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MILITARY STANDARDIZATION HANDBOOK

NONDESTRUCTIVE TESTING METHODS OF COMPOSITE MATERIALS - ACOUSTIC EMISSION

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MILITARY HANDBOOK

Nondestructive Testing Methods of Composite Materials Acoustic Emission

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DEPARTMENT OF DEFENSE
WASHINGTON D.C. 20301

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Military Handbook for Nondestructive Testing Methods of Composite Materials - Acoustic Emission.
1 October 1984

1. This standardization handbook was developed by the Department of Defense with the assistance of the Army Materials and Mechanics Research Center and Dr. Marvin Hamstad of University of Denver, Denver, Colorado, in accordance with established procedure. It is approved for use by all Departments and Agencies of the Department of Defense.

2. It is the intent to review this handbook periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and any recommendations for changes or inclusions to Army Materials and Mechanics Research Center, ATTN: AMXMR-SMS, Arsenal St., Watertown, MA 02172-2719.

FORWARD

1. This handbook will eventually become a chapter in a larger volume which will probably include the following chapters:

Part I:	Overview of Characterization Techniques for Composite Reliability
Part II:	Liquid Chromatography, A State-of-The-Art-Review
Part III:	Infrared and Raman Spectroscopy, A State-of-The-Art-Review
Part IV:	Radiography, A State-of-The-Art-Review
Part V:	Ultrasonics, A State-of-The-Art-Review
Part VI:	Acoustic Emission, A State-of-The-Art-Review
Part VII:	Thermography, A State-of-The-Art-Review
Part VIII:	Annotated Bibliography
Part IX:	Applications to the Manufacture of Composite Main Rotorblade.

2. Each chapter will be coordinated separately as the amount of materials to review at one time is large. After acceptance of the individual chapters as smaller handbooks, they will be incorporated into a single volume.

3. It is intended that this volume serve as a reference in which answers may be found to the more general questions concerning the technical aspects and applications of Acoustic Emission.

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1. Introduction

1.1 General. Technical principles will be discussed which must be followed in order to insure that a technically sound AE test is performed on a composite sample. It is relatively simple to attach an AE sensor to a composite and then load the sample. It is a much more complicated process to carry out an AE test which conforms to the known physics relating to AE testing. This handbook will assume that the reader is planning on doing "production testing" of composites with AE monitoring ("production testing" in the sense that at least several identical samples will be tested). The organization of this handbook will be to first treat each of the physical entities involved in an AE composite test; then aspects such as AE data and its analysis will be treated.

2.0 Basic Source of AE.

2.1 General Expression of a Stress Wave. An AE event is a complicated stress wave which is generated at a location in a structure by a rapid change in the local stress state. This can be expressed by the following

$$\Delta\sigma_{ij}\,(\underset{\sim}{x},\,\Delta t,\,\Delta V)$$

Where $\Delta\sigma_{ij}$ is the change in each of the independent stress components necessary to describe the stress state at that point in the structure, $\underset{\sim}{x}$ is a vector describing the location at which the rapid change in stress state occurs, Δt is the time interval over which the stress change occurs, and ΔV is the volume (or area for certain AE sources) of the structure which experiences the stress change. A typical example might be a microscopic failure of a fiber in a composite structure. In this case the stored energy which is rapidly released supplies (among other things) the energy contained in the resulting stress wave or AE.

2.1.1 Simplification of Model. In reality the model we have adopted is simplified in that the AE event is actually generated by the change in $\Delta\sigma_{ij}$ as a function of both time and spacial coordinates in the region defined by ΔV. But since this more complicated model adds nothing to our development here, we will use the simplified model.

2.1.2 Intensity of Acoustic Event Generated. The factors shown in expression (1) can provide some insight into the intensity of the AE event which is generated. For example, the AE event will be more intense for larger $\Delta\sigma_{ij}$'s, for shorter Δt's, and for larger ΔV's. Conversely, the AE event will be less intense for smaller $\Delta\sigma_{ij}$'s, for longer Δt's, and for smaller ΔV's.

Certain dynamic processes can also generate AE events; for example, sliding friction between two surfaces moving relative to each other. By including "surface" tractions in the $\Delta\sigma_{ij}$ of expression (1), these dynamic processes can also be included in the general simplified formulation.

2.1.3 Acoustic Emission Event as a Complex Propogating Stress Wave. It is important to emphasize that the AE event at the level at which we can currently measure it (or observe it) is a complex propagating stress wave which will follow the physical laws which govern stress waves. Hence, the wave propagation will be intractable for all but the most simple structures (for example isotropic-infinite mediums). It will be important to keep these ideas in mind as we discuss AE testing of practical composites which are normally of complex and finite geometry, as well as anisotropic.

3.0 Composite Test Specimens or Structures.

3.1 Acoustic Emission Testing as a Comparison Technique. Due to the complexity of stress wave propagation in composites as well as other factors (such as the currently unknown AE source events and the usual commercial AE sensors that respond to surface displacements and velocities in a complex frequency dependent fashion), it is not possible at present to make measurements of a real AE event and then calculate the source function (that represented by expression 1.). Hence, AE as a nondestructive evaluation technique for composites is, at this time, primarily a comparison technique. This fact means that, to be useful, baseline AE data must be gathered from a series of "identical" samples. Then techniques can be established to identify various deviations from the "identical" samples. It is necessary to establish what is meant by the term "identical samples."

3.1.1 Controlling Factors for Comparison. The following factors must be controlled for samples to be identical. First, the relevant stress wave propagation characteristics must be the same. This requirement means that the sample geometry must be the same, the sample material (mechanical properties e.g., modulus and density) must be the same, and the stress wave observation points and techniques must be the same (i.e., sensors and sensor locations). Second, the stress field throughout the sample must be the same. This fact inherently implies that the sample is loaded or stressed in the same way and that the general flaw structure in the sample shall be the same (i.e., same sizes and locations or same sizes and uniformly distributed throughout the structure). Thirdly, the local microscopic AE sources (e.g., microscopic failure mechanisms) must be the same. This requirement means that typical microscopic strengths and deformation properties must be the same. Now since composites can only be reliably described by statistically based analysis procedures, the sameness that is required here is statistical in nature. It should be noted that we have taken a relatively restricted point of view about the definition of the identical samples needed for comparison. There are currently AE applications for which this level of identicalness has not been necessary, but in our opinion it is best to start with the above approach and then prove, if possible, that a less restrictive definition of identicalness is sufficient.

3.2 Acoustic Emission for Basic Studies of Composites. In addition to its application for NDE, AE can be used for basic studies of composite materials or structures. For these studies, there are some additional comments which need to be made with respect to test specimens and relevant requirements. For these types of studies, the first requirement is to test a sufficient number of identical samples so that the AE that occurs for each sample can be characterized relative to the AE that randomly occurs from different samples. The characteristic AE patterns can then be correlated with deformation and micro-failure mechanisms which are known to occur at various loads from other inputs (e.g., mathematical analysis, microstructural studies, microfailure observations, etc.).

4.0 Test Installation or Test Fixturing

4.1 Fixturing and Interface Characteristics. Since the composite test specimen must be supported in some way and is normally externally loaded, the test fixturing becomes a key part of the test system. Normally, the task of assuring that the load is applied in the same way is not difficult. A more subtle but probably just as important a factor concerns the interaction of the test fixture and the test specimen from the point of view of wave propagation characteristics. The stress waves generated by an AE event will propagate throughout the test specimen as well as the test support and loading fixturing. The two major variables which are of importance here are first, the wave propagation characteristics of the fixturing and second, the wave propagation charactristics of the interfaces between the composite specimens and the fixturing. The time varying amount of energy which reaches the AE sensor from a given AE event will depend on how much of the original energy goes to and is dissipated in other parts of the test fixture. A significant variable in this partition of energy from test to test can be the condition of interfaces, particularly between the specimen and the test fixture, and to a lesser degree between the various parts of the test fixture. For example, an interface between the test specimen and the test fixture which is coupled by oil or water will result in significantly more of the energy (from a given AE event) going into the fixture rather than reaching the AE sensor. Thus comparing tests with dry vs. "wet" interfaces may be very difficult. Another typical example which might be encountered is in proof testing of composite pressure vessels. Here a metal liner will result in considerably different coupling (with respect to AE wave propagation) of the AE energy into the hydraulic fluid than when a rubber liner is used. Similarly, during proof testing of composite tanks by filling them with fluid, the potential wave propagation paths change depending on the fluid level. Hence, AE energy from a particular AE event reaching an AE sensor will vary depending on the fluid level.

4.2 Effect of Size or Volume of Composite Article. There are significant signal propagation losses in composites, and in the composite - fixture interfaces. The relative significance of fixture changes will depend on the size or volume of the composite article under test. In general, effects will be much more significant for small articles, but even in a large composite structure effects of changes in the near vicinity of AE source locations could be significant. Again, we have taken a view that may be more restrictive, but it seems to be best to start with the more restrictive, and relax if it is not required.

4.3 Use of Artificial AE Sources. The use of artificial AE sources (e.g., pencil lead breaks) can be used to determine the potential significance of unavoidable fixture changes. But some care should be exercised since the source events (expression 1) in a composite may be considerably different than that for the lead break. Potentially different types of artificial sources may need to be developed to correspond to the different sources in composites. It should be noted that the lead break could also be used to check effects of some changes in specimens. But again, similar precautions must be applied, since at this point we do not know how closely the lead-break source event corresponds to the different real AE events which can occur in composites.

4.4 Other Factors. Even identical test and support fixturing may not result in the same wave propagation characteristics each time a new test specimen is mounted in the fixturing. Lack of cleanliness or changes in the test specimen installation procedure can result in significantly different wave propagation characteristics of the specimen/fixture assembly. Again, this aspect can be checked for significance by use of a pencil lead break (this technique is discussed in Section 6.0).

5.0 Couplants and Waveguides.

5.1 Properties of Couplants. The stress wave energy from an AE event is usually transferred from the test specimen to the commercial AE sensor by means of a couplant. The couplant, which is normally viscous, provides for more efficient coupling than dry coupling (i.e., the face of the AE sensor in contact with the test structure). There are several desired properties which guide the selection of the couplant material. First, it must provide good acoustic coupling over the desired frequency range. Second, the couplant should be compatible (from a chemical point of view) with both the composite and the AE sensor. Third, the couplant material should be easy to remove from both the composite and the AE sensor without damaging either. Fourth, the couplant should have a consistent viscosity from batch to batch, or if the couplant is an adhesive it should have consistent moduli. Fifth, the couplant or adhesive should maintain a consistent viscosity or modulus over the time period it is used and at the temperatures used.

5.2 Application of Couplant To AE Transducers. In the past, too little attention has been paid to the application of couplant to AE transducers. There has been little or no control of the amount of couplant or of the volume of voids in the couplant. The philosophy has often been to use a lot of couplant in a rather sloppy fashion. Unfortunately, this is the only way to do it when it is not feasible (for economic or time reasons) to use special fixturing such that a small, precise amount of couplant can be effectively used (more on this in Section 6.0). With the advent of the lead-breaking technique for calibration purposes, it has been found that there are several improvements that can make the coupling more uniform for repeated application to test parts. These concepts have come as a result of capturing the AE event output with a transient recorder for lead breaks made with a precise mechanical lead breaker. By varying different parameters, the following practices or techniques have been found to lead to the most repeatable coupling practices. First, use a small diameter sensor. Second, use a large hypodermic needle to apply a uniform volume of couplant to the center of the transducer face. Third, do not hand spread the couplant, but allow it to be spread when the transducer is brought against the test specimen by a fixed coupling force. Fourth, do not "ring" the sensor in or apply any force in the direction which will tend to pull the sensor away from the test specimen. Development of these techniques requires that the technicians undergo training and practice with the use of a mechanical lead breaker and a transient recorder (to evaluate the development of their technique). The amount of couplant used should not be such that it overflows at the edge of the sensor face. The reason for this is that since the couplant is viscous, excess couplant or couplant spilled on the test sample will absorb AE energy and thereby potentially reduce the sensitivity of the AE equipment.

5.2.1 Special Cases. For composites made with certain fabrication techniques (e.g., filament winding), the composite surface may not be as smooth as is normally the case with other materials. In such cases, in order to have relatively uniform coupling from part to part, the best amount of couplant to use may have to be determined experimentally by applying various amounts to several parts and determining which amount gives the most uniform time domains for mechanical lead breaks.

6.0 Sensors - Type, Location, Attachment.

6.1 Background. Commercial AE sensors have a piezoelectric crystal which gives a voltage output related to its deformation. At this point in the development of AE monitoring of composites, there do not seem to be overwhelming technical reasons that dictate the selection of one AE sensor type over another design. In spite of the fact that sensor manufacturers advertise sensor resonances of tens to hundreds of kilohertz, we have found that these same sensors perform quite well down to a few kilohertz. Hence, one philosophy has been to purchase the least expensive sensors and to machine the epoxy face down such that the contact area is reduced to about 1/4 inch in diameter (to improve coupling consistency). The low cost sensor is chosen since when samples are taken to failure, the sensor can be damaged due to the energy released at macroscopic failure.

6.2 Resonant And Non-Resonant AE Sensors. There are basically two classes of AE sensors which are commercially available, resonant and non-resonant. The resonant sensor will normally have more sensitivity, but often the signals from composites are of high amplitude, so sensitivity is not a problem. Further, at the lower frequency bandpasses, which seem to be most useful for composites (see discussion in Section 15.2.2) the signal amplitudes are even larger. The non-resonant sensor has a flatter frequency response curve than the resonant sensors, but, to date, this characteristic has not been exploited in routine testing.

6.2.1 Calibration of AE Sensors. In general, commercial AE sensors respond to deformation (stress) waves in a complex fashion which involves both normal and inplane deformations and velocities in the test samples. For this reason, it is currently impossible to calibrate such sensors in an absolute sense with respect to the way they actually operate in practice. Since commercial sensors currently cannot be absolutely calibrated, even sensors of the same design should be treated as unique until it has been proven otherwise. This means keeping track of sensor serial numbers.

6.2.2 Choice of Sensors. To return to choice of sensors, a few more comments can be made. For large composite structures, there may be significant manpower economies in using sensors which have an integral pre-amplifier. On the other hand, such sensor-preamplifier combinations preclude the technique of connecting more than one sensor to the same preamplifier. This latter technique will result in significantly less electronic equipment costs to effectively "cover" a large composite tank, but it will result in higher manpower costs. In general, use of two sensors into the same preamplifier will result in a loss of about 6 dB in signal amplitude for a given event.

6.3 Sensor Locations. There are several factors which enter into the decision concerning sensor locations. The key information which is required is the AE signal propagation loss which occurs with distance in the composite structure as a function of the electronic bandpass. This information can be gathered by using pencil-lead breaks right next to the AE sensor (unless it is possible to always locate sensors some distance from all AE sources) and at various distances and directions from the sensor. Since composites are in general anisotropic and of varying thickness, the signal propagation losses may vary in different parts of the composite. Hence, the relevant propagation data needs to be generated throughout the structure. Normally, the lowest electronic bandpass is chosen which is consistent with the frequencies of any extraneous noise sources that are present in the test environment and cannot be eliminated for cost or other reasons (see Section 15.3). Once the propagation characteristics of the selected bandpass have been determined, then it is necessary to decide how much signal propagation loss is acceptable. Since peak amplitude is one characteristic that has been used to judge the severity of the damage mechanism which caused an AE event in a composite, it may be necessary to limit potential amplitude propagation losses to no more than 6-12 dB. The acceptable propagation loss along with the relevant experimental propagation losses will determine the spacings of AE sensors in order to effectively cover the composite article which is to be monitored with AE. For large composite structures, the number of sensors required may be over 100. In many cases, the number of sensors required can be cut significantly due to prior knowledge of likely failure regions based on stress analysis and/or test experience. In such cases, it is only necessary to monitor the regions where failure can occur.

6.4 Propagation Losses. It is important to note that propagation losses of AE event energy are not as severe as those with AE peak amplitude (see Section 15.4). Hence, if event energy measurements are used instead of peak amplitude, sensor spacings can be greater and still effectively cover the whole part.

6.5 Attachment Techniques for AE Sensors. The attachment technique for AE sensors (i.e., the means by which the AE sensor is held in contact with the composite article) needs a good deal of attention for a number of reasons. Ideally, the best technique is to hold the sensor by means of some external fixturing which does not come in contact with the composite. The reason for this is that any attachment fixturing which comes into contact with the composite can change the AE wave propagation characteristics and provide a path for AE energy away from the sensors. This could reduce the sensitivity at best, and at worst could cause extraneous AE to be generated due to the strains in the composite during testing (strains for the design stresses in composites are often greater than those in metal structures). Also, unless special care is taken in the design and installation of the attachment fixturing, it may not couple the sensor the same way each time, or it may result in changes for each installation in the amount of AE event energy which is transferred away from the specimen into the attachment fixturing. In either of these cases, there are problems due to inconsistencies from sensor to sensor and from test to test.

6.5.1 Basic Design Principles for Attachment of AE Sensors. In actual practice, it is not always easy or cost effective to attach sensors in the ideal manner. When compromises must be made, the effect of these compromises should be evaluated by the use of mechanical lead breaks while capturing the analog AE events on a transient recorder with oscilloscope. Based on the changes in AE event amplitude, event duration, and time distribution of AE energy, the significance of attachment compromises can be evaluated. The basic design principles for attachment of AE sensors are: 1) the attachment device should hold the sensor in contact with the specimen such that the sensor face is parallel to the tangent plane of the composite at that point; 2) the sensor should be held against the composite with sufficient force such that gravity does not cause the sensor "contact" force to be much larger or smaller in certain places on the composite (i.e., the sensor contact force should be uniform for all locations); 3) each sensor should be placed at the same position on each successive composite part; 4) the sensor contact force should be sufficient to spread the couplant without "ringing in" the sensor; 5) the attachment fixturing should allow easy replacement of the couplant (i.e., removal of the sensor and cleaning the sensor face and composite and reapplying the couplant); 6) the attachment fixturing should create no significant extraneous AE during the test and should not constrain normal deformation of the composite; 7) the attachment device should perturb the AE wave propagation as little as possible and the perturbation which does occur should be the same for each sensor installation; and 8) the attachment fixturing should be simple and quick to install.

7.0 Cables.

7.1 General. The cable that connects the preamplifier to the AE sensor is normally a coaxial cable. There are three aspects of its application with which to be concerned. First, since the cable is not perfectly shielded, it can act as an antenna with respect to electro-magnetic radiation. Thus, to keep this electronic noise low (to improve the signal to noise ratio), the length of this cable should be kept relatively short (e.g., a few feet) unless electro-magnetic radiation can be eliminated. Second, the AE sensor is a receiver and looks electrically as if it is a capacitor. The electrical charge from the sensor element is divided between the "capacitance" of the sensor and the combined capacitance of the cable and preamplifier. Since the capcitance of the cable varies with length, the result is that the sensitivity of the AE sensor can vary considerably with changes in the length of this cable. To overcome this potential difficulty, a standard cable length is often used for all preamplifier cables. Third, the characteristic impedance of this cable is also an important factor because the cable should be terminated with its own characteristic impedance for maximum power transfer. Typically, the AE preamplifier and secondary amplifier have 50 Ω output and input impendances respectively. Thus, normally 50 Ω cable is used for all cable attachments in the AE system. In some cases where the AE secondary amplifier does not have a 50 Ω input impedance, it is necessary to externally terminate the system with a 50 Ω terminator.

7.2 Cable Length For other cables in the AE system, the primary consideration is cable length. For example, the length of cable between the preamplifier and the main AE electronic unit can vary from a few feet to 1,000 ft or more. Unless a line-driver is used, the losses in a long cable can be considerable.

7.3 Choice of Cables Special cables are normally used between the preamplifier and the main AE electronics unit. The reason for this is that the commercial AE equipment manufacturers have chosen different ways to power their preamplifiers. Some use regular coaxial cables while others use a four-conductor cable. When using AE components from different manufacturers, care must be exercised in the choice of cables for the preamplifier to main unit connection.

7.4 Ground Loops. In practice, the primary difficulty with cables is the introduction of ground loops due to broken connections which occur during use. Ground loops cause the electronic noise level to increase and thereby reduce the signal to noise ratio.

8.0 Preamplifiers.

8.1 Primary Function. Preamplifiers provide gain to the analog AE signals. Their primary function is to increase the signal level of the AE signals so that they are considerably above the level of the electronic noise that is induced by the antenna effect of the total length of cable between the AE sensor and the main electronic unit. Normal commercial AE preamplifiers come in either 40 dB or 60 dB gain models (Note: $dB = 20 \log_{10} \frac{V_{out}}{V_{in}}$, where dB is the gain in decibels, V_{in} is the input voltage and V_{out} is the output voltage). In most cases, commercial AE preamplifiers are powered by DC voltage coming from the main AE electronic unit. Preamplifiers can also be purchased as battery powered units. The battery powered preamplifiers reduce extraneous electronic noise since they are independent of normal commercial power which can be quite "dirty".

8.2 Performance. There are four main criteria for the performance of preamplifiers. First is the gain. Since composites often have relatively high amplitudes of AE signals compared to metals, often 20 dB or 40 dB is sufficient (preamplifiers with 0 dB gain have been used in some cases). The best solution to the need for variable preamplifier gain is probably to purchase preamplifiers with a switch that will allow a choice of either 20 or 40 dB. The need for variable preamplifier gain leads to the second main specification, namely the maximum output voltage of the preamplifier. A typical figure might be 10 volts peak-to-peak. When the input voltage is large and a fixed gain of the preamplifier is applied resulting in an output voltage of greater than 10 volts peak to peak. (1 volt p.p. in some cases) the preamplifier is said to be saturated (or the signal is clipped). This condition results in a distorted wave form and a loss of the real signal level. Since it is often difficult to determine if saturation will occur, it is normally best to be on the safe side, which means using lower preamplifier gain. The third main concern with the preamplifier is its electronic bandpass say, 100-300 kHz. There are two reasons for this concern: i) low frequencies do not attenuate as rapidly with distance as do high frequencies; and ii) to reduce signal propagation losses the high frequencies must be filtered out electronically for AE events which orginate near the AE sensor. It should also be mentioned that the electronic noise out of the preamplifier depends on the bandpass. The wider the bandpass, the greater the electronic noise. Hence, when comparing electronic noise specifications of different preamplifiers, the bandpass must be the same.

8.3 Dynamic Range. The fourth concern with the preamplifier is its dynamic range. The dynamic range is the range in signal level between the background electronic noise level and the maximum output voltage of the preamplifier. Since the noise level of the preamplifier is normally quoted in root-mean-square (rms) voltage, the dynamic range is not always readily apparent. The electronic noise has random amplitudes, and hence the peak noise amplitudes can be on the order of 12-18 dB above the rms noise level. Since the AE events in composites have a very wide dynamic range, it is useful to have a preamplifier with a dynamic range considerably greater than 60 dB as a minimum. Ideally, 80-100 dB of dynamic range would be useful.

9.0 Secondary Amplifiers and Filters.

9.1 Functions. Secondary amplifiers normally provide two functions: i) additional variable amplification (in increments of 1 to 3 dB); and ii) additional filtering (it is most convenient if these filters are of the plug-in variety). In the past, the basic design of the secondary amplifiers of commercial AE equipment often did not allow going down to frequencies below 20-30 kHz. This fact meant that expensive modifications were required to do AE monitoring on composites at low frequencies.

9.2 Various Bandpass Studies. Sometimes it is useful to operate the preamplifier and secondary amplifier wide-band and use a variable filter. This approach is useful when signal propagation studies are being made at various bandpasses. The alternative is to purchase a large number of plug-in filters.

9.3 Maximum Voltage Limitation. Both filters and secondary amplifiers have limits on the maximum voltage that can be passed. Often, their maximum output voltages are on the order of 7-10 volts peak to peak. For larger voltages, saturation and/or clipping occurs in the same fashion as for preamplifiers.

10.0 Time Domains and Characterization of Analog AE Signals.

10.1 Characteristics of AE Signal. Classically, an AE signal from a single AE event has an exponential increase followed by an exponential decay (see figure 1). From the point of view of AE equipment, the definition of an AE event depends on the analog voltage exceeding a pre-set or floating voltage threshold. When the voltage exceeds the threshold an AE event is said to have been sensed. Typical AE equipment can characterize the AE event in several ways (see figure 1): i) the peak amplitude of the AE event; ii) the duration of the AE event (i.e., the time that the signal is above the threshold); iii) the rise time of the AE event (i.e., the time from the first threshold crossing to the peak voltage); iv) the time of arrival of the AE event (i.e., the time at which the first threshold crossing occurred or the time the threshold crossing occured relative to the time at which another AE event occurred); v) the energy in the AE event during the duration; and vi) the number of counts of the event (i.e., the number of positive threshold crossings during the event). When AE is characterized by discrete AE events, then it is called burst type AE.

10.1.1 Continuous AE. There is a second classical type of AE signal. This is called continuous AE. Continuous AE is distinguished from burst type AE by the fact that there are so many AE events occuring over such a short time period that the AE events superimpose on each other in time such that it is no longer possible to distinguish discrete AE events. For continuous AE many of the parameters which are used to characterize burst-type AE no longer make sense. The typical characterization of continuous AE is the measurement of the rms voltage level. This approach gives a measurement of the energy rate of the AE out of the AE sensor. AE counts can also be measured for continuous AE. Usually, the counts are expressed as count-rate in this case. Peak amplitudes can be measured, but the real meaning of this measurement is not clear, since it will be a complex function of the number of AE events (and their individual amplitudes) which make up the continuous AE and the dead time (see paragraph 10.2) of the AE instrumentation.

10.1.2 Combination of Burst and Continuous Type AE. Often the AE observed in composites can be a combination of both burst type AE and continuous AE. This combination of AE requires a careful selection of AE equipment parameters such as threshold and dead time to obtain meaningful results. Often, the best characterization of such AE can be obtained using an rms meter which measures the energy rate of continuous AE and the energy in individual AE bursts (provided the bursts are sufficiently separated in time). The rms data can be particularly useful to determine the level at which the threshold of the AE system should be set.

10.2 Dead Time. A key parameter which the operator must select is the dead time of the AE system. The dead time is used to allow the AE equipment to know when one AE event is completed so that the system can be reset to be able to process another AE event. The dead time is the time increment during which if the threshold is not penetrated, then the AE system concludes that the AE event is over. If the dead time is set at too large a value, then the AE system will measure more than one AE event as one event. If the dead time is set too short, then the AE system will measure one AE event as several events. For composites, since the AE event rate can be quite high, it is important to set the dead time quite short (particularly for computer based AE systems). Typically, choosing the dead time to be 10-15% of the typical event duration seems to give satisfactory results. For values less than this, the quarterperiod of the nominal frequency in the AE bandpass should be calculated to make sure that the dead time is at least 8 to 16 times this value (i.e., 2 to 4 times the period).

10.3 AE Event as an Approximation of True Energy. In nearly every case, the AE event measured by commercial AE equipment is an approximation of the true energy which is defined by the equation

$$E_{\alpha} = \int_{0}^{t_d} \left\{ v(t) \right\}^{2} dt$$

where E is the energy in the AE event, t_d is the event duration, and v(t) is the voltage as a function of time. Until such time as the equipment manufacturers provide, for their equipment, an explicit correlation curve for measured value vs. the true energy for real AE events in the bandpass of interest, it is best to consider the measured energy values as approximations. Note these energy measurements are measurements of the energy out of the AE sensor.

11.0 AE Sources in Composites.

11.1 General Idea of AE Generation. Before discussing specific AE sources in composites, it is important to point out that most sources of interest are stress driven. Stress driven means that AE is generated as a response of a specimen or structure to applied stress and/or residual stresses which are present. Without stress no AE would be generated, since no stored energy would be available. Thus, the general picture of the generation of AE is: 1) externally applied or residual stress; 2) a local micro- or macro-damage or deformation mechanism; 3) a rapid change in the stress state caused by the local damage or deformation mechanism; and 4) stress waves generated by the local change in stress state. In some cases, AE is generated as a response to stress and time; e.g., when there is an incubation period after the application of stress before the deformation or damage mechanism occurs.

11.2 Categories of Composite Material. Before discussing sources of AE in composites, it is in order to define composite materials. Composite materials can be divided into three broad categories: dispersion strengthened, particle reinforced, and fiber reinforced [1]. In each category, the composite is made of a matrix material and second-phase material distributed throughout the matrix.

12.0 Dispersion-Strengthened Composites.

12.1 General. Dispersion-strengthened composite materials have a small (0.01- to 0.1 μm diameter) and hard second phase (volume concentration (15%)) dispersed throughout the matrix. These composite materials are distinct from precipitation alloy systems; for example, they are made normally by powder-metallurgy techniques, and the second phase does not go into solution when the material is heated near the melting temperature of the matrix.

13.0 Particle-Reinforced Composites.

13.1 General. Particle-reinforced composite materials are distinguished from dispersion-strengthened composites by larger dispersoid size ($>$ 1.0 μm) and increased concentration of the dispersoid volume ($>$25%). In addition, particle-reinforced composites are strengthened by the inherent relative hardness (compared to the matrix) of the dispersoid and by dispersoid constraint of matrix deformation. This strengthening mechanism is different from that in dispersion-strengthened composites, where restriction of the motion of dislocations by the second phase provides the strength enhancement.

14.0 Fiber-Reinforced Composites.

14.1 General. The distinct microstructural difference of fiber-reinforced composites is that the second phase (i.e., the fiber) has one dimension larger than the other two. This characteristic leads to anisotropic composite properties rather than the isotropic properties of the first two categories.

14.2 Characteristic AE Sources in Fiber-Reinforced Composites. Since few AE results have been published on dispersion- and particle-strengthened composites, this section will emphasize fiber-reinforced composites. Only a few sentences will be devoted to the other two types of composites. The three main parts of a fiber composite are the fibers, the matrix, and the interfaces. The sources of AE associated with the fibers are: i) fracture, ii) cracking and splitting, and iii) plastic deformation. The sources of AE that orginate with the matrix are: i) cracking, ii) crazing, and iii) plastic deformation. Interfaces can also lead to several sources of AE: i) interlaminar debonding, ii) fiber-matrix debonding, and iii) rubbing (e.g., fiber pull-out or relative motion of fracture or delamination surfaces). Figure 2 shows a schematic of a fiber composite and a listing of these sources. It is to be expected that these fundamental source events or damage mechanisms do not act in an isolated fashion. Hence, characteristic AE sources in fiber composites can be expected to be combinations of these sources.

14.3 Sources in other Composites. Sources in dispersion-strengthened and particle-reinforced composites will be, in general, cracking of both phases and at the interfaces as well as plastic deformation. Plastic deformation will occur primarily in the matrix materials with most AE sources being those that are present in metals.

15.0 Wave Propagation Aspects.

15.1 General. In general, wave propagation is a complex subject even in homogeneous and isotropic materials. Since composites have neither of these characteristics, wave propagation for composites is particularly complex. The aim here is to give the reader a general understanding of key aspects which relate directly to practical AE testing of composites.

15.2 Aspects of Stress Wave Propagation. As in all AE testing, the stress waves generated by each AE event propagate through the composite and any other possible paths to the transducer. This propagation greatly influences the resulting electrical signal out of the transducer. Aspects of stress-wave propagation that significantly influence the electrical signals are: geometric spreading of the stress wave, losses due to material absorption of the stress-wave energy, direct and reflected paths from the AE source to the transducer, different modes and speeds of propagation of the stress waves along with dispersion of the stress waves, and scattering from "obstacles" encountered in the line of travel of the wave.

15.2.1 Geometric Spreading of the Stress Wave. Geometric spreading is the loss in signal amplitude due to the fact that, as the wave travels away from the point AE source in a two-or three-dimensional medium, the total area of material through which the wave front is passing increases. Conservation of energy can be used to calculate the resulting change in amplitude. As a reference, it is well known that for an infinitely thin flat plate the amplitude (not in the immediate vicinity of the source) is inversely proportional to the square root of the distance the wave front has traveled from the source. In real structures, geometric spreading does not always decrease the signal amplitude with increased distance of propagation. For example, in a spherical pressure vessel, geometric spreading is approximate to $\sin^{-1/2}\theta$, where θ is the angle between a radius to the AE source and a radius to the center of the AE transducer. Hence, at 90° from the source the amplitude is smallest, but at 180° the theoretical amplitude approaches that near the vicinity of the source.

15.2.2 Losses Due to Material Energy Absorption of Stress Wave Energy. Losses due to material absorption of the stress-wave energy result in attenuation of the amplitude of the wave as it propagates. This attenuation is more severe for stress waves at higher frequencies and in viscoelastic materials such as epoxy. Analytically, this loss of energy by heat can be expressed by an exponential dependence on distance of propagation (the exponent depends on frequency). Material energy absorption is a major difficulty in monitoring the AE generated in fiber composites. To a certain degree this difficulty can be partially overcome by the use of a relatively low-frequency bandpass (e.g., 5 to 30 kHz).

15.2.3 Wave Speeds. Acoustic-emission stress waves in composites have several significant components that propagate at different speeds. Typically, two wave packets can be distinguished on the basis of wave speed: A generally lower-amplitude first arrival and a higher-amplitude second arrival. Depending on the relative amplitudes of these waves and the distance between the AE event and the transducer, this feature significantly affects the AE signal out of the transducer. Also, for fiber composites depending on the orientation of the fibers, the wave speeds in the composite can vary for different directions of propagation of the AE waves. If the fibers are at several different directions, such as in many filament-wound vessels, then the wave speeds do not vary significantly with direction. But, if all the fibers are in the same direction, then the wave speeds in the direction of the fibers can be substantially higher (up to a factor-of-four difference, depending on frequency, for an undirectional graphite/epoxy composite). It is also possible for part of the stress waves from a given AE event to propagate totally in a fiber. If this fiber happens to pass directly under a transducer,a completely unexpected path to the transducer is possible. Typically, in a fiber/epoxy composite with fibers in many directions, the actual composite wave speeds are dominated by the wave speeds through the epoxy matrix. This situation results from substantially slower speeds of propagation in the epoxy than in the fiber. All of the above propagation effects can substantially effect the use of arrival times at multiple AE transducers to locate the AE events. In section 16.0 we will give an example of some of these effects. Note that the differences in path can cause propagation losses of peak amplitude, but not AE event energy.

15.2.4 Dispersion of Stress Waves. Dispersion of AE stress waves in composites refers to propagation of different-frequency components at different speeds. The net result of dispersion is spreading in the time domain of the stress wave as a function of distance traveled. This results in a decrease in peak signal amplitude but not energy in the AE burst. This is the second reason why event energy does not attenuate as rapidly as peak amplitude.

15.2.5 Scattering of Stress Waves. Scattering is an inherent aspect of wave propagation in a composite. Energy is lost due to propagation of part of the energy in directions different than the line of travel of the wave. The second phase material (e.g., fibers) can be considered to be "defects" which cause scattering. This effect depends on the wavelength of the sound wave and the cross-section area of the "defects."

15.3 Distinguishing Between Different Types of AE Sources. Because of all the complications noted above, the stress wave that reaches an AE transducer bears little resemblance to that which was generated at the AE source. For this reason it is very difficult to use frequency spectra to distinguish between different types of AE sources in a useful fiber-composite structure. In fact, for a repeatable source such as a pencil-lead break, the spectrum of the AE burst is different for the lead being broken at different locations on the composite part.

15.4 Effect of Signal Propagation Losses on Peak Amplitude. The fact that the peak amplitude can be greatly effected by signal propagation losses needs to be emphasized. This problem can only be minimized by the use of more AE sensors and/or a lower frequency bandpass (in a few cases, a waveguide can also be used effectively). The importance of minimizing this effect is due to the use of peak amplitude to distinguish source mechanisms in composites or to determine the severity of micro-damage in the composite. Wasin and Pollock showed that up to 45 dB in AE amplitude could be lost over 50 cm of propagation in a glass/epoxy composite [2], for steel the loss over an equivalent distance is 3-5 dB [3].

15.5 Reducing Random Flaw Generated Events. For certain applications of AE to composites, it is not necessary to use a low frequency bandpass. In fact, it is desirable to use a high frequency bandpass. This application uses signal propagation losses such that random flaw generated AE events do not propagate to the sensor with sufficient amplitude to be sensed. Hence, only events in the near vicinity of the sensor are sensed. This is desirable when the purpose of the AE study is to monitor the micro-deformation and failure mechanisms which are uniformly distributed throughout the composite. In this case, random flaw generated events only confuse the results.

15.6 Components of AE Signal Duration. There is another aspect of wave propagation that is important to discuss. This relates to signal durations. The AE signal duration is made up of two components: first, the ringing of the AE sensor; and, second, the paths of propagation of the AE signal before it is attenuated below the system threshold level. Often with a low frequency bandpass and a composite test sample which is not too large, the largest component in the AE event duration is the "ringing" of the stress waves in the test sample. Experimentally, these two components can be evaluated by looking at the time domains from lead breaks on the test sample vs. the domains for lead breaks on the face of the AE sensor.

16.0 Source or Flaw Location in Composites.

16.1 Triangulate Method for Locating AE Source Event. Since the AE stress waves which are generated at a specific location propagate with certain velocities in all directions, by using more than one transducer, AE practitioners in composites have been able to locate the region or point of origin of the AE source event. Basically, the same techniques that are used to "triangulate" the epicenter of an earthquake are used. This approach measures the relative arrival times of the AE event (from a specific AE event) at transducers which are located at several points on the composite. For relatively simple structures (e.g., rods or uniform thickness plates) with constant velocities of wave propagation in all directions (usually not the case in composites) simple calculations can be used to determine where the AE source (e.g., a growing flaw) originated.

16.2 Area Location Technique - To Determine Most Damage. Since more useful composite structures do not meet the above requirements, alternative techniques have been used in composites. The technique which has proved most useful is called area location. This technique has been implemented in two ways. The first approach makes use of the high signal propagation losses in composites. In this approach, a combination of frequency bandpass and AE sensor spacing is chosen such that only the sensor in the immediate vicinity of the AE source senses the AE event. Thus, using this technique, regions of the composite which are experiencing the most damage can be identified. This approach works best when there are a few known regions of relatively high stress in the composite. It does not work well when AE sources could be any place in the composite. In this latter case, either source events can be missed or the events can "hit" more than one sensor.

16.3 Area Location Technique - More Sophisticated Approach. The second approach has been developed to overcome the weakness of the first. This approach requires more sophisticated AE equipment and a lower frequency band-pass and/or more closely spaced AE sensors. For each AE event the arrival time at the AE sensors which it hits (a sensor is hit when the signal from the AE sensor has sufficient amplitude to be above the set voltage threshold) is recorded as well as the peak amplitude at that sensor. Then using the general principle that the first hit sensor is the sensor closest to the AE source location, each particular AE event can be assigned to a certain region. Again, the cumulative results would indicate the region on the composite structure where most damage was taking place, e.g. during a proof test.

16.4 Summary. The classical techniques of source location discussed in 16.1 to 16.3 which result in a much more precise location have not yet been fully implemented in most acoustic emission testing of composites.

17.0 Kaiser Effect/Felicity Ratio.

17.1 Felicity Ratio. The more general term is the Felicity ratio. The Felicity ratio is the numerical value which results when the load at which "significant AE" begins on a subsequent cycle is divided by the maximum load during the previous cycle. At the current time, there is no fixed definition of "significant AE." Hence, most AE practitioners use their own past experience. The factors that the AE practitioner looks for are the numbers of AE bursts as a function of certain load increments compared to the number of events over the same load increment during the prior loading and the signal levels of these AE bursts compared to those during the initial loading. The CARP recommended practice [4] suggests three guidelines for the determination of the onset of significant AE:

1) More than 5 bursts of emission during a 10% increase in load;
2) More than 20 counts during a 10% increase in load;
3) Emission continues at a load hold.

17.1.1 Effect of Variables on Felicity Ratio. There are a number of variables which can effect the value of the Felicity ratio: loading and unloading rates, time at peak load, AE system sensitivity, time between load cycles, stress state during loading, AE source mechanism, test or storage (between load cycles) environment, and proof load level relative to the expected ultimate strength. Materials which have rate dependent properties have the largest effects with most of these variables. Many fiber composites with plastic matrices have this characteristic.

17.2 Kaiser Effect. If a composite material is loaded to a given stress level and then unloaded, usually no emission will be observed upon immediate reloading until the previous load has been exceeded. This is known as the Kaiser effect. The Kaiser effect is said to hold when the Felicity ratio is $\geq$ 1.0. If the Felicity effect is $<$ 1.0,. then the Kaiser effect is said to be violated. Hence, it is clear that when the Kaiser effect holds, no new AE sources have operated and no reversible AE sources were present during the subsequent load cycle of the specimen being tested. But, if the Kaiser effect is violated, then either or both of these cases has occured.

18.0 Factors of Significance in AE Data.

18.1 Six Basic Factors. There are six basic factors which must be taken into account when determining the significance of the AE which has been recorded during a test of a composite. First, since AE is generated as a response of a specimen or structure to stress, the stress levels at which the AE events occur are of importance. Normally, the lower the stress at which AE events occur, the poorer the structure. The second factor is the energy (or amplitude) of the AE bursts. The usual conclusion is: the higher the energy of an AE event, the larger or more significant the damage to the specimen. Most AE data indicate large increases in AE amplitudes near the failure level of composites. Third, the total number of AE events is also of significance. Normally, the larger the number of AE events, the greater the damage to the composite. Fourth, the location of the AE sources is of key significance for composites. Composites often have a considerable number of AE events which originate at random locations throughout the specimen. These random location events often have little or nothing to do with the strength or life of the structure. Of much greater importance are AE events which originate at the same location. These AE events are indicative of a growing region of damage and of potential serious damage to the structure. Fifth, the value of the Felicity ratio is also a significant factor in AE data for composites. Normally, the lower the value (i.e., < 1.0) of the Felicity ratio, the poorer the composite sample. Sixth, the rate of accumulation of AE events as a function of increasing stress (or time) is significant. When the slope of such a curve changes significantly, or becomes exponential, the rapid growth of damage indicates changes in source mechanisms or flaw growth becoming unstable as a percursor to total failure. Similarly continued AE with time at a load hold implies creep processes which may be becoming unstable.

18.2 Interpretation of Significance of AE Data. The interpretation of the significance of AE data for a specific instance is largely a matter of experience. The key experience is gained by monitoring good vs. bad specimens. This fact points to the reason why section 3.0, placed such an emphasis on doing identical AE tests. A key factor, is the identity of the source mechanism which produced the AE. Since there are currently no standard techniques which can be used to identify the source for a given AE burst, we can't as yet include this as a factor of significance. Future developments in the field may result in such techniques. These techniques could be very useful for composites such as fiber reinforced composites where fiber failures are often of much greater significance than matrix cracking.

19.0 In situ Calibration of AE Tests.

19.1 Advantages. Since there is a large emphasis on comparison of AE data from one test to another, it is important to adopt an *in situ* calibration technique. Such a technique will allow for checking the following: i) propagation characteristics of the test specimen and associated test fixturing; ii) the efficiency of the AE couplant; iii) the sensitivity of the AE sensor; and iv) the operation of the preamplifier and other AE equipment. By adopting certain minimum and maximum outputs of the calibration signal, the AE test can be certified as identical for each composite structure.

19.1.1 Additional Advantage. There is a further reason for using an *in situ* calibration. An *in situ* calibration checks every aspect of the AE test. This is important to do because if something is wrong with the AE test, it is not possible to repeat the test as most AE which is generated is irreversible, and so the first load cycle has unique AE data which can never be repeated.

19.2 Calibration Using Fracture of Pencil Lead. To date, the most convenient simulated AE source event for calibration purposes is the fra^ture of pencil lead in contact with the test specimen. The rapid release of the Hertzian contact stresses simulates the $\Delta\sigma_{ij}(\underset{\sim}{X}, \Delta t, \Delta V)$ of a real AE event. The best approach is to build a mechanical lead breaker so that each lead break takes place at the same location and under the same geometric conditions. By building a load cell into the lead-breaker, the load at which the lead breaks can be measured. This assures that the lead break used for calibration was at the normal load. The length of lead must be controlled as well as rebounds of the broken lead against the test part. The lead breaker must be isolated with respect to wave propagation from the test specimen and AE sensor. This isolation is necessary so that AE generated in the lead-breaker does not reach the AE sensor. Typically best results occur with 0.3 mm or 0.5 mm diameter 2H lead. Since the lead sometimes fractures in other than normal fashion, usually 3 or 4 breaks are used. The first and last few breaks from a length of lead should not be used for calibration.

20.0 Extraneous AE.

20.1 Typical Extraneous Sources of AE. It is a relatively simple procedure to attach an AE sensor to a composite, load the composite, and obtain AE data. Along with the AE data of interest (i.e., that which originiates from the specimen as it is loaded) there may be considerable amounts of AE from extraneous sources. Some typical extraneous sources of AE are: 1) AE from the loading apparatus or test fixture, 2) AE from the test machine or specimen grips, 3)AE from other machinery in the test environment, 4) AE from strain gages, and 5) AE from unexpected sources. Ground loops, voltage spikes and other stray electromechanical signals may be mistaken as AE. Since it is often necessary to go to a lower frequency bandpass with composites to overcome signal propagation losses, extraneous noises can be expected to be present in greater amounts for composite testing. But, this situation does not necessarily imply that the AE signal to extraneous noise ratio will be worse for a low frequency bandpass. The reason for this is that at lower frequencies the amplitudes of the real AE signals are considerably larger.

20.1.1 Determining if Significant AE is Present. There is one fundamental way to prove that significant AE from extraneous sources is not present (at the particular AE sensitivity used) in a particular test. The technique is to replace the test specimen with a dummy specimen which is known not to emit AE under load. Then the test is run with the dummy in place and any AE which is generated will be from extraneous sources. It is possible to check for most extraneous AE sources for test specimens/structures which have a high Felicity ratio (i.e., $\geq$1.0). In such a case, the test sample can by cycled twice (to prove the Felicity ratio is $\geq$1.0), then it can be completely removed from the test fixture, reinstalled and tested again. If the Felicity ratio is greater than or equal to what it was before, then all but a few possible sources of extraneous AE have been shown to be insignificant at the AE sensitivity that was used. It is an important step to completely remove the test specimen from the test fixture, and also, to tear down the test fixture if that is normally done between or at the end of a set of AE tests. Often, unexpected extraneous AE sources will be uncovered by such an approach. The use of the Felicity effect does not check all potential extraneous AE sources. For example, with "tab type" composite tensile samples, the use of the Felicity effect would not prove that the adhesive between the tabs and the specimen was not a source of extraneous AE.

20.1.2 Elimination of Extraneous Sources of AE. Extraneous sources of AE can often be eliminated by better design of the test set-up or the test environment. Also, absorbing materials can be used or the AE equipment can be operated at less sensitivity. In some cases, it may be necessary to redesign the test specimen or the test fixturing, or to test at a different location or time of day. In an extreme case it may be necessary to conclude that AE in its present state of development is not an appropriate test.

21.0 Control Checks on AE Testing.

21.1 Running Charts. In production testing or other regular testing of composites with AE, there are certain measurements which can warn the responsible person that all is not correct for the AE test. A simple approach to this is to use so-called "running charts." These charts are historical plots of some key measurements which relate to the overall health of the AE system. When steady or step changes occur in these charts, then it is time to fully check out the AE test system or test technicians. Typical measurements which might be recorded on such charts are: 1) load at which the lead fractures; 2) the AE peak amplitude from the lead fracture event, and 3) the electronic rms value of the background noise level.

21.2 AE Electronics. It is also necessary to periodically check the AE electronics as well. Electronic equipment does suffer breakdowns, and these breakdowns are not always characterized by a complete loss of functions. AE equipment, particularly computer based systems, can apparently function quite nicely, but at the same time be making incorrect measurements [5].

22.0 Additional Instrumentation.

22.1 General. In addition to what is normally sold as AE equipment, there are several electronics instruments which are quite valuable. These can be used both to make decisions on instrument level settings of the AE equipment and also to diagnose problems with the AE data.

22.2 Types of Equipment. Typically, these additional pieces of equipment are a combination of a transient recorder and an oscilloscope, a variable oscillator with variable dB attenuator, and a true rms meter (if it is not already a part of the AE system). The scope-transient recorder can be used to determine the levels to set such parameters as the dead time and the threshold of the AE system. It can also be used to determine the type of AE which is present (e.g., burst-type vs. continuous). The oscillator can be used to check gains and bandpass in combination with the rms meter. The scope is also useful to check for extraneous electronic noise sources such as ground loops.

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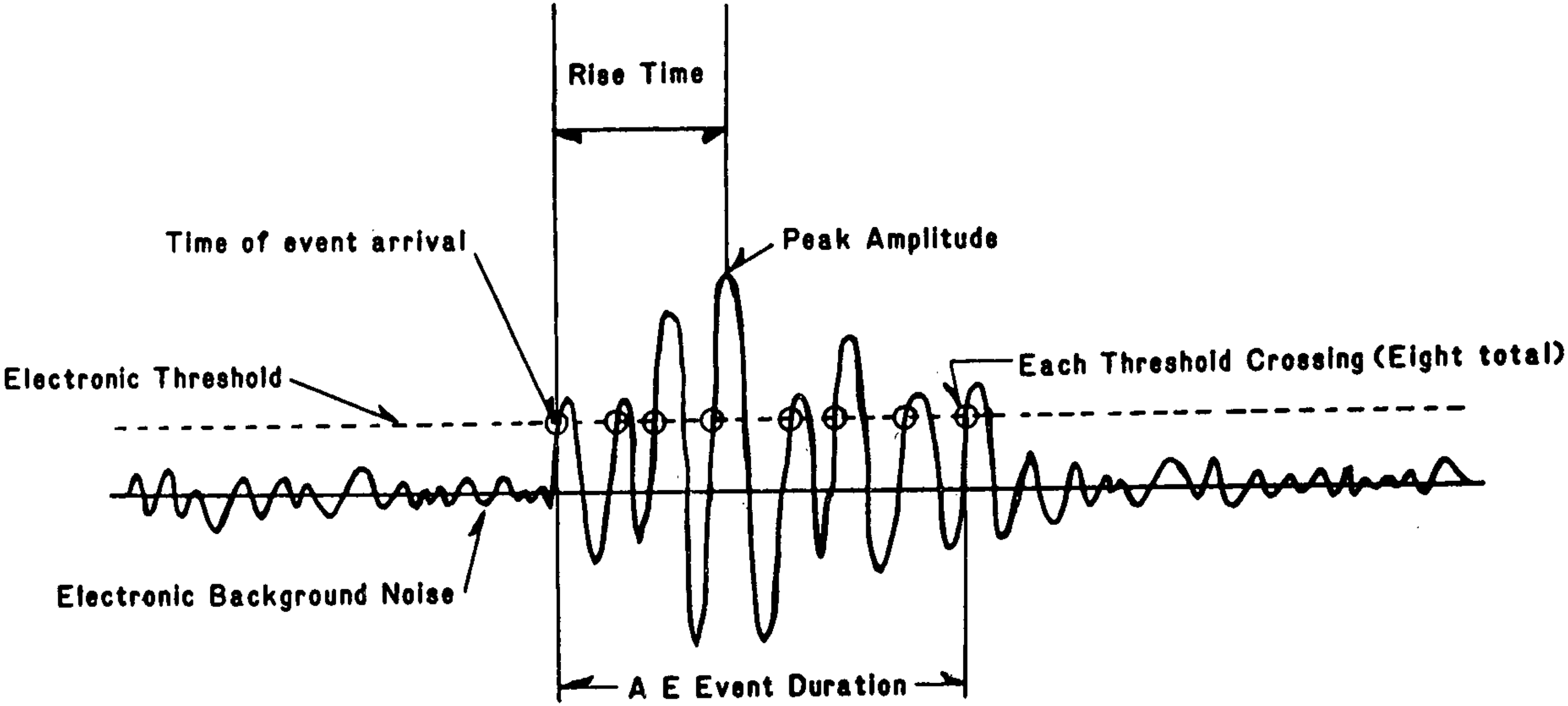
Figure Captions

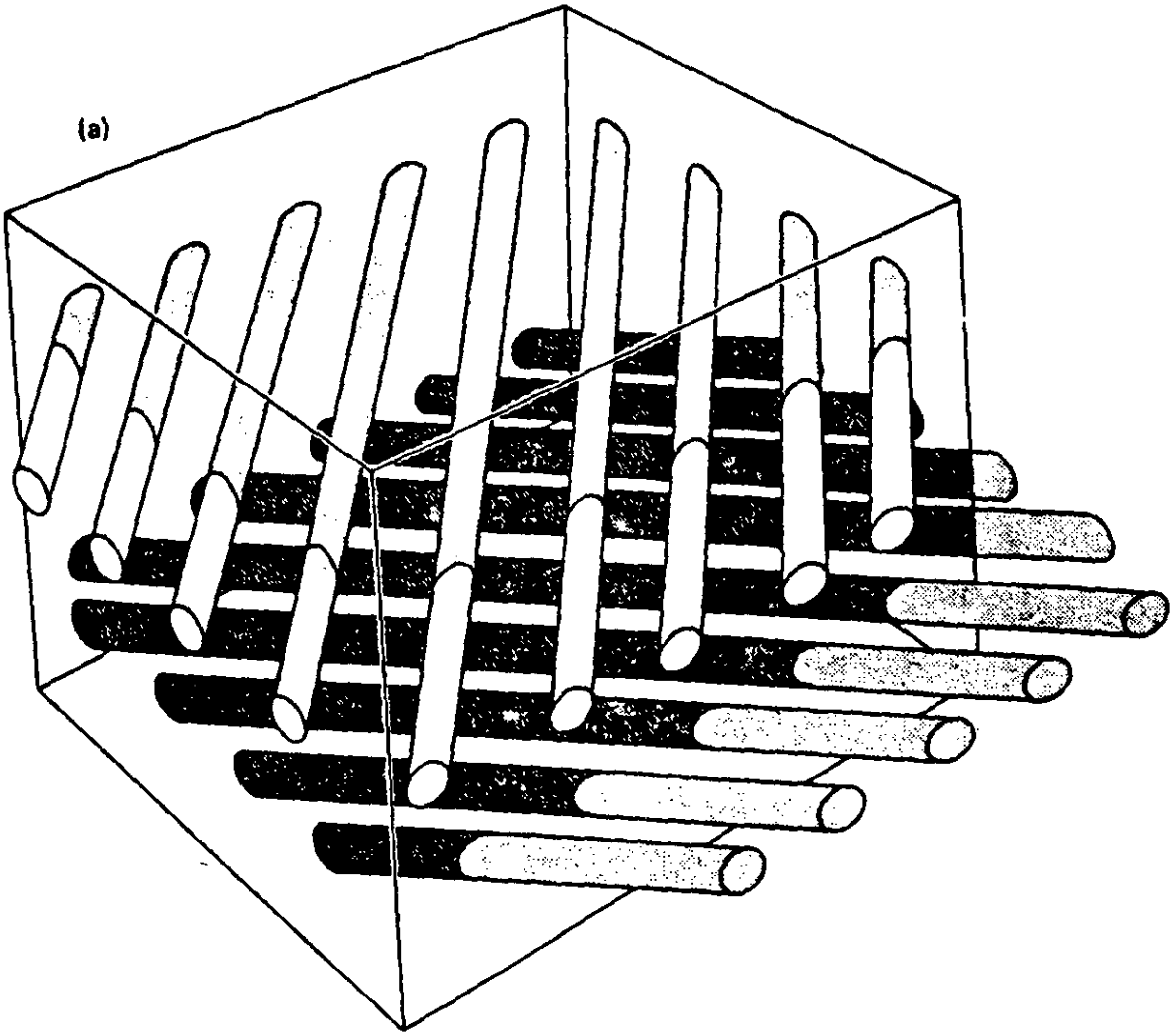
Figure 1. Classical AE burst event.

Figure 2. Schematic of fiber composite a); and list of AE source mechanisms b).



Classical AE Burst Event

Figure 1



(b)

- Fiber
  - Fracture
  - Cracking & splitting
  - Plastic deformation
- Matrix
  - Cracking
  - Crazing
  - Plastic deformation
- Interfaces
  - Interlaminar debonding
  - Fiber-matrix debonding
  - Rubbing (pull-out)

Schematic of Fiber Composite a); and list of AE Source Mechanisms b)

Figure 2

Custodians:

Army -- ME
Navy -- AS
Air Force -- 20

Preparing activity:

ARMY -- MR

Project No. NDTI-0087

Review activities

Army -- ME, AV, AT, AR
Navy --SH, OS
Air Force -- 70, 71, 82, 99

User activities:

Army -- MI
Navy -- YD
Air Force -- 94, 80

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