monitoring structural integrity by acoustic emission

Spanner/McElroy

STP 571

AMERICAN SOCIETY FOR TESTING AND MATERIALS

MONITORING STRUCTURAL INTEGRITY BY ACOUSTIC EMISSION

A symposium
presented at
Ft. Lauderdale, Fla., 17-18 Jan. 1974
AMERICAN SOCIETY FOR
TESTING AND MATERIALS

ASTM SPECIAL TECHNICAL PUBLICATION 571
J. C. Spanner, editor
J. W. McElroy, co-editor

List price $23.75
04-571000-22

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race Street, Philadelphia, Pa. 19103

Library of Congress Catalog Card Number: 74-28978

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Printed in Baltimore, Md.
March 1975

Foreword

The symposium on Monitoring Structural Integrity by Acoustic Emission was presented in Ft. Lauderdale, Fla., 17-18 Jan. 1974. The symposium was sponsored by Committee E-7 on Nondestructuve Testing, American Society for Testing and Materials. J. C. Spanner, Westinghouse Hanford Co., presided as symposium chairman. J. W. McElroy, Philadelphia Electric Co., presided as symposium co-chairman.

Related
ASTM Publications

Acoustic Emission, STP 505 (1972), $22.50, (04-505000-22)

Contents

Introduction

A wide variety of nondestructive testing methods and procedures are utilized during the fabrication of structures when the consequences of failure are costly, constitute a hazard to the public, or both. In addition, a final proof test (pressure test) is applied to most pressure vessels and many pressurized systems. The consequences of catastrophic failure during proof testing are often such that almost any method for reducing the probability of failure is economically justified. Present acoustic emission technology offers this capability and, in addition, provides a viable method for evaluating the basic integrity of many other types of engineering structures. Numerous successful applications of acoustic emission during proof testing of aerospace tanks, pressure vessels, and piping systems have been reported in the literature of the past 15 years.

Acoustic emission is the transient elastic energy that is spontaneously released when materials undergo deformation, fracture, or both. Efforts toward utilizing this phenomenon in materials research studies, and for nondestructive testing, have increased substantially in recent years. Materials investigated have included both metals and nonmetals, although most of the work published to date has been concerned with metallic specimens or structures. Analogous studies have been conducted on geologic materials (rocks, etc.), where the terms "microseismic activity" or "rock noise" are often used in lieu of the term "acoustic emission."

The continued increase in the number of reported applications of acoustic emission to monitor structural integrity influenced ASTM to authorize this special technical publication to publish the papers presented during an ASTM Symposium on Monitoring Structural Integrity by Acoustic Emission. This symposium was held in Fort Lauderdale, Florida, in January 1974, under the sponsorship of the ASTM E-7 Committee on Nondestructive Testing, and was a sequal to an introductory ASTM Symposium on Acoustic Emission which was held in December 1971. That symposium was documented in ASTM STP 505.

The purpose of the 1974 symposium, and of this STP, is to present a collection of papers selected to provide a representative coverage of recent activities in applying acoustic emission to monitor the integrity of engineering structures. It is significant that many of the speakers at this symposium are among the leading U.S. experts in this new and rapidly expanding area of technology.

The first few papers provide background information on the acoustic emission method and its applications, and discuss specific characteristics of the signals that are emitted by structural materials. The next series of papers describe the techniques that were used, and the results that were obtained, when commercial and developmental acoustic emission instrumentation systems were employed to monitor the integrity of a wide variety of engineering structures and components. The last paper is a bibliography containing 412 references on acoustic emission that were published during the years 1970–1972.

This publication is intended to provide a permanent record on the technological status of Monitoring Structural Integrity by Acoustic Emission as it existed in early 1974. It is expected to be of value to those who are actively engaged in this field, as well as to those with structural integrity monitoring applications requiring the unique capabilities offered by this relatively new nondestructive testing method.

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Why Acoustic Emission—Why Not?

REFERENCE: Schofield, B. H., "**Why Acoustic Emission–Why Not?,** *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 3-10.

ABSTRACT: The relative apathy of the industrial community to take advantage of the significant benefits of acoustic emission is discussed against the background of the current state of the technology. Examples of immediate applications are noted. It is suggested that developing trends necessitate timely initiation of industrial utilization and that such efforts and the experience gained therein are a prerequisite to the realization of the technical benefits of acoustic emission and the establishment of proper and adequate guidelines.

KEY WORDS: acoustics, emission, pressure vessels, defects, hydrostatic tests

The purpose of this paper and, undoubtedly the material presented in many of the papers of this symposium will fortify this purpose, is to encourage and promote more widespread practical utilization of the acoustic emission (AE) technology, at least in those specific areas where the acoustic method has been shown to be effective and of technical and economic value.

Background

Following the first comprehensive and continuing research studies in the early 1950's, a number of proposals for the practical commercial and industrial utilization of AE emerged. These applications related principally to the determination of the integrity of pressure vessels under hydrotest. At this early stage there was little commercial or industrial motivation to apply the technique as it was almost entirely an art, known by a few, and what instrumentation there was available appeared to be the typically disorganized conglomerate of the eccentric researcher. However, it was not long before equipment and systems were being produced and made generally available specifically for AE studies, and by the middle 1960's both

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technique and instrumentation had been developed to a reasonable state of the art. A number of practical nondestructive testing (NDT) applications had been successfully demonstrated, while versatile and sophisticated instrumentation components and systems were developed contemporaneously to put the technique into practical use. Nevertheless, as we now approach the mid 1970's it can be undeniably stated that here in this country we find that relatively little industrial and commercial advantage has been taken in benefiting from this new technology; the generic question seems to be—Why acoustic emission? In the following, the author does not pretend to fully answer this question but hopes to present a sufficient premise to propose the question, Why not?—in appropriate applications. Although numerous cases could be cited showing the current applicability of AE as a research tool, the emphasis of this discussion is confined to industrial utilization.

Current Case for Acoustic Emission

The basis for the first question can be found quite readily, albeit, it abounds in a mixture of cynicism and questionable technical logic, if not a lack of common sense. Probably more important, however, is that the prevalence of the question evidences the disappearance, to a large degree, of technical entrepreneurship to explore innovation, but it also reflects both the sophisticated complexities and subtleties involved in the technical-business decision processes within large firms and industries.

For example, several years ago the author undertook a survey of a particular large industry to determine the nature and magnitude of the market that could and would utilize AE at its then present state of the art. The specific acoustic application was the determination of the structural integrity of large, heavy wall, expensive pressure vessels. The technique involved the nondestructive testing in the manufacturer's shop prior to installation. Results expected from these tests would be the detection of structural defects and their propagation, if any, induced by pressure loading; the accurate determination of the physical location of these defects anywhere in the vessel; and a very high probability of precluding catastrophic failure of the vessel during the hydrostatic test.

The survey respondents showed a unanimous and authentic interest in the AE method and acknowledged the existence of many applications where the technique would not only be helpful but also where such information was urgently needed, and no other tools were available to meet their unique requirements. Nevertheless, coupled with this technical interest and need was an overriding concern and indulgence with the limitations of the technology and the possibility of some uncertainties or ambiguities in the data. The source of these concerns was less related to any technical shortcomings than to the structured problems of decision making within the respective firms—between the technical and the administrative executive staff levels. If there are uncertainties and ambiguities in the data, how would these be explained and resolved to the satisfaction of upper management?

Many of the modern, high-pressure, high-temperature vessels are constructed from new materials using new techniques and methods of fabrication, and the structures themselves are of increasing geometric complexity. The engineering staff of the firm procuring the vessel is thereby faced with many difficulties, some of uncertain or ambiguous technical basis requiring decisions in design, manufacture, and operation. The addition of a relatively unknown technology with its attendant problems and educational burdens was not relished by the survey respondents, and it was a general concensus of the respondents that they would be better off without the information obtained by the acoustic method. Technical questions, for which difficult or uncertain decisions would have to be formulated to the satisfaction of upper management, would be thereby eliminated. One may be sympathetic to the sensitivities expressed, but it cannot be denied that such a "head in the sand" philosophy is not technically acceptable and could be financially disastrous in time. Further, this approach would not appear to be justifiable on the basis of current AE technology. In the following discussion the author expects to show, by selected examples, that the advantages of AE outweigh still existing shortcomings and, furthermore, that elimination of the latter can only be accomplished through the practical experience gained in utilizing the technique on real, full size, industrial "specimens."

As an example of the remarkable potential of the AE techniques, as specifically related to pressure vessels, the results of a relatively recent test program are noteworthy.

The vessel under test was about 16 in. in diameter, 4 ft long, and had a wall thickness of 0.5 in. in the cylindrical section. The material was ASTM A516 having a yield strength of about 70 000 psi. The prime purpose of the tests was to study the influence of yield strength on the vessel failure. AE tests were appended for whatever information could be gleaned and were undertaken at the expense of the AE investigator. On-line computer facilities were not utilized in these emission tests; hence, the data were analyzed subsequent to the actual pressure testing rather than in real-time.

Figure 1 is a pictorial representation of the acoustic data prior to general yielding of the vessel. Each data point represents a located source of acoustic emission. Only a fraction of the total number of sources obtained are presented in the figure; nevertheless, the overall pattern remains unchanged. It is evident from the pattern that a line of clustered emission

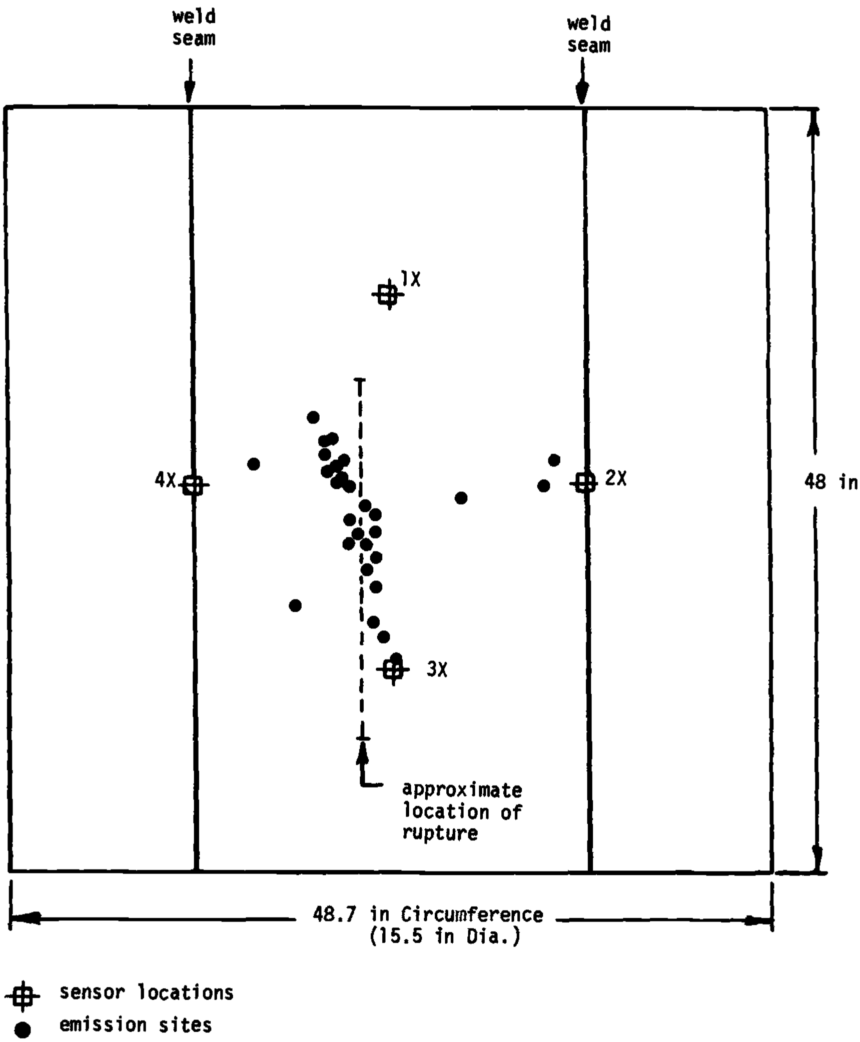

FIG. 1—*Emission sources located during hydrotest of vessel.*

sources developed during the pressurization. The dense line of dots actually outlines, approximately, an artificial defect that had been machined into the vessel prior to test and was the precise location where final fracture eventually occurred. However, more interesting than the final appearance of the emission pattern is the "pressure-time-emission location" pattern as it developed. Emission sources began to appear in the center region of the length of the defect and continued in activity as new emission sources progressed outwardly along the length of the defect line. Such a pictorial display could be obtained by a computerized real-time display of the emission sources and would show the early initiation and the dynamic growth of the deformation pattern associated with the defect. In the case of a defect which is acoustically active along its entire length, as in this case, the emission pattern has the capability to show the geometric shape of the defect and with sufficient discrimination could, in conjunction with additional emission parameters, provide growth rate data for a propagating defect.

This is not to say that the specific type of defect, or other geometric details, would be discernible, nor would the degree of severity necessarily be assessable in terms of the ultimate response of the vessel. The previously discussed emission pattern could be, for example, produced by a region of local plastic deformation, by a stringer of macroscopic metallurgical defects, or by a crack. To date no definitive and consistent characteristics of the emission signal has been found that distinguishes defects in such detail. Complementary methods such as ultrasonics, radiography, etc. would be essential to define the type of defect and its exact geometric dimensions and metallurgical details. This is especially obvious for the case where a relatively long crack may be acoustically active in only a small region of the total defect, such as at the tip of the crack. The acoustically inactive portions of the crack, of course, do not provide any information concerning the total extent of the defect, and other complementary techniques would be called for in such an instance.

There is, however, one notable emission characteristic indicative of defect severity, in that the emission data do signal the onset of impending failure. This is the distinct change in the emission rate, invariably accompanied by an increase in signal energy, from a relatively uniform, linear count rate to an exponentially rising count rate at a given and identified location in the vessel. An obvious requirement for observation of the impending failure characteristic is, of course, the detection and observation of the emission rate prior to the onset of the unstable propagation of the defect. A test of a vessel which at the outset contains a defect of critical dimensions would be most difficult to evaluate but, with the proper preparatory studies of the vessel material, could provide the quantitative emission criteria, which coupled with the versatility of the high-speed computer, could in turn provide the capability of detecting impending failure even under such extreme conditions. The laboratory studies would, of necessity, have to be rather extensive and undoubtedly expensive. Not only would it be necessary to establish emission reference data for the basic material but also for various welding configurations as well as fracture mechanics-emission experiments.

Nevertheless, the efficacy of the AE method is preeminently apparent. What other method can identify the presence and location of an active "defect" so quickly and efficiently. Consider for a moment the surface area of a vessel represented by a diameter of 25 ft, and a length of 60 ft, spherical heads, and several complex nozzle and other configurations. A full volumetric NDT inspection of the vessel material is normally a formidable task involving considerable expense. Consequently, in the usual case it is necessary to exercise engineering judgment as to the extent of economically and technically justifiable inspection, with some calculated probability of risk that significant defects would remain undetected. The emission method immediately shows economical and technical benefits in vastly reducing, if not eliminating, this factor of ignorance since in essence the total vessel is subject to surveillance. Without doubt one can approach the evaluation of the integrity of a vessel much more confidently with the added knowledge provided by the acoustic method.

The second subject I would like to pursue, but briefly, concerns the controversy regarding the propriety of the hydrotest *per se,* and the practical solution offered by the use of AE. There is a school of thought that the hydrotest itself may produce damage or worsen an already existing defect condition and that the extent or probability of such damage or degradation of the vessel integrity will be unknown and not subject to analytical determination. The acoustic method offers a unique means of detecting whether or not such additional damage is induced by any given hydrotest. With the exception of a vessel or structure that is undergoing general and gross yielding, experience has shown that the propagation of a defect in the vessel will produce detectable AE. The location of the source or sources can be determined, and, if deemed necessary, close examination by complementary techniques can be made. Clearly, if the vessel exhibits no emission, or only a minor amount widely distributed over the vessel surface, one can be confident that the hydrotest has not affected the vessel adversely. For those cases wherein the hydrotest does produce structural damage, the emission data will provide the information to locate the area of such damage, as well as to provide a qualitative assessment of the extent of the defect activity. For those circumstances where hydrotests are to be conducted periodically after the vessel is in service, the advantages of having AE data from the manufacturer's shop hydrotest and the initial hydrotest following installation cannot be overstated. These two tests will provide an invaluable reference for all subsequent emission surveys relative to defect areas and their significance to vessel integrity.

Certainly a philosophy not to conduct a hydrotest to assess existing integrity for fear of producing additional damage in the vessel is merely exchanging one form of ignorance for another. The availability of the acoustic method substantially mitigates such concerns, and the balance of risks between conducting a hydrotest or eliminating the hydrotest is shifted in favor of the test monitored by AE.

There are, of course, numerous additional considerations and examples which could be cited in favor of industrial utilization of AE, and the papers of this symposium are excellent examples. It should also be noted that the American Society of Mechanical Engineers' (ASME) Code, to a limited extent, has recognized the NDT potential of AE (Section XI), and, of course, ASTM holding a second symposium in as many years and the forming of the Subcommittee E07.04 has shown the presence of widespread interest. It should be recognized by those in the pressure vessel industry that development of codes and standards is inevitable and that they will play an influential role within this industry. It is imperative that personnel within the industry play a part in these developments and that they contribute from a background of knowledge and experience with the subject matter. It is through the knowledge gained from actual experience with AE that appropriate and relevant codes and standards will evolve.

It is certainly not inappropriate in this day and age to also mention that the public demands for increased safety of large pressure vessels, particularly those in the nuclear industry, will also play an influential role, and the impact of the public interest on industry will depend, to a large extent, on industries' own initiatives. Nothing would be more detrimental to all than the premature demand to foster an undeveloped technology on an inexperienced, unprepared industry.

Lastly, I wish to note, not only the escalating interest in the emission technique in foreign countries but also their rather zealous production and placement of AE systems into diverse industrial applications. Without doubt the experience being currently accumulated by these systems will place these countries in a foremost position in this technology. What was once essentially a U. S. monopoly in practical AE is rapidly disappearing, and, considering the fact that this country has many of its large, complex, and expensive vessels built in foreign plants, there should be keen interest in advancing our own knowledge of the technologies that may well be in common use in these countries in the near future.

Conclusion

Over the past 15 years there has been an evergrowing and accelerating need for not only improvement and advancement in our existing stock of NDT tools but also an urgent requirement for new methods answerable to the increased complexities and demands of modern structures and standards. With the possible exception of the yet undeveloped field of holography, AE is the only new tool that has appeared on the technical scene and which holds a promise of meeting those modern needs.

Such promise has not been met with an enthusiasm in the utilization of the technique. There appears to be a philosophy to await the ultimate and full technical development of the method whereby ambiguities and uncertainties will be eliminated; hence, until then, why use AE? Such an approach ignores the current state of the art for certain and particular applications and the present advantages that can be realized while imposing a more demanding standard.

It is to be recognized that it is through the experience of utilization that the full potential of AE will be developed. In the area of pressure vessel integrity the method has no peer in terms of ultimate potential. Currently AE offers significant practical benefits; hence, why not take advantage of these and by so doing also produce the additional benefits which will naturally develop as a consequence of intimate involvement with the technique.

Undoubtedly, AE will find increased utilization and broader application, accompanied by the development of codes and standards within these uses. The rate of progress and the wisdom of the guidelines will depend, to a large extent, on the participants in this development.

L. J. Graham[1] and G. A. Alers[1]

Acoustic Emission in the Frequency Domain

REFERENCES: Graham, L. J. and Alers, G. A., "**Acoustic Emission in the Frequency Domain,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 11–39.

ABSTRACT: A means for quickly and easily determining the broadband frequency content of acoustic bursts as short as 20 μs in duration has been developed using a video tape recorder and a standard spectrum analyzer. It is shown by examples from several tests on laboratory specimens and on large structures that the frequency content of an acoustic burst is related to the mechanism which produced it and is not affected substantially by the specimen size or by mode conversion due to multiple reflections in the structure. The frequency content of the burst can be changed in two ways, however: by the frequency-dependent attenuation of the propagation medium and in the cases where the medium is dispersive. Results of measurements on the effect of these factors in a variety of structures are given. Although acoustic emissions from many materials tend to be "white noise," several examples of acoustic emissions and extraneous background noise bursts having distinctive frequency spectra are given which suggest possibilities for discriminating true acoustic emission signals from background noise on the basis of frequency content alone.

KEY WORDS: acoustics, emission, spectrum analysis, tape recorders, plastic deformation, crack propogation, ultrasonic frequencies, transmission loss, wave dispersion, Lamb waves

There is a twofold impetus for determining the frequency content of individual acoustic emission (AE) bursts. The first one is for possible identification of source mechanisms and for insight into the physical parameters associated with their operation. These mechanisms include dislocation motion, crack propagation, phase transformations, and twinning [*1–8*].[2] The second one is for identifying differences between the AE generated by any of the effects just mentioned and those produced by other extraneous noise sources [*9–11*]. This information is essential in some AE triangulation applications where extraneous noises from the test environ-

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

ment are so numerous as to saturate the information handling capabilities of the computer used to analyze the incoming signals. If the frequency content of the signals and the noises are both known, filtering or other electronic means can help to reduce the amount of irrelevant information early in the data processing. Of these two general areas of study, the latter is of most immediate technological interest. This paper will present results of some studies in this area concerned with identifying differences in the frequency spectra of noise from different sources.

Most mechanically produced resonant vibrations of structures and laboratory test specimens occur in the low kilohertz frequency range. Early studies of the frequency content of AE were limited to just this range because of limitations in the techniques available at the time to frequency-analyze transient acoustic bursts. Due to this limitation, the results obtained were highly dependent upon the geometry of the specimen [*12–14*]. This tendency for the lower frequency modes of structures to be excited mechanically can be advantageous, however. Mechanical signature analysis of structures and machinery is an important technological area, and real-time frequency analysis eqiupment covering the frequency range to 50 kHz is available for this purpose [*15*]. Also, this low-frequency range has been successfully utilized in AE studies of the fracture of fiber composites where the resonant frequencies of the fibers excited during fracture can be identified [*16*]. A third advantage, one that is more pertinent to the present discussion, is that AE tends to be very broad banded in frequency content while many mechanical components such as solenoids, gears, cams, and bearings excite only the low-frequency components. This can allow the discrimination of one against the other by simple electronic means.

There are also other types of mechanically and hydraulically produced noises which can have frequency components extending up into the low megahertz frequency range, and examples of these will be given later. These can be particularly troublesome in AE testing because they have frequency components covering the same general frequency range as the flaw-generated bursts. It is, therefore, desirable to be able to frequency analyze these acoustic bursts in detail over a broad frequency range in order to find characteristic features of their spectra which can be used to distinguish them from AE. It is only recently that instrumentation has been developed for the broadband frequency analysis of short duration, transient acoustic bursts. The three most promising methods are: (1) digital conversion with computer analysis [*7,9*], auto-correlation techniques [*2*], and (3) record and playback with a helical scan video tape recorder [*3,17*]. Of these methods, the latter has the advantage of being able to record every AE event for later analysis at the discretion and convenience of the investigator.

The present studies extend over a two-year period during which a video tape recorder and commercial frequency analyzer were used to determine the frequency spectra of acoustic bursts from many different test situations. Means for determining the broadband response of the acoustic transducers and for evaluation of associated broadband electronics were also developed. A summary of the important results of this study which previously have been points of conjecture are:

1. The frequency content of an AE burst is not substantially altered by mode conversion during reflections at the boundaries of a solid structure.
2. The observed frequency spectrum of an AE depends both on the frequency dependence of the acoustic attenuation and on the dispersive character of the transmission medium between the source and the transducer.
3. Although AE in many materials tends to be nearly "white noise" at least up to 2 MHz, several cases have been observed where there is a strong structure in the frequency spectra.
4. Extraneous noise bursts can often be distinguished from flaw-generated emissions by differences in their frequency spectra.

Experimental Method

A Sony video tape recorder intended for home use was modified for use as an analog signal recorder [*3*]. The principal modifications made were to eliminate extraneous synchronization signals required in the TV recording format, to provide for internal synchronization, and to realign the FM amplifier to increase its bandwidth and dynamic range. This instrument was then used in conjunction with a broadband transducer, amplifier, and spectrum analyzer system as shown in Fig. 1. A key feature of this recorder is its "stop-action" capability which allows a repetitive playback of any 16.7 ms time interval of the recorded signal for steady viewing on an oscilloscope or for presenting to a standard frequency analyzer (such as the Hewlett-Packard Model 8552A/8553B). With synchronized electronic gating of this repetitive signal, any portion of the recorded signal as short as 20 μs in duration can be analyzed independently for its frequency content.

The frequency response of the recording and analyzing system should be considered in two parts—the electrical and the acoustical. The component limiting the electical response is the tape recorder which is down 3 dB at 3 kHz on the low end and 2.5 MHz on the high end, but with a useable frequency range to 3 MHz. All other electronic components are considerably more broadbanded. The acoustic response of the system is governed by the transducer and its acoustic coupling to the specimen, so considerable effort has gone into determining this characteristic. To do this, an acoustic "white noise generator" (WNG) similar to that described by Chambers [*1*] was built and is shown schematically in Fig. 2. It consists of a steel plate

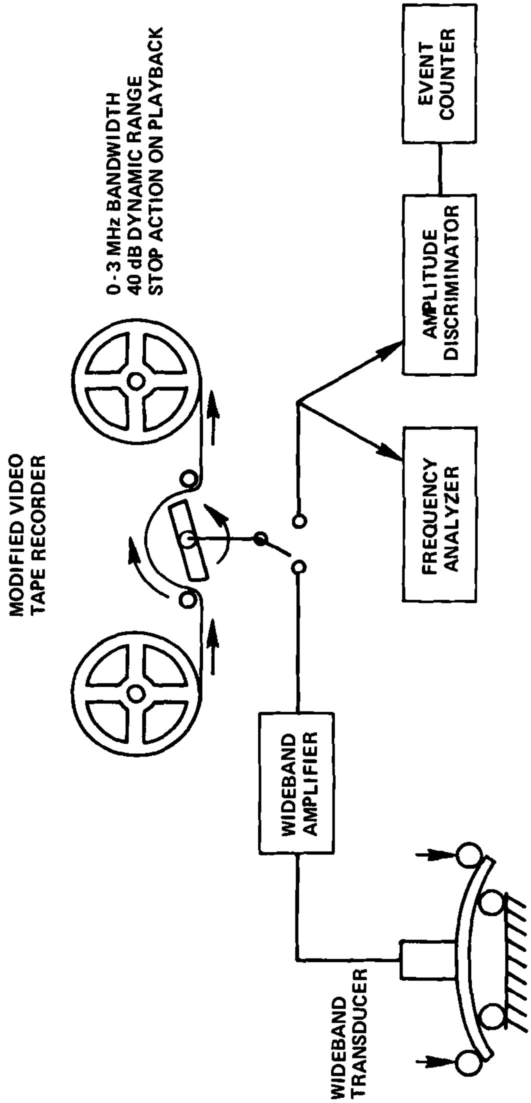


FIG. 1—*Broadband system for recording and analyzing acoustic emissions.*

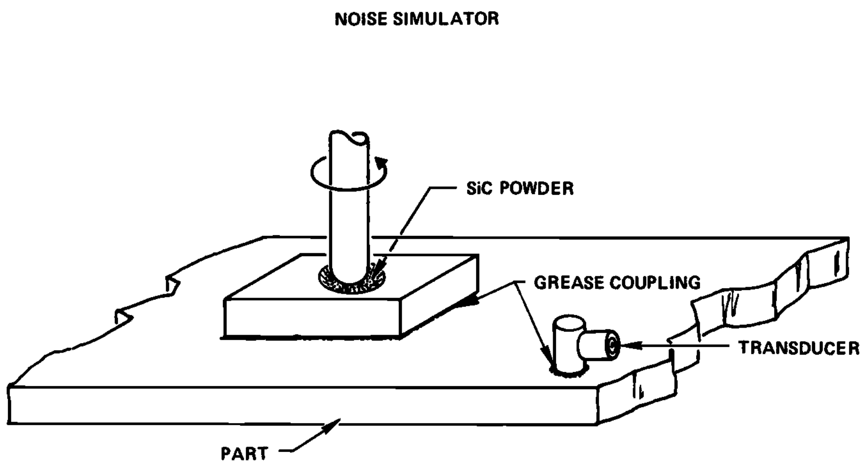


FIG. 2—*Acoustic "white noise" source for determining transducer response and for acoustic attenuation measurements.*

having a depression on one face in which fine particles of silicon carbide are fractured continuously under the rotating action of a fused silica rod. A specially built high-fidelity capacitor microphone mounted directly on the steel plate was used to determine the acoustic output of this noise generator. Its output voltage, shown in Fig. 3, exhibits a fairly smooth $1/f^2$ dependence upon being excited by the WNG. Since the voltage output of a capacitor microphone is proportional to displacement amplitude, this dependence is as would be expected for an acoustic source with a periodic driving force of constant amplitude at all frequencies [*18*]. The response of a typical piezoelectric transducer, also shown in Fig. 3, does not fall off as

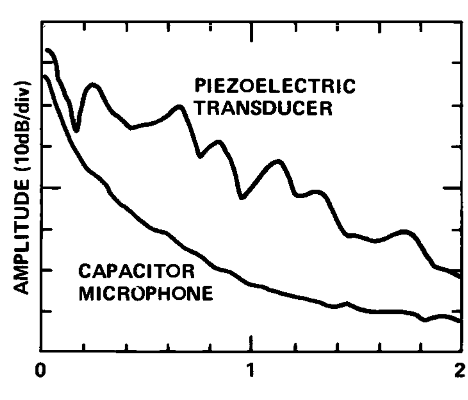


FIG. 3—*Response of two types of transducers to a "white noise" source.*

rapidly with increasing frequency since its response is more nearly proportional to particle velocity in the acoustic disturbance than to displacement. The particle velocity due to acoustic white noise as just defined has a $1/f$ dependence. However, the internal mechanical resonances of the piezoelectric element produce a very irregular response curve.

Examples of the responses of several piezoelectric transducers to the WNG are shown in Fig. 4. In Fig. 4*a*, three laboratory-assembled transducers are compared which were made from about 3-mm (1/8-in.) diameter, longitudinally poled PZT-5A of three different thicknesses. The choice of one of these transducers for a particular application is determined by its having the maximum sensitivity in the frequency range of interest. For broadband testing the 1.1 MHz transducer has the overall greatest sensitivity. In Fig. 4*b* are shown the responses of this transducer and of two commercial transducers (from Dunegan-Endevco) to allow a comparison between our method of determining transducer response and other methods which are in common usage. In obtaining these response curves, it was found that no special care needed to be taken in bonding the transducers to the white noise generator beyond using normal ultrasonic coupling techniques. Viscous oil or thin solid bonds couple the higher frequencies slightly better than less viscous liquids such as glycerine or water, for example.

A question might be raised concerning the suitability of using a continuous white noise source for determining the response characteristics of transducers intended for the detection of short-duration AE bursts. However, experience has shown that AE from many sources produce the same

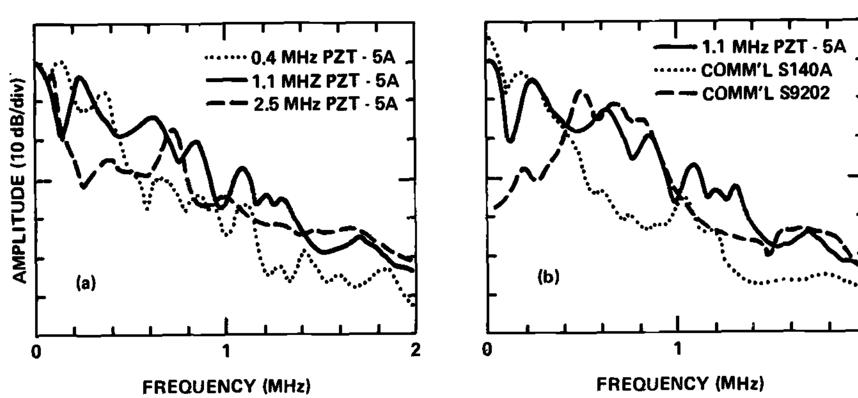
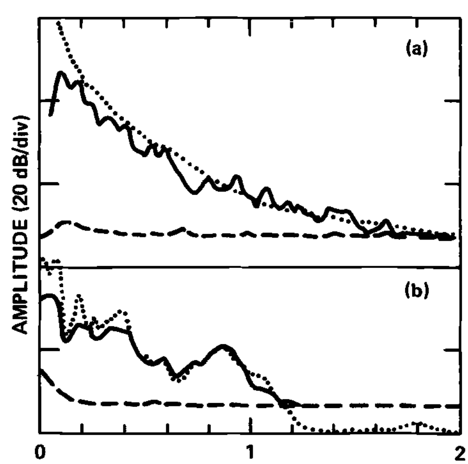


FIG. 4–Response of several piezoelectric transducers to a "white noise" source.

transducer response as does the WNG. Two examples are shown in Fig. 5, and others have been observed such as the deformation of 7075 aluminum and 9Ni-4Co steel, and the slow crack growth in several polycrystalline ceramic materials [5]. In Fig. 5*a* the AE was detected with a capacitor microphone transducer, and in Fig 5*b* the AE was detected with a piezoelectric transducer. In these figures, as in many of the figures in the following sections, there are three curves. The solid curve is the transducer response to the AE burst being analyzed. Its amplitude scale is shown relative to the dashed line which is the electronic noise level at the preamplifier input (2 μ V peak at 1 MHz). The dotted line is the response of the particular transducer used to the acoustic output of the WNG. It is shown superimposed on the AE frequency spectrum for comparison purpose, although its amplitude may be an order of magnitude greater. In some cases it was necessary to obtain the recorded AE data using a high-pass filter to keep from saturating the amplifiers with the high-amplitude, low-frequency components of the acoustic bursts. The frequency spectrum of Fig. 5*a* was obtained using a 100-kHz to 3-MHz bandpass filter. Its effect is seen in the droop in the low-frequency end of both the acoustic emission spectrum and in the electronic noise spectrum. Similar effects will be seen in some of the spectra presented later.

The similarity between the frequency spectra of the AE and the WNG in Fig. 5 lends support to the use of the continuous white noise source as a practical means of determining AE transducer response. It has also been



(*a*) Plastic deformation of single crystal MgO using a capacitor microphone transducer.
(*b*) Plastic deformation of Ti-6Al-4V using a piezoelectric transducer.

FIG. 5—*Examples of "white noise" acoustic emission bursts.*

useful in determining the frequency-dependent acoustic attenuation in structures by systematically changing the separation between the WNG and the pickup transducer on the structure. Typical results of this type of measurement for various structures are given later.

Spectral Analysis

In the previous section, emphasis was placed on the similarity between the frequency spectra of AE from several materials and the frequency spectrum of the continuous white noise provided by the WNG. We have also observed several examples in which the frequency spectra of AE and of background noises are not white noise and which in some cases are very distinctive. These will be presented in the following paragraphs in order to support the contentions made in the introduction and to illustrate the usefulness of frequency analysis to AE technology.

Tests on Low-Alloy Steel

Acoustic emissions produced during tension tests of A533-B steel specimens are shown in Fig. 6. Repeating the identification of the three curves on each figure, the solid curve is the frequency spectrum of the AE, the dashed curve is the electronic noise level of the preamplifier, and the dotted curve is the transducer response to acoustic white noise. The frequency spectra of all the AE produced throughout the first 95 percent of the test were like the one in Fig. 6*a*. As necking of the tension specimen proceeded there was a tendency for the spectra of many of the AE to take on more of a white noise character as in Fig. 6*b*. Also, bursts started to appear which had the frequency spectrum shown in Fig. 6*c*. This type of burst occurred more frequently as neck formation progressed and the specimen finally fractured. The oscilloscope trace of Fig. 6*e* shows two AE bursts which occurred within a few milliseconds of each other near the end of the test and which had the quite different spectra shown in Fig. 6*b* and *c*, respectively. This observation of two adjacent bursts with different frequency content supports the contention that the spectral content at high frequencies is not dominated by specimen resonances.

A significant observation regarding these bursts is that frequency analysis of each 20 μs time increment within the ring-down time of the AE results in the same frequency spectrum. This indicates that the burst of elastic strain energy forming the AE does not change its frequency content upon multiple internal reflections in the specimen. Subsequent studies on various specimens showed that the spectra did not depend upon the specimen geometry except for details in the spectra at lower frequencies caused by specimen resonances. These studies also identified the source mechanisms of the low-frequency AE of Fig. 6*c* as crack extension and of the high frequency AE of Fig. 6*a* as plastic deformation [*8*].

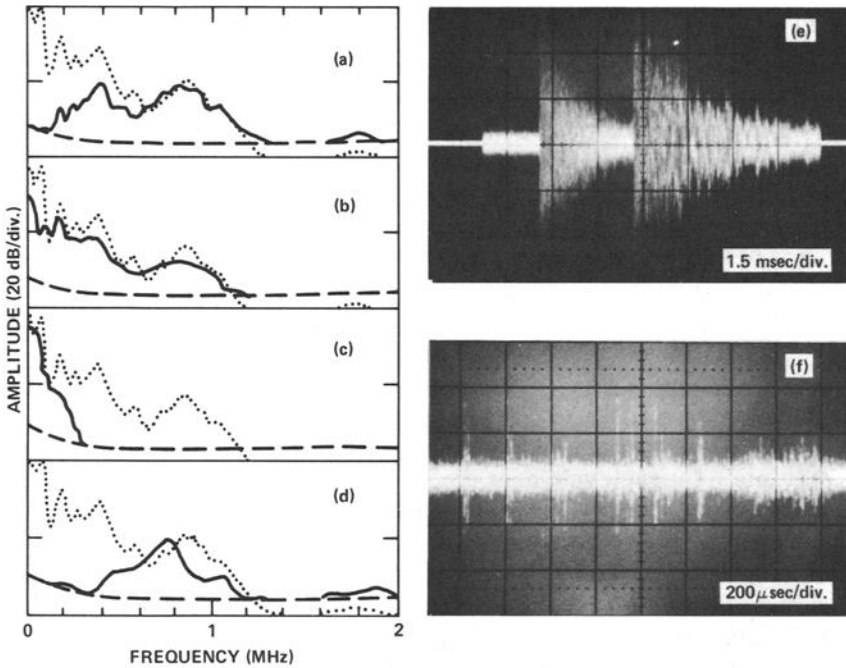


FIG. 6—*Examples of distinctive acoustic emissions generated in A533-B low-alloy pressure vessel steel.*

The AE shown in the oscilloscope trace of Fig. 6*f* were recorded during fatigue crack growth in the 15-cm-thick wall of a nuclear reactor pressure vessel made from a low-alloy steel similar in composition and mechanical properties to A533-B [*19*]. Their frequency spectrum is shown in Fig. 6*d*. Two points should be observed. First, the time duration of the AE bursts in the thick-walled pressure vessel was only about 10 to 20 μs. This is very short compared to laboratory test results on small specimens, presumably because in this structure there is no opportunity for alternate acoustic paths to produce an apparent lengthening of the burst. Therefore, these signals are probably related more closely to the time during which the energy is actually released at the source than is typically seen in the laboratory. Because of the large size of the structure, its resonances do not appear on this time scale. The second point is that the frequency spectrum of these AE's is very similar to the spectrum identified with plastic deformation in A533-B steel in Fig. 6*a* in that the predominant energy content of the AE is at higher frequencies. We have, therefore, identified tentatively their source as the plastic deformation at the crack tip accompanying fatigue crack growth, although laboratory tests on specimens of the reactor material are needed to confirm this.

Fatigue Test of 2219-T87 Aluminum

The AE's in Fig. 7 were recorded during fatigue crack growth in a 1.2-m by 1.2-m by 0.63-cm plate of 2219-T87 aluminum containing a machined-in part-through crack near its center [*11*]. A five-channel electronic lock-out system was used in monitoring the AE so that the source of the emissions recorded could be positively identified as being in a small region of the specimen around the crack. The Types 1 and 2 bursts were generated at the location of the growing fatigue crack, with the Type 1 AE occurring more frequently. With the transducer located 3 cm from the crack, the duration of the AE ringdown was fairly short but increased as the transducer was moved to a distance of 50 cm from the crack, as can be seen in the upper right-hand picture of Fig. 7. The frequency spectrum of the AE remained the same, however.

The Type 3 bursts occurred continuously over about one quarter of each 20 s duration fatigue cycle near the maximum load and originated in the hydraulic load cylinder of the test machine. These are of unusually high-frequency content and of very short duration even though the acoustic path from their source to the transducer was several meters in length through a steel bar, plate, clevis pin joint, and compression lap joint. Amidst these Type 3 bursts there would occasionally be a burst which had a frequency spectrum like that of the Type 2 burst. Their source could not be positively identified since the lock-out module was turned off during these recording periods. They are believed to be due to the fatigue crack growth, however.

Fatigue Test of 2024-T851 Aluminum

Figure 8 contains results of another fatigue test on a 0.5-cm-diameter by 10-cm-long bar of 2024-T851 aluminum at 1 to 8 Hz. The majority of the AE has the spectrum shown in Fig. 8*a* and appeared as in Fig. 8*e*. A 100-kHz high-pass filter was used while recording these emissions. Occasionally, a burst having five times the ring-down time would occur. These had the spectrum of Fig. 8*b* which nearly approaches the white noise spectrum except for some lack in energy at low frequency. A 100-μs duration burst occurred repetitively on every cycle near zero load which had the spectrum shown in Fig. 8*c*. This is assumed to be a mechanically produced burst because of its short duration. The dominant acoustic noise which occurred during the test was the hydraulic noise near maximum load. This had the spectrum shown in Fig. 8*d* and appeared as in Fig. 8*f*. These results are rather atypical and are presented for that reason. The noises produced by other hydraulic machines more typically have strong spectral components up to 300 to 500 kHz. Also, most mechanically produced acoustic bursts, at least due to impact, produce bursts with spectral components only below 200 kHz.

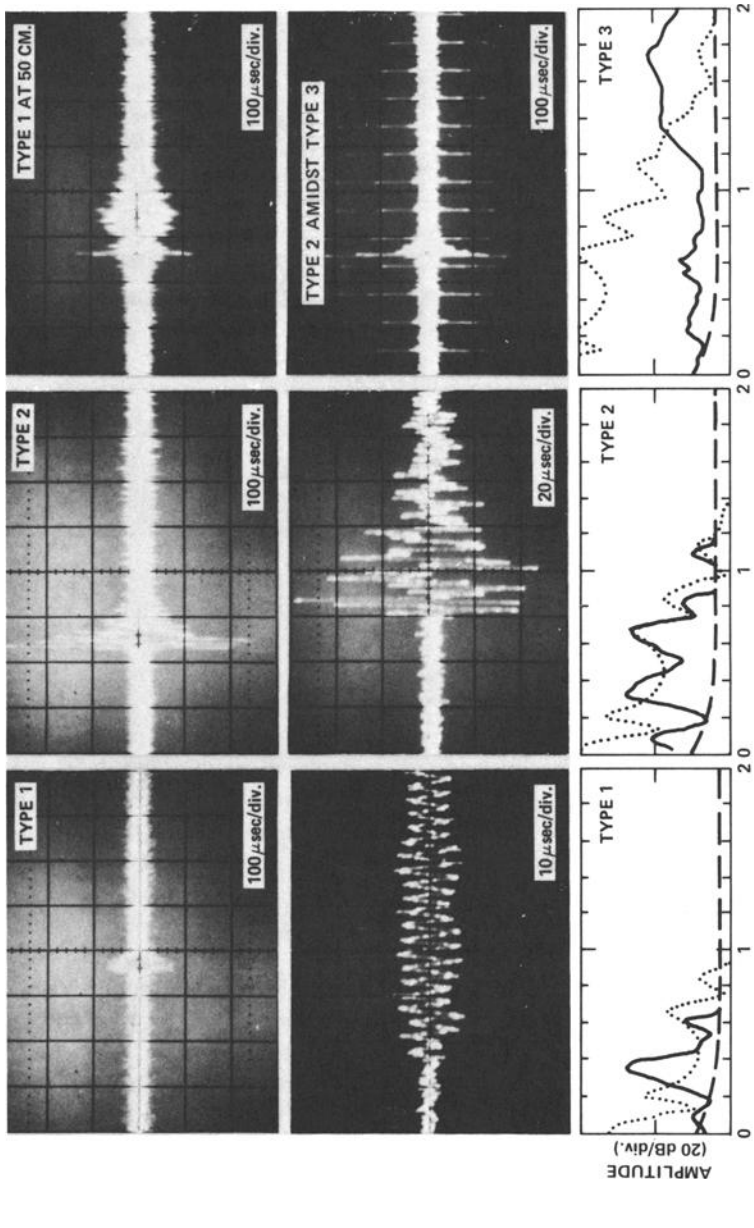


FIG. 7—*Acoustic bursts observed during fatigue of 2219 aluminum. The Types 1 and 2 bursts were generated at the fatigue crack and the Type 3 burst was produced by the loading machine.*

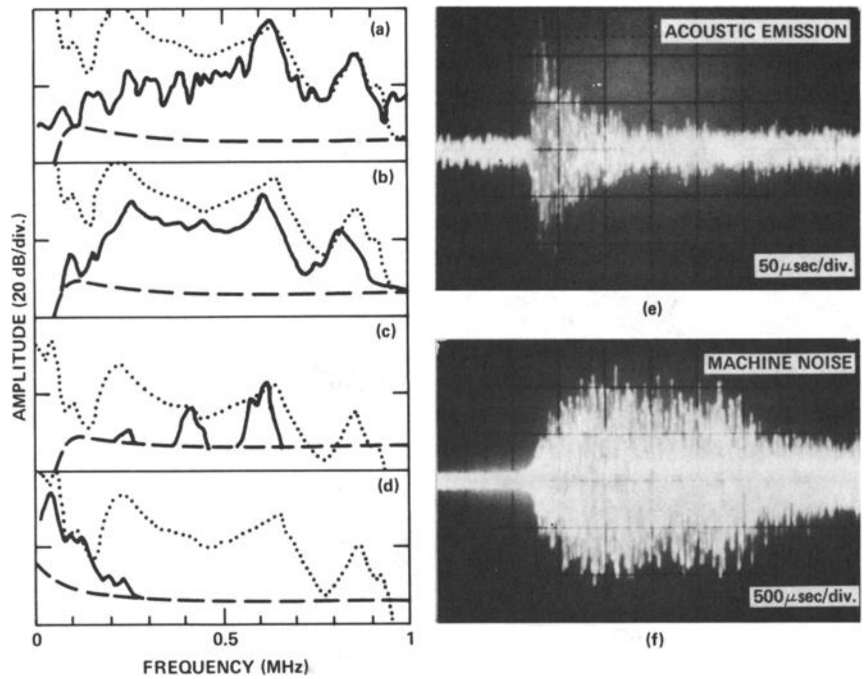


FIG. 8—*Examples of acoustic emission and machine noise produced during fatigue of a 2024 aluminum specimen.*

Crack Growth in Alumina Ceramic

Controlled slow crack growth in polycrystalline ceramics produces AE which in general are nearly white noise [*6*]. This is illustrated in Fig. 9 by the Type 1 burst observed for a pure alumina ceramic. About 1 percent of the AE appear on the oscilloscope with a much longer ring-down time, and invariably these Type 2 bursts contain more of their energy at higher frequencies. Similar results have also been observed for other ceramics. These tests were made in a very quiet environment in three-point bending under essentially dead-weight loading conditions so that misinterpretation of the source of these bursts is not likely. One other type of burst that was observed during these tests is illustrated by Type 3 in Fig. 9. These bursts only occurred when the ceramic specimen had a roughness in its surface exceeding about 50 μm, which would cause "punchout" impressions in the surface of a 125-μm-thick Mylar shim used to cushion the loading points. It should be emphasized that the large difference in waveform and in spectral content of these acoustic bursts can not be attributed to specimen geometry or transducer resonances, since they are all observed under the same conditions, sometimes within milliseconds of each other. Their differ-

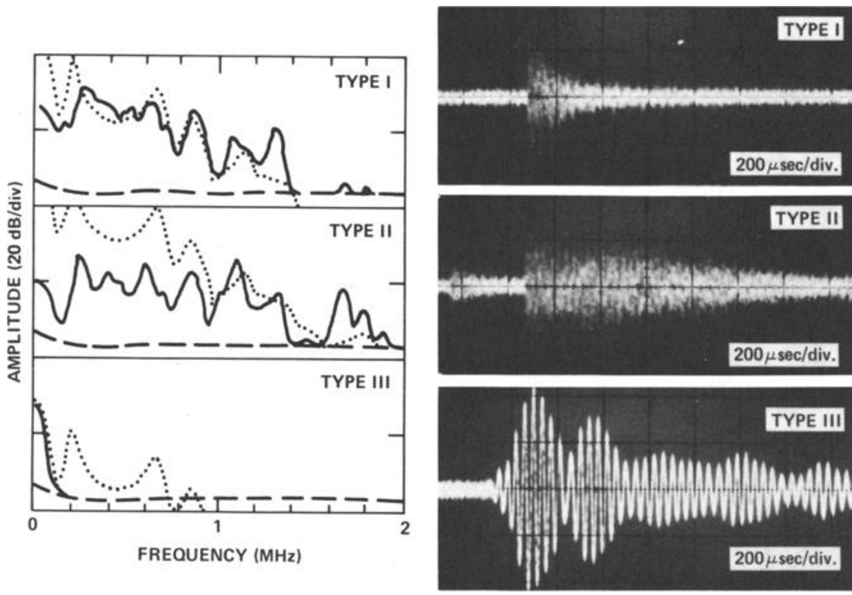
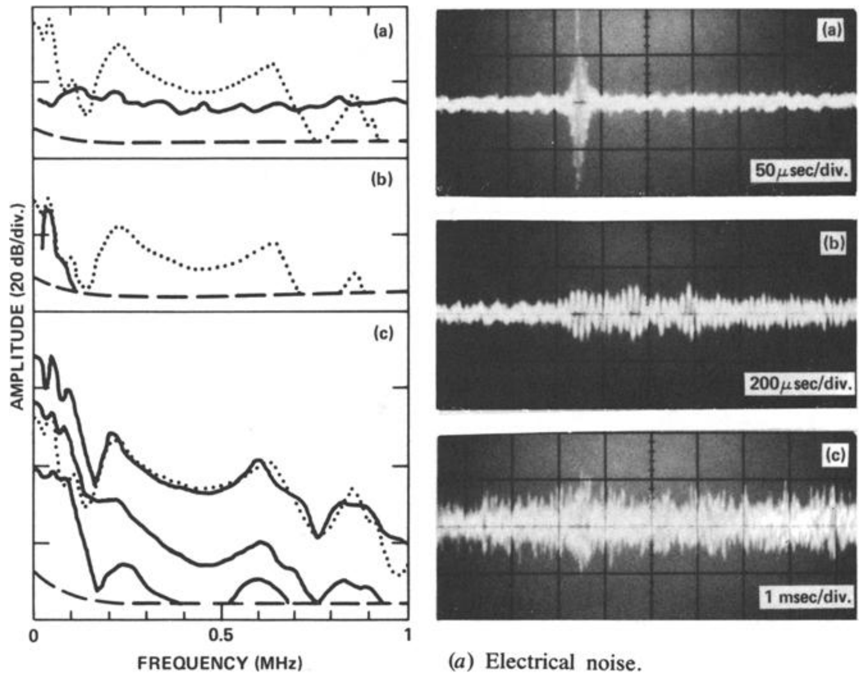


FIG. 9—*Examples of acoustic bursts observed during slow crack growth in polycrystalline alumina ceramic.*

ences, therefore, must be due to their generation mechanisms. This is true of all the frequency spectra illustrated but is particularly relevant to these results because of the simplicity of the specimen and test conditions.

Examples of Other Extraneous Noises

Some further examples of extraneous background noises are shown in Figs. 10 and 11. Electrical noise spikes, as in Fig. 10*a*, are very broad-banded and show none of the characteristics of the acoustic response of the transducer. Many types of mechanical impact noise are typified by the spectrum in Fig. 10*b* which is for a burst produced by the meshing of metal gears. The broadband continuous noise of Fig. 10*c* was produced by a steam turbine. The three spectra shown are for three rates of steam flow and illustrate the broadband nature of this noise. The multiple bursts shown in Fig. 11 are believed to be due to a "stick-slip" friction mechanism caused in this case by shear stresses produced by differential thermal expansion across a mechanically coupled joint between two pieces of metal. Other observations of similar acoustic bursts have been made during the tightening of bolts. Another example might be the Type 3 bursts of Fig. 7 which were generated during the motion of the piston in a hydraulic ram. The frequency spectra of the bursts in these three cases were all similar in that



(*a*) Electrical noise.
(*b*) Gear meshing noise.
(*c*) Three steam flow rates in a turbine.

FIG. 10—*Examples of background noises recorded during acoustic emission tests.*

they had either one or two prominent peaks in their spectra at relatively high frequency.

General Comments on Spectral Analysis

It is obvious from the diversity of the frequency spectra in the foregoing examples that the separation of extraneous noise bursts and AE by recognizing differences in their frequency content is not simple but is certainly feasible. Each test situation is different and will have to be analyzed individually. The fact that there are differences between the spectra is encouraging, however. These results can only hint at the scope of the future use of spectral analysis in AE technology and in studies of the AE generation mechanisms. It is apparent that simple impulse models of AE generations which have been discussed [*1,13,20,*] do not predict all of the frequency spectra which have been observed.

It should be pointed up at this time that most of the frequency spectra just described were obtained for acoustic bursts which were recorded with the

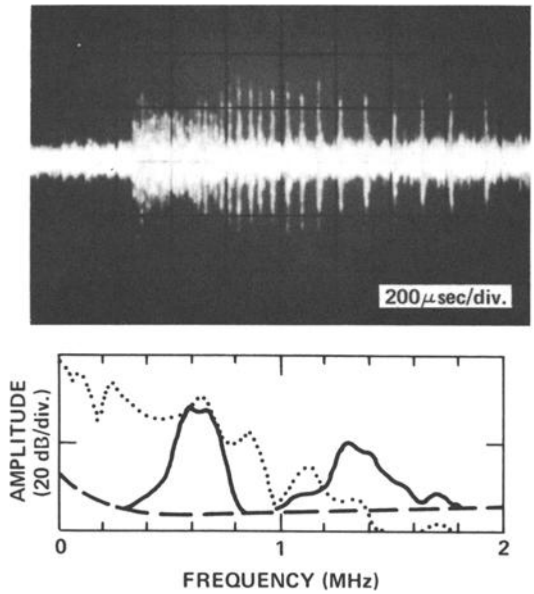


FIG. 11—*Multiple acoustic bursts believed to be due to "stick-slip" friction.*

transducer located on the specimens or structures close to the source of the burst. In flaw-locating systems on large structures using triangulation methods, the effect of the frequency dependence of the attenuation in the acoustic path between the transducer and the source must also be considered. Some results obtained on typical structures toward providing this information are presented in the following section.

Acoustic Transmission

The acoustic white noise generator and broadband transducer described previously were used to determine the frequency dependence of the acoustic attenuation in various structures. The generator and pickup were acoustically coupled at various separation distances on the structures, and the frequency spectra of the sound transmitted along the various paths were obtained. From a series of these spectra for each of the acoustic paths the loss in amplitude as a function of distance could be determined over a wide frequency range.

Large Pressure Vessels and Other Structures

The attenuation was determined over several acoustic paths on the large gas pressure vessels shown in Fig. 12. The inner vessels were A283 steel; the dome ends, bands, and the large manway at one end were A212-B steel;

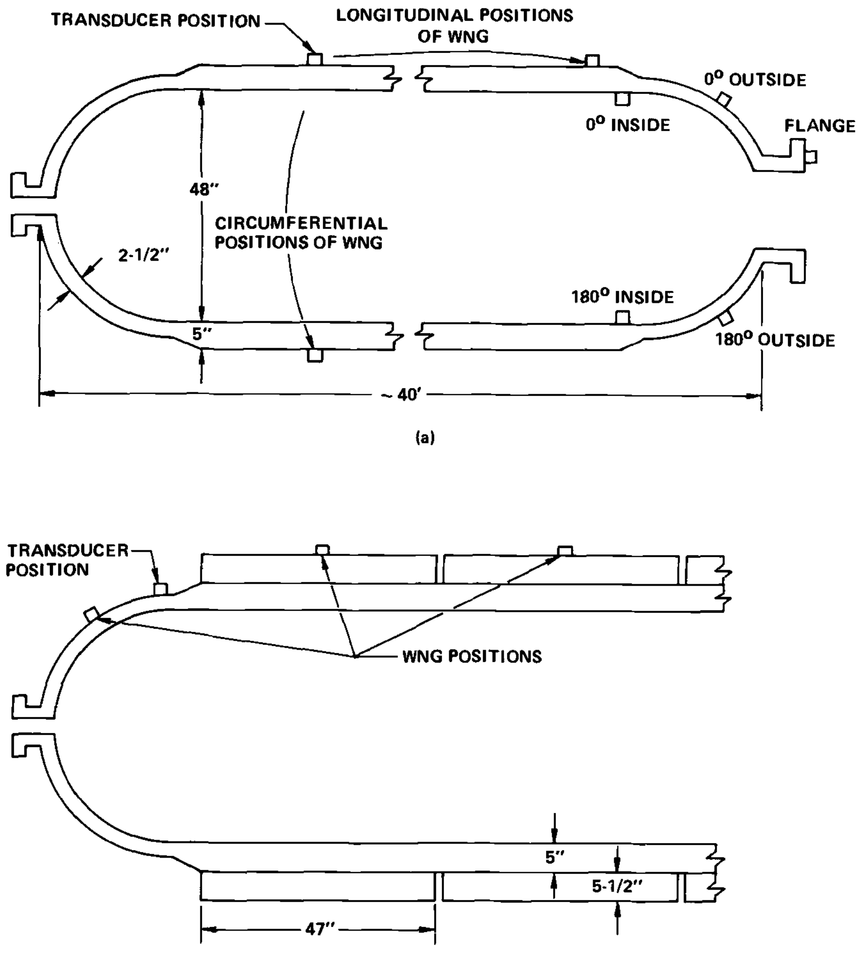


FIG. 12—*Gas pressure vessels on which acoustic attenuation measurements were made.*

and the pipe flange at the other end was A105 steel. In Fig. 13 are shown the relative amplitudes of the acoustic noise at various frequencies which was received by the transducer as the separation distance between the WNG and the transducer was changed along the length of the pressure vessel. The attenuation rate changed as the separation distance between the WNG and transducer increased due to the so-called geometrical attenuation, which is the result of the energy contained in the acoustic wave being spread over an increasing area as the wave advances. In the pressure vessel the rate of attenuation was constant beyond about 1.5 m (5 ft) due to a waveguide

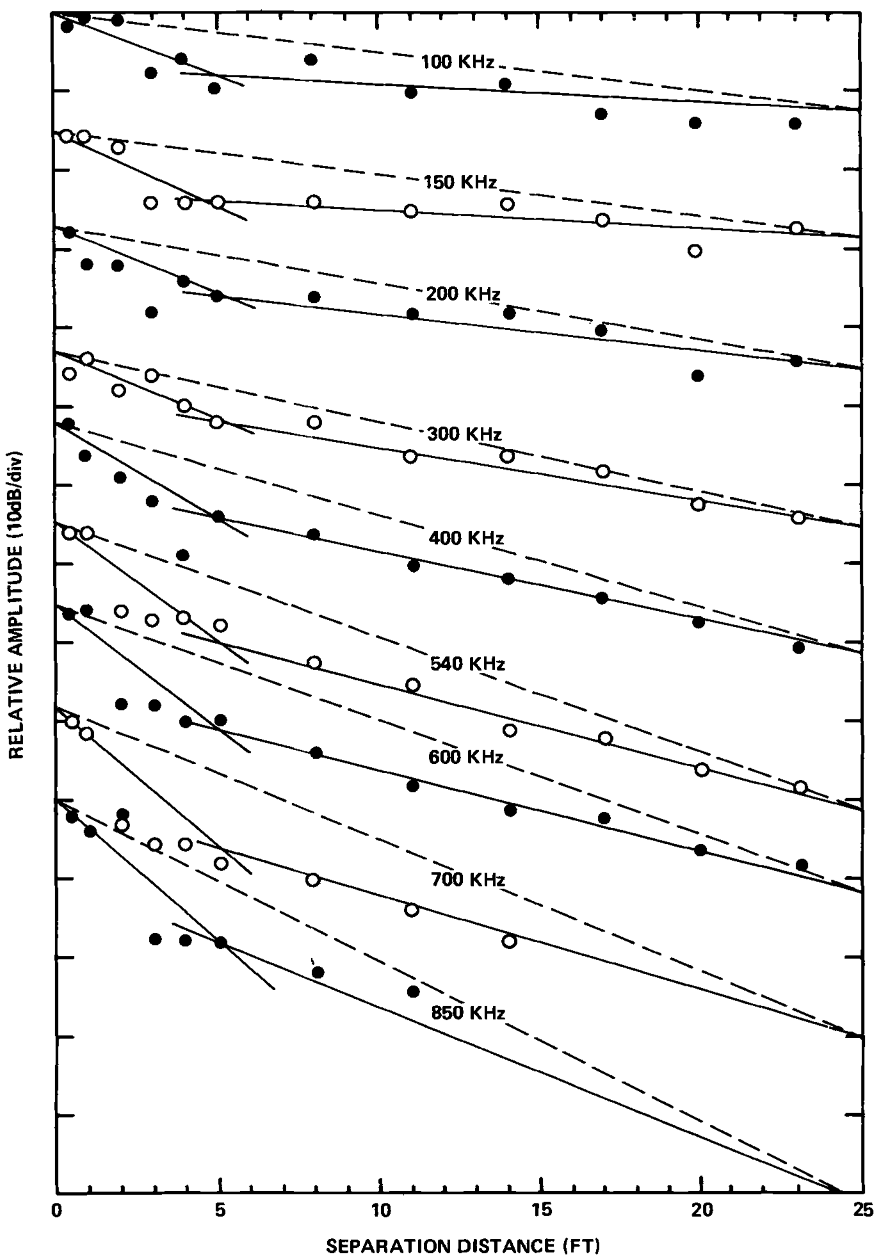


FIG. 13—*Signal loss as a function of distance and frequency along the outer surface of the gas pressure vessel of Fig. 12*a.

effect along the length of the vessel. The average rate of attenuation at 1.5 m (5 ft) and 7.5 m (25 ft) obtained from the straight line approximations to the data of Fig. 13 are shown in Fig. 14. Included are the results of measurements around the circumference of the vessel as well as along its length which showed no difference between these two paths. This pressure vessel was located outside and had many layers of paint to protect it from oxidation. This apparently added to the attenuation because similar data on a variety of large aluminum and steel plates and girders having no paint on their surfaces show a similar shape to the frequency dependence but with values in the range of 0.6 to 3.0 dB/m (0.2 to 1.0 dB/ft) at 1 MHz instead of about 8.2 dB/m (2.5 dB/ft) [*11*]. One girder which was heavily oxidized had about the same attenuation rate as the pressure vessel, however, suggesting that either a damping or scattering material on the surface of a structure is deleterious to the transmission of AE signals.

The relative circumferential position of the WNG and transducer on the outer surface of the vessel was found to have no effect on the attenuation rate, but putting the WNG on the inside wall of the vessel introduced an additional attenuation as shown in Fig. 15*a*. The unusual frequency depen-

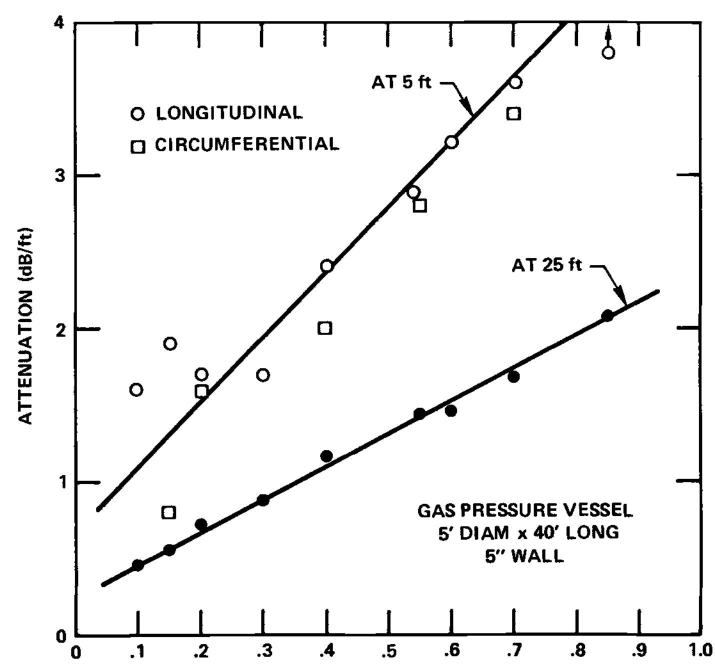
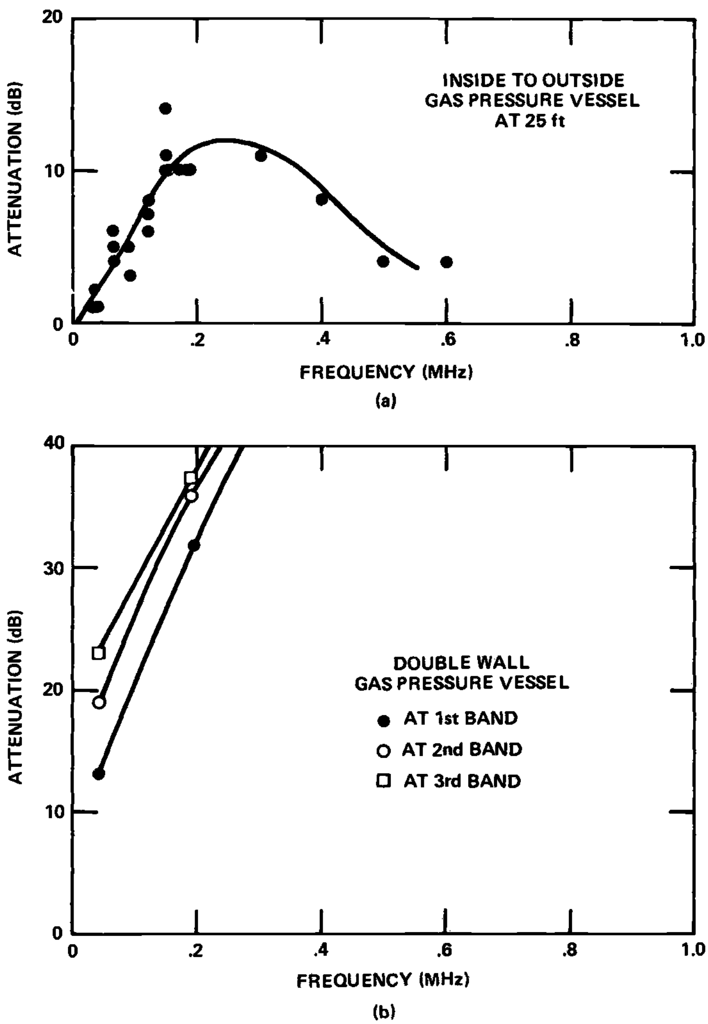


FIG. 14—*Acoustic attenuation in the gas pressure vessel of Fig. 12*a.



(*a*) From inner wall to outer wall.
(*b*) Across compression fit joint.

FIG. 15—*Additional acoustic attentuation due to specific transmission paths in gas pressure vessels.*

dence of this source of attenuation could influence the choice of the frequency range for a flaw location system. For example, if it was desired to monitor the growth of an inner surface crack with transducers located on the outer surface of such a vessel, the frequency range between 100 to 500 kHz should be avoided if possible. Other considerations such as the frequency content of the AE and extraneous noises and the normal attenuation over the acoustic path may prohibit this choice. This example illustrates the necessity of knowing all of these factors when designing a monitoring system.

Another significant source of attenuation was found on the pressure vessel shown in Fig. 12*b*, which had thick steel strengthening bands compression fit around its outer circumference. The additional attentuation of the acoustic energy across the interface between the vessel wall and the strengthening bands is shown in Fig. 15*b*. The successful monitoring of AE where such an interface is in the path seems improbable.

Foam-Insulated Vessel

Another example of a structure which resulted in a very high acoustic attenuation was a cryogenic liquid storage tank which had a foam insulation material bonded to one side of the aluminum plate which formed the tank [*10*]. The data of Fig. 16 were obtained with the WNG and transducer bonded to one side of the aluminum plate and with the foam insulation bonded to the opposite side. A large difference in the attenuation was observed between spraying the material onto the plate to a thickness of 5 cm or preforming it in a slab of that thickness and then gluing it in place. This experience and the experience with the strengthened gas pressure vessel suggest that alternate construction methods should be considered in the design of structures such as these if AE monitoring of the structures are anticipated.

Bearings and Shafts

Figure 17 illustrates acoustic transmission across a ball bearing journal. The signal received by the transducer when it was bonded to the shaft is compared in each case to the signal received when it was bonded to the bearing housing. In Fig. 17*a* and *b* the bearing was dry and there was a side load on the shaft of about 0.5 kg (1 lb) and 13 kg (30 lb), respectively. In Fig. 17*c* medium-weight machine oil filled the bearing housing, and in Fig. 17*d* the oil had been allowed to drain out over a 20-h period so that only a light film remained on the bearings. In both of the latter cases there was a 0.5 kg (1 lb) side load on the shaft. This test illustrates that AE monitoring across stationary mechanical linkage and of rotating machinery components might be feasible if acoustic coupling through a grease or oil layer is provided.

Effect of a Dispersive Medium

The examples just given of the acoustic transmission characteristics of various structures were obtained using the WNG as a source of continuous

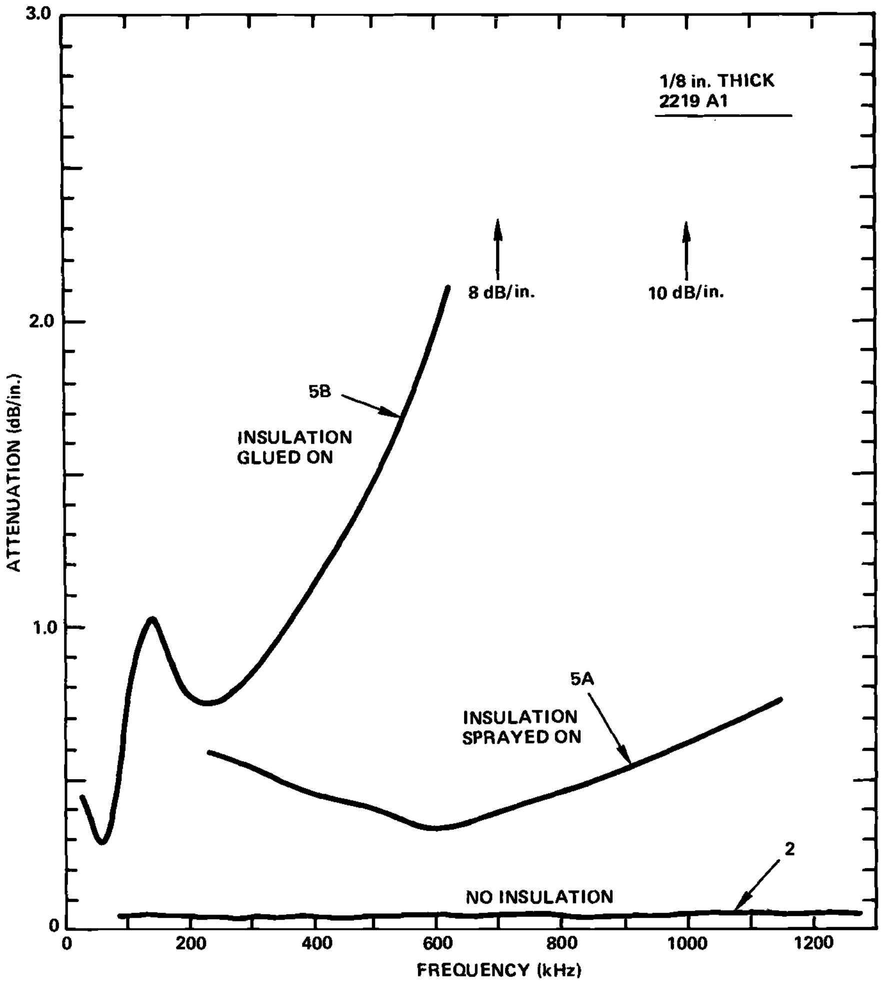
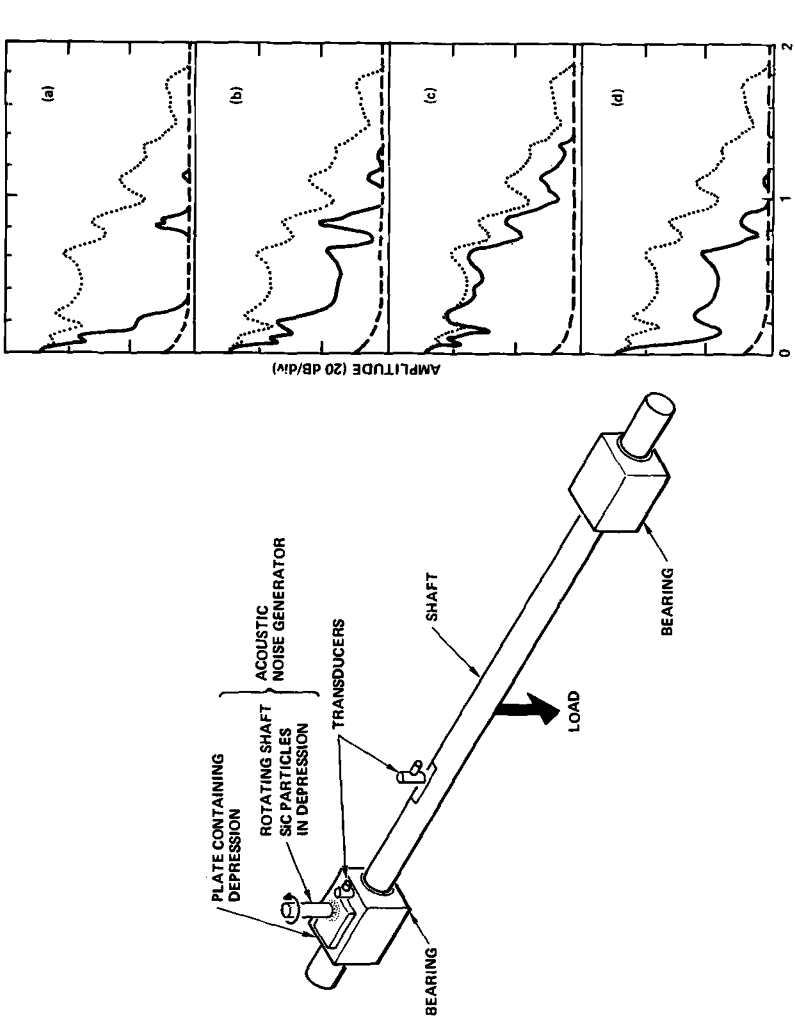


FIG. 16—*Acoustic attenuation of aluminum sheet having a foam insultation material on its reverse side.*

noise which could be monitored at various positions on the structures. It was demonstrated earlier that the transducer response to a continuous or a pulsed white noise source was the same and that the frequency content of an AE was not changed due to multiple reflections within a specimen. Therefore, the results of the attenuation measurements would be valid when applied to AE monitoring.

There is an interesting case where analyzing the transmission of a continuous noise does not tell the whole story, however. In a dispersive me-



(*a*) Dry bearing, no load.
(*b*) Dry bearing, 13 kg side load.
(*c*) Oil-filled bearing, no load.
(*d*) After oil drained out, no load.

FIG. 17—*Acoustic attenuation across a ball bearing journal.*

dium the different frequency components of a broadband acoustic wave propagate with different velocities so that after the wave has traveled some distance the different frequency components are separated in space and arrive at the transducer at different times. One example of such a medium is sheet material where the thickness of the material is small compared to the wavelength of the acoustic waves. The principal propagation modes in this case are the symmetric and antisymmetric Lamb modes. The frequency dependence of the group velocities of these modes depend on the elastic properties and the thickness of the sheet. This dependence for a 1.6-mm (1/16-in.) thick sheet of 2219 aluminum taken from tabulated computer calculations [*21*] is shown in Fig. 18. A bulk longitudinal wave velocity of 6374 m/s and a Poisson's ratio of 0.345 were used in constructing this figure.

During a fatigue test of a 1.8-m (6-ft) long by 0.3-m (1-ft) wide by 1.6-mm (1/16-in.) specimen of 2219-T87 aluminum, broadband acoustic bursts were recorded which appeared as shown in Fig. 19 at three positions 50 cm (20 in.) apart along the length of the specimen. The increasing separation of the symmetric (SM) and the antisymmetric (AM) modes with distance traveled is clearly seen in these oscillographs. With reference to Fig. 18, the fastest wave component is the lowest frequency symmetric Lamb mode followed

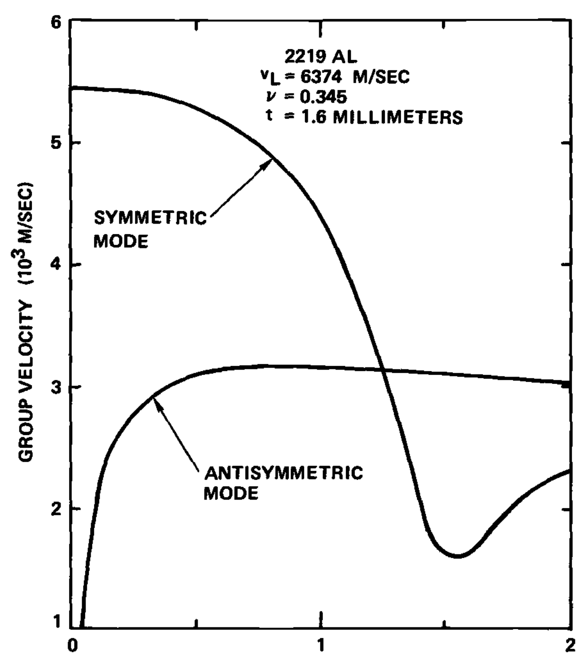


FIG. 18—*Dispersion curves for Lamb waves in sheet aluminum.*

by the higher frequency components of this mode. It is this mode which appears first as a small burst at the left side of the oscilloscope traces of Fig. 19. The fastest antisymmetric component is very broadbanded, containing all frequencies above about 0.5 MHz. Most of the energy of the acoustic wave is concentrated in this mode because of its broadbandedness, and this results in the appearance of the high-amplitude signal in the oscilloscope traces. This is followed by the slower, lower frequency components of this mode. Observations of this same phenomenon have been described previously using a repetitive, low-frequency acoustic emission simulator as the source of the acoustic signal [*22*].

The freqency analysis of successive 20 μs portions of the acoustic burst recorded at the greatest distance from the source and labeled *A, B,C,* · · · *Y* in Fig. 19 are shown in Fig. 20. The same qualitative behavior as previously described can be observed. In *B* through *F* the higher frequency components of the symmetric mode are seen to occur at later times, and at *K* the broadband antisymmetric mode is seen to occur. This is followed in *L* through *W* by the lower frequency, slower moving components of this mode.

The source of the acoustic bursts can be determined in two ways from the oscilloscope traces of Fig. 19. Knowing the distance between any two observation points and the increase in the mode separation time at these two points determines the distance of either point to the source and also determines the difference in the reciprocals of the principal velocities of the two modes. Alternatively, if the two principal mode velocities are known, that is, the velocities of the broadband portion of each mode, then the location of the source can be determined from the mode separation time on any one of the oscilloscope traces [*10*]. The implication of this possibility is that source location could be accomplished using only one transducer in certain cases. In the test just described the source was 30 cm (12 in.) from the nearest transducer location which was where the end of the specimen was gripped for the fatigue test.

General Comments on Acoustic Transmission

In summarizing the results of the tests described in which the acoustic transmission properties of structures were evaluated, two points should be emphasized. When designing an AE monitoring system, a knowledge of the frequency dependence of the attenuation in any acoustic path under consideration is important in establishing the operating frequency range of that system. The second point is that the observation and analysis of frequency dispersion under special test conditions lends support to the conclusion that under most conditions the frequency content of an AE brust is not changed during transmission through the medium or upon mode conver-

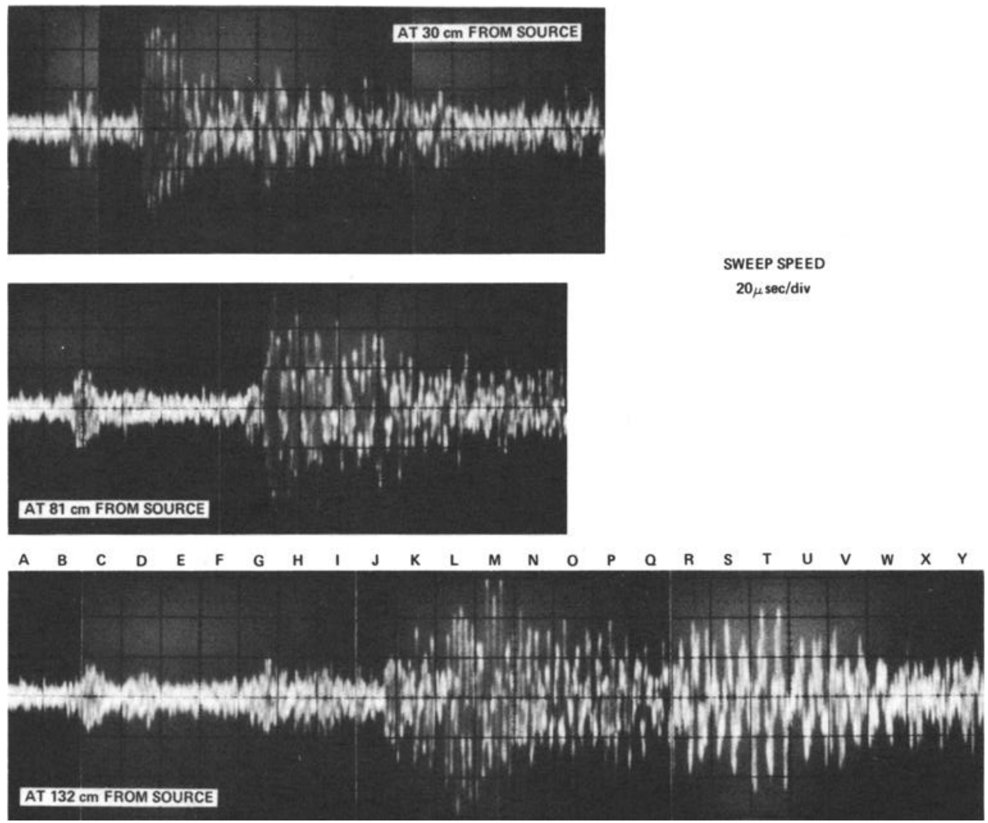


FIG. 19—*Acoustic bursts after transmission through three distances in sheet aluminum showing effect of dispersion.*

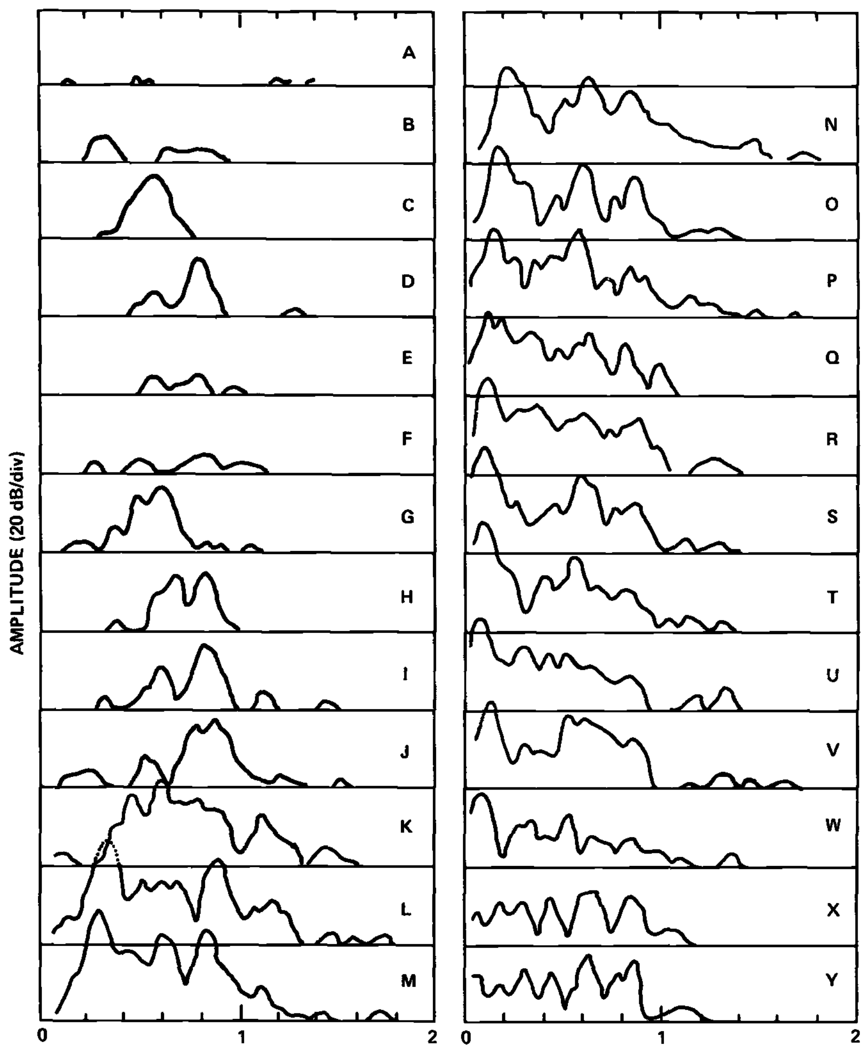


FIG. 20—*Frequency analysis of successive 20 μs increments of the acoustic burst at the bottom of Fig. 19.*

sion upon reflection at its boundaries. If a change in the frequency content did occur, it would have been certainly observed under the conditions of our tests.

Summary

A means for quickly and easily determining the broadband frequency content of acoustic bursts as short as 20 μs in duration has been developed which will allow a rapid survey of the different types of AE and extraneous background noise bursts in an AE test environment. This can be done early in a test and provides information regarding transducer spacing and the noise discrimination and sensitivity requirements of the electronic components of a triangulation system.

The frequency content of an acoustic burst is related to the mechanism which produced it and is not affected substantially by mode conversion during multiple reflection in a solid. This is substantiated by the observation that in most cases the frequency content near the leading edge of an AE is the same as at a time later in its ringdown. This ring-down time is determined by the size of the structure and how many internal reflections can be effected before the energy in the burst is dissipated. Bursts from a few microseconds to a few milliseconds in duration have been observed. In the special case of a dispersive medium, a change in the spectrum during ringdown is observed and understood. It was also shown that the frequency spectrum of an AE does not depend substantially upon the specimen size or shape, although minor changes occur in the spectra at lower frequencies due to excitation of specimen resonances. The studies of the acoustic transmission characteristics of a structure have shown that frequency-dependent attenuation and dispersion do affect the frequency content of an acoustic burst which has propagated some distance through a structure.

Several examples of AE bursts with unusual frequency spectra have been observed. A thorough study of two types of AE generated in A533-B steel has resulted in the identification of the two types as being due to plastic deformation and crack extension, respectively. Other unique spectra have also been observed, but the identification of their sources requires further study. The generalizations that mechanical impact noises have low-frequency spectra and hydraulic noises tend to have more broad-banded spectra have been demonstrated, but exceptions to these generalizations have also been shown. Examples of several distinctive types of frequency spectra have been given which suggest that discrimination of noise bursts from different sources can be accomplished in some cases by frequency content alone.

In conclusion, broadband frequency analysis has been demonstrated to serve a useful function in the AE technology. Its use in the study of the

mechanisms governing the mechanical properties of materials is also suggested.

Acknowledgments

We wish to acknowledge the valuable assistance of several key people in the various divisions of Rockwell International in obtaining the results described. These are J. S. Buck of Atomics International Division, F. E. Sugg of Space Division, and J. F. Moore of B-1 Division. Parts of the work were supported by the Naval Air Systems Command and by the Rockwell International Interdivisional Technology Program.

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Acoustic Emission During Phase Transformation in Steel

REFERENCE: Speich, G. R. and Schwoeble, A. J. "**Acoustic Emission During Phase Transformation in Steel,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 40–58.

ABSTRACT: Acoustic emission was monitored during phase transformations that occur during cooling in a wide variety of steels. Acoustic emission was generated during the formation of martensite but not during the formation of ferrite, bainite, or pearlite. This observation is consistent with the rapid, diffusionless, shear-like nature of martensite formation and the slow, diffusion-controlled growth of ferrite, bainite, or pearlite. The martensite start temperatures, and the temperature range of martensite formation determined by acoustic emission were in good agreement with those determined by metallographic or dilatometric methods. The intensity of acoustic emission generated during martensite formation decreased markedly as the carbon content of the steel decreased, becoming nearly undetectable in a maraging steel. This decrease in intensity correlates with a morphological change from large plate-shaped martensite units to smaller lath-shaped martensite units as the carbon content of the steel is decreased.

KEY WORDS: acoustics, emission, phase transformations, monitors, crack propagation

Acoustic emission (AE) is defined as the high-frequency stress waves generated by the rapid release of energy that occurs within a material during crack growth, plastic deformation, or phase transformation. This energy may originate from the stored elastic energy as in crack propagation or from the stored chemical free energy as in a phase transformation. Refinement in the detection systems for AE has led to a rapidly accelerating interest in its use for detection of crack growth in small laboratory specimens, detection of incipient failure in large engineering structures, weld

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monitoring, and studies of plastic deformation and phase transformations in various materials [*1,2*].[2]

The "clicks" that occur during the formation of martensite in high-nickel steel were reported by Förster and Scheil in 1936 in one of the first studies of AE in the literature [*3*]. However, from that time until only a few years ago, no further work was done on AE generated during phase transformations in solids. Recently, several studies of AE during phase transformation in metals have been reported. Liptai et al [*4*] have studied AE during formation of martensite in gold-cadmium and indium-thallium alloys and in cobalt and plutonium, during both heating and cooling. They also studied the eutectoid transformation in a tin-cadmium alloy and showed that such a diffusion-controlled transformation did not generate AE. Speich and Fisher [*5*] have studied martensite formation in a 28Ni-0.1C steel which transformed below room temperature. They correlated the acoustic emissions with the number and size of the martensite plates and determined that a number of plates are involved in each emission because of the autocatalytic nature of the martensite transformation. More recently, Ono et al [*6*], using AE techniques, have determined the M_s temperatures of a number of steels that transform below room temperature. However, a general study of AE during formation of the various transformation products in steel has not been attempted.

In the present work we have made a study of AE generated in a wide variety of steels during transformation into ferrite, pearlite, bainite, and martensite. Such a study was needed for a number of reasons. First, it provided needed information on the mechanism of phase transformation responsibility for strengthening steel. Second, since phase transformations occur in the heat-affected zones of weldments, it is necessary to understand AE arising from these causes before it can be used to detect microcracking during welding operations [*7*]. Finally, phase transformations serve as a controlled AE source and can be used to study the effect of different variables on the propagation of the elastic waves that make up the AE signal [*8*].

Experimental Procedures

Materials

The steels studied in this work included a series of AISI 4300 steels, an AISI 52100 steel, an AISI 410 stainless steel, a maraging steel, several iron-nickel alloys, an iron-carbon alloy, a line-pipe steel, and iron. Their chemical compositions are given in Table 1. The AISI 4300 steels, the AISI

[2] The italic numbers in brackets refer to the list of references appended to this paper.

TABLE 1—*Chemical compositions, weight percent.*

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Co	Cu	Ti	Cb	Al	N
Fe–C:														
Fe	0.007	<0.01	0.002	0.005	0.016	0.003	0.007	...	...	...	0.15	...	0.005	0.00
Line pipe	0.15	1.61	0.007	0.008	0.31	0.018	0.027	...	...	0.30	...	0.02	0.006	...
Fe–0.97C	0.97	0.009	0.001	0.021	0.037	0.032	0.005	0.001	...	...	...	...	...	...
AISI steels:														
4330	0.32	0.80	0.001	0.010	0.29	1.80	0.85	0.24	...	...	...	...	...	...
4340	0.41	0.72	0.002	0.010	0.26	1.90	0.82	0.28	...	...	...	...	...	...
4360	0.64	0.74	0.003	0.013	0.27	1.85	0.86	0.29	...	...	...	...	...	...
4380	0.83	0.80	0.003	0.013	0.27	1.85	0.86	0.29	...	...	...	...	...	...
52100	1.00	0.36	0.008	0.016	0.28	0.11	1.47	0.02	...	...	...	...	...	...
Fe–Ni:														
9Ni	0.10	...	...	...	...	9.00	...	...	...	...	...	...	...	...
20Ni	0.01	...	...	...	...	20.0	...	...	...	...	...	...	...	...
Maraging	0.003	0.02	0.001	0.004	0.011	17.0	...	4.72	7.60	...	0.52	...	...	...
AISI stainless:														
410	0.11	0.57	...	...	...	...	13.1	...	...	...	...	...	...	...

52100 steels, the Fe-20Ni, and the maraging steel permitted AE generated during martensite formation to be monitored from essentially 0 to 1.1 weight percent carbon. This wide range of carbon content also permitted the entire range of martensitic structures from lath to plate martensite to be studied. These steels also have sufficient hardenability so that they transform completely to martensite with the cooling rate used in this work (6°C/s).

The iron, iron-carbon alloy, and line-pipe steel permitted AE to be monitored during both ferrite and pearlite formation during continuous cooling. Acoustic emission generated during isothermal formation of bainite was monitored in the AISI 4360 and 4380 steels.

Equipment

The furnace used in the present work is shown in Fig. 1. Particular care was exercised in the design of this furnace to eliminate all random noise caused by heating and cooling of refractory elements. The specimen was

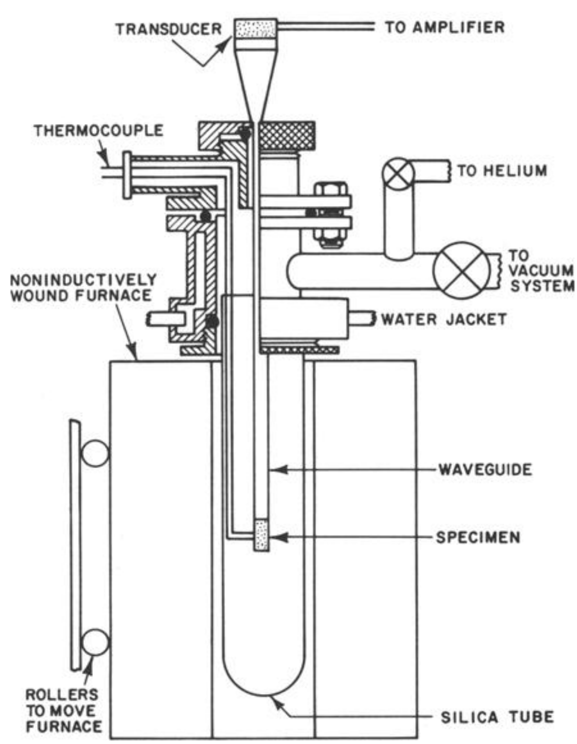

FIG. 1—*Furnace for acoustic emission studies at high temperatures.*

enclosed in an evacuated fused silica tube to prevent oxidation. The furnace was arranged so that it could be lowered away from the fused silica tube to permit the specimen to cool continuously to room temperature. Temperature of the specimen was monitored by a chromel-alumel thermocouple spotwelded to the specimen. Fused silica tubes rather than refractory tubes were used to insulate the thermocouple wires. When the specimen was to be cooled to room temperature, the vacuum was replaced with helium, and the furnace lowered. The cooling rate in helium was 7°C/s at 800°C, 1.5°C/s at 400°C, and 0.4°C/s at 200°C. In a few cases, the fused silica tube was surrounded by a smaller furnace maintained at 400°C after the main furnace was lowered. This permitted AE to be monitored during isothermal formation of bainite.

Acoustic emission from the specimen was monitored by use of an externally mounted transducer and a stainless steel waveguide. The specimen (3/8 by 1/8-in.-diameter) was welded to the stainless steel waveguide (26 by 1/8-in.-diameter) using a resistance wire welder; good welds and good acoustic coupling were obtained in all cases.

The AE equipment was a standard commercial unit [9]. A block diagram indicating the various electronic components is given in Fig. 2. The piezoelectric transducer was also obtained from a commercial supplier [9]. It is a 150-kHz resonant frequency lead-zirconate transducer constructed so that much of the background electrical noise was minimized. The transducer was coupled to the waveguide with a couplant grease. The waveguide was expanded smoothly near the end so that the 1/2-in.-diameter transducer could be attached and yet allow all the acoustic energy to reach the transducer. Electrical signals from the transducers were fed directly into the preamplifier, which had a fixed amplification of 40 dB. Signals were then passed through a bandpass filter (100 to 300 kHz) which removed much of the background noise. Finally, the AE signals were further amplified 20 to 55 dB with a variable broadband amplifier. These amplified signals either were fed directly into an electronic counter or were shaped in a digital envelope processor and then fed into the electronic counter. The digital envelope processor makes a single envelope of signals resulting from multiple reflections within the specimen, waveguide, and transducer. The electronic counter operated with a fixed threshold of 1 V. The output from the counter was fed into a digital to analog converter which gives a fixed millivolt signal for a given number of counts. The output of the digital to analog converter was used to drive the Y-axis of an X-Y recorder. The thermocouple output was used to drive the X-axis of the same recorder to obtain a plot of acoustic counts versus temperature. In a few cases, a reset clock was used to obtain count rate data rather than total counts. Also, the cooling curves of a few specimens were recorded using a separate millivolt recorder.

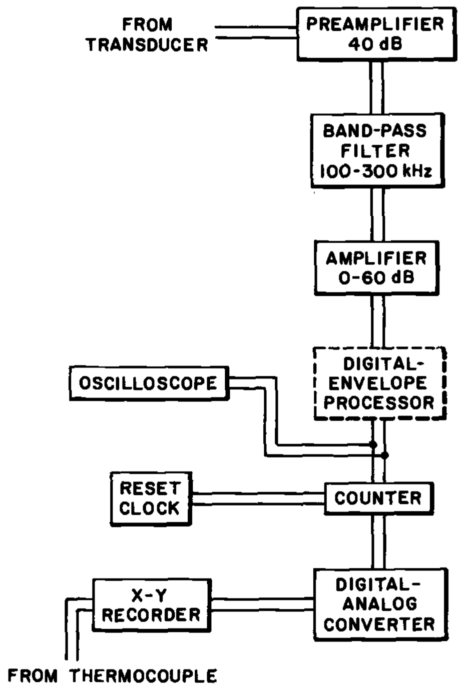

FIG. 2—*Block diagram of electronic components.*

Total counts per unit volume which include multiple reflections will be referred to as N_v. When these counts were digital-envelope-processed to correct for multiple reflections, they will be referred to as N_v^e or the total number of acoustic emissions per unit volume.

After cooling to room temperature, all the specimens were examined by standard light metallography techniques to determine the morphology of the various transformation products.

Results

Ferrite-Pearlite

Acoustic emission during ferrite and pearlite formation was monitored in the iron, line-pipe steel, and Fe-0.97C alloy during cooling from 1000°C, and the results are given in Fig. 3*a*. Total counts per unit volume, N_v, at an amplification of 95 dB were recorded. Cooling curves for the same specimens are given in Fig. 3*b*. A thermal arrest occurs at 900°C in the iron specimen, indicating formation of ferrite. Similarly, a thermal arrest occurs at 620°C in the Fe-0.97C specimen, indicating the formation of pearlite. Comparison of the two sets of curves shows that no AE was observed

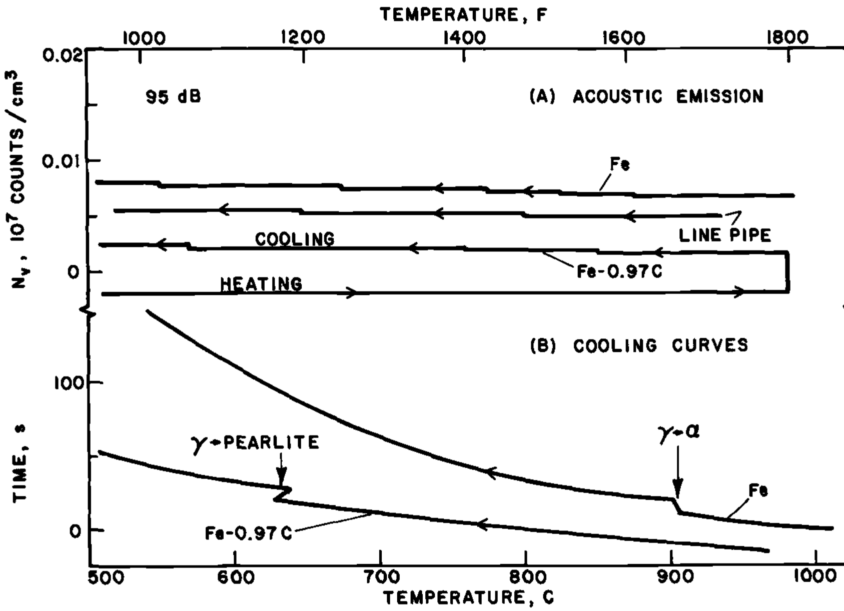

FIG. 3—*Absence of acoustic emission during ferrite and pearlite formation in steel.*

during the formation of either ferrite or pearlite. Examination of specimens by light microscopy revealed an equiaxed ferrite grain structure in the iron, and a fine pearlite structure in the Fe-0.97C alloy. Similar results were obtained for the line-pipe steel, which transforms into a mixture of ferrite and pearlite during continuous cooling. AE results obtained during heating are also shown in Fig. 3*a* for the Fe-0.97C alloy. No AE was observed during heating of any of the steels.

Bainite

Acoustic emission during bainite formation was monitored in specimens of the AISI 4360 and 4380 steels that were transformed isothermally at 400°C by using a small furnace to surround the quartz tube after the austenitizing furnace was lowered. Total counts per unit volume, N_v, at an amplification of 90 dB for the AISI 4360 specimen are shown in Fig. 4 along with metallographic determinations of the volume fraction of bainite formed [*10*]. No AE was observed during bainite formation in this steel. Similar results were obtained for the AISI 4380 steel.

Martensite

To investigate acoustic emission generated during martensite formation in low-carbon steels, the maraging, 20Ni, and 9Ni steels, and the AISI 410

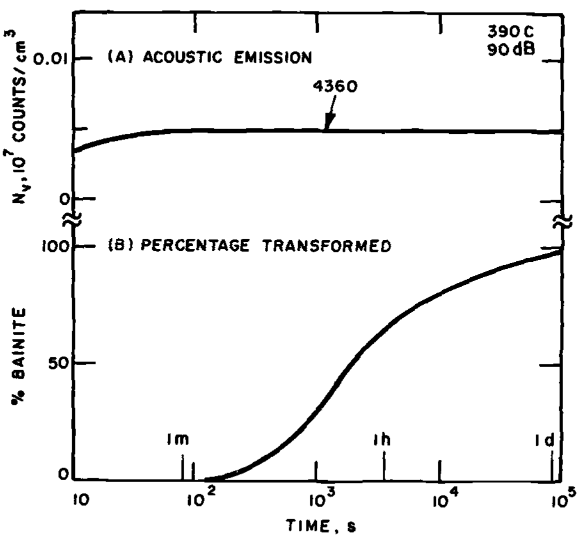

FIG. 4—*Absence of acoustic emission during bainite formation in steel.*

stainless steel were austenitized at 1000°C and continuously cooled in helium at 6°C/s. The hardenability of these steels is sufficient so that they transform completely to martensite with this cooling rate. Total counts per unit volume, N_v, at an amplification of 90 dB are given in Fig. 5. The AE in the maraging steel and the 20Ni steel was just barely detectable, whereas the 9Ni and 410 stainless steels had considerably higher levels of acoustic emission.

No AE is observed until the martensite start temperature, M_s, is reached. The total counts then increase with decreasing temperature because the amount of martensite increases with increased degree of undercooling below M_s [*10*]. A maximum in the total counts is reached eventually at about 60°C below M_s where the austenite has completely transformed to martensite. Similar results were obtained for the other steels as subsequently discussed.

To investigate AE during martensite formation in medium-carbon steels, the AISI 4300 steels with various carbon contents were austenitized at 1000°C and continuously cooled in helium at 6°C/s. The hardenability of these steels is sufficiently high so that they transform almost completely to martensite with this cooling rate. Total counts per unit volume, N_v, at an amplification of 90 dB are given in Fig. 6. AE in these steels was nearly the same as in the 9Ni steel, but it increased gradually with increasing carbon content.

To investigate AE in a high-carbon steel, the AISI 52100 steel was austenitized at 1050°C and continuously cooled in helium at 6°C/s. The

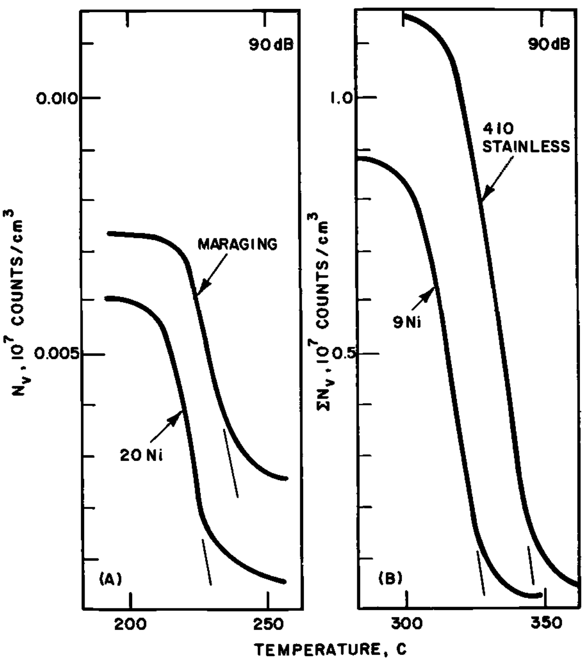

FIG. 5—*Acoustic emission resulting from martensite formation in low-carbon steels.*

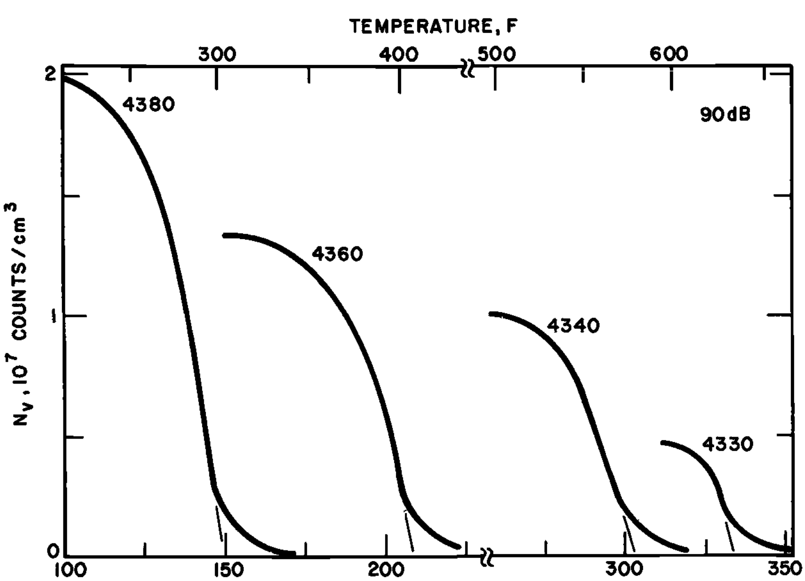

FIG. 6—*Acoustic emission resulting from martensite formation in medium-carbon steels.*

hardenability of this steel is sufficient so that complete transformation to martensite occurred at this cooling rate. Total counts per unit volume, N_v, at an amplification of 90 dB are given in Fig. 7*A*. The count rate, dN_v/dt, is given in Fig. 7*B*. The rate of change of the total counts with temperature is reflected in the counting-rate curve because the cooling rate is nearly constant in this temperature range. The counting rate was low, just below M_s, increased to a maximum at 50°C below M_s, and then decreased to a low value at lower temperatures. The temperature at which no martensite was detected was 120°C below M_s.

M_S *Temperature*

The M_s temperature of the steels can be determined by AE although some uncertainty results because of the long tail present near M_s. The simplest procedure was to extrapolate the straight-line portion of the AE curve to the temperature axis. The temperature at which the straight line intercepted the temperature axis was taken as the M_s temperature (see Figs. 5 to 7). A similar scheme has been used by Brook et al [11]. The M_s temperatures obtained in this manner are given in Table 2. In general,

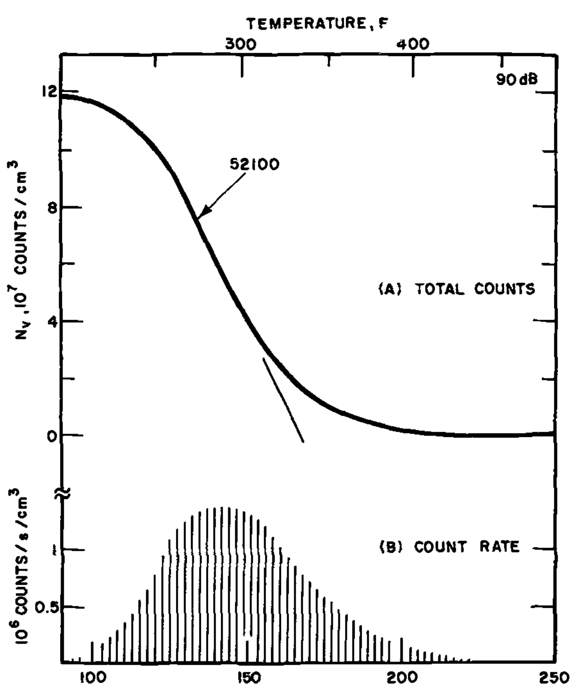

FIG. 7—*Acoustic emission resulting from martensite formation in high-carbon steel.*

TABLE 2—*Comparison of* M_s *temperatures determined by acoustic emission and by metallograpic methods.*

Steel	M_s (acoustic emission), °C	M_s (other work), °C	
9Ni	328	360	(12)
20Ni	227	234	(13)
Maraging	238	...	...
410 stainless	340	350	(12)
4330	345	...	...
4340	302	290	(12)
4360	210	210	(10)
4380	150	...	...
52100	167	140[a] 240[b]	(12)[c]

[a] Austenitized at 1065 °C.
[b] Austenitized at 843 °C.
[c] References at end of paper.

good agreement was found between the M_s determined by AE and by metallographic [*10, 12*] or dilatometric means [*13*]. The M_s temperatures of the AISI 4300 steels are also shown in Fig. 8 along with those determined for iron-carbon alloys [*14*]. The M_s temperature of the 4300 steels was lower than that for iron-carbon alloys of the same carbon content presumably because of the additional alloying elements present in these

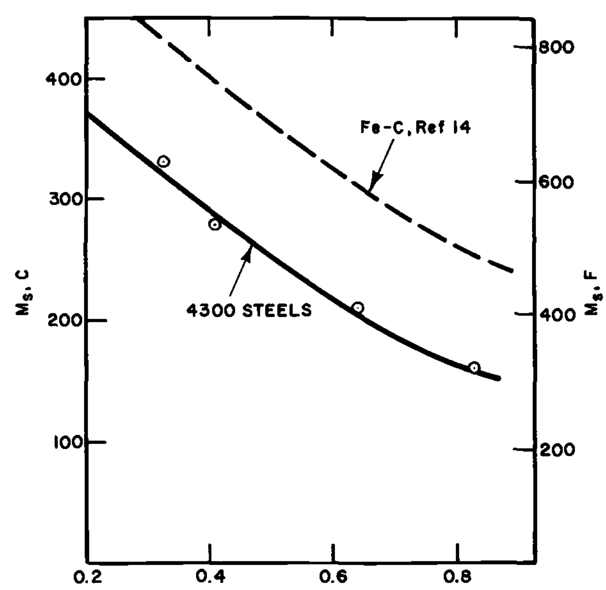

FIG. 8—M_s *temperatures of medium-carbon steels determined by acoustic emission.*

steels. However, the dependence of the M_S temperature on carbon content was similar to that reported for iron-carbon alloys.

The total counts per unit volume for 100 percent transformation to martensite for the various steels was very sensitive to carbon content, as can be seen in Fig. 9. The total counts from the very low-carbon maraging steel and the Fe-20Ni alloy were very small but increased gradually between carbon contents of 0.1 to 0.8 percent and then increased sharply at higher carbon contents. The AISI 52100 steel gave a total count that was almost an order of magnitude higher than that for the AISI 4380 steel.

Since the total counts per unit volume previously discussed include the counts caused by multiple reflections within the specimen, waveguide, and transducer, a number of specimens were transformed and AE recorded using digital envelope processing. Here, the envelope of the "ring down" pulse is obtained and counted as one pulse. These digital-envelope-processed counts represent true acoustic emissions and are referred to as acoustic emissions per unit volume, N_v^e. A comparison of the total counts

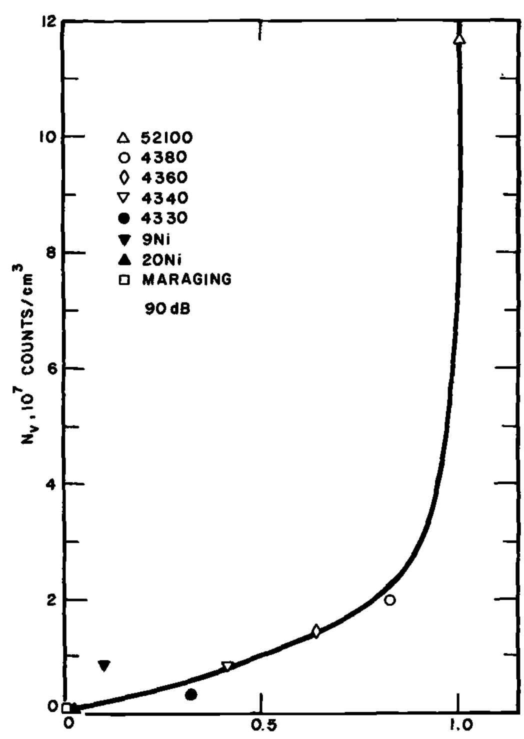

FIG. 9—*Effect of carbon content on acoustic emission for formation of 100 percent martensite in steel.*

per unit volume, N_v, and the acoustic emissions per unit volume, N_v^e, at an amplification of 90 dB for a 4380 steel is given in Figs. 10*A* and 10*B*. The digital-envelope-processed counts were also recorded at amplifications of 85 and 80 dB, and the results are given in Fig. 10*B*. Digital envelope processing at 90 dB reduced the total counts by a factor of 10, which appears reasonable since this is about the number of ring-down reflections observed in AE pulses when they are examined on a memory oscilloscope. The decrease in the total counts with decreasing amplification was expected and reflects the 1 V threshold voltage of the counting system. Pulses not amplified to this voltage are not counted.

A summary of the digital-envelope-processed results for 100 percent martensite is given in Fig. 11 for different steels and different amplifications. It is clear that higher values of N_v^e were recorded at all amplifications for the AISI 52100 steel than for the lower carbon steels. The lowest value of N_v^e was recorded for the maraging steel.

Metallography

The metallographic structures of the various steels after cooling from 1000°C to room temperature at 6°C/s are shown in Figs. 12*A* to 12*F*. The microstructure of the iron specimen consisted of equiaxed ferrite (Fig.

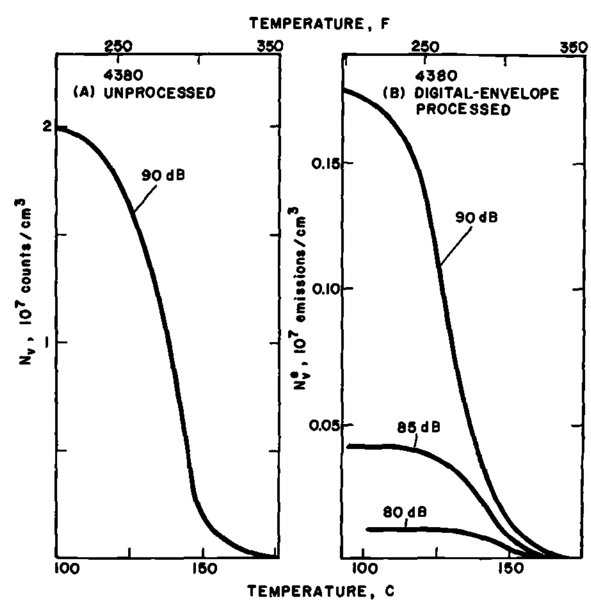

FIG. 10—*Effect of digital-envelope processing and amplification on total martensite counts.*

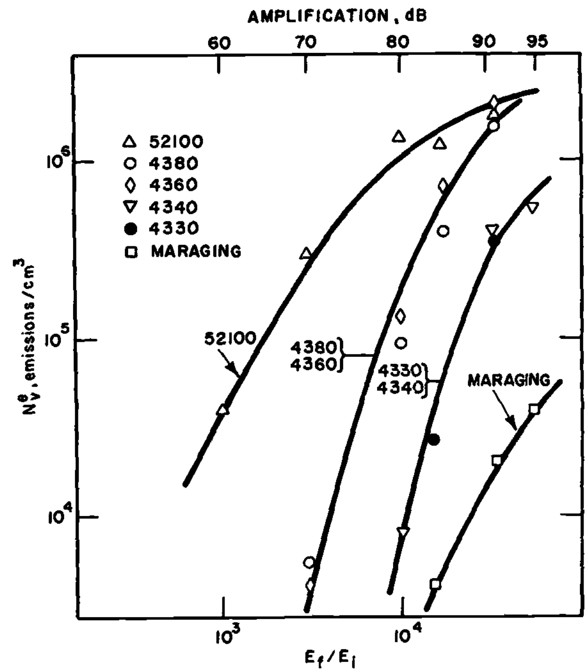

FIG. 11—*Effect of amplification on digital-envelope-processed counts for formation of 100 percent martensite in various steels.*

12*A*); the microstructure of the line-pipe steel consisted of acicular ferrite and pearlite (Fig. 12*B*); the microstructure of the Fe-0.97C steel consisted of fine pearlite (Fig. 12*C*); the microstructures of the 9Ni and maraging steels consisted of small lath-shaped martensite units arranged into larger block-like units (Fig. 12*C* and *D*); and the microstructure of the 52100 steel consisted of large individual plate-shaped martensite units which contained some microcracks (Fig. 12*F*). Since detailed studies of the substructure of lath and plate martensite[3] using transmission electron microscopy have been published elsewhere [*15*], no attempt was made to duplicate this work. In general, the substructure of lath martensite consists of a high-density dislocation network, whereas the substructure of plate martensite consists of fine internal twins.

Discussion

Copious acoustic emission is generated during the transformation of steel into martensite. In contrast, no AE is generated when steel transforms

[3] Common nomenclature for the lath-shaped martensite units formed in low-carbon steel is lath martensite. The plate-shaped martensite units formed in high-carbon steels are referred to commonly as plate martensite [*15*].

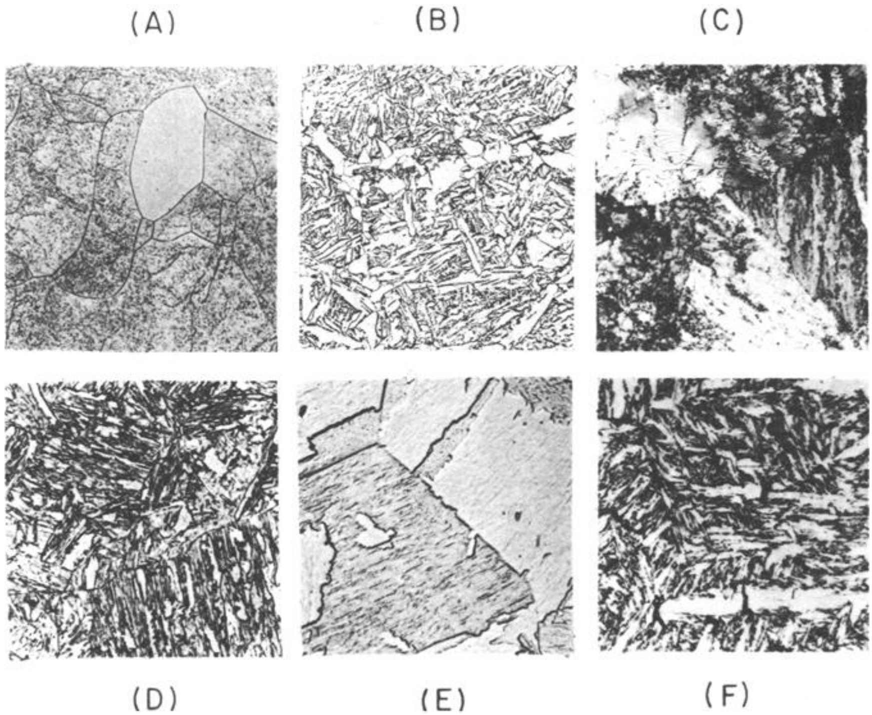

FIG. 12—*Microstructures of acoustic emission specimens:* (a) *iron,* (b) *line-pipe steel,* (c) *Fe-0.9C,* (d) *9Ni steel,* (e) *maraging steel, and* (f) *AISI 52100 steel.* (a), (b) ×*500;* (c) *to* (f) ×*750.*

into ferrite, pearlite, or bainite. This is not surprising since the growth of martensite occurs in a diffusionless manner at nearly the shear velocity of elastic waves in steel (~10^5 cm/s) [*16,17*]. Also, this transformation occurs at low temperatures and releases a large amount of stored energy (~300 cal/mol). The rapid release of part of this energy in the form of elastic waves is detected as AE. The attenuation of these elastic waves results in the generation of heat.

In contrast, the tranformation of steel into ferrite, pearlite, or bainite occurs at higher temperatures and involves slow, diffusion-controlled growth (~10^{-4} cm/s). Also, much smaller amounts of stored energy are released [*18-22*]. Thus, it is expected that AE would not be generated by such transformations. The present results are also in agreement with earlier studies by Liptai et al [*4*] who found no AE generated during a eutectoid transformation in a tin-cadmium alloy but found copious AE generated during martensite formation in gold-cadmium and indium-thallium alloys, and in cobalt and plutonium.

The good agreement between the martensite start temperature observed by normal metallographic means or by dilatometry and those determined by AE (Table 2) indicate the reliability of this method for determining M_s temperatures. The AE method is much faster than the metallographic method and much more sensitive than the dilatometric method. It appears generally applicable to a wide variety of steels except for those with very low hardenability.

The variation of the total acoustic emission for the martensite transformation with carbon content (Fig. 9) appears to be related to the morphology of the martensite formed. The low-carbon steels (below 0.2 percent carbon) all form lath martensite (Fig. 12).[4] This structure consists of small lath-shaped martensite units (~0.25 by 2 by 50 μm) which are arranged into larger block-shaped units [*15*]. In contrast, the high-carbon steels (above 0.8 percent carbon) all form plate martensite. This structure consists of large plate-shaped martensite units (~5 by 50 by 50 μm diameter) [*15*]. For medium-carbon steels (0.2 to 0.8 percent carbon) mixed lath/plate martensite microstructures are observed [*15,23*]. The shape of the curve in Fig. 9 simply reflects the amount of plate martensite in the steels. At 0.8 percent carbon where the steels begin to transform completely to plate martensite [*15,23*], a sharp increase occurs in the total counts.

The much greater acoustic emission accompanying the formation of plate martensite in contrast to lath martensite may simply be caused by the larger volume of the transformation units in plate martensite. The lath-shaped units in lath martensite occupy a volume of 25×10^{-12} cm^3, whereas the larger plate-shaped martensite units in plate martensite occupy a volume of 4.5×10^{-9} cm^3. If the amplitude of the stress wave generated by formation of martensite was proportional to the volume of the transformation unit, we would expect the voltage generated at the transducer would also to be proportional to the volume of the transformation unit. Examination of Fig. 11 indicates that AE signals are detected from the 52100 steel at amplifications about 1/50 those required for the maraging steel. The volume ratio of lath and plate martensite for these steels is 1/160. More sophisticated analysis of the relationship of the amplitude of the stress wave to the size of the martensite unit will be needed before agreement with experiment can be improved. Obviously, in addition to the size of the unit, the magnitude and direction of the shear strains are involved.

Alternative explanations of the increased acoustic emission, other than morphological changes, such as the lower transformation temperatures of high-carbon martensites or microcracking in high-carbon martensites can be eliminated. The transformation temperature of maraging steel (227°C) is

[4] An exception to this rule is high-alloy steels such as 28Ni-0.1C steels which form plate martensite.

nearly the same as that of the 52100 steel (167°C); yet, hardly any AE is observed in the maraging steel in comparison with that found in the 52100 steel. Although microcracking was found in the 52100 steel as reported by other investigators [24,25], no microcracking was observed in plate martensite formed in the 28Ni-0.1C steel studied in our earlier work [5]. Yet, AE even greater than that found in the 52100 steel is observed in this steel. The copious AE accompanying the formation of plate martensite in 28 to 30 percent nickel, low-carbon steels [3,5] emphasizes that martensite morphology and not carbon content is the primary cause of the increased AE. The variation of the AE in low-alloy steels with carbon content simply reflects the effect of carbon content on morphology.

Another possible explanation of the much smaller AE in low-carbon lath-martensite structures compared to that in high-carbon plate-martensite structures is a lower martensite growth rate. Owen et al [26] argue that because of the rapid decrease of the M_s temperature with small carbon additions in the case of lath martensite, its growth rate is controlled by the requirement that carbon moves with the interface in the form of a Cottrell atmosphere. This results in growth velocities for lath martensite much lower than the velocity of growth for plate martensite and could account for the lower AE. Additional research will be required to differentiate between this explanation and that based on simple differences in the size of the martensite units.

The total acoustic emissions per unit volume should be comparable to the number of martensite plates in the specimen. Because of the large number of steels studied here, it was not possible to make the detailed quantitative metallographic studies used in our earlier work [5]. However, using an average martensite plate volume determined by metallography for the 52100 steel of 4.5×10^{-9} cm^3, the total number of martensite plates should be $\sim 2 \times 10^8$ cm^{-3}. The total acoustic emissions per unit volume observed for this steel is only 3×10^6 cm^{-3}. Each emission thus must involve about 60 plates. This is not surprising because of the autocatalytic nature of the martensite transformation [27]. Earlier work based on more detailed metallography indicated that about 15 plates were involved in each AE [5]. Similar techniques cannot be applied to lath martensite because the amplitude of the signals from most of the martensite units are too small to detect.

It is clear that if AE is to be used to detect flaws during welding operations, considerable caution must be exercised so that the AE arising from formation of martensite in the weld heat-affected zone is not misinterpreted as microcracking. The decrease of the martensite AE with lower carbon contents may make it possible to avoid this problem in some of the lower carbon steels.

Summary and Conclusions

Acoustic emission is generated when steels transform into martensite but not when they transform into ferrite, pearlite, or bainite. This is attributed to the rapid (~10^5 cm/s), diffusionless, shearlike growth of martensite. Ferrite, pearlite, and bainite, which exhibit slow (~10^{-4} cm/s), diffusion-controlled growth, are not expected to give rise to acoustic emission.

Acoustic emission may be used to determine the M_s temperature of steels. Such measurements are in good agreement with both metallographic and dilatometric determinations of the M_s temperatures of alloy steels. This technique is much more sensitive than other techniques and can be used to examine the transformation mechanism in great detail.

Acoustic emission during martensite formation is markedly sensitive to carbon content. Low-carbon maraging steels generate an extremely low level of acoustic emission when they transform to martensite, whereas high-carbon steels generate a very high level of acoustic emission. This is attributed to the different morphologies of martensite present in these steels. In steels with less than 0.1 percent carbon, lath martensite is formed exclusively, and the small volume of the martensite units results in a very low level of acoustic emission. As the carbon content is increased, plate martensite is formed in increasing amounts, and the larger volume of these martensite units now results in increased acoustic emission. The acoustic emission continues to increase rapidly up to 1.0 percent carbon where plate martensite is formed exclusively.

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Development of Acoustic Emission Testing for the Inspection of Gas Distribution Pipelines

REFERENCE: McElroy, J. W., "**Development of Acoustic Emission Testing for the Inspection of Gas Distribution Pipelines,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 59–79.

ABSTRACT: This paper describes how a utility became interested in acoustic emission testing for the survey inspection of its buried gas pipelines. Several weld failures emphasized the need to develop inspection techniques to monitor these pipelines in order to locate weld flaws in high-stress regions to permit prompt weld repairs and assure system integrity. It was found that a weld must have a certain metallurgical flaw and must be located in a high-stress region in order to precipitate an inservice oxyacetylene weld failure in a pipeline. It was found that metallurgical flaws in high-stress regions can be located by acoustic emission tests.

This paper describes the field development of the acoustic emission testing technique and the correlation of the field results with the laboratory results. It was found that the stress levels imposed by either internal pressurization or by external loading in the field tests are sufficient to cause critical flaws to emit and be located. Then replacement or reparation of the critical flaws located in this manner would restore the integrity of the pipeline. Discussed in the paper are the other nondestructive correlations such as radiography and correlations through tension tests, hydrostatic tests, bend tests, and fatigue tests.

KEY WORDS: acoustics, emission, pipelines, nondestructive tests, crack propagation, gas pipes, residual stress

Between the mid-nineteen-teens and mid-nineteen-fifties, approximately 500 miles of steel pipe, 4 in. in diameter and larger, were installed by oxyacetylene joint welding techniques in what is now the Philadelphia Electric Company's gas distribution system (Fig. 1). This is approximately

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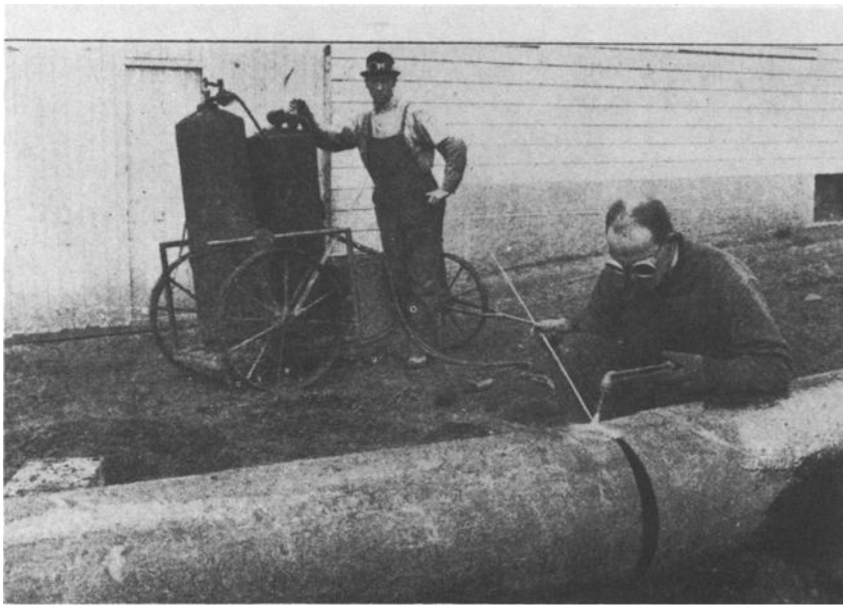


FIG. 1—*1911 style of oxyacetylene welding.*

20 percent of the total steel mains in the system. Though the quality of many of these welds would be questioned by today's standards, the incidence of failure has been small, averaging about one a year for the past seven or eight years. These failures have emphasized the need to develop an inspection technique to monitor these pipelines for the purpose of locating weld flaws in high-stress regions.

Pipelines Stresses

To better understand the mechanism of failure, a study of the stresses associated with underground gas pipelines was conducted. The major stresses are residual, long-term cyclic from changes in ground temperature and short-term cyclic from heavy vehicular traffic. Some residual stress is introduced into a pipeline at the time of installation. Over a period of years, the residual stress is increased by soil settlement or movement. The general range of residual stress was found to be from 3000 to 20 000 psi oriented in random directions. The thermal stresses during a mild winter can be expected to contribute 5000 psi tension, whereas a severe winter contributes 7200 psi. The maximum stress recorded for fully loaded five axle sand trucks over smooth pavement was 1000 psi coaxial with the pipe at the top side. Rough pavement was found to increase the magnitude of stress up to 200 percent.

Fatigue Tests

Pipe sections containing a weld were removed from selected locations on the older oxyacetylene welded pipe systems. Some were cut into test specimens. Prepared test coupons and whole pipe sections were tested to failure on fatigue life testing machines imposing stresses of the magnitude found to exist in high-stress regions of the system. Examination of the fracture surface from fatigue life test specimens showed similar patterns to field weld failure specimen we had examined. We concluded that the field weld failures were due to fatigue.

The fatigue process occurs in three stages.[2] The first stage is crack initiation. This complex stage includes the period in which microstructural changes occur. Crack propagation is the second stage. The crack grows with each stress cycle leaving a path of transcrystalline structure (Fig. 2). Eventually the net section becomes too small to support the load, and an almost instantaneous failure occurs leaving a path of intercrystalline structure (Fig. 2).

Since the transcrystalline structure was the only structure that sustained cyclic loading, Fig. 3 plots the fatigue life versus transcrystalline area. It would seem reasonable to assume that those data points in the figure that fall within a narrow band around the mean would be suitable for distribution service. However, those that fall below the general pattern would be of a critical nature, and these welds should be considered unacceptable.

Critical metallurgical flaws causing zero cycle failures were identified as pre-existing cracks. These cracks were found by means of radiographic and destructive examination of the fracture face. These welds were observed to be well into the second stage of fatigue, about to enter the third.

Since acoustic emission (AE) testing can detect the first stage of fatigue and warn of impending failure, it was decided to run a field test to see if it could be adapted for use as a survey method.

Acoustic Emission Field Tests

First Field Test

The first test was conducted on a 1000-ft section of 16-in.-diameter line. Six 30-kHz transducers were placed on the pipe at 180-ft intervals. The emissions were monitored as the pressure in the line was increased from 0 to 100 psi with nitrogen pressure. Figure 4 shows a block diagram representative of the equipment used in monitoring the pipeline. After being amplified through the transducer preamplifier-amplifier arrangement, the

[2] Mason, S. A. and Hirschberg, M. H., *The Role of Ductility, Tensile Strength and Fracture Toughness in Fatigue*, Franklin Institute Publication, Permagon Press, Philadelphia, Pa.

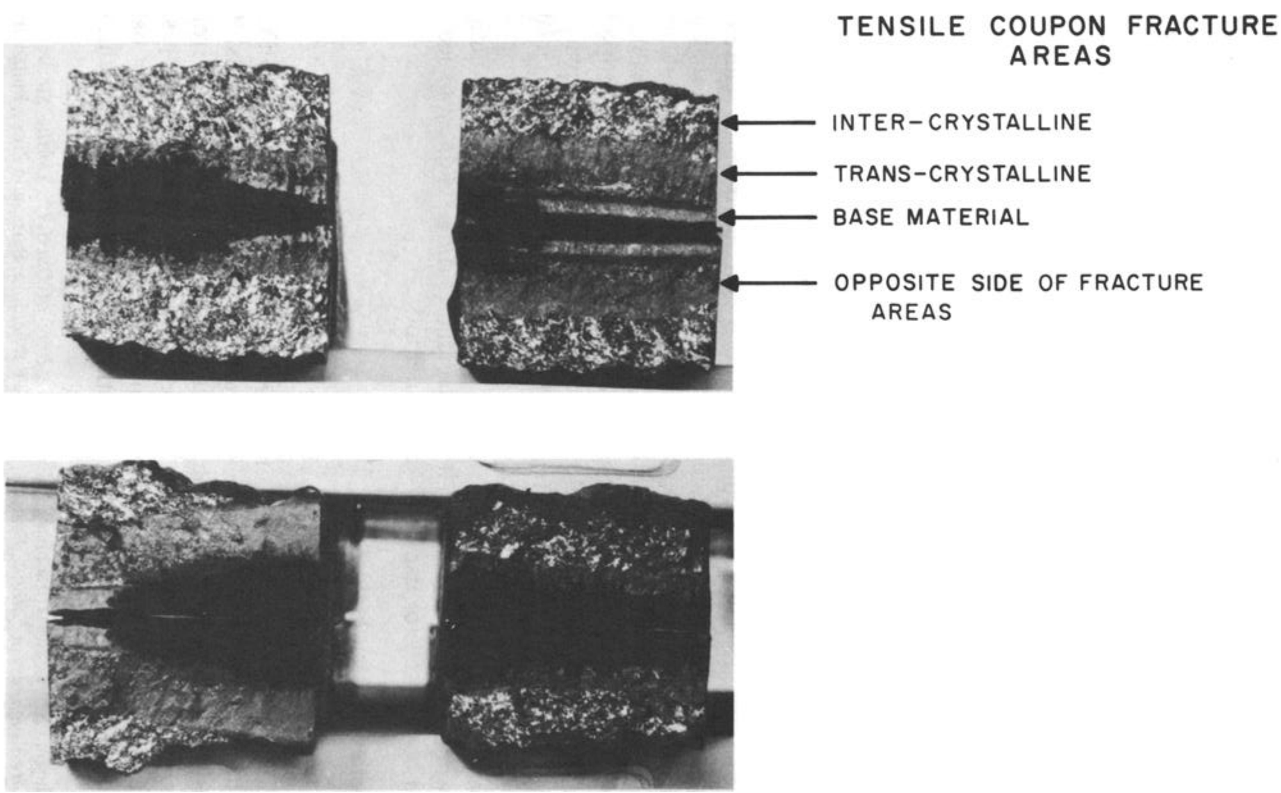


FIG. 2—*Tensile coupons showing transcrystalline and intercrystalline fracture areas.*

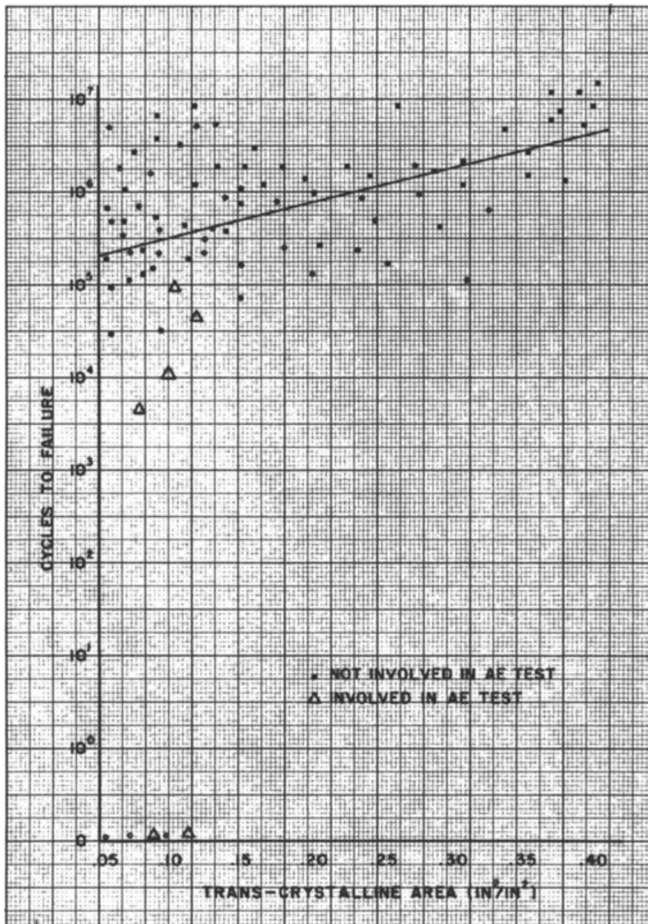


FIG. 3—*Coupon fatigue test results.*

emission signals are processed and sent to the time analysis computer. Here the time difference of arrival of the emission signal at adjacent transducers is computed and memorized for locational analysis at the conclusion of the test.[3]

This test showed that neither traffic noise, nor noise of gas flowing during pressurization, would interfere with AE monitoring. Signal attenuation was considerably higher in this pipe than expected; however, signal transmission appeared adequate to survey sufficiently long sections during a

[3] Parry, D. L., *Industrial Application of Acoustic Emission Analysis Nondestructive Testing Technology*, Exxon Nuclear Company, Richland, Wash., Jan. 1974.

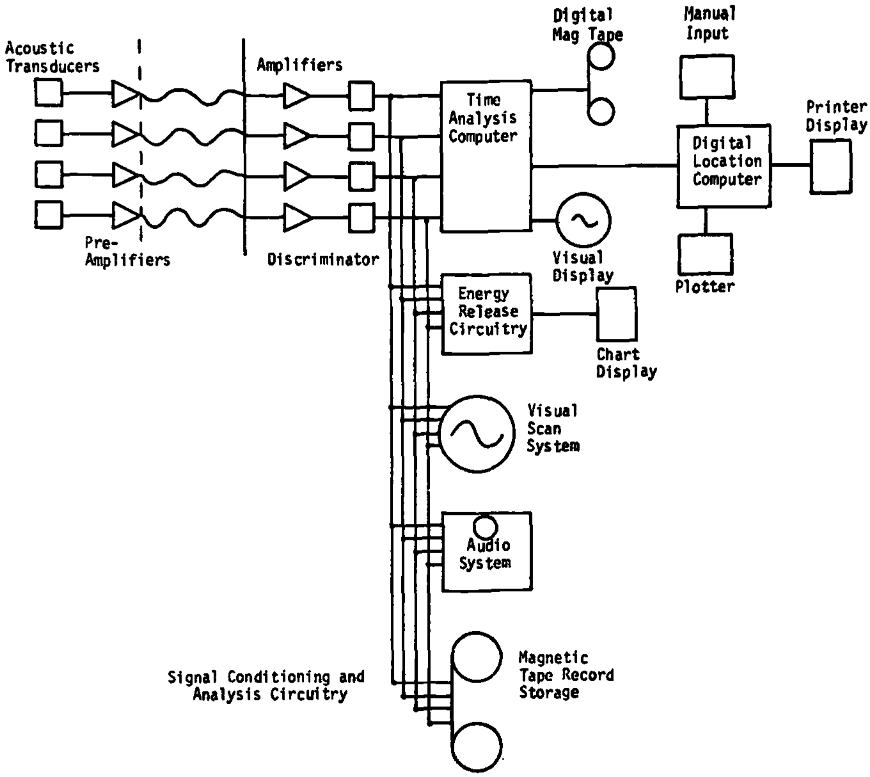


FIG. 4—*Block diagram of the monitoring equipment used in the field.*

single pressure cycle to make the technique feasible. It was found that previous operating pressures must be exceeded in order to produce sufficient emissions.

Several prime emitters were located in the test section (Fig. 5). Two were excavated and found to be welds. One was a butt weld of two sections of straight pipe, and the other was a miter joint weld. Only the butt weld could be cut into tensile coupons. Several of these coupons, when tested in a tensile machine, were found to fail at the loading condition defined in the fatigue tests and, therefore, could be considered failures at zero cycles (Fig. 3).

Second Field Test

The second test was run on a section of 4-in. pipe about 2000 ft long. This pipe section was instrumented with eleven transducers spaced about 200 ft apart. Two types of tests were conducted, the first being a heavy vehicle

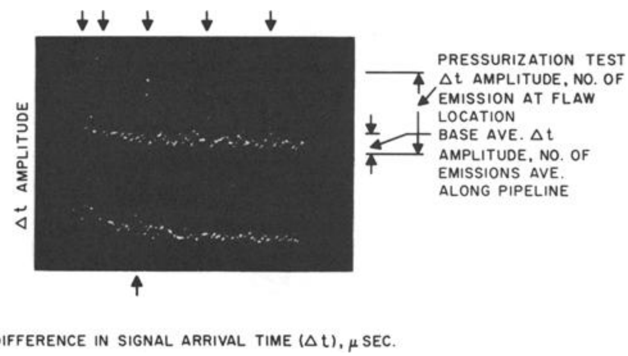


FIG. 5—ΔT *amplitude data between two transducers for the pressure test during Field Test 1.*

experiment where a heavy truck was driven down the road with one set of wheels kept as nearly as possible directly over the pipe. The purpose of using the heavy vehicle was to determine if it would be possible to induce a stress in the pipe by external mechanical loading from earth shift. This induced stress would be more representative of the stresses that cause failures experienced in the field.

The second phase of this test was conducted using pneumatic pressure as the stressing medium. As with the first test, bottled nitrogen was used to raise the pressure to 100 psi.

The AE activity during the pneumatic test was very low and did not indicate significant crack growth at any point in the line. Only on a bridge (200-ft section of test) did the emission levels reach significance; however, the noise caused by the wind masked the emission sites. Signals were also obtained by stressing the pipe by traversing the underground section of the pipeline with the heavy vehicle. Figure 6 shows the data between two transducers for this test.

Although significant crack growth was not indicated, three welds producing some emission activity during pneumatic loading and one producing activity during heavy vehicle loading were excavated and the welded pipe sections removed from the line. Three welded sections were chosen at random from the bridge section. All seven of these weld specimens were fatigue tested under the loading conditions defined earlier.

In confirmation of the field test results, which indicated that no significant flaws existed in the underground section of the test, the number of cycles required to fail the four welds tested was above the average (Points 1, 2, 3, and 4*A* on Fig. 7). Visual examination of the specimens (Fig. 8, 2*B*), reveals little or no corrosion after more than 50 years of service and more than 90 percent weld penetration.

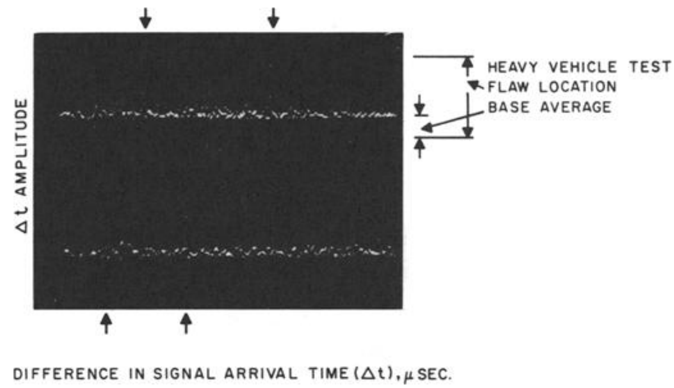


FIG. 6—ΔT *amplitude data between two transducers for the heavy vehicle test during Field Test 2.*

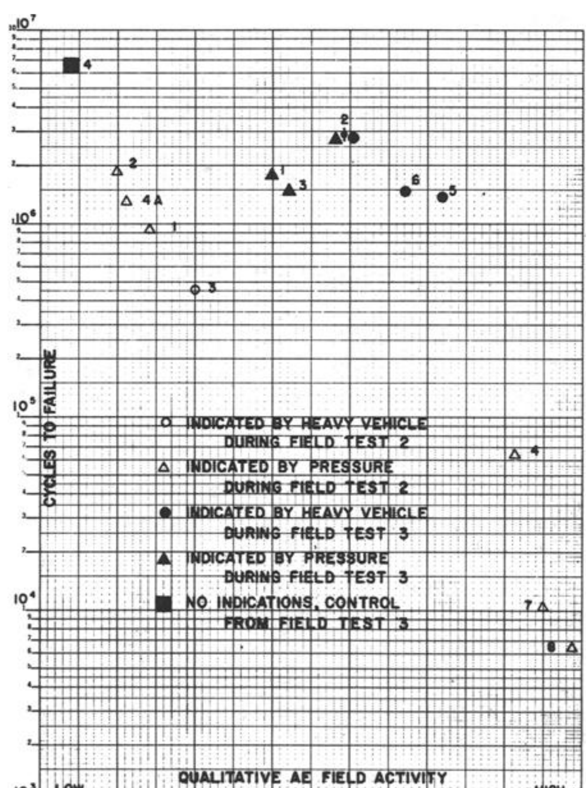


FIG. 7—*Fatigue data for whole pipe specimens from Field Test 2 and Field Test 3.*

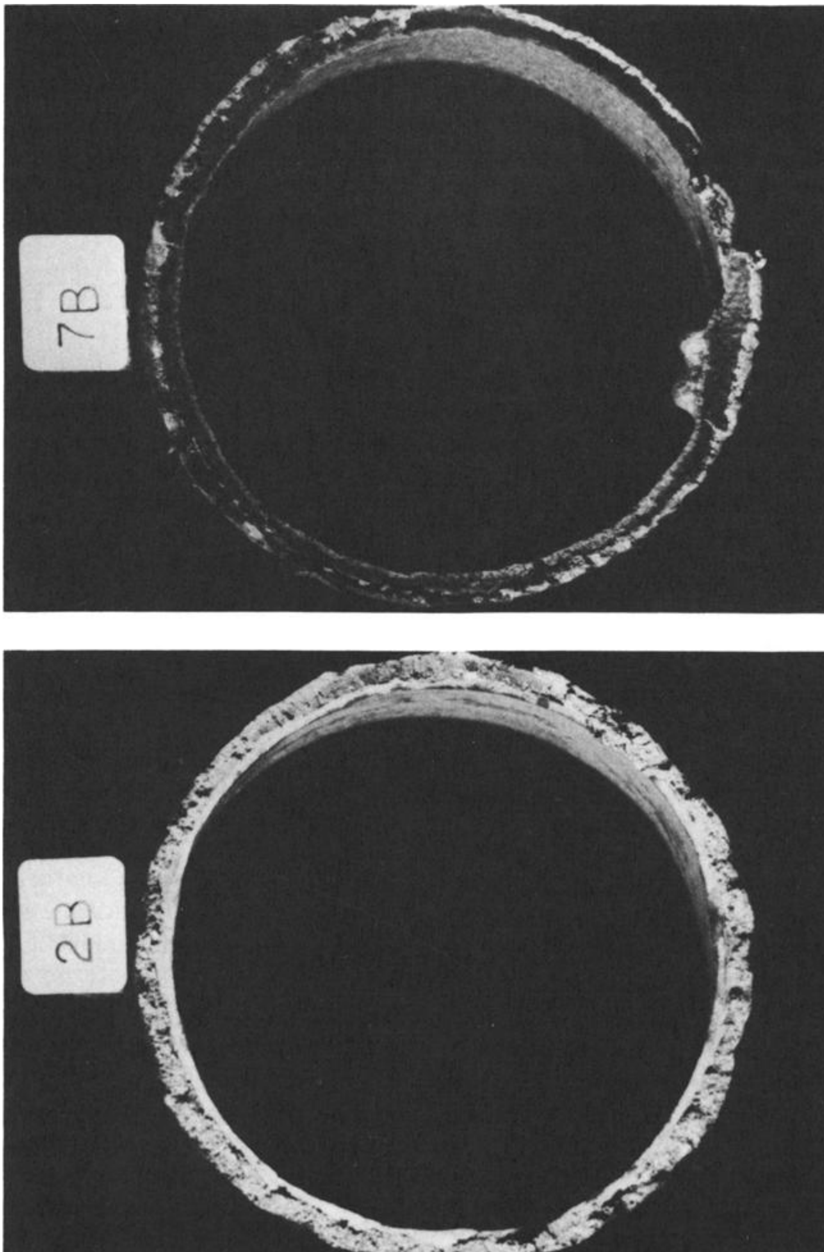


FIG. 8—*Fracture areas from two specimens from Field Test 2.*

The three welds from the bridge fractured below the average number of cycles (Points 4, 7, and 8 on Fig. 7) correlating with the significant emission levels observed. Figure 8 (*7B*) shows the fracture area for one of these bridge specimens. It can be seen that specimen *7B* had 20 percent weld penetration.

Third Field Test

A third test was run on 1600 ft of 12-in. steel main. Fourteen sensors were located along the line. Again, both pneumatic and heavy vehicle tests were run. The level of emission activity for all tests run on this section of line was low. However, two sources from the pneumatic test (Points 1 and 3 of Fig. 7), two from the truck test (Points 5 and 6), one from both (Point 2), and one for control (Point 4) were chosen for excavation. Upon excavation, it was found that all six sources were located at welds. All of these welds were cut out and fatigue tested.

The results of the fatigue testing correspond with the results found in the field. The level of emission activity in the field was in general low, and the specimens performed well in the fatigue tests (Fig. 7). All the specimens identified by emission activity during the field test failed at a much lower number of cycles than the control specimen, which produced no emissions during the field test.

Fourth Field Test

A fourth test was run on 6600 ft of 12-in. gas line. This line was tested in two sections, each about 3300 ft long. The test differed from previous tests in that a small hole probe was used (Fig. 9) for remote attachment of the sensor to the line. This eliminated the need for digging a hole large enough to allow a man to instrument the pipe directly.

Again both pneumatic and heavy vehicle stressing was used. A total of 35 emission sites were detected and located. Six of the most significant were excavated and found to be at welds. Selection of the most significant is made by comparing the number of events occurring at a given location on the pipeline to the base average number of events occurring along the pipeline. If the number of events occurring at that location is many times the base average number of events the emission site can be considered to be significant (Figs. 5 and 6). Two control welds from this line were also removed for further testing. Six of the eight welds were removed, capped, and prepared for hydrostatic testing. The two remaining whole pipe sections were stressed by bending to a maximum stress of 2000 psi.

The failure pressures of the six correlate with the emission activity observed during the field test (Fig. 10). Those specimens which were observed as significant failed at much lower pressures than the control welds. The two specimens involved in the bend test did not fail.

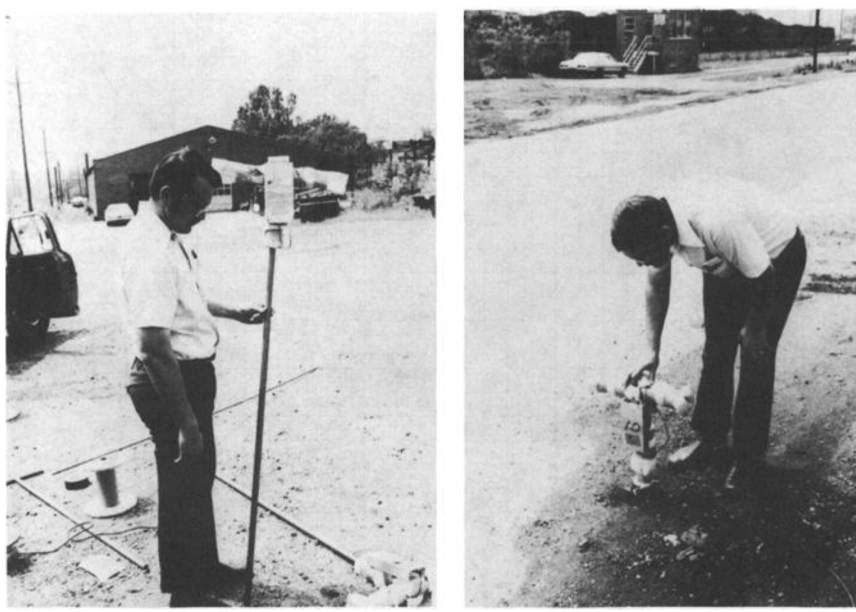


FIG. 9—*Small hole probes.*

Conclusions of the Field Tests

AE testing to locate faulty welds appears to be feasible. The hoop stresses involved in pneumatic stressing of lines appear to be high enough to cause movement of critical flaws in the oxyacetylene welds and to produce emissions. However, the compression and tensile stresses induced by heavy vehicle stressing appear to be adequate to cause the more critical flaws to emit. Figure 7 shows that except for the welds from the bridge (Points 4, 7, and 8) on Test 2, the weld detected by the truck (Point 3) failed at a number of cycles less than those indicated by the pressure test. Figure 7 shows that the welds indicated by the truck in Test 3 (Points 5 and 6) again failed at a lower number of cycles than the ones indicated by the pressure test. In Test 4, Fig. 10 shows that the welds indicated by the truck (Points 1 and 5) failed at lower pressures than the welds indicated by the pressure. In addition to its economic advantage, heavy vehicle loading appears to be the most advantageous stressing medium due to the kind of stressing involved.

Laboratory Results

The specimens from Test 4 were monitored for emissions during destructive tests in the laboratory. The purpose of these tests was to see if there

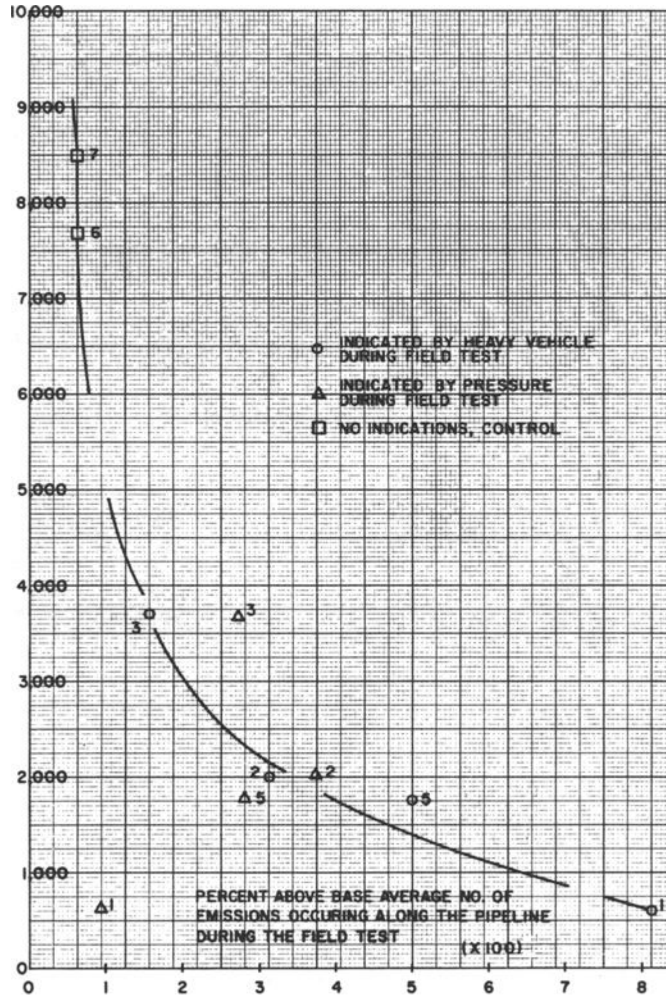


FIG. 10—*Failure data for whole pipe specimens from Field Test 4.*

was a relationship between weld emission activity under typical field stressing conditions and the ultimate strength of the piping. Five 215-kHz transducers were used during the hydrostatic tests. Three were placed circumferentially around the weld to locate emission sites, and the remaining two were placed equidistant from the weld as coincidence monitors to assure that the emissions were coming from the vicinity of the weld (see **Fig. 11*a***). In conjunction with the preamps, amplifiers, filters, and discriminatory functions, a ΔT digital printer and two X-Y recorders were used.

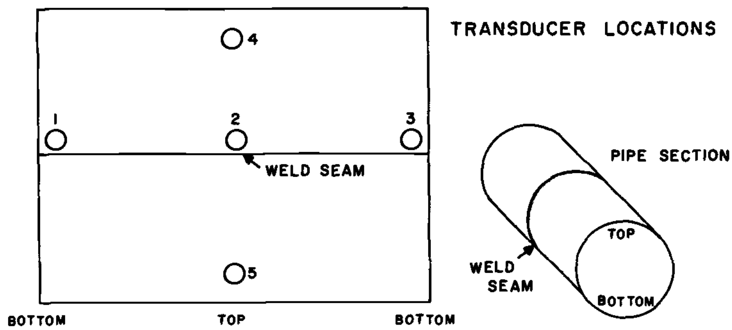


FIG. 11*a*—*Sketch of transducer locations.*

Figure 11*b* shows the ΔT amplitude at 600 psi along the weld seams of the six specimens used during the hydrostatic testing. The most significant growth can be seen in Specimen 1 which produced the most emission activity during the field test by heavy vehicle loading. The least emission activity occurred in Specimen 7, a control specimen. Specimen failures occurred at locations predicted by their AE activity (Table 1). Specimen 1 failed at the weld at -40 μs between transducers 1 and 2 and $+95$ μs between 2 and 3 (10 μs = 1 in. along the weld seam and the 0 reading is midway between the transducers). Specimen 2 failed off the weld at $+50$ μs between transducers 1 and 2. Specimen 3 failed off the weld at $+20$ μs between transducers 1 and 2. Specimen 5 failed at the weld at $+20$ μs between transducers 2 and 3. Specimen 6 failed off the weld -50 μs between transducers 2 and 3. Specimen 7 failed off the weld at $+70$ μs between transducers 2 and 3. It can be seen that there is a correlation between emission sites and failure locations.

A correlation can also be seen between the radiographs and AE data from the welds. Figure 12 compares the radiograph interpretation and the AE interpretation along the weld seam of Specimen 1. Wherever a crack existed on the radiograph, a large ΔT amplitude was also located. This figure shows that lack of penetration is not as critical a flaw as an existing crack. Only under a severe lack of penetration did any other ΔT amplitude build up.

Figure 13 exhibits the event counts for all the specimens versus pressure during the hydrostatic tests. In general, at a given pressure the weaker welds produce more counts than the stronger welds. At 600 psi this assumption is true for all the specimens. It should be noted in this figure that the emission sites located during the heavy vehicle field test failed first in the weld. The emission sites located during the pressure field test did not fail in weld but in corrosion pits. This indicates that pressure tests may not

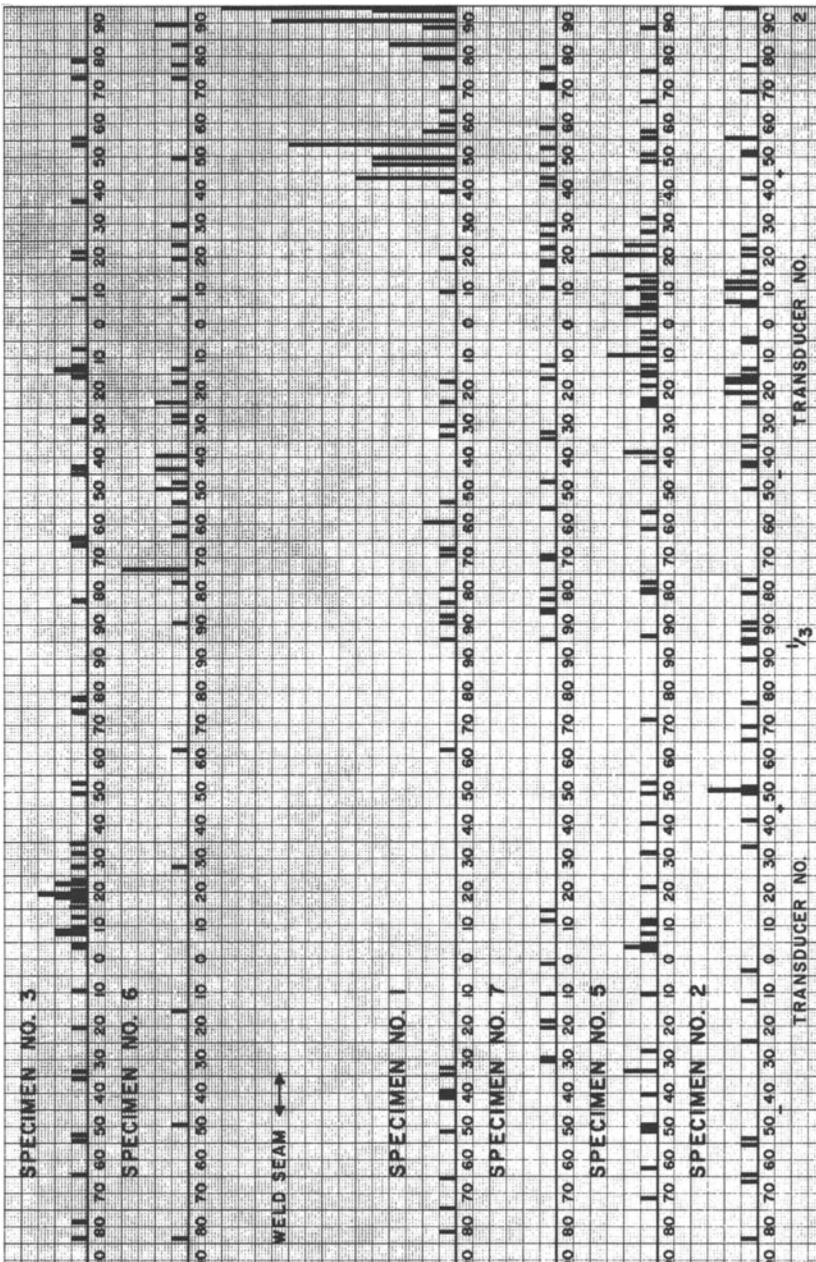


FIG. 11b—ΔT amplitudes along the weld seams for specimens from Field Test 4.

TABLE 1—*Field and laboratory test results of the welds removed from Field Test 4.*

Specimen No.	Field Results: Field Emission Activity % of Base Average Number of Emissions		Laboratory Results							
	Heavy Vehicle	Pressure	Type of Stress	Event Count at Typical Field Stress Level	ΔT,μs	Most Significant Emission Site Along Weld Seam Between Transducers	ΔT,μs	Failure Site Along Weld Seam Between Transducers	Failure Characteristics: Location	Failure Characteristics: Pressure, psi
1	810	95	hoop at 1580 psi	33	+95	2 and 3	+95 −40	2 and 3 1 and 2	at weld	600
2	310	375	hoop at 1580 psi	2	+50	1 and 2	+50	1 and 2	off weld	2000
3	150	275	hoop at 1580 psi	12	+20	1 and 2	+20	1 and 2	off weld	3700
5	500	285	hoop at 1580 psi	20	+20	2 and 3	+20	2 and 3	at weld	1750
6	50	50	hoop at 1580 psi	4	−73	2 and 3	−50	2 and 3	off weld	7700
7	50	50	hoop at 1580 psi	12	none (control)		+70	2 and 3	off weld	8500
8	on bridge	250	flexural at 1000 psi	484	−7	1 and 2	no failure		no failure	
9	not stressed	350	flexural at 1000 psi	789	+90	1 and 2	no failure		no failure	

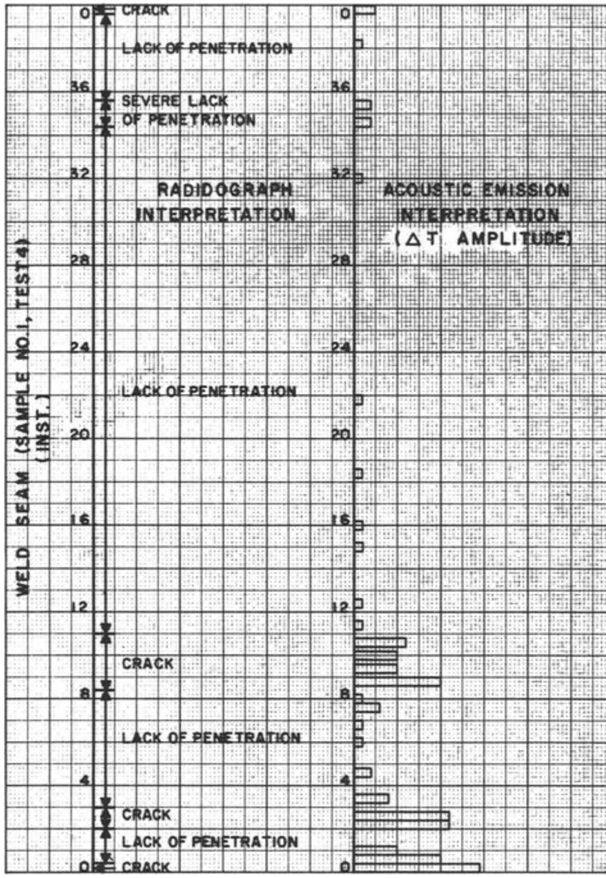


FIG. 12—*Comparison between radiograph indications and acoustic emission indications.*

create sufficient field stress on the pipe to cause all weld flaws to emit AE's. It also suggests that the flexural stresses induced by heavy vehicle loading causes significant emission from weld flaws.

Table 1 shows the emission activity at typical field stress levels for both field testing and laboratory testing. The emission activity in the field is described as a percentage of the base average number of emissions occurring along the pipeline. The emission activity in the laboratory is in the form of event count. If the field emission activity from the pressure test is used to determine which emission site is most critical, Specimen 1 or 2, the wrong decision could be made. The emission site corresponding to Specimen 1 had 95 percent of the base average number of emissions occurring along the pipeline, and the emission site corresponding to Specimen 2 had 375 per-

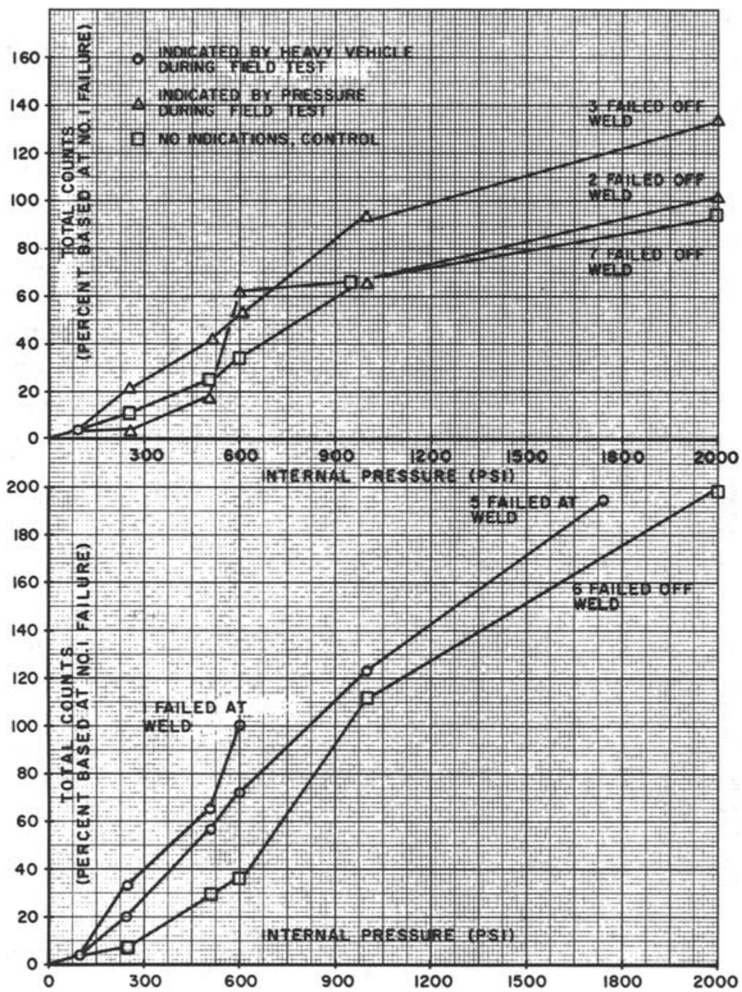


FIG. 13—*Total counts as a function of pressure for specimens from Field Test 4.*

cent. The decision made from the pressure test would be that Specimen 2 is more critical than Specimen 1. However, if the hevy vehicle field data were used, the 810 percent from Specimen 1 would be judged more critical than the 310 percent from Specimen 2 which is in agreement with the failure data. The cause of this discrepancy may be the stress involved. Pressurization creates hoop stresses that tend to be in the same direction as the plane in which the critical flaws lie. Heavy vehicle loading creates stresses perpendicular to the plane in which critical flaws lie.

In additional to the six welds tested hydrostatically, two were tested by bending. The same monitoring equipment with the same sensitivities was used in this portion of the laboratory tests. The pipe section was supported at the two ends and loaded vertically at the weld. The purpose of these tests was to determine the effect of hoop stresses and flexural stresses on the generation of AE's. Table 1 compares the event counts at the field stress level for both types of stress.

The maximum pipe stress recorded in earlier heavy vehicle loading tests was 1000 psi. The magnitude of this flexural stress on a pipe will vary depending upon type of road, depth of pipe, temperature, etc. A flexural stress range of 0 to 1000 psi was applied to Pipes 8 and 9. The pressure range in a pressurization field test is 0 to 100 psi. Therefore, hoop stresses from the pressure range 0 to 100 psi (0 to 1580 psi hoop stress) were applied to Pipes 1, 2, 3, 5, 6, and 7. The advantage for using flexural stresses is obvious from looking at the event count at field stress levels in Table 1. This advantage is confirmed by comparing the field emission activity with the event count obtained in the laboratory tests (at the field stress level). More significantly, these data also show that the AE field activity results can be used to locate weak welds with a high degree of accuracy.

If heavy vehicle loading were to be used in the field, a study of the Kaiser effect would be necessary. The Kaiser effect is the immediately irreversible characteristic of AE phenomenon resulting from an applied stress. The effect results in little or no AE until previously applied stress levels are exceeded. A heavy vehicle can only stress a given point on the pipe once during a run, and this stressing cycle takes place in a short period of time. According to the Kaiser effect, it is only during the first stressing that significant emissions are produced. This is very undesirable since the stressing rate during AE monitoring should be sufficiently slow to allow the detection of sufficient emissions for flaw site location. This procedure allows for a buildup of emission events at a given ΔT location.

There is evidence, however, that despite limitations caused by the Kaiser effect, repetitive heavy vehicle loading continues to cause emissions in weld flaws. The plot of pressure versus emission count rate, Fig. 14 (*bottom*) confirms the Kaiser effect for a line pressure test. This is expected since pressurization allows growth. Figure 14 (*top*), load versus emission count rate, shows that the Kaiser effect does not appear to be valid for a second run of the same bend test. This fact allows the heavy vehicle to repeat its runs over the pipe to allow a buildup of emission events at critical regions. Figures 15*a* and *b* are prints of radiographs of welds found in the field. The weld shown in Fig. 15*a* did not emit during the heavy vehicle field test, but the weld shown in Fig. 15*b* produced emissions with each run of the heavy vehicle loading.

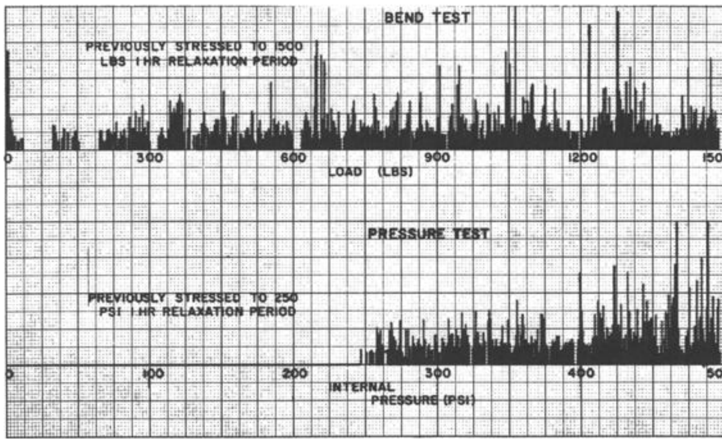
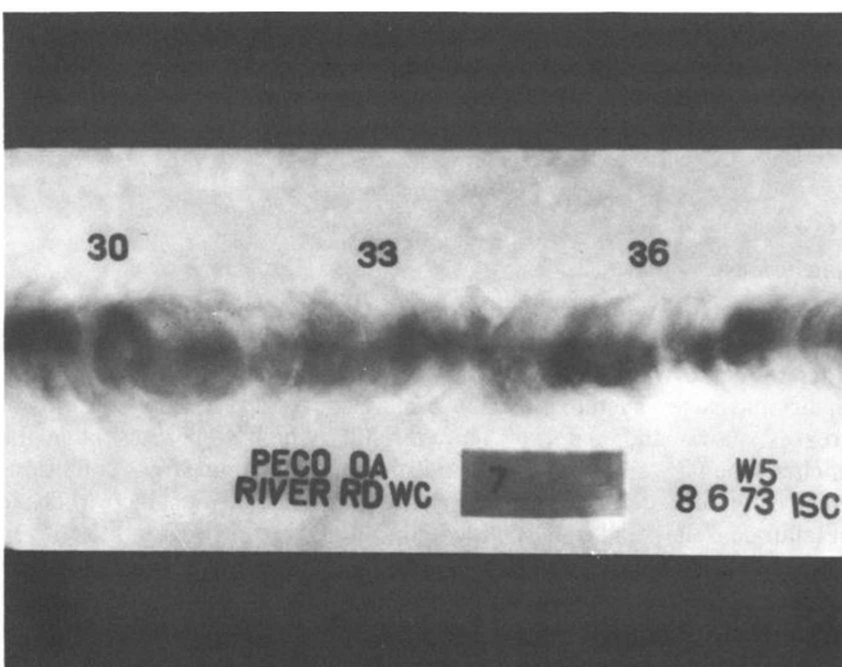
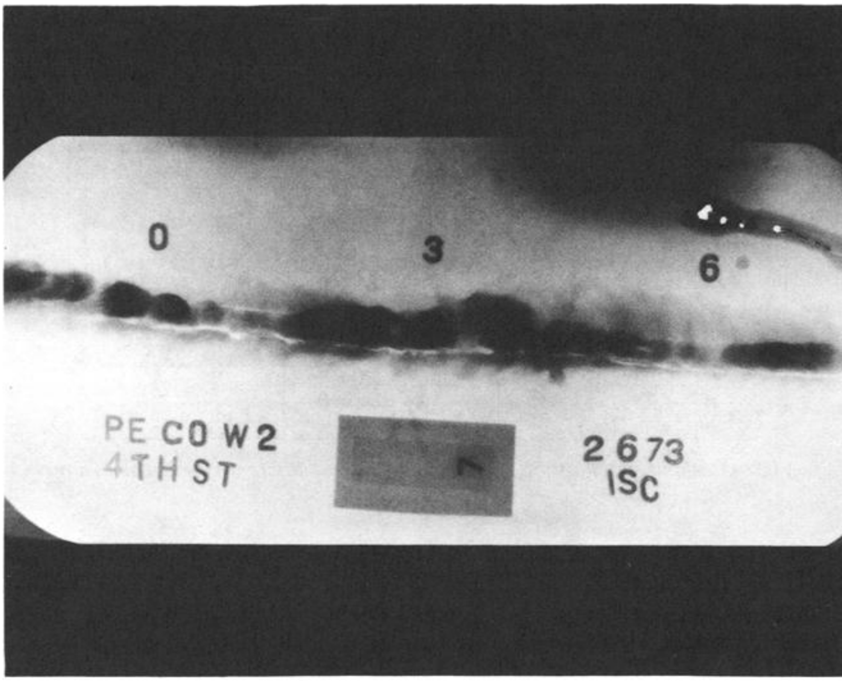


FIG. 14—*Comparison of the Kaiser effect for two different types of stressing.*



(*a*) Sound weld.

FIG. 15—*Prints of radiographs.*



(*b*) Weld containing existing crack as found in the field.

FIG 15—*Continued.*

Conclusions

Several oxyacetylene weld failures have emphasized the need to develop inspection techniques to monitor the welded gas mains on our system in order to locate weld flaws in high-stress regions to permit prompt weld repairs and assure system integrity. Failures occur due to a combination of stresses, flaws, and material characteristics which were present in the pipeline when it was constructed, and static and dynamic stress conditions which occur after construction. It was found that a weld must have a certain metallurgical flaw and must be located in a high-stress region in order to precipitate inservice oxyacetylene weld failure in a pipeline.

AE testing was found to be a feasible technique to locate the flaws, usually existing cracks. Cracks were found to emit more frequently than any other flaw in oxyacetylene welds during field and laboratory tests (Fig. 12). The stressing means preferred in AE field tests is the bending moment caused by the heavy vehicle loading. There may be certain areas where this loading may be impossible; however, pneumatic pressurization can be substituted satisfactorily. By removing the critical flaw located by AE testing, the integrity of the gas distribution system can be reconfirmed.

Acknowledgments

I would like to thank Exxon Nuclear for the field work they performed. I also acknowledge Trodyne and NDT International for the necessary acoustic emission equipment for the laboratory work. I would also like to thank R. W. Whitesel for his assistance and his encouragement to the project.

H. R. Hardy, Jr.[1]

Evaluating the Stability of Geologic Structures Using Acoustic Emission

REFERENCE: Hardy, H. R., Jr., **"Evaluating the Stability of Geologic Structures Using Acoustic Emission,"** *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 80–106.

ABSTRACT: This paper describes the application of acoustic emission to the study of geologic structures. Evaluation of the overall mechanical stability of large-scale geologic structures such as underground and open-pit mines, highway and waterway cuts, petroleum reservoirs, and underground gas storage reservoirs is extremely complex. Acoustic emission appears to be one of the most suitable techniques available for such purposes.

A brief review of the associated literature is presented along with a description of a mobile monitoring facility developed by the writer for field use. Two current field projects, associated with underground gas storage and longwall coal mining, presently underway by the writer are described.

KEY WORDS: acoustics, emission, microseisms, rock mechanics, mining, gas storage, slopes, hydrofracturing, geologic structures, rocks, tests, stability, rock bursts

In the discipline of rock mechanics the major effort relative to the application of acoustic emission (AE)[2] techniques has been associated with field studies on geologic structures, that is, structures composed of, and located in, geologic materials. Unfortunately until recently (circa 1960) results of such studies have been of limited value. An earlier paper by the writer [*1*][3] describes in considerable depth the

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[2] The terms microseismic activity, rock noise, seismo-acoustic activity, subaudible noise, elastic shocks, and micro-earthquake activity are also utilized by workers in various geologically oriented disciplines such as mining, civil engineering, etc.

[3] The italic numbers in brackets refer to the list of references appended to this paper.

general application of acoustic emission techniques in rock mechanics (material behavior, model tests, and field studies) and includes an extensive literature review (some 90 references) on this subject. The present paper will concentrate mainly on acoustic emission field studies carried out since 1965, and in particular those involved in the evaluation of the stability of geologic field structures. The application of AE techniques in the study of such structures will first be briefly reviewed; development of a suitable mobile monitoring facility will then be described, and finally the preliminary results of two current Penn State AE field studies will be discussed.

Review of Acoustic Emission Field Studies

Historically, AE studies associated with geologic materials were initiated in order to evaluate the stability of underground mining operations and as a method for predicting the occurrence of violent underground disturbances such as rock and coal bursts. During the late 1930's and early 1940's Obert and Duvall [*2–6*] showed that, in the laboratory as well as in the field, the AE rate increased greatly as the specimen or structure became more highly loaded. Conversely, as equilibrium was reached, after a structural failure or a reduction in the applied load, the rate decreased. In other words, the AE rate appeared to be a factor indicative of the degree of instability of the structure. With the exception of a few other isolated basic studies, the early work of Obert and Duvall has provided the basis for the majority of the geologically oriented AE field studies carried out in North America. A recent paper by the author [*1*] discusses in some detail a number of the early AE field studies. In this selection a number of the current applications of AE in the evaluation of the stability of geologic structures will be described.

Underground Mining Applications

In the late 1930's and early 1940's government agencies both in the United States and Canada became involved in AE studies related to underground mining. At about the same time similar studies became active in Europe and Asia. These programs were initiated as a result of difficulties experienced in mining at increasing depths or in highly stressed zones, the most spectacular of these being the sudden violent failure of mine structures known as rock bursts [7]. Such studies continued in a relatively routine and uneventful manner until the early 1960's when more sophisticated techniques for monitoring underground AE activity were investigated, and in particular techniques for accurate source location were developed. During this period Cook [*8*] developed a refined monitoring system for use in the Witwatersrand gold mining area. The system was capable of recording the outputs of up to 16 sensors on magnetic tape for a continuous period of 25 h. Normally eight sensors were utilized each being connected into two channels of the recording system, the sensitivities of which differed by a factor of 30. In this way events having a wide range of energies could be recorded. As a preliminary investigation had indicated that a large proportion of the AE energy in the mining area under study occurred in the frequency range 20 to 50 Hz, the frequency response of the overall monitoring system was restricted to approximately 15 to 300 Hz. In terms of monitoring facilities developed more recently, such a system would be termed "narrowband."

In order to determine source locations underground it is necessary to know the velocity of propagation in the associated material. Cook determined this by detonating two or three pounds of explosive at known locations and monitoring the arrival of the resulting stress waves at each of the sensors. Velocities determined in this manner were found to be accurate to within ±5 percent, and it was estimated that the detonation locations could be determined (using the recorded data) to an accuracy of ±10 ft.

The later work of Blake [*9,10*], Blake and Duvall [*11*], and Blake and Leighton [*12,13*] are of particular interest since their monitoring facilities were "wideband" compared to most earlier instrumentation. The system developed by Blake and Leighton [*12*] was designed to have a flat frequency response in the range of 20 to 10 000 Hz. It is interesting to note these authors state that "the frequencies generated by rock noise contain many high-frequency components." In contrast, Cook [*8*] indicated that the majority of the events occurred in the frequency range 20 to 50 Hz. This seeming disagreement is further evidence of our limited appreciation of the overall frequency spectrum involved in acoustic emission phenomena associated with geologic materials.

Blake and Leighton [*12*] utilized commercially available piezoelectric accelerometers as AE sensors. In use these were cemented to the walls of boreholes drilled in various underground locations. The output of each sensor was connected to a preamplifier located in the borehole itself, the signal from which was transmitted by cable to a post amplifier and to one channel of a 7-channel FM magnetic tape recorder located at a central monitoring location. Using an array of at least five sensors, studies have been carried out in a number of hard rock mines. Data recorded on magnetic tape were processed by re-recording it on a multichannel oscillograph to determine a series of travel time differences. These data, along with propagation velocity data obtained in the mine, in a manner similar to that described by Cook earlier, were used to calculate source locations *[13]*. They estimate the accuracy of such locations to be within ±10 ft. Blake and Leighton concluded that, in hard rock mines, broadband monitoring provides much more quantitative information about the behavior of a rock structure than can be obtained using traditional narrowband facilities. It is their opinion that "when used regularly by experienced personnel, it can become a valuable engineering tool in detecting, delineating and estimating the stability of potential failure zones in rock structures."

Although a number of AE studies are underway in Europe, the majority of these have been associated with coal mines. Exceptions are those in Sweden[4] and early studies in East Germany *[14]*.

To date relatively few AE studies have been conducted in North American coal mines partly due to the fact that most active mines are relatively shallow (approximately 500 ft and hence do not suffer from high-stress conditions), and due to the existence of strict laws associated with the use of electrical equipment in such mines. At present however, two coal oriented projects are in progress supported by the U. S. Bureau of Mines. The first is an in-house project[5] underway in a rock burst prone Rocky Mountain coal mine south of Denver, Colorado. Here sections of the mine have been instrumented with velocity sensitive AE sensors (geophones). Monitoring facilities located outside the mine are similar to those used earlier by Blake and Leighton *[12]* in hard rock mine studies with the exception that the system is operated narrowband (90 to 180 Hz). Results to date have been very encouraging in that it has been possible to define in advance potential zones of instability.

The second coal mine project is being carried out by the writer as part of a research project sponsored by the U. S. Bureau of Mines. Studies are underway in a longwall coal mine in central Pennsylvania to investigate the feasibility of using AE techniques to locate potential zones of instability around coal mine workings. This field study involves monitoring the AE generated by working mines during their normal operation using surface sensors located in shallow boreholes positioned over the working area of the mine. This study is unique in the fact that measurements are made from the surface rather than underground. This approach provides several advantages, including the fact that there are no electrical limitations on the monitoring system, and that the study will in no way interfere with normal mine operations. A more detailed discussion on this project is included later in this paper.

[4] H. Helfrich, Terratest AB, Bromma, Sweden, personal communication.
[5] F. Leighton, U. S. Bureau of Mines, Denver, Colo., personal communication.

In contrast to most North American coal mines, many European coal mines are relatively deep (approximately 2000 ft) and therefore suffer from high stress conditions, and in many cases frequent rock bursts. At present extensive underground AE studies are underway in Poland [*15–20*], Czechoslovakia [*21*], and Russia [*22*]. Limited underground AE studies are underway in West Germany [*23*]; however, an extensive study of coal mine rock bursts in the southern Ruhr valley (Bochum area) is presently underway at the Ruhr University[6] using surface mounted transducers. When completed, their system will involve a three station array with distances between stations of the order of miles. Each station contains displacement sensors mounted in three orthogonal directions. Sensors, with resonant frequencies of the order of 2 Hz, are utilized and AE events are recorded on magnetic tape at each station. Arrangements for a radio or telephone data link between stations is presently under consideration.

Surface Mining Applications

In the last few years research in the field of slope stability associated with open pit mining has increased rapidly. AE techniques appear to provide a useful tool for monitoring slope stability, and research by the U. S. Bureau of Mines has contributed a great deal to the development of this technique. The design and installation of AE monitoring equipment for slope stability studies presents a number of unique problems which are discussed by Broadbent and Armstrong in a recent paper [*24*].

Paulsen et al [*25*] have utilized AE techniques to study slope stability in an open-pit mine at Boron, California. They sum up the situation by stating that a plot of the AE with time provides a graphic picture of what is going on in the Boron open-pit. An increase in activity over and above the normal background probably indicates that a potential slope stability problem exists. A decrease in activity indicates stabilization may be being achieved, whereas an accelerating activity rate indicates failure may be imminent.

During a recent study at Kennecott's Kimbley pit, near Ruth, Nevada, extensive AE studies were undertaken as part of the routine monitoring of the pit slope stability during slope steepening [*26*]. In this study AE sensors were installed inside two adits (horizontal shafts) driven into the pit wall, as well as in the pit wall itself. Cables from these were connected to a mobile monitoring facility located on the surface behind the pit slope. Due to the high ambient noise generated by the mining operation itself, measurements were restricted to the

[6] H. Baule and A Cete, Geophysics Institute, Ruhr University, Bochum, Germany, personal communication.

times between shifts and on weekends when mining facilities were inactive. During the Kimbley study the pit slope was steepened from about 45 to about 60 deg. Although the new slope was considered to be a stable one, AE studies were included in the test program as a safety measure as well as to investigate the correlation, if any, with slope angle. During slope steepening, changes in AE rate were erratic but appeared to be related to the development of temporary stress concentrations occurring during mining. Following completion of the 60-deg slope the AE rate dropped to a low value indicating the new slope configuration was stable.

Petroleum and Natural Gas Applications

AE has wide field application in the petroleum and natural gas industry. The study of hydrofracturing being one application of considerable importance. Here fluids are injected under pressure into low permeability strata with the purpose of fracturing these strata, and increasing their permeability and porosity. Such techniques are commonly used to stimulate a poorly producing oil or gas well or to increase the capacity of an underground gas storage area. Aside from information obtained from surface monitoring of injection pressure and volume, observation well measurements, and examination of rock core drilled after the hydrofracturing, little is really known in regard to the fracturing process that is going on perhaps 5000 to 10 000 ft below surface. A number of workers are giving consideration to the utilization of AE techniques to monitor the initiation and propagation of underground fractures associated with hydrofracturing. For example, studies presently underway by Overbey and Pasini[7] are concerned with the development of techniques for determining the location and orientation of underground fractures developed during hydrofracturing.

At present the writer is directing a project [27] which involves the use of AE techniques to study the stability of underground gas storage reservoirs (basically zones of porous rock surrounded by impermeable cap rock). This project is supported by the Pipeline Research Committee of the American Gas Association, and will be discussed in detail later in this paper. Additional studies are also under consideration in which the stability of large cavities located in salt, and commonly utilized for storage of pressurized gases, will be investigated using similar techniques.

Civil Engineering Applications

AE techniques appear to be gaining increased attention in civil engineering oriented projects. For example one of the earlier applications

[7] W. K. Overbey and J. Pasini III, U. S. Bureau of Mines, Morgantown, W. Va., personal communication.

of this technique was that of Crandell [*28*] who employed it as a safety monitor for use in tunneling projects. More recently Beard [*29*] lists a number of tunneling projects where simple AE monitoring devices have been used with great success. Consideration has been given to using the technique for investigating leakage of water reservoirs and the stability of earth filled dams.[8]

Cadman et al [*30*] describe an automated monitoring system for studying landslides. Goodman and Blake [*31–33*] have investigated slope stability associated with potential landslide areas and unstable highway cuts. They determined that there was a definite correlation between the estimated state of slope stability and the observed AE rate. They also noted that no AE's were observed in rock cliffs and steep rock cuts subjected to frequent rock falls. According to Goodman and Blake [*33*], the observed activity in soft landslide materials was found to be in the audio frequency range and appeared to originate within a distance of 100 ft from the AE transducer. Furthermore their studies indicated that the source of AE events could be located in rockslide areas, but such location was not practical in soft landslide areas, due to the extreme attenuation of high-frequency signals and spatial variation of propagation velocity inherent in such materials.

Other civil engineering problems such as those associated with the underground disposal of radioactive wastes, acid mine water, and other undesirable liquids by injection into deep boreholes (drilled to depths well below the water table) may well be investigated using AE techniques.

Other Applications

In recent years geophysicists concerned with the prediction and causes of earthquakes have become increasingly interested in the study of AE [*34,35*], since it is felt that the background pattern of AE may provide important information relative to future earthquakes.

Consideration has also been given recently to the use of AE techniques in a variety of other geologically oriented applications including investigation of the stability of glaciers, snow avalanche warning systems, flame front location in underground coal gasification studies, and stability of underground compressed air storage facilities.

Penn State Research Program

Since 1970 the Rock Mechanics Laboratory at The Pennsylvania State University has been involved in AE studies associated with the

[8] R. M. Koerner and A. E. Lord, Drexel University, Philadelphia, Pa., personal comminication.

evaluation of stability in geologic structures. To date the major field effort has been concentrated on two projects, namely:

1. Study of underground gas storage reservoirs, with the purpose of developing techniques for evaluation of the mechanical stability of such structures as a function of storage pressure and duration.

2. Study of the feasibility of using surface mounted AE sensors for investigating the mechanical stability of underground coal mines.

Both projects are related directly to the economics and safety interests of the gas and coal industry, and as such are particularly appropriate in light of the current energy shortage.

Before discussing these projects and the associated instrumentation it is important to briefly consider the frequency spectrum of anticipated AE from large geologic structures. The writer has shown in an earlier paper [*1*] that when dealing with geologic materials AE's in the frequency range of at least 10 Hz to 500 kHz have been observed; however, as the distance from the AE source to the point of detection increases, this range decreases dramatically. The dominant frequency spectra depends of course on the overall sensitivity of the monitoring system, and the attenuation characteristics of the media; however, field studies by other workers suggest that for distances on the order of a few thousand feet relatively little energy would be expected in the frequency range above 10 kHz. However, the monitoring system developed at Penn State was designed to cover a wider range, making it possible to initially scan the overall frequency range in order to select the most suitable frequency band for final measurements.

Monitoring Facilities

In order to carry out field studies at gas storage and coal mine sites, it has been necessary to develop a suitable mobile monitoring facility. Figure 1 illustrates a block diagram of this facility. The electronic system is housed in a large air conditioned camper van and has been designed to operate from 110 VAC line voltage, an associated motor generator, or a d-c battery supply. The battery supply and motor generator are located in a small trailer unit; the monitoring system, therefore, can be operated completely independent of commercial power, and studies may be carried out in remote locations.

The monitoring system has facilities for simultaneously recording the output of 14 AE sensors (*S*). During recording, the output of each sensor is amplified by a preamplifier (*PR*) followed by a post amplifier (*A*). The resulting signal then passes through a filter unit (*F*) and to one channel of the tape recorder. The tape recorder has been equipped with both direct and FM electronics so that signals from dc to 600 kHz may

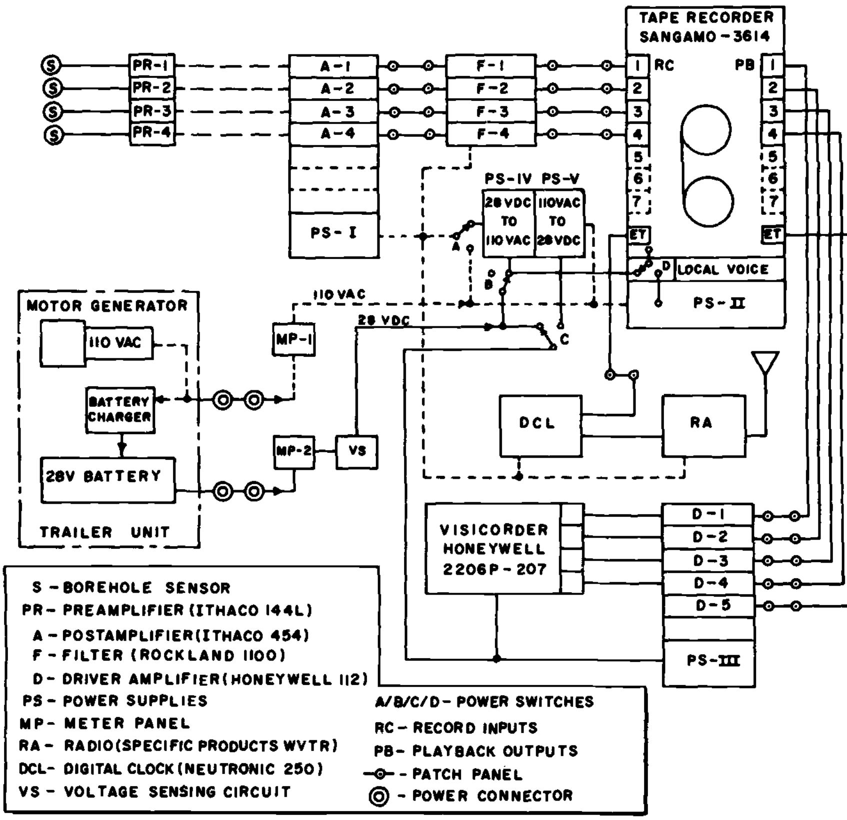


FIG. 1—*Block diagram of Penn State acoustic emission field monitoring facility.*

be recorded and played back if necessary. It should be noted that in most studies, however, filters have been set to reject frequencies above 10 kHz. In recent tests this limit has been reduced to 2.5 kHz and lower.

The facility was designed to monitor and record field data for later detailed analysis; however, a visicorder-type ultraviolet recorder has been incorporated in the facility to provide visual display and preliminary analysis of data in the field. A timing unit, standardized against the U. S. Bureau of Standards radio station WWV, is also included in the monitoring system. This unit provides continuous coded time signals to one channel of the tape recorder so that the time of occurrence of all AE events will be accurately known.

Figure 2 shows an overall view of the monitoring facility. The main electronics are mounted in an antivibration rack, as shown in Fig. 3,

FIG. 2—*Mobile monitoring facility.*

located in the van. The preamplifier units are normally located close to the sensors. Considerable effort was expended to develop a highly reliable facility. Since an initial two to three month break-in period, during which a number of refinements were introduced, the facility has been essentially trouble-free. A detailed report describing the design and development of the mobile monitoring facility is available [*36*].

Sensors and Installation Techniques

Figure 4 illustrates various methods investigated for mounting AE sensors at different field sites. During early studies at gas storage sites sensors were attached directly to wellhead facilities. Results from these studies were inconclusive, and further investigation of this potentially useful and inexpensive technique is planned for the future. In general surface mounting of sensors is the least satisfactory due to the high attenuation of the surface media (usually soil). Type D installation utilizing a borehole probe has proven to be the most successful; however, it is unfortunately also very expensive. Type B installation in which sensors are buried in shallow holes has had limited success; however, a modification of this installation, Type C, in which sensors are cemented at the bottom of 15 to 20-ft-deep boreholes drilled through the soil into bedrock, has proved more satisfactory.

At present, two basic types of sensors are utilized—geophones[9] (velocity gages) and accelerometers.[10] The latter are utilized in the

[9] Geospace Type GSC-11D (Marsh Case), Model M-4, resonant frequency: 14.0 ± 0.5 Hz, frequency response: 30 to 3000 Hz (relatively flat).

[10] Endevco, Model 2219E, mounted resonant frequency: 16 000 Hz ± 10 percent, frequency response (±2 percent): 2 to 3000 Hz.

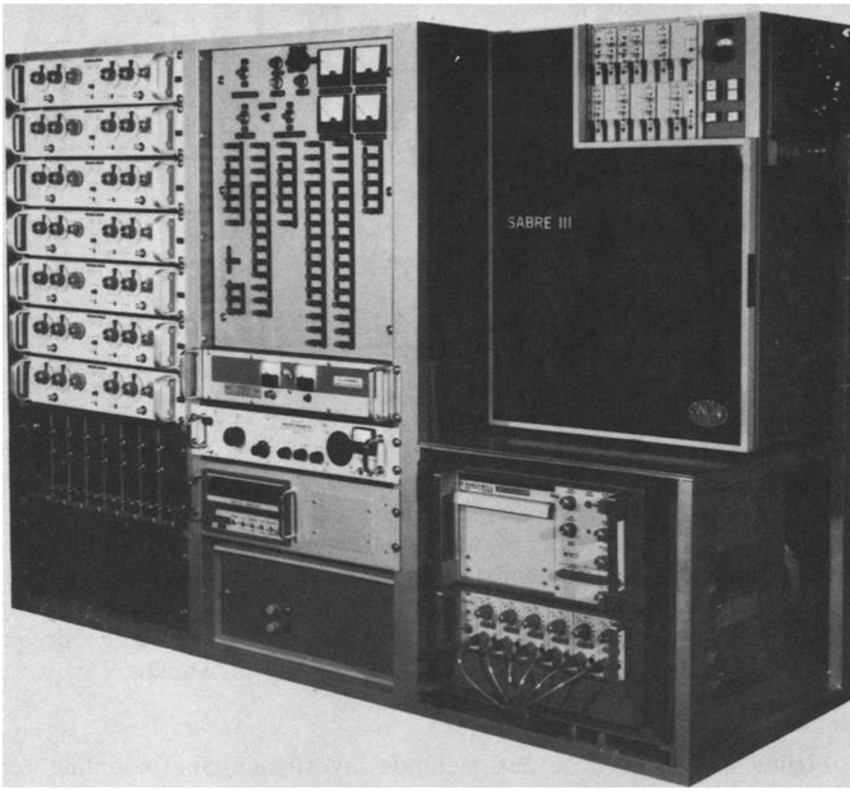


FIG. 3—*Overall view of monitoring electronics.*

borehole probe and were used early in the gas storage study directly on the wellhead surface facilities. Geophones are utilized in all installations where sensors are buried or cemented in holes. Figure 5 shows a typical geophone unit mounted in a waterproof marsh-type case. These units have been extremely reliable and a number mounted permanently in extremely wet ground have preformed reliably now for a period of over one year.

Figure 6 illustrates the principle of the borehole probe. It contains a rubber-walled inflation chamber which can be expanded by externally applied gas pressure. An AE sensor (accelerometer) located inside the chamber is bolted through the rubber wall to a sensor shoe on the outside surface. In use, the probe is located at the desired location in the test borehole and then pressurized. This forces the sensor shoe tightly against the borehole wall, effectively clamping the attached accelerometer in position. The borehole probe has been used with great

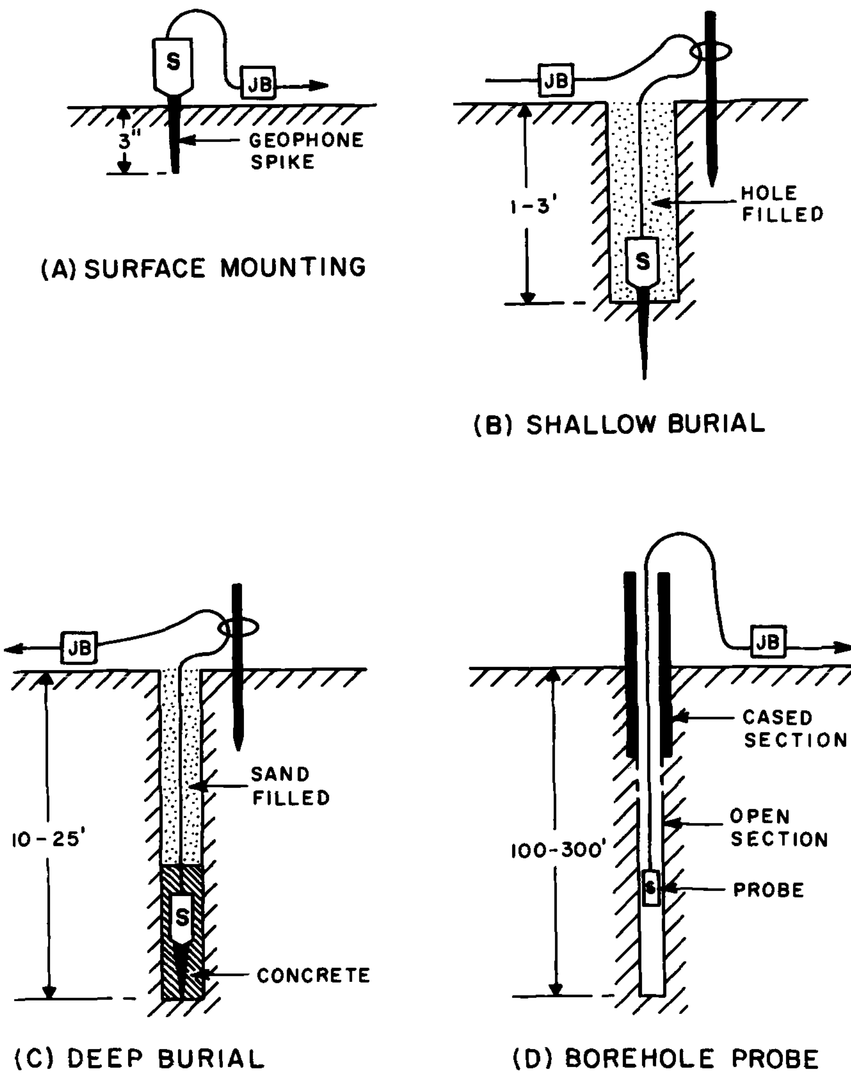


FIG. 4—*Various methods of mounting acoustic emission sensors at field sites* (S = *sensor,* PA = *preamplifier, and* JB = *junction box*).

success at a number of locations, including one test site where it was used at the bottom of a 300-ft borehole containing 150 ft or more of water. In recent installations a support rod, attached to the lower end of the probe (see Fig. 6) and bearing on the bottom of the borehole, has been utilized to support the probe. This arrangement eliminates any tendency for the probe to slip vertically in the hole after pressurization.

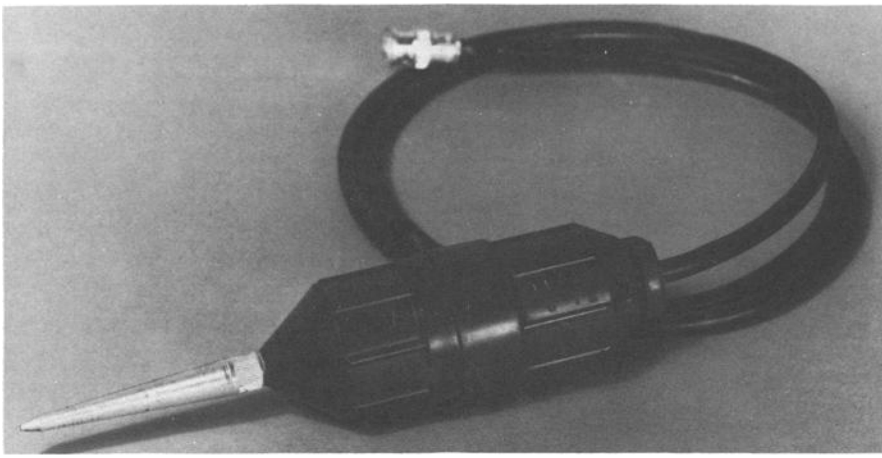


FIG. 5—*Typical geophone (velocity gage) installed in marsh-type case.*

Figure 7 shows two views of the Mark II model borehole probe developed for use in BX (2 ⅜ in. diameter) diamond drillholes.

Analysis Techniques

As has been noted earlier the prime purpose of the mobile monitoring facility is to record field data for later analysis. To date the majority of such analysis has been done "manually." Figures 8*a* and *b* illustrate the system used. Initial editing of the field data is carried out as shown in Fig. 8*a*. Here data recorded on Tape Recorder 1 in the field are played back through amplifiers and filters into either an ultraviolet recorder, Tape Recorder 2 or both. Such play-back may be accomplished for up to seven channels simultaneously. The ultraviolet recorder provides permanent chart records (hard copy) of the field data which may be examined for the presence of specific types of AE events or in order to study ambient background characteristics. At this stage in the analysis the tape fottage of each feature of interest is logged for future reference. Normally when operating directly into the ultraviolet recorder the replay tape speed is increased considerably over the original recording speed in order to compress the recording in time and thus provide a convenient length of hard copy. When a set of AE events of particular interest are noted on the hard copy then the appropriate sections of tape are replayed at different speeds and at various filter settings in order to study these events in more detail. For example, this arrangement has been utilized to carry out simple frequency analysis of specific signals by replaying these for a number of filter settings and

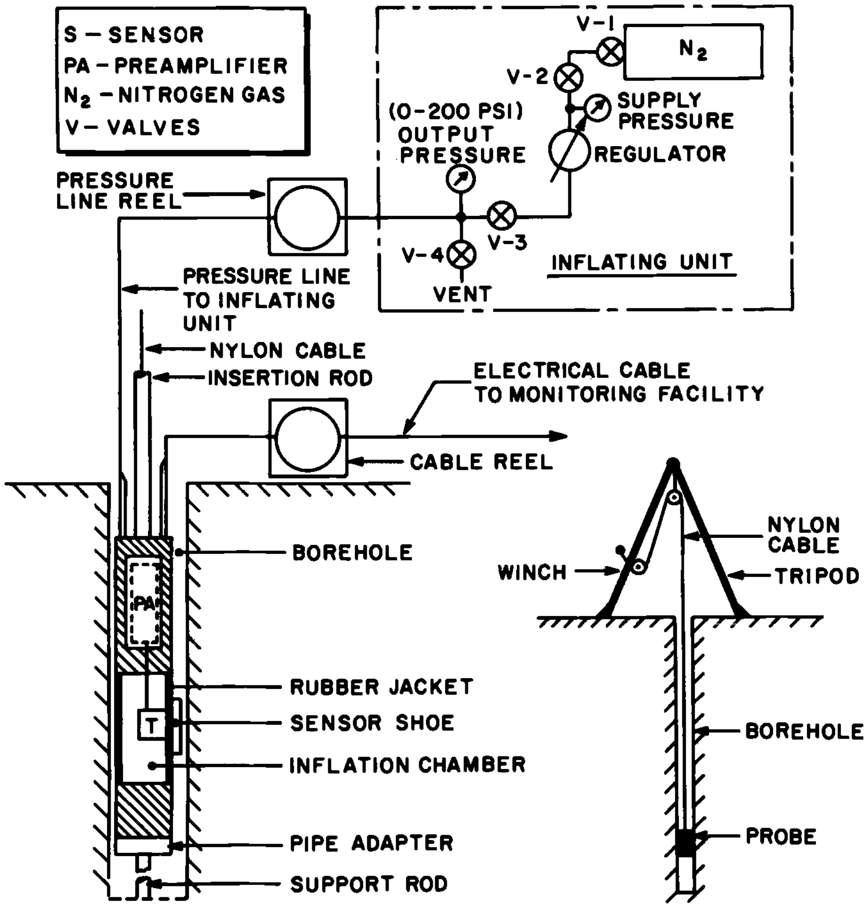


FIG. 6—*Principle of operation and installation of acoustic emission probe.*

measuring the change in amplitude of the signal on the ultraviolet recordings.

The circuit in Fig. 8*a* also provides a convenient means of actually "editing" the original field data so that only specific sections are re-recorded on Tape Recorder 2 for further anlysis. For example sections of data containing signals due to known culteral noise (for example, trucks and cars, mine machinery, electrical transients, etc.) may be eliminated. Such editing is a prerequisite for later manual or computer analysis.

For more detailed analysis of field data the system illustrated in Fig. 8*b* is employed. Here field data re-recorded on Tape Recorder 2 during

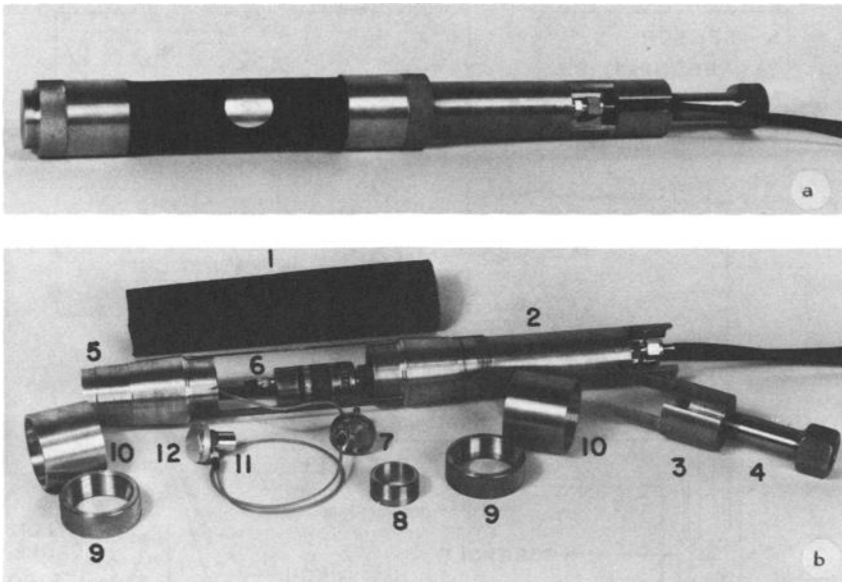
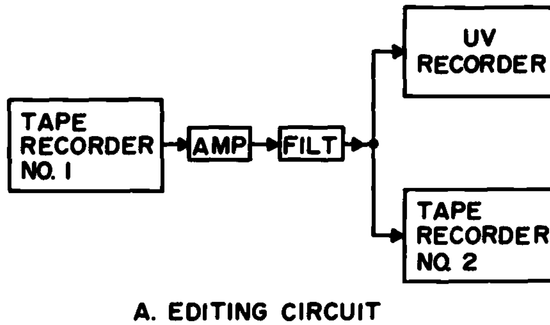
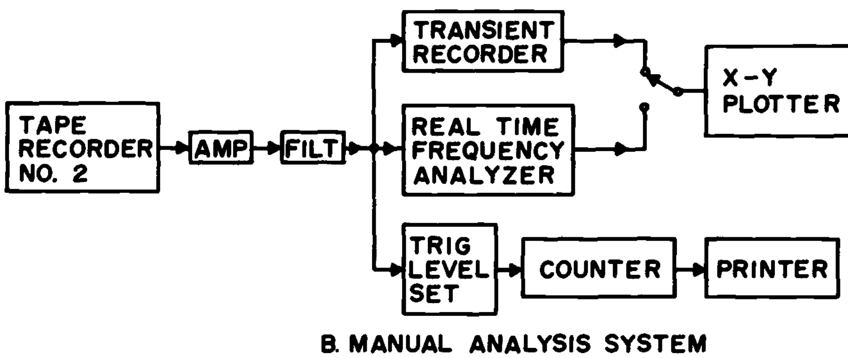


FIG. 7—*Mark II model acoustic emission borehole probe (support rod and associated adapter not shown).* (*a*) Probe assembled ready for use. (*b*) Borehole probe dissembled showing component parts (1 = rubber bladder, 2 = probe body, 3 = connecting rod yoke, 4 = pipe adaptor, 5 = probe end section, 6 = preamplifier, 7 = plug, 8 = plug nut, 9 = bladder clamp nut, 10 = bladder sleeve, 11 = accelerometer, and 12 = sensor shoe).

editing may be analyzed by a variety of techniques. It should be noted that until recently (when Tape Recorder 2 was acquired) the output of Tape Recorder 1 was played directly into the analysis system without prior editing. The manual analysis system incorporates the following: (*a*) a transient recorder, so that selected AE signals may be "captured" and recorded on the *x-y* plotter; (*b*) a real-time frequency analyzer, so that either individual AE signals, groups of such signals, or ambient background signals may be analyzed for frequency content and the resulting frequency spectra recorded on the *x-y* plotter; and (*c*) a digital counter and associated printer, so that the total number of acoustic events above a specific magnitude (defined by trig level set), or the rate of occurrence of such events during a specific interval may be recorded. It should be noted that the manual analysis system allows only one channel of data to be processed at a time.

At present a computer based analysis system, utilizing the Penn State Hybrid computer facility, is under development. A simple block diagram of this system is shown in Fig. 8*c*. Here edited field data (7 channels) is played directly into the analog section of the computer,





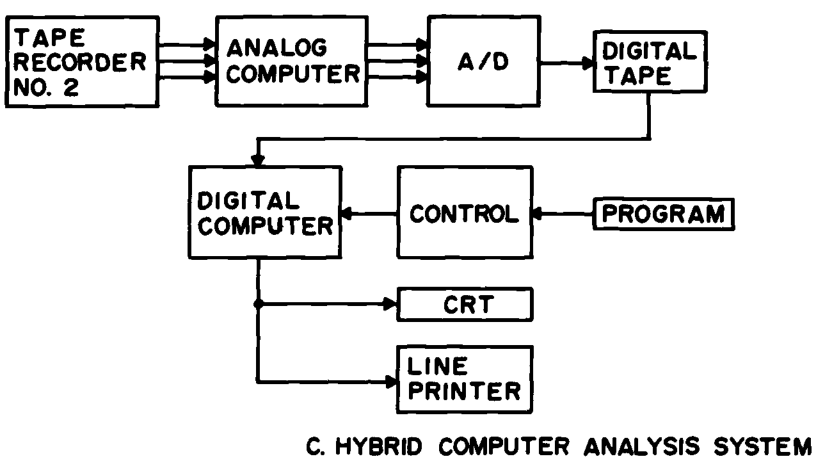


FIG. 8—*Block diagrams of data analysis systems.*

analog processing (if necessary) is carried out, and the resulting signals are digitized and placed on digital tape within the computer. This digitized data may then be processed in a variety of ways, and the results displayed on a cathode ray tube (CRT), line printer, or other output device. To date, programs for interfacing the field data to the system, and for frequency analysis of selected sections of data have been developed and "de-bugged." At present a program for amplitude distribution analysis is under development.

Underground Gas Storage Project

Since 1966, a continuing research program, supported by the American Gas Association (AGA), has been underway by the Rock Mechanics Laboratory at Penn State. This program is concerned with the optimization of pressures in underground gas storage reservoirs, namely, development of analytical and experimental techniques for evaluating the mechanical stability of such structures. Prior to 1970, this program mainly involved analytical and laboratory model studies. AE techniques were employed first in the laboratory studies in order to define initial and ultimate failure of the test models. For this purpose sensors, consisting of semiconductor strain gages bonded to small brass plates, were attached to the models prior to jacketing and testing under triaxial loading conditions. Details of the laboratory test procedures and results obtained have been described in a number of recent papers [*27,37-40*].

Field oriented studies in which the feasbility of using AE techniques to monitor the stability of full-scale underground gas storage reservoirs were initiated in 1970. Field measurements were first carried out in the summer of 1972 at a gas storage reservoir in northern Pennsylvania. These have continued along with field studies initiated at a northern Michigan storage site in the spring of 1973. Figure 9 illustrates diagrammatically an instrumented gas storage field site. Here, a number of AE sensors installed in boreholes and shallow surface holes are used to monitor acoustic activity in the storage reservoir area. By suitable analysis of the AE data, it is hoped to determine: (*a*) degree of overall reservoir stability and (*b*) location and intensity of any major sources of instability. The areal extent and depth of most reservoirs, as well as the intrinsic AE background level, introduce a number of experimental difficulties. Many of the studies carried out to date have been associated with the development and modification of experimental techniques to overcome these difficulties and ensure that meaningful field data are obtained.

Since the summer of 1973 an extensive study has been underway at

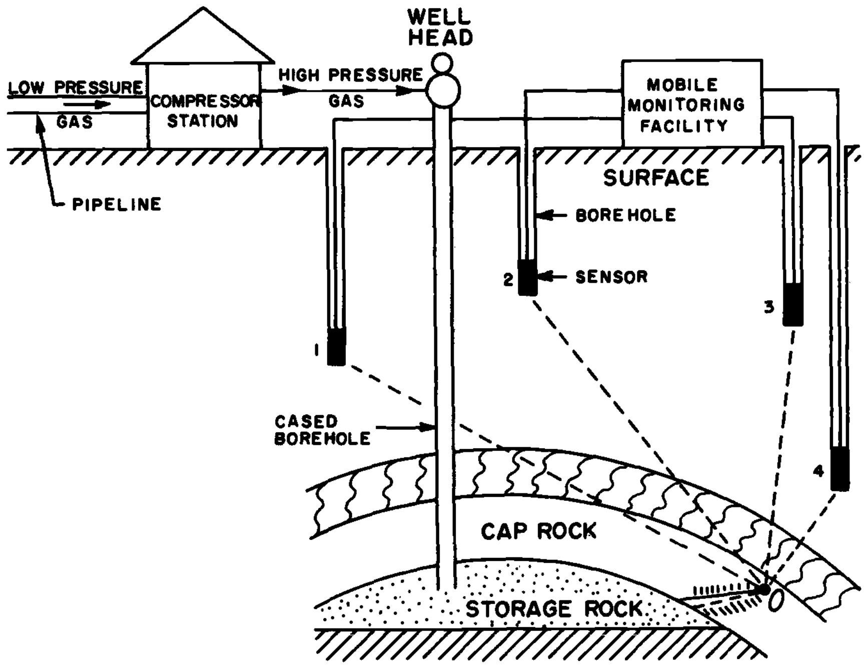


FIG. 9—*Instrumented gas storage field site.*

the Michigan field site. During this study, AE signals were detected by a borehole probe, shallow burial geophones, and geophones cemented into boreholes drilled 20 ft deep into bed rock. The monitoring facilities and techniques described earlier in this section were utilized. The main object of these studies was to study in detail the signals originating from the reservoir while it was being pressurized to full capacity. Injection was carried out over a two week period in September. During the injection period, AE measurements were made at some 20 test periods ranging from 25 to 165 min in length; following this, measurements were made at intervals of one week and three weeks. Such measurements will continue at intervals of approximately one month through the spring of 1974.

To date, only very preliminary analysis has been carried out on the recent Michigan data; however, a number of low frequency AE signals were positively identified. Figure 10 illustrates the expanded form of one such signal, monitored by the borehole probe located at a depth of approximately 300 ft, showing both *P*- and *S*-wave components. The low frequency character of the signal (approximately 20 Hz) is evident from the figure. Considering only data monitored by the borehole

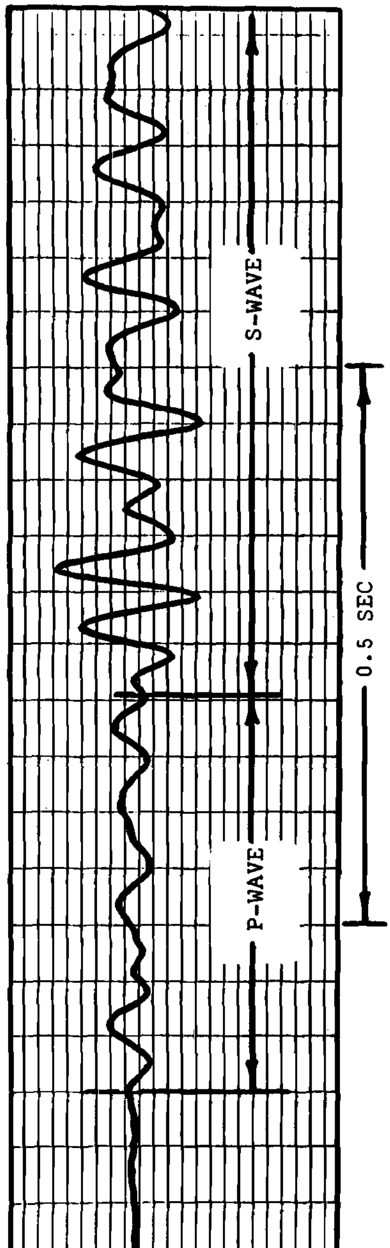


FIG. 10—*Typical low frequency acoustic emission signal detected at the Michigan gas storage site (recorded using an accelerometer in a borehole probe and monitoring system bandwidth of 0 to 2.5 kHz).*

probe, it is estimated that, at the relatively low resolution used in the preliminary analysis, background activity was of the order of 5 to 6 events per hour. Following major increases in wellhead pressure, particularly at pressure levels of the order of 1000 psi, AE rates were found to jump to as high as 50 events per hour. When the reservoir pressure became stable either after a pressure rise or drop, the AE rate fell to a value close to original background level (approximately 5 to 6 events per hour). More detailed analysis of these data will be carried out during the next few months.

In general, the field studies carried out to date (particularly those at the Michigan test site) indicate that detectable AE signals are generated from pressurized underground gas storage reservoirs. Those signals positively identified have been of relatively low frequency ($\simeq$20 Hz) which is realistic when it is considered that transducer to reservoir distances are on the order of a few thousand feet. The major problem in the analysis of field data is associated with the presence of a strong background noise level.

Longwall Coal Mine Project

Since 1970, a detailed field program, supported by the U. S. Bureau of Mines, associated with the measurement of AE generated by longwall coal mining operations has been underway by the Penn State Rock Mechanics Laboratory. The monitoring facilities described earlier in this section have been employed. Figure 11 illustrates the sensor

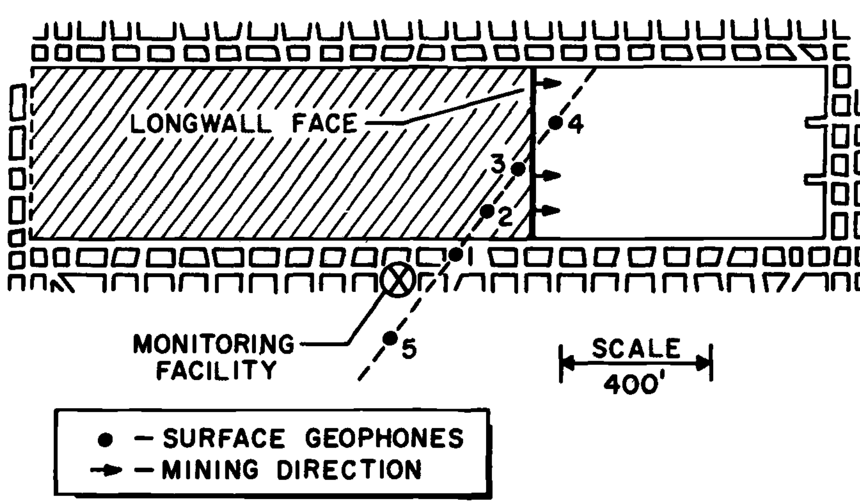


FIG. 11—*Sensor array over a longwall coal mine in central Pennsylvania (distances between transducers 1 to 4 are approximately 125 ft).*

array utilized in a recent study over a central Pennsylvania coal mine. In this figure the crosshatched section is the mined area, and the position of the longwall (area being mined) is shown by the heavy line. A variety of sensor installations, similar to those discussed earlier (see Fig. 4), have been employed during the coal mine project; however, in the study illustrated here, only surface mounted geophones (see Fig. 4*a*) were used. Figure 12 illustrates AE signals detected by the five sensors during a selected 60 s period. It is interesting to note that Sensors 2 and 3 are directly over the area being mined and exhibit maximum activity; Sensor 4 is over the unmined area (solid coal); Sensor 1 is over the edge of the mining area. Sensor 5 is approximately

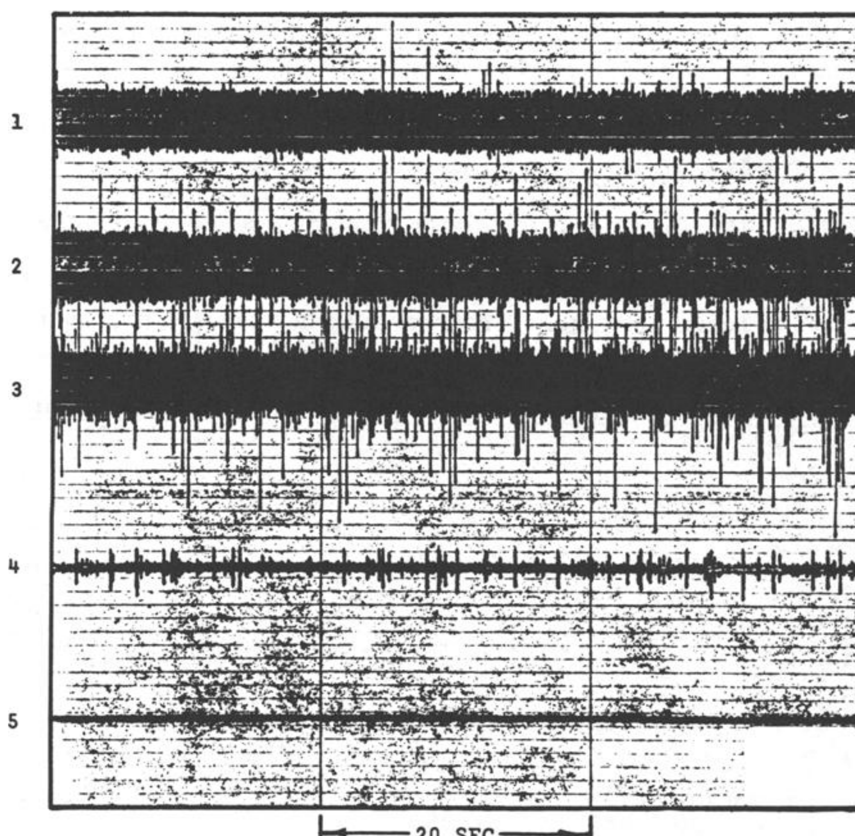


FIG. 12—*Acoustic emission signals detected during a 60 s period over a longwall coal mine (recorded using geophones (velocity gages) and monitoring system bandwidth 0 to 2.5 kHz).*

300 ft from the mining area, over a development area mined considerably earlier, and exhibits minimum activity.

During these measurments, filter limits in the monitoring system were set at 0 to 2.5 kHz. Figure 13 illustrates a number of typical AE signals detected during a 2 h monitoring period. In Fig. 13*a* the near coincidence of events *M*, *N*, and *O* indicate that they are a result of the

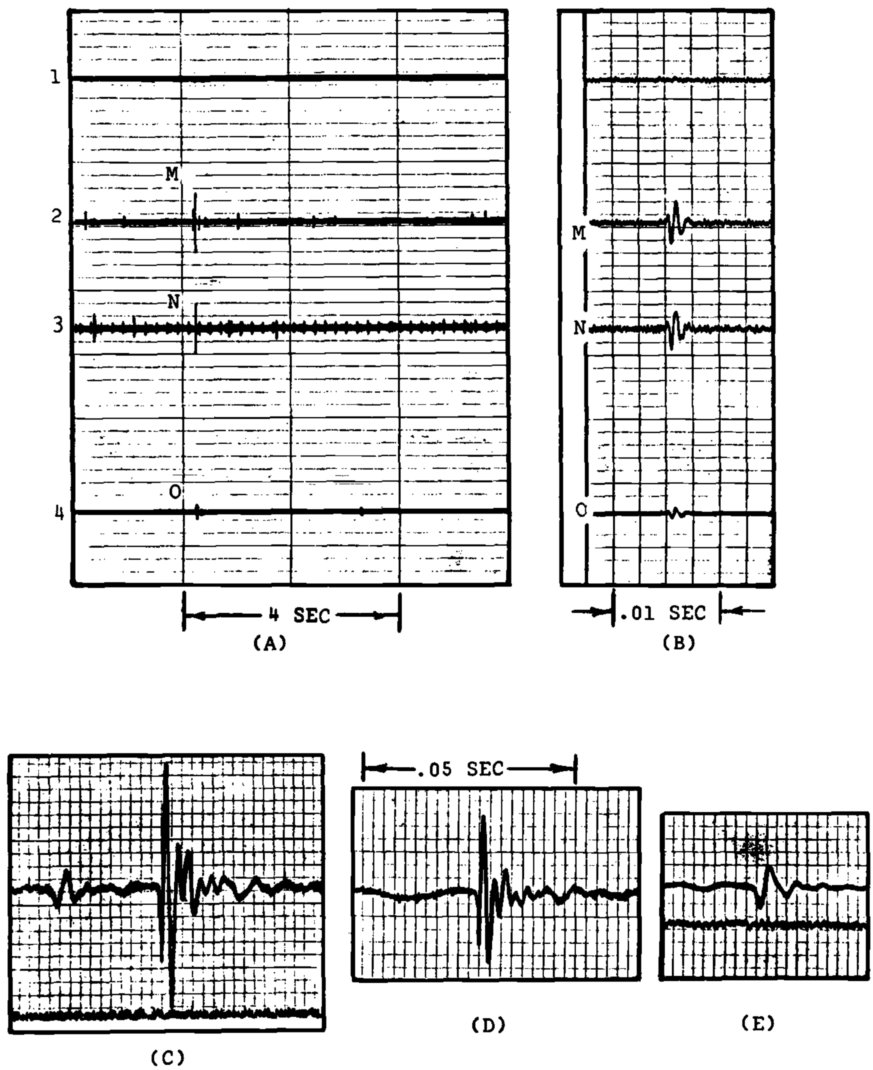


FIG. 13—*Typical acoustic emission signals observed over a longwall coal mine (recorded using geophones (velocity gages) and monitoring system bandwidth 0 to 2.5 kHz).*

same underground instability. Figure 13*b* shows the same events with data played back at a slower tape speed in order to display the detailed character of the signals. Figures 13*c*, *d*, and *e* illustrate a number of other typical AE signals observed during the study.

A simple frequency analysis study (as described earlier under "analysis techniques") was carried out on a number of AE signals and on sections of typical background. Results of this study are shown in Fig. 14. It is apparent that the background covers a wide frequency range. In contrast however, typical AE events have their major energy in the range 160 to 560 Hz with a pronounced peak around 320 Hz.

Magnetic tapes containing the field data from the study were also processed using sections of the manual analysis system shown in Fig. 8*b*. In particular, the number of signals on each monitoring channel having amplitudes well above the general background (defined by trigger level set) were counted and recorded on a digital printer. This analysis was carried out for a series of 10 min intervals over the total test period. The results are shown graphically in Fig. 15. The fact that

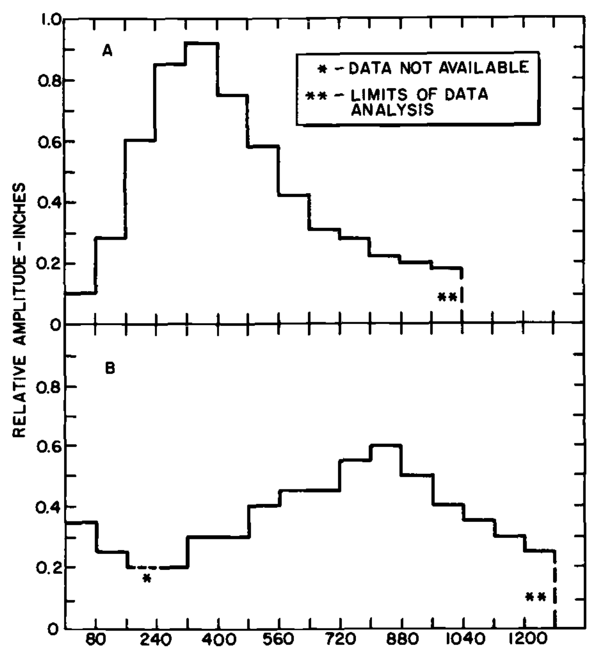


FIG. 14—*Frequency spectra of typical acoustic emission signal* (A) *and background* (B).

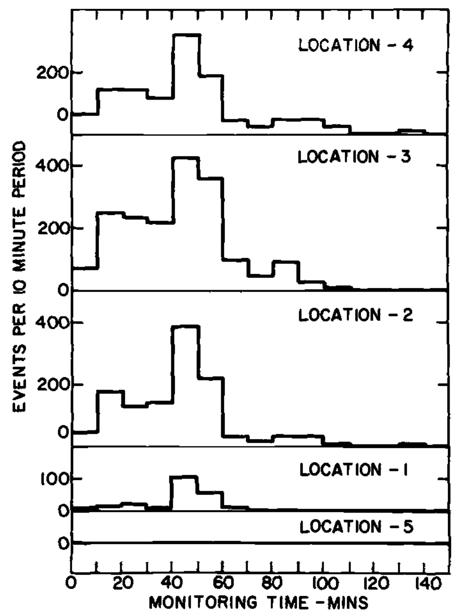


FIG. 15—*Rate of acoustic emission activity at different sensor locations during test period.*

the major AE activity occurs at Locations 2, 3, and 4, immediately over the mine workings, is further evidence that it is directly associated with mining. There is no positive explanation for the pronounced peaks which occur at approximately 50 min. They are probably associated with mining operations; however, no underground observations were made during the study.

AE studies associated with longwall coal mining are continuing. To date, measurements at the mine site have been carried out at four different locations. A detailed analysis of the data is presently underway.

Discussion

This paper has reviewed the use of AE as a tool for evaluating the stability of geologic structures. Studies by a number of workers have indicated that this technique has wide potential application in the fields of mining, petroleum and natural gas, and civil engineering. The development, by the writer, of a mobile AE monitoring facility has been described, and its application to studies of underground gas storage reservoirs, and longwall coal mines has been discussed.

At present a number of factors limit the usefulness of AE in such applications, namely:

1. Difficulty in separating AE signals from ambient background noise.

2. Inability in most geologic structures to obtain an equivalent unloaded condition.

3. Large dimensions of most geologic structures and resulting attenuation (usually highly frequency dependent) of signals with distance from source.

4. Electrical and mechanical difficulties in instrumenting such structures.

5. Difficulty in source location due to anisotropic propagation velocity characteristics of geologic materials.

In spite of these limitations, AE has proven increasingly useful in such applications in recent years. With the development of better monitoring facilities, improved transducers and field installation techniques, and development of computer based analysis methods, the successful application of AE techniques to geologic structures should increase manyfold.

Acknowledgments

The major financial support for the field studies conducted at Penn State described in this paper has been provided by the Pipeline Research Committee of the American Gas Association (Project PR-12-43), and the U. S. Bureau of Mines (Projects G0101743 and G0144013).

Development of the mobile facility for field monitoring and AE was supported jointly by the American Gas Association and the U. S. Bureau of Mines. Assistance in construction of the facility provided by members of the Penn State College of Earth and Mineral Sciences MI Shop is greatly appreciated.

The author would also like to express his thanks for the assistance provided by other members of the Mineral Engineering Department at Penn State, in particular, Dr. A. W. Khair and Dr. R. Y. Kim, research associates; E. Kimble, research aide; and W. Comeau, M. Gopwani, G. Mowrey, and L. Beck, graduate assistants.

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P. H. Hutton[1]

Acceptance Testing Welded Ammunition Belt Links Using Acoustic Emission

REFERENCE: Hutton, P. H., "**Acceptance Testing Welded Ammunition Belt Links Using Acoustic Emission,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 107–121.

ABSTRACT: The objective of the work described in this paper was to provide a reliable method for 100 percent acceptance testing resistance welds used in the fabrication of 40-mm automatic weapon ammunition belt links. Links contain rounds of ammunition and are coupled together to form a belt which is automatically fed into the weapon. If one of the links in a belt fails, the immediate result is a jammed weapon. Four projection resistance welds (two on each side) are used to assemble the link, and weld quality can vary widely. Conventional nondestructive test techniques cannot distinguish a sound resistance weld from a weak one in the post-weld condition. This work has shown, however, that by applying a moderate proof load to the weld joint, weak welds can be detected by acoustic emission. The technique is being adapted to production application with an expected inspection rate of 1200 links per hour in its initial version. This work is representative of many applications of acoustic emission to measure component structural integrity that can be accomplished within existing state-of-the-art technology.

KEY WORDS: acoustics, emission, nondestructive tests, welded joints, ammunition belt links

"Structural integrity" is usually thought of in the context of large complex structures such as buildings, bridges, aircraft, etc. It is equally significant, however, when applied to a single system component. These components are structures in themselves, and their integrity is vital to system operation. This discussion concerns one such component.

Production of large quantities of items such as mechanical system

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components imposes a challenging problem of determining if the finished components meet quality requirements. If the consequence of failure of one component is critical, inspection must approach 100 percent. This, of course, introduces the problem of method and cost to accomplish 100 percent nondestructive inspection.

A specific case in point is links used to make up ammunition belts for automatic weapons. The particular links of concern in this discussion are for a 40-mm aircraft weapons system. Link fabrication involves making four simultaneous projection resistance welds, and the integrity of these welds is a primary factor in link structural integrity. If one of these welds fails in service, often the immediate result is a jammed weapon. Since many thousands of these links are used, assurance of 100 percent high quality links is a significant problem.

Inspection by destructive testing of random specimens on a batch basis has been used for want of a better method. Since failure of a single component (link) is critical in this case, random specimen testing is not satisfactory. Alternate approaches, however, which provide higher assurance of integrity are very limited. Conventional nondestructive testing methods (radiography, ultrasound, eddy current, etc.) are of little value in measuring the quality of a resistance weld. Mechanical proof loading is one potential method for 100 percent inspection which has been tried by the Weapons Command. This met with limited success because loads sufficient to fail a weak weld often permanently distort sound links.

A unique combination of moderate mechanical proof loading with simultaneous monitoring of acoustic emission (AE) from the link is an approach which has been successfully demonstrated and is the subject of this paper.

Background

The AE phenomenon is becoming quite well known, and its use for nondestructive evaluation of structural integrity is increasing. The phenomenon *per se* will not be discussed here other than to point up that concerted investigation of AE began about 1950 [*1–3*].[2] Since that time, it has been the focal point of considerable effort to better understand the phenomenon and develop specialized instrumentation and techniques to apply it for nondestructive evaluation of material and structural integrity [*4–8*].

A good reference on AE technology through 1971 is provided in the American Society for Testing and Materials [*9*]. Also, comprehensive bibliography of publications on AE is included in this publication.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

The work described in this paper does not represent a major advancement of AE technology. Its significance lies in the fact that it is an example of the many specific applications of AE that can be made within the framework of existing technology.

Link Proof Test by Acoustic Emission

Problem

As mentioned earlier, the weld joint in these ammunition links is the primary factor in link integrity. Figure 1 shows the link as used in making up an ammunition belt. The link is fabricated from approximately 1/32-in.-thick steel strip. The strips are preformed into link halves which are then joined by two projection welds on each side where the sections overlap.

All four welds on a link are made simultaneously. With the various parameters that must be controlled to produce a good resistance weld, there is significant potential for producing some faulty welds in mass producing links. The contrast between a good and a bad weld is presented in Fig. 2. In the good weld, the strips are used to produce a joint nugget which is usually stronger than the base material in tension, that is, the base material will tear before the weld will break. With a poor weld, the joint interface is literally just stuck together. A moderate force, particularly impact, will fail the joint at the interface.

A preliminary feasibility investigation showed that the poor welds produced more AE under load than did the good welds. This was true even though the load was insufficient to fail a poor weld. It appears

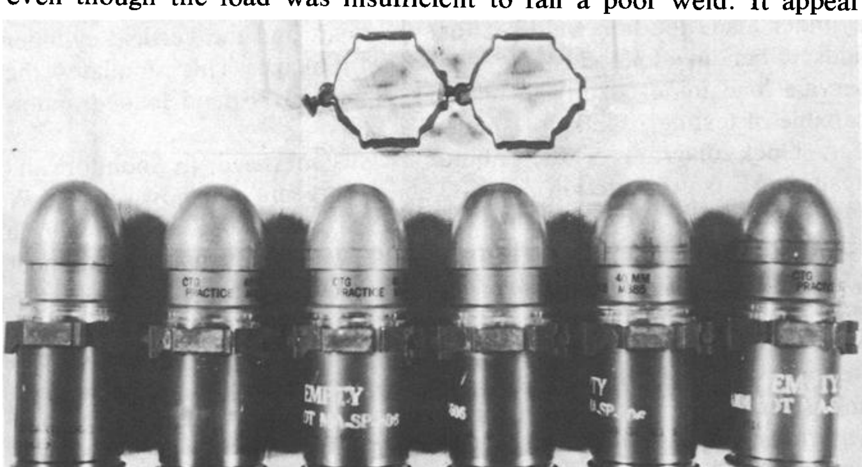


FIG. 1—*Forty mm ammunition belt links.*

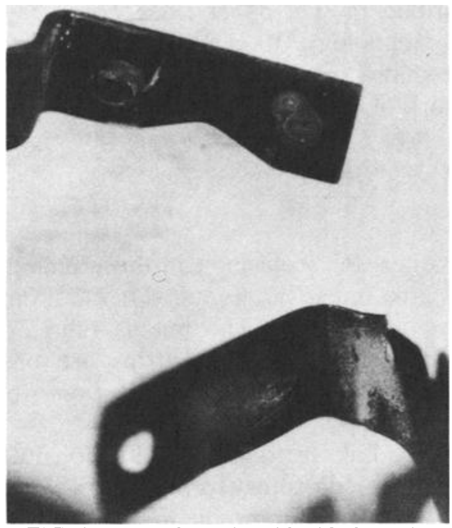


FIG. 2—*Typical good and bad link welds.*

that the AE is being generated by preliminary cracking of a weak weld under proof loading. The decision was thus made to develop a link proof test which utilized an existing mechanical link tester to stress the links and use AE analysis to detect poor welds.

Proof Test Development

The mechanical link tester is shown in Fig. 3. The link test fixtures (Fig. 4) position the link for testing as shown in Fig. 5. A horizontal air cylinder loads the link weld sections in shear, and the vertical cylinder adds a bending load through a spreader linkage. This simulates the service load imposed on the link. The machine is hand loaded and is capable of testing 20 links per minute.

A block diagram of the laboratory system used to monitor and analyze AE is presented in Fig. 6. The instruments are shown in Fig. 7.

At the outset, AE was sensed directly from the link by attaching a sensor to each link before testing. This was the simplest and most direct method for confirming feasibility. Once feasibility was demonstrated, it was necessary to consider a monitoring technique that would be compatible with production testing. The first and most crucial step was to modify the sensing method since attaching a sensor to each link is obviously not practical for quantity testing. The sensing function was transferred to the link spreader arms. Piezoelectric crystals were embedded in the spreader arms as shown in Fig. 8. A recess was machined in the edge of each arm, and a crystal was mounted in the

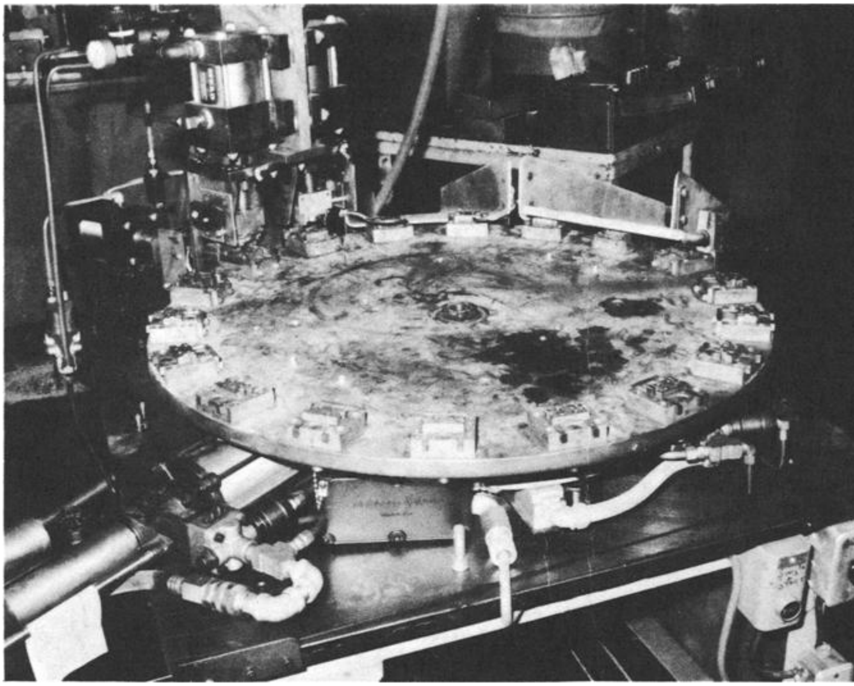


FIG. 3—*Proof test machine 40-mm ammunition links.*

recess using a room temperature curing epoxy. Simultaneous monitoring of link emission using these sensors and one mounted on the link confirmed that the arm sensors do detect essentially all of the information available directly from the link. It was concluded that a spreader load of about 60 lb produced the best results. At a 60 lb spreader force on the link, the link-spreader arm interface pressure is about 5000 psi which appears to provide good coupling of acoustic information across the interface.

The nature of the acoustic information detected is shown in Fig. 9. The top photo shows the total information obtained during the first 0.3 s of the spreader cycle for three different links. About the first 0.024 s of this information is primarily noise. The mechanical process for stressing the links is very noisey. The sliding action of the spreader mechanism produces a wide frequency range noise which cannot be electronically filtered out without also filtering out the AE information. The approach chosen to overcome this problem is to gate out the noise from moving parts of the link stressing mechanism and monitoring for AE during static stressing of the link after the spreader arms have reached full displacement. See also Fig. 10. Testing has shown the

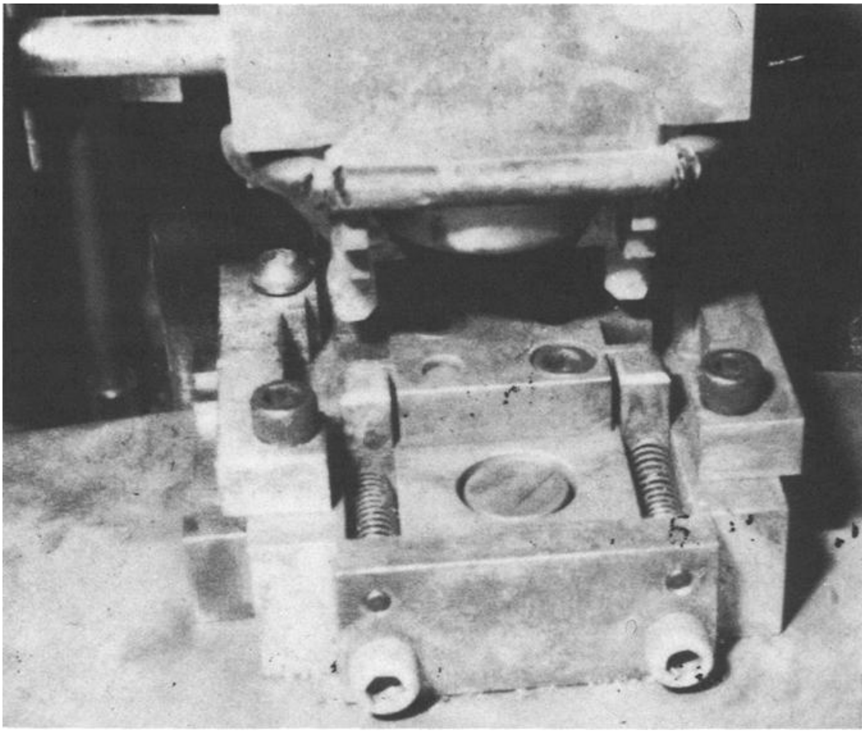


FIG. 4—*Link test fixture.*

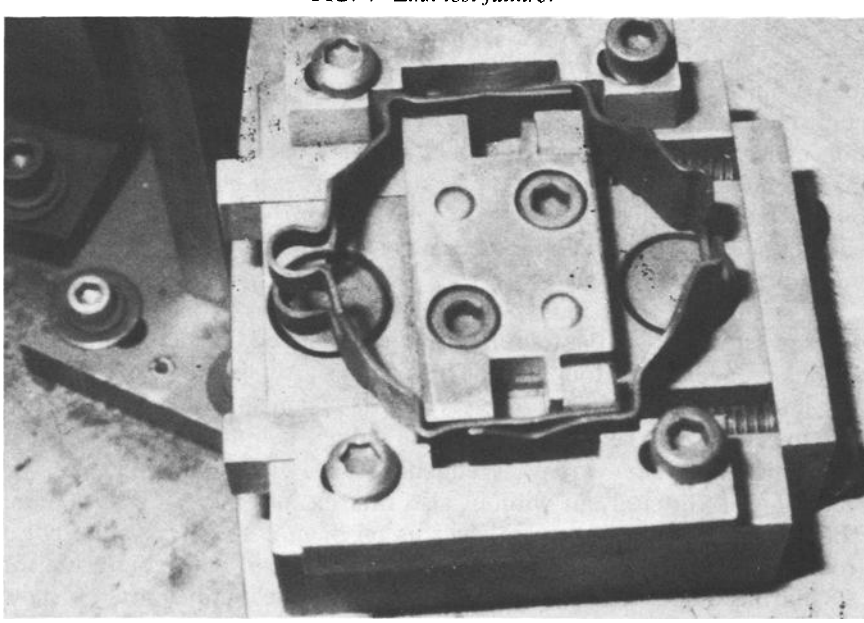


FIG. 5—*Link installed for test.*

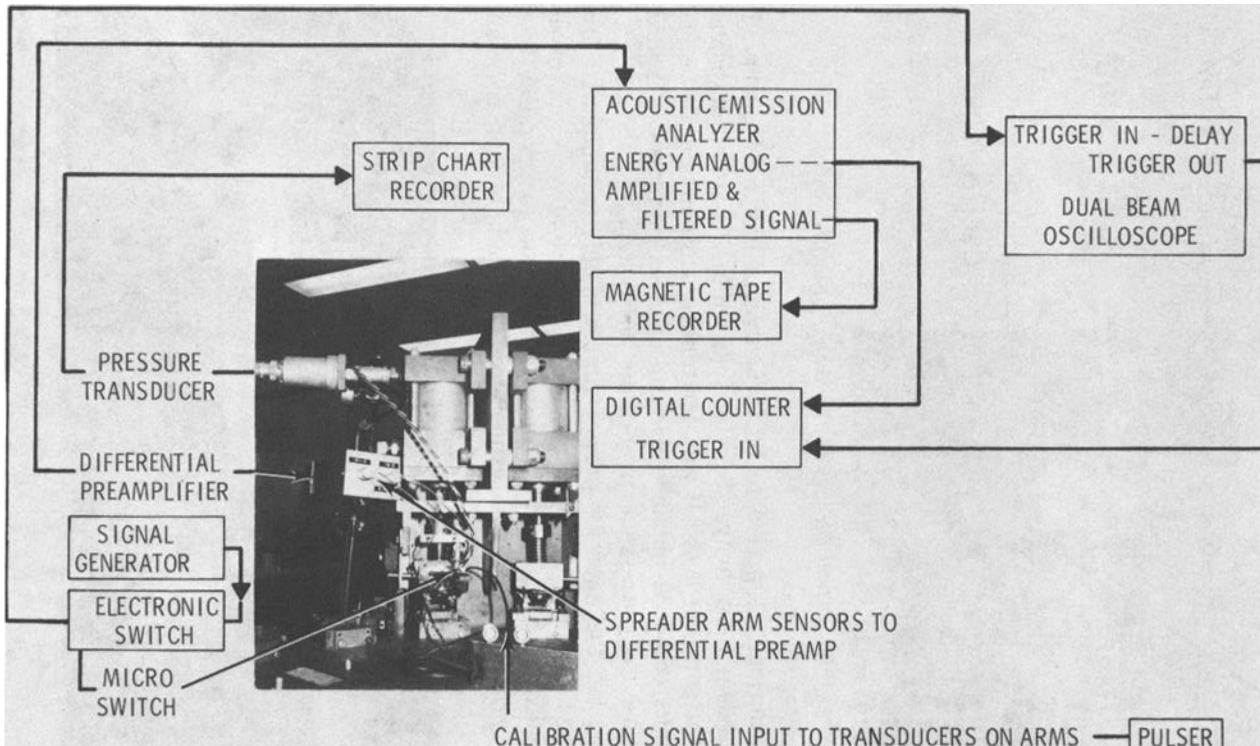


FIG. 6—*Laboratory acoustic emission system for link proof test.*

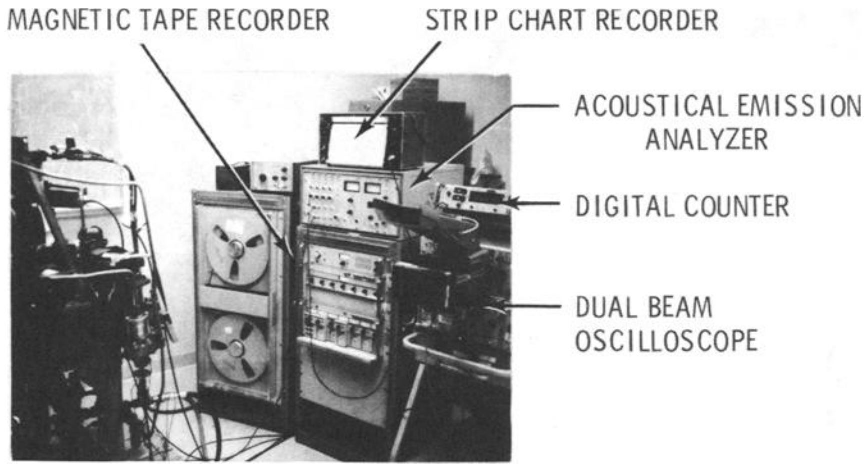


FIG. 7—*Instrument system to analyze acoustic emission.*

emission during this period to be indicative of link weld quality. Initially, the data were analyzed for periods up to 2 s after full displacement of the spreader arms. It was determined subsequently that equally good results could be obtained with an analysis period of 0.25 s, and thus increase the process capacity of the AE system.

Evidence of the need for precise timing in this technique for overcoming noise interference was obtained inadvertently. A microswitch was installed to reference monitor system turnon to operation of the spreader arms. Subsequent testing produced rather poor correlation

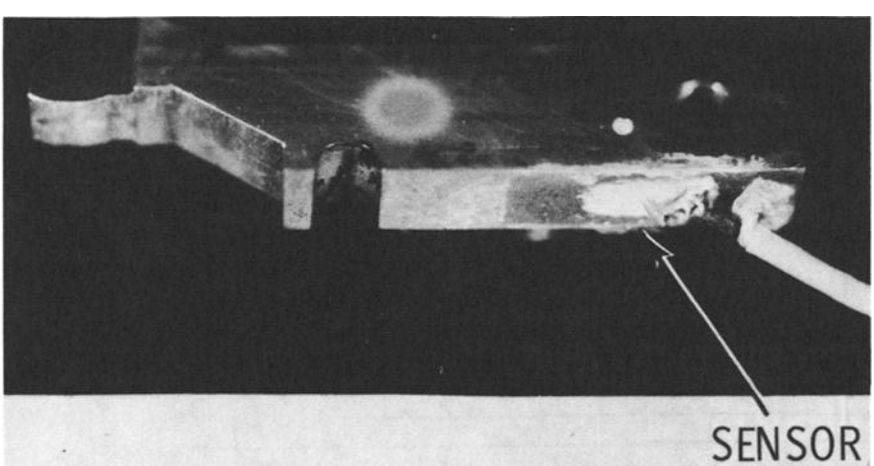


FIG. 8—*Sensor mounted in spreader arm.*

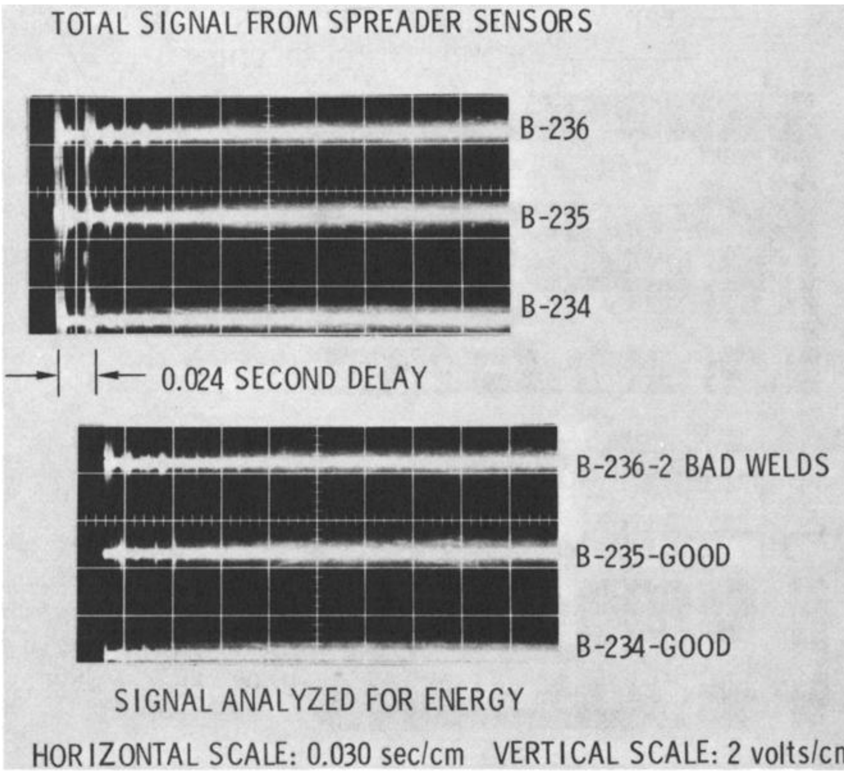


FIG. 9—*Selection of significant data.*

between acoustic information and link weld quality. It was ultimately determined that the particular microswitch used would close momentarily on initial setdown of the vertical head and trigger the monitor system about 0.015 s early (Fig. 10). This had the effect of including so much machine noise that the contrast of information from a good and a bad link was obscured. This problem was remedied easily by using a different microswitch orientation.

Results

A form of signal energy analysis has produced the best results in this work. This consists of electronically integrating for the area under the half-wave rectified envelope of the emission signal in terms of volts amplitude and time duration. One unit is chosen to be an area equivalent to 1 V for 50 μs. In the laboratory development phase, the number of energy units measured from a given link was totalized with a digital

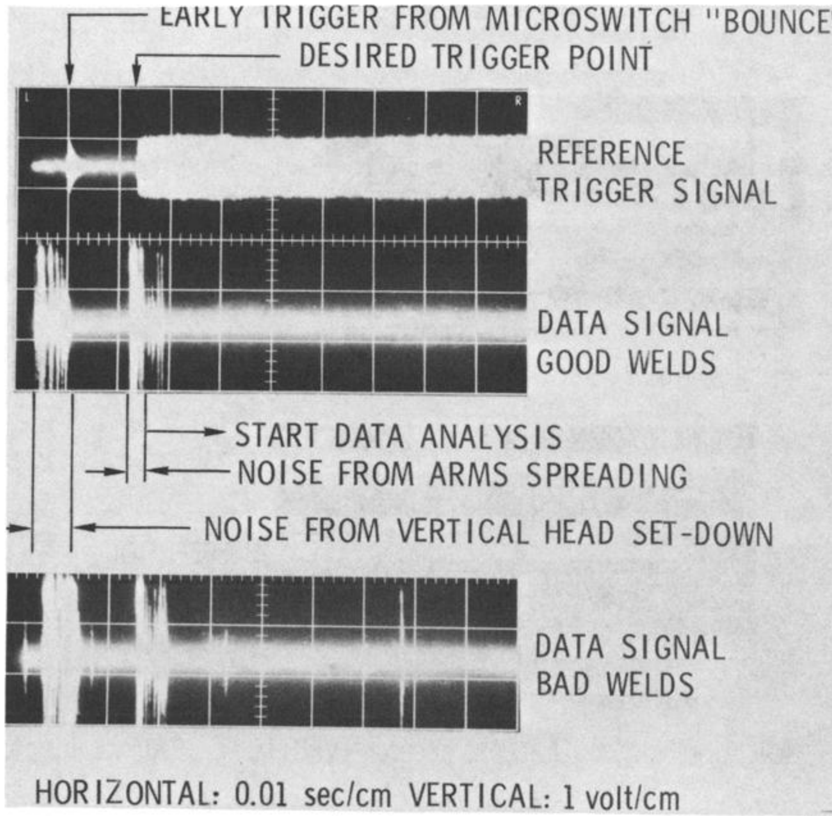


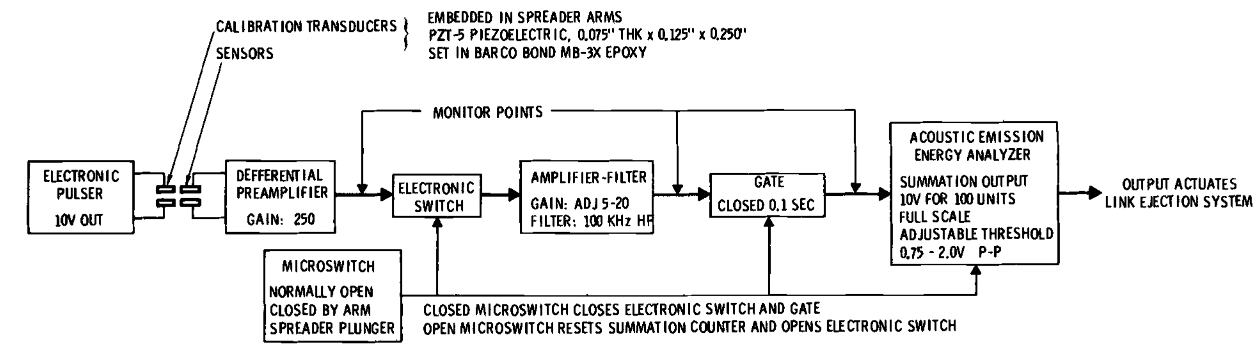
FIG. 10—*Detail acoustic data from link.*

counter and recorded manually. Some of the results obtained are given in Table 1.

The rate of success in identifying links with good welds as opposed to those with bad welds has been 85 to 90 percent using the laboratory system. The faulty indications are attributed to improper triggering of the monitor system. This has been confirmed in several cases where the basic data were preserved on magnetic tape so that it could be reanalyzed. The prototype system with more precise adjustment on the triggering microswitch is expected to overcome this problem.

Prototypic System

A prototypic system for production application has been fabricated. As the block diagram of this system (Fig. 11) shows, the prototype is a simplified version of the laboratory monitor system. The same basic



NOTE:
THIS SYSTEM OPERATES IN CONJUNCTION WITH THE MECHANICAL LINK TESTER FABRICATED BY THE ARMY WEAPONS COMMAND. THE MECHANICAL TESTER PROVIDES NECESSARY PROOF LOADING OF THE LINK.

FIG. 11—*Acoustic emission system for M16A2 link proof test.*

TABLE 1—*Typical link weld proof test results using acoustic emission.*

Link No.	Total Energy Units	Weld Condition from Destructive Testing
B-234	17	all good
B-235	81	all good
B-236	198	2 bad inner welds
B-237	551	1 bad outer weld
B-238	90	all good
B-239	33[a]	1 bad outer weld
B-240	743	2 bad welds on one side
B-241	104	1 bad outer weld
B-242	412[a]	all good
B-243	53	all good
B-244	310	2 bad welds on one side
B-245	58	all good
B-246	122	1 medium and 1 bad weld on one side
B-247	76[a]	1 bad outer weld
B-248	32	all good
B-249	335	2 bad welds on one side
B-250	330	1 bad outer weld
B-251	240	1 bad outer weld

[a] Inconsistent values attributed to improper triggering of analyzer system (assumes > 100 units denotes a bad weld).

NOTE: Inner welds designate those at the end of the inner overlap section.
Outer welds designate those at the end of the outer overlap section.

analysis functions are retained, but, having established the various parameter values within a narrow range, the functions can be performed more simply. The analyzer produces a d-c voltage proportional to the total AE energy measured. The system sensitivity is adjusted so that a 10 V energy analog output will represent the division point between a good and a bad link weld. If a given link generates enough emission to produce a 10 V analyzer output, the link will be rejected. If the value is less than 10 V, the link will be accepted. The selective eject function is performed rather easily with the mechanical tester. It was designed to eject the links into the reject or accept container based on whether or not the spreader arms could displace the link weld section sufficiently to contact a limit switch. The limit switch is now replaced by an electronic switching function which is to be controlled by the output voltage of the emission analyzer.

Calibration of the monitor system is accomplished by introducing an artificial signal into the spreader arms where it is detected and processed by the monitor system. The most suitable of several methods tried is to generate a signal in the spreader arms using a transducer installed in the arms the same as the AE sensors. A 10 V, 10 μs pulse is fed to

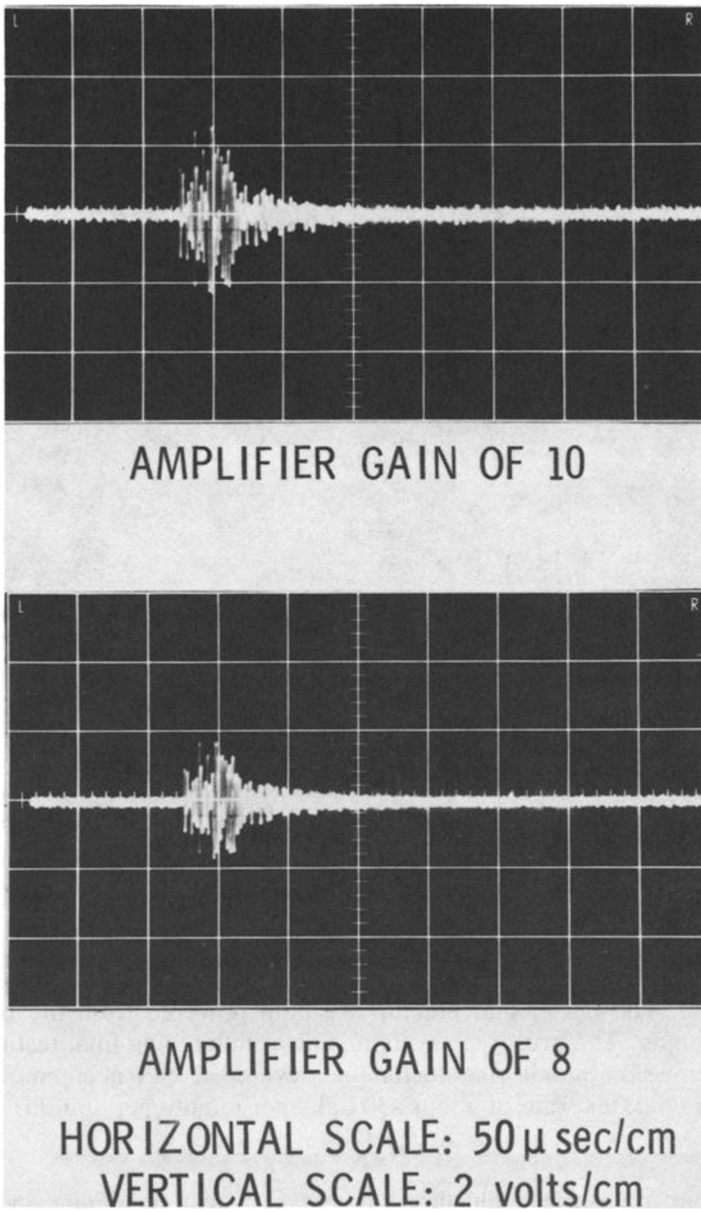


FIG. 12—*Calibration.*

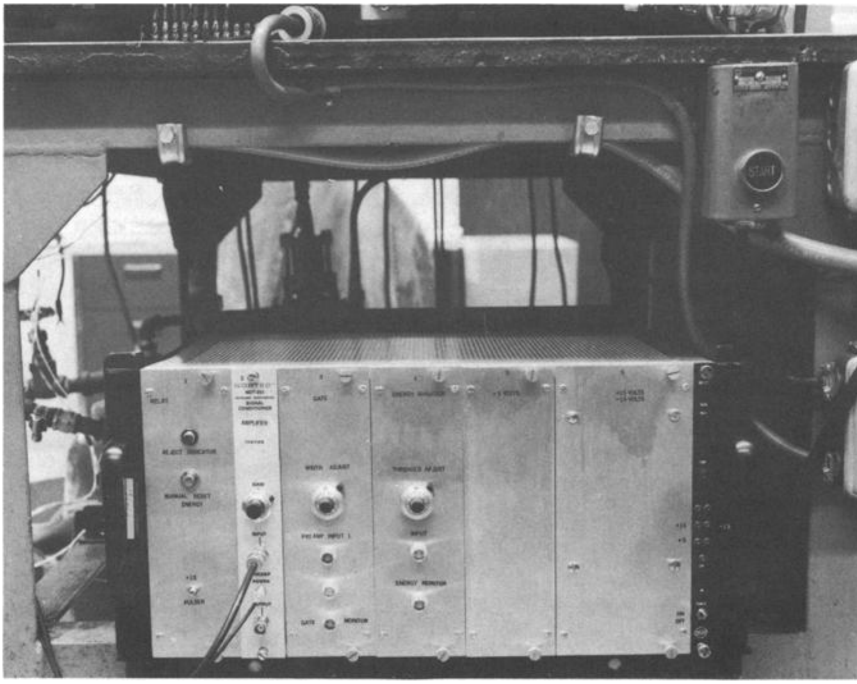


FIG. 13—*Prototype acoustic emission monitor for link welds.*

these transducers from a pulse generator. The resulting signal as detected by the monitor system is shown in Fig. 12. This is a reproducible signal which is a reasonable simulation of the real data, and it is quite simple to generate. The signal can be used to effectively calibrate system gain, threshold setting, and energy analysis.

The prototypic system is packaged in a standard, 12 wide IM bin with exception of the calibration pulser and the preamplifier as shown in Fig. 13. The pulser and preamp are both powered from the IM bin power supply. The prototype system is now undergoing final testing.

The emission monitoring technique developed can accommodate a maximum link test rate of about 450 links per minute per station.

Summary

This paper describes the development of a test technique and prototypic equipment to apply AE for evaluating the quality of resistance welds in 40-mm ammunition belt links. The work is significant in two respects: (1) AE is the only currently available nondestructive test method that could perform the needed function and (2) this work is a specific example of the many beneficial applications of AE that can be accomplished within existing state-of-the-art technology.

Acknowledgments

The author wishes to recognize the significant contribution of J. F. Dawson, T. J. Davis, and G. D. Shearer to the work discussed. This work was sponsored by the U. S. Army Weapons Command, Rock Island Arsenal.

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Industrial Use of Acoustic Emission for Nondestructive Testing

REFERENCE: Drouillard, T. F., Liptai, R. G., and Tatro, C. A., **"Industrial Use of Acoustic Emission for Nondestructive Testing,"** *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571*, American Society for Testing and Materials, 1975, pp. 122–149.

ABSTRACT: The industrial use of acoustic emission is presented. Emphasis is given to the characteristics of acoustic emission as a unique nondestructive testing method for use in the evaluation of the structural integrity of materials, components, and engineering structures. Several applications of acoustic emission testing are discussed.

KEY WORDS: acoustics, emission, nondestructive tests, pressure vessels, crack propagation, plastic deformation, phase transformations

The use of acoustic emission (AE) to characterize and evaluate a material or engineering structure under load is exciting much interest in the scientific and engineering communities. It is one of the first nondestructive testing (NDT) methods to provide a means of evaluating structural integrity by the detection of active flaws that may ultimately cause failure of the material or structure. Sources of AE which generate stress waves in material include local dynamic movements, such as the initiation and propagation of cracks, twinning, slip or plastic deformation, sudden reorientation of grain boundaries, bubble formation during boiling, or martensitic phase transformations. The stresses in a metallic system may be well below the elastic design limit, and yet the region near a flaw or crack tip may undergo plastic deformation and fracture from locally high stresses, ultimately resulting in premature or catastrophic failure under service conditions. The industrial use of AE,

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particularly as applied to the assessment of structural integrity, could lead to great economies in testing high-performance components with the added advantage that the serious flaw cannot be missed, since it would be a principal contributor to an AE record.

Figure 1 is a graphic illustration of examples of various uses of AE and how the technique has been used increasingly since 1966 to assess structural integrity. Although the figure is not meant to be totally inclusive of all applications of AE techniques, it does indicate the many facets of application of the technology and also the increasing uses of AE. Most uses, of course, involve plasticity and fracture of materials.

This paper will discuss the industrial use of AE for NDT quality assurance programs. Also discussed will be some of the concepts and considerations important in applying AE and some of the problems associated with introducing AE into a production atmosphere. Various examples will be presented along with some information about how to effectively use AE on the production line. This discussion will address itself to the testing of relatively small engineering structures and pressure vessels and to testing situations where real-time interpretation and evaluation of test data are requisite.

New Methods for Nondestructive Testing

Have you ever thought, "If I only had it to do over again." The authors feel that many of us are having that second chance with AE. Some 20 years ago many of us had the experience of pioneering in the field of ultrasonic testing. Equipment was crude and always seemed inadequate for the job. There were no experts or sources of authority on the applications of ultrasonics. Learning was primarily by cross correlating ultrasonic results with radiography, then the backbone of NDT, and by actually probing suspect areas and exposing defects or discontinuities.

In the past few years AE has emerged from a well researched technology to a promising new tool for NDT. Much like ultrasonics, AE started out with equipment limitations. Those of us who were working in the field before commercial equipment was available had to build our own systems from component instruments that were designed for other purposes. These systems were limited in capability. Noise was our worst enemy. Probably most all of us can look back at our early test results and wonder what was real emission and what was noise. Early equipment was of the vacuum tube type which limited frequency and gain with a tradeoff for noise. Today solid-state electronics has virtually eliminated instrument limitations. A number of instrument manufacturers provide a wide variety of commercially avail-

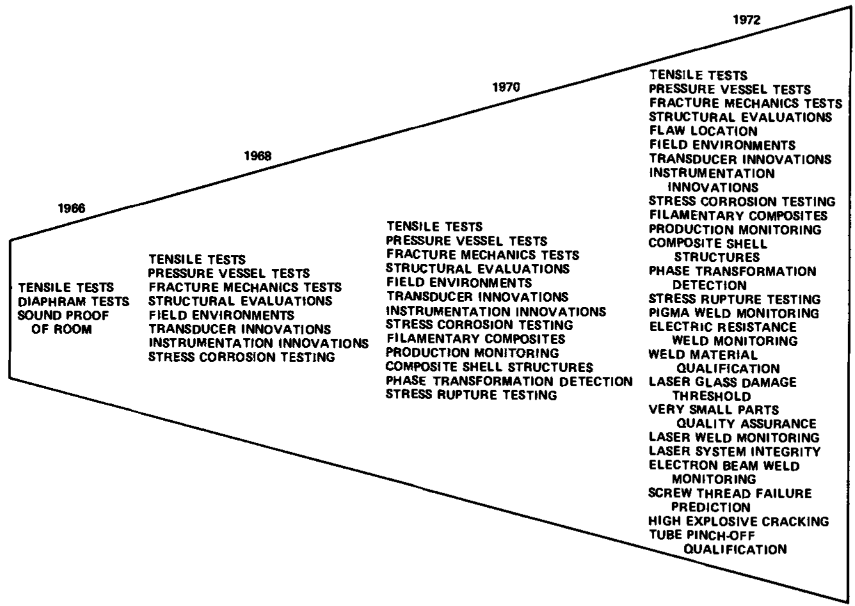

FIG. 1—*Growth in the use of acoustic emission techniques for the materials research and assessment of structural integrity.*

able equipment. Technical services are available from many well qualified people, some pioneers in the field of AE. A valuable source of information is the Acoustic Emission Working Group (AEWG) meetings which provide a forum for the exchange of information and informal discussion of current work in the field of AE. Also there is a wealth of technical information in the open literature. Included in this publication is a bibliography of most all of the literature on AE published during 1970 through 1972. These provide the NDT engineer with almost unlimited resources in equipment, technical assistance, and information for the application of AE as a tool for NDT.

The determination of stress intensity by AE monitoring has been readily demonstrated, and the correlation between acoustic emission and stress intensity factor is clear [*1–5*].[3] Much effort has been expended in the last few years in attempting to ensure the safe operation of high-performance components. Meticulous searching for flaws by conventional NDT techniques is conducted on these components, and, once located, additional time is expended determining the size and shape of the flaw. Then an analysis is made using pertinent information

[3] The italic numbers in brackets refer to the list of references appended to this paper.

such as defect size, shape, and location pertaining to the local stress intensity. These findings are compared with the critical stress intensity factor for the material, derived from specialized specimen testing, and with material properties, stress levels, and geometry to reach a decision on whether or not the part or structure can be used safely.

Application of AE testing could lead to great savings in evaluating components. AE emission is not an approximation, but rather it is the actual detection of fracture events as they occur under known applied stress conditions. Many discontinuities presently considered to be unacceptable defects based on ultrasonic and radiographic standards have little or no effect on structural integrity. The added consideration and advantage of AE testing is that a serious flaw cannot be overlooked, regardless of its size, since it is indeed an active or unstable flaw and is therefore a principal contributor to the AE record. After all, a discontinuity is a defect only if it can grow and eventually cause failure. If a defect grows and gives off AE, when properly instrumented that emission can be detected.

Basic Concepts of Acoustic Emission

The basis for most conventional NDT methods is the detection of a perturbation in the interaction of a defect or a discontinuity with a directed beam of some sort of energy such as *X* or gamma radiation, ultrasound, thermal energy, microwaves, and so forth. Similarly, AE involves the interaction of a defect and energy that is used to interrogate the integrity of a material or structure, the energy being a strain field. Here the energy or strain field interacts with the defect itself; hence, the defect acts as a meter of information about itself, assessing its own part in the evaluation of structural integrity of the material or component. In AE the defect plays a very active role rather than the passive role it usually plays during evaluation by conventional NDT methods. In other words, if the defect is large enough or oriented in such a way as to be affected by the strain energy during the loading of a material or a structure the defect will play an active role in heralding its own abuse. If the defect is not affected by the strain field, it will not be an active emitter of AE; hence, the defect is in a stable condition and will not affect the structural integrity of the material being tested. Herein lies a new concept in NDT. Thus, AE is a dynamic test, limited to the detection of an active flaw during a change in the stress field around the flaw. It cannot detect static flaws. This is why AE must be applied during tests which stress the material or structure, for example, proof testing of a pressure vessel and tension or bend testing of a weld joint. So in a sense, an AE technique requires that a defect act as its own assessor in that only active crack growth or crack initiation mechanisms will be sources of AE. Those which do not interact in such a manner as to generate AE might not be or probably are not important to the structural integrity of the material.

AE detection is nondirectional. Most defects act as point source emitters, radiating acoustic energy in spherical wavefronts. Thus, a sensor can be placed most anyplace on a structure and detect emissions produced anywhere in that structure. This is converse to other methods of NDT which depend on directing a beam of energy through a prescribed path in the part under test. Consequently, by using AE, a structure can be monitored to detect emission producing events, in many cases, without prior knowledge of their existence or location. Because AE data describe volumetric deformation and fracture processes, we have perhaps one of the most useful tools to study, in real-time, dynamic processes and local transient instabilities.

AE is an extremely sensitive test method. To give some idea of its sensitivity, relative to the more familiar NDT methods, the minimum detectable crack size for ultrasonics, radiography, and eddy-current techniques is about 10^{-3} in.; for strain gages, about 10^{-6}; and for AE, about 10^{-12} in. [*6*]. Thus, the dynamic range of sensitivity to events that can be detected by most basic commercially available AE systems extends from gross events that produce audible signals to microevents such as dislocation movements.

Application to 100 Percent Inspection

In recent years, much effort has been expended in developing 100 percent NDT inspection procedures. Whole industries have evolved to meet the demands of scanning 100 percent of the surface of test parts with the narrow energy beams required to locate small flaws. Although various combined efforts have met with considerable success, testing of this type is very expensive, and few consumer products can be inspected with this degree of thoroughness. AE testing can quite often be used in production line situations where 100 percent inspection is desirable. If a part or material is stressed to a suitable level and monitored by AE techniques, a critical defect will play an active role by being the source of AE that will attest to the structural integrity, or lack of integrity, of the part. The results of such tests may not be definitive in terms of flaw size and location; however, such tests can be readily incorporated into the production line with an entirely different goal in mind. One might consider the goal to be one of determining whether the part is the same or different from a part that has been judged acceptable by other techniques and procedures. The AE signature or activity of each part, when properly recorded, is unique to that part. Deviations from the normal signature can be used to reject a part or to assign it to a more detailed study by conventional NDT methods.

Again, the noteworthy feature of AE activity is the active role that an existing flaw plays in the presence of a stress or strain field. Flaws which are oriented such that they do not emit AE activity are stable and static in nature and, hence, do not detract from the structural integrity of the material or part being tested. Conversely, active flaws trumpet their abuse and growth by emitting AE; hence, they are self-proclaimed prophets of impending failure. Such testing philosophies can be used in proof testing, periodic proof testing, or monitoring during the service life of a component. In recent times an increased effort has been directed toward testing and quality assurance programs in industry. It is said that a good engineer is a cautious engineer because he understands the laws of nature, the first of which is Murphy's law. This law states, "If anything can go wrong, it will." Sir Isaac Newton pointed up that "the harder you push, the faster it goes," but it was Mr. Murphy who informed us that "the harder you push, the quicker you'll break your pusher." There is a perversiveness in nature which almost always assures that disaster lurks in new designs. Physicians have a motto, *Primum non nocere* which means, "First do no harm." It would be nice if each engineer could glance up from his design board and see this injunction just before he releases drawings to the shop. Paper designs are fine, but engineers must be sure that all considerations are taken into account. This necessitates some type of testing program of the material or component, a procedures which is becoming very expensive and yet more widely used.

The authors consider the field of AE as a tool for NDT with more enthusiasm than was experienced in the introduction of ultrasonic testing some 20 years ago. As in the success of any supply and demand situation, AE testing has rapidly developed to a point where it is now ready for application as a NDT tool, and the market or need for such a test, because of fabrication tolerances, new high-strength and more exotic materials, and the demand for greater performance from engineering structures, is here and now.

Considerations in Setting Up an Acoustic Emission Test

In order to effectively set up a meaningful AE test there are a number of steps that must be considered.

Objectives

What is the purpose of the test? What emission producing events are to be detected? Is source location required? Where will the test be conducted? What is the environment in which the test will be performed?

When will the test be performed, at what stage of fabrication or service life? It is important to plan during the design stages when to use AE most effectively so that allowances can be made in the fabrication sequence. For example, a pressure vessel should be monitored during the initial proof pressure test to establish a baseline record against which subsequent proof test emission records can be compared.

Mechanics of Materials and Structures

The materials and geometry of the part or structure to be tested must be analyzed. How do the materials in the structure emit? Are they brittle materials (good emitters) or ductile materials (poor emitters)?

All of the possible source mechanisms of AE from the materials and joints in the structure must be determined. Various known sources of AE which are related to the metallurgical properties of materials include dislocation and slip movement, twinning, plastic deformation, sudden grain boundary reorientation, stable crack growth, Luder's line propagation, and phase change which may be martensitic transformation or liquid/solid transformation. Other sources of AE may be electronic sources, such as radio frequency (RF) noise and electronic system noise. A third source of AE is mechanical noise, such as impact of two bodies, friction from rubbing surfaces, cavitation or bubble collapse, boiling or bubble formation, fluid flow (either by gas or liquid), gas fill (which includes expansion and impingement), and grip noise caused by deformation and slipping.

It must be decided at what locations emissions are most likely to occur such as high-stress areas. Once this is decided the part or structure can be properly instrumented and environmentally prepared so that only relevant emissions are detected and nonrelevant ones can be excluded.

A means of stressing the part must be selected, for example, pressurization, tensile or compressive loading, and thermal stressing. What is the maximum load that can be applied without causing plastic deformation, yet be sufficient to accomplish the test? It must be remembered that AE testing is nondestructive to acceptable parts but may be destructive to defective ones.

Classification of Defects and Failure Modes

A clear definition of failure must be made. Usually failure can be defined by one or more of the following conditions; (*a*) excessive change in shape due to plastic deformation, either due to localized yielding or because of gross yielding of the entire structure, (*b*) development of a leak path through the structure, or (*c*) loss of structural integrity by collapse, fracture, or rupture. Is failure due to overload, fatigue, stress corrosion, hydrogen embrittlement, faulty design, etc.?

It is necessary to have an understanding of the types of defects associated with the structure under test, how these defects can affect structural integrity, and how these defects will emit under stress. What defects are inherent in the base materials? What defects are associated with the joining processes, with forming processes such as forging, machining, etc., and with heat treatments involved in the fabrication and service life of the structure? What defects can be produced in base material by joining processes, heat treatment, incorrect machining, and forming practices?

Failure modes and emission characteristics representing defective conditions must be known and emission signatures established. For example, if the purpose of the test is to prevent catastrophic failure of a pressure vessel during proof pressure testing, signatures of all failure modes for that particular vessel design must be experimentally determined by actual burst testing mockup vessels that are fabricated under close control to study variables such as material variations, forming and machining effects, and welding procedures. Figures 2 and 3 show a comparison of AE records from two similar pressure vessels that were pressurized to rupture. Figure 2 is the signature of a vessel in which failure occurred in base material, while Fig. 3 is the signature of a vessel that failed in a more brittle manner in the heat-affected zone of the waist weld.

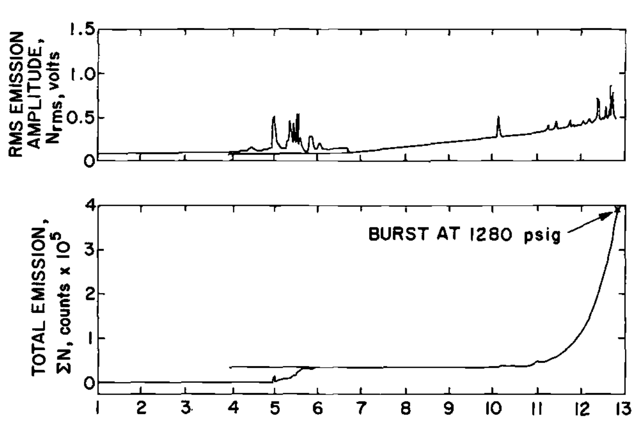

FIG. 2—*Typical acoustic emission of a pressure vessel that failed in base metal.*

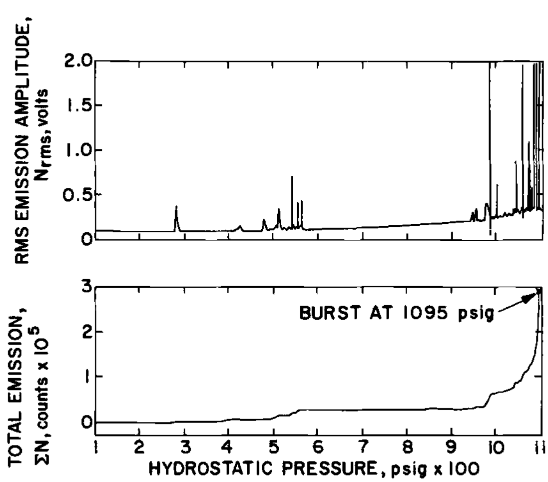

FIG. 3—*Typical acoustic emission record of a pressure vessel that failed in the heat-affected zone of the waist weld.*

Data Evaluation

Acceptance and rejection criteria must be established. What degree of acoustic activity can a flaw exhibit before there is concern about structural integrity? What system gain and signal conditioning must be used to detect emissions produced by events of concern?

The AE test engineer or operator must be given authority to "call the shots" during the test. He must have prior knowledge of the stress and environmental limitations under which he can perform the test. For example, in testing a pressure vessel he should be able to stop, hold, reduce, and reapply pressure to verify relevant from nonrelevant (noise) emissions. He should be able to recycle, that is, repeat the load or pressure cycle several times to determine the trend towards more or less emission activity. And by all means he must have the authority to stop and abort a test when catastrophic failure is imminent, particularly if failure means loss of life or property.

Finally, disposition must be designated for the part under test exhibiting unacceptable AE activity. Can the part be repaired or does it go to the scrap pile? If component parts or a defective structure can be salvaged or if repairs can be made it then becomes necessary to locate the source of emission. This will dictate the test procedure and extent of instrumentation. Will subsequent testing by other NDT methods be used to further evaluate or disposition the part?

Data Presentation

For most testing situations one or more of the following methods of data presentation may be utilized:

1. Plotting summation of all AE events on an *X-Y* recorder. Either linear or logarithmic plots can be made, depending on the type of final stage amplifier used.

2. Plotting count rate on an *X-Y* recorder. Most commonly used is linear count rate at some convenient reset time interval. Count rate plotted from a logarithmic tachometer has been effectively used to display data where log compression over up to four decades is required [*7*]. The log tachometer has no reset time as do digital count rate systems, rather it has an averaging time constant that can be set to various time intervals. Equivalent to the log tachometer plot is the log frequency plot. This is accomplished by using a combination of a Hewlett-Packard 5210A frequency meter and an H-P 7563A logarithmic voltmeter/amplifier to provide a logarithmic-related d-c output voltage.[4]

3. Plotting root mean square (rms) voltage of AE events on an *X-Y* recorder [*8,9*]. Either linear, logarithmic, or squared rms voltage can be plotted, depending on the type of voltmeter used. For example, a Hewlett-Packard 3400A rms voltmeter provides a d-c output voltage proportional to the meter deflection or input voltage; an H-P 7562A logarithmic voltmeter/converter produces a d-c output voltage in a logarithmic relationship to the true rms value of an a-c input voltage or to a d-c input voltage; and a Ballantine Model 323 true rms voltmeter provides a d-c output which is a squared function of the input voltage.

4. Listening to the audible sound of emissions over a speaker. To do this the raw signal is heterodyned with a carrier-wave from an oscillator to produce an audible signal.

5. Visual observation of the emission signals on an oscilloscope screen to evaluate their ringdown characteristics.

6. Amplitude distribution analysis may be considered to assess the evaluation analysis [*21,33*].

7. Triangulation and source location techniques may be used to locate the source of AE activity [*10-12,20,24,33,*].

The most useful information plotted in a typical AE test such as proof testing a pressure vessel is the summation of AE events and the rate at which they occur as a function of some engineering parameter;

[4] No specific intent is made to recommend any one manufacturer's equipment. The authors cite certain instruments simply because they have successfully used these instruments for the described purpose. Equivalent instrumentation of different manufacturers may perform equally well.

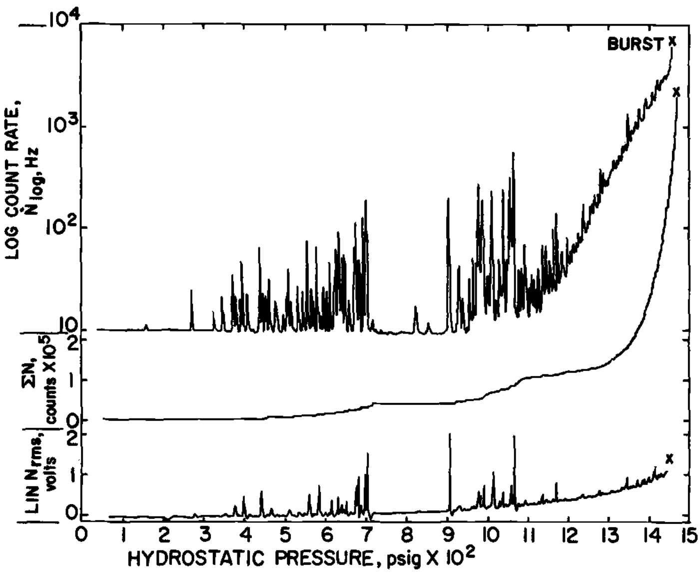

FIG. 4—*Comparison of linear root mean square voltage, total emission, and log count rate as a function of pressure for a pressure vessel taken to burst at 1470 psig (Run 561).*

for example, changes in stress, such as load or pressure, or as a function of time. Figure 4 shows a comparison of three methods of plotting AE from a pressure vessel taken to burst. The lower plot is linear rms voltage or rms emission amplitude (N_{rms}); the middle plot is summation or total emission (ΣN); and the upper plot is log count rate from a logarithmic tachometer with a 1 s averaging time constant ($\dot{N}_{log}$). The method or methods of plotting these data are selected to best display the events as they happen, so that real-time interpretation can be made as the test progresses.

Applications of Acoustic Emission

The most practical approach to applying an effective nondestructive testing program in the manufacture of a high-quality engineering structure or weldment is to first evaluate incoming materials. This assures that only good materials enter the production stream. Next is to inspect material after a forming operation and welds after the welding operation to assure that the operations did not introduce defects into the structure. Finally, an evaluation of the finished produce must be made to guarantee quality and reliability to the customer and to minimize the manufacturer's liability in the event of accident or failure of the product in service.

Monitoring Vessels During Pressure Testing

One of the most common uses of AE is to monitor small (as opposed to nuclear reactor size) pressure vessels during a proof pressure test or during pressurization to destruction. This is an excellent way to evaluate base material, the weld joint, and the fabrication process. Destructive burst tests can be run during the design and development stages to facilitate selection of materials and joining process and to optimize weld joint configuration and welding procedure. Once the pressure vessel design and fabrication techniques have been established and put into production, the finished product can be monitored with AE during proof pressure testing to establish its integrity and reliability as a pressure vessel.

The simplest technique of monitoring a pressure test with AE is with a single transducer to detect all emission activity during pressurization. This technique merely detects emission events but provides no information as to location of the emission source. A simple technique of locating the general source of emission in zones in the vessel is by coincidence gating. Figure 5 shows a block diagram of an AE system, including two coincidence gates, which can be used effectively on a symmetrical pressure vessel up to some 3 ft in diameter [*10*]. The two coincidence gates discriminate and identify indications from the waist weld area and from around the inlet/outlet tube joint of the pressure vessel. Assuming the inlet/outlet tube is located at some place off the pole of the vessel, a transducer array could be utilized as shown in Fig. 6. The two transducers located at the poles form a coincidence (*W*) to detect any indication originating in a band around the waist of the vessel. The three equal spaced transducers (one of which is common to both coincidence circuits) around the inlet/outlet tube form a coincidence (*T*) to isolate any indication from the tube joint. All other indications from the vessel outside of the two gated areas cause no coincidence.

Assuming a weldment is designed and made properly, that is, the weld is stronger than base material, if the vessel is pressurized to burst, failure would be expected to occur in the base material—most likely in the heat-affected zone of the waist weld joint or in some high-stress area in the base material well away from the weld. The AE signatures for such burst tests (Figs. 2, 3, and 4) would be representative of failure of "healthy" pressure vessels of this particular design. If a vessel was defective in any way, due to faulty material, weld joints, or fabrication techniques, failure would occur premature to that of a "healthy" vessel, yet produce a similar AE signature. Thus, the premature emission would provide warning that fracture is occurring, and the slope of the

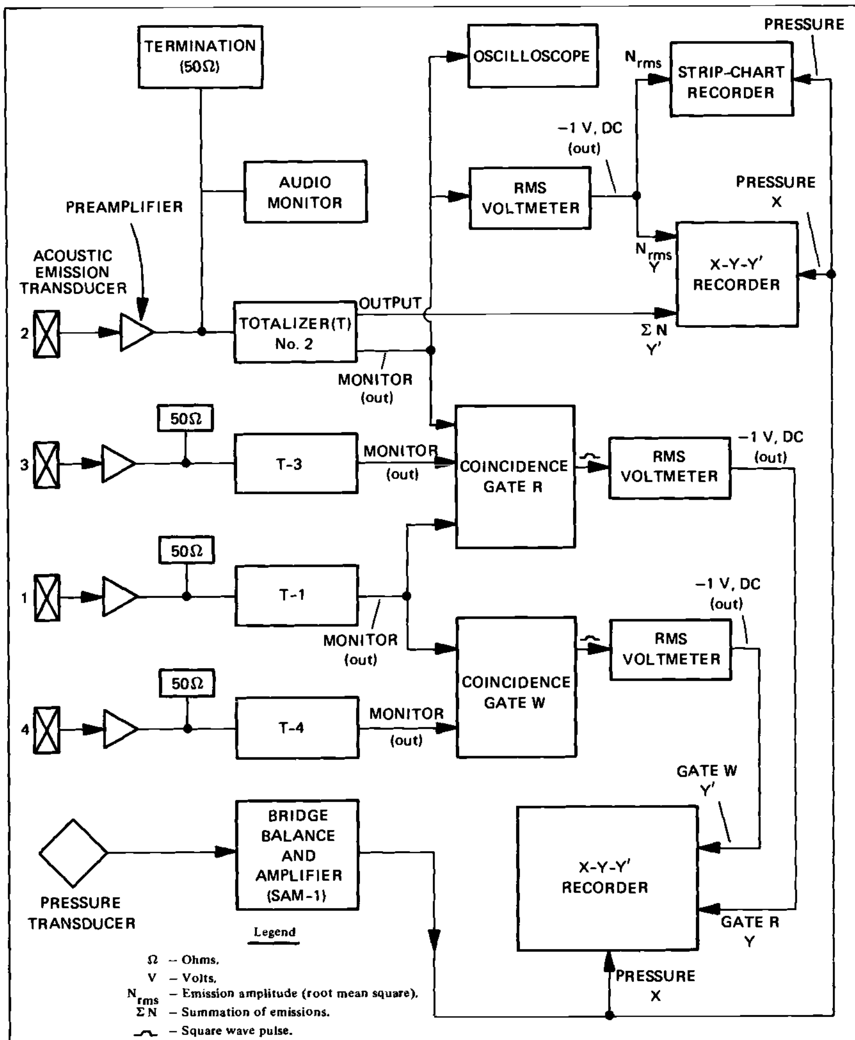

FIG. 5—*Block diagram of acoustic emission system with two coincidence gates.*

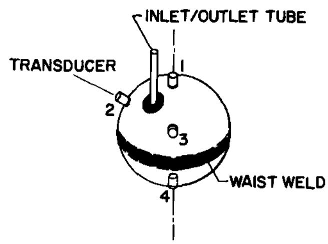

FIG. 6—*Transducer array on a pressure vessel instrumented with two coincidence circuits to discriminate acoustic emissions from the tube joint area (Transducers 1, 2, and 3) and the waist weld area (Transducers 1 and 4).*

curve could be extrapolated to predict imminent failure, in some cases within 5 percent of the failure pressure. Figure 7 shows the AE record from a pressure vessel that failed at approximately 50 percent of the expected burst pressure of a healthy vessel, yet at less than proof pressure of the required certification test. Figure 8 is a plot of the coincidence gate output showing that essentially all emission came from the waist where, indeed, failure did occur. This illustrates the effectiveness of a proof pressure test in detecting defective product and preventing catastrophic failure. It is easily seen that imminent failure was approaching and that the test could have been stopped prior to failure, thus facilitating repair or salvage of parts and material.

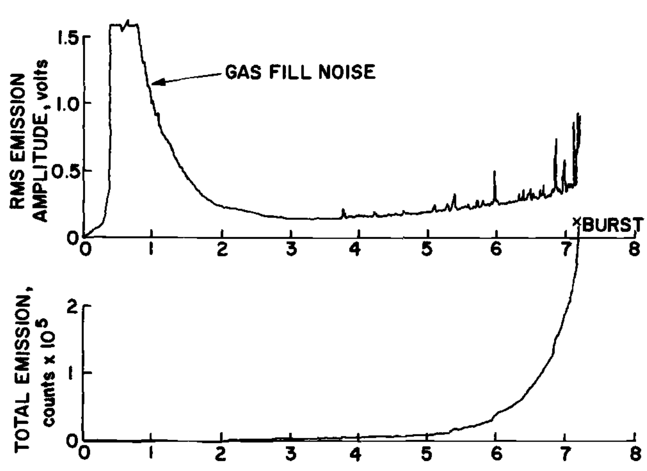

FIG. 7—*Acoustic emission record of a defective pressure vessel that failed in the heat-affected zone of the waist weld at approximately 50 percent of the design burst pressure.*

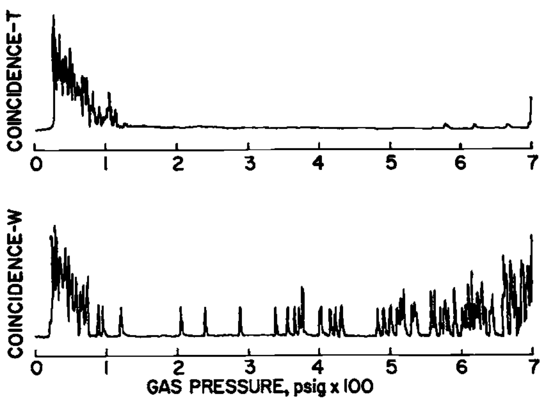

FIG. 8—*Coincidence plots of acoustic emission activity in the waist weld area* (W) *and in the inlet/outlet tube joint area* (T) *during pressurization to failure of a defective pressure vessel (acoustic emission from burst test plotted in Fig. 7).*

Once it has been established that AE can be effectively used to monitor a proof pressure test for the given material and design involved and that a high degree of reliability has been established, it may be advantageous because of cleanliness requirements and corrosion conditions to pressurize a vessel with gas rather than some liquid medium. Thus, gas proof pressure testing could be utilized safely without fear of catastrophic explosion.

Often it is important to know precisely where AE signals are originating from in a pressure vessel or structure. Randomly located, single event microcracks can occur in many materials under stress. These cleavage cracks occur in highly stressed or embrittled grains and terminate and arrest in more ductile, tougher surrounding grains. Unless one of these microcracks continues to propagate it is not considered serious. If, however, one continues to grow and approach critical crack size it can be of significant interest to have such knowledge when evaluating test data. Therefore, it may be considerably more meaningful to have the capability to determine the location of the source of AE within a structure. The literature cites many techniques for flaw location in large planar surfaces and large vessels such as nuclear reactor pressure vessels [*11–23*]. Several papers discuss techniques, show transducer arrays, and present computer programs for flaw location on thin-wall spherical vessels [*24*] and nonspherical vessels [*25*], both surfaces of revolution.

One particular condition that has been experienced by the authors in testing weldments is the case where the only warning of premature, catastrophic failure of the weld is the audible sound of emission. The audible sound of emission is a very important and valuable means of analyzing AE data because of the spectral content from various emission producing events. The path through which AE's have to travel to reach the transducer can alter the spectral content of the sound packet if there are any changes in material properties that can affect sound transmission characteristics. In simple structures such as a one-piece tension or fracture specimen there is no significant spectral information simply because there is no change in material properties of the specimen between the source of emission and the transducer to alter or filter the spectral content of the sound packet. Therefore, the spectrum from specimen to specimen would be the same. However, when a weld joint is located in the sound path the structure becomes complex. The weld acts as a filter that can alter the sound transmission characteristics in as many ways as there are variables and types of defects associated with that particular welding process base material combination.

It has been observed in aluminum welded beryllium fracture specimens [*26*] that both continuous and burst-type emissions are produced. Normally these data are sufficient to plot against some engineering parameter such as load to produce a characteristic signature by which failure of the material can be predicted. In this test it was found that conventional techniques of displaying test data were inadequate. The audible sound of emission was the only warning that the load on the specimen was within 10 percent of failure load. Normally, all of the emission produced by these aluminum welded beryllium fracture specimens is associated with dynamic processes in the beryllium and not in the aluminum weld. The weld is generally tough and ductile and any emission producing process going on in the aluminum does not produce detectable emission at the 90-dB system gain that was used.

During tension testing of several specimens, failure occurred at about 60 to 70 percent of the expected ultimate failure load. In both cases the test operator noted an abrupt and persistent drop in pitch of the audible sound of emission events just prior to failure. Based on the audible signal he called out failure of the third specimen within 5 percent of the failure load. The fourth specimen he unloaded after the drop in pitch and prior to failure.

This condition was found to be associated with fracture in the aluminum weld and was not related to base metal. Metallographic analysis of several of these weld joints (one that failed and the one that was unloaded prior to failure) showed that two conditions were present: A gross amount of porosity throughout the weld as shown in Fig. 9 and embrittlement of the weld metal. The porosity is believed to have been produced by dissolved hydrogen or hydrocarbon contamination of

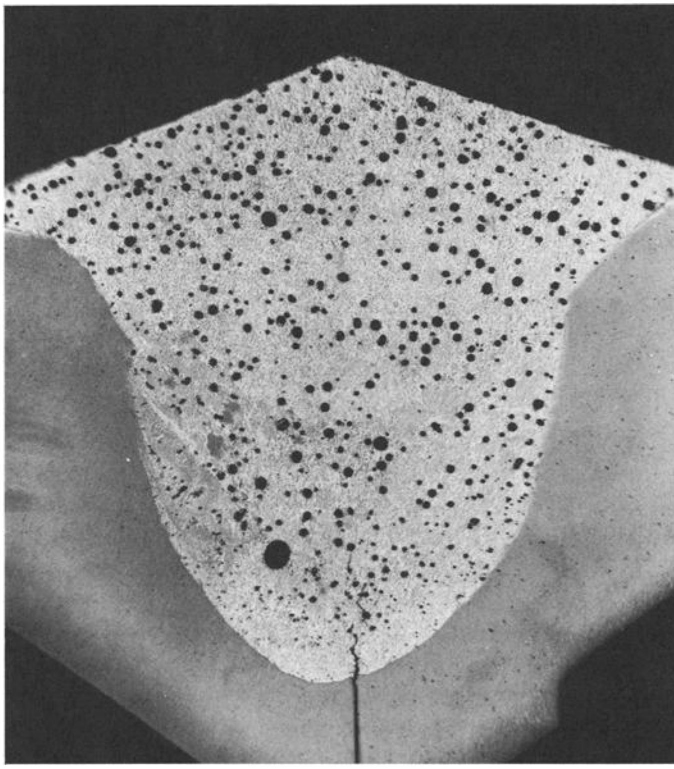

FIG. 9—*Cross section of weld joint in beryllium fracture Specimen 617-3 showing excessive porosity and root crack in the aluminum weld deposit (as polished, ×20).*

the weld wire, probably drawing compound that was not properly cleaned off the wire.

Two possible causes of embrittlement investigated were an unusually high silicon content (40 to 50 percent) from the weld wire (normal silicon content of the wire is approximately 12 percent) and interstitial embrittlement. Porosity in this type of weld is not uncommon and will not, by itself, cause failure. However, embrittlement in addition to porosity provided a situation where random brittle fracture of ligaments between pores could occur as load increased. The majority of such ligament fractures occur at the root of the weld where the greatest tensile stress is produced. Within 10 percent of the failure load proximal fractured ligaments at the root abruptly started to coalesce (Fig. 10), producing the drop in pitch of the audible signal. The porous condition of the weld reflects, scatters, diffracts, and mode converts the higher frequency ultrasonic waves. Applying Huygen's principle,

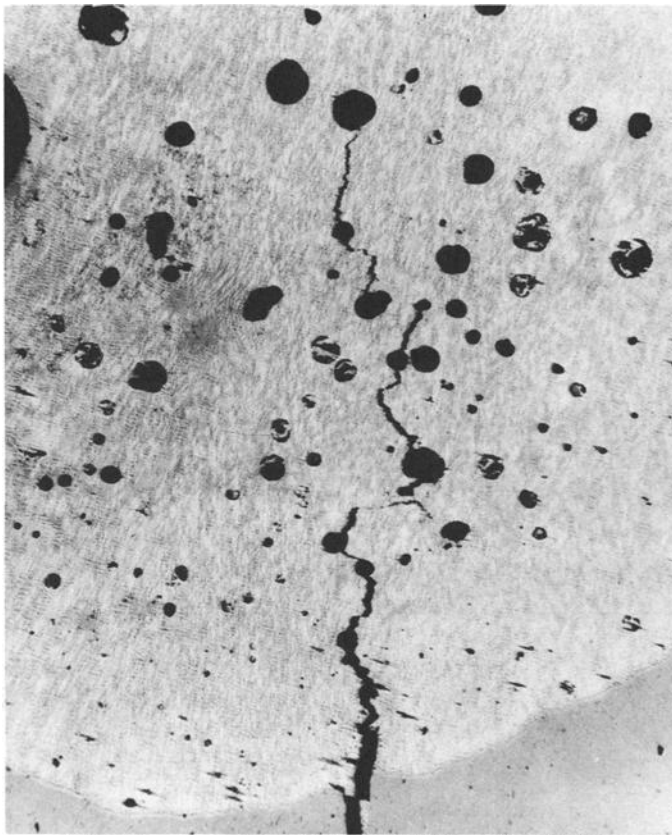

FIG. 10—*Details of crack tip at the root of embrittled and porous aluminum weld in beryllium fracture Specimen 617-3 showing unfractured ligaments between pores (as polished, ×100).*

each pore becomes a point source radiator for frequencies of approximately the same wavelength as the pore diameter. Thus, only the lower frequency waves can propagate through the weld to the transducer—thus the drop in pitch.

Monitoring Welding Processes

A number of people have reported successful application of AE techniques for monitoring various welding processes [*27–31*], including submerged arc, gas tungsten arc (GTA), pressurized inert gas metal arc (PIGMA), metal inert gas (MIG), and electron beam (EB) processes. Defects formed during welding, as well as post weld cracking and martensitic phase transformation can be detected. Figure 11 shows a

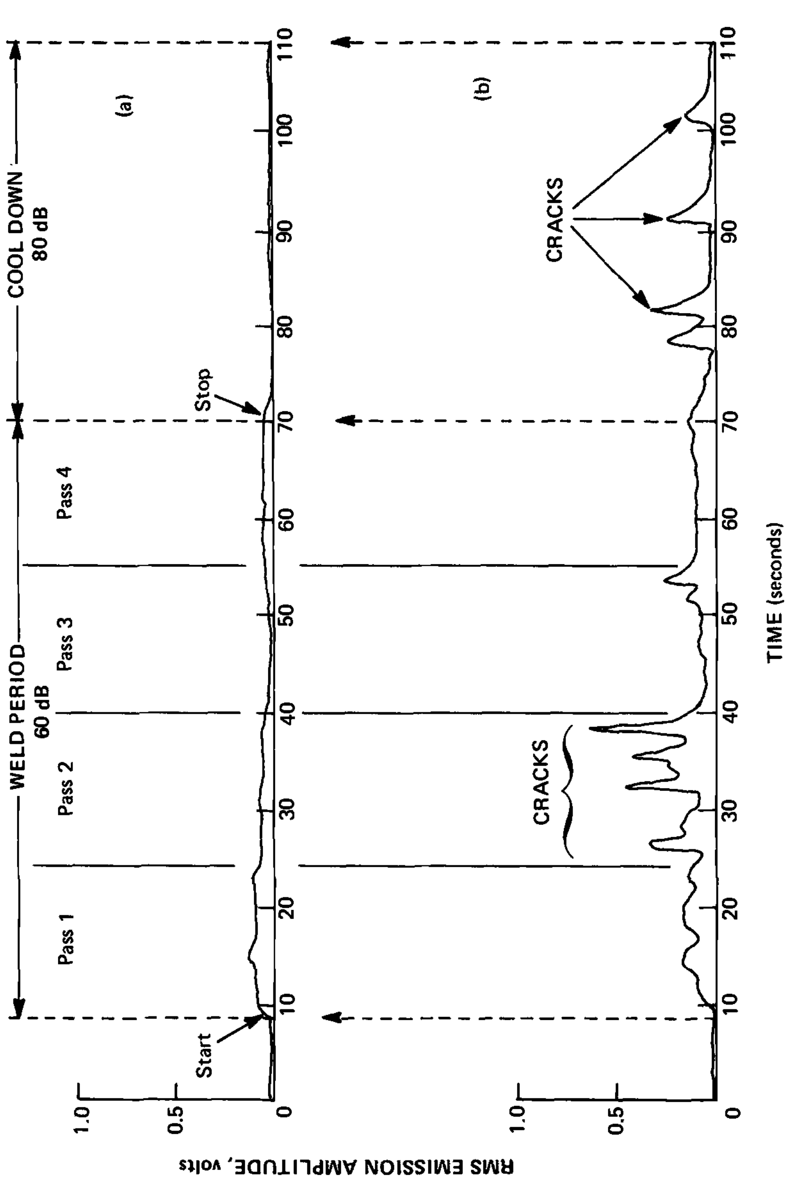

FIG. 11—*Acoustic emission records of linear root mean square voltage plotted as a function of time for a defect-free PIGMA weld in beryllium Specimen AE-220) (a) and for Specimen AE-225 in which cracking occurred (b).*

comparison of AE records for a "good" PIGMA weld and one exhibiting crack formation during welding and post-weld cooldown. The 4-pass butt welds were made in 8-in.-diameter, 0.250-in.-thick wall beryllium pipe sections using aluminum filler metal. Cracking was induced by inserting short segments of copper wire into the root of the weld groove.

In addition to detecting defect formation, AE emission can be used to record the signature or noise of the welding process which is the summation of all emission producing processes. Welding and metallurgical processes can include liquid-to-solid and solid-state phase transformations, expulsion of droplets of molten weld metal, cavitation and sloshing of the molten pool, arc noise, slag formation and cracking, and deformation processes due to thermal expansion and contraction in the joint area. These emissions are a function of welding parameters—voltage, amperage, wire feed, and travel speed—and therefore should produce a signature that can be related to the characteristics of the weld joint configuration, materials, and welding process. Any deviation in the welding process due to malfunction of equipment, power transients, material defects and changes in material properties, such as wrong alloy, will affect the AE signature and facilitate immediate corrective action.

For noisy welding processes where noise is due to the RF generated by the arc, a differential transducer can be used to minimize arc noise. For stable arc welding processes, a single ended transducer provides greater sensitivity.

A unique application of AE and a welding technique is the determination of crack susceptibility of pressed powder beryllium [*32*]. It is difficult to establish uniform weld parameters for joining pressed powder beryllium because of its inconsistent material properties. Each pressing, or log, is inherently nonhomogeneous, exhibiting throughout the log variations in density, chemistry, and mechanical properties. Also, there is variation in properties of material made to the same specification by different manufacturing processes.

The purpose of this program was to determine by AE the susceptibility to cracking of 0.250-in.-thick beryllium specimens subjected to a thermal shock. To accomplish this the specimen is clamped between two flat plates, each containing a circular relief hole. The clamping blocks provide both restraint and a heat sink to the specimen. Welding torch access to the specimen is through the relief hole in the top plate with an electrode-to-work distance of 0.040 in. Figure 12 shows the clamping fixture with the GTA welding torch in place.

The specimen is subjected to a welding environment for a short

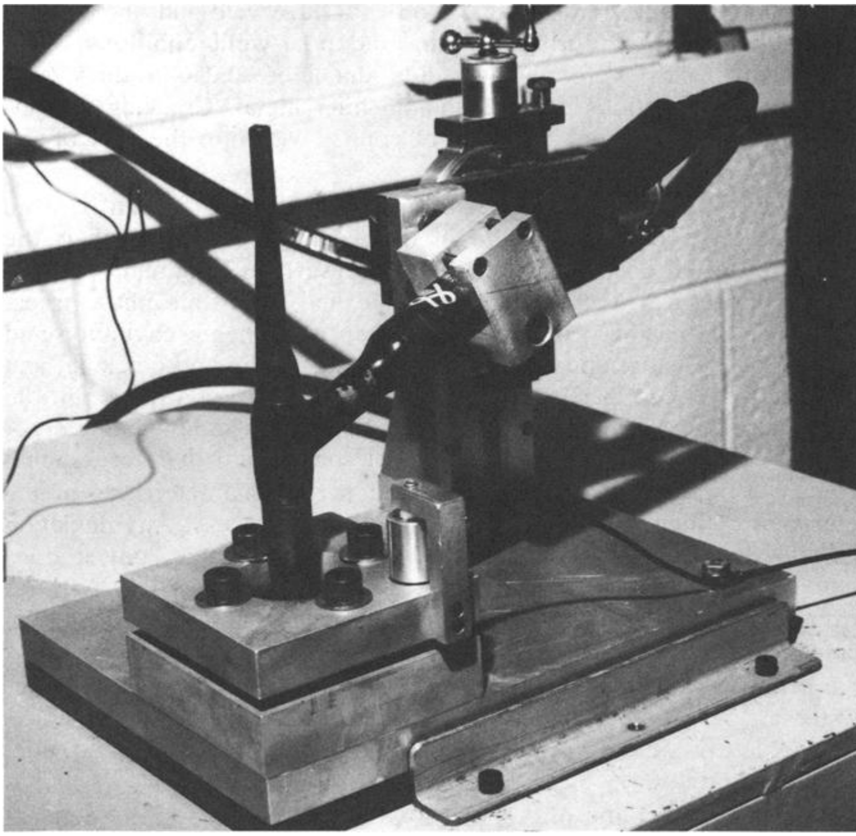

FIG. 12—*Clamping fixture used to hold beryllium coupon in determining crack susceptibility by the acoustic emission produced as a result of a thermal shock. The GTA welding torch and acoustic emission sensor are shown in place.*

period of time while monitoring the process for AE. The AE produced during the process is caused by gross crack propagation and is a measure of the weldability and fracture toughness of the beryllium material. Gross cracking usually starts several seconds after the arc is shut off and lasts about 10 s. All of the cracking takes place usually in less than 30 crack increments.

Figure 13 shows the test setup including the rack of instrumentation. Figure 14 shows a block diagram of the AE system. AE's are detected with a single ended transducer, since the GTA welding process involves an extremely stable arc which causes no acoustic noise. Signals are amplified for a total system gain of 60 dB and bandpassed 100 to

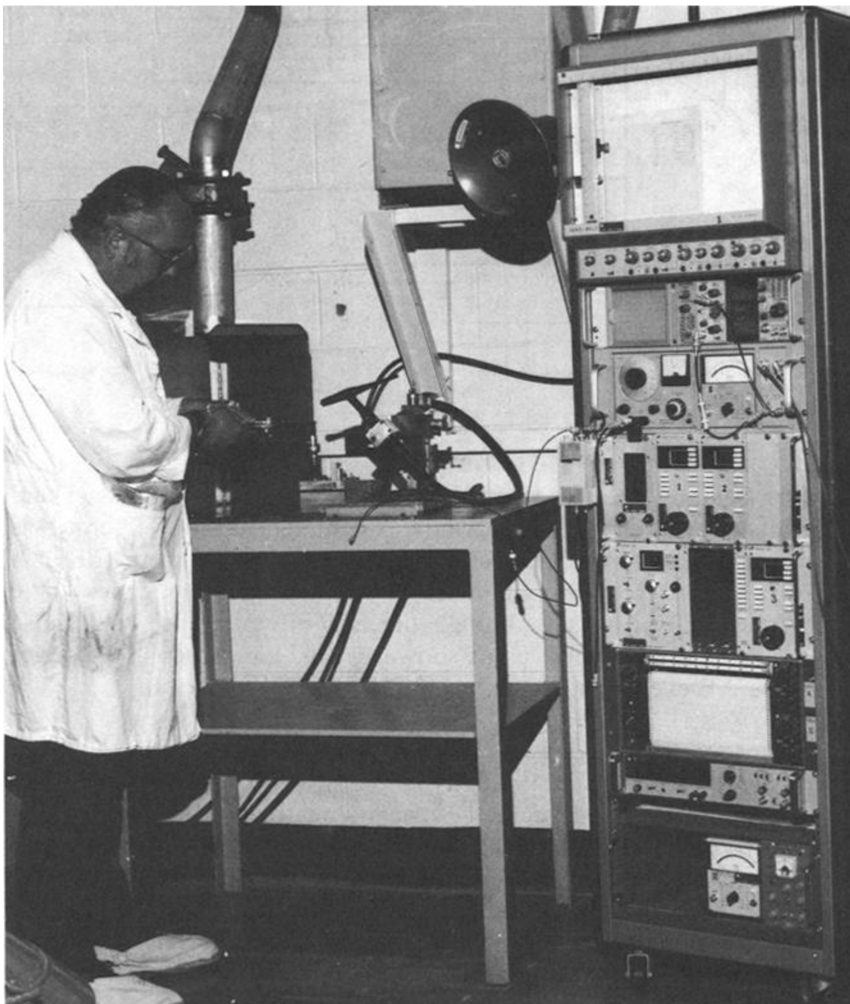

FIG. 13—*Test setup and acoustic emission instrumentation used in the crack susceptibility test of beryllium coupons.*

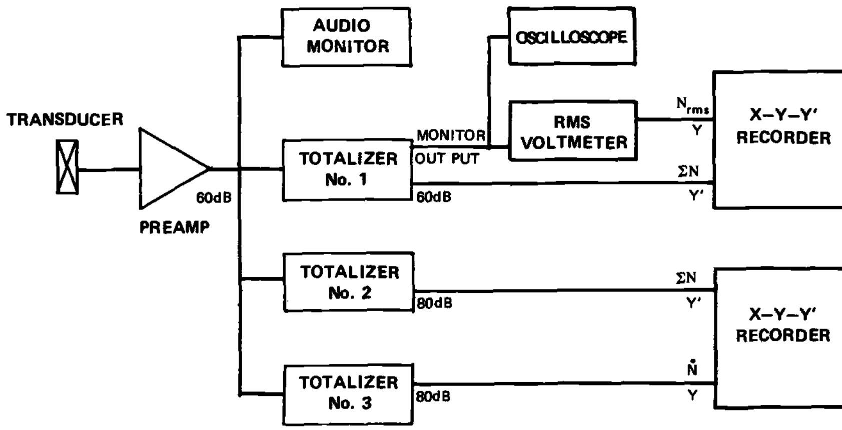

FIG. 14—*Block diagram of acoustic emission system used to determine crack susceptibility of beryllium coupons.*

300 kHz. Desirable beryllium material has good fracture toughness and will produce a star shaped crack which is confined to the weld crater as shown in Fig. 15*a*. This crater cracking produces no AE at 60 dB gain as shown in Fig. 16. In beryllium having poor fracture toughness—the crater crack will propagate through the heat-affected zone and cause gross cracking in the specimen as shown in Fig. 15*b*, producing a series of discrete AE events as shown in Fig. 17.

Summary

Acoustic emission is an extremely sensitive, dynamic method of nondestructive testing. It detects signals from real events when they occur. The real "name of the game" is to interpret emissions as to the mechanisms that generated them and then analyze this information in relation to the entire structure. From this type of analysis one can get detailed information about how a specific structure is failing. This in terms of fracture mechanics provides us with one of the most useful and reliable tools to evaluate the integrity of engineering structures.

AE monitoring during proof testing of a structure or pressure vessel, guided by fracture mechanics principles, can ensure that there are no active flaws to cause failure during the service life of that structure or pressure vessel. Therefore, AE provides us with a new concept in nondestructive testing—not merely a means of detecting discontinuities and the traditional NDT concept of accept or reject based on size, location, and distribution of these discontinuities—but a decision based

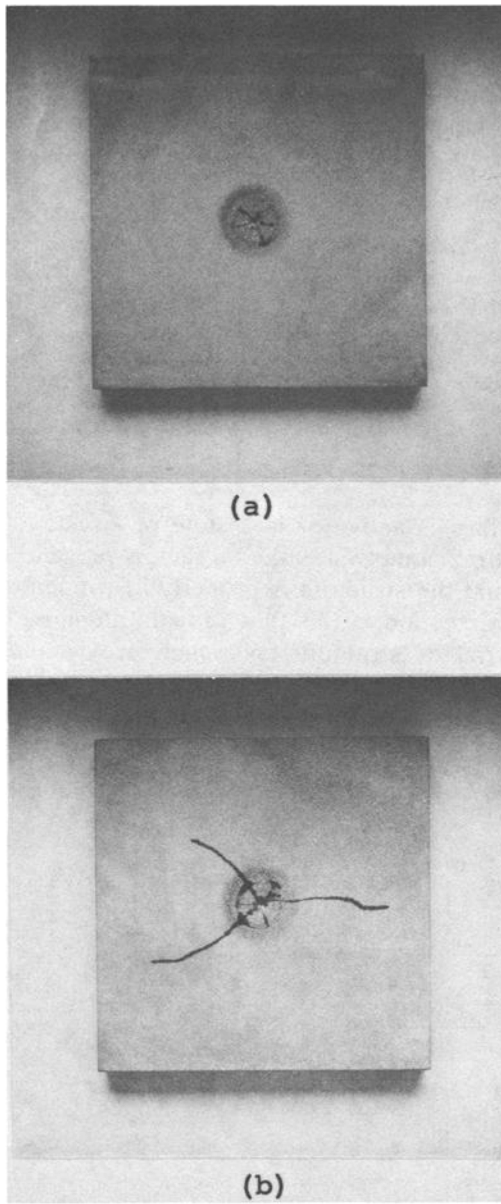

FIG. 15—*Beryllium weld test coupons showing crater cracking in Specimen WT-70* (a) *and gross cracking in Specimen WT-71* (b).

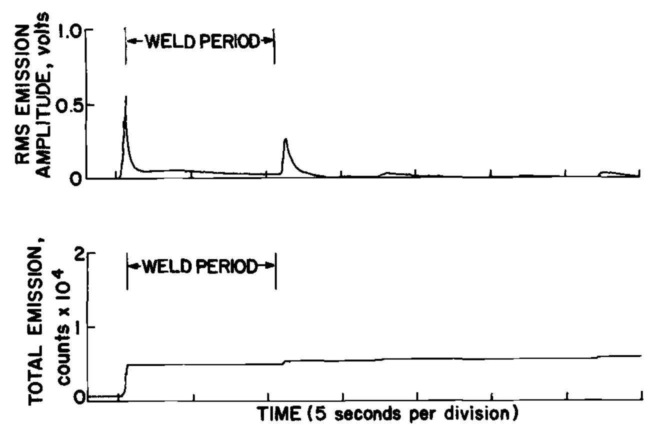

FIG. 16—*Acoustic emission record of crater cracking in beryllium weld Specimen WT-70.*

on whether a flaw is active or in a state of arrest. It must be remembered, a structure cannot fail unless a flaw is present and grows. When that happens and the structure is properly instrumented, AE activity is detected. The detection of this flaw growth, along with a knowledge of how the material or structure fails, then provides us with a tool to detect incipient failure in that structure.

For a more complete background in the fundamentals and broad application of AE technology the reader is referred to Refs 33 through 48.

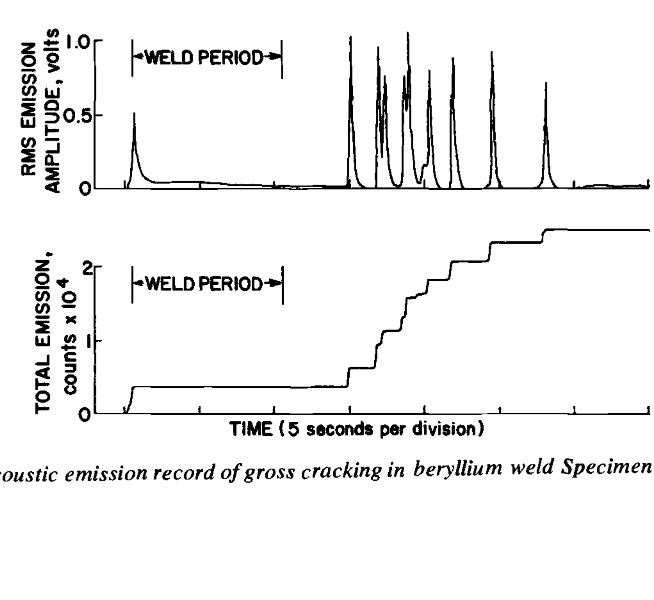

FIG. 17—*Acoustic emission record of gross cracking in beryllium weld Specimen WT-71.*

Acknowledgment

This work was performed under the auspices of the U. S. Atomic Energy Commission.

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Industrial Application of Acoustic Emission Analysis Technology

REFERENCE: Parry, D. L., "**Industrial Applications of Acoustic Emission Analysis Technology,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 150–183.

ABSTRACT: Acoustic emission analysis technology as a nondestructive testing tool is being applied in industry to a wide variety of structures. Its acceptance, however, has been more rapid in industries where it is applied to metallic pressure containment structures. These applications include pipelines, piping systems, storage vessels, pressure vessels, and even complex pressure containments such as the primary coolant systems of large nuclear power plants.

The application techniques used and a description of typical results obtained during field applications provides additional insight into a new powerful testing tool that is rapidly gaining acceptance throughout the industry.

KEY WORDS: acoustics, emission, nondestructive tests, pressure vessels, pipelines, nuclear power plants, steel structures, tanks (containers)

Less than a decade ago acoustic emission (AE) analysis was primarily a research subject. Today it has developed into a testing tool which is rapidly expanding the capabilities of the nondestructive testing (NDT) field.

The technology, which in this paper will be referred to as acoustic emission analysis, detects and analyzes minute AE signals generated by discontinuities in materials under applied stress. Proper analysis of these signals can provide information on the location and structural significance of the detected discontinuities.

AE analysis provides the following distinct advantages over traditional NDT techniques such as ultrasonics and radiography:

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1. It provides a complete integrity analysis of a structure during a fast, one-step test.
2. It is a dynamic testing tool in that it measures the response of a discontinuity to imposed structural stresses.
3. It can detect and evaluate the structural significance of flaws which may be inaccessible to the traditional NDT techniques.
4. It requires only limited access and downtime for the requalification of inservice structures.
5. It can be used to limit the maximum pressure during pressure testing of containment systems and prevent failure if the structure contains a significant discontinuity.

AE analysis is now being used in the United States, Europe, and Japan for the nondestructive evaluation of structures ranging in complexity from simple fluid transmission pipelines to the complex primary containment systems of large nuclear power plants. The technology is equally applicable for the acceptance testing of new structures or the requalification of in-use structures. Its acceptance as a NDT tool is now being evidenced by a special American Society of Mechanical Engineers (ASME) ad hoc committee which is formulating application and acceptance standards for AE analysis technology.

In the last three and one half years alone Exxon Nuclear Company, Inc.'s nondestructive test services organization has tested 83 major industrial structures using their AE systems. These tests have been conducted on such structures as pipelines, heat exchangers, storage tanks, petrochemical pressure vessels, nuclear pressure vessels, and the entire primary coolant systems of large nuclear power plants.

This paper discusses the field application of AE analysis, and describes specimens of the results that have been obtained by application of the technology for the integrity analysis of large, complex industrial structures.

Discussion

AE analysis techniques can be applied to a wide variety of structures and materials [*1-7*].[2] The technique has been applied by imposing stress on materials such as wood, plastic, fiberglass, concrete, and, of course, metals. The emission producing mechanisms in each type of material is different, but the result is the same; pulses of energy are generated.

The generation of AE usually requires that a stress be applied to the structure undergoing test. It need not be a large amount of stress nor does it generally need to be a specific type of stress. Beamed structures can be loaded, torsional stress can be applied to rotary shafts, thermal

[2] The italic numbers in brackets refer to the list of references appended to this paper.

stresses are applied to materials during welding, or pressure induced stress can be applied to pressure containment systems.

This paper deals primarily with metallic pressure containment structures which can be stressed either pneumatically or hydrostatically. Exxon Nuclear, however, has tested other types of structures utilizing both thermal stresses and mechanical loading.

Structures that are stressed for the first time will emit acoustic signals from all structural discontinuities, including deformation emission due to minor yield in localized regions of high-stress concentration. Immediate reloading of a large structure will produce 50 to 75 percent less emission and only from discontinuity regions. Additional repeated loadings will normally produce approximately 10 percent of the original amount of AE; this AE release generally begins at approximately 90 percent of the maximum stress level previously applied.

Some investigators have chosen to call this phenomena the "Kaiser effect" [*8*]. However, the Kaiser effect relates more specifically to irreversible dislocation movement. In a nondefective material under stress, dislocations will move until pinned, thus producing a relatively irreversible emission source.

In a large structure small minor discontinuities may grow under a certain amplitude of externally applied stress until opposing internal regions, such as the plastic zone around the leading edge of a microcrack, match the stress levels imposed by external mechanisms; this produces a temporary irreversible emission source. However, cyclic stress application will cause an opening and closing of the larger cracks which result in incremental crack growth. This crack growth produces acoustic signals on each cycle. In addition, acoustic signals are produced by surface-to-surface movement of the crack and possibly various other mechanisms.

The end result is an output of AE's from the more prominent discontinuities near the top peak of each stress cycle which is imposed on a large structure. These signals, just as in a standard one cycle stress test, can be utilized to determine the presence and relative significance of defects.

It has also been noted on large structures that a short period of relaxation of structural stress will allow a partial recovery of the structure's AE activity. For example, vessels that have been operating at high continual stress loadings, and then shut down for four to five days will, upon restressing, produce AE from the majority of structural discontinuities regardless of their size or significance. The vessel acoustic signature produced by restressing usually represents a total acoustic energy release value of within 15 percent of that experienced during the initial preservice pressurization.

AE analysis techniques, therefore, may be equally applicable for the integrity analysis of new structures or the requalification of in-use structures. The only major variant is the method or stress technique best suited for evaluation of the structure.

Test Systems

This paper describes the AE analysis system and application techniques used by Exxon Nuclear in field service testing of industrial structures. However, most acoustic analysis test systems function by using the same basic principles. AE's are detected by the placement of acoustic transducers on the surface of the structure to be tested, the detected signals are amplified and analyzed to determine the severity of the defects and their locations.

Detection and Signal Conditioning

Figure 1 shows a block diagram of Exxon Nuclear's ACOUST[3] systems. Acoustic signals detected by transducers located on the structure are amplified by special low-noise, high-gain preamplifiers. These signals are transmitted through signal cabling to the main unit, where additional signal conditioning takes place. The detection and signal conditioning circuitry may be operated at several select frequencies ranging from 30 kHz to 2.5 mHz. One hundred kHz are utilized for the testing of most pressure containment structures.

After conditioning, the signals are processes through two analysis systems. These systems are the energy release system, and the significance and location computer systems.

The energy release system monitors the amount of acoustic energy per unit stress being released from a structure and displays this signature for visual scan on a chart recorder. In actuality, several energy release circuits are utilized on complex structures; each circuit monitors different components of the structure, that is, pressure containment system pump casings, piping, valves, pressure vessels, etc.

The energy release circuitry is regarded as an early warning system that can provide immediate warning of possible "significant" crack growth. Figure 2 is an example of a signature showing the growth of a defect which is considered "significant" to the integrity of the structure undergoing test. The signature gives warning that a source or sources within the structure are producing AE's at an unstable rate. Normally, the occurrence of such a signature would require that the application of stress be halted while a cross check with computer data is made. The computer data display the location of the energy source and its relative magnitude.

[3] Trademark of Exxon Nuclear Company, Inc.

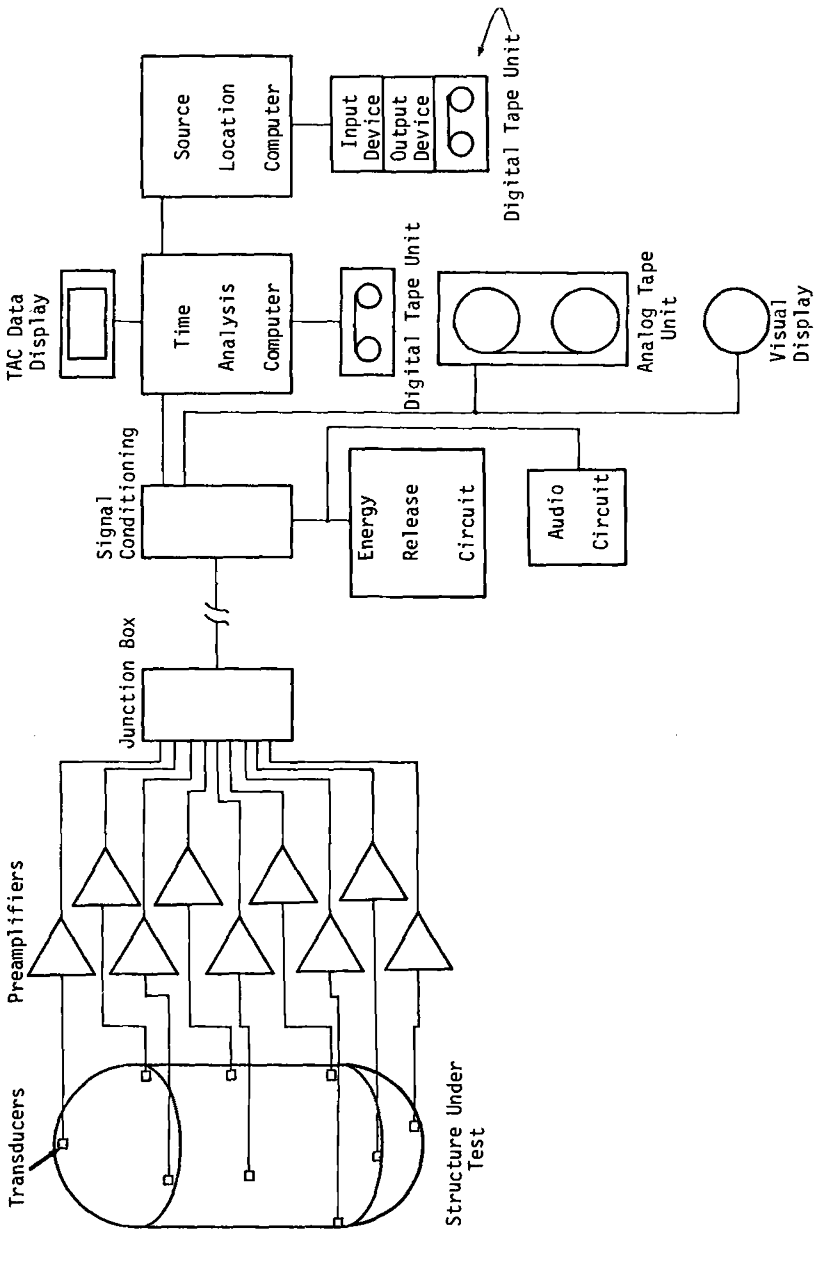

FIG. 1—*Block Diagram of Exxon Nuclear ACOUST systems.*

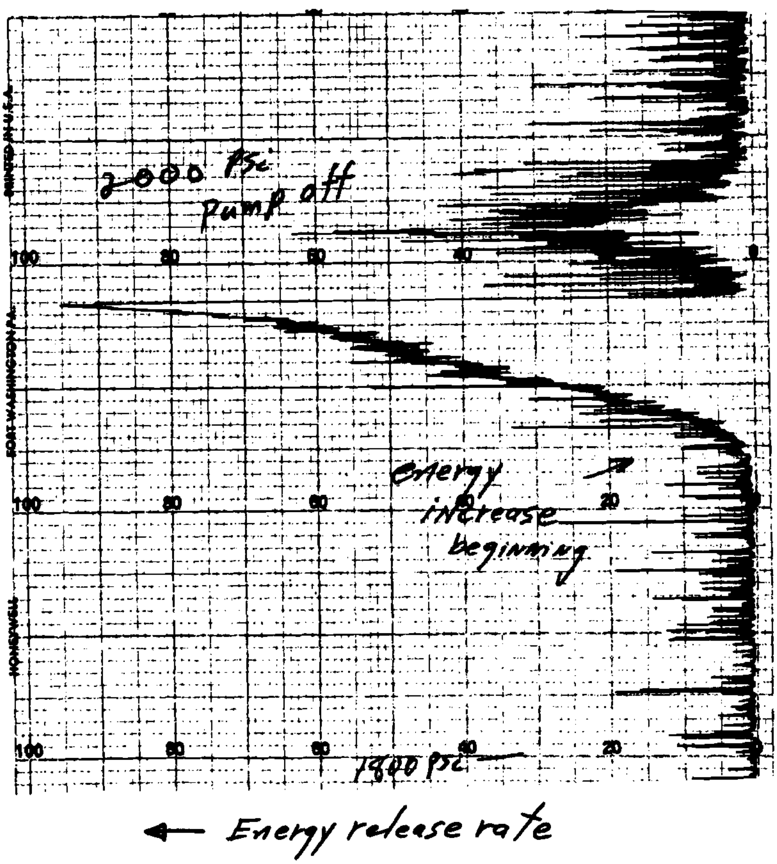

FIG. 2—*Acoustic energy release pattern showing significant defect growth.*

The computer significance and location analysis is actually accomplished by two computers, the time analysis computer (TAC) and a digital minicomputer. The TAC is a statistical computer which utilizes the input signals from the detection channels to determine the difference in the time-of-arrival (Δt) of the AE's at various tranducers. The Δt data generated by various AE sources are accumulated in the computer memory until they have become statistically valid. At this point the Δt information is fed into the digital minicomputer which has been programmed with information concerning structural geometry, exact transducer locations on the structure, and signal transmission velocities.

Defect locations and relative significance are computed by special

```
SPAIN
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          MAXIMUM COUNTS=
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44311212444443446443344566411134
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43210011244544545321234444423344
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31000012244575321202333334333443
440012444435344211122222232344332
120232335344333422222332224532432
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422121013431124344443003442144444
32222100034324334124333443222 3244 4
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21010111444444754444544354422 1111
21110102454465665445642443111111
12211023444358566555632344011121
22212023444355587646542343011121
22212223444245669675223321121 32
22212324444425677876412342112232
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22242234454423668564533331122222
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33433024453434455664443221113332
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44343234454434445654443211013342
43343234444434444654444211013342
NEXT?  (DATA,XDCR,PRNT,PLOT,CHNL,MTCH,
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FIG. 3—*Typical computer map of a pressure vessel showing six defects analyzed over a pressure range from 100 to 122 kg/cm².*

probability programs and displayed on a computer map (printout) which is a scaled geometrically accurate layout of the test structure. The computer maps display source location and significance by probability numbers ranging from "9" for the highest probability, to "0" for the lowest. An energy factor is displayed with the printout to allow a significance rating of data to be made. Figure 3 is a typical computer map of a pressure vessel showing six defects analyzed over a pressure range from 110 to 122 kg/cm^2. This map indicates that there were six defects emitting during this stress range. The most prominent source is designated as a "9", the next most prominent in a 9-in.-diameter area designated by "8", "8", "7"; there are four locations designated as "7" which are the least prominent emitters.

Computer maps such as these are summarized as they come from the computer by use of a scaled transparency of the structure under test. Figure 4 shows the summary map for the test from which the Fig. 3 example was taken. It can be noted that the computer summary shows all physical attachments and weld seams associated with the vessel. Upon completion of a test the computer summary shows all defects that emitted during the test; it tells the stress range during emission and their relative significance to structural integrity.

In the case where a significant defect is detected during the test, the TAC output is utilized as a first step confirmation of the energy release signature, that is, the energy associated with the defect is computed. The minicomputer probability map is utilized to cross check both the TAC and energy release analysis.

Auxiliary Systems

In addition to the data analysis circuitry of the ACOUST systems, visual and audio scan circuitry are employed to aid the system operator. All signals are placed on analog magnetic tape for the purpose of post-analysis of the test, should it be required, and also to provide a permanent record of the test. Digital magnetic tapes are used to store all computer derived data.

Figures 5 and 6 show the type of units used by Exxon Nuclear in field service application of acoustic analysis technology.

Application Techniques

The application of the ACOUST system for the integrity analysis of large structures requires that a coordinate system be established for location of transducers and the referencing of pertinent physical features of the structures. For example, in preparation for testing a large vessel, engineering prints and tape measurements are utilized to estab-

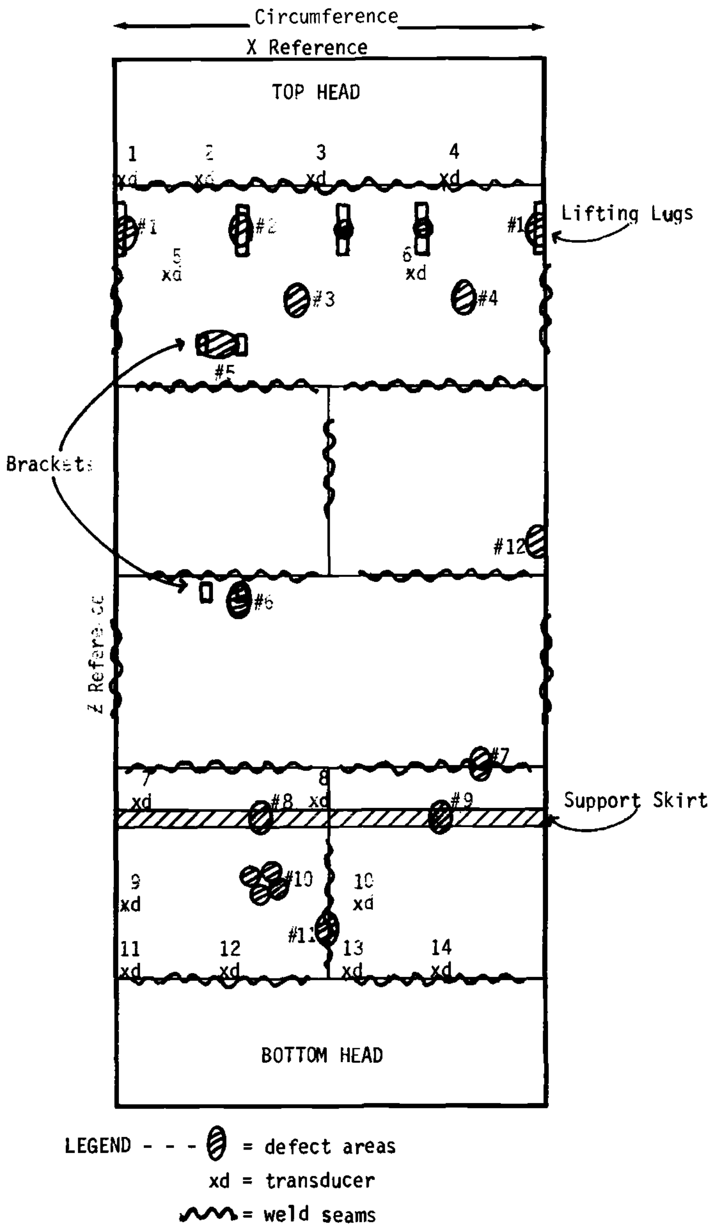

FIG. 4—*Computer summary map transparency of vessel layout.*

FIG. 5—*Type of units used in field service application.*

lish a coordinate system. After establishment of the coordinate system, transducer locations are chosen, and their position is referenced to the coordinate system. Transducer coordinates and vessel geometry are fed into the computer program.

The number of transducers is governed by the complexity of the structure and not its size. On a simple structure, such as a large cylinder, only four transducers may be required to analyze the entire cyclinder. However, if the cylinder contains numerous nozzles, weld attachments, and internals, then additional transducers will be required to provide precise defect location capabilities. This necessity becomes obvious when it is recognized that each nozzle represents a void in the cylindrical shell which acoustic signals must travel around in traversing the vessel. In Fig. 7, it is evident that if only Transducers 1 through 4 are used there will be deviations in transmission path lengths as the signals travel from the flaw to the transducers. This path length deviation will cause inaccuracy in flaw location. However, if four more transducers are added in the nozzle region, represented as Transducers 5 through 8; these four transducers will observe no perturbation in signal transmission path length, and precise flaw location analysis will

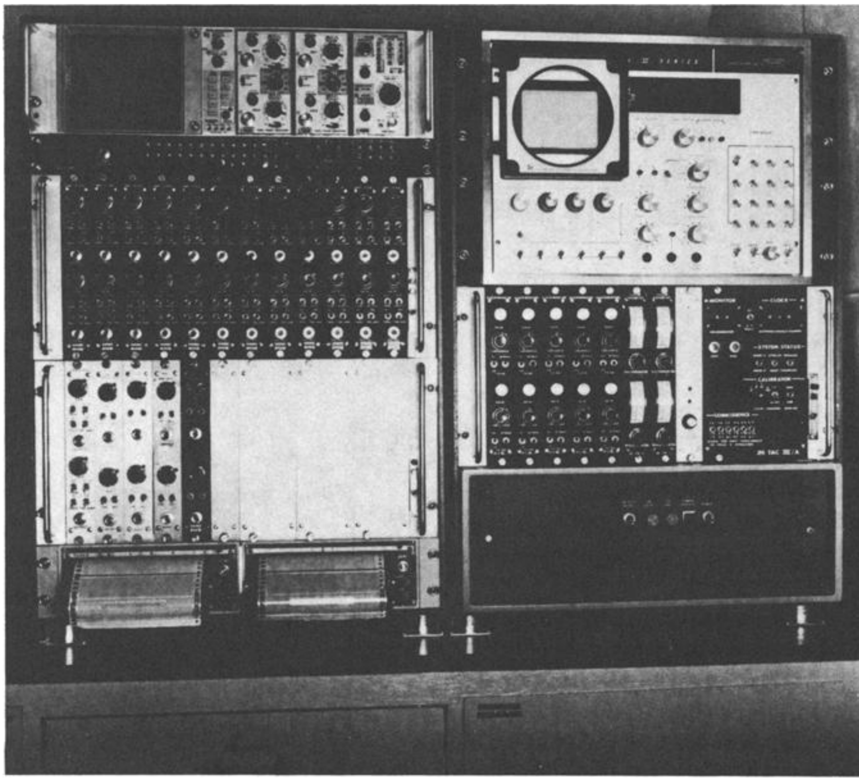

FIG. 6—*Type of units used in field service application.*

be possible. It is reiterated then that the number of transducers required to analyze a structure depends upon its complexity rather than its size. Normally 12 to 16 transducers are required to analyze a large chemical or nuclear pressure vessel. However, there are exceptions such as a boiling water nuclear reactor pressure vessel which contains up to 24 nozzles and, accordingly, may require up to 24 transducers.

Once the transducer positions are selected, a small area at each location is buffed free of scale or corrosion, and a transducer is attached by either epoxy or by magnetic mounts.

Preamplifiers are positioned adjacent each transducer (within 15 ft), and signal cables are connected to transmit the detected AE signals back to the unit.

Once the system instrumentation is completed, calibration begins. Calibration requires that simulated acoustic signals be induced into the

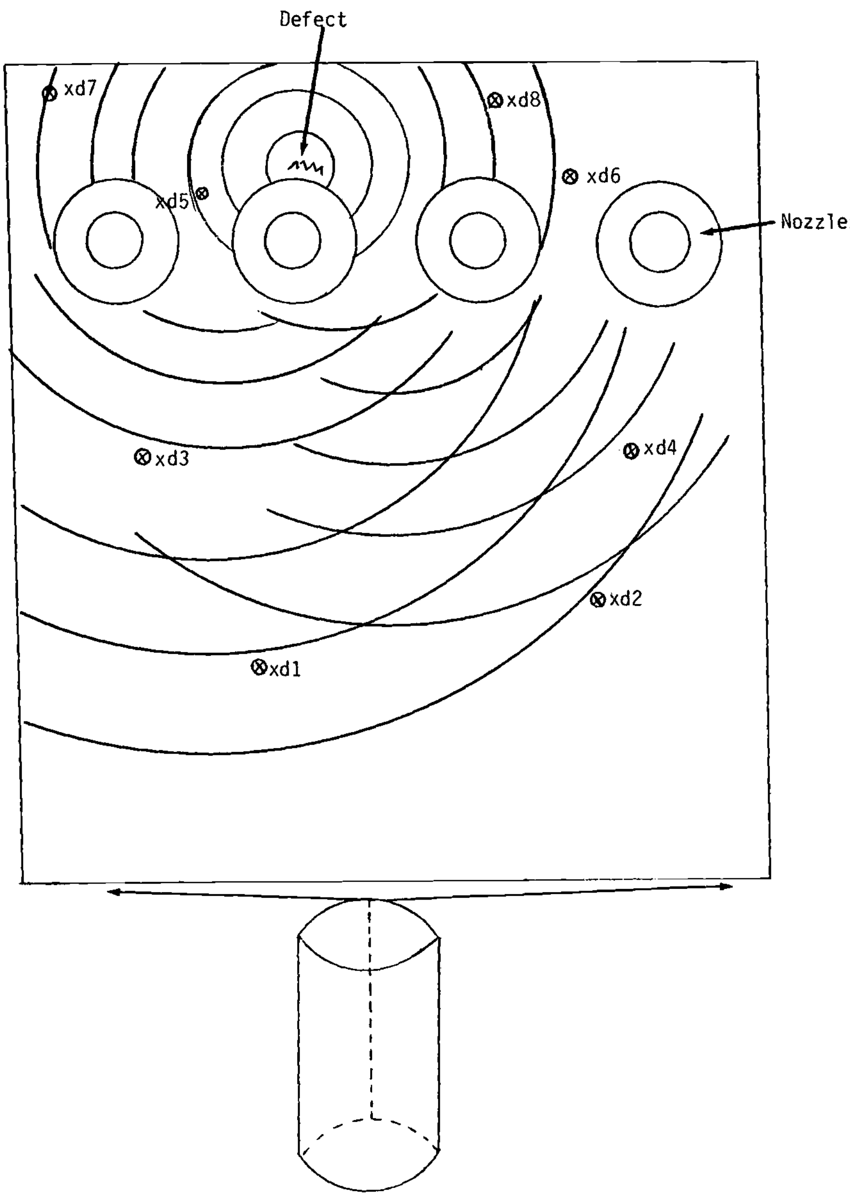

FIG. 7—*Vessel layout.*

structure. These signals are of known energy content and are utilized to determine transducer sensitivity and total system detection and defect location capabilities.

The vessel coordinate survey, transducer positioning, hookup of electronics, and system calibration usually require one to two days on a simple structure and three to four days on a more complex structure such as large nuclear or chemical vessels. It may take up to 14 days to prepare for conducting an integrity analysis of the entire primary coolant system of a large nuclear power plant. However, it should be understood that the setup and calibration of an acoustic analysis system can be conducted simultaneously with the conduct of normal operation or maintenance. Schedule delays are not incurred normally in the application of AE emission analysis for the qualification of new structures or the requalification of in-use structures.

Acoustic data acquisition and analysis start with the application of structural stress and continue through the structural loading period. On pressure containment systems this period is described by a hydrostatic or pneumatic stress ramp up to maximum pressure.

Computation of defect significance and locations is conducted throughout the test. On completion of the test the computer summary map may be used to define the position of various structural discontinuities, the stress range through which they emitted acoustic signals, and their significance to structural integrity.

The on-line analysis is supplemented normally by a post-analysis period using magnetic tape recorded data. The post-analysis is conducted to cross check and confirm all data results obtained during the test.

Test Results

NDT in industry, using AE analysis, encompasses many types of structures and structural materials. However, the tests chosen for discussion in this papèr are confined to various types of containment systems such as pressure vessels, storage vessels and tanks, piping systems, and nuclear power plant primary coolant systems. Ninety percent of the service tests conducted to date have involved these types of structures.

Pressure Vessels

AE analysis is being extensively used for the qualification of new pressure vessels and for the requalification of inuse pressure vessels.

Preservice acceptance tests of petrochemical or nuclear pressure

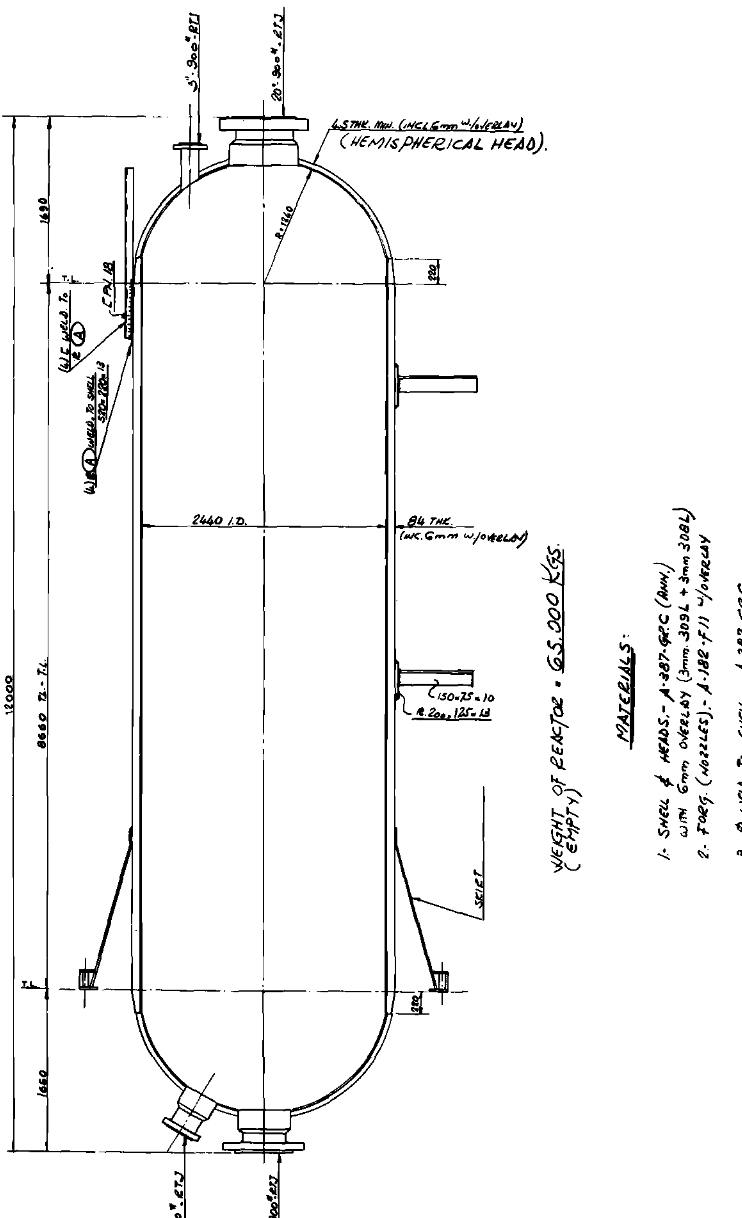

FIG. 8—Chemical pressure vessel.

vessels or both are conducted normally at the manufacturing plant in conjunction with the acceptance hydrostatic test. The vessel is located usually in the production shop in a readily accessible position. The vessel is surveyed, transducer positions are selected, and the transducers are mounted. Instrumentation is hooked up and calibrations completed. These operations can be conducted in conjunction with normal manufacturing preparations for hydrotest. However, some complications can arise from the manufacturer's requirements to heat (using gas heaters) and rotate the vessels up to the time of test. These types of complications can be overcome by locating transducers on regions of the vessel not exposed to the flames from the gas heaters. Calibration and checkout of instrumentation is conducted during a short period where vessel rotation is slowed or stopped. During this period the signal cables are connected, and the calibrations are conducted. Then the cables are disconnected so that rotation can be resumed.

Figure 8 illustrates a chemical pressure vessel tested under the conditions just described [9]. Fourteen transducers were used to instrument the vessel as shown in the vessel layout of Fig. 4. The vessel was approximately 39 ft tangent to tangent with an inside diameter of 8 ft, a wall thickness of 3.3 in.; with 0.2 in. of weld overlay cladding on the inner surface. The vessel was constructed of A387 Grade C steel and contained seven penetrations. The hydrostatic test involved a steady stress ramp of 5 kg/cm^2 per min up to a maximum pressure of 122 kg/cm^2.

Figures 3 and 9 show two of the six computer maps generated during the test. Figure 4 is the computer summary map transparency of the vessel (in layout form). Twelve discontinuity regions were identified on the vessel, eleven of these discontinuities were analyzed as Grade 1; Source 7 was analyzed as a Grade 2.[4]

Customer confirmation of these sources was obtained following the test by the use of dye penetrant, visual inspection, X-ray records, and ultrasonics.

The majority of the discontinuities were identified as fillet weld cracks on external appendages; some extending 4 in. in length. Source 7 was identified as a weld slag inclusion 8 mm in length and 18 mm below the surface; this discontinuity was analyzed and classified as a Grade 2 which was within the acceptance levels for the vessel. It should be noted that Source 7 was detected during one of the first computer analysis in the stress range from 12 to 23 k as shown in Fig. 9. Its presence was observed throughout the test.

[4] An explanation of Exxon Nuclear's grading levels are defined in the Appendix.

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PROBABILITY MAP
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          MAXIMUM COUNTS=
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63211111232335532111100000133335
66211112231323532211100000123236
65111112222212533211100000123355
63111223222102533211100001122356
52212253121102333321100001123376
52322353111102323332100001235376
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12332112111121111001111100122211l
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22233563113200111001112012252101
23533555212210112111012122551012
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11233555522535655333556665553110
11235353552223665555265556353210
12355353552222656555365555533210
12353553552332656555656535553310
23553535532322666555656355555320
23553535532222555655565355655330
NEXT?  DATA,XDCR,PRNT,PLOT,CHNL,MTCH,
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FIG. 9—*Computer map showing pressure data point for range 12 to 23 kg/cm*^{2}.

The vessel was analyzed by AE analysis and confirmed by standard NDT techniques; it was found to be of high integrity. It contained only one discontinuity of Grade 2 level which was within the acceptance levels of the vessel.

The use of AE analysis for the requalification of inservice vessels has definite advantages over standard techniques such as ultrasonics and radiography. For example, requalification of a catalytic reactor vessel used in the oil industry would normally require the following:

1. Take vessel out of service.
2. Remove insulation.
3. Open vessel and remove catalyst.
4. Clean inner surface.
5. Scaffold interior and exterior surfaces.
6. Scan welds with ultrasonics.

This operation is expensive in terms of catalyst lost and unit down time.

The simultaneous requalification of two such vessels using AE analysis was accomplished as follows [*10*].

1. Six-inch "plugs" of insulation were removed from the vessels, and acoustic transducers were installed.

2. System signal cable was connected and the system calibrated.

3. Both vessels were heated to near operating temperature and pressurized using hot flowing hydrogen (an operational gas).

4. Acoustic analysis of both vessels was accomplished during the pressurization and the vessels declared free of significant discontinuities.

5. The vessels were ready to be placed back in immediate service.

Inservice vessels are requalified normally by AE analysis during a pneumatic or hydrostatic pressurization to operating pressure or 10 percent above. However, in certain cases where a vessel or piping system cannot be taken out of service, a cyclic stress technique can be used to evaluate acoustically the integrity of the structure. This technique requires instrumenting the vessel during operation. After calibration and checkout are completed, cyclic stress is applied to the vessel by repeatedly dropping the pressure as low as possible and then increasing it back to the operating pressure level. The majority of the AE data is acquired normally during the top 10 percent of the stress cycle as explained in the "Discussion" section.

Acoustic source information is collected during each cycle; These data may be analyzed in an identical manner to that used for a straight one-cycle hydrostatic or pneumatic test.

A classical example of the potential of this method for integrity

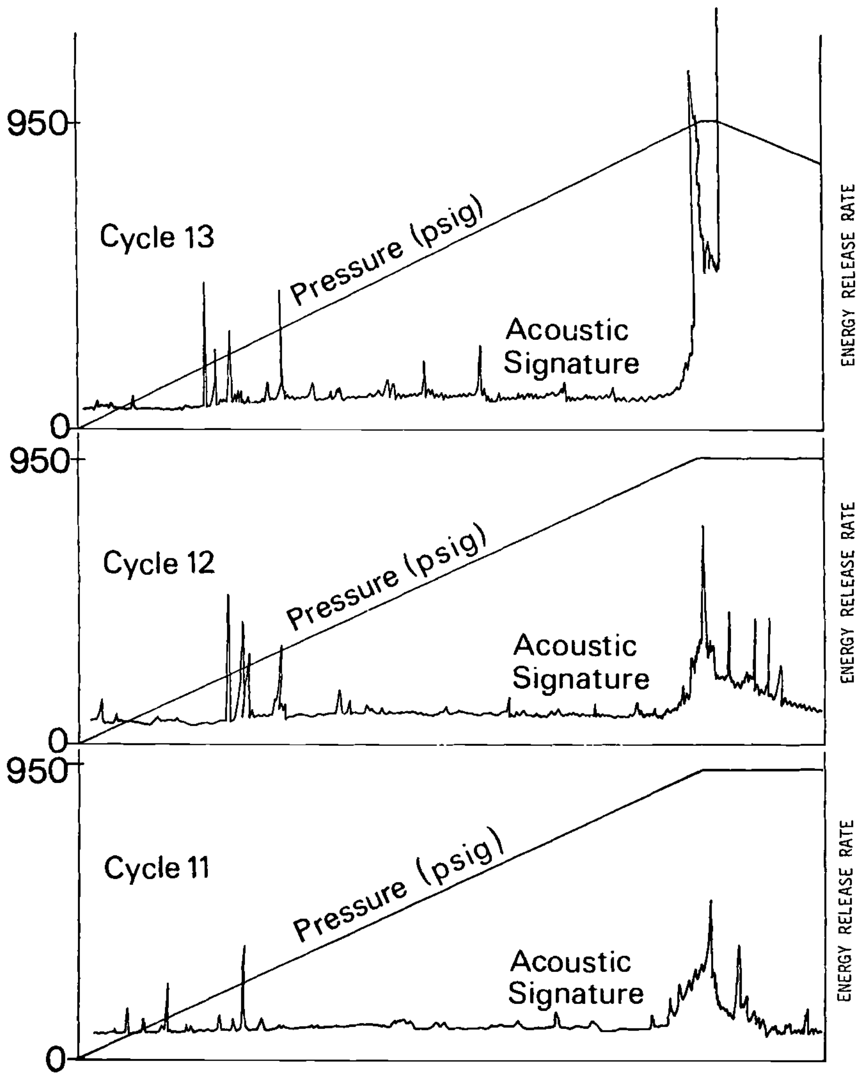

FIG. 10—*Acoustic signature of cyclic failure.*

analysis of a vessel is demonstrated by a recent test for the evaluation of the capabilities of AE analysis [*11*].

In this test, AE analysis was applied to an experimental pressure vessel which contained four concealed defects. The primary purpose of the test was to assess the capability of the technology to detect and

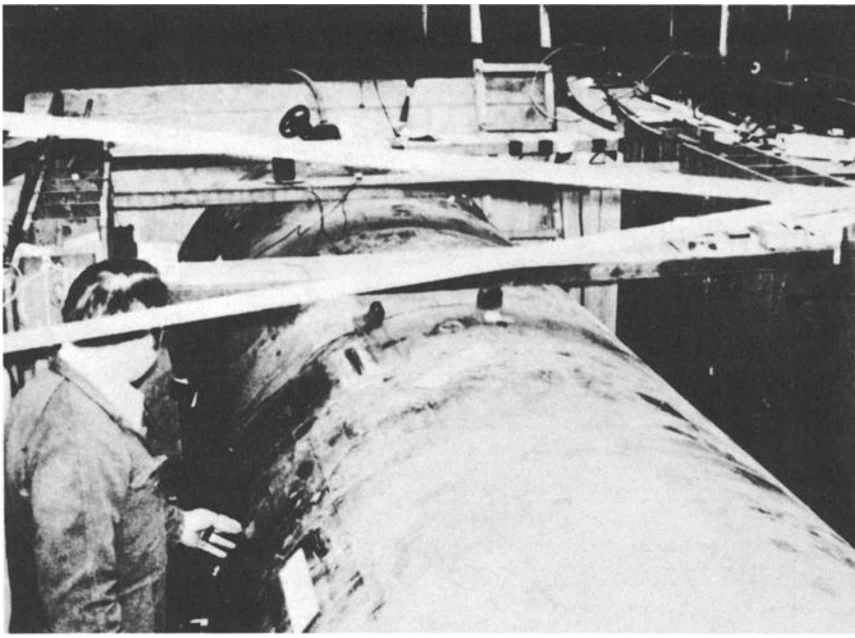

FIG. 11—*Failed pressure vessel.*

locate defects and predict impending vessel failure under the stress conditions imposed by a cyclic hydrostatic pressurization.

One of the defects was detected only in the early stages of the test; however, the remaining three defect regions were observed throughout the test. Two of these three were identified as primary sources during the final pressure cycles to failure; one of which caused vessel failure. Vessel failure was predicted two cycles before it actually occurred. The acoustic energy release signatures allowing this prediction are shown in Fig. 10. Note that more acoustic data are present at lower pressures during each successive cycle; also note the rapid increase in energy release rate during the last 10 percent of each cycle.

Figure 11 shows the vessel and one of the uncovered defects following the test.

Storage Vessels and Tanks

Storage vessels and tanks are often periodically requalified for service by a random ultrasonic inspection of sections of various structural welds. This technique leaves some doubt that all of the welds are in the same condition as the sections that were chosen to be scanned.

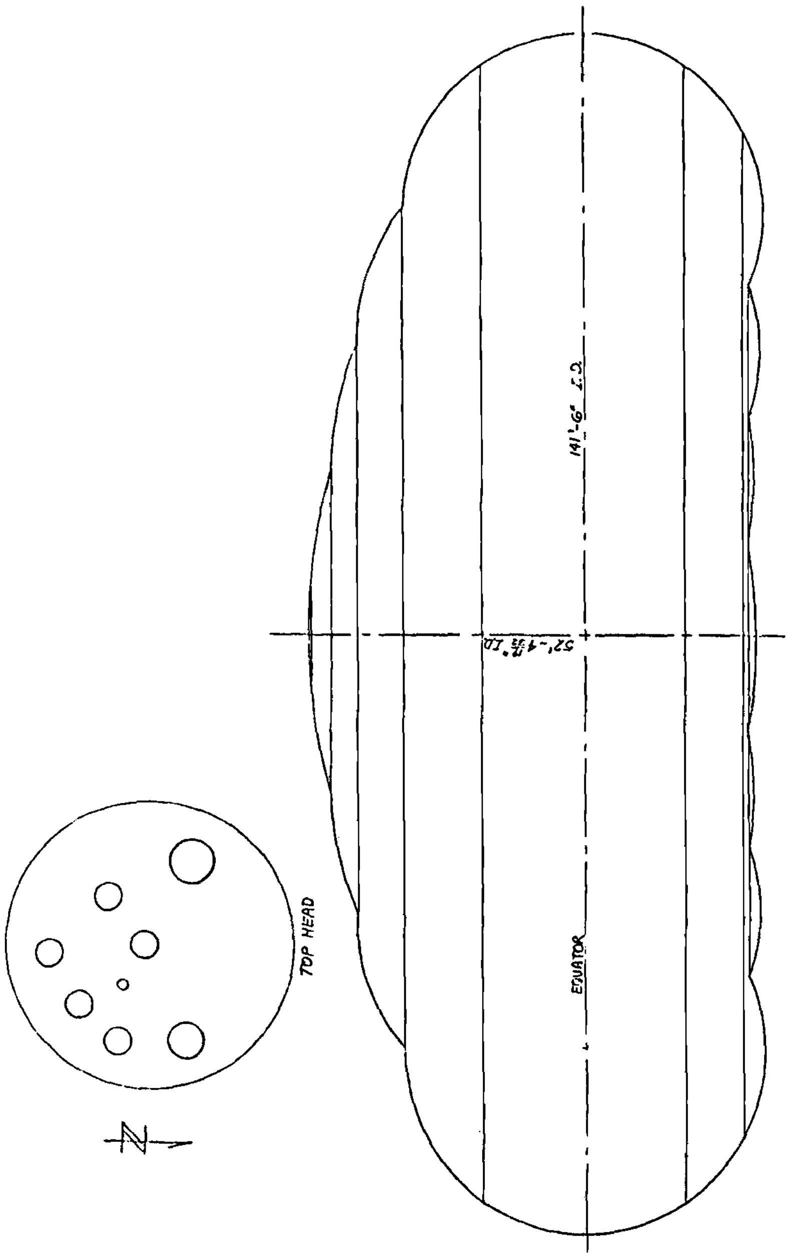

FIG. 12—*Hortonspheroid sphere storage tank.*

AE analysis provides a means of requalifying such structures by a 100 percent analysis of all welds. Such a test is illustrated by the requalification of a Hortenspheroid storage tank measuring 142 ft in diameter and 52 ft in height [*12*]. This vessel, a sketch of which is shown in Fig. 12, was surveyed and instrumented with 20 transducers as shown in Fig. 13. The vessel which contained 25 ft of fluid was first stressed by filling slowly to the 29 ft level; this fill operation placed stress primarily on the vessel walls. The vessel roof was next stressed by the injection of 12.5 psig of air. AE data were detected, processed, and analyzed through both fill and pressurization stages.

During the test, 16 minor discontinuities, as shown in Fig. 13, were detected, located, and classified as Grades 1 and 2, that is, insignificant to the integrity of the structure. Table 1 describes each discontinuity location. The majority of the discontinuities were attributed to minor weld defects and in some cases support bracket and flange movement. Accordingly, the vessel was requalified for service.

Pipeline Analysis

A NDT problem common to many industries is the integrity analysis of buried pipelines. AE analysis provides a quick, accurate, and efficient means of evaluating miles of buried pipelines. Exxon Nuclear, to date, has conducted nine pipeline tests using AE analysis.

These lines have included a wide variety of types such as radioactive waste transfer lines, diesel fuel oil transfer lines, and natural gas transmission and distribution lines.

TABLE 1—*Discontinuity locations.*

Source	Phase of Test	Location Description
S1	Phase I	circumferential weld junction
S2	Phase II	circumferential weld
S3	Phase I and II	buckle in tank
S4	Phase II	circumferential weld
S5	Phase I and II	fire line support brackets
S6	Phase II	circumferential weld junction
S7	Phase I	ladder support
S8	Phase II	circumferential weld
S9	Phase II	buckle in tank at weld
S10	Phase I	circumferential weld
S11	Phase II	circumferential weld junction
S12	Phase II	circumferential weld
S13	Phase I	circumferential weld joint
S14	Phase I	circumferential weld joint
S15	Phase I	circumferential weld
S16	Phase I and II	possible flange movement

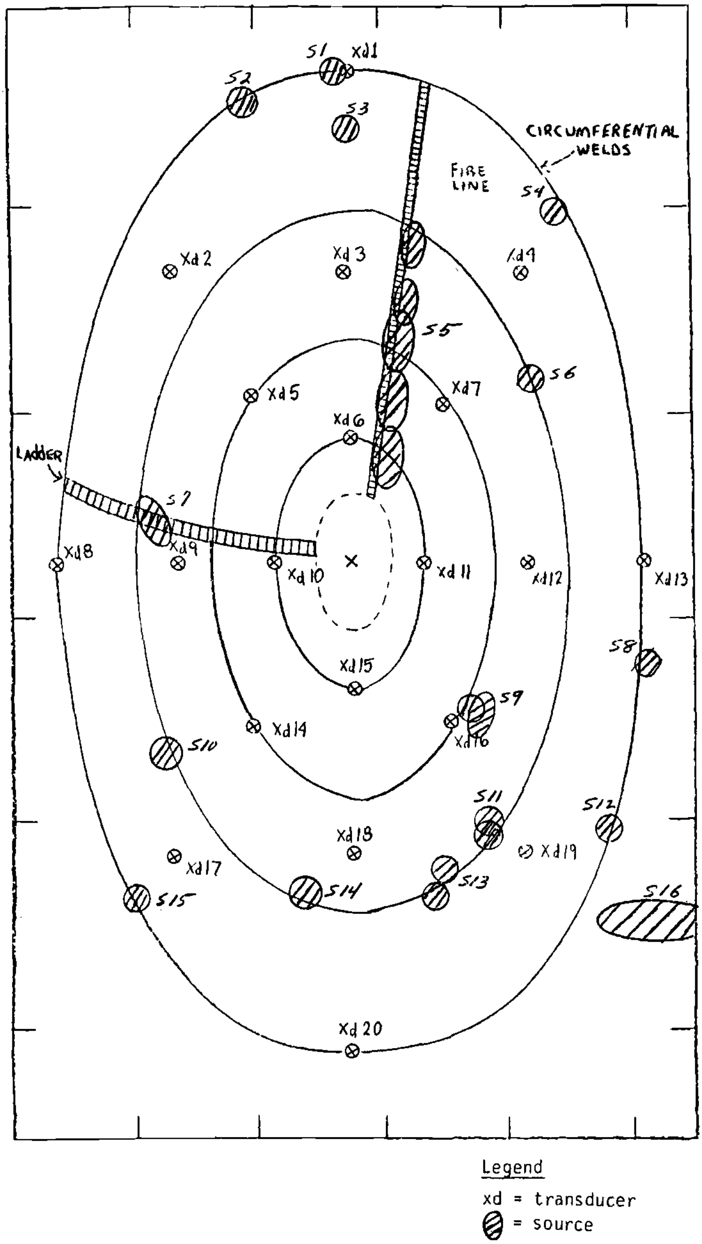

FIG. 13—*Minor discontinuities in Hortonspheroid sphere storage tank.*

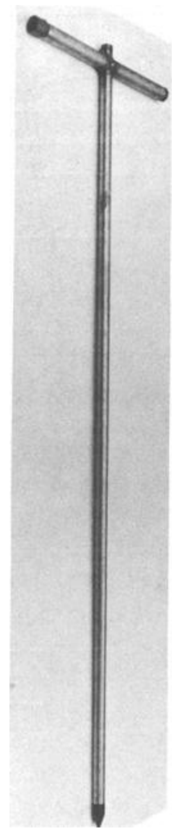

FIG. 14—*Special pipeline acoustic probe.*

AE analysis techniques were utilized in these tests for both crack and leak detection. The ability of the systems to detect and locate minute leaks is phenomenal as demonstrated by a recent test on a 1400 ft section of buried diesel fuel line. Five detectors applied to the line were able to detect and locate a 1-ft^3/h leak when the line was pressurized with air.

The number of transducers required to test a pipeline is dependent upon the quality of the pipe, that is, grain size, type of joining welds, etc. On old lines joined by poor quality butt welds, transducer spacing may have to be as close as 200 ft; however, on high quality lines with full penetration welds, transducer spacings can be as great as 1000 ft.

The ability of AE analysis to evaluate the integrity of a pipeline was demonstrated on a 6600-ft section of 12-in. low pressure gas distribution line [*13*]. Attenuation measurements on this butt welded line, which had been buried over 50 years ago, indicated the need for transducer spacings of 230 ft.

To instrument the line the customer bored 2-in. holes through the covering earth every 230 ft. A special pipeline acoustic probe (Remote Acoustic Probe[3]), as shown in Fig. 14. was placed down each hole and into contact with the pipe surface. Surface contact for good acoustic coupling was made by a special sharp tip transducer located on the end of each probe. Signal cables were run to each probe from a centrally positioned mobile system.

The line was tested in two phases for comparison of stressing techniques. The first phase required pressurizing the line to 120 psig using nitrogen; during this pressurization acoustic data were accumulated and analyzed. The second phase involved overhead loading of the line by stressing with a heavy vehicle. Figure 15 shows the vehicle stressing the line (which was buried 4 to 6 ft) by driving its length with one set of wheels directly above the line.

Thirty-five emission sources were detected and located in the 6600-ft pipeline. Figure 16 shows an example of a TAC display locating these types of sources. All were analyzed as insignificant to the integrity of the line under the imposed stress conditions.

Following the test the pipeline was excavated at the locations where the six most prominent sources were indicated. Pipe welds were found at each of the six locations. A section of pipe containing each weld was removed from the line and capped for hydrostatic pressurization. Two other weld sections not indicated by acoustic analysis as containing defects (sources) were removed and capped for hydrotest as control specimens.

These eight sections were cyclic stressed to failure in the laboratory by the customer. All six welds that were indicated by AE analysis to contain discontinuities failed after a relatively low number of cycles, as compared to the two control sections [*13*].

After a series of such tests the customer concluded that AE analysis, as applied during both pressurization and overhead loading of buried pipelines, could detect and accurately locate defects in joining welds.

Acoustic analysis technology is now planned for use by this customer in evaluating hundreds of miles of gas distribution pipelines.

Nuclear Plant Primary Coolant Systems

Perhaps the most complex use of AE analysis today is its application for the integrity analysis of the primary coolant systems of large nuclear power plants. These systems contain large thick-wall, multinozzled

FIG. 15—*Heavy vehicle stressing the line.*

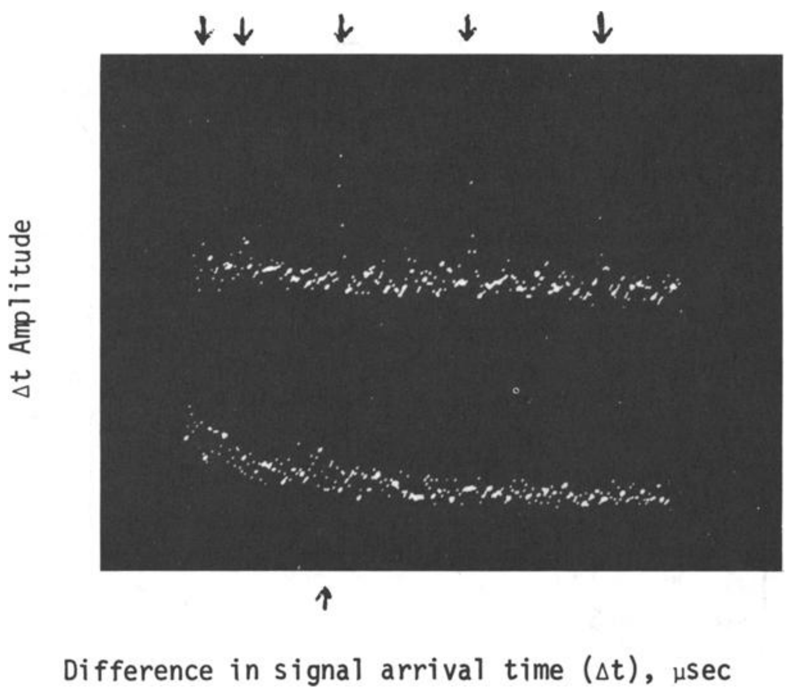

FIG. 16—*Defective welds in 180 ft section of low-pressure gas line.*

pressure vessels, three to four large pumps and steam generators, a large pressurized vessel, valves, and hundreds of ft of thick-wall high-pressure piping.

The preservice and inservice qualification of such systems requires thousands of manhours of effort using ultrasonics and surface inspection techniques. AE analysis can provide an analysis of the complete system during the perservice hydrostatic test or upon repressurization for approach to power after shutdown maintenance and refueling periods.

Figure 17 represents one loop of a four loop plant showing acoustic transducer locations on pumps, valves, piping, and the reactor pressure vessel. Note that each component is instrumented with four to six transducers. These transducers are required for precise location of structural discontinuities detected during the test.

Normally, 60 to 80 acoustic transducers and signal conditioning channels are required for the integrity analysis of the complete primary coolant system of a nuclear plant.

Figure 18 shows typical transducer locations on the reactor vessel of

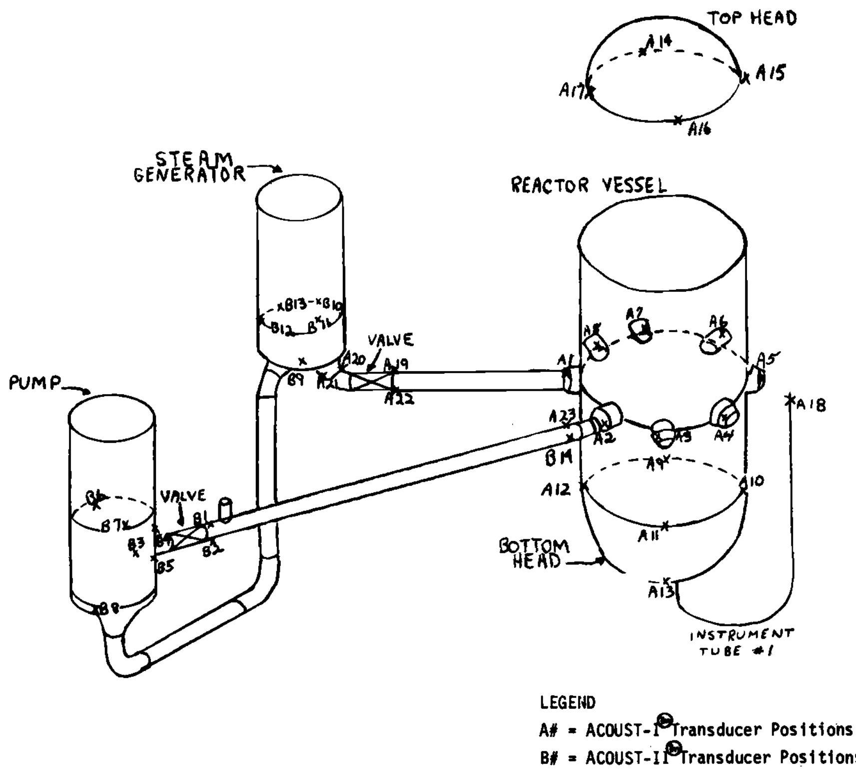

FIG. 17—*Plant showing acoustic transducer locations on pumps, valves, piping, and reactor pressure vessel.*

a pressurized water reactor plant (PWR). Transducer locations are governed by the accessibility to the vessel. Accessibility is normally available at the main nozzles and on the bottom head of the vessel.

The top head of such a vessel is a complicated structure containing up to 60 penetrations as seen in Fig. 19. The top head is instrumented with five to six transducers and is treated as a separate component. This is required because it is isolated acoustically from the remainder of the vessel by seal rings.

Figure 20 shows a top view of a complete PWR primary system. Sixty transducers were used to conduct an integrity analysis of this system during the preservice hydrotest [*14*]. (Not all transducers are shown in Fig. 20). The transducers are positioned such that they may be used to analyze each component of the system as well as the attached piping. For example, Transducer 54 on the steam generator

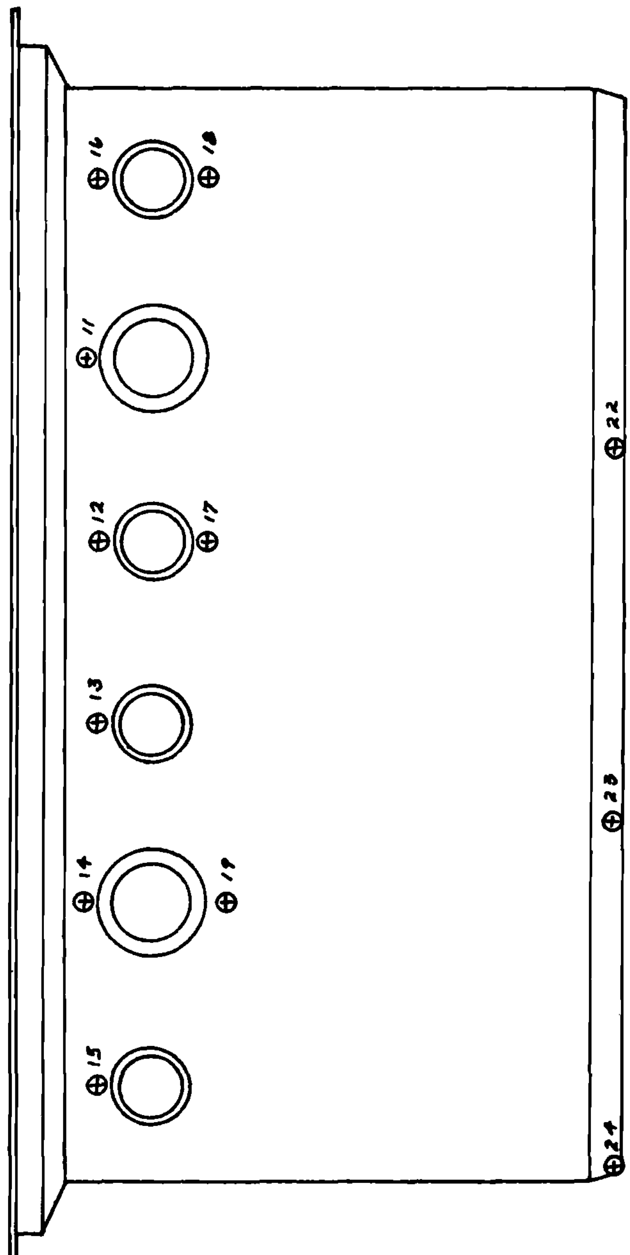

FIG. 18—*Reactor pressure vessel transducer locations.*

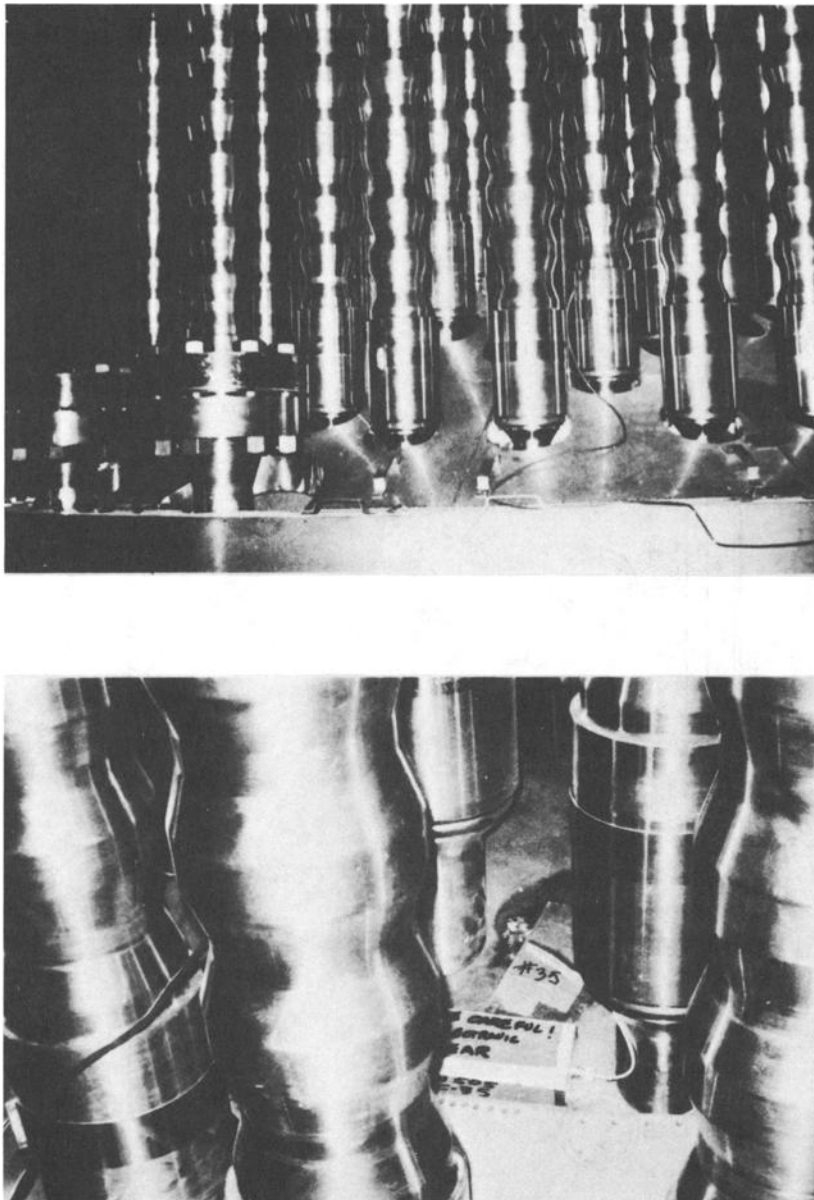

FIG. 19—*Nuclear reactor closure head.*

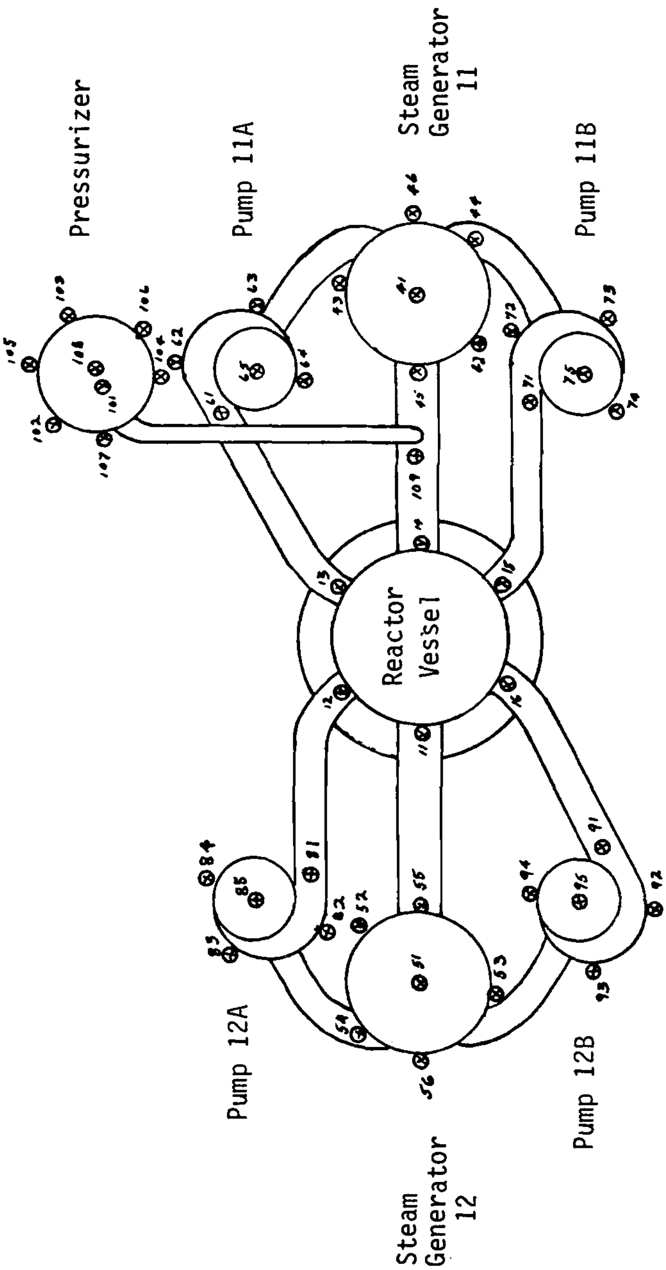

FIG. 20—*Nuclear power plant primary coolant system transducer placement.*

and Transducer 85 on the coolant pump are used in conjunction with other transducers to analyze the steam generator and pump volute. However, they also are used to analyze the main coolant piping which connects the two units.

The primary difference between the testing of a single structure and the testing of a nuclear plant primary coolant system is that the nuclear system contains multiple structures with multiple configurations all of which have to be tested simultaneously. The entire system has to be analyzed as a whole. This becomes obvious when it is realized that acoustic signals appearing at the reactor vessel nozzle may not be originating from the nozzle; they may be coming down the connecting

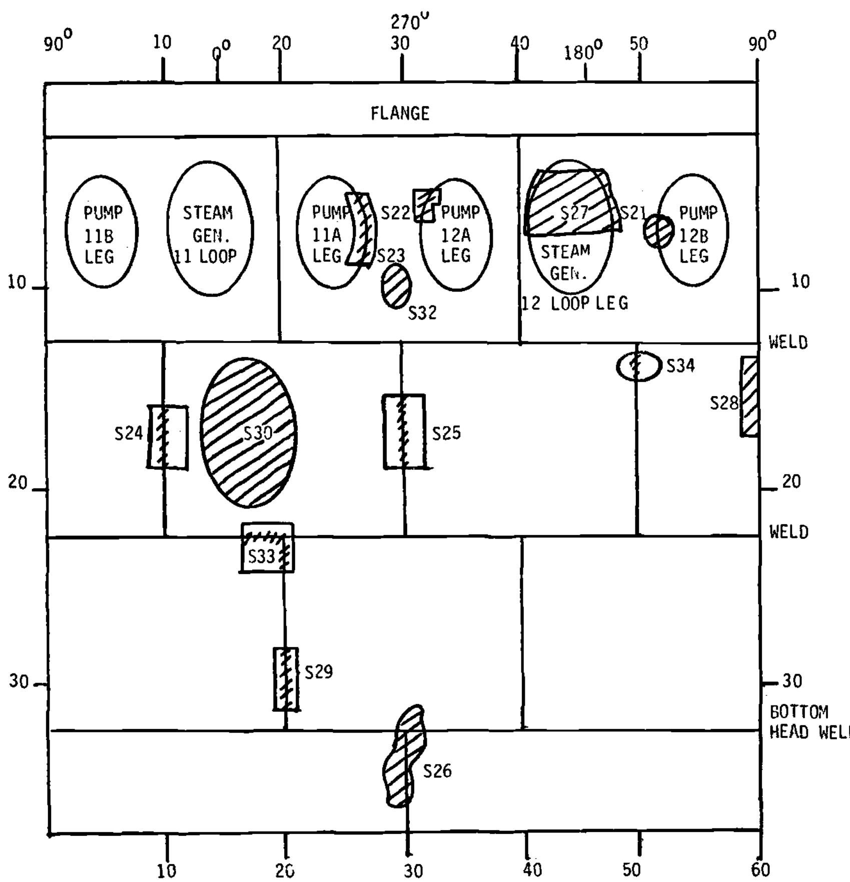

FIG. 21—*Nuclear vessel computer summary map.*

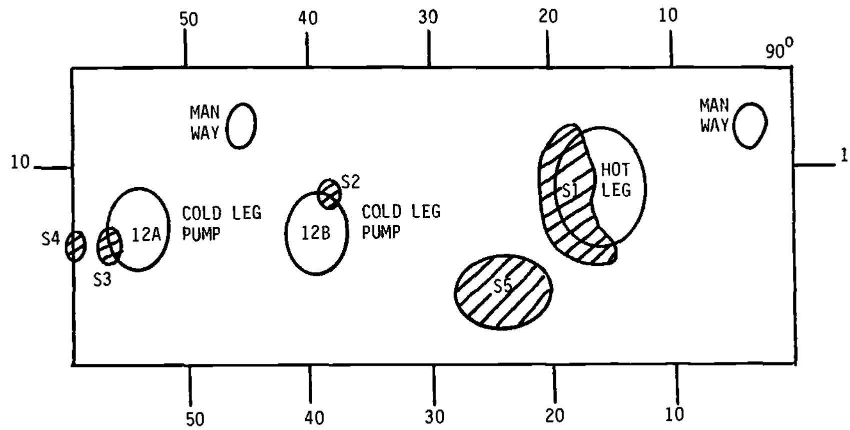

FIG. 22—*Steam generator 12 view inverted from computer map.*

piping from a discontinuity in the pump or steam generator, or perhaps from the pipe itself.

Each system component, therefore, has to be analyzed in conjunction with other system components that are associated with it. An example of this is shown by Figs. 21 and 22. Acoustic Source S27 located on the reactor vessel steam generator nozzle and Source S1 located on the steam generator hot leg nozzle are both actually caused by emissions generated by discontinuities located in the hot leg piping connecting the reactor vessel and steam generator.

Additional complications that are imposed in the AE analysis of a nuclear plant are the generation of AE's from component mounts, flanges and bolts, internal structures, insulation drag, and fillet weld cracks in attached brackets and supports. All of these sources have to be recognized and identified.

Figure 21 shows the nuclear vessel acoustic sources defined during the preservice testing of the primary system of an 880 MW nuclear plant. Sources S23 and S27 were caused by discontinuities in attached piping, Sources S21, S22, S24, S25, S26, S29, S33, and S34 were attributed to minor weld discontinuities, for example, Source S25 showed up on X-ray as minor slag inclusions over a length of several inches.

Sources S28 and S30 were areas of insulation drag as identified by AE signal characteristics. Source S26 was cross correlated by transducers on the bottom head of the vessel as shown in the computer summary transparency Fig. 23. This source was not defined with stan-

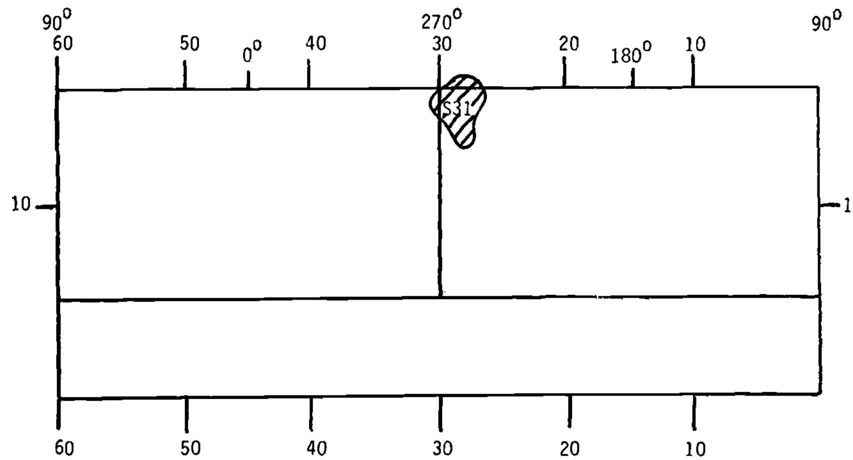

FIG. 23—*Reactor vessel bottom head view inverted from computer map.*

dard nondestructive techniques but is suspected to be a small area of cladding disbonding.

The potential value of using AE analysis for the preservice and inservice integrity analysis of nuclear plant primary coolant systems is obvious. It is complete; it is rapid and it is accurate.

Conclusions

Acoustic emission analysis technology has application in a wide variety of industries for the integrity analysis of an even wider range of structures and structural materials. Its acceptance, however, has been more rapid in industries where it is applied to metallic pressure containment structures. These structures include pipelines, piping systems, storage vessels, pressure vessels, and even complex pressure containments such as the primary coolant systems of large nuclear power plants.

The results being obtained by this technology are showing it to be a powerful new tool which has added a new dimension to the NDT field.

APPENDIX

Grade I

An acoustic source (defect or discontinuity) which is a minor emitter and is "insignificant" to structural integrity.

Grade 2

An acoustic source which is a predominate acoustic emitter, representing a definite defect or discontinuity, but the presence of which will not cause structural failure under the imposed stress conditions.

Grade 3

A "significant" defect which will grow to critical size if stress or loading of the structure is continued.

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C. F. Morais[1] *and A. T. Green*[1]

Establishing Structural Integrity Using Acoustic Emission

REFERENCE: Morais, C. F. and Green, A. T., "**Establishing Structural Integrity Using Acoustic Emission,**" *Monitoring Structural Integrity Using Acoustic Emission, ASTM STP 571*, American Society for Testing and Materials, 1975, pp. 184–199.

ABSTRACT: Acoustic emission techniques have advanced from laboratory use to applications such as establishing the quality of pressure containment and many other structures. The authors discuss the statistical relationship between acoustic emission data and the structural integrity of a series of production pressure vessels. In this application, acoustic emission data obtained from the first 25 percent of a required hydroproof test determined the bursting strength of the vessel. Additional information contained in the data is shown to establish the mode of structural degradation.

At least seven ways of utilizing acoustic emission data to establish the quality of pressure vessels are presented. Use of acoustic emission techniques to detect and locate a growing defect in a structure, while under a relatively severe environmental condition, is presented.

Various methods of data processing are described and the relations to parameters which may indicate the degree of quality of the structure are shown. Data from materials such as glass-reinforced plastics, concrete, glass, and metallics are presented. References to less well known efforts show the universal nature of the technology.

KEY WORDS: acoustics, emission, pressure vessels, parameters, plastic deformation, hydrostatic tests

The advent of filament-wound structures in the early 1960's required the development of unique methods for verification of structural integrity. This was particularly true in the area of nonhomogeneous rocket motor cases. Early in the development of these motor cases it was apparent that the required hydrostatic proof test was no guarantee of remaining structural adequacy. Motor cases which had passed hy-

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drotest successfully failed catastrophically during pressurization upon rocket test firings. Motor cases which were not hydrotested also failed during test firings. One leading project engineer, commenting on the requirement for hydroproof test, observed that for this particular instance "virginity was no proof of virtue."

In early 1961 the authors began a program to determine the relationship between the "sounds" emanating from the rocket motor case during pressurization and the residual structural integrity of the chamber. The program results showed the existence of a distinct relationship between the acoustic emissions and the residual integrity of the chamber. The measured acoustic emission (AE) amplitude (measured as the root mean square (RMS) of the total signal) during the proof pressure hydrostatic testing is inversely related to burst pressure. In addition the amplitude and frequency components of the AE data were analyzed to show that two events were significant to establishing chamber integrity. These were glass-filament laminar motion (that is, interlaminar shear) and glass-filament strand fracture. Both events were detected as AE data, each having distinct amplitude and frequency components. The integration of the AE data resulting from these events, over the hydrostatic test pressure increment, allowed a prediction of the chamber burst strength from the developed relationship between RMS AE (integrated) and burst pressure.

In recent years AE techniques have been used as a nondestructive test method for providing early and ample warning of impending failure, detecting and locating hidden flaws, and detecting AE associated with subcritical flaw growth. More generally, acoustic emission data have been used in the following ways to establish the quality (that is, structural integrity) of structures:

1. Detection of propagating defects or flaws.
2. Detection and location of propagating defects of flaws [*1*].[2]
3. Detection of gross or localized yielding.
4. Determination of pressure vessel burst strength.
5. Early warning of impending failure [*1*].
6. Determination of effective welding process parameters.
7. *In situ* monitoring of welding processes.

Each of these applications is a means of using AE techniques to assure the quality or structural integrity of structures or both.

Filament Wound Pressure Vessels

The data acquisition system utilized accelerometers bonded directly to the chamber as AE sensors, amplifiers, a magnetic tape recorder,

[2] The italic numbers in brackets refer to the list of references appended to this paper.

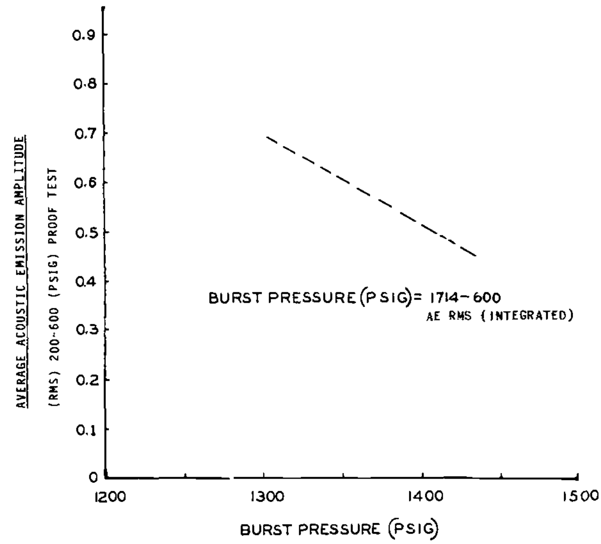


FIG. 1—*Integrated acoustic emission amplitude versus chamber burst pressure.*

and an analog computer. Similar portable systems were utilized at various chamber manufacturer's facilities throughout the United States. Up to five channels of data were processed through an analog computer in order to perform the integration of the AE data versus pressure in real time. The AE integrated value was then correlated with the burst pressure value of the particular chamber. During the course of this production run, approximately 1 out of every 16 chambers fabricated was tested to failure [*2-5*]. The relationship established between the cumulative AE signal level and the burst pressure is shown in Fig. 1. The AE signal level (cumulative RMS) data were obtained over the pressure increment from 20 to 60 percent of the maximum prooftest pressure level. Figure 2 illustrates the AE RMS (integrated) data versus hydroproof pressure for a single AE sensor. Additional analysis determined that the integration could have been reduced to include the AE data between only the 20 to 40 percent of hydrotest pressure level with little loss in accuracy. It may be seen that between the 20 and 40 percent of full-scale hydrotest pressure the AE RMS (integrated) value attains approximately 85 percent of its value at 60 percent of the pressure. A statistical analysis of the data was used to develop the mathematical relationship shown in Fig. 1. Production chambers, only hydrotested, were monitored by this AE method, and the AE RMS (integrated) value from a portion of the full hydrotest pressure range was used to predict that chamber's burst pressure.

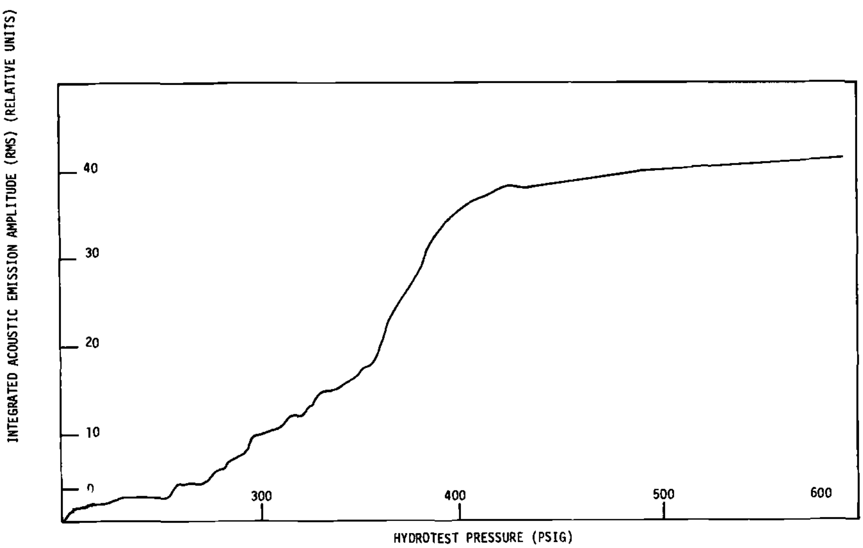


FIG. 2—*Integrated acoustic emission amplitude versus hydrotest pressure.*

An additional feature of the technique developed was its sensitivity in detecting manufacturing process changes. The AE data shown in Fig. 3 illustrate that a change in chamber material (upper and middle curve) and a new manufacturing mandrel design (middle and lower curve) were both defined clearly.

Similarly, frequency spectrum analysis of the AE data and further detailed laboratory research clearly identified at least two of the modes of chamber degradation; these being interlaminar motion between the layers of glass rovings and fracture of discrete glass filaments. Figure 4 indicates the variations in the AE data which describe these events.

Metallic Pressure Vessels

The objective of these tests was to demonstrate the use of AE as a nondestructive test method for providing early warning of impending failure of A508 grade B, reactor steel, model pressure vessels. Minor objectives were to demonstrate the ability to detect AE associated with subcritical flaw growth [*6*].

Test Procedure

A block diagram of the test setup used in these investigations is shown in Fig. 5. Three cylindrical pressure vessels were tested. They were fabricated by welding end caps on to a machined section 7.7 in.

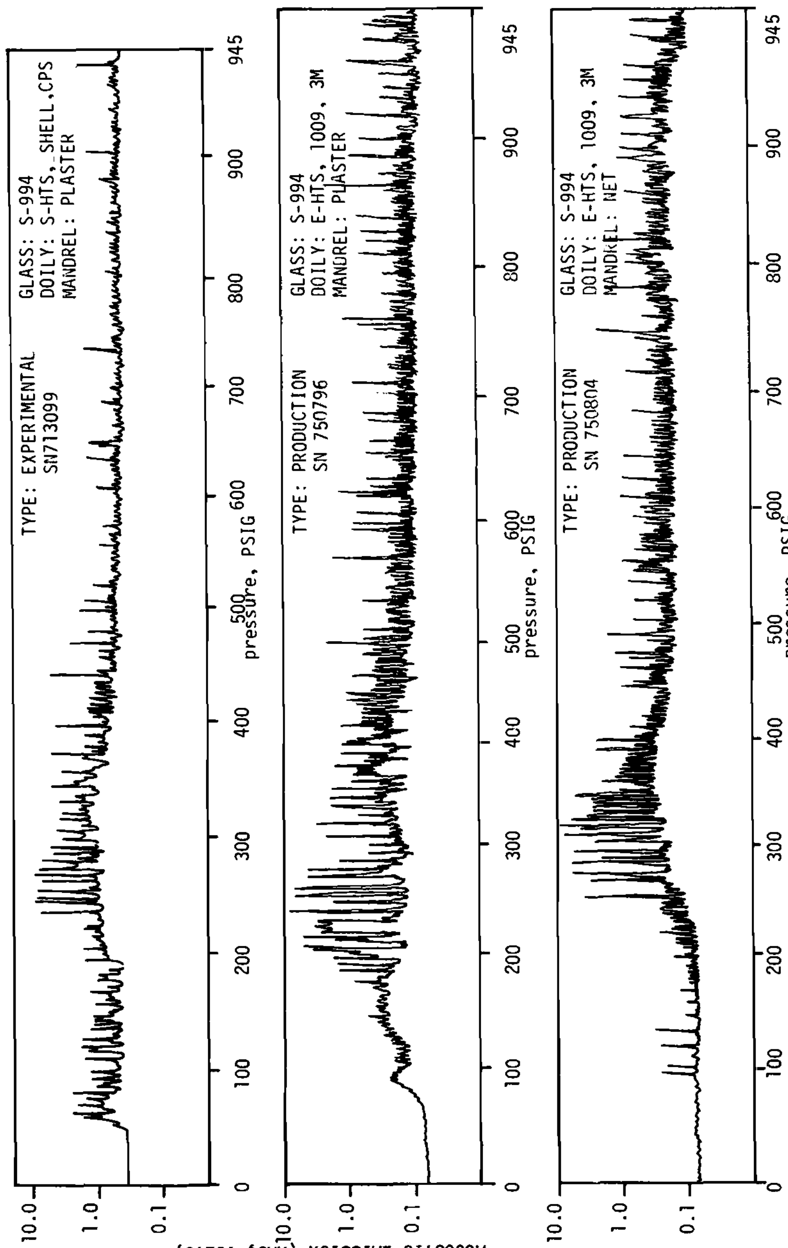
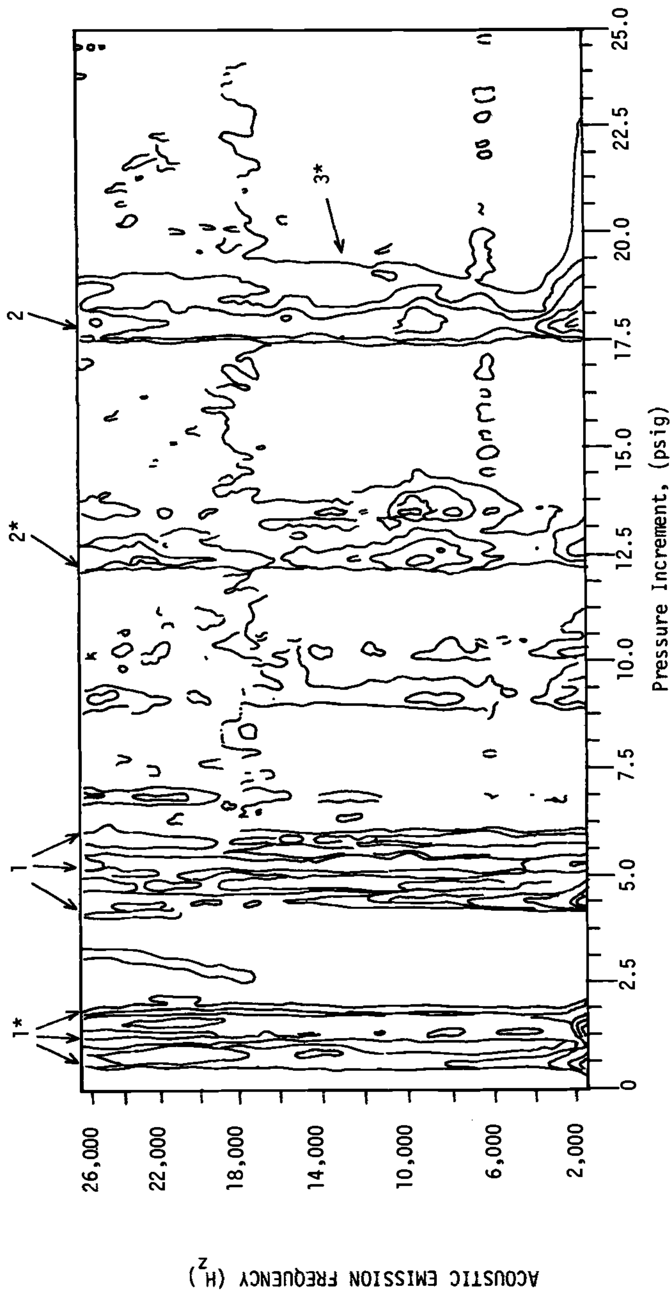


FIG. 3—*Acoustic emission versus pressure for each of three motor cases.*



*NOTES:
1. Filament Failures
2. Interlaminar Shear Failures
3. Amplitude Shown as 6dB (Acceleration Ratio of 2) Between Contours

FIG. 4—*Acoustic emission frequency versus pressure increment.*

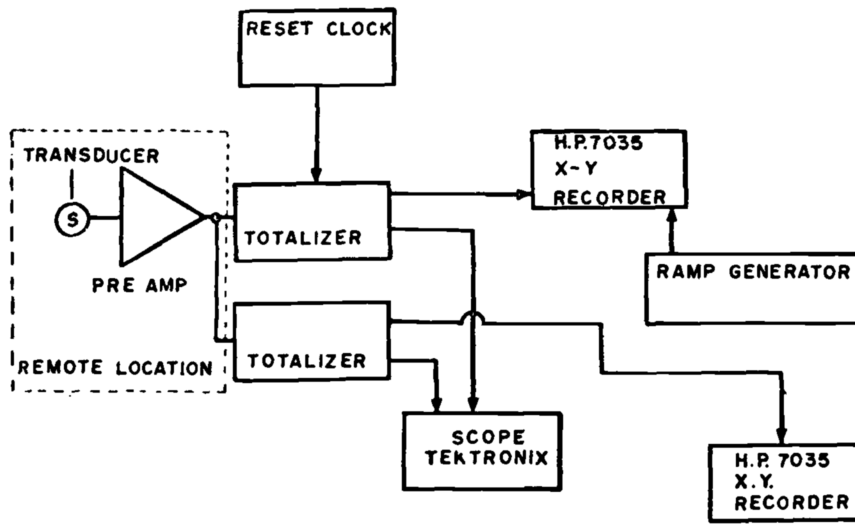


FIG. 5—*Acoustic emission system block diagram.*

long, 0.850 thick, and 5.52 in. outside diameter, each machined from the middle of a shell forging of A508 steel. A circular arc flaw, 1.18 in. long, 0.072 in. opening, and 0.23 in. deep was machined with a milling cutter in the central portion of the vessels. The flaw was oriented in the longitudinal direction. The bottom of the flaw was then electron beam (EB) welded and exposed to an electrochemical process which caused the EB weld to crack. As a result of this cracking a sharp crack front was produced, which extended the overall crack depth to 0.33 in.

Two of the vessels were tested at a temperature of 130°F and the other at 0°F. A light weight oil was the pressurization medium used for both temperatures. The pressure was recorded by manually reading a pressure gage located in the control room. The pressure was controlled by the opening and closing of a hand value on an air operated intensifier.

With minor variations, a single test consisted of the following steps.

1. Initial incremental pressurization with continuous AE monitoring to reach a given pressure step level and hold period. The hold periods would vary depending upon the time it would take to monitor the strain gages. After reaching a maximum pressure level and hold period, the pressure was released.

2. A second incremental pressurization with continuous AE monitoring to reach a new maximum pressure level and subsequent release of the pressure.

3. A third incremental pressurization with continuous AE monitoring until failure of the vessel was imminent. The pressure was then maintained constant at this peak value until the AE subsided and the strain gage reading was recorded. The pressure was then increased to failure.

Discussion of Results

The results obtained during these tests were conclusive regarding the detection of AE from subcritical crack growth and crack instability.

Each of the three vessels underwent at least one repressurization cycle. The total amount of emissions during repressurization was very small or nonexistent. This absence of emission upon repressurization was to be expected due to the irreversible nature of AE.

Vessel Al-C Tested at 130°F

The first pressurization was 0 to 9000 psi and was accomplished in 1500 psi steps. The second pressurization was from 0 to 15 000 psi in 1500 psi steps. The third pressurization was from 0 to 15 000 psi in 3000 psi steps. Pressure was then increased in 1000 psi steps until 29 000 psi was reached, at which time the pressurization was increased to produce strain steps of 0.2 percent. The data from these pressurizations are shown in Fig. 6.

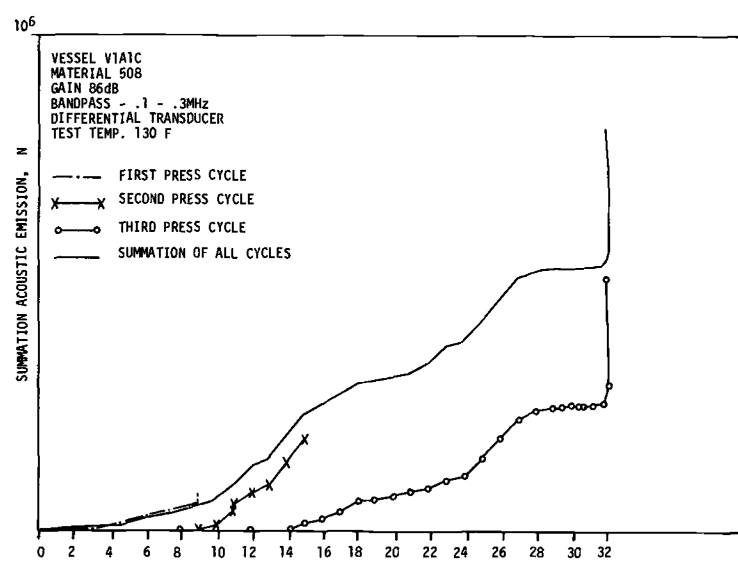


FIG. 6—*Summation of acoustic emission versus pressure (composite) Vessel Al-C.*

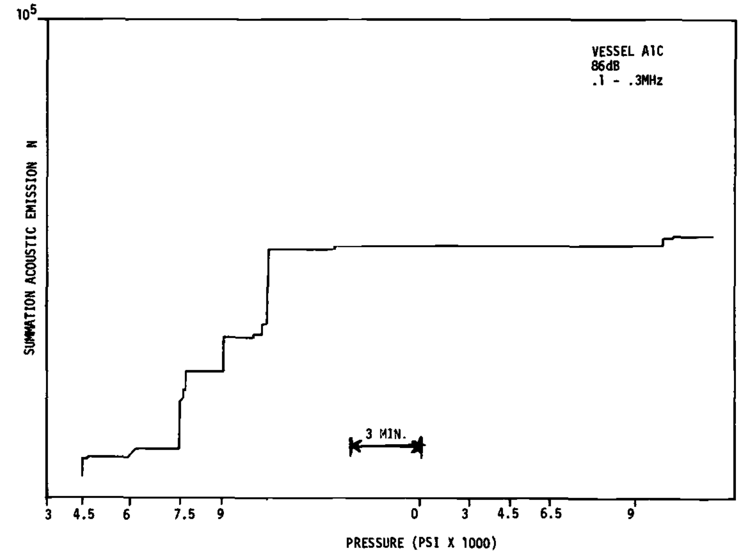


FIG. 7a—*Summation of acoustic emission versus pressure to 9000 psi Vessel A1-C.*

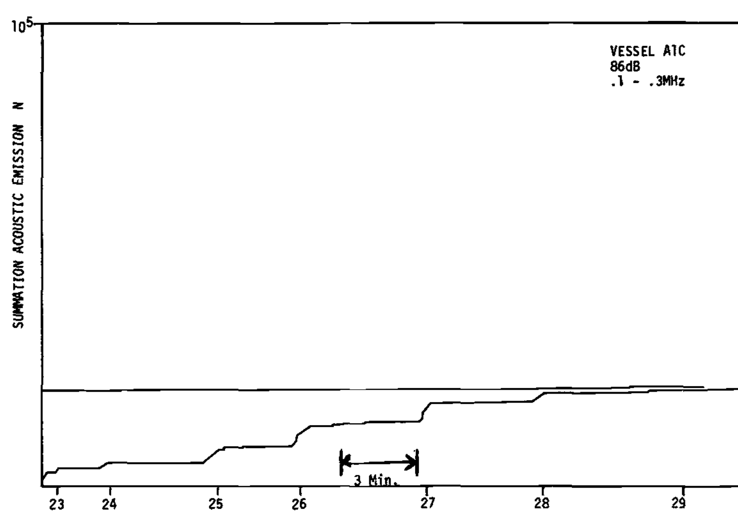


FIG. 7b—*Summation of acoustic emission versus pressure 23 to 29 000 psi Vessel A1-C.*

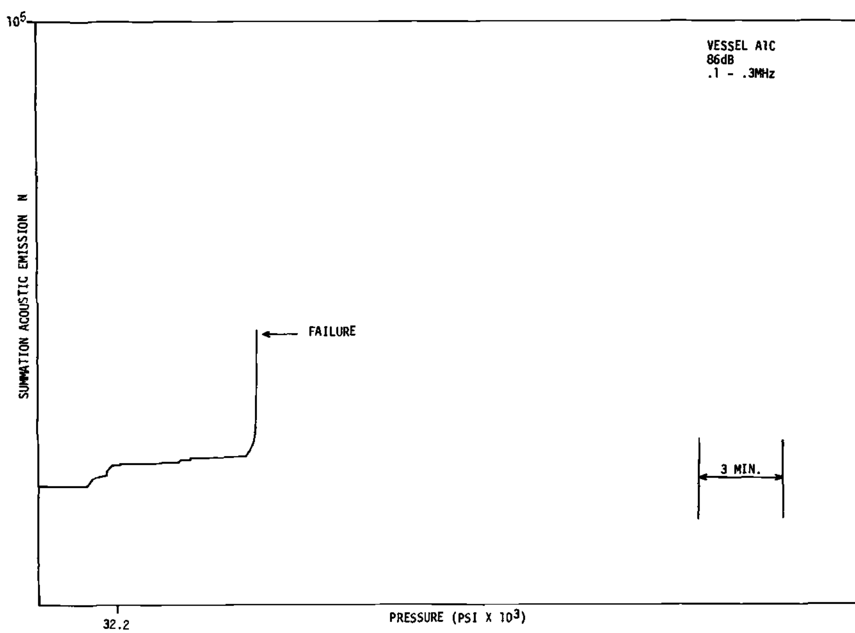


FIG. 7*c*—*Summation of acoustic emission versus pressure 32 200 psi to failure Vessel A1-C.*

Replotted AE data obtained during pressurization are shown in Figs. 7*a*, *b*, and *c*. These data were replotted as a function of pressure due to the step pressurization process used. At the 19 000 psi hold period, increase in cumulative counts was observed. This observation remained true for each of the subsequent 1000 psi loadings and hold periods up to 29 000 psi.

Continuous emissions were observed starting at the 22 000 psi pressure level. Prior to this point, all emissions were of the burst type. This early continuous emission is thought to be indicative of the intervessel wall yielding. From 22 000 to 29 000 psi both types of emission were observed with less and less burst type as the vessel pressure neared the 29 000 psi level. At this point, burst emission gave way to the continuous emission only. This would be indicative of the pressure vessel undergoing gross plastic deformation.

It was also observed that the continuous emission decreased at each higher pressure step beginning with 30 000 psi, at which point the burst type of emission started increasing. This became more evident at the 31 300 psi pressure step. See Figs. 7*b* and *c*.

At pressure step level 32 000 psi, it was evident that the vessel was nearing failure. It was predicted to fail within the next strain level (pressure) step (normal pressure loss during each of the hold periods was approximately 700 psi). The next strain level step was never reached. At 32 000 psi, the vessel failed without reaching the maximum pressure previously obtained.

Vessel A1-B Tested at 0°F

The vessel was submerged in an ethylene-glycol-water solution. Dry ice was used as a cooling medium. The sensor was attached in the same manner used for the elevated temperature (130°F) tests. The cumulative emission data from this test were replotted as a function of pressure and are shown in Fig. 8.

The total AE counts from this vessel were approximately 47 percent lower than for Vessel V1-A1-C and 56 percent lower than for Vessel A1-D. A few possible reasons as to why this lower value was obtained were: (1) pressurization medium was oil and would stiffen at the 0°F test temperature which may have an attenuating effect upon the AE signal; (2) glycol-water solution may tend to have the same effect as just described but to a much less degree; (3) acoustical couplant used during the 0 to 22 000 psi portion of

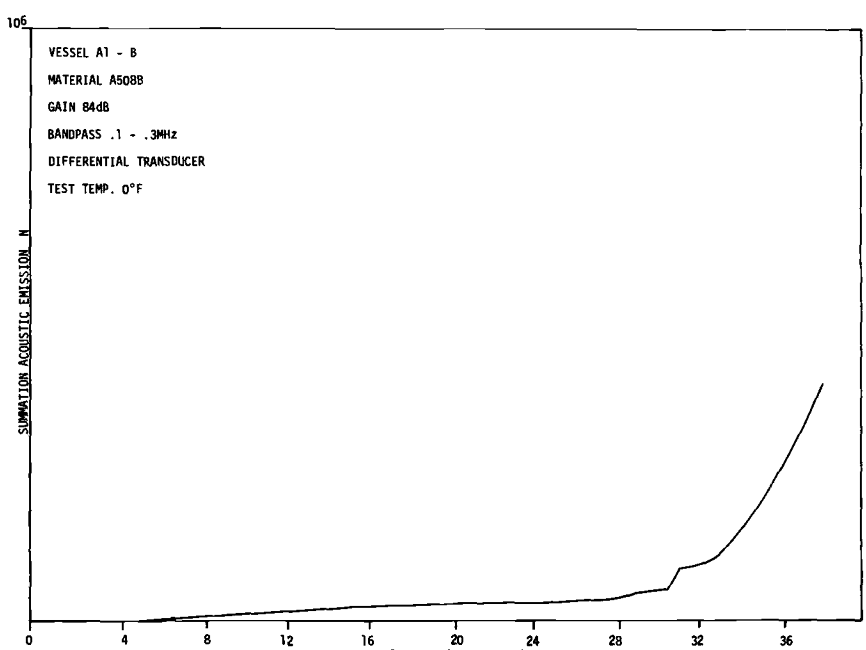


FIG. 8—*Summation of acoustic emission versus pressure (composite) Vessel A1-B.*

this test was found to be frozen, no couplant was used after that time; and (4) possible differences in the sensor sensitivity at 130°F and 0°F. From the continuous emissions it was observed that the inside of the vessel was yielding at approximately 20 000 psi. At 29 000 to 30 000 psi, general yielding occurred and the visual pressure gage indicated a loss of 10 000 psi during the 5 min hold period. The vessel was then repressurized but only reached a maximum pressure level of 29 500 psi. At this point, the test engineer suspected a leak in or at the pressure vessel. AE did not show any indication of a leak at or in the vessel. The leak was found at the pressure relief valve in the control room.

Again, the vessel was repressurized (19 000 to 30 000 psi). It was observed on the oscilloscope that the continuous emission was passing its peak. During the entire yielding process (continuous emission) oscilloscope observation showed that the burst type of emission never disappeared. This would lead one to surmise that the crack continued to grow during yielding which was not the case for Vessel A1-C. (This can be readily seen by comparing cumulative emission plots of Vessel A1-C to this vessel.)

Upon reaching 33 000 psi, continuous emission was nonexistent, and the burst type emission rate increased with a much larger amplitude. It was noted during the hold period at 29 000 psi that the emission generally continued shortly after the beginning of the hold period.

The pressurization line froze at the vessel during hold periods which necessitated clearing the system. This was accomplished by opening and closing the pressure relief valve to produce a shock to the pressure system. As a result, this would decrease the start of the new maximum pressure step to a lower pressure level, normally anywhere from 8000 to 10 000 psi lower than the maximum pressure achieved during the previous pressure step.

After reaching 35 000 psi and holding until AE had subsided, the frozen pressure system was then shocked and cleared. Repressurization commenced at 22 000 psi, and AE data began at 31 500 psi. This apparent lack of irreversibility should be a subject for further investigation.

The AE data showed that the vessel was nearing failure at 33 000 psi. The test engineer was notified of impending failure at 35 000 psi. The vessel fractured at approximately 36 800 to 40 000 psi. The visual pressure gage was oscillating between these values, and therefore an exact pressure value was unavailable.

Vessel A1-D Tested at 130°F

Pressurization Cycle 1 was 0 to 15 000 psi in 3000 psi steps with a hold period at each pressure step level. The repressurization cycle was 0 to 32 300 psi in 5000 psi steps until 15 000 psi after which the pressure steps

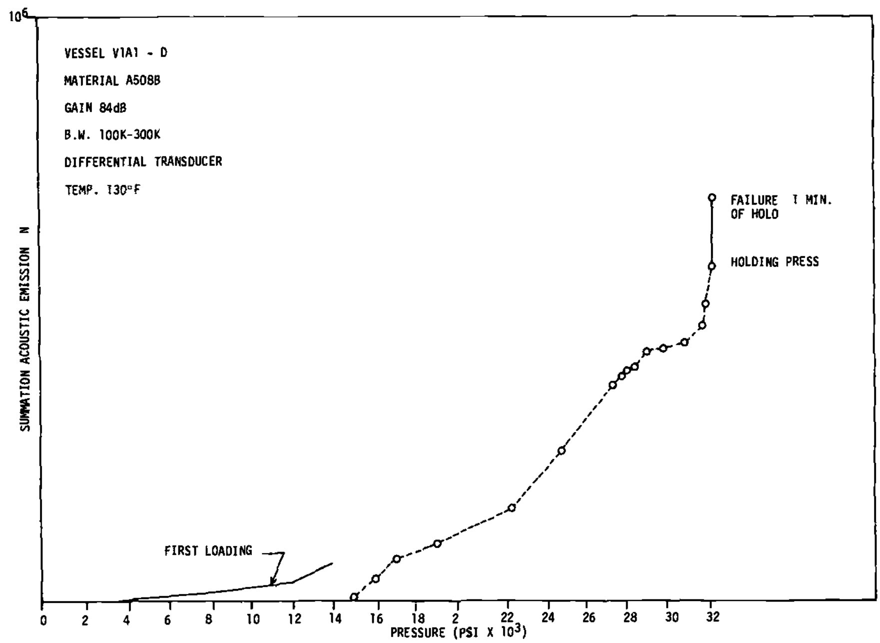


FIG. 9—*Summation of acoustic emission versus pressure (composite) Vessel A1-D.*

were variable with a hold period at each pressure step level. Each hold period would depend upon the time it would take to read and record the strain data.

The cumulative emission data from this test were replotted as a function of pressure and are shown in Fig. 9. AE data obtained during pressurization are shown in Figs. 10*a* and *b*. As indicated in Figs. 10*a* and *b*, increased cumulative emission counts were observed during the pressurization period. Increase in cumulative counts during the hold periods started with the 22 500 psi hold.

This vessel behaved in much the same manner as the previous 130°F test vessel in the following ways: (1) increase in cumulative counts during the hold periods started with the 22 500 psi hold; (2) continuous emission was observed at 21 000 psi (believed to be due to yielding from the interwall as in the autofrettage process); (3) peak gross yielding occurred at the 29 000 to 30 000 psi level; and (4) continuous emission decreased and became nonexistent after reaching 36 000 psi. It was also observed that the rate and amplitude of burst type emissions increased at the 31 000 psi level, and it became evident that the vessel was nearing failure. The test engineer was then notified of the impending failure at 32 300 psi at this point, pressuriza-

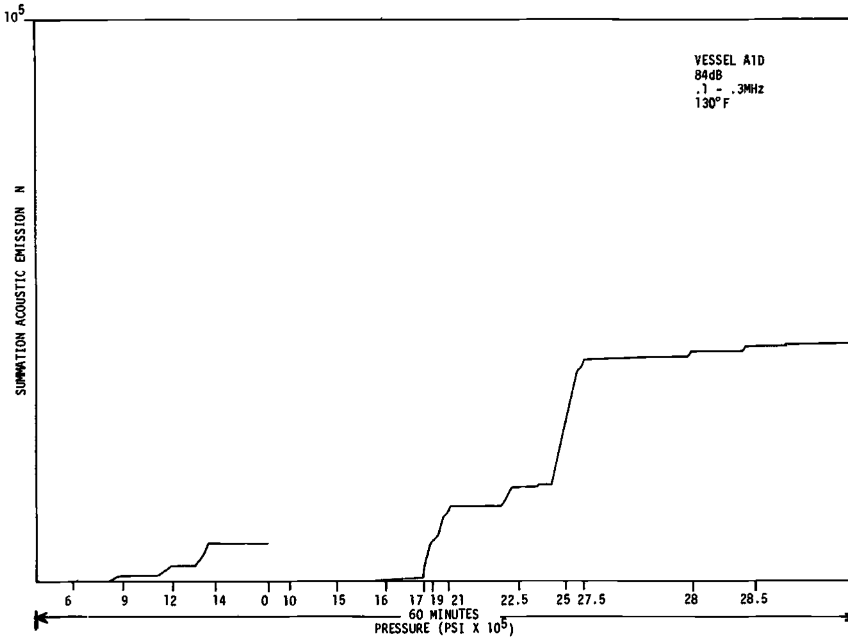


FIG. 10a—*Summation of acoustic emission versus pressure 0 to 28 5000 psi Vessel A1-D.*

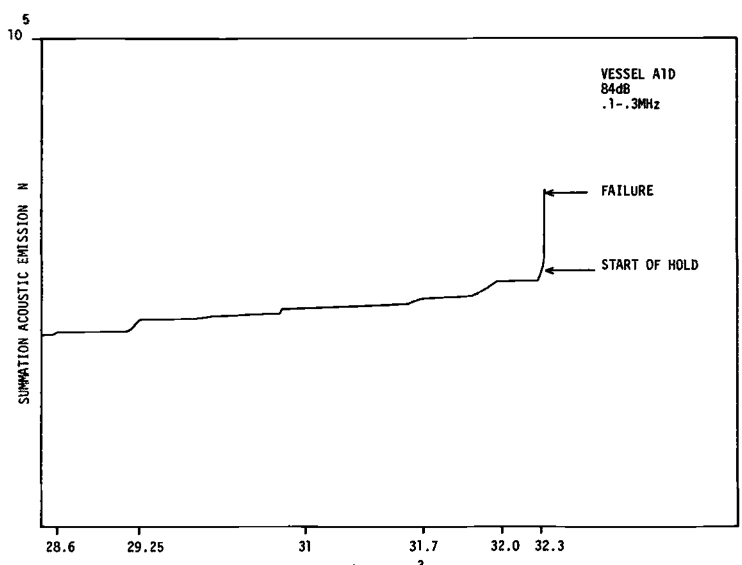


FIG. 10b—*Summation of acoustic emission versus pressure 28 600 to 32 200 psi Vessel A1-D.*

tion was stopped and locked off. The vessel failed approximately 1 min later.

Concrete Materials

During this investigation, a group of compressive concrete test cylinders of three aggregate types was tested to failure under standard ASTM test procedures. Standard cylindrical concrete compressive test specimens were compressively loaded to failure in a hydraulic test machine, and the acoustic emission date obtained from sensors attached either to the specimen itself or the test machine platens were recorded on magnetic tape and processed for the analysis and program report. In brief, the results illustrated that the AE data from concrete is an indicator of failure processes. Early warning of total compressive failure and preliminary correlation with the material modulus were obtained. [7].

Amplitude distribution information was obtained for each of the nine compressively loaded specimens. A statistical distribution showing the probability of larger signal levels occurring has been plotted from the average of the three specimens of each aggregate type. Figure 11 shows the cumulative probability plot for AE recorded during the tests. For compara-

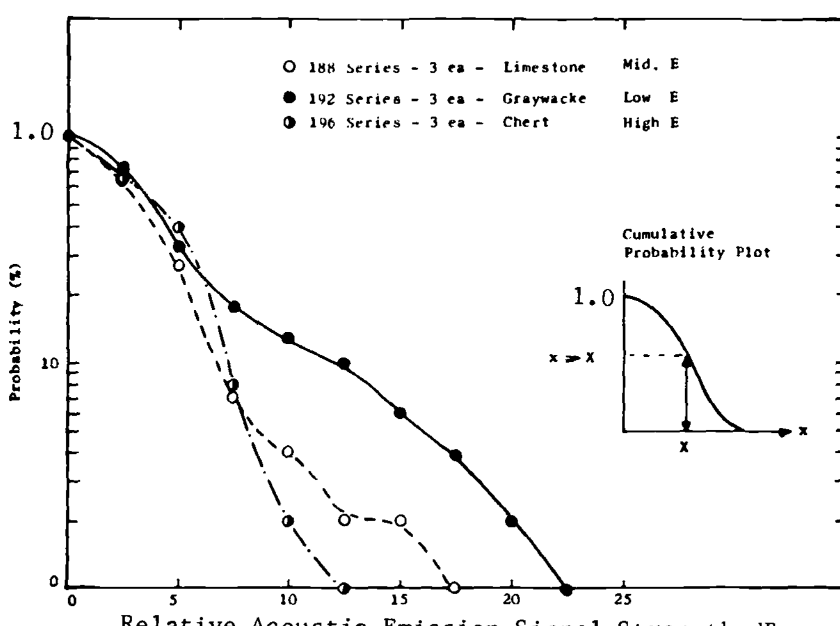


FIG. 11—*Probability of* x > X *versus relative AE signal strength.*

tive purposes, the probability of larger signals occurring is inversely related to the modulus of the concrete. Degradation of concrete strength is denoted frequently by changes in modulus; thus, AE techniques may provide a means of determining structural integrity of concrete structures *in situ*.

Conclusions

The AE data gathered on these programs, each encompassing different materials, have been shown useful in providing a measure of the structural integrity of the monitored item. With limited test specimens the AE data are useful as a comparative evaluator. However, with a larger test specimen population the AE data have shown itself to be capable of quantitative analysis.

The data processing methods, as utilized in these efforts, are straightforward and relatively simple to implement. Newer more sophisticated methods hold promise for continued success as the technology advances.

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Raj Gopal[1]

Acoustic Monitoring Systems to Assure Integrity of Nuclear Plants

REFERENCE: Gopal, Raj, "**Acoustic Monitoring Systems to Assure Integrity of Nuclear Plants,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 200–220.

ABSTRACT: A comprehensive program is underway at the Westinghouse Electric Corporation to develop and evaluate acoustic monitoring systems as a nondestructive testing tool for nuclear power plants that will assure structural integrity with minimum interference to normal power plant activities. A prime requirement for instrumentation for nuclear reactors is that it should function reliably in severe environments for several years. Sensors and instrumentation for source location and display developed for this application are described. Results of tests performed in major test facilities for vessel flaw growth, vessel rupture, and pipe rupture under various operating conditions are summarized. Evaluation performed in nuclear power plants both during hydro tests and operation of plant is presented. Laboratory tests for studying relationships between acoustic emission and fracture mechanics technologies are presented along with a summary of wave propagation results. Measurements, to date, indicate that an acoustic monitoring system has practical applications in nuclear power plants for improving safety and availability of plants.

KEY WORDS: acoustics, emission, nuclear power plants, nuclear reactors, instruments, pressure vessels, monitors

Inservice monitoring of the integrity of nuclear reactor pressure vessels and pressure boundaries using acoustic emission (AE) activity appears to hold considerable promise for ensuring safe operation of a plant with minimum interference to normal power production. This technique is a new, nondestructive testing (NDT) tool, which with further experience and development, should provide a valuable addition to the presently accepted methods of testing.

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Increased demands on improved safety are being put forth by environmentalists and regulators on nuclear plants. An astronomical amount of engineering and financial resources, both private and public, have been and are continuing to be used to develop, design, and build systems which alleviate the adverse consequences of component and equipment failures. Another approach to safety is to reduce the probability of the unwanted event to an acceptably low value through monitoring of certain components and equipment for abnormal performance during operation. Acoustic monitoring systems may be employed to reduce significantly the probability of any major failures during operation of a plant. The systems are designed to monitor critical components and equipment for abnormal performance during operation. The detection of abnormal conditions is at the incipient level which then provides ample time for corrective action before the situation deteriorates to a significant failure condition.

Improvements in availability, required by plant operators based on economic considerations, can also be achieved by reduction of inspection requirements and preplanning of inspection areas through effective utilization of surveillance systems. Vessel inspection intervals, as well as the areas to be inspected, can be selected based on AE activity.

Development of dependable surveillance systems represent a great opportunity to increase the safety and economy of nuclear power plants. An inherent advantage to the approach proposed here is the fact that these systems contribute in a positive way to plant economics, both in operating costs (improved availability) and capital cost (potential reduction in standby safety systems), as well as the improvement in safety.

Background

Surveillance of pressure boundary integrity by AE techniques may enable on-line detection of developing cracks and flaws and detection of small leaks of the coolant in critical areas.

Zones of AE activity can be located in large structures by using a moderate number of widely spaced sensors, and measuring the relative arrival times of AE pulses at these sites. Source location is possible by computation based upon relative signal arrival times to three or more known locations.

Practical implementation of this monitoring technique in nuclear power plants requires that the instrumentation meet a number of severe requirements. For example, the sensor must be mounted on the reactor pressure vessel where it will see high temperature and high radiation for extended periods of time. All other instrument components housed within the reactor containment vessel will also be subject to relatively high temperature, humidity, and radiation. In addition, the AE monitoring system must be able to detect and locate the AE sources in the noisy environment of the working reactor. This means that the frequencies used for detection must be above the frequencies of the acoustic background noise and below the frequency where severe sound attenuation begins to occur in the pressure vessel material.

Acoustic Emission and Fracture Mechanics

The ability of the large steel pressure vessels that contain the reactor core and its primary coolant to resist fracture constitute an important factor in ensuring safety in the nuclear industry. In nuclear reactor pressure vessels, some regions (beltline) are subjected to irradiation embrittlement. The complexity of any safety analysis is increased by the effects of irradiation damage.

Fracture mechanics technology has advanced to the stage where it is of direct engineering value for the prevention of fast fracture in vessels and piping of the type employed by the nuclear industry. Utilization of fracture mechanics technology requires information and data in three areas; material properties, stresses existing in the structure, and defects in the structure. Expressions relating these three factors for the particular components and defect geometry of concern are also prerequisites for the successful use of the technology. The total useful life under cyclic loading conditions, as in a nuclear power plant, is dependent upon the rate of growth of flaws from subcritical to a critical size. Detection of subcritical crack growth is an important aspect of any surveillance program. Thus, AE surveillance and fracture mechanics technology complement each other and they provide a potential tool to decrease the probability of failure in nuclear power plants.

Westinghouse Program on Acoustic Emission

A comprehensive program to develop AE technology for application in preventing pressure boundary rupture of nuclear power plants is underway at Westinghouse.

The functional requirements are:

1. Detect and locate onset of flaw growth in the pressure boundary.
2. Characterize flaw growth.
3. Evaluate effects of rate of growth and flaw size on planned inspections and allowable operating modes.

Major phases of the program are shown in Fig. 1.

This paper will summarize Westinghouse accomplishments in

1. Acoustic emission instrumentation developments.

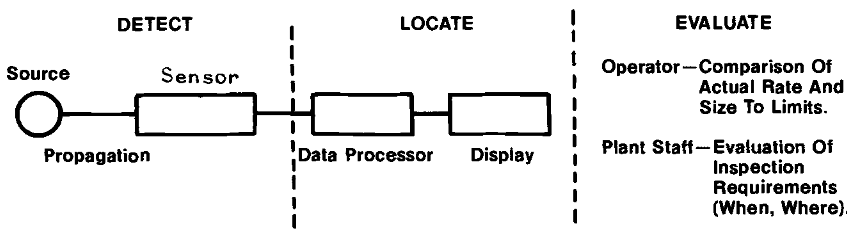

FIG. 1—*Various phases of acoustic emission technology.*

2. Evaluation of major test facilities.
3. Evaluation in nuclear plants.
4. Evaluation in laboratory facilities.

Acoustic Emission Instrumentation System

An AE instrumentation system primarily consists of a matched and balanced sensor-cable-amplifier subsystem which permits the piezoceramic sensor's low-level electrical output signal to travel with relatively little attenuation or interference over a long distance and a data processor for source location and analysis.

Sensor and Electronics

Significant breakthroughs in sensor design and signal transmission have been made by Westinghouse to meet the requirements for reactor pressure vessel acoustic surveillance. A sensor that is expected to operate for long periods of time (years) in the high-temperature, high-radiation, and high-humidity environment has been designed. The sensor acoustically couples directly to the metal structure that is being monitored, eliminating the need for waveguides, and it can drive long lengths (500 ft or more) of cable without a preamplifier.

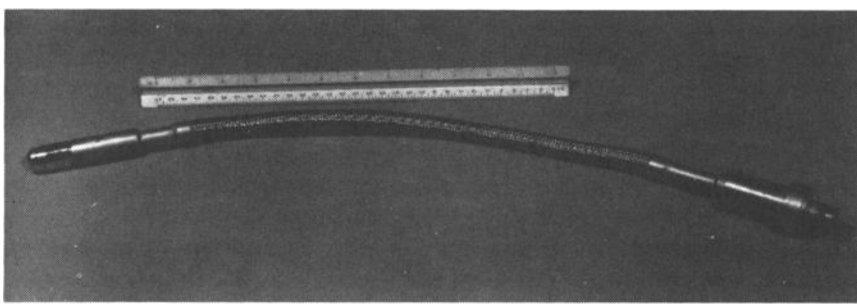

FIG. 2—*Westinghouse acoustic emission sensor.*

The sensor is designed to be part of a matched and balanced passive electrical transmission system. The sensor crystal's impedance is matched to the impedance of a transmission line, and this line impedance is then matched to a high input impedance preamplifier. This system is able to drive several hundred feet of cable between the crystal and preamplifier with very little signal attenuation.

Figure 2 shows the nuclear reactor grade severe environment AE sensor.

The sensor is hermetically sealed and meets the following environmental specifications:

Temperature: +550°F at the face of the transducer and +300°F at the connector

Pressure: 100 psia

Humidity: 100 percent

Radiation: 500 R/h

Vibration: 0.03 in. double amplitude ±0.003 in. in the 10 to 30 Hz range and 1.0 g (0 peak) ±0.1 g in the 30 to 500 Hz range

Shock: 15 g (11 ms, halfsine)

The sensor is made to be easily coupled acoustically to any structure using a minimum of surface preparation. All that is required is to press the sensor face against the structure's surface using a moderate compressive force, which is supplied by a spring. The spring force is transmitted to the sensor's face through a retaining ring which snaps into a special groove located near the face. The mounting fixture is attached to the test structure either mechanically, using C-clamps or large hose clamps, or magnetically with a group of magnets having a total rated holding force of about 280 lb.

Figure 3 shows the electroacoustic sensitivity of a sensor compared to a primary standard lithium sulfate sensor. The sensor is calibrated by comparing its output signal against that of a primary standard. Both sensors are acoustically loaded by a medium that is representative of a nuclear reactor pressure vessel, and both are exposed to the same sound field. The primary standard has a flat response and a sensitivity of −124 dB referenced to 1 V per microbar. The sensitivity of the sensor is 34 dB above that of the standard at a frequency of 500 kHz; that is, its equal to about −90 dB referenced to 1 V per microbar.

The AE sensor system presently uses a RG-22B/U cable. This cable has a 95 ohm characteristic impedance, a propagation velocity equal to 65.9 percent of free space velocity, and a 1 MHz attenuation constant of 0.24 dB per 100 ft length.

In the signal-conditioning electronics, special care is taken to ensure that the preamplifier first stage has as small a noise figure as possible.

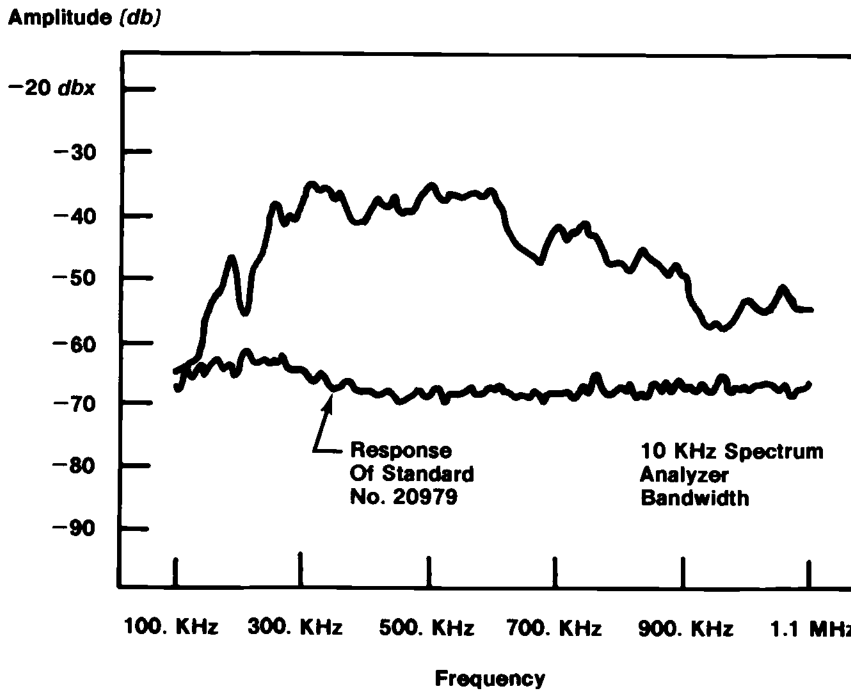

FIG. 3—*Acoustic emission transducer sensiticity calibration.*

All subsystems are compatible with each other for impedance-matching and for achieving a high signal-to-noise ratio. A bandpass filter with sharp cutoff characteristics (>50 dB/octave) is used to pass only frequencies in the range of 300 to 700 kHz. The filtered and amplified signal then is led into a discriminator which produces a digital pulse for analog signals above a threshold voltage level. The threshold level is variable and generally set at a level slightly into the background noise. Digital pulses are fed into the analysis system.

Analysis System

AE signal totalization, source location, and some source display are performed in CAMAC modules and a mini computer. The analysis system along with an optional rack containing a cathode ray tube (CRT) display and a hard copy unit installed at a nuclear plant is shown in Fig. 4. This system is capable of monitoring an entire vessel with 20 or more channels by arranging transducers in zones made up of four transducers each. From the measured differences in time of arrival of

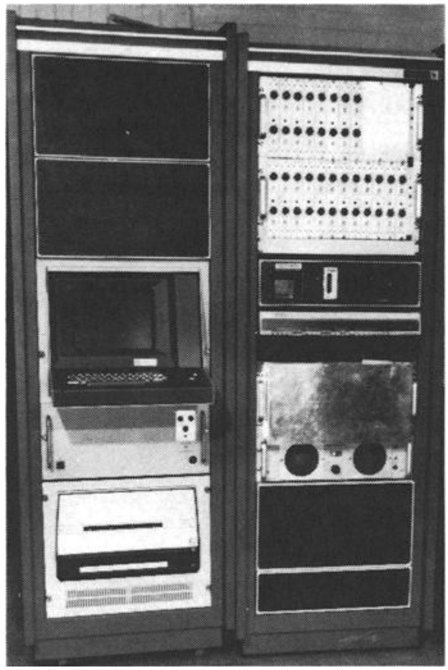

FIG. 4—*Westinghouse acoustic emission monitoring system.*

the acoustic pulses, the known location of the transducers, and a known (empirical) velocity of pulse propagation, the computer performs calculations to locate and display any flaws that may be present in the vessel being monitored. A modular approach to system design has been followed using a CAMAC-type interface so that a complete system may be configured and easily modified or updated for a given requirement.

Location and totalization systems are configured in modular forms to accommodate multisensor inputs. The location module contains circuitry for addressing, interrupt requests, and buffer registers to store data for input to the mini computer. A module contains eight identical circuits.

A totalization module contains eight identical counter circuits to monitor eight sensor inputs. Each circuit has a 24-bit counter associated with it to register a possible 2^{24} acoustic events. The counter output signals are fed to data selectors which decode the bindary data for presentation to the PDP-11 mini computer via the CAMAC dataway.

A mini computer is used to process the acoustic data and drive the CRT display. The computer processes the data, supplied by the

CAMAC location modules, using a hyperbolic triangulation technique to find flaw locations. Once a location is found, the "hit" is scaled and plotted on the CRT, and also stored in a buffer for further analysis offline. A flat pattern of the reactor vessel outline is traced on the CRT by the computer, with each hit plotted on the flat pattern to enable easy reference on the actual vessel. The hard copy unit can be used to keep a permanent record of the hits as they appear on the flat pattern, along with corresponding *X*, *Y* values in reference to a known location on the vessel. Hard copies can also be made from a display of total counts for each channel that is displayed on the CRT on demand. Cassette storage of the total counts per channel can be used to provide rate information as these data are logged on a periodic basis, usually once an hour.

Measurement Programs in Test Facilities

Of prime importance in determining the worth of AE monitoring is testing the detection of emitted acoustic signals against natural background noise. Several tests were performed in major test facilities to obtain information on the nature and magnitude of acoustic signals emitted by reactor pressure vessels and piping having intentional defects leading toward catastrophic failure.

Nondestructive Test Method Evaluation Facility (NDTF) Tests

The NDTF testing was performed under the Edison Electric Institute Research and Development Program for Inservice Inspection of Nuclear Reactor Pressure Vessels [*1*].[2] This test facility provided the proper environment for determining the capability of various NDT systems to detect existing or developing flaws in a pressure vessel operating in environments typical of those found in present-day, large nuclear power plants.

The facility was constructed by modifying the experimental beryllium oxide reactor (EBOR) vessel which was 11 ft in diameter, 26 ft high, and had wall thickness varying from 3 to 8 in.

A flaw was introduced into the pressure vessel or appurtenances, and the area was then stressed hydrostatically or by mechanical means to provide failure sites for evaluation of acoustic and other NDT equipment.

The filling, circulating, and pressurizing system provided the normal sounds associated with water flow and operating equipment. Additional noise similar to that in large nuclear power plants was provided by external generators to evaluate the capability of the acoustic system

[2] The italic numbers in brackets refer to the list of references appended to this paper.

being tested to detect and locate the various flaws in the noisy environment typical of operating reactors.

The significant conclusions resulting from testing at the EBOR test facility are:

1. AE technology is applicable for use in monitoring the integrity of the primary system boundary of a nuclear reactor.

2. AE's from flaws in the vessel and fatigue bars welded to the vessel could be detected in the presence of simulated normal reactor background noise and at elevated temperatures.

3. AE sources resulting from flaws both in the interior and exterior of the test vessel were successfully detected and located.

Vessel Rupture Tests

Intermediate size reactor vessel rupture tests performed under the Heavy Section Steel Technology program at Oak Ridge National Laboratory [2] have been monitored for acoustic activity during pressurization until rupture.

The test specimen was a cylindrical forging of 6-in. carbon steel. The outside diameter was 39 in., and, after welding heads on the top and bottom, it was about 8 ft tall. The vessel was installed upright in a concrete cavity which was sealed prior to the start of the test.

The significant results of three tests are summarized as follows:

Summary of Vessel Rupture Tests

Test No.	Test Conditions	Results
1.	Single flaw: 8 in. long, 2 in. deep, 130°F	all four channels showed exponential increase in activity; location system showed location of flaw growth
2.	Two flaws: one in base metal and other in weld—both 8 in. long, 2½ in. deep, 75°F	all our channels showed activity; weld flaw acoustic emission activity was greater; triangulation showed growth near both flaws—higher concentration near the top of weld flaw and greatest increase from 26 000 psi to rupture at 26 450 psi at the weld flaw
3.	Three flaws: A.0° weld exterior, B. base metal exterior, C. 180° weld interior, 190°F	eight channels were used; exponental increase in counts was not predominant; location showed initial flaw growth to be higher at C than at A and B; however, towards end of test (from 29 000 to 32 000 psi) significant growth was observed at Flaw A where eventual failure occurred

Pipe Rupture Tests

Westinghouse has participated in tests at the Atomic Energy Commission sponsored pipe rupture test facility at San Jose [3] to measure AE signals indicative of the failure of reactor grade pipes. In the initial two tests significant electrical and mechanical noise problems were encountered. However, true AE burst signals correlated qualitatively with defects observed by ultrasonic techniques. Noise problems were solved by appropriate selection of electrical and mechanical isolation techniques for the third test. Excellent data were obtained during this test.

The test specimen was a 6-in. Schedule 40, Type 304SS elbow, one end of which was welded to a short vertical stainless pipe which was bolted to the test stand. The other end was welded to a short horizontal section which in turn, was welded to a carbon steel section connected to the hydraulic loading mechanism.

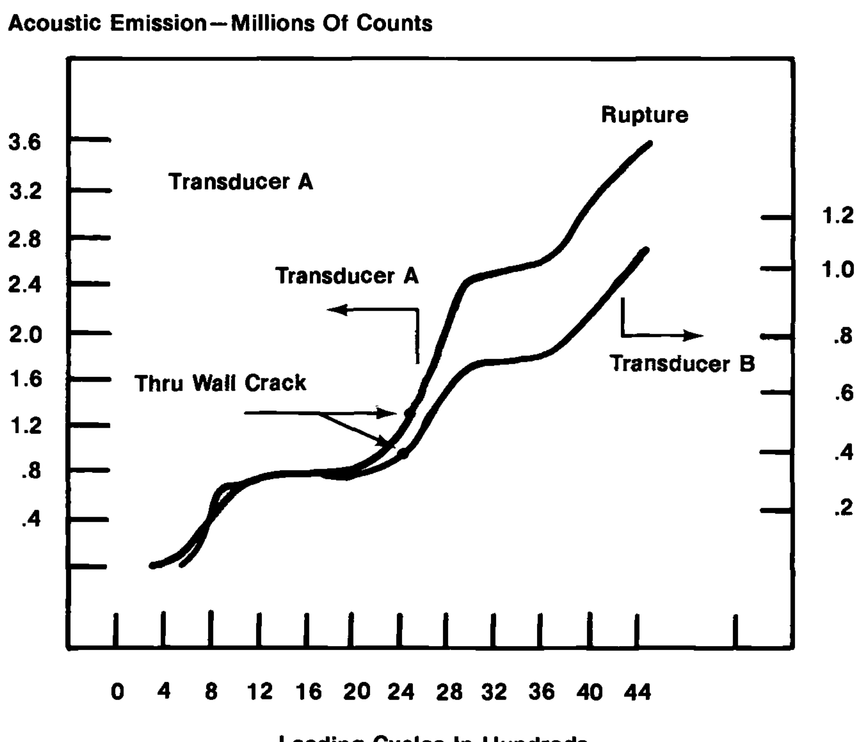

FIG. 5—*Fatigue cycles versus total counts.*

The test plan called for cyclic pressure and flexural loading at a frequency of 12 cpm.

Periodic inspections were carried out with ultrasonic detectors.

After initial failure of the specimen, cycling was continued without pressurization for additional AE data acquisition.

The results of the tests are:

1. The quiescent noise of the transducer-amplifier system was very low.
2. The physical appearance of the signals were the burst type emission with a sharp leading edge. They appeared to come in packets.
3. Even in the presence of electrical and mechanical noise sources during the first two tests, qualitative correlation was observed between true AE signals and flaws observed by ultrasonic techniques.
4. Cumulative counts from a channel as a function of number of cycles is plotted in Fig. 5 which reflects the classical data pattern for the fracture of a stainless specimen.

Leak Detection System Tests

The goal of an acoustic leak system test is to develop a system that will detect "through wall" leaks from the reactor coolant system boundary of less than 0.02 gal/min during plant operation even in the presence of larger leaks in less critical areas such as pump seals.

A series of tests were conducted at Westinghouse Forest Hills facilities to determine the properties of continuous AE's generated from pressurized water leaks. Special piping was mounted on top of an autoclave (Fig. 6). Water leaks were analyzed and data recorded for conditions varying in pressure and leak flow rates. The results indicate that the acoustic monitoring system is capable of detecting small leaks on the order of 0.02 gal/min or smaller, as shown in Fig. 7.

Plant Tests

Westinghouse has pioneered the development of AE instrumentation systems for use in severe environments such as found on nuclear power plants. Extensive conceptual and feasibility tests have been carried out in the following locations:

1. Saxton Reactor.
2. Robinson Unit 2.
3. Turkey Point Units 3 and 4.
4. Ginna.
5. Prairie Island Unit 1.
6. Beaver Valley Unit 1.

Significant results obtained using recent instrumentation are covered in the following sections.

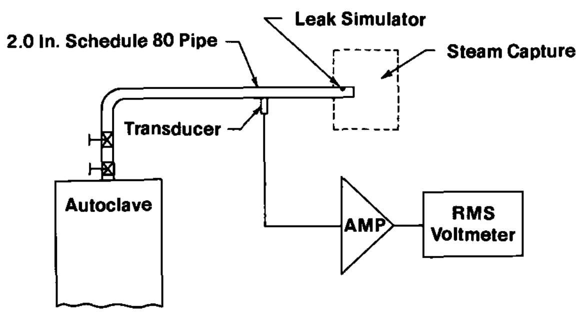

FIG. 6—*Leak detection system test.*

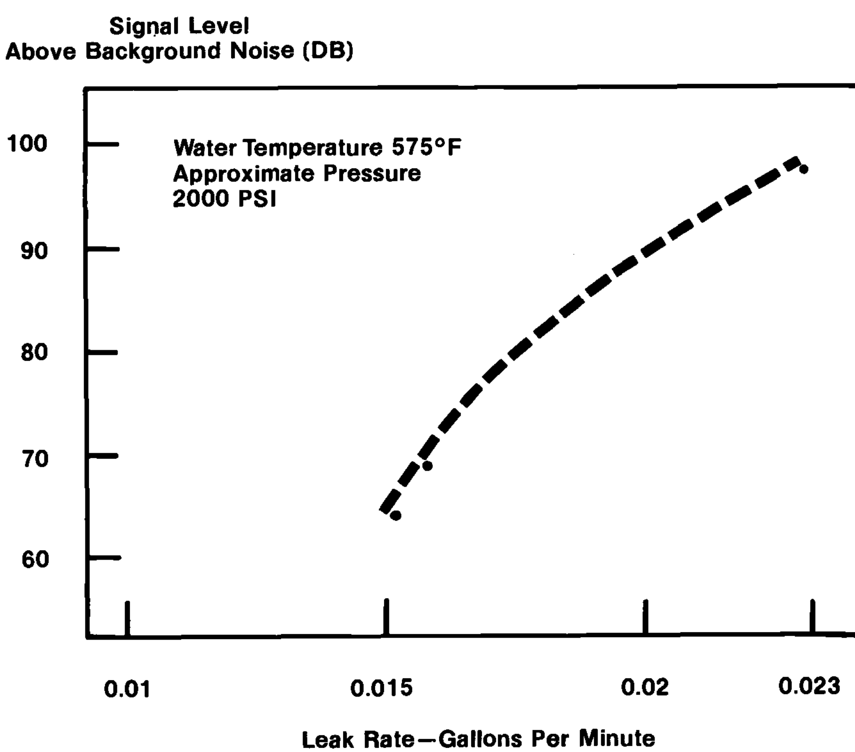

FIG. 7—*Acoustic signal level at various leak rates.*

Primary System Attenuation Tests

The attenuation test consisted of introducing an acoustic signal at a point on the vessel and measuring response characteristics at several points on the system. An isometric view of a plant primary system is shown in Fig. 8. With signal injection at the top flange of a typical reactor vessel, attenuations measured at various points are summarized in Table 1.

Surface discontinuities, for example, welds increase the attentuation of the acoustic wave.

The characteristic wave shape of the simulated acoustic wave changes when the signal is introduced on the vessel interior and detected by exterior transducers. The sharp leading edge, present for waves generated on the exterior, is not as predominant in waves originated from the interior.

Attenuation on the head structure was high, but signals could be detected by transducers mounted on the lifting lugs.

Hydro Tests

Acoustic monitoring of in-plant hydro tests have been made on two nuclear plants.

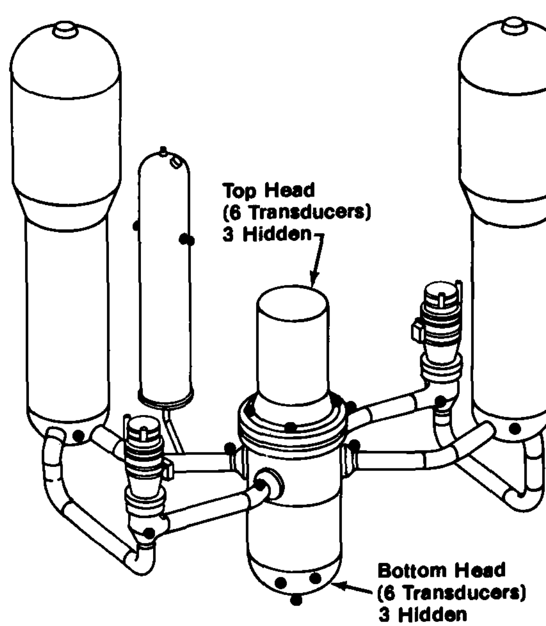

FIG. 8—*Isometric view of primary system.*

TABLE 1—*Primary system attenuation.*

Point	Location	Signal Level
1	Top flange of vessel; 0 deg	0 dB
2	Top flange of vessel; 180 deg from point	−14 dB
3	Inside vessel 1 in. below 0 deg nozzle	−26 dB
4	Pump to vessel pipe 0 deg; 8 ft from vessel	−34 dB
5	Bottom of vessel	−37 dB
6	Steam generator to pump piping	−45 dB

Typical installation of transducers is shown in Fig. 8. The location of the pressure vessel transducers was dictated in large measure by accessibility. The biological shield restricts access to the circumference except at the nozzle area and bottom of the vessel.

The ventilating shroud limits top head access. The compromise locations were control rod ports and head lifting lugs as the outermost available points.

Signals typically encountered are classified into three groups:

1. Long-duration signals with a sharp leading edge and decaying envelope characterize acoustic emissions from flaw propagation and stress relieving of welds.

2. Signals with a slow rise time and a decaying envelope are typically associated with a mechanically induced signal.

3. Spikes are typically associated with electrical interference. Confirmation of this fact is accomplished by noting zero time difference between different channels.

A planar layout of the reactor, Fig. 9, is used for location. The vessel shell is examined by using transducers on the nozzles and bottom of the vessel. The nozzles are shown in a planar view to establish minimum path lengths. The nozzle transducer position is rotated 90 deg into the plane of the pressure vessel outer surface. Total minimum path lengths between transducers on the bottom of the pressure vessel and nozzle are obtained by adding the nozzle minimum path to the pressure vessel shell minimum path. Figure 9 also shows a typical triangle used for source location.

Location of sources in the bottom head is identical to that used for the cylindrical portion except that it involves calculation of angles and time lengths of the spherical triangle formed by the great circle paths connecting transducer locations. Although transducer location was dictated by accessibility, this did not interfere with source location.

The results show that reactor vessels were relatively quiet, acoustically, during hydrostatic testing, with few large amplitude bursts from different locations near welds. This phenomenon is probably caused by

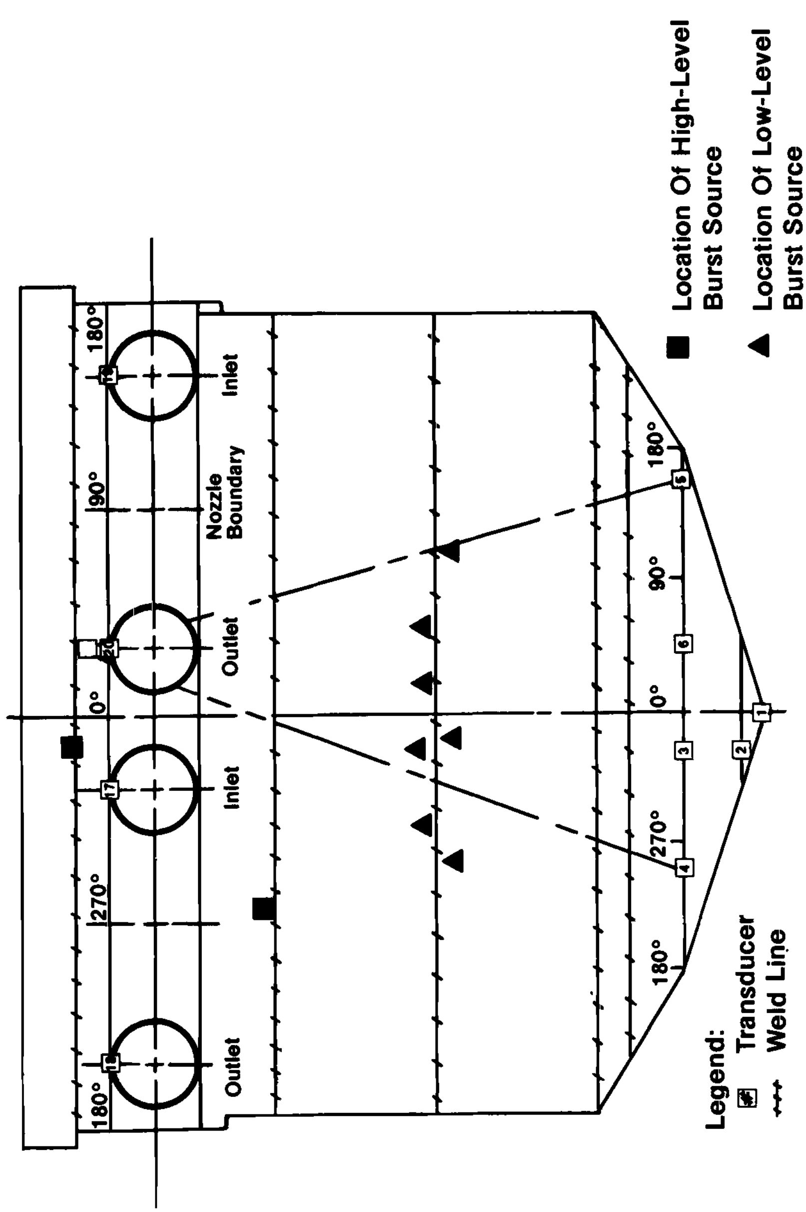

FIG. 9—*Prairie Island pressure vessel layout and source locations.*

redistribution of residual stresses since only a few bursts were observed during the test.

Measurements During Plant Operation

Results of background noise readings taken at various temperatures are summarized in Table 2.

The background noise decreased significantly with increase in temperature.

Signal propagation characteristics measured with simulated acoustic signals showed little variation at ambient (no noise) conditions and normal operating condition as shown in Table 3.

Laboratory Testing

Acoustic Emission and Fracture Mechanics Program

At Westinghouse work has recently started on a joint acoustic emission and fracture mechanics program. This work is being pursued to develop the relationship that exists between AE activity and the magnitude of the stress intensity factor, K, or the crack emitting the sound. The stress intensity factor is a fracture mechanics parameter that describes crack severity in terms of crack size and the stresses acting on the structure. By knowing the relationship between AE activity and the stress intensity factor for different materials, geometrics, and loading arrangements, it should be possible to determine to some degree flaw severity by "listening" on the surface of the structure with appropirate instrumentation. This can possibly be done even when the flaw site is completely hidden—the only requirement being that there be a good acoustic transmission path between the flaw site and the transducer location.

The study of the relationship between AE and fracture mechanics is still in its infancy. Some of the pioneering work by Tetleman [4] has shown that the AE count rate dn/dt is proportional to the stress intensity factor raised to the fifth power; that is, $dn/dt = C_1K^5$. Consequently, small changes in K lead to rapid increases in count rate. In this manner, it is possible to associate a critical count rate with a critical K-value (K_c), and hence with the onset of failure.

AE monitoring of the fatigue testing of compact-tension (CT) specimens made of A533B pressure vessel material has been recently initiated at Westinghouse. Westinghouse AE instrumentation is being used. Several 2T-CT specimens (that is, 2 in. thick) and 4T-CT specimen (4 in. thick) have been tested. To prevent extraneous noise, such as rubbing noises generated at the specimen load pin interface, undersize load pins were made and encased in electrical shrink fit tubing. In addition, glass

TABLE 2—*Effect of temperature on background noise.*

Reactor Condition		Root Mean Square Noise at Typical Locations				
Temperature, °F	Pumps	Botton, V	Inlet Nozzle, V	Outlet Nozzle, V	Head, V	Steam Generator, V
70	0	0.035	0.035	0.035	0.035	0.038
250	2	0.53	0.29	0.42	0.2	0.122
350	2	0.34	0.19	0.275	0.115	0.097
530	2	0.095	0.048	0.066	0.041	0.054

TABLE 3—*Effect of temperature on signal attenuation signal levels, volts peak to peak.*

Channel	70°F	350°F	530°F
Bottom center	15	15	20
Shell 0 deg	8	. . .	8
Shell 180 deg	7	4	7

tape was laid on the specimens on all areas where the specimen might touch the load clevis.

The testing was conducted in conventional test machines in the fatigue laboratory using hydraulic actuators and electromechanical servo control systems.

This setup worked well and ensured that only noise generated at the fatigue crack tip reached the AE instrumentation.

A system gain of 60 dB, a pulse width of 10 μs, and a discriminator setting of 80 mV was selected for the tests based on previous experience. For the latest tests, a "gate" was built for the system which disabled the discriminator and totalizer near minimum load and thus permitted data to be collected separately on signals emitted at or near the maximum test load. This was done because acoustic signals occurring at maximum load were

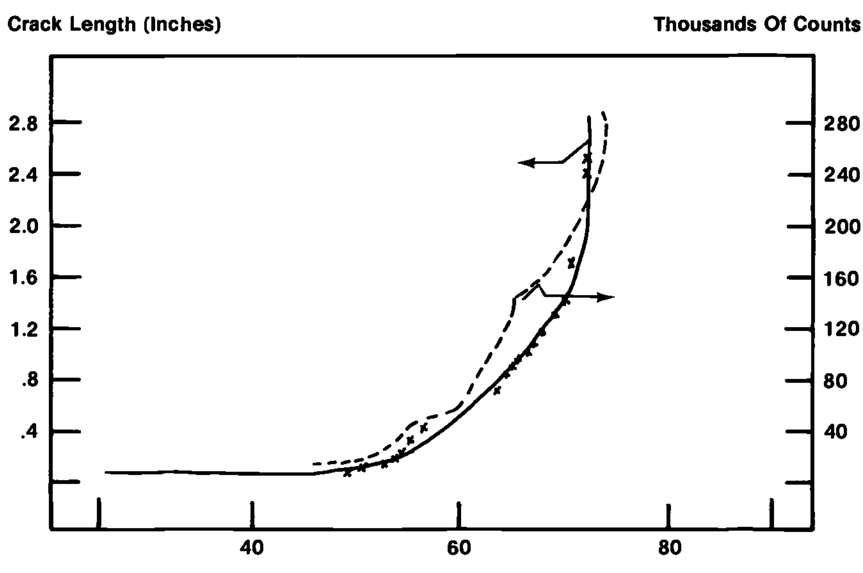

FIG. 10—*Crack length and gated counts versus cycles for 4-in. specimen.*

considered more meaningful. When this gate was used two discriminator and totalizers were used, one being gated and one not.

Fatigue cycling was conducted in a tension-tension mode with an R ratio of 0.1, that is, $P_{min} = 0,1\, P_{max}$ and a sinusoidal waveform A test frequency of 1 Hz was used throughout all testing except in some selected cases where a frequency of 10 Hz was used to initiate the fatigue crack.

Typical results are shown in Figs. 10 and 11. An apparent relationship is seen between counts and crack length.

Acoustic Emission Wave Propagation and Wave Mode Detection Studies

On its travel through a structure such as a pressure vessel, from the point of origin to the point of detection, the waveform of an AE burst becomes distorted. First of all, the intensity of the signal diminishes as the wavefront diverges from the source because of spreading loss, absorption, and reflection from obstacles. Also, the waveform's temporal structure changes because the relative energy distribution between compressional, shear, and surface waves is constantly shifting due to reflection and mode conversion at the surfaces and because of sound velocity differences. A detailed understanding of the manner in which the waveform distorts is

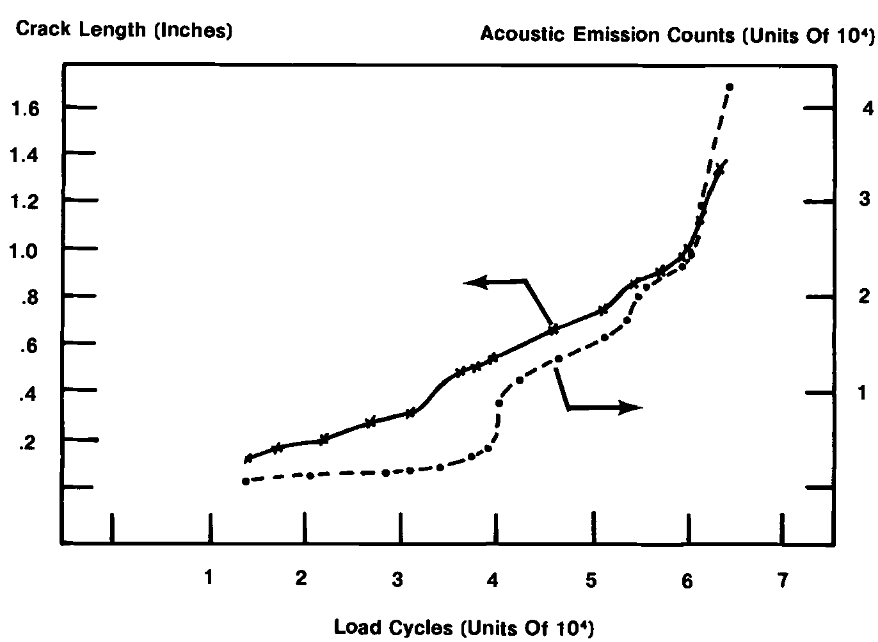

FIG. 11—*Crack length and gated counts versus cycles for 2-in. specimen.*

necessary if information measured at the transducer face on the structure's surface (far-field data) is to be intelligently related to what is happening at the crack tip (near-field data), and to what is measured on fracture mechanics specimens in the fracture laboratory (reverberant data).

In order to study such distortion and predict location of the crack from the signature itself, controlled tests have been run on an 8-in.-thick by 7-ft-wide by 12-ft-long steel plate. It was found that the waveshapes of the received signals differed markedly depending on whether the plate was excited acoustically on the top or the edge. For top side excitation, the received signal waveform was independent on the spacing between the sound source and receiving transducer, with the waveform primarily composed of a single surface of Rayleigh wave of short-time duration.

For edge excitation, the received waveform comprised a group of individual pulses, with the number of pulses increasing as the spacing between the sound source and receiving transducer increased. The multiple pulses were caused by reflections and mode conversions of acoustic signals striking the top and bottom surfaces of the plate.

Test data, for both major surface and edge excitation, were confirmed theoretically. A computer program was written to predict the shape of the received acoustic pulse group for the thick flat plate case.

Conclusions

Results obtained from various phases of the program demonstrate:

1. Availability of a direct mounted transducer and a data processing system suitable for nuclear plants.
2. Feasibility of identifying various stages of failure in pipes and vessels such as flaw initiation, growth, and leak in the presence of noise.
3. Feasibility of locating flaws within a few inches.
4. Ability of systems to monitor plants on a continuous basis.
5. Feasibility of correlating AE events to crack growth under controlled condition on specimens and test vessels.
6. Problem areas in characterizing AE signals measured at distances from source.

Acknowledgments

In Westinghouse Electric Corporation, principal investigators are: W. C. Leschek and C. F. Petronio in the transducer and electronic area; M. A. Lebeda and P. J. Hite in analysis and display systems; A. F. Schmidt, T. R. Sanders, and J. Craig in measurements; and V. J. McLoughlin and J. Craig in laboratory tests. Excellent cooperation and participation of personnel at various plants and test facilities are gratefully acknowledged.

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Detection and Location of Flaw Growth in Metallic and Composite Structures

REFERENCE: Kelly, M. P., Harris, D. O., and Pollock, A. A., "**Detection and Location of Flaw Growth in Metallic and Composite Structures,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 221–240.

ABSTRACT: The application of a multichannel real-time acoustic emission location system to the detection and location of structural defects in three different materials and geometries is presented. Test results from welded steel pressure vessels demonstrate that incremental crack growth during pressurization can be accurately located and assessed. Additional results from graphite-epoxy honeycomb structures indicate that acoustic emission is also a viable tool in detecting and locating impending failure in composite materials.

KEY WORDS: acoustics, emission, pressure vessels, crack propagation, composite materials, failure, honeycomb structures

Acoustic emission (AE) is the term applied to the impulsively produced elastic waves produced by a material subjected to stress. Plastic deformation and the nucleation and growth of cracks have been found to be two of the primary sources of AE from metals. The use of AE techniques to ascertain the integrity of pressure vessels has been extensively covered in the literature [*1-16*].[3]

AE techniques can be used to locate defects in structures, in addition to detecting them. Source locations are determined by placing arrays of sensors on the part and comparing the relative arrival time of the stress wave at the various sensor locations. Most of the previously published work on AE locational techniques [*1,7-16*] have been restricted to metallic

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[2] Dunegan/Endevco UK, Royston, England.

[3] The italic numbers in brackets refer to the list of references appended to this paper.

structures, and the location of the source has been usually determined by post-test analysis.

The purpose of this paper is to present test results obtained with a recently developed real-time source location system. The applicability of a multichannel location system to the detection and location of structural degradation in three independent tests will be discussed:

1. Graphite-epoxy honeycomb panel punch tests (performed in conjunction with Lockheed Missiles and Space Company, Inc., Sunnyvale, California).
2. Cylindrical steel pressure vessel test (performed in conjunction with the Dutch Acoustic Emission Working Group at the KEMA facility in Arnhem, The Netherlands).
3. Spherical steel pressure vessel test (performed in conjunction with CEA-Saclay, France).

All source location work reported to date has been on isotropic and homogeneous materials, such as metals and glass. The results to be reported on the graphite-epoxy honeycomb are the first presented for such a complex material and demonstrate the applicability of source location techniques to this important class of materials.

Instrumentation

A block diagram of the 10-channel source location system used in these tests is presented in Fig. 1. Several features and components of the system are worth noting:

Transducer

Differential transducers were used in these tests because of the immunity to electromagnetic interference afforded by the differential design.

Audio Monitor

The audio monitor heterodynes the high frequency signal from the signal conditioner down into the audio range to provide an audible measure of the AE activity.

*Delta-*T *Interface*

When an AE event has occurred, the delta-T interface determines the transducer arrival sequence, measures the corresponding arrival times, and stores the event information in a data buffer in computer memory.

Computer

The computer performs validity checks on the incoming data, calculates X-Y coordinates of the source, and prepares the event data for display and printout.

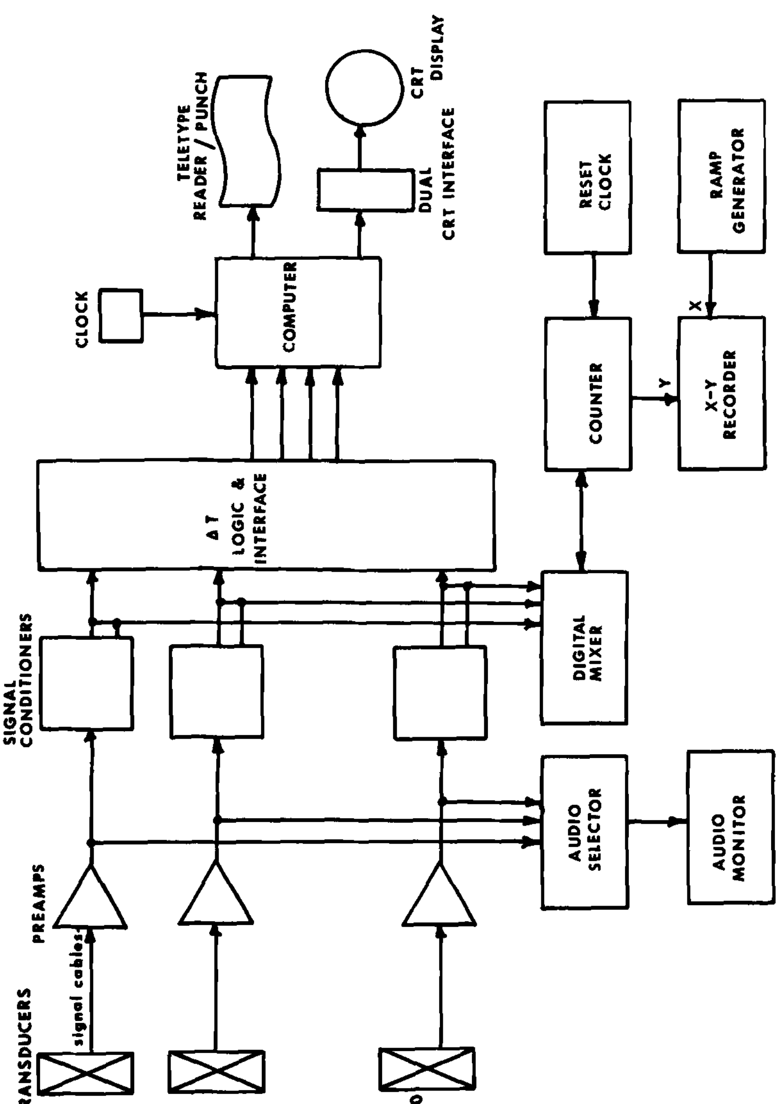

FIG. 1—*Block diagram of computerized location system.*

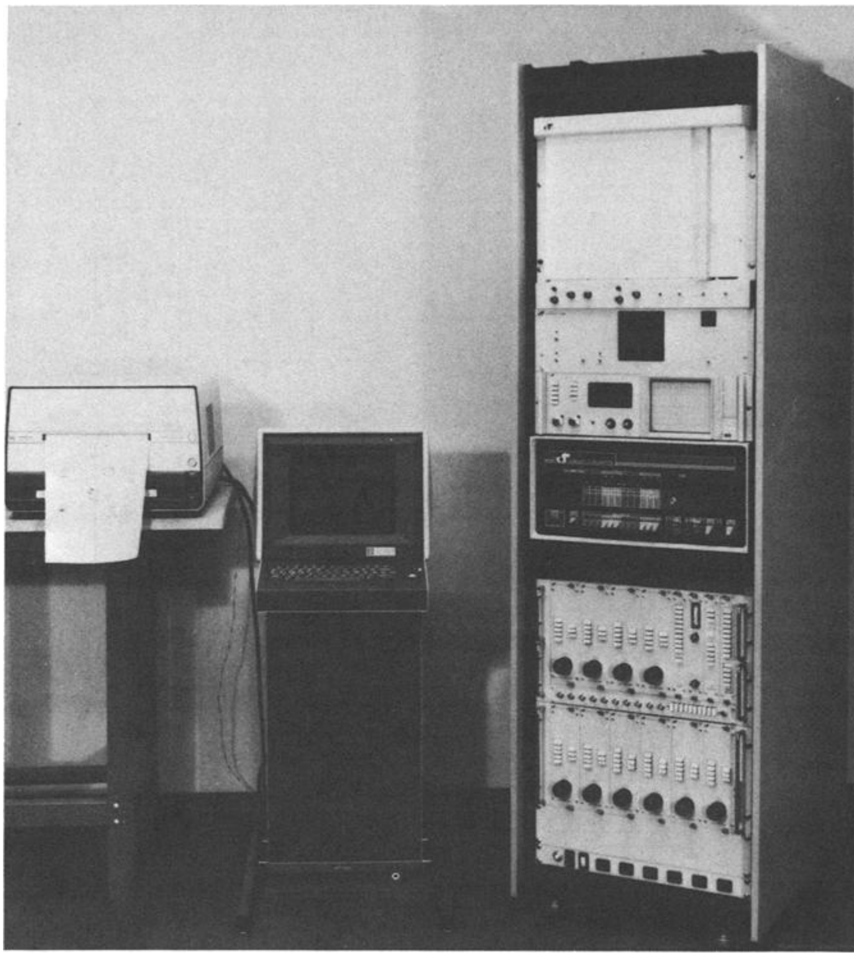

FIG. 2—*Photograph of source location system.*

X-Y *Display Scope*

The cathode ray tube (CRT) provides an instantaneous display of the location of each source in relation to the position of the sensors involved. In lieu of the normal display, a histogram, indicating the source activity by area and first sensor excited, can be chosen.

Teletype

Besides serving as the input device between the operator and system, the teletype printer-punch combination provides a hard copy output of each event for test analysis. The arrival sequence, corresponding arrival times, test time, and X-Y coordinates are output for each event. The paper punch allows the operator to either duplicate the test results at a later date or recalculate the X-Y coordinates using a new calibration value, if desired.

Calibration

The source location system is "self-calibrating" since the wave velocity of the material is measured automatically by the system in a special calibration run prior to testing. A piezoelectric transducer used as a pulser is attached to the structure next to one of the pickup sensors and excited by an electrical signal to simulate an AE event. The closest transducer detects the event immediately and enables three counters which are disabled as the other sensors are hit. This technique provides the system with the maximum time of flight between neighboring transducers for use in calculating X-Y coordinates during the test. Figure 2 shows a photograph of the source location system.

Graphite-Epoxy Honeycomb Panel Tests

This work was performed to assess the applicability of AE techniques to the detection and location of localized failures in composite materials.[4] A 48-cm-square panel of 1.3-cm-thick honeycomb with graphite-epoxy facesheets was loaded locally to destruction in several places by forcing a 1.3-cm-diameter flat-ended punch into the facesheet. Local failure occurred by fiber breakage and delamination of the facesheet (which had several crossplys), and debonding between the facesheet and core. A 45-kN-capacity Instron test machine which produced a load-time plot of the test was utilized.

A square monitoring section with 41-cm spacing between 140-kHz resonant frequency transducers was incorporated for this work. The punch was indented on one side of the honeycomb, and tests were performed with transducers mounted on both sides of the sheet in order to determine the effect of the honeycomb material on stress wave transmission.

Test results from two punch tests (one with the punch and transducers on the same side, and one with the transducers on the opposite side) are presented in Figs. 3 and 4. (The square pattern of bright spots are the sensor locations.) These photos include all emission recorded during the test up to final failure, which occurred when the 1.3-cm-diameter punch penetrated the first graphite-epoxy facesheet. The scatter of sources appears to be excessive until you consider that the structure is designed to spread the load (and hence the damage) over a wide area. A comparison of the teletype

[4] Work performed in conjunction with Lockheed Missiles and Space Company, Inc., Sunnyvale, Calif.

test printout with the load-time chart indicated that emission occurred in short duration bursts just prior to major load drops in the load-time curve.[5] Figures 5 and 6 illustrate the AE activity just prior to major load drops in the two tests just described. These photos indicate that scatter is less severe during actual localized destruction than during the course of an entire punch test. From these results it is reasonable to assume that the damage is indeed spread over a much larger area during a total load cycle.

These tests results demonstrate that AE source location techniques can be used to detect and locate incipient failures in composite materials (at least composites with multiple layers of fibers to minimize anisotropy).

Cylindrical Pressure Vessel Test

A hydrostatic test on a cylindrical pressure vessel of API 0.5L grade X60 steel was monitored.[6] The material treatment and chemical composition of the pressure vessel material are listed in Table 1.

The vessel was a double-ended cylinder 2.79 m in length with a diameter of 1.22 m. Several defects in the form of brittle welds, sawcuts, and eloxed (electrodischarge machined) notches were introduced into the vessel, as shown in Fig. 7. A software routine for use with cylindrical structures was incorporated to calculate source coordinates during the test. Interlocking equilateral triangular arrays of 140-kHz resonant frequency transducers spaced 130 cm apart were used. Figure 8 illustrates the CRT presentation for a development of the cylinder along with all weld, nozzle, and defect locations.

Table 2 includes the maximum pressure attained, system gain, and the number and identification of artificial defects for the three pressure cycles. Figure 9 represents the source location display for simulated AE introduced at the five artificial defect areas which generated emission during one or more pressure cycles.

TABLE 1—*Chemical composition and material treatment for pressure vessel used in KEMA test.*

Material treatment:	API 0.5L Grade X60	
	Hot rolled	1.5% cold expanded
Chemical composition, %:	C = 0.20	S = 0.012
	Mn = 1.28	Al = 0.034
	Si = 0.26	V = 0.106
	P = 0.006	Cb = 0.005

[5] A drop in the load curve would represent failure in a full-scale structural test, but for this work the load was continued until the punch penetrated the face sheet.

[6] Test performed in conjunction with Dutch Working Group on Acoustic Emission at KEMA facilities, Arnhem, The Netherlands.

FIG. 3—*Location results for punch test on honeycomb. Results for entire test to destruction (Test 1) are shown. Transducers and punch on same side of panel.*

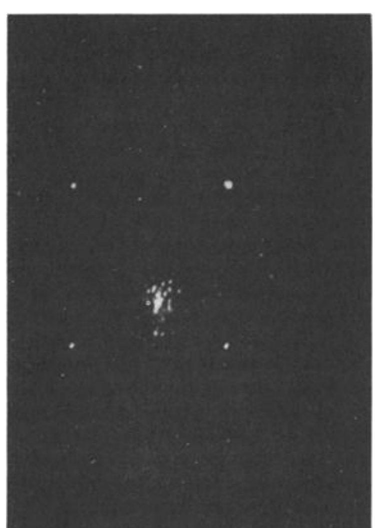

FIG. 4—*Location results for punch test on honeycomb. Results for entire test to destruction (Test 2) are shown. Transducers and punch on opposite sides of panel.*

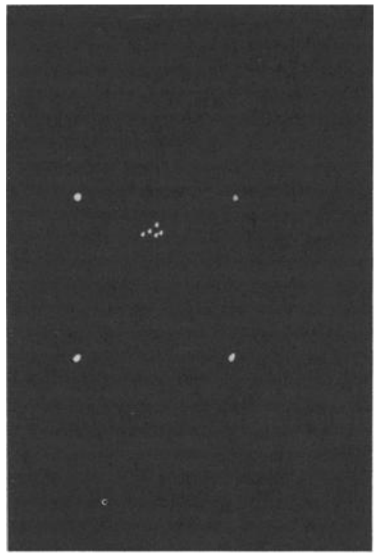

FIG. 5—*Emission from honeycomb panel just prior to load drop in Test 1.*

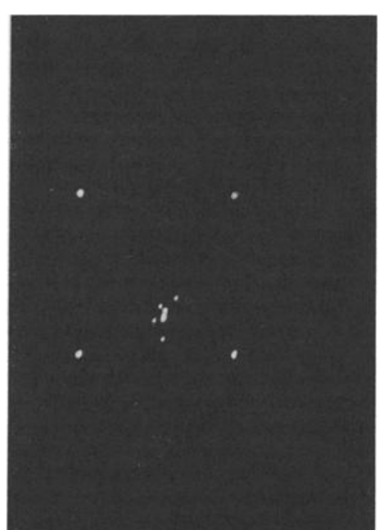

FIG. 6—*Emission from honeycomb panel just prior to load drop in Test 2.*

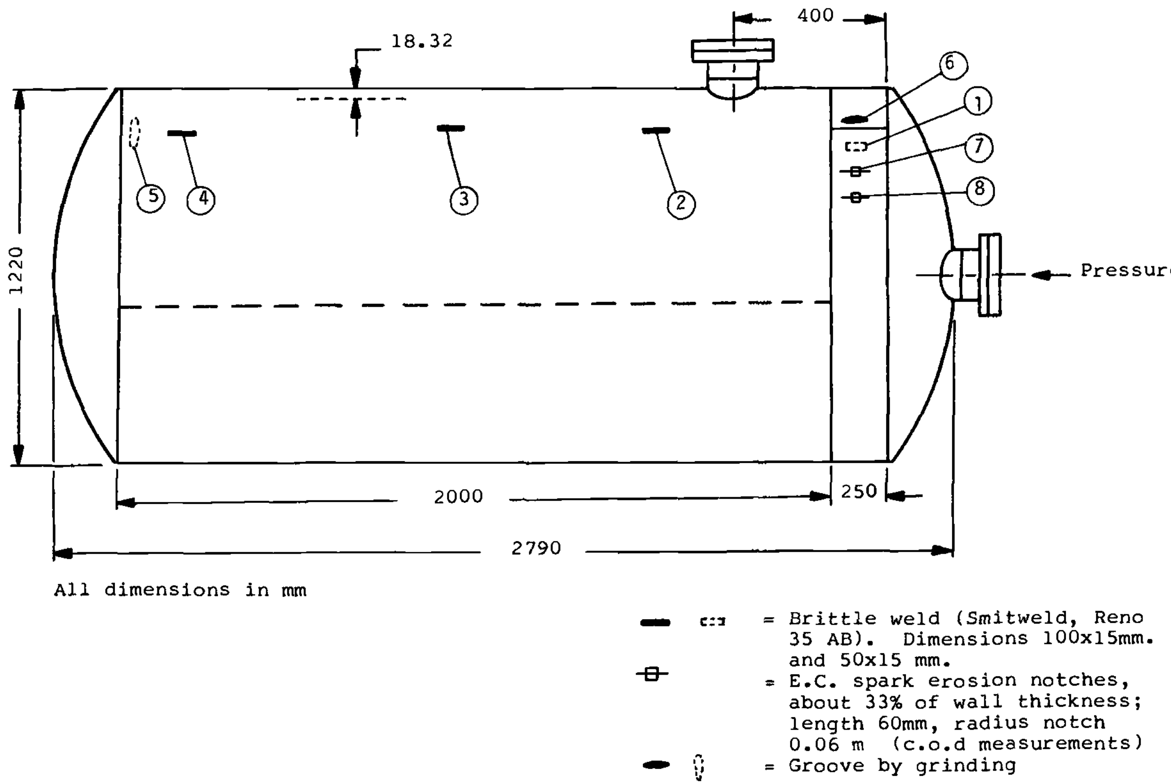

FIG. 7—*Cylinder vessel showing artificial defects.*

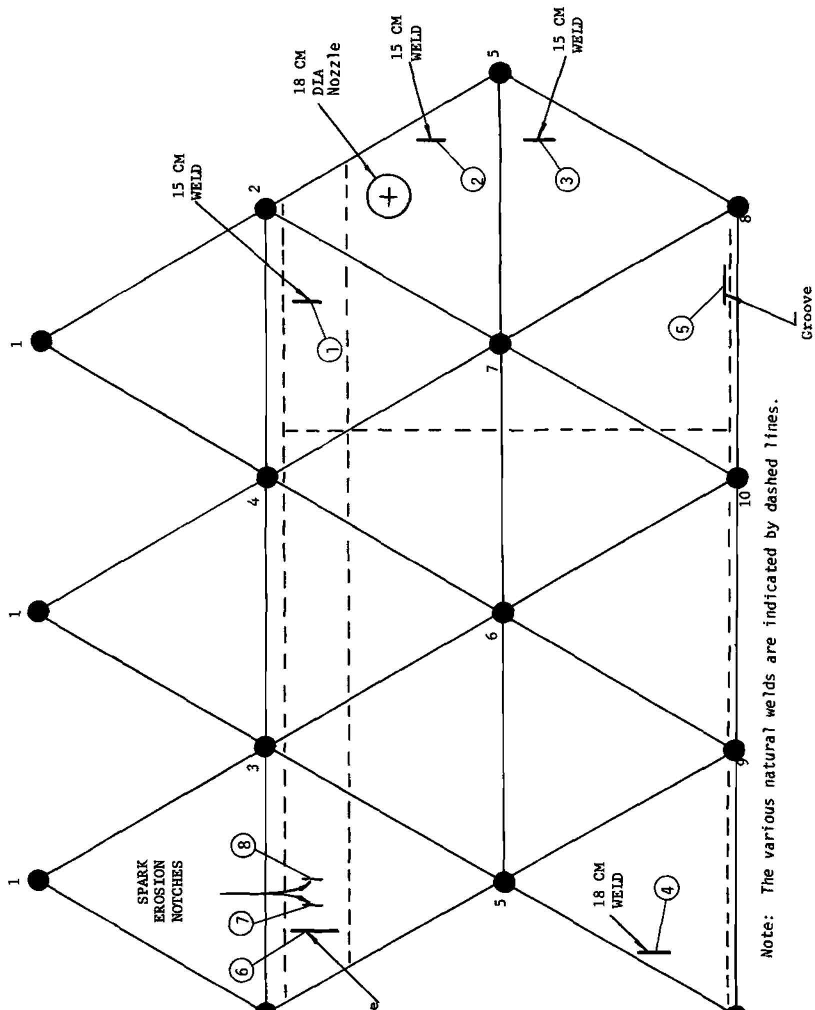

FIG. 8—*CRT presentation of cylindrical vessel with flaws, nozzle, and welds.*

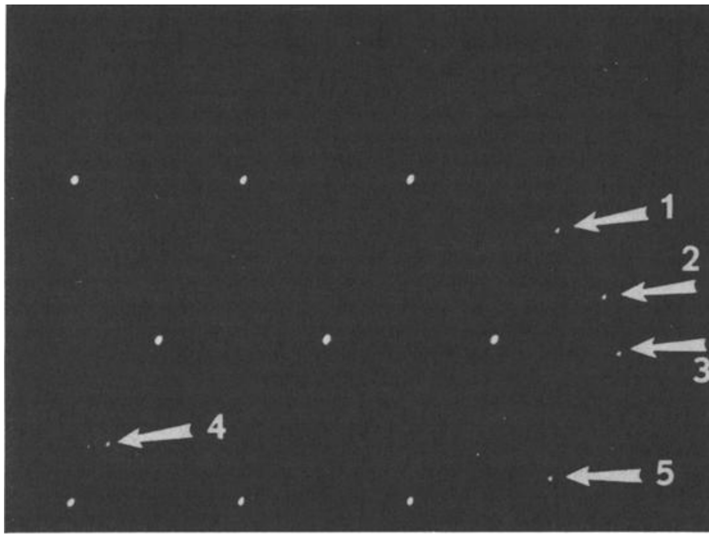

FIG. 9—*CRT display of location of simulated emission introduced at the defects in the cylindrical vessel.*

FIG. 10—*CRT display of emission sources for cylindrical pressure vessel Cycle 1.*

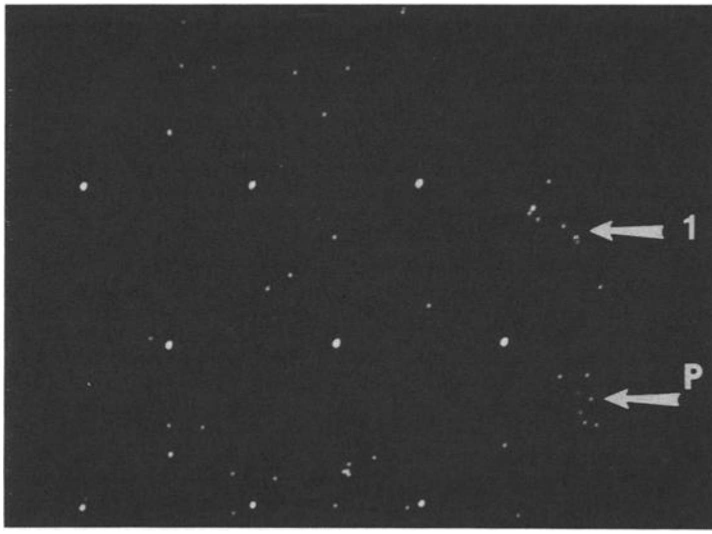

FIG. 11—*CRT display of emission sources for cylindrical pressure vessel Cycle 2.*

Photographs of the CRT test data for Cycles 1 and 2 are presented in Figs. 10 and 11. Emission from Defect 1 is evident in both pictures, and most of the other sources are associated with the many natural welds in the structure. No emission was received from either of the eloxed notches (Defects 7 and 8). The first 2 cycles were performed with gains of 90 and 84 dB which turned out to be higher than necessary or desirable. This accounts for much of the scatter observed in Figs. 10 and 11.

The computer program requires that the transducers be arranged in a series of interlocking equilateral triangles. In order to cover the vessel with ten sensors, it was necessary to make some of the triangles nonequilateral which adversely affects locational accuracy.

The emission from the area indicated by the letter *P* in Figs. 10 and 11 initiated from an area where two preamplifiers were sitting on the vessel. The preamplifiers were removed for the third cycle and emission from that area ceased. A post-test ultrasonic inspection indicated there were no defects in this region; therefore, the lack of emission during the third pressurization can be attributed to the removal of the preamplifiers rather than the Kaiser effect.

The third pressure cycle is divided into three photos: 0 to 2.3 MN/m^2, 2.3 to 2.8 MN/m^2, and 2.8 to 3.7 MN/m^2. Figures 12–14 show the effect of crack extension during these cycles. The CRT was cleared of all current sources at 2.3 and again at 2.8 MN/m^2. Figure 12 shows cracking initiated in Defect

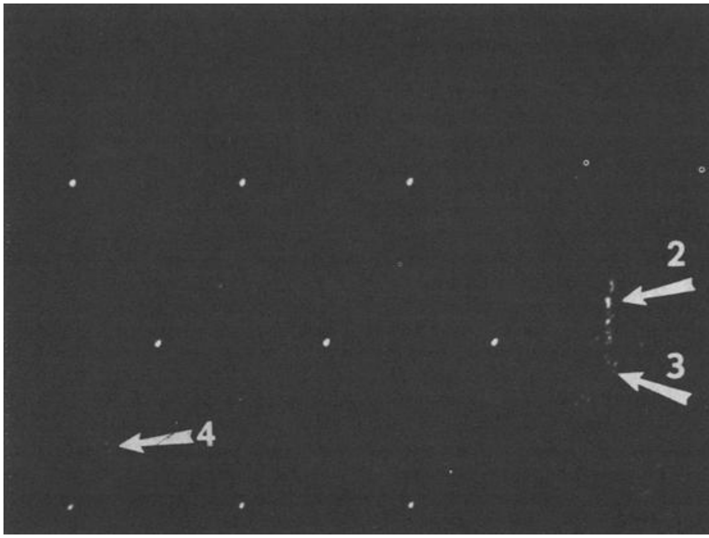

FIG. 12—*CRT display of emission sources for cylindrical pressure vessel Cycle 3 (0 to 2.3 MN/m²).*

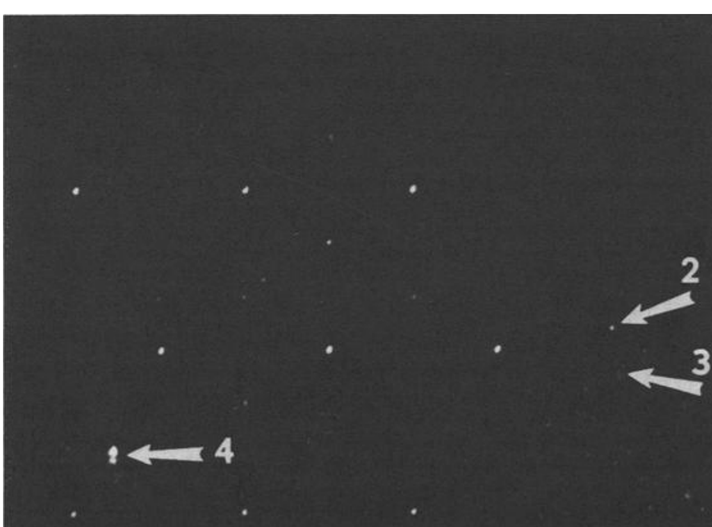

FIG. 13—*CRT display of emission sources for KEMA pressure Cycle 3 (2.3 to 2.8 MN/m²).*

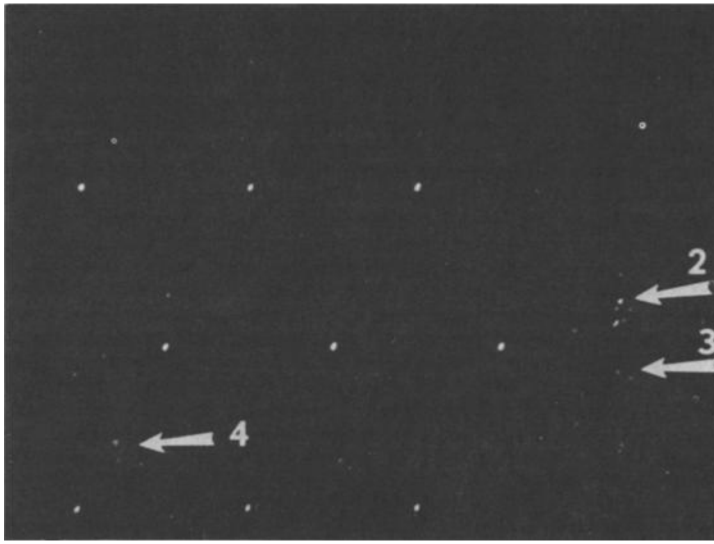

FIG. 14—*CRT display of emission sources for KEMA pressure Cycle 3 (2.8 to 3.7 MN/m²).*

2 prior to 2.3 MN/m² with scattered emission from Defects 3 and 4. Defect 4 had substantial crack growth during the 2.3 to 2.8 MN/m² (Fig. 13) period with a few scattered events from the remaining flaws. In the final period (2.8 to 3.7 MN/m², Fig. 14) light activity was detected from several of the defect areas.

The source locations in these photos (Figs. 12–14) correlate very well with the pulser generated AE simulated flaw data shown in Fig. 9. A post-test ultrasonic and dye-penetrant inspection (reported in Ref *17*) substantiated the crack growth in each of the brittle welds as well as the absence of crack extension in the eloxed notches. The vessel was not taken to failure.

Spherical Pressure Vessel Test

A test conducted in conjunction with CEA Saclay in France was performed on a welded spherical pressure vessel made of AMMO steel. The

TABLE 2—*System gain, maximum pressures attained and number of defects in test of cylindrical vessel.*

Cycle	Max Pressure Attained, MN/m²	System Gain, dB	Number of Defects	Identification of Defects
1	0.65	90	3	1, 7, 8
2	3.7	84	3	1, 7, 8
3	3.7	74	8	1 to 8

TABLE 3—*Chemical composition and mechanical properties of AMMO steel.*

Chemical composition, %:	C = 0.12
	Mn = 1.20
	Mo = 0.45
	Cr = 0.05
	V = 0.07
	S = 0.015
	P = 0.007
Mechanical properties:	σ ultimate strength = 579 MN/m^2
	σ yield strength = 469 MN/m^2
	% reduction in area = 24%

chemical composition and mechanical properties of the AMMO steel, as reported in Ref *18*, are listed in Table 3.

The pressure vessel was 918 mm in diameter with a wall thickness of 4.7 mm. A full-thickness sawcut 205 mm long was machined in the parent metal and sealed on the inside to contain the pressure.

The vessel was instrumented with eight 750-kHz resonance frequency transducers spaced 58 cm apart. A diagrammatic representation of the vessel with transducer locations is shown in Fig. 15. A routine developed for testing spheres was used to calculate source coordinates during the test. Figure 16 illustrates the CRT presentation for the sphere along with all flaw, weld, and nozzle locations.

Table 4 shows the pressure and total system gain for each of the pressure cycles which were recorded on punched paper tape.

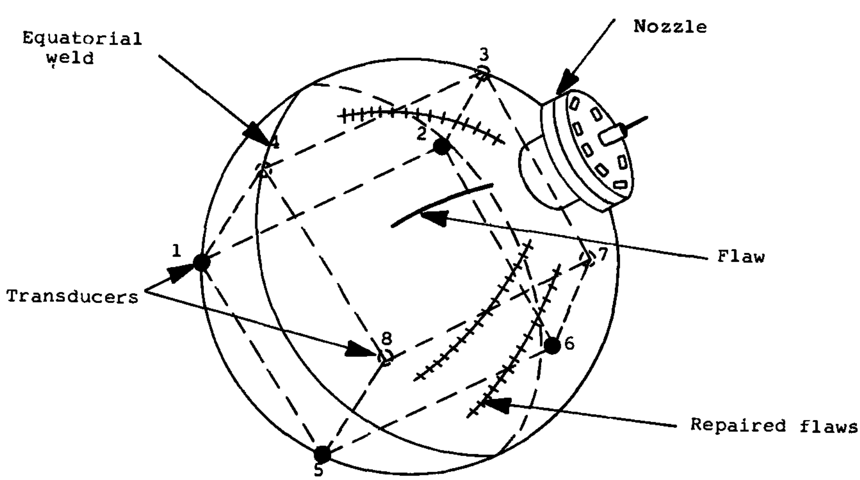

FIG. 15—*Position of flaw and transducers in Saclay vessel.*

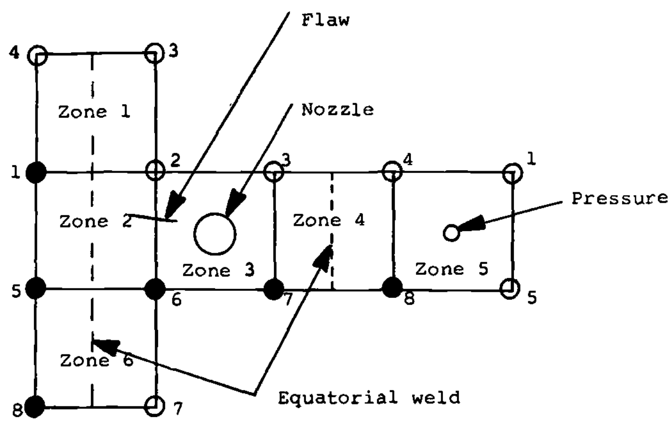

FIG. 16—*CRT presentation of sphere with flaw, nozzle, and weld.*

The crack extremities (simulated with a pulser) are indicated by the two bright spots in Fig. 17.

Although extension of the flaw was visually observed during each pressure cycle, a relatively small amount of emission was detected from the defect area. Therefore, the total system gain was gradually increased from 76 to 90 dB during the course of the test. Photographs of the CRT display during several cycles are shown in Figs. 18–20. Note that emission from the weld and nozzle is evident in every photo, but source activity from the defect area is nonexistent in some cases. Figure 20 represents the emission recorded during the final pressure cycle, which resulted in severe bulging at the defect and leaking of the pressure vessel.

Because crack growth was difficult to detect in the presence of welds and nozzles, a laboratory investigation was initiated to study the AE characteristics of AMMO steel. Tests were conducted on flawed and unflawed tension specimens of both the parent and weld materials. Figure 21 presents the results of a test on a fatigue precracked specimen of the base

TABLE 4—*Total system gain and maximum pressure attained for recorded pressure cycles in Saclay test.*

Cycle	Max Pressure Attained, MN/m^2	Gain, dB
1	2.0	76
2	2.1	76
3	2.5	76
4	2.5	80
5	2.5	86
6	4.0 to (burst)	90

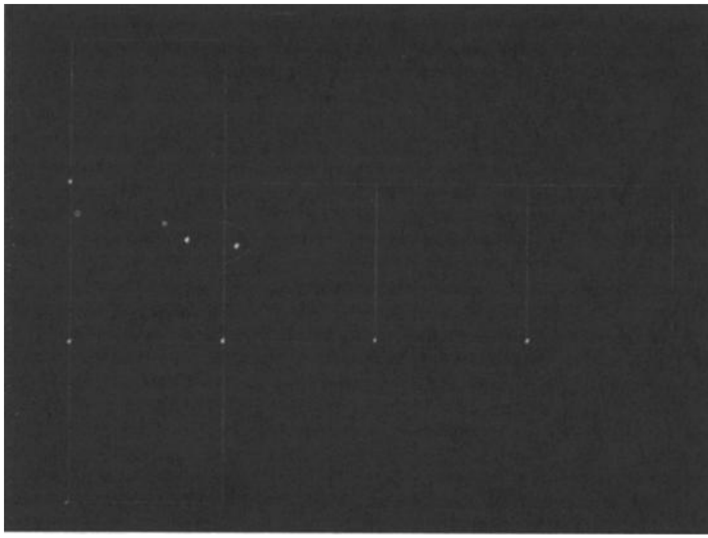

FIG. 17—*Flaw boundaries in spherical pressure vessel.*

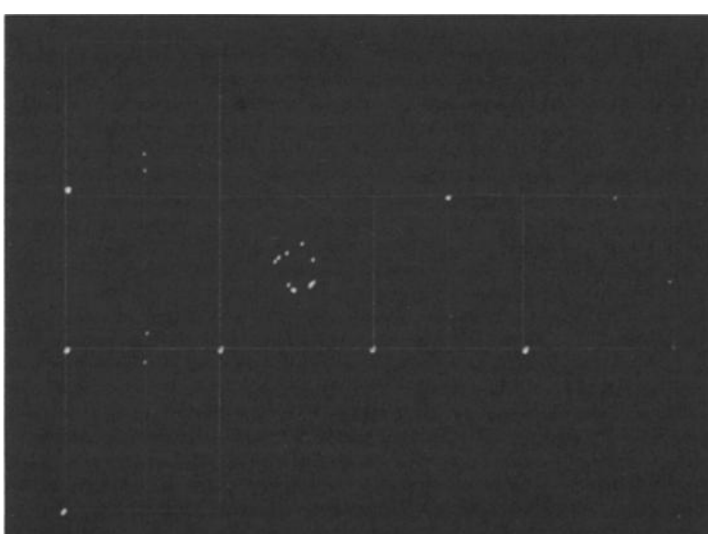

FIG. 18—*CRT display of emission sources for spherical pressure vessel Cycle 1.*

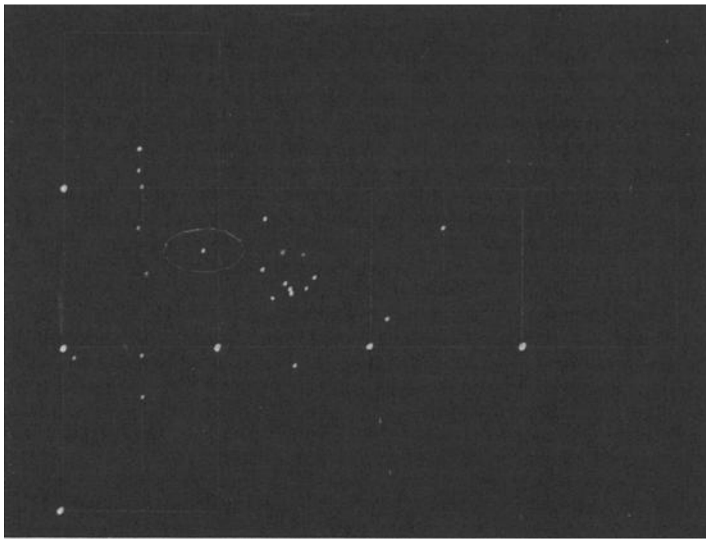

FIG. 19—*CRT display of emission sources for spherical pressure vessel Cycle 4.*

FIG. 20—*CRT display of emission sources for spherical pressure vessel cycle 6 (final cycle).*

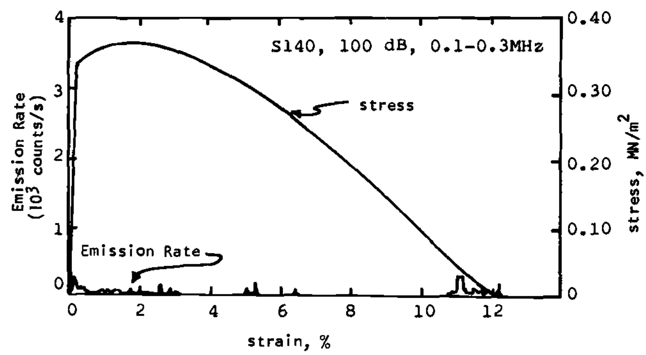

FIG. 21—*Acoustic emission stress strain plot for fatigue precracked specimen of AMMO steel.*

material. It is evident from this graph that the material (AMMO steel) is very "quiet" even at a gain of 100 dB. The system locational accuracy is demonstrated by the exceptional nozzle and equatorial weld emission detected during several of the pressure cycles.

The lack of emission from the parent metal defect, even though the defect was observed to be growing, points up the possible danger of performing source location tests without a knowledge of the AE characteristics of the material. Some quiet materials do exist, in which case a lack of emission does not necessarily imply the absence of defects.

Conclusions

The test results presented show that AE source location techniques provide accurate information on the location of defects in a variety of materials and structures. The three tests presented were for widely varying conditions and materials, yet the results showed (except possibly for parent metal defects in AMMO steel) that standard AE location techniques provide a powerful tool for the verification of integrity of pressure vessels and other structures. The lack of emission from the parent metal defect in the AMMO steel vessel points up the desirability of performing an AE characterization of an unfamiliar material prior to testing a structure of that material.

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Acoustic Emission—A Bibliography for 1970-1972

REFERENCE: Drouillard, T. F., "**Acoustic Emission: A Bibliography for 1970–1972,**" *Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571,* American Society for Testing and Materials, 1975, pp. 241–284.

ABSTRACT: The bibliography includes nearly all references in the literature on acoustic emission published during the three-year period, 1970 through 1972. Included in the 412 references are several for each of the associated technologies including: signature analysis, boiling detection, cavitation, leak detection, seismology, and rock mechanics. Information has also been obtained from eight abstracting and indexing services searched in compiling the bibliography. The bibliography has been arranged alphabetically by author and is cross referenced with a list of approximately 400 authors. Also included is a subject index. Technical articles listed were published in some 90 different journals and in 8 different languages.

KEY WORDS: acoustics, emission, bibliographies, indexes (documentation)

Acoustic emission (AE) is a new and rapidly developing technology for materials research and nondestructive testing (NDT). In materials research, deformation and fracture processes studied as sources of emission include: dislocation pile up and break away, slip, twinning, Luders line formation, martensitic phase transformation, stress corrosion and stress corrosion cracking, and crack initiation and propagation. As an NDT tool, acoustic emission testing is used to evaluate structural integrity and, in the surveillance of pressure vessels and structures, to detect incipient failure during proof loading, periodic overloading, and in-service monitoring. Since the amount of literature on AE being published has increased at an exponential rate, a bibliography of current literature is timely and valuable to those persons already working in the field of AE, as well as to those just coming into the field.

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The bibliography has been organized to include the literature on AE published in the form of technical reports, journal articles, technical presentations, proceedings, doctoral and master theses, patents, and bound volumes during the three-year period 1970 through 1972. Included in the 412 references are several references for each of the associated technologies involving AE phenomena. These include: signature analysis, boiling detection, cavitation, leak detection, seismology, and rock mechanics. With few exceptions, copies of all reference material have been obtained by the author for the purpose of accuracy and to establish their availability.

In addition to references cited in AE literature, the following abstract and index services were searched in compiling the bibliography: *Nuclear Science Abstracts, Metals Abstracts, The Engineering Index, Physics Abstracts, Chemical Abstracts, Corrosion Abstracts, Scientific and Technical Aerospace Reports,* and *Dissertation Abstracts*. Another valuable source of information has been the Acoustic Emission Working Group (AEWG) meetings at which members and guests informally discuss their current activities in the field of AE and report on work that will be reported in future publications.

The bibliography is arranged alphabetically by the first author, then the second author, etc., and finally by title. Each reference is numbered; these numbers provide a cross reference to the Author Index and Subject Index. Each reference lists all of the known publications and presentations in which a paper or report has been included. Approximately 400 persons are listed in the Author Index. Technical articles were published in approximately 90 different journals and 8 different languages: English, Russian, Japanese, German, French, Italian, Portugese, and Dutch. Some references, however, are not technical articles but consist of editorials or staff-written journal articles or new briefs which are included because they represent a part of the literature.

Several references do not report directly on AE, but discuss material that borders on or directly relates to AE and, therefore, are considered a valuable part of the bibliography.

Names of all journals are given in full and are followed by the CODEN, a five-character code intended to identify and facilitate machine handling of journal titles.

Many reports and translations are available to the public from the National Technical Information Service (NTIS), Springfield, Virginia 22151. Most of the listed report references are so designated and can be ordered by referencing the report number or the accession number appearing in brackets [ ].

Comments or recommendations for additions which may have been omitted, or other improvements to the bibliography would be welcomed.

Under a second project, acoustic emission literature through 1969 is being researched and compiled. The receipt of papers or reports or entries for inclusion, or other pertinent information would be appreciated.

Acknowledgments

In compiling the bibliography the cooperation of many persons was required. Sincere appreciation is expressed to the many authors who so generously responded to requests for copies of their reports and papers. Particular thanks go to F. J. Laner, technical editor, Rocky Flats Division, Dow Chemical USA for her many helpful suggestions in preparing the manuscript and encouragement to compile such a complete bibliography, to I. L. Bowen for her extensive secretarial assistance, and to the library staff of the Rocky Flats Division of Dow Chemical USA for their persistent efforts in helping to obtain much of the referenced material. In addition, appreciation is expressed to W. A. Dowden, C. P. Merhib, M. J. Pettigrew, P. P. Savage, and J. C. Spanner who have compiled extensive bibliographies and generously forwarded copies which served as cross checks for the current compilation. Finally, grateful acknowledgment is extended to R. G. Liptai for his encouragement to prepare a subject index.

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