unit uses a magnetic vibrator to control the abrasive flow rate. The flow is adjusted by varying the voltage on the vibrator. The abrasive is carried through the nozzle by a high velocity air stream.

Several factors were investigated for their influence on the acoustic spectrum generated by an abrasive stream. Pressure and abrasive flow rate appear to affect the amplitude and leave the spectrum shape unchanged. The material in the test block or specimen and the abrasive particle size appear to affect the shape of the acoustic emission spectrum to a limited degree. Abrasive normally used for calibration is 50 micron alumina powder. The relative position of the transducer and the abrasive stream, and specimen geometry appear to have no effect.

Figure 5 shows the characteristic response pattern obtained for four different size acoustic emission sensors using the air abrasive unit as an excitation source. These responses were measured with a Hewlett Packard 8552A/8553B spectrum analyzer. This technique offers a simple, reproducible method of relating the response characteristics of all types of acoustic emission sensors.

Location of the acoustic emission source by triangulation is an important consideration in developing an acoustic emission monitor system. Triangulation accuracy should be enhanced through the use of wedge mounted shear crystals where the wedge is made of a material with a low shear wave propagation velocity, such as silver or brass, and where the wedge angle is about equal to the shear critical angle. The advantages of this method are that the faster traveling compressional waves, and shear waves mode converted from compressional waves would tend to be received only with low

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0 1 2
Frequency, MHz
0.070 in. Diameter, PZT-5
Epoxy Backed

0 1 2
Frequency, MHz
0.080 in. Diameter, PZT-5
Air Backed

0 1 2
0.120 in. Diameter, PZT-5
Air Backed

0 1 2
0.240 in. Diameter, PZT-5
Air Backed

FIGURE 5. Typical Calibration Spectra for Acoustic Emission Sensors
with Air Abrasive Unit as Excitation Source

sensitivity, thus eliminating a potential source of ambiguity in propagation velocity. Also, if the wedge angle is optimized to receive shear waves traveling nearly parallel to the surface, then propagation velocity would be essentially constant at shear wave velocity.

Some signal waveform comparisons have been made as a first step in evaluating a wedge mounted shear crystal design. Rectangular PZT shear crystals were cemented to a brass wedge and the wedge cemented to the surface of a 4 in. by 4 ft by 8 ft plate at a distance of about 36 in. from one end. Alongside the wedge was a flat mounted 0.080 in. diameter thickness poled PZT crystal with primary resonance centered at about 670 kHz.

With amplifier gains set at approximately similar noise backgrounds, photographs were taken comparing the response of the two sensors to excitation from an electric spark on the plate surface and from acoustic emission generated by manually bending a notched metal tab welded at the plate's end.

Sensor responses to excitation from an electric spark are shown in Figure 6. In each photograph, the upper waveform is from the wedge mounted sensor and the lower waveform is from the flat mounted sensor. Photographs show comparisons when the wedge mounted sensor response is limited to >300 kHz in Figure 6a and >1 MHz in 6b. Figure 6c shows same as 6a except the location of the spark source is at the edge of the plate instead of the top of the plate, and 6d shows same as 6a except spark source is at the underside of the plate instead of the top. In all cases, the flat mount sensor response was limited to >700 kHz. These photos show that both crystals are somewhat sensitive to energy arriving at velocities faster than pure shear velocity. Both crystals are more sensitive to the slower traveling shear energy and, to a lesser degree, other late arrivals such as combinations of mode conversions and multiple reflections. The wedge mount crystal in this experiment showed more sensitivity for the edge and bottom source locations than did the flat mount sensor, however, it also had an advantage of being tuned to accept lower frequency components.

(a) Top: Wedge Mount > 300 kHz
Bottom: Surface Mount > 700 kHz
Excitation: Top of Plate at End

(b) Top: Wedge Mount > 1 MHz
Bottom: Surface Mount > 700 kHz
Excitation: Top of Plate at End

(c) Top: Wedge Mount > 300 kHz
Bottom: Surface Mount > 700 kHz
Excitation: Edge of Plate at End

(d) Top: Wedge Mount > 300 kHz
Bottom: Surface Mount > 700 kHz
Excitation: Underside of Plate at End

Sweep Rate For All Photos: 50 μ sec/cm

FIGURE 6. Comparisons of Wedge Mounted Shear Sensor and Flat-Mounted Sensor Responses to Electric Spark Excitation

Some comparisons of response to acoustic emission generated by bending tabs at the end of the plate are shown in Figure 7. Figure 7a compares the wedge mounted sensor to the flat mounted sensor when the signal from the wedge mounted sensor is amplified at a narrow band frequency of $\Delta f_w \approx 230 - 340$ kHz whereas the signal from the flat mounted sensor is amplified at a narrow band frequency of $\Delta f_f \approx 600 - 800$ kHz;

7b same as 7a except $\Delta f_w \approx 340 - 510$ kHz;

7c same as 7a except $\Delta f_w \approx 510 - 760$ kHz;

7d same as 7a except $\Delta f_w \approx 760 - 1140$ kHz;

7e same as 7a except $\Delta f_w \approx 1140 - 1700$ kHz; and

7f same as 7a except $\Delta f_w \approx 1700 - 2560$ kHz.

These photographs demonstrate good sensitivity for the wedge mounted sensor up to about 1.5 MHz. At higher frequencies, the transducer becomes more vulnerable to compressional wave components and becomes less sensitive overall. Due to changing tabs positions, but not changing scope trigger sensor location, the time position of the received signals in the photographs do not bear a constant relationship to propagation velocity.

The wedge technique offers a potential method of obtaining the advantages of high frequency shear sensors for acoustic emission detection on a practical basis; i.e., it does not require access to the edge of the material. Further work is required to refine this technique.

A different technique for fabricating sensors produced sensors with response characteristics superior to the metal encased units. This involved injection molding the cases from high temperature silicon resin with the crystal and lead wires in place. The resin case, however, exhibited a problem of spalling and cracking after a short service period. It is felt that this problem could be overcome with limited additional development work, but the opportunity was not available as part of this program. The primary incentive for perfecting this approach is the fact that sensors can be fabricated by this method for about one third of the cost by conventional methods of metal encasing.

(a) Top: Wedge Mount, 230-340 kHz
Bottom: Surface Mount,
600-800 kHz

(b) Top: Wedge Mount, 340-510 kHz
Bottom: Surface Mount,
600-800 kHz

(c) Top: Wedge Mount, 510-760 kHz
Bottom: Surface Mount
600-800 kHz

(d) Top: Wedge Mount, 760-1140 kHz
Bottom: Surface Mount,
600-800 kHz

(e) Top: Wedge Mount, 1140-1700 kHz
Bottom: Surface Mount,
600-800 kHz

(f) Top: Wedge Mount, 1700-2560 kHz
Bottom: Surface Mount,
600-800 kHz

Sweep Rate For All Photos: 50 μ sec/cm

FIGURE 7. Comparisons of Wedge-Mounted Shear Sensor and Flat-Mounted Sensor Responses to Acoustic Emission

SIGNAL CONDITIONING

Interference from intense low frequency noise is a concern in attempting to detect acoustic emission on an operating system such as a reactor pressure system. A high pass filter with 36 db/octave attenuation below the pass point and with selectable pass points of 200, 500, 800 kHz and 1 MHz, has been developed and tested. As shown in Figure 8, this is a compact solid state device which can be accommodated as an integral part of an emission monitor instrument. Since commercial filters of this type with this level of attenuation are not available, this represents a significant improvement in noise suppression.

FIGURE 8. Solid State, Variable High-Pass Filter with 36 db/octave Attenuation

Transient signals from ground potentials, electromagnetic radiation, and power supplies are a problem to reliable acoustic emission detection. Elimination of these signals by filtering is essentially impossible. They generally affect an acoustic emission analyzer the same as an authentic emission signal. With the voltage gain normally used for acoustic emission monitoring, these transients can also saturate or over drive amplifiers with the result that all information is lost while the component is saturated. In an effort to alleviate this problem, the total emission monitoring technique was examined for ways to eliminate or reduce sensitivity to transients without compromising acoustic emission detection. Details of the results of this work are discussed in a separate topical report.⁽⁵⁾ In summary, however, the findings of this study indicate the following solutions:

- Use of a combination two-element balanced transducer, three wire input system, and differencing amplifier with good common mode rejection over its complete band width to combat ground potentials and electromagnetic radiation. The unique part of this approach is its application in the high frequency range. A differential amplifier design was developed which provides good common mode rejection up to about 8 MHz.
- Use of silver cadmium, quick recharge batteries as a power supply for the complete monitor system. The high energy/unit volume and the quick recharge capability (5 hr) of these batteries make this approach practical.

DATA ANALYSIS AND READOUT SYSTEM

Identification of the location of a flaw generating acoustic emission is one of the unique and valuable features of the acoustic emission flaw detection technique. Basically, this is accomplished by examining the relative time of arrival of an acoustic emission signal at three or four sensors and combining this information with signal propagation velocity to produce spatial parameters which locate the source of the signal.

The source location determination can be accomplished in various ways. Data from the various sensors can be recorded simultaneously on a multi-channel tape recorder and then be played back to determine delta times. This information, together with propagation velocity, can be used to determine the source by triangulation methods (either graphical or computational) similar to those used in seismic work to locate the source of disturbances such as earthquakes. This approach has the disadvantages of not being real-time, i.e., determination is made after the test, and it is extremely time consuming.

A refinement of the triangulation method uses a multichannel analyzer to determine the statistical distribution of delta time among sensors for a quantity of emission data. This information is then fed into a computer to determine the source locations corresponding to the peaks in the time distribution. This system can operate essentially in real time, and it can realistically process large quantities of data. It does, however, involve an expensive instrumentation system, in the vicinity of \$50,000 to \$75,000 capital equipment costs for just the analyzer, computer and interfacing. Software costs for computer programming are additional.

A simplified and versatile approach to source location was developed under this program. This approach is based on independent examination of the source relative to the axis between two sensors. Relative time of a signal arrival at these two sensors will define a hyperbola about the axis which will contain the source location. In applications involving a long slender member, this is adequate location information because of the confining lateral boundaries. Where this is not the case, a similar examination of two sensors on an axis perpendicular to the first will define a second location hyperbola which will identify the source at its intersection with the first. A further variation of this approach involves three sensors in a triangular array which provides three independent axes with only three sensors. This approach lends itself to use of a nomograph or a "look up table" in a small computer to establish actual physical location of the source. This greatly simplifies the operation because it is not necessary to perform the triangulation calculations.

Figure 9 shows a prototypic system capable of monitoring four data channels, analyzing for emission rate or energy rate, totalizing, and analyzing on two independent axes for source location. Total cost for the entire system including the commercial printer is about \$25,000. The number of channels surveyed can be expanded by adding more detection and conditioning units.

PRINTER

SOURCE LOCATION
ANALYZERSIGNAL CONDITIONER
&
EMISSION RATE ANALYZER

FIGURE 9. Automatic Source Location Analyzer
with Four Channel Monitor and
Emission Counting Unit.

APPLICATION ENGINEERING

One of the major needs in acoustic emission technology at this time is substantiated criteria for interpretation of acoustic emission information. Investigation of acoustic emission from metal fatigue has contributed a criterion point and also provided evidence toward defining minimum detectable flaw size.

Fatigue testing a variety of metals (2024-T3 aluminum, 304 stainless steel, high nickel steel, and mild carbon steel) in both high and low cycle fatigue has shown a consistent acoustic emission change prior to the appearance of a visible macrocrack. Although it was suspected that this indication was generated by the initial nucleation of a macrocrack, confirming information was needed. A simple notched, cantilever beam fatigue specimen of Type A 212B carbon steel was chosen for investigation of the mechanism producing the acoustic emission benchmark. This was tested in high cycle, tension-tension fatigue. Figure 10 shows the specimen shape and load cycle. Also shown in Figure 10 is the acoustic emission response curve. The increasing emission response from 390,000 to 630,000 cycles is attributed to microcracking. The test was shut down over night at 570,000 cycles and when the test was resumed, the emission started at essentially the same level it had attained when the test was stopped. At 630,000 cycles the test was again stopped and the specimen was removed for examination. The surface was polished and lightly etched to inspect microscopically for any evidence of a macrocrack. Since none was found, it was again installed in the test fixture and cycling resumed. The emission level, however, started much lower than the previous point. This is attributed to the polishing removing many microcrack sites from the high stress area. The abrupt increase in acoustic emission which precedes appearance of a visible crack occurred at 705,000 cycles. The specimen was cycled an additional 11,000 cycles and then removed for metallographic examination.

Metallographic inspection revealed an abundance of microcracks on both sides of the specimen near the root of the notch. Figure 11 shows an example of these at a depth of ~ 0.010 in. from the surface. Further investigation revealed one macrocrack at a depth of ~ 0.125 in. into the specimen. This is shown in Figures 12 through 14. It was ~ 0.002 in. deep and estimated to be ~ 0.030 in. long. No other macrocracks were discovered. These data provide substantiation for the conclusion that the abrupt increase in acoustic emission observed in fatigue testing is a result of macrocrack nucleation. They also indicate that microcracking, at least in carbon steel, is readily detectable by acoustic emission which contributes to definition of minimum detectable flaw size.

Neg 701386-1

FIGURE 10. Acoustic Emission from Carbon Steel Fatigue Specimen

Neg 701386-5

FIGURE 11. Carbon Steel Fatigue Specimen - Microcrack Emission Sources

Neg 701386-4

FIGURE 12. Carbon Steel Fatigue Specimen - Macrocrack Emission Source-A

Neg 701386-3

FIGURE 13. Carbon Steel Fatigue Specimen - Macrocrack Emission Source-B

Neg 701386-2

FIGURE 14. Carbon Steel Fatigue Specimen - Macrocrack Emission Source-C

Much of the investigation of acoustic emission has been performed using relatively short term tests which inherently tend to promote high crack growth rates. An opportunity to monitor acoustic emission from a stress rupture test being performed for other purposes was utilized to look at emission from slow crack growth. The material used in this test was a proprietary chromium-nickel-manganese high temperature alloy. The test section was maintained at about 1100°F during the test. Three sensors were used to detect acoustic emission: a PZT-5A shear chip mounted on the edge of the specimen, a PZT-5A, 0.120 in. diameter encased crystal on the specimen surface, and a wave guide with a PZT-5A crystal also on the surface. All three showed generally similar results. Figure 15 shows a summary of the acoustic emission results. The specimen was an ASTM tensile specimen with a side notch to generate stress concentration. It appears that the crack formed and started to grow at about 50 hr of test time. At 60 hr, the specimen was removed for examination and a crack with an estimated area of 0.0017 in.² and a crack opening of ~0.003 in. had developed.

The specimen was then tested for another 4 hr at which time it was removed and broken through the test section at room temperature. Heat etching showed that the crack grew another 0.018 in.² during this latter period. Since the test section was enclosed in a furnace, it was impossible to visually confirm the initial crack formation point. Unfortunately, the source location analyzer was not available for this test. This could have been used to identify the time at which a crack formed because source indications at that time would have changed from a random indication associated with deformation to a consistent indication associated with a crack front. Crack formation at the 50 hr point is inferred from the fact that permanent measurable elongation occurred at constant load between 50 and 60 hr.

The significant feature of these results is the fact that readily measurable acoustic emission was produced in the course of generating and growing the crack over an extended period.

FIGURE 15. Acoustic Emission From Stress Rupture Test

TECHNICAL INFORMATION DISSEMINATION

Reports, technical papers, and journal articles prepared as an outgrowth of this program are listed in the reference section.⁽⁵⁻²³⁾ This list includes 10 technical papers, 5 formal reports, 3 journal articles, and 1 contribution to a book. Routine quarterly program progress reports are not included in this list.

In addition, an "Acoustic Emission Working Group" was organized in November 1967 to disseminate technical information among those working in the field of acoustic emission. Formation of this group was to promote more efficient utilization of manpower and funding available. In an increasingly competitive field there has continued to be a beneficial free technical interchange. The original membership of 14 representing 8 different companies or locations has grown to a current membership of 50 representing 30 different companies or locations. Affiliation of the group with one of the national technical societies will probably be considered in the near future.

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