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DETECTION OF INCIPIENT FAILURE
IN
NUCLEAR REACTOR PRESSURE SYSTEMS
USING ACOUSTIC EMISSION

April 1969

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DETECTION OF INCIPIENT FAILURE
IN
NUCLEAR REACTOR PRESSURE SYSTEMS
USING ACOUSTIC EMISSION

By

P. H. Hutton

Nondestructive Testing Department
Systems and Electronics Division

April 1969

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ABSTRACT

"Acoustic emission" is a term adopted to describe the elastic wave produced in solid materials by energy imparted as the material plastically deforms and fractures.

The Division of Reactor Development and Technology, USAEC, is sponsoring development work at Battelle-Northwest to apply acoustic emission detection as a means of continuously monitoring nuclear reactor pressure boundaries for flaw formation and/or growth. The purpose of this report is to summarize the work to date under this program.

The nature of the acoustic emission signal has been clarified, specialized detection techniques have been developed, identification of acoustic emission in the presence of hydraulic noise has been demonstrated, and the technique has been beneficially applied to selected problems both in the field and in the laboratory.

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INTRODUCTION

Industry in general has a continuing interest in, and need for, new and improved methods of assessing the integrity of structures. "Structures" in this sense include physical assemblies of solid materials ranging from items such as a small capsule for containing a radioactive isotope, to assemblies such as a bridge, an aircraft frame, or a nuclear reactor coolant system. A new technique with exciting potential in this area consists of detection and analysis of "acoustic emission."

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 propagating through the material and detectable at the material surface by high sensitivity sensors. Two outstanding features of acoustic emission as an integrity monitoring device are the ability to detect crack formation or movement 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 by triangulation.

Some of the more significant of the many 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.
- Detection of micrometeorite penetration into space vehicles.
- Determining the onset of stress corrosion cracking in susceptible structures.
- Serving as a study tool for investigation of fracture mechanisms and material behavior.

The first basic study of the acoustic emission phenomenon appears to have been done in the late 1940's and 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. To the author's knowledge, the first application of acoustic emission as a true surveillance device was made by Aerojet-General Corporation in 1964.⁽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.

At the AEC's Pacific Northwest Laboratory, 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 the USAEC's Division of Reactor Development and Technology. This program, in progress since February 1966, is 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. Three levels of refinement are 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 is 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.

The purpose of this report is to review work done and conclusions derived to date under the AEC sponsored program. The work of Battelle-Northwest (BNW) in the specific application of acoustic emission to such other areas as detection of cracking in welds, and detection of stress corrosion cracking either has been or will be reported separately.^(4,5)

SUMMARY AND CONCLUSIONS

Acoustic emission technology and instrumentation has been developed to the stage where it can be reliably applied to detect and locate flaw growth in pressure containers undergoing hydrostatic testing. It can also be applied with confidence to surveillance of localized areas of known high potential for flaw development in operating systems such as the piping connections to the pressure vessel in the primary coolant system of a nuclear reactor. Additional development work, however, is required to apply the technique to general

surveillance of a complete reactor pressure system during operation with a high degree of confidence that all active flaws will be detected without generating false indications that cause unnecessary interruption of reactor operation. Improved detection methods must be adapted to field use, data analysis methods need to be optimized, and maximum detection range with various geometries must be established. Also, a "catalog" of emission characteristics is required to establish a set of standards for judging the significance of a given quantity of acoustic emission data.

Evidence indicates that the acoustic emission signal, at least in steels, is a very short period transient (less than 0.03 μ sec). Wave propagation studies show a sensing technique, sensitive primarily to one propagation mode, produces much shorter and better defined signal detection.

High sensitivity transducers using PZT-5A piezoelectric crystals sensitive primarily to Rayleigh and shear waves have been fabricated. The transducers are suitable for long term service at temperatures up to about 625 °F. Lithium niobate piezoelectric material offers a possibility of extending the temperature range of these transducers to at least 1500 °F.

Solid state signal conditioning and processing instrumentation, light in weight, rugged, and small, has been developed to facilitate easy transportation to field test locations. The system, consisting of a tuned, 400 kHz bandwidth low noise pre-amplifier with a voltage gain of 100 to 150, operates into a filter-amplifier combination to provide additional voltage gain ranging from 10 to 100. The signal at this point is split between a magnetic tape recorder serving to store raw data, and a detector-count rate section generating emission rate data and total number of emissions. Emission rate and total number of emissions are read out on a strip chart recorder. Source location is accomplished by interrogation of the data stored on magnetic tape.

Analysis of nuclear reactor background noise during operation (Hanford production reactors and Dresden I power reactor) has shown that acoustic emission in an operating plant must be detected in the low megahertz frequency range to avoid noise interference. Follow-up laboratory tests have demonstrated acoustic emission detection in the frequency range of 1 to 3 MHz to be relatively immune to interference from hydraulic noise including moderate cavitation. At the same time, this frequency range is low enough to avoid the extreme signal attenuation with distance experienced in the material at higher frequencies.

Acoustic emission detection has been successfully applied, in field tests, to studies of pipe rupture employing 24-in. diameter, 1.7-in. wall pipe specimens, to the surveillance of known flaws in a Containment Systems Experiment pressure vessel, and to the monitoring of suspected slow fatigue crack growth in reactor process piping. The technique has also been demonstrated applicable to detection of flaw formation in welds, to stress corrosion cracking, and to high cycle fatigue failure. The resolution attainable appears to significantly exceed that of any of the conventional nondestructive testing techniques such as ultrasonics, eddy current, or radiography.

DISCUSSION

Practical methods of further assuring the integrity of nuclear reactor pressure boundaries are of continuing interest from the standpoint of nuclear safety. A nondestructive technique with considerable potential in this area involves detection of "acoustic emission" produced by metal as it deforms and fractures. The technique, applicable on a continuous surveillance basis for detecting and locating the formation or growth of flaws, demonstrates resolution potential exceeding that of such conventional nondestructive testing methods as ultrasonics or radiography.

Work to develop application of acoustic emission techniques to reactor system integrity surveillance has been sponsored at Pacific Northwest Laboratory by the USAEC, Division of Reactor Development and Technology, since February, 1966. Related work has also been sponsored by DRDT at the Phillips Petroleum Company's Idaho Test Site, Idaho Falls, Idaho.

Most of BNW'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 to date is simply to limit the outside variables while searching for significant acoustic emission parameters.

SIGNAL ANALYSIS

One of the major areas of investigation in the BNW 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.

A tentative frequency categorization of signals produced by plastic deformation, ductile fracture, and brittle fracture was proposed on the basis of early test results.⁽⁶⁾ The categorization is now considered to be very questionable. The data are valid, but the interpretation appears to be erroneous. What was thought to be a failure mode dependent frequency appears, instead, to represent acoustic emission event rate for a given circumstance. One of the observations supporting this latter line of reasoning is illustrated by Figure 1. The signal shown is the detected response from acoustic emission generated by flaw increment during a test

25 K H. P. Filter
1.0 msec/cm
2 V/cm

25 K H. P. Filter
.1 msec/cm
2 V/cm

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FIGURE 1. Acoustic Emission Signal Observed from Flaw Growth
During Battelle-Columbus Pipe Burst Test No. 9
(PT. 4, 23.3 Ref.)

to study fracture characteristics of 24 in. diameter by 1 3/4 in. wall carbon steel pipe. Application of the frequency category concept would indicate this to represent failure of only one grain. A flaw increment restricted to one grain is not logical in this circumstance. The response becomes more rational, however, by considering the high frequency packet at the front of the signal to represent a number of individual emission events.

Another problem which became evident was the duration of the transducer response generated by a single emission event. The response signal lasted at least 6 to 8 msec as shown in the photo on the top in Figure 1. Depending on the type of transducer used, the duration could be much greater. Since these times were in excess of the transducer ring down time, the reflected signals apparently were extending the response duration. The signal duration becomes a problem when several emission events occur in close succession. Under this circumstance, it can become impossible to accurately resolve individual events, and the accuracy of emission rate and total emission analysis is compromised.

The preceding considerations lead to the conclusion that an analysis of acoustic emission wave propagation and development of improved sensing techniques is a necessary next step before flaw mechanisms and materials can be reliably characterized in terms of acoustic emission. Such work is now in progress.

Mathematical relationships have been developed to define the number of reflected signals from a single source event that would be observed along with the directly transmitted signal in terms of plate thickness, distance from the source, propagation velocity in the materials and couplant, sensor diameter, and frequency. These relationships provide a tool

for predicting the length of signal detected with a given sensor from a single source event. Briefly, the mathematical relationships show that either an increase in the sensor size or an increase in the detection frequency will serve to reduce the angular aperture of the sensor and thus reduce both the number of observed signal reflections and length of the received signal. Fortunately, these requirements are compatible with the practical aspects of emission detection in the field. Reactor noise measurements⁽⁷⁾ and a test of emission detection in the presence of hydraulic noise⁽⁸⁾ both substantiate the need to work in the low megahertz frequency range. A brief study shows that the acoustic emission signal per se is not the limiting factor on high frequency detection. Sensors up to 30 MHz were used to study emission, and the signal transmitted in the metal (steel) was sufficiently short to cause the sensor to respond at its fundamental frequency of 30 MHz. This response indicates the transmitted emission signal to be a pulse transient with a period of less than 0.03 μ sec. The 30 MHz frequency is well above any practical level for field surveillance application because of frequency dependent attenuation in the material.

The different modes of signal transmission--longitudinal, shear, and Rayleigh--were studied for their respective merits as a vehicle for emission detection. It appears that detection of shear waves would involve the least interference from other modes and produce the sharpest signal. Figure 2 shows an example of the variation in detected signal produced by the same acoustic emission event using different sensors and detection technique. Results of the wave propagation study and direction obtained therefrom for improving detection techniques is being reported in a separate topical report.⁽⁹⁾

The type of correlation attainable between acoustic emission and fracture parameters is illustrated in Figure 3. In this test, a double cantilever beam specimen of D2 tool

SHEAR SENSOR
1.7 MHz
EDGE MOUNTED
GAIN OF 100
HI-PASS FILTER-1.2 MHz
0.05 VOLTS/CM
0.001 SEC/CM

ULTRASONIC SENSOR
1 MHz CUT, SURFACE MOUNT
GAIN OF 100
HI-PASS FILTER-600 kHz
0.01 VOLTS/CM
0.001 SEC/CM

ACCELEROMETER
ENDEVCO #2213E, SURFACE MOUNT
GAIN OF 100
HI-PASS FILTER-30 kHz
0.05 VOLTS/CM
0.001 SEC/CM

Neg 0684222-5

FIGURE 2. *Response of Different Sensors to the Same Acoustic Emission Signal*

steel with a preformed starter crack was loaded until the crack started to grow. At this point, the load was held and allowed to decay by slow crack growth. This process is shown in the upper curve. The lower curve shows the accompanying emission rate curve. Each inflection in the load decay curve denotes a change in crack velocity. Examination of the emission rate curve shows that a change in crack velocity is accompanied by a proportionate change in emission rate. Figure 4 shows the relationship between crack velocity and emission rate derived from these data.

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FIGURE 3. Acoustic Emission Rate as a Function of Load Decay by Crack Growth in a Fracture Specimen

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FIGURE 4. Acoustic Emission Versus Crack Velocity

SENSOR DEVELOPMENT

Considerable effort has been devoted to developing a high temperature, high sensitivity transducer capable of withstanding extended operation in an environment of about 800 °F temperature and nuclear radiation. The electrostatic transducer showed

considerable promise initially for fulfilling the requirements. Development work on this concept, however, disclosed two major problems. The sensitivity was marginal and fabrication procedures were complex, with the resulting assembly too delicate for field application. Further work on this concept has been discontinued as part of this program in favor of high temperature piezoelectric materials.

Referring again to Figure 2, the responses of three currently available transducer types to excitation by acoustic emission in steel are shown. The three transducer response signals were generated simultaneously by a single acoustic emission event. This approach is necessary to obtain a valid comparison of response from different transducers because of the randomness of acoustic emission. The shear sensor shown in the top trace produces the most desirable signal. The front is quite sharp and the duration of the main signal, less than 100 μ sec, provides good resolution of other closely following signals. Transducer material is PZT-5A piezoelectric cut to a 1.7 MHz primary frequency and poled in the shear direction. This transducer is sensitive almost exclusively to shear waves. With a curie temperature of ≈ 685 °F, this material can be used for extended periods in a temperature environment up to 600 to 625 °F. It also has good resistance to nuclear radiation damage. In order to obtain optimum results, the sensor must be mounted on the edge or thickness plane of the specimen and at least 1/16 in. below the surface. Adaptation of this technique to field application is still in progress; however, it can be applied currently for laboratory specimen study. Several techniques for field application are being investigated for feasibility.

The middle trace shows the response of a surface mounted, longitudinally poled, PZT-5A piezoelectric sensor currently in routine use in both laboratory and field tests to study

acoustic emission. The response is primarily to shear and Rayleigh waves. Although the wave front is quite well defined, the undesirable duration of the signal (1 1/2 to 2 msec) is evident. Also, although the transducer is operated in a high frequency mode (≈ 700 kHz) by filtering, strong modes at frequencies as low as 100 kHz have also been discerned. In a strong noise field such as hydraulic cavitation, these lower frequency responses can create problems by saturating preamplifiers and/or passing through a filter with sufficient strength to show up as erroneous data. Circuit tuning is presently used to minimize this problem. With a PZT-5A sensing element, this transducer has the same environmental capabilities described above.

Acoustic emission generated response from a conventional, commercial accelerometer is shown in the bottom trace. The problems of low frequency response and extremely long signal duration are apparent. Although the sensing element (basically PZT-5) does have a higher frequency response component, it is quite weak compared to that at 30 to 50 kHz. This characteristic produces the same system problem, except in a much more aggravated form, as that previously described under the surface mounted ultrasonic sensor.

Lithium niobate (LiNbO_3) is presently under study for application as a high temperature (1500-2000 °F) sensing element. The material is a piezoelectric demonstrating marginal sensitivity as a longitudinally poled sensor. Recent work using it in a shear-poled, edge mounted form, however, shows sensitivity comparable to PZT-5A.

Arrangements have been made to test LiNbO_3 crystals for their ability to withstand exposure to gamma and fast neutron (>1 MeV) nuclear radiation at temperatures up to 1000 °F. This information is vital to ultimate application for reactor pressure system surveillance.

Transducer coupling to the specimen surface is an important consideration in the detection of acoustic emission. General Electric Company RTV-116 silicone rubber has been found to perform well in coupling surface and longitudinal waves to the transducer face. Although rated for a maximum service temperature of 600 °F, this material has been used quite successfully as a couplant in applications approaching 700 °F. One advantage of this material is its ability to remain sufficiently pliable to permit removal of the transducer for reuse without destroying the front electrode. It also acts as a good insulator to prevent grounding of the system at the transducer and thus incurring the problem of electrical ground loops.

A "hard" mount has proven to be much better than silicone rubber for coupling shear waves. An adhesive such as Eastman 910 within its 200 °F temperature limit or one of the several ceramic strain gage bonding materials shows good shear wave coupling properties. A disadvantage in the use of these adhesives, however, is that a transducer, once mounted, usually cannot be removed without destroying the crystal.

SIGNAL CONDITIONING AND ANALYSIS

Although the transducer is obviously the primary key to successful detection of acoustic emission, the supporting electronics system is vital to beneficial use of the detected information. The monitor system currently used by BNW is shown in schematic form in Figure 5. The signal from the transducer is fed into a low noise preamplifier, located as close as possible to the transducer, where it is amplified by a factor of 100. From here it goes through a variable, 24 db/octave, electronic filter to screen out unwanted low frequency information. The remaining data goes to a times

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FIGURE 5. Block Diagram - Acoustic Emission Monitor System

100 amplifier. At this point, the system divides into two branches. One branch goes to a magnetic tape recorder for raw data storage and to an oscilloscope for continuous data surveillance. The other branch goes to a discriminator and gate circuit wherein an incoming signal above a set threshold voltage value will produce a shaped output signal (square wave) to be fed into a count rate circuit and a count totalizer circuit. These two parameters are then read out on a two-pen trip chart recorder versus time, or some other test parameter.

Since many of the acoustic emission signals are of very low level, it is important to minimize electronic noise. With the preamplifier as the component primarily responsible for establishing the final system noise level, considerable attention has been given to producing a low noise, high frequency preamplifier. The preamplifier, shown in Figure 6, is an all transistorized device with a noise level of 7.6 μV rms referred to input, a bandwidth of 30 kHz to 2.5 MHz, and a gain of 100.

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FIGURE 6. *Low Noise, Broadband Preamplifier
for Acoustic Emission Detection*

The coin (a quarter) shown in the lower right corner provides a measure of actual assembly size. In a very recent modification, this preamplifier was tuned to operate over a 400 kHz band about a selected center frequency. The center frequencies of 700 kHz and 1.5 MHz used to date have been based on characteristics of the particular transducers. The tuned version provides the advantages of reducing noise level to 3.5 μV while increasing the gain to 150, eliminating need for a separate filter by virtue of the inherent roll-off on either side of the pass band (effectively 14 db/octave), enhancing selected transducer response characteristics, and blocking low frequency signals at the preamplifier to alleviate preamplifier saturation created by high level, low frequency extraneous signals. This preamplifier is stable and unaffected by long output leads (500 ft long leads have been used satisfactorily).

The necessity to transport the monitor system considerable distances to monitor special tests has prompted effort to minimize system size and weight. The solid state version of the system currently in use is illustrated in Figure 7. For comparison, the functional counterpart of each instrument in general purpose laboratory instruments is shown in each photograph. The lower photograph shows a six-channel filter-amplifier instrument, and the upper photograph shows an instrument incorporating a single-channel filter, amplifier, discriminator, gate, and count rate circuit, with integral strip chart recorder.

To date, the primary acoustic emission characterization parameters have been emission rate and a running total of emission count. In general, they have given consistent results. Pulse height, pulse duration, and pulse energy are currently being investigated as characterization parameters.

Work at BNW on automating the source location readout or other data interpretation has been intentionally deferred. A companion part of this overall program sponsored by the AEC with Phillips Petroleum Company at the Nation Reactor Test Site, Idaho Falls, Idaho, concerns plant application aspects. By mutual agreement, development of automatic readout systems is being conducted there.

A recent innovation beneficial to either manual or automatic source location is the processing of the raw data through a detector circuit. Effectively, this step produces a rectified signal describing the envelope of the raw data signal. Such a modification aids in wave front definition, provides a noise-free signal for subsequent operation, and permits the storing of high frequency data in a low frequency storage system.

┌── New ──┐ ┌── Old ──┐

A

Emission Rate Analyzer

┌── New ──┐ ┌── Old ──┐

A

Six Channel Signal Conditioner System

Neg 0680655-4

FIGURE 7. Solid State Acoustic Emission
Monitoring Equipment

APPLICATION ENGINEERING

Discussion of the application-oriented aspect of this research is considered appropriate at this point. One of the basic questions related to the intended application of acoustic emission for continuous surveillance of nuclear reactor pressure boundaries concerns the problem of detecting and identifying acoustic emission in the presence of the inevitable hydraulic noise background. Two major tests have been conducted in an effort to answer this question. The first consisted of monitoring the background noise spectrum of the Dresden I nuclear power reactor during start-up to full power operation. The results of this test, reported in detail elsewhere,⁽⁷⁾ showed, in brief, that the noise field above 500 kHz is quite low for this reactor (General Electric Co. boiling water design). Figure 8 shows typical spectrum analyzer response for turbulent flow and for turbulent flow with probable cavitation. Figures 9 and 10 provide typical compilations of analyzed data. There is a frequency region nominally from 750 kHz to about 3 MHz (where signal attenuation with increasing frequency rises sharply for ferrous materials) where the low noise level is conducive to reliable detection of acoustic emission signals.

This work was followed with a test wherein a hydraulic test loop was used to generate noise spectra similar to those observed at Dresden I and detection of actual acoustic emission signals in such an environment was evaluated. Results, reported in a separate document,⁽⁸⁾ showed that an acoustic emission sensing system operating with shear sensors in the 1.5 to 2.5 MHz frequency range can detect emission signals with no noticeable interference from hydraulic noises created either by turbulent flow or cavitation. A schematic of the test system and photos of the test arrangement are given in Figures 11 and 12, respectively. Comparison of Figure 13 with Figure 8 shows

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FIGURE 8. *Hydraulic Noise Spectra - Dresden I
Nuclear Power Reactor*

the similarity of the noise environment produced for this test with that measured on the Dresden I reactor. Acoustic emission signals were produced by bending the "fingers" on the test plate shown in the lower right corner of the right hand photograph in Figure 12. Response of various sensors to the acoustic emission signals thus produced is presented in

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FIGURE 9. Noise Spectrum - 22 in. West Recirculation Header - Dresden I

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FIGURE 10. Noise Spectrum - 6 in. By-Pass Line, "D" Secondary Steam Generator - Dresden I

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FIGURE 11. Sketch of Test System - Detection of Acoustic Emission in the Presence of Hydraulic Noise

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FIGURE 12. *Test Arrangement - Detection of Acoustic
Emission in the Presence of Hydraulic Noise*

Neg 0683998-6

FIGURE 13. *Hydraulic Noise Spectra - Turbulent Flow and Cavitation Conditions*

Figures 14 and 15. A sensor near the emission source was used to trigger the oscilloscope in order that the response of the data sensors, located 3 ft from the source, could be viewed in full form in the middle of the screen. Also, position of the response on the screen verified that the detected signal originated at the emission source. The top trace in all photographs was produced by the same sensing system to provide a basis for comparing the various other sensor arrangements. As the

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FIGURE 14. *Acoustic Emission Signals Detected in the Presence of Hydraulic Noise - A*

photographs show, good response was obtained from all of the shear sensors for all test conditions, and a usable response was obtained from the surface mounted longitudinal sensor for turbulent flow noise only. The response of the surface mounted longitudinal sensor was seriously obscured when cavitation noise was introduced.

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FIGURE 15. *Acoustic Emission Signals Detected in the Presence of Hydraulic Noise - B*

Acoustic emission was included as part of the monitor network for another AEC sponsored program to study rupture of ductile reactor pressure piping materials. Four of these tests have been monitored for acoustic emission to date. An example of the results is shown in Figures 16 and 17. The test specimen in this case was a 12 ft long section of 24 in. diameter by 1.64 in. wall A 106B carbon steel pipe containing

Neg 0680076-5

FIGURE 16. Data Trace Samples from the Final 10 min - Burst Test of 24 in. Diameter x 1.6 in Wall Steel Pipe

Neg 0673121-1

FIGURE 17. Emission Rate Curve from Final 10 min - Burst Test of 24 in. Diameter x 1.6 in. Wall Steel Pipe

a milled flaw at one point in the pipe wall. One of the functions of acoustic emission monitoring was to determine the onset of crack growth and to predict impending failure far enough in advance to permit turning on a movie camera, to monitor the final stages of crack growth. Real time data interpretation was accomplished by measuring emission rate. Figure 16 shows acoustic emission data samples from the last 10 min of the test. Figure 17 shows the corresponding emission rate curve. Initial crack movement was indicated about 9 to 10 min prior to failure. From high speed movie film of the flaw, it was evident that this initial indication was well in advance of a visible crack forming on the specimen surface. Figure 18 shows the magnitude of the final rupture. This test is an example of detecting flaw growth in steel under relatively adverse field conditions. Pressurizing of the specimen by the heating of contained water resulted in boiling water noise throughout most of the test. The specimen temperature reached about 700 °F. It was necessary to use 300-ft long signal leads. In spite of these adversities, the acoustic emission was detected rather easily.

Preliminary study of acoustic emission from Type 304L SS specimens failing in tension-tension high cycle fatigue showed significant acoustic emission activity well before formation of a visible surface crack. The specimen configuration is shown in Figure 19a. This specimen was preloaded as shown in the loading diagram (Figure 19b) and then cycled at 1800 cycles/min until failure. Representative acoustic emission produced by these samples is shown in Figure 20. Practically no emission was observed until after approximately 6000 cycles. From this point, the emission rate increased gradually to about 22,000 cycles, at which point the rate increased sharply. A visual surface crack, detected at approximately 34,000 cycles, grew to 1/8 in. in length by

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FIGURE 18. Ruptured 24 in. Diameter $\times$ 1.6 in. Wall Steel
Pipe Test Vessel

a. Fatigue Specimen

b. Specimen Loading Diagram

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FIGURE 19. Cantilever Beam Specimen Fatigued by Cyclic Loading

55,000 cycles. The large fluctuations in the acoustic emission rate after 34,000 cycles are apparently due to the crack growing in steps. It is significant that acoustic emission activity was first evident at 20% of the cycles necessary to form a visible surface crack. Also, the most intense activity occurred in the region from shortly before

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FIGURE 20. *Plot of Acoustic Emission from Specimen Undergoing Fatigue*

to shortly after initial formation of a visible crack. Further study is necessary to answer questions such as the material condition giving rise to the initial emission activity, and the possibility of identifying emission rate fluctuations with step increments in the fatigue crack.

An acoustic emission system is currently in use on the reactor simulator vessel used in the Containment Systems Experiment program (a reactor safety program sponsored by DRDT, USAEC) to monitor the status of known laminar flaws in the vessel heads. During proof testing, only one small indication of flaw action was indicated. As an indication of system response, however, initial flexing of new support bracing and plastic deformation of flange blank plates were detected and the source located by means of acoustic emission. The system is being used on a continuing basis to monitor the status of the flaws during routine program tests conducted at temperatures of 550 °F.

FURTHER R&D NEEDED

One of the problems in applying acoustic emission for integrity surveillance at this point is the degree of resolution inherent. With limited calibration information available, the significance of limited indications of flaw movement is difficult to judge. In many cases, the resolution of conventional nondestructive test methods is not sufficient to confirm the acoustic emission indication and measure the amount of flaw movement represented by the acoustic emission. Technology permitting a valid estimate of crack area increment represented by a given quantity of emission data, as well as standards or criteria for judging the significance of a given amount of emission must be developed.

Other areas of future work include adaptation of the improved shear sensing technique to practical field application, and characterization of different fracture modes (brittle,

ductile, etc.) in terms of emission parameters using a high frequency (1 to 3 MHz) detection system. The maximum distance at which emission signals can be reliably detected must, also, be more firmly resolved. Another need is line filtering to reliably screen out power line transients.

In summary, there is little question that acoustic emission constitutes a powerful tool for both structural integrity surveillance and for basic study of material failure mechanisms. Full utilization of the technique will require considerable additional development work. In the meantime, however, the current state-of-the-art can be reliably and beneficially applied to many selected industrial and laboratory problems. Some examples of these are 1) monitoring for flaw growth during hydrostatic proof test of pressure containers, 2) continuous surveillance of known or suspected flaw areas in an operating pressure system, 3) evaluation of weld quality from the standpoint of crack formation during weld cooling, and 4) study of fatigue crack growth characteristics under various loading conditions.

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