Introduction

ACOUSTIC EMISSIONS are stress waves produced by sudden movement in stressed materials. The classic sources of acoustic emissions are defect-related deformation processes such as crack growth and plastic deformation. The process of generation and detection is illustrated in Fig. 1. Sudden movement at the source produces a stress wave, which radiates out into the structure and excites a sensitive piezoelectric transducer. As the stress in the material is raised, many of these emissions are generated. The signals from one or more sensors are amplified and measured to produce data for display and interpretation.

![Basic principle of the acoustic emission method](image)

The source of the acoustic emission energy is the elastic stress field in the material. Without stress, there is no emission. Therefore, an acoustic emission (AE) inspection is usually carried out during a controlled loading of the structure. This can be a proof load before service, a controlled variation of load while the structure is in service, a fatigue test, a creep test, or a complex loading program. Often, a structure is going to be loaded anyway, and AE inspection is used because it gives valuable additional information about the performance of the structure under load. Other times, AE inspection is selected for reasons of economy or safety, and a special loading procedure is arranged to meet the needs of the AE test.

Relationship to Other Test Methods

Acoustic emission differs from most other nondestructive testing (NDT) methods in two key respects. First, the signal has its origin in the material itself, not in an external source. Second, acoustic emission detects movement, while most other methods detect existing geometrical discontinuities. The consequences of these fundamental differences are summarized in Table 1.

| Characteristics of acoustic emission inspection compared with other inspection methods |
### Acoustic emission

<table>
<thead>
<tr>
<th>Acoustic emission</th>
<th>Other methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detects movement of defects</td>
<td>Detect geometric form of defects</td>
</tr>
<tr>
<td>Requires stress</td>
<td>Do not require stress</td>
</tr>
<tr>
<td>Each loading is unique</td>
<td>Inspection is directly repeatable</td>
</tr>
<tr>
<td>More material-sensitive</td>
<td>Less material-sensitive</td>
</tr>
<tr>
<td>Less geometry-sensitive</td>
<td>More geometry-sensitive</td>
</tr>
<tr>
<td>Less intrusive on plant/process</td>
<td>More intrusive on plant/process</td>
</tr>
<tr>
<td>Requires access only at sensors</td>
<td>Require access to whole area of inspection</td>
</tr>
<tr>
<td>Tests whole structure at once</td>
<td>Scan local regions in sequence</td>
</tr>
<tr>
<td>Main problems: noise related</td>
<td>Main problems: geometry related</td>
</tr>
</tbody>
</table>

Often in NDT there is no one method that can provide the whole solution; for cost effectiveness, technical adequacy, or both, it is best to use a combination of methods. Because acoustic emission has features that distinguish it so sharply from other methods, it is particularly useful when used in combination with them.

A major benefit of AE inspection is that it allows the whole volume of the structure to be inspected nonintrusively in a single loading operation. It is not necessary to scan the structure looking for local defects; it is only necessary to connect a suitable number of fixed sensors, which are typically placed 1 to 6 m (4 to 20 ft) apart. This leads to major savings in testing large structures, for which other methods require removal of insulation, decontamination for entry to vessel interiors, or scanning of very large areas.

Typically, the global AE inspection is used to identify areas with structural problems, and other NDT methods are then used to identify more precisely the nature of the emitting defects. Depending on the case, acceptance or rejection can be based on AE inspection alone, other methods alone, or both together.

### Acoustic Emission Inspection

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### Range of Applicability

Acoustic emission is a natural phenomenon occurring in the widest range of materials, structures, and processes. The largest-scale acoustic emissions are seismic events, while the smallest-scale processes that have been observed with AE inspection are the movements of small numbers of dislocations in stressed metals. In between, there is a wide range of laboratory studies and industrial testing.
In the laboratory, AE inspection is a powerful aid to materials testing and the study of deformation and fracture. It gives an immediate indication of the response and behavior of a material under stress, intimately connected with strength, damage, and failure. Because the AE response of a material depends on its microstructure and deformation mode, materials differ widely in their AE response. Brittleness and heterogeneity are two major factors conducive to high emissivity. Ductile deformation mechanisms, such as microvoid coalescence in soft steels, are associated with low emissivity.

In production testing, AE inspection is used for checking and controlling welds (Ref 1), brazed joints (Ref 2), thermocompression bonding (Ref 3), and forming operations such as shaft straightening (Ref 4) and punch press operations. In general, AE inspection can be considered whenever the process stresses the material and produces permanent deformation.

In structural testing, AE inspection is used on pressure vessels (Ref 5), storage tanks (Ref 5), pipelines and piping (Ref 6), aircraft and space vehicles (Ref 7), electric utility plants (Ref 7), bridges (Ref 7), railroad tank cars (Ref 8), bucket trucks (Ref 7), and a range of other equipment items. Acoustic emission tests are performed on both new and in-service equipment. Typical uses include the detection of cracks, corrosion, weld defects, and material embrittlement.

Procedures for AE structural testing have been published by The American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM), and other organizations. Successful structural testing comes about when the capabilities and benefits of AE inspection are correctly identified in the context of overall inspection needs and when the correct techniques and instruments are used in developing and performing the test procedure (Ref 9).

Acoustic emission equipment is highly sensitive to any kind of movement in its operating frequency range (typically 20 to 1200 kHz). The equipment can detect not only crack growth and material deformation but also such processes as solidification, friction, impact, flow, and phase transformations. Therefore, AE techniques are also valuable for:

- In-process weld monitoring (Ref 10)
- Detecting tool touch and tool wear during automatic machining (Ref 10)
- Detecting wear and loss of lubrication in rotating equipment (Ref 10), and tribological studies (Ref 11)
- Detecting loose parts and loose particles (Ref 12)
- Detecting and monitoring leaks, cavitation, and flow (Ref 12, 13)
- Monitoring chemical reactions, including corrosion processes (Ref 14), liquid-solid transformations, and phase transformations (Ref 14)

When these same processes of impact, friction, flow, and so on, occur during a typical AE inspection for cracks or corrosion, they constitute a source of unwanted noise. Many techniques have been developed for eliminating or discriminating against these and other noise sources. Noise has always been a potential barrier to AE applicability. This barrier is constantly being explored and pushed outward, bringing previously impractical projects into the realm of feasibility.

**References cited in this section**

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Acoustic Emission Waves and Propagation

The primitive wave released at the AE source is illustrated in Fig. 2. The displacement waveform is basically a steplike function corresponding to the permanent change associated with the source process. The corresponding velocity and stress waveforms are basically pulselike. The width and height of the primitive pulse depend on the dynamics of the source process. Source processes such as microscopic crack jumps and precipitate fractures are often completed in a few microseconds or fractions of a microsecond, so the primitive pulse has a correspondingly short duration. The amplitude and energy of the primitive pulse vary over an enormous range from submicroscopic dislocation movements to gross crack jumps. The primitive wave radiates from the source in all directions, often having a strong directionality depending on the nature of the source process, as shown in Fig. 3. Rapid movement is necessary if a significant amount of the elastic energy liberated during deformation is to appear as an acoustic emission.
**Fig. 2** Primitive AE wave released at a source. The primitive wave is essentially a stress pulse corresponding to a permanent displacement of the material.

**Fig. 3** Angular dependence of acoustic emission radiated from a growing microcrack. Most of the energy is directed in the 90 and 270° directions, perpendicular to the crack surfaces.
The form of the primitive wave is profoundly changed during propagation through the medium, and the signal emerging from the sensor has little resemblance to the original pulse. This transformation of the AE waveform is important both to the researcher interested in source function analysis and to the practical NDT inspector interested in testing structures. The researcher who wants to determine the original source waveform uses broadband sensors and performs a detailed analysis of the early part of the received signal. This is an important but very demanding line of inquiry. It may take an hour of computer time to process a single waveform. Most materials-oriented researchers, along with NDT inspectors, are interested in broader statistical features of the AE activity and do not need to know the precise details of each source event. They use narrowband sensors and electronic equipment that measures only a few features of the received waveform but is able to process hundreds of signals per second. The salient wave propagation factors are different for these two lines of work, as discussed below.

Factors in Source Function Analysis. The relationship between the source pulse and the resulting movement at the point of detection has been intensively studied during the last 10 to 15 years. Research groups at the NDT Centre at Harwell, UK (Ref 15), the National Bureau of Standards (Ref 16), Cornell University (Ref 17), and the University of Tokyo (Ref 18) have led the attack on this surprisingly difficult problem. A long-term goal of these studies has been to learn how to calculate a description of the source event from observation of the output of a distant sensor.

The difficulty of the problem is indicated in Fig. 4, which shows the vertical component of the surface movement at point B, resulting from the abrupt application of a vertical force at point A on a semi-infinite body. Even with this simple geometry and source function, the resulting waveform is quite complicated. In the case of a plate, it is more complicated yet, because the second surface also plays its role in the elasto-dynamics of the wave propagation process. In plates, the motion at the point of detection depends strongly on the ratio of source distance to plate thickness.

![Displacement waveform produced by an abrupt application of a downward force at point A.](image)

**Fig. 4** Displacement waveform produced by an abrupt application of a downward force at point A. The waveform can be viewed as either a "snapshot" of surface displacement (in which case \( x \) = position) or as a graph of the displacement at point B as a function of time (\( x \) = time).

In addition, the source function is not instantaneous, it will in fact be a force dipole and/or double couple rather than a point force, its orientation is in general unknown, and horizontal as well as vertical components of motion need to be considered. With these complications, it has understandably taken many years of effort to develop mathematical theory, computational tools, and experimental techniques equal to the task of calculating the source function.
In recent years, the leading laboratories have attained the ability to quantify crack growth increments, orientations, and time characteristics in some of the simpler specimen geometries ordinarily encountered (Ref 19). High-fidelity sensors must be used, and the analysis involves only the first part of the AE waveform, which is recorded in full detail with a high-performance transient recorder. This effort in the characterization of the source pulse has been one of the leading areas of AE research, and it can be expected eventually to yield returns in applied NDT.

**Factors in Source Location and Typical AE Measurements.** Whereas source function analysis utilizes only the first part of the AE waveform, mainstream AE technology accepts the waveform in its entirety. The later part of this waveform is made up of many components reaching the sensor by a variety of paths. Figure 5 illustrates this principle, but shows only a few of the indefinitely large number of possible paths by which the wave can reach the sensor. Typically, the highest peak in the waveform is produced, not by the first component, but by the constructive interference of several of the later components. The AE wave bounces around the testpiece, repeatedly exciting the sensor until it finally decays away. This decay process may take 100 $\mu$s in a highly damped, nonmetallic material or tens of milliseconds in a lightly damped, metallic material—much longer than the source event, which is usually finished in a few microseconds or less.

![Figure 5](image)

**Fig. 5** Three possible paths from source to sensor in a water-filled pipe. 1, direct path; 2, spiral path; 3, waterborne path

It is important to understand that the shape of the received waveform is fundamentally the result of these wave propagation processes. Other important aspects of wave propagation in typical AE testing are attenuation and wave velocity. Attenuation is the loss of signal amplitude due to geometric factors and material damping as the wave travels through the material (Ref 20). Attenuation governs detectability at a distance and is therefore an important factor in choosing sensor positions and spacing. Acoustic emission procedures typically call for attenuation measurements to be made before a test and specify permissible sensor spacing based on these measurements.

Wave velocity is an additional factor to be considered when AE technology is used for source location. Source location is an important technique that is widely used both in laboratory studies and in structural testing. It is particularly significant in testing large structures, for which AE inspection is used to identify active regions for conclusive follow-up inspection with other NDT methods. Large cost savings have been realized through this combination of global AE inspection and focused inspection by other methods.

There are several strategies for source location. Zone location places the source within a broad area. Point location places the source precisely, by calculating from the relative arrival times of the AE wave at several sensors. Wave velocity is involved in these calculations. The attainable accuracy is governed by wave propagation processes and depends on such factors as geometry, plate thickness, and contained fluids. In effect, these factors render the wave velocity uncertain and this leads to errors in source location. In favorable cases, the attainable accuracy is better than 1% of the sensor spacing; in unfavorable cases, worse than 10%. The wave propagation effects underlying these variations are reviewed in Ref 20.

**References cited in this section**


Acoustic Emission Sensors and Preamplifiers

The key element in an AE resonant sensor is a piezoelectric crystal (transducer) that converts movement into an electrical voltage. The crystal is housed in a suitable enclosure with a wear plate and a connector, as shown in Fig. 6. The sensor is excited by the stress waves impinging on its face, and it delivers an electrical signal to a nearby preamplifier and then to the main signal-processing equipment. The preamplifier can be miniaturized and housed inside the sensor enclosure, facilitating setup and reducing vulnerability to electromagnetic noise.

Sensor Response. One of the most sought-after properties in an AE sensor is high sensitivity. Although high-fidelity, flat frequency response sensors are available, most practical AE testing employs resonant-type sensors that are more sensitive, as well as less costly, than the flat frequency response type. These sensors have one or more preferred frequencies of oscillation, governed by crystal size and shape. These preferred frequencies actually dominate the waveform and spectrum of the observed signal in typical AE testing.

The sensitivity calibration of AE sensors was the subject of a substantial developmental program at the National Bureau of Standards (NBS) through the late 1970s. This program has led to the routine availability of NBS-traceable plots showing the absolute sensitivity of AE sensors in volts per unit velocity as a function of frequency (Ref 21).

Acoustic Emission Waveform Transformation. In addition to the wave propagation factors discussed earlier, the transformation of a single AE waveform is further compounded by the sensor response. When a resonant sensor is excited by a broadband transient pulse, it rings like a bell at its own natural frequencies of oscillation. Therefore, the electrical signal at the sensor output is the product of this ringing, thus compounding the effects of multiple paths and multiple wave modes by which the wave travels from source to sensor. A typical AE signal from a piezoelectric sensor is shown in Fig. 7; the radical difference between this observed signal and the simple waveform at the source (Fig. 2) cannot be overemphasized.
Frequency Response. By selecting a resonant sensor from the wide range available, one can effectively choose the monitoring frequency. This is a useful feature that allows the inspector to make a suitable trade-off between the desired detection range and the prevailing noise environment. In practice, the vast majority of AE testing is well performed with sensors that are resonant at about 150 kHz.

Preamplifier Response. The signals generated by the sensor are amplified to provide a higher, more usable voltage. This is accomplished with a preamplifier, which is placed close to (or even inside) the sensor so as to minimize pickup of electromagnetic interference. The preamplifier has a wide dynamic range and can drive the signal over a long length of cable so that the main instrumentation can be placed hundreds of meters from the testpiece if necessary.

The preamplifier typically provides a gain of 100 (40 dB) and includes a high-pass or bandpass filter to eliminate the mechanical and acoustical background noise that prevails at low frequencies. The most common bandpass is 100 to 300 kHz, encompassing the 150 kHz resonant frequency of the most commonly used sensor. Other operating frequencies can be used, but there are limitations. At lower frequencies, there are increasing problems with mechanical background noise. At higher frequencies, the wave attenuates (damps out) more rapidly, and the detection range of the sensor will be smaller. Choice of operating frequency is therefore a trade-off between noise and detection range. Lower frequencies are used on pipelines, where detection range is at a premium, and in geological work because rocks and soils are highly attenuating. Higher frequencies are used to test steam lines in electricity generating stations, where background noise is unusually high.

Attainable Sensitivity. Preamplifiers inevitably generate electronic noise, and it is this noise that sets the ultimate limit to the smallest movement detectable with AE equipment. The smallest signal that can be detected is about 10 $\mu$V at the transducer output, corresponding to a surface displacement of about 25 pm ($1 \times 10^{-6}$ $\mu$m) for a typical high-sensitivity sensor. This sensitivity is more than enough for most practical NDT applications.

Installation. Typically, the sensor is coupled to the testpiece with a fluid couplant and is secured with tape, an adhesive bond, or a magnetic hold-down device. In some applications, however, the AE sensor may be mounted on a waveguide, as in Example 1.

After the sensor is installed and connected to the monitoring equipment, system performance is checked by "lead break" before monitoring begins. This involves the breaking of a lead pencil near the sensor to verify the response from an acoustic signal. Properly performed, the lead break delivers a remarkably reproducible signal that closely matches the "point impulse loading" source discussed above (see the section "Factors in Source Function Analysis" in this article).
Example 1: Acoustic Waveguide Sensors Used in Monitoring the Cooling of Molten Vitrified Nuclear Waste.

Acoustic emission monitoring was used to help correlate cracking in vitrified high-level waste with cooling procedures. There was a need for a method capable of performing in an environment consisting of approximately 900 °C (1650 °F) temperatures and 500 Gy/h (50,000 rad/h) gamma radiation for the continuous monitoring of vitrified waste in canisters during cooling to detect glass cracking. Waveguide sensors about 4.6 m (15 ft) long were used; one end was submerged in the glass, and a sensing crystal and preamplifier were positioned on the other end. The signal from the sensor was passed through coaxial cables to the outside of the hot cell, where it was received by an AE monitor system for analysis. At the end of the testing, the AE sensors had been in the environment for 120 days, and the accumulated dose of gamma radiation had reached $14 \times 10^5$ Gy ($14 \times 10^7$ rad). The sensors were still functioning properly.

Reference cited in this section


Note cited in this section

* Example 1 was provided by Phil Hutton, Battelle Northwest Laboratory.

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Instrumentation Principles

During an AE test, the sensors on the testpiece produce any number of transient signals. A signal from a single, discrete deformation event is known as a burst-type signal. This type of signal has a fast rise time and a slower decay, as illustrated in Fig. 7. Burst-type signals vary widely in shape, size, and rate of occurrence, depending on the structure and the test conditions. If there is a high rate of occurrence, the individual burst-type signals combine to form a continuous emission. In some cases, AE inspection relies on the detection of continuous emission (see the sections "Mechanisms of AE Sources" and "Leak Testing" in this article).

The instrumentation of an AE inspection provides the necessary detection of continuous emissions or detectable burst-type emissions. Typically, AE instrumentation must fulfill several other requirements:

- The instrumentation must provide some measure of the total quantity of detected emission for correlation with time and/or load and for assessment of the condition of the testpiece
- The system usually needs to provide some statistical information on the detected AE signals for more detailed diagnosis of source mechanisms or for assessing the significance of the detected signals
- Many systems can locate the source of detectable burst-type emissions by comparing the arrival times of the wave at different sensors. This is an important capability of great value in testing both large and small structures
- The systems should provide a means for discriminating between signals of interest and noise signals from background noise sources such as friction, impact, and electromagnetic interference

Instruments vary widely in form, function, and price. Some are designed to function automatically in automated production environments. Others are designed to perform comprehensive data acquisition and extensive analysis at the hands of skilled researchers. Still others are designed for use by technicians and NDT inspectors performing routine tests defined by ASME codes or ASTM standards.
**Signal Detection and Emission Counts.** After sensing and preamplification, the signal is transmitted to the main instrument, where it is further amplified and filtered. Next is the critical step of detecting the signal. This is accomplished with a comparator circuit, which generates a digital output pulse whenever the AE signal exceeds a fixed threshold voltage. The relationship between signal, threshold, and threshold-crossing pulses is shown in Fig. 8. The threshold level is usually set by the operator; this is a key variable that determines test sensitivity. Depending on instrument design, sensitivity may also be controlled by adjusting the amplifier gain.

![Comparator circuit diagram](image)

**Fig. 8 Principle of AE signal detection and threshold-crossing counts**

One of the oldest and simplest ways to quantify AE activity is to count the threshold-crossing pulses generated by the comparator (Fig. 8). These acoustic emission counts are plotted as a function of time or load, either as an accumulating total or in the form of a count rate histogram. The all-hardware AE systems of the early 1970s could draw these count and count rate displays on x-y recorders as the test proceeded, and much of the early AE literature presents results in this form. Figure 9, a typical plot of this type, shows cumulative counts as a function of applied load during a rising-load test on a precracked specimen of high-strength steel. The vertical scale is 10,000 counts full-scale. The vertical steps on the first parts of the plot are individual AE events. The larger events score several hundred counts each. By 35 kN (8000 lbf), 10,000 counts have been accumulated. The pen resets to the bottom of the graph, and resumes plotting. As the load rises, the AE rate increases, and the individual events are no longer discernible on the plot. As the specimen approaches failure, there are multiple resets of the pen corresponding to the generation of hundreds of thousands of AE counts.
Fig. 9 Acoustic emission from a welded three-point bend specimen of 12% Ni maraging steel. Steps in the curve are discrete, burst-type emissions caused by plastic zone growth and later, crack front movement.

**Hit-Driven AE Systems.** All-hardware systems reached an apex of development in the late 1970s, but they were eventually superseded by computer-based systems. The development of AE technology coincided with the development of computers, and computers were probably used earlier for AE inspection than for any other NDT method. Computers were first used for AE multichannel source location systems around 1970. Although source location was the first task (and a very advanced one), computers soon came into use for the more general purposes of AE data storage, analysis, and display. At the same time, personnel involved in AE inspection became interested in other signal features of burst-type emissions beyond the threshold-crossing counts (see the section "Signal Measurement Parameters" in this article).

These trends led to a new principle of AE instrumentation that has dominated the technology ever since. This principle involves the measurement of key parameters of each hit, that is, each AE signal that crosses the threshold. A digital description of each hit is generated by the front-end hardware and is passed in sequence with other hit descriptions through a computer system, which provides data storage, a variety of graphical displays, and replay for posttest analysis.

A generic block diagram is shown in Fig. 10, and a typical modern system is shown in Fig. 11. The larger, multichannel systems divide the data-processing tasks among many microprocessors. In the system shown in Fig. 11, for example, a separate microprocessor serves each pair of signal measurement channels. The highest priority for this microprocessor is to read the results of each signal measurement as soon as the measurement process is completed, so that the measurement circuitry can be reset for the next event. The front-end microprocessor can rapidly store several hundred hit descriptions in its buffer, pending further processing. With this parallel processing architecture, added channels will automatically bring added data processing power. With the front-end buffers supplemented by other, even larger buffers in the later stages of the microcomputer network, the system has the versatility to absorb sudden surges of AE activity and to handle widely varying data rates in an optimum manner (Ref 22).
**Signal Measurement Parameters.** The five most widely used signal measurement parameters are counts (Fig. 8), amplitude, duration, rise time, and the measured area under the rectified signal envelope (MARSE) (Fig. 12). Some tests make do with fewer parameters, and some tests use others, such as true energy, counts-to-peak, average frequency, or spectral moment. However, the five principal parameters have become well standardized and accepted through the market processes of the last 10 years.
Along with these signal parameters, the hit description passed to the computer typically includes important external variables, such as the time of detection, the current value of the applied load, the cycle count (if it is a cyclic fatigue test), and the current level of continuous background noise. The length of the total hit description is usually between 20 and 40 bytes.

**Amplitude**, \( A \), is the highest peak voltage attained by an AE waveform. This is a very important parameter because it directly determines the detectability of the AE event. Acoustic emission amplitudes are directly related to the magnitude of the source event, and they vary over an extremely wide range from microvolts to volts. Of all the conventionally measured parameters, amplitude is the one best suited to developing statistical information in the form of distribution functions (Ref 23). The amplitudes of acoustic emissions are customarily expressed on a decibel (logarithmic) scale, in which 1 \( \mu V \) at the transducer is defined as 0dBae, 10 \( \mu V \) is 20dBae, 100 \( \mu V \) is 40dBae, and so on.

**Counts**, \( N \), are the threshold-crossing pulses (sometimes called ringdown counts) discussed above. This is one of the oldest and easiest ways of quantifying the AE signal. Counts depend on the magnitude of the source event, but they also depend strongly on the acoustic properties and reverberant nature of the specimen and the sensor.
**MARSE**, sometimes known as energy counts, \( E \), is the measured area under the rectified signal envelope. As a measure of the AE signal magnitude, this quantity has gained acceptance and is replacing counts for many purposes, even though the required circuitry is relatively complex. MARSE is preferred over counts because it is sensitive to amplitude as well as duration, and it is less dependent on threshold setting and operating frequency. Total AE activity must often be measured by summing the magnitudes of all the detected events; of all the measured parameters, MARSE is the one best suited to this purpose.

**Duration**, \( D \), is the elapsed time from the first threshold crossing to the last. Directly measured in microseconds, this parameter depends on source magnitude, structural acoustics, and reverberation in much the same way as counts. It is valuable for recognizing certain long-duration source processes such as delamination in composite materials (Ref 24), and it can be useful for noise filtering and other types of signal qualification.

**Rise time**, \( R \), is the elapsed time from the first threshold crossing to the signal peak. Governed by wave propagation processes between source and sensor, this parameter can be used for several types of signal qualification and noise rejection.

**Multichannel Considerations.** Measurement of the signal proceeds simultaneously on every channel that detects (is hit by) the AE wave. Acoustic emission systems are available in sizes from 1 channel to over 100 channels, depending on the size and complexity of the structure to be tested. Typical laboratory systems have 2 to 6 channels, while most structural tests are accomplished with 12 to 32 channels.

An individual AE event may hit just one channel or it may hit many channels, depending on the strength of the event, the wave attenuation in the structure, and the sensor spacing. Therefore, an early task for the multichannel system is to determine whether a group of closely spaced hits on different channels is from the same source event. Depending on the system design, this can be accomplished either in hardware or in software. The second, third, and later hits from a source event can be either retained for the purposes of source location or discarded to keep the data clean and simple. After this task of event/hit identification has been performed, the system can deal in event descriptions as well as hit descriptions. The event description usually includes channel identification and relative timing information for all the channels involved, along with the signal characteristics of the first hit and perhaps the other hits as well.

The stream of hit (or event) descriptions is passed through a central processor that coordinates the tasks of data storage, display, and operator communications. In larger systems, these tasks can be divided among several processors. In many systems, the entire stream of hit descriptions is stored to disk; this provides unlimited posttest analysis capability. Full data storage is a vital aspect of applied AE technology. It reduces dependence on the on-site operator for ultimate test results, allowing him to concentrate on the vital task of correct data collection (Ref 11).

**Data Displays.** A software-based, hit-driven AE system can produce many types of graphic displays. The operator is not limited to what can be observed during the test, because the results can be refined, filtered, and redisplayed in any manner during the posttest analysis.

Broadly, AE data displays can be classed as:

- History plots that show the course of the test from start to finish
- Distribution functions that show statistical properties of the emission
- Channel plots showing the distribution of detected emissions by channel
- Location displays that show the position of the AE source
- Point plots showing the correlation between different AE parameters
- Diagnostic plots showing the severity of AE indications from different parts of the structure

Some of these generic display types are illustrated in Fig. 13.
Fig. 13 Typical AE data displays. (a) History plot of the cumulative count or energy. (b) History plot of the count rate or energy rate. (c) History plot of AE data versus load. (d) Cumulative amplitude distribution showing the number of hits that exceeded an amplitude. (e) Differential amplitude distribution showing the number of hits of a particular amplitude. (f) Planar source location display. (g) Point plot of counts (or duration) versus amplitude.

Figures 13(a) and 13(b) show history plots of AE data versus time in cumulative and rate form, respectively. A cumulative plot is the more convenient format for reading off a total emission quantity, while a rate plot highlights the changes in activity that occur during the test.

Figure 13(c) is a history plot of AE data versus load. This is the most fundamental plot because it directly relates cause to effect. This type of plot is especially useful for separating good parts from bad; bad parts characteristically begin to emit at lower loads and give more emission than good parts at all load levels. This basic plot of AE data versus load is also the best way to display the Kaiser and Felicity effects, as shown in Fig. 14.
Figures 13(d) and 13(e) show the cumulative and differential forms, respectively, of the amplitude distribution function. The $x$-axis shows amplitude, and the $y$-axis shows how many hits had that amplitude (differential form) or exceeded it (cumulative form). The differential amplitude distribution (Fig. 13e) is useful for distinguishing between deformation mechanisms and for observing changes in AE intensity as the test proceeds. The cumulative form (Fig. 13d) is more useful for quantitative modeling and for assessing how the detectability of AE will be affected by changes in test sensitivity. The amplitude distribution is a standard AE display, and the underlying theory is well developed (Ref 23). Distribution functions using the other signal measurement parameters are also employed for special purposes.

Figure 13(f) is a planar source location display. This display is basically a map of the structure, with the computed location of each emission event shown as a single point in the appropriate position. Sensor locations are shown as large dots, providing a reference frame. The eye is drawn to clusters of located events, which correspond to the most active sources, typically structurally significant defects.

Figure 13(g) is a point plot of counts (or duration) versus amplitude. Each hit is shown as one point on the display, and its position shows information about the size and shape of the waveform. This type of display is used for data quality evaluation, specifically for identifying some commonly encountered types of unwanted noise (Ref 25). Acoustic emission signals from impulsive sources typically form a diagonal band running across this display. Noise signals from electromagnetic interference fall below the main band (circled area, lower right, Fig. 13g) because they are not prolonged by acoustic reverberation. Noise signals from friction and leaks fall above the main band (circled area, upper left, Fig. 13g) because the source process is extended in time, not a short impulse. This is only one of the many point plots that have proved useful in practical AE testing.

The typical software-based system can generate many displays simultaneously in memory while the test is running, presenting them to the operator upon demand. In addition to these graphic displays, the system may present tabulated data and/or listings of the individual event or hit descriptions.

**Special-Purpose AE Systems.** The software-based, hit-driven AE system has the architecture of choice for application development and general-purpose laboratory and structural testing, but not all AE systems require this kind of computational power and versatility of display. Once the needs of the test have been defined, simpler equipment is often appropriate for routine application.
Production testing can often be done with a basic, all-hardware instrument that simply measures counts or energy and trips an alarm when the emission exceeds a predetermined quantity. Automatic self-checking for good sensor contact can be incorporated into the function of such an instrument.

Resistance weld monitoring and feedback control is accomplished with all-hardware systems that have special gates, timers, and interfaces to synchronize the AE monitoring with the operation of the weld controller. Other types of weld monitoring instruments incorporate pattern-recognition algorithms for automatically recognizing and classifying specific kinds of weld defects.

Leak testing is a major and relatively simple application of AE instrumentation (see the section "Structural Test Applications" in this article). Leak testing can be performed with instruments that measure only the root mean square (rms) voltage of the continuous emission from a leak. Sometimes, detectability is enhanced by the occurrence of burst-type signals from particle impact or structural degradation of the local material. Small size is a major advantage when the instrument has to be carried around an industrial complex or power generating plant.

Specific Applications. Instrument manufacturers have also developed special instruments for specific, well-established applications, such as bucket truck testing and tank car testing. These instruments are based on the applicable codes or standard procedures for performing the test. Simplification of hardware and software leads to a lower-cost instrument. Customized software provides more positive guidance and fewer operator choices, so that a lower level of skill can be used on-site and the test can be performed reliably and economically.

References cited in this section


Acoustic Emission Inspection

Adrian A. Pollock, Physical Acoustics Corporation

Noise

Precautions against interfering noise are an integral part of AE technology. Enormous progress has been made since the early days when students worked at night, using specially constructed loading machines in underground laboratories to avoid disruption of their experiments by street traffic and people moving nearby. With current technology, many tests can be performed without special measures, and a wide range of techniques have been developed to make AE inspection applicable in extremely noisy environments.

A basic starting point is the selection of an appropriate frequency range for AE monitoring. The acoustic noise background is highest at low frequencies. The 100 to 300 kHz range has proved suitable for perhaps 90% of all AE testing. In noisy environments (an electric power plant, for example), higher frequencies, such as 500 kHz, have been
necessary to reduce the noise detected from fluid flow. Because higher frequencies bring reduced detection range, there is an inherent trade-off between detection range and noise elimination.

Acoustic noise sources include fluid flow in pumps and valves, friction processes such as the movement of structures on their supports, and impact processes such as rain and wind-blown cables striking the structure. Electrical and electromagnetic noise sources include ground loops, power switching circuits, radio and navigation transmitters, and electrical storms.

Noise problems can be addressed in many ways. First, it may be possible to stop the noise at the source. Second, it may be possible to eliminate an acoustic source by applying impedance-mismatch barriers or damping materials at strategic points on the structure. Electrical noise problems, which are often the result of poor grounding and shielding practices, can be eliminated by proper technique or by using differential sensors or sensors with built-in preamplifiers. If these measures are inadequate, the problem must be dealt with by hardware or software in the AE instrument itself.

Sensitivity adjustments, including floating-threshold techniques, can be very effective as long as they do not also cause the loss of essential AE data. Methods for selective acceptance and recording of data based on time, load, or spatial origin are well developed. Beyond this, because noise sources often give characteristically different waveforms, they can often be separated from true acoustic emissions by computer inspection of the measured signal characteristics (Ref 25). This can be accomplished immediately after measurement (front-end filtering), during the display process (graphical filtering), or after the test by playing the data through a posttest filtering program or advanced waveform analysis package.

Through the development and application of these techniques, AE inspection has been brought into service in increasingly demanding environments, and this trend is expected to continue. Examples of difficult applications in which noise elimination was key to the successful use of AE inspection include the on-line monitoring of welding (Ref 1, 26) and the detection of fatigue crack growth in flying aircraft (Ref 7).

References cited in this section


Acoustic Emission Inspection

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Load Control and Repeated Loadings

Because acoustic emission is produced by stress-induced deformation of the material, it is highly dependent on the stress history of the structure. Emission/stress/time relationships also depend on the material and on the type of deformation producing the emission. Some materials respond almost instantly to applied stress, emitting and then quickly stabilizing. Other materials take some time to settle down after a load is applied; this is readily observed in materials that show viscoelastic properties, such as resin-matrix composites. In other cases, a constant load may produce ongoing damage, and the structure may never stabilize. An example of this is hydrogen-induced cracking, which may proceed under constant load to failure, with continual emission.
Acoustic emission testing is often carried out under conditions of rising load. The first load application will typically produce much more emission than subsequent loadings. In fact, for instantaneously plastic materials, subsequent loadings should produce no emissions at all until the previous maximum load is exceeded. This behavior was first reported by Kaiser in 1950 (Ref 27) and has been a leading influence in the development of AE test methodology. Dunegan (Ref 28) showed that for materials that obey the Kaiser effect, emission on a repeat loading will indicate that structural damage occurred between the first loading and the repeat. This became the conceptual basis of much of the AE testing of the 1970s, when the first AE field test organizations undertook periodic inspection of pressure vessels and other structures.

Recent test strategies pay much attention to emission that occurs at loads below the previous maximum and to emission that continues when the load is held at a constant level. The evidence is that structurally significant defects will tend to exhibit these behaviors, while emission related to stabilization of the structure, such as the relief of residual stress, will tend not to recur when the structure is loaded again.

Figure 14 is a generic illustration of these contrasting behaviors. Emission is observed upon initial loading from A to B, but not upon unloading (B to C). Upon reapplying the load, there is no emission (line is horizontal) until B is reached again; this is the Kaiser effect. The load is increased to D, with more emission, and another unload-reload cycle is applied. This time, because of the higher stress levels, significant defects begin to emit at point F, below the previous maximum load. This behavior is known as the Felicity effect. It can be quantified with the Felicity Ratio (FR):

\[
FR = \frac{\text{Load at which emission begins again}}{\text{Previous maximum load}}
\]

Technically, the Kaiser effect can be construed as a Felicity Ratio of 1.0 or greater. Systematic decreases in the Felicity Ratio as material approaches failure have been well documented for fiber-reinforced plastics (Ref 29) and a Felicity Ratio less than 0.95 is cause for rejection of an FRP tank or pressure vessel tested by AE inspection according to ASME Article 11 (Ref 30). Under ASME Article 12 (Ref 31) for the AE testing of metal pressure vessels, it is in some cases admissible to ignore AE data from the first loading of a vessel and to consider only AE data from a second loading. The basis for this is that much emission on the first loading comes from local yielding (structurally insignificant), while only the significant defects will emit on the second loading (Felicity Ratio < 1).

Figure 14 also illustrates the graphical appearance of emission continuing during a load-hold period (G to H). The Felicity effect and the occurrence of emission during load holds may share a common underlying explanation; both are associated with the unstable nature of structurally significant defects. Emission during load holds has been known since the early years of AE inspection (Ref 28) and was incorporated in FRP evaluation criteria in the mid 1970s. In the late 1980s, emission during hold has been made the entire basis of Monsanto’s successful procedure for the AE testing of railroad tank cars (Ref 8). In this interesting development, data analysis is greatly simplified because the background noise sources present during rising load are much less obtrusive during the load-hold periods.

Careful attention must be paid to the loading schedule if AE testing is to be successful. Procedures for an AE test typically specify the loads that must be applied (relative to the working load or design load) and the upper and lower limits on the loading rate. Fiber-reinforced plastic tanks and vessels must be conditioned by a period at reduced load before the AE test is conducted (Ref 30). An AE test can be invalidated if the structure is inadvertently loaded beforehand to the AE test pressure. For success in dealing with these points, there must be good communication and coordination between the personnel loading the structure and those collecting the AE data.

References cited in this section

Acoustic Emission in Materials Studies*

Acoustic emission is a remarkable tool for studying material deformation because the information it provides is both detailed and immediate. With its sensitivity to microstructure and its intimate connection with failure processes, AE inspection can give unique insights into the response of material to applied stress. Acoustic emission analysis is most useful when used in conjunction with other diagnostic techniques, such as stress-strain measurements, microscopy, crack-opening-displacement measurements and potential drop (for crack growth), or ultrasonic damping measurements (for dislocation studies). Acoustic emission complements these techniques and offers additional information on the dynamics of the underlying deformation processes, their interplay, and the transitions from one type of deformation to another.

Many materials studies involve the development of a test approach for eventual field application. Such work can be valuable, but it is subject to the difficulty of simulating defect emissivities and other field conditions in the laboratory. Laboratory tests are often done with simple uniaxial stresses applied parallel to the rolling direction, while materials in industrial service are often subjected to complex biaxial or triaxial stress fields. In such cases, the acoustic emissions from the laboratory tests will not be a good model of the acoustic emissions from materials in industrial service.

Mechanisms of AE Sources. Needless to say, acoustic emissions are not generated by the reversible, homogeneous alteration of interatomic spacings that constitutes elastic deformation. Acoustic emissions are only generated when some abrupt and permanent change takes place somewhere in the material. Mechanisms that produce acoustic emissions in metals include the movement and multiplication of dislocations; slip; twinning; fracture and debonding of precipitates, inclusions, and surface layers; some corrosion processes; microcrack formation and growth; small and large crack jumps; and frictional processes during crack closure and opening.

The amount of AE energy released depends primarily on the size and speed of the local deformation process. The formation and movement of a single dislocation does produce an AE stress wave, but it is not a large enough process to be detected in isolation. However, when millions of dislocations are forming and moving at the same time during yielding of a tensile specimen, the individual stress waves overlap and superimpose to give a detectable result. The result is a continuous excitation of the specimen and sensor that is detectable as soon as the voltage it produces becomes comparable with the background noise. The higher the strain rate and the larger the specimen, the larger this signal becomes. This so-called continuous emission is different from burst-type emission in that the individual source events are not discernible. Continuous emission is best measured with rms or energy rate measuring circuitry.

Continuous emission from the plastic deformation of steels, aluminum alloys, and many other metals has been extensively studied, and there have been many detailed findings relating acoustic emissions to dislocation activity and precipitates, microstructure, and materials properties (Ref 32). Such studies can yield valuable insights for alloy and material development. Most studies have focused primarily on continuous emission during and after yield; burst-type emissions sometimes observed in the nominally elastic region are less well explained.

The following example illustrates the dependence of continuous emission on microstructure. The fracture of small-scale precipitates (in this case, pearlite lamellae) generates continuous emission, which can be related to the microstructure that results from heat treating.
Example 2: Relation of Acoustic Emissions With the Optimum Heat Treating of Ferritic/Pearlitic Steel.

Figure 15 illustrates the dependence of continuous acoustic emissions on the microstructure of a deep-drawing ferritic/pearlitic steel subjected to a spheroidizing heat treatment to improve its formability. Data are shown from representative underannealed, optimally annealed, and overannealed conditions. Figure 15 shows AE energy rate as a function of time from dog-bone tensile specimens pulled to failure in a screw-driven test machine. All the graphs display peaks around the yield region, a common feature in the high-sensitivity tensile testing of unflawed specimens. Figure 15 also shows a second, shallow peak at higher strain levels.
The interesting result is that the optimally annealed specimen shows a much smaller peak (gives much less emission) than the other two specimens. The explanation is found by carefully relating AE behavior to microstructural deformation processes. It is known that dislocations can pile up against pearlite lamellae during plastic deformation, eventually causing the lamellae to fracture. This fracture of pearlite lamellae is believed to be the cause of the first peaks in Fig. 15.

With the test material in the underannealed condition, microscopy reveals the presence of many untransformed pearlite lamellae that can intercept the moving dislocations, so the peak is high. With the test material in the optimally annealed condition, microscopy shows that virtually all the lamellae have been transformed to spheroids. These have a smaller cross-sectional area and present less of an obstacle to the moving dislocations, so deformation can proceed without breaking pearlite. Ductility is enhanced, and there is very little emission from this optimally annealed material.

With the test material in the overannealed condition, microscopy shows that additional carbon has come out of solution, growing the spheroids and forming doglegs at the grain boundaries. These larger particles interfere more strongly with dislocation motion and produce larger emissions when fractured, so the emission peak is strong again. It is an interesting result that the optimum material condition is the condition of lowest emissivity, suggesting that AE inspection could be used for inspection and quality control of this material as well as for research.

**Acoustic emission from crack growth** is of the greatest interest for practical NDT applications of the AE phenomenon. By virtue of the stress concentrations in their vicinity, cracks and other defects will emit during rising load, while unflawed material elsewhere is still silent. Acoustic emissions from crack initiation and growth have been extensively reported in the literature. Many of these reports deal with specialized forms of crack growth, such as fatigue, stress-corrosion cracking, and hydrogen embrittlement (Ref 33).

It is useful to distinguish between AE signals from the plastic zone at the crack tip and AE signals from movement of the crack front itself. Growth of the plastic zone typically produces many emissions of rather low amplitude. These emissions are typically ascribed to the fracture of precipitates and inclusions (for example, manganese sulfide stringers in steels), and the triaxial nature of the stress field is implicated in the emissivity of these sources.

Acoustic emissions from crack front movement depend critically on the nature of the crack growth process. Microscopically rapid mechanisms such as brittle intergranular fracture and transgranular cleavage are readily detectable, even when the crack front is only advancing one grain at a time at subcritical stress levels. Slow, continuous crack growth mechanisms such as microvoid coalescence (ductile tearing) and active path corrosion are not detectable in themselves, but if general yield has not occurred, they may be detectable through associated plastic zone growth. Quantitative theory, which explains why some processes are detectable and others are not, was developed by Wodley and Scruby (Ref 33). The possibility of silent crack growth in ductile materials caused much consternation when it was first recognized in laboratory conditions, but it has not been a deterrent in real-life NDT, in which emission from defects is characteristically enhanced by environmental embrittlement, emissive corrosion products, crack face friction, or emissive nonmetallic materials entrained in the defect during the fabrication process.

Many fracture mechanics models have been developed to relate acoustic emissions to crack growth parameters. An important early approach was to relate acoustic emissions to the plastic zone size with the hope of estimating directly the stress intensity factor at defects found in the field (Ref 34, 35). Other models relate acoustic emissions to crack tip movement in situations of cyclic fatigue (Ref 33) or stress-corrosion cracking (Ref 36) for various materials. These models are commonly framed as power-law relationships, with the acoustic emission described by conventional parameters such as threshold-crossing counts, \( N \). In the more recent but difficult technique of source function analysis discussed in the section "Acoustic Emission Waves and Propagation" in this article, individual crack growth increments can be quantified in absolute terms by computer-intensive analysis of the early portion of the AE waveform.

**Nonmetallic layers** on metal surfaces also exhibit acoustic emissions for potential NDT applications. Examples of acoustic emissions from nonmetallic layers include:
The acoustic emission from high-temperature oxidation (Ref 37)  
The extensive study of acoustic emissions from room-temperature corrosion processes (Ref 38, 39)  
The use of acoustic emissions to optimize the performance of ceramic coatings used in high-temperature components (Ref 40)

**Metal-Matrix Composites.** The following example illustrates one application involving the testing of a metal-matrix composite.

**Example 3: Acoustic Emissions From the Microcracking of the Brittle Reaction Zones of Two Metal-Matrix Composites.**

During the tensile testing of two metal-matrix composites, microcracking of the brittle interphase between the fibers and the matrix produced distinguishable peaks in AE count rates well before ultimate failure from ductile failure of the matrix. This may suggest a potential application of AE inspection for the real-time monitoring of structures made of these or similar metal-matrix composites to provide indications of structural problems before critical damage occurs.

The materials tested were metal-matrix composites that consisted of a titanium (Ti-6Al-4V) matrix reinforced with continuous, large-diameter silicon carbide (SiC, \( \approx 0.142 \) mm, or 0.0056 in., in diameter) or boron carbide coated boron (B(B\(_4\)C), \( \approx 0.145 \) mm, or 0.0057 in., in diameter) fibers (with fiber volume fractions of 0.205 and 0.224, respectively). Standard straight-edge tensile test coupons were used. Specimens were cut with the fibers either parallel or perpendicular to the load axis (longitudinal or transverse tension specimens, respectively). Steel end tabs were used, and all surfaces were sanded and cleaned.

Specimens were tested to failure in a servohydraulic testing machine operated at constant crosshead displacement. For each test, a single AE transducer was coupled to the midpoint of the specimen (within the gage section) with vacuum grease, and the acoustic count rate was measured as a function of the longitudinal displacement (strain). After each test, the fracture surface was examined with optical and scanning electron microscopes to determine the fracture processes that occurred.

The values given in Table 2 for rupture or failure strains of the fibers and the brittle reaction compounds formed at the fiber/matrix interface during the hot pressing process were used to find the correlations between fracture processes and AE count rates, with differences in the AE count rates between the two materials related to the differences in their brittle components. As shown in Fig. 16(a), for longitudinal tension specimens of B(B\(_4\)C)/Ti-6Al-4V, there was a distinguishable rise in the AE count rate near the rupture strain of titanium diboride and a peak near the rupture strain for boron carbide. The final peak resulted from ultimate fiber failure. For transverse tension specimens, Fig. 16(b) and 16(c) show large peaks in AE count rate near the rupture strains of the major brittle components (titanium diboride in B(B\(_4\)C)/Ti-6Al-4V and titanium carbide in SiC/Ti-6Al-4V). There were also minor peaks near the rupture strains of the other brittle components. The larger brittle reaction zone in B(B\(_4\)C)/Ti-6Al-4V relative to SiC/Ti-6Al-4V results in the larger area for the AE count rate plot. The ultimate failure in the transverse specimens consisted largely of ductile matrix failure with lower AE count rates (relative to the microcracking).

**Table 2 Brittle phase mechanical properties**

<table>
<thead>
<tr>
<th>Metal-matrix composite</th>
<th>Brittle compound</th>
<th>Failure strain, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(B(_4)C)/Ti-6Al-4V</td>
<td>Titanium diboride</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Boron carbide</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Boron</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Titanium carbide 0.28
Titanium silicide 0.66
Silicon carbide 0.91

Fig. 16 Area plot of AE count rate versus strain. (a) Longitudinal tension test of a B(B_{4}C)/Ti-6Al-4V specimen. (b) Transverse tension test of a B(B_{4}C)/Ti-6Al-4V specimen. (c) Transverse tension test of a SiC/Ti-6Al-4V specimen

References cited in this section

Use of AE Inspection in Production Quality Control

In a small but important class of applications, AE inspection is applied during a manufacturing process to check the quality of the product or one of its components before final assembly and/or delivery. Of the production testing applications discussed in the section "Range of Applicability" in this article, common application of AE inspection in production quality control is the monitoring of welding and shaft straightening processes. Other efforts have been directed toward the inspection of integrated circuits. In the early 1970s, for example, an entire satellite launch mission failed because of a loose particle inside the cavity of a single integrated circuit. As a result, integrated circuits for critical applications are now routinely tested by particle impact noise detection technology, an inexpensive derivative of AE testing (Ref 12). During the manufacturing process, other types of flaws in integrated circuits can also be effectively controlled with AE inspection. Acoustic emissions from bonding processes and from ceramic substrate cracking were investigated by Western Electric researchers during the 1970s and were used as accept/reject criteria for parts on automated assembly lines (Ref 3).

The AE monitoring of welding processes has been part of the technology since its early days. Slag-free, more-automated weld techniques such as resistance welding, laser and electron beam welding, and gas tungsten arc and gas metal arc welding are the easiest to monitor. In the case of resistance welding, AE monitoring is carefully synchronized to the weld cycle, and the various phases of the weld process are treated separately. Emission during solidification and cooling is correlated with nugget size and therefore with weld strength, while high-amplitude signals from expulsions can be used to switch off the weld current at the optimum time to avoid overwelding and to save power and electrode life. In the case of gas tungsten arc and gas metal arc welding, real-time computer algorithms have been developed to recognize the characteristic AE signatures of particular types of defects and to report these defects while the weld is being made. These procedures are effective even in the presence of substantial background noise. Gas tungsten arc welded injector tubes for the space shuttle are among the welded components routinely monitored by AE inspection in the production environment.

Shaft straightening is another production process that lends itself to quality control by AE monitoring. Forged shafts are routinely straightened in special machinery that detects any imperfections in alignment and applies suitable bending forces to correct them. The quality of the product is threatened by microcracking of the hardened surface of the shaft during the bending process. Acoustic emission inspection detects this very effectively and is incorporated into the machinery to warn personnel and to halt the process when potentially damaging microcracking occurs (Ref 4).

In welding and shaft straightening, the stresses that activate acoustic emissions are already present in the normal production processes (in welding, they are thermal stresses). In other cases, the stress is applied for the express purpose of AE testing. This is akin to the loadings routinely applied for the AE inspection of new and in-service pressure vessels and other large structures. Examples include the production testing of brazed joints (Ref 2), and the proof testing of welds in steel ammunition-belt links described in the following example.

Example 4: Acoustic Emission Inspection of Projection Welds in 1050 Steel Ammunition-Belt Links.

The ammunition-belt link shown in Fig. 17(a) was made of 0.81 mm (0.032 in.) thick 1050 steel strip. The steel was preformed into link halves that were joined by two projection welds on each side where the sections overlapped. Although the welding schedules were carefully controlled to produce good resistance welds, there was a significant potential for producing some faulty welds in the mass-produced links. In a good weld, a weld nugget is formed that is usually stronger than the base metal in tension; that is, the base metal will tear before the weld will break. In a poor weld, the joint interface is literally just stuck together, and a moderate force, particularly one imposed by impact, will cause the joint to
fracture at the interface. A preliminary feasibility investigation showed that poor welds produced more acoustic emission under load than good welds, even though the load was insufficient to break a poor weld.

**Fig. 17** Ammunition-belt link, of 1050 steel, joined by four projection welds that were inspected by AE monitoring during proof testing in the fixture shown. Dimensions given in inches. Source: Ref 41

**Proof-Testing Equipment.** A mechanical link tester (Fig. 17b) was designed to apply both a shear load and a bending load to the ammunition-belt link at the welded joints. This simulated the service load that would be imposed on the link.

Initially, piezoelectric sensors were attached to each link before testing to monitor acoustic emissions. This was the simplest and most direct method of confirming feasibility. Because attaching sensors directly to the link was not feasible for production testing, piezoelectric sensors were embedded in the spreader arms of the link-test fixtures in an area adjacent to the welded joints in the link.

A spreader force of 270 N (60 lbf) on the link provided a link-spreader-arm interface pressure of about 35 MPa (5 ksi), which provided good coupling of acoustic information across the interface. The sliding action of the spreader mechanism produced a wide-frequency noise range that could not be electronically filtered without also filtering the acoustic emission. This problem was overcome by gating out the noise from moving parts of the link-stressing mechanism and monitoring for acoustic emission during static stressing of the link after the spreader arms had reached full displacement. A microswitch was installed in the fixture to turn on the AE monitoring system in proper relation to operation of the spreader arm.

**Acceptance Levels.** The form of signal energy analysis that produced the best results consisted of electronically integrating for the area under the half wave rectified envelope of the emission signal in terms of volts amplitude and time duration. The analyzer used for the production application produced a dc voltage proportional to the total AE energy measured. The system sensitivity was adjusted so that an energy analog output voltage of 10 V represented the division point between a good and a bad projection weld in a link. If the welded joint generated enough acoustic emission to produce a 10-V energy output, the link was rejected. If the value was less than 10 V, the link was accepted. The selective ejection function of the mechanical tester was designed to eject the links into the accept or reject container based on an electronic switching function that was controlled by the output voltage of the emission analyzer.

The monitoring system was calibrated by introducing an artificial signal into sensors in the spreader arms, where it was detected and processed by the monitoring system. A 10-V, 10-μs pulse was fed into these sensors from a pulse generator. The resulting signal was reproducible, was a reasonable simulation of the real data, and was simple to generate. Monitoring by acoustic emission was the only available nondestructive method that could perform the necessary 100% inspection of these projection resistance welds.
Acoustic Emission Inspection

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Structural Test Applications

Acoustic emission inspection has been successfully applied in the structural testing of aircraft, spacecraft, bridges, bucket trucks, buildings, dams, military vehicles, mines, piping systems, pipelines, pressure vessels, railroad tank cars, rotating machinery, storage tanks, and other structures. The typical goal of an AE structural test is to find defects and to assess or ensure structural integrity. Acoustic emission inspection has been described as condition monitoring of static plant (Ref 42), which is parallel to the vibration monitoring techniques that are effectively used to monitor the condition of rotating plant. Both of these methods are useful for predicting failures (Ref 43) and reducing maintenance costs.

Key to structural testing with AE inspection are the stress concentrations that cause defects and other areas of weakness to emit while the rest of the structure is silent. Acoustic emission inspection thus highlights the regions that threaten the integrity of the structure. As a whole-structure test using fixed sensors, AE inspection is normally complemented by other NDT methods that are used to follow up the AE findings and to assist in determining the type, severity, and acceptability of the AE sources.

A major advantage of AE inspection is that it does not require access to the whole examination area. Removal of external insulation or internal process fluids, typically a major expense associated with other NDT methods, is not required for the AE test. In fact, this procedure can be avoided altogether if the AE test indicates that the structure is in good condition.

For AE inspection to function reliably as a whole-structure test, the structure must be loaded in such a way as to stimulate emission from all structurally significant defects. Continuous monitoring in service is a possible test approach that has been applied, for example, to aircraft (Ref 7) and nuclear reactors. This approach guarantees appropriate stressing, but it is difficult because a small amount of emission from defect growth must be separated from a large amount of noise over a long time period. More commonly, the AE test is conducted over the course of a few minutes or hours, during which the structure is stimulated by applying a controlled stress (Ref 44). In most cases, this is satisfactorily accomplished by going somewhat above the normally apparent service loads (for example, 110% of the working pressure for an in-service pressure vessel, 200% of the rated load for an aerial manlift device). However, there are cases in which this approach will not work. For example, if defects are being induced in service by thermal stresses rather than mechanical stresses, an applied mechanical loading may not give a good match to the stress field that is causing the defects to grow in service. The defects, effectively unstressed, may not emit. To overcome this problem, inspectors testing steam lines in electric power plants have conducted AE monitoring during thermal overloads and cool-downs and have reported better success from this type of stressing.
In performing a successful AE test, careful attention must be paid to the type, magnitude, and rate of the applied stimulation (loading). Previously applied stresses will have a very strong influence on the emission that will be observed, as discussed in the section "Load Control and Repeated Loadings" in this article. Precautions must be taken to avoid inadvertent loadings of the structure. Many tests have been spoiled when site personnel, eager to ensure that the pressure system is leaktight, have taken the vessel up to the test pressure before the arrival of the AE inspectors. Accurate load measurement and the ability to hold load at a constant value are other requirements that may demand special attention from site personnel.

Load history is less important for leak testing because leak testing relies primarily on the detection of turbulent flow through the leak orifice. Major structural test applications of acoustic leak testing include flat-bottom storage tanks and nuclear reactor components. In the case of nuclear reactor components, millions of dollars have been saved through the selected use of AE instrumented inspection technology as an alternative to hydrotesting (Ref 45).

Data evaluation procedures depend on the context and content of the test. In one-of-a-kind and developmental testing, the skill and experience of the investigator are of prime importance. This fact inhibited the widespread use of AE inspection until standard test procedures started to become available in the late 1970s. The development of standard test procedures made it possible for AE tests to be efficiently conducted by regular NDT inspectors (given the proper training), while the more innovative investigators moved on to the development of new application areas. Some of the well-developed and standardized structural test applications of AE inspection will be briefly summarized below.

**Bucket Trucks.** The AE inspection of aerial manlift devices (bucket trucks) was pioneered by the author for Georgia Power Company in 1976 and was carried forward into routine practice by independent testing laboratories and several electric utilities in the years that followed. The ASTM F-18 Committee on Electrical Protective Equipment for Workers published the Standard Practice on the subject in 1985 (Ref 46).

First intended for use on the fiberglass boom sections of insulated bucket trucks, the method was soon extended to cover the pedestal, pins, and other metal components. An estimated 70,000 to 100,000 AE tests have been conducted up to 1988. Bucket trucks can develop problems through accidents, overloads, and fatigue in service. A thorough, regular inspection and test program can identify potential problems before they cause injuries or downtime (Ref 47).

Acoustic emission inspection is a major part of the structural integrity evaluation that complements functional tests of the bucket truck. Of all inspection methods, it is the most effective for detecting problems in fiberglass components, while for metal parts and 100% structural coverage, it serves as a cost-saving screening test that directs the inspector's attention to problem areas. The AE test is preceded by a visual inspection, and any AE indications are normally followed up with magnetic particle, dye penetrant, or ultrasonic inspection.

The AE test typically requires 12 to 16 sensors. System performance is checked by lead break before monitoring begins (see the section "Installation" in this article). Monitoring begins with a noise-check period, followed by two loadings to a predetermined proof load. Emissions during rising load, load hold and load release are separately recorded.

Data evaluation procedures are difficult to spell out because of the wide variety of possible noise and AE sources and the wide range of bucket truck constructions. The experienced inspector uses his knowledge of the truck as he evaluates high- and low-amplitude emission on the different channels during the different stages of the test. Aware of possible noise sources, he looks for indications that may lead to confirmation of damaged fiberglass, cracked metal components, or maintenance problems such as lack of lubrication in visually inaccessible areas.

Using an AE instrument specially designed for economical bucket truck testing, an experienced test crew can perform five to ten AE tests in a single day. When the required visual, operational, ultrasonic, magnetic particle, and dye penetrant testing operations are also performed, typically two to three trucks can be inspected per day.

**Jumbo Tube Trailers.** Acoustic emission inspection for testing jumbo tube trailers was developed by Blackburn and legitimized in lieu of hydrotest by a Department of Transportation exemption granted in 1983 (Ref 48). These tube trailers carry large volumes of industrial gases on the public highways, typically at a pressure of 18,200 kPa (2640 psi). Fatigue cracks can grow in service, but the hydrotest will not detect these cracks unless they actually cause rupture of the tube. The AE test will detect the cracks while they are still subcritical, during a 10% overpressure applied during the normal filling operation. The AE test is therefore more meaningful than the hydrotest. The AE test is also less expensive and avoids disassembly of the trailer and contamination of the internals with water.
The trailer typically holds 12 tubes, which are all tested at the same time. The AE test requires just two sensors on each 10 m (34 ft) long tube; wave propagation and attenuation characteristics are very favorable in this structure, and AE sources can be accurately located. If ten or more valid events are located within a 200 mm (8 in.) axial distance on the cylindrical portion of the tube, ultrasonic inspection is carried out and the tube is accepted or rejected based on the ultrasonic evaluation of flaw depth. The accept/reject criteria are based on a conservative fracture mechanics analysis of in-service fatigue crack growth. Between March 1983 and March 1988 about 1700 jumbo tubes were AE tested, and the method has been further extended to other shippers of compressed gas and other tube types.

Fiberglass Tanks, Pressure Vessels, and Piping. In the 1970s, the chemical industry was experiencing worldwide failures of fiberglass storage tanks and pressure vessels. Causes included inadequate design and fabrication, mishandling during transportation, and misuse of this relatively unfamiliar material. The situation was aggravated by the lack of a viable inspection method.

An AE test methodology was pioneered by Monsanto, resulting in elimination of the tank failure problem (Fig. 18). The method came into widespread acceptance through the formation and activities of the Committee for Acoustic Emission in Reinforced Plastics (CARP), which is currently affiliated with the American Society for Nondestructive Testing. The written procedure developed by CARP and first published by the Society for the Plastics Industry in 1982 was the basis for the introduction of AE inspection into the ASME Boiler and Pressure Vessel Code in 1983 (Ref 30, 49). An estimated 5000 tests have been carried out using this procedure as of 1988. The work of CARP was also extended to cover methodology for testing fiberglass piping (Ref 50).

![Fig. 18 Failures of FRP tanks. An FRP tank failure problem was eliminated by 100% AE inspection starting in 1979. The isolated failures in 1982 and 1984 occurred after these tanks had failed the AE test, and damage-preventive measures were taken.](image)

The AE test typically requires 8 to 30 sensors, depending on the size of the vessel or tank. High-frequency (typically 150 kHz) channels are used to cover regions of known high stress, such as knuckles, nozzles, and manways; low-frequency (typically 30 kHz) channels having a larger detection range are used to complete the coverage of less critical regions. In the case of a storage vessel, the test is typically conducted during filling with process fluid after an appropriate conditioning period with the contents at a reduced level. In the case of a pressure vessel, appropriate overpressure is applied. The loading is conducted in several stages, with load-hold emission, Felicity Ratio, and other accept/reject criteria evaluated at each stage. System performance checks and background noise checks are part of the test procedure.

Metal Pressure Vessels and Storage Tanks. In the 1970s, many research and engineering organizations and test companies were active in the AE testing of metal pressure vessels. A 1979 survey estimated that about 600 pressure vessels had been tested by AE inspection on a production basis up to that time, mostly in the petroleum, chemical, and nuclear industries (Ref 51). (Although tests on pipes, heat exchanger tubing, and miscellaneous components were much
more numerous, pressure vessels have always been a focal point for AE testing.) Much of this testing was done with *ad hoc*, undocumented procedures that relied heavily on the individual experience of the teams performing the work. The main emphasis was usually placed on source location, technically a most attractive feature of AE testing. Located sources would be graded according to their AE activity and/or intensity, and the vessel owner would be advised regarding which areas to inspect with other NDT methods. Many structural defects were successfully identified with these methods.

A significant maturing of the technology took place when Fowler at Monsanto engaged on a systematic program of methods development, using the results of follow-up inspection to refine and improve the AE data analysis procedures. Starting in 1979, this program included destructive tests on decommissioned vessels, field tests on many hundreds of in-service vessels and tanks, and development of analytical procedures for recognizing and eliminating extraneous noise (Ref 25). The program de-emphasized the calculation of source location (which requires several sensors to be hit) because in practice many AE events hit only one sensor. To use all the AE hits, zone location was employed instead of point location. The outcome of this program was a comprehensive test procedure backed by detailed case histories and available to licensees under the trademark MONPAC. This procedure has been applied to approximately 2000 metal vessels and storage tanks as of 1988 Ref 8.

A typical MONPAC test result is shown in Fig. 19. Here a 30-year old ethylene storage bullet was AE tested on-line, raising the pressure by turning off a compressor. Results are presented in the form of an unfolded map of the vessel, with the evaluation of appropriate zones on the map being displayed in color codes (Fig. 19 only shows the color as a dark region). The zone evaluations indicated "no significant emissions," so a hazardous and possibly deleterious internal inspection was avoided (Ref 42).

![Display of MONPAC test results for an ethylene storage vessel. In this case, no significant emissions were detected, and there were only minor indications from zones 3, 6, and 8. The need to take the vessel off-line for other forms of inspection was avoided.](image)

Other MONPAC tests have found external and internal corrosion, stress-corrosion cracking, weld cracking, lack of fusion, lack of penetration, and embrittled material. Plant shutdowns have been shortened through early diagnosis of major
problems, or have been eliminated through positive demonstration of structural integrity. Savings achieved through this method run to tens of millions of dollars.

An AE methodology for metal vessel testing has also been introduced into the ASME Boiler and Pressure Vessel Code as of the December 1988 Addendum (Ref 31). The article states requirements for written test procedure, personnel qualification, equipment, system calibration, preexamination measurements, background noise check, and vessel pressurization. An illustrative loading schedule and sensor layouts are included. Evaluation criteria are to be supplied, class by class, by the referencing code section; they will be based on emission during load hold, count rate, number of hits, large amplitude hits, MARSE, and activity trends. This entry into the ASME Code represents a major milestone in the establishment and maturity of AE technology.

References cited in this section

References


40. P. Pantucek and U. Struth, Behaviour of Thermal Barrier and of Corrosion Protective Coating Systems
Radiographic Inspection

Revised by the ASM Committee on Radiographic Inspection*

Introduction

RADIOLoGY is the general term given to material inspection methods that are based on the differential absorption of penetrating radiation—either electromagnetic radiation of very short wavelength or particulate radiation—by the part or testpiece (object) being inspected. Because of differences in density and variations in thickness of the part or differences in absorption characteristics caused by variations in composition, different portions of a testpiece absorb different amounts of penetrating radiation. These variations in the absorption of the penetrating radiation can be monitored by detecting the unabsorbed radiation that passes through the testpiece.

The term radiography often refers to the specific radiological method that produces a permanent image on film (conventional radiography) or paper (paper radiography or xeroradiography). In a broad sense, however, radiography can also refer to other radiological techniques that can produce two-dimensional, plane-view images from the unabsorbed radiation. Recently, the American Society of Testing and Materials (ASTM) defined radioscopy as the term to describe the applications when film or paper is not used and defined radiology as the general term covering both techniques.