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Acoustic Emission for Periodic Inspection of Composite Pressure Vessels

Bao Rasebolai Mosinyi

Embry-Riddle Aeronautical University - Daytona Beach

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ACOUSTIC EMISSION FOR PERIODIC INSPECTION OF COMPOSITE PRESSURE VESSELS

by

Bao Rasebolai Mosinyi

A Thesis Submitted to the Graduate Studies Office in Partial Fulfillment of the Requirements for the Degree of Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
December 2001
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Bao Rasebolai Mosinyi

This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Eric v. K. Hill, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Department of Aerospace Engineering, and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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AKNOWLEDGEMENTS

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ABSTRACT

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Title: Acoustic Emission for Periodic Inspection of Composite Pressure Vessels
Institution: Embry-Riddle Aeronautical University
Degree: Master of Science in Aerospace Engineering
Year: 2001

Cost savings can be achieved in a wide range of applications by replacing the current procedure for hydrostatic recertification of high-pressure composite gas cylinders with acoustic emission (AE) nondestructive testing. Advantages of AE recertification over the current hydrostatic method include: (1) no water contamination, since pressurization of the cylinders is done with air as opposed to water; (2) the risk of damage is decreased since the test pressure is reduced from 166% of design pressure to 110% of operating pressure; (3) the ability of acoustic emission to detect and locate flaws increases safety; and (4) the in-situ method will reduce cost and downtime.

A method for testing of filament-wound composite pressure vessels has been proposed by the draft ASTM standard E07.04.03-95/1 (Standard Test Method for Examination of Filament-Wound Composite Pressure Vessels Using Acoustic Emission). The research presented follows the proposed acoustic emission technique and shows results that validate the draft ASTM standard in the case of aluminum-lined graphite/epoxy Type 3 vessels.

Over a period of several months, pressure cycling, controlled impact damage, and controlled chemical attack were used to degrade the structural conditions of several pressure vessels in a fashion representative of service-induced damage. Once the cylinders had been subjected to a known amount of damage and cycling, they were pneumatically pressurized and monitored with AE during the pressurization cycles. The results from the AE monitoring are reported herein. Finally, AE data from the pressurization tests were correlated with the associated damages, and a level of AE activity that corresponds to a damaged bottle was defined.
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CHAPTER 1
INTRODUCTION

1.1 OVERVIEW

Acoustic emission (AE) has proven to be one of the best nondestructive testing (NDT) methods for validating composite structures. It has been invaluable for testing structures like the composite boom of bucket trucks. The primary reason for its success is that a damaged region in a composite will produce copious emission when it is stressed somewhat above its normal load. This has led to the rather simple procedure of loading a structure to between 110% and 150% of its normal operating load while monitoring the structure with acoustic sensors. A good structure is relatively quiet and therefore passes, while a flawed or damaged structure will emit lots of acoustic signals under the proof load. Such a test is what is described in the draft ASTM standard E070403-95/1 "Standard Test Method for Examination of Gas-Filled Filament Wound Composite Pressure Vessels Using Acoustic Emission".

Specifications for AE testing of all-metal pressure vessels and those made of composite materials exist. The American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code covers AE testing of newly fabricated metallic pressure vessels in Section V, Non Destructive Examination, Article 12. Article 11 of the same section is for fiber reinforced plastic vessels, and Section X, Article RP-6 is the "Acceptance Test Procedures for Class II Vessels". Also widely used is the "Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic (FRP) Tanks/Vessels" published by the Society of the Plastic Industry (SPI).
This research is part of an industry wide search for an acoustic emission test method for rectification of composite pressure vessels used for the storage of compressed gases. Recertification of the cylinders investigated in this research and other high-pressure composite vessels is currently accomplished by hydroproof testing. This procedure consists of filling a cylinder with water and pressurizing it to 166% of its design pressure. Although hydroproofing has "proven successful in verifying the structural integrity of metal cylinders, it has not always been as successful in composites" [Hill]. AE is being considered to replace hydrotest because it has proven successful in testing composite structures, uses a lower test pressure, and offers the advantage of testing without removing vessels from operational status. Depending on what the cylinders are used for, the process of their removal and the associated reinstallation for hydrotesting can be expensive.

Composite containers used to store compressed gases are classified into three types. Type 2 has a thick metal liner and a composite hoop wrap up to the shoulder. Type 3 has a thin metal liner with a composite cross-ply wrap covering all but the threaded ends. Type 4 has a thin plastic liner with a hybrid composite wrap covering the whole cylinder except the threaded end. The cylinders, most of which fall under the regulatory authority of the Department of Transportation (DOT), are used in a wide variety of applications, including containment of diving gas mixtures, Natural Gas Vehicles (NGV), and nitrogen receivers for missile launchers (LAU-7) in fighter aircraft. In this work, Type 3 graphite/epoxy FRP pressure vessels used for diving gas mixtures were investigated. The vessels have a 0.11 inches thick 6061-T6 aluminum alloy liner, followed by 8 layers of filament wound carbon at +45/-45 degrees with a thickness of 0.24 inches. The vessels
also have two outer layers of continuous hoop-wrapped glass with a thickness of 0.021 inches. The overall diameter of the cylinders is 10.15 inches, while the length is 29.20 inches.

1.2 METHODOLOGY

A total of thirteen cylinders were used in this work. The first step was to study the properties of acoustic waves propagating in the cylinders. Such a step was important, among others, for the selection of an appropriate AE sensor to be used. Previous research on AE testing of FRP cylinders has used low resonant frequency 60 kHz sensors rather than the more commonly used 150 kHz sensors [Akhtar, et. al, Connolly]. The performances of sensors with a wide range of resonant frequencies were evaluated. The next step involved the development of a source location procedure using the knowledge acquired in the first step.

The rest of the work is divided into two phases. In Phase I, a set of three cylinders were subjected to pneumatic cyclic loading in order to simulate normal use over a long period of time. The cylinders were inspected periodically with AE in order to understand their AE response with an increasing number of cycles. Also in this phase, varying degrees of damage were induced to some cylinders, and the AE activity of such damaged cylinders was studied. The aluminum liner of one cylinder was also subjected to corrosion, and AE generation from the cylinder was analyzed.

Phase II, which used a total of eight damaged and undamaged cylinders, was a more elaborate version of the first phase. Here, the source location method developed in Phase I was used for monitoring the cylinders while pressurizing them to 8000 psi. Hydrostatic cycling of the cylinders up to 780 cycles was also performed.
Acoustic emission is, by definition, an elastic stress wave generated by the rapid release of energy within a material. The classic sources of acoustic emissions are defect related deformation processes such as crack growth and plastic deformation [Pollock]. For detection, the amplitude of the signal must exceed the detection threshold of a recording system, and the frequency distribution must at least be partially covered by the transducer bandwidth.

Unlike almost all other NDT methods, the energy that is converted to AE signals comes from the material itself. As a result, the technique is sensitive to defects that have the potential to grow. Since the acoustic signals from defects radiate throughout the structure, relatively few transducers can detect and quantify defects over a large area. The source of the acoustic emission energy is the elastic stress field in the material. The process and generation of such waves is illustrated in Figure 2.1.

![Figure 2.1 Basic principle of the acoustic emission method](image-url)
Figure 2.2 shows the various parameters associated with an AE signal. There are six parameters commonly used to quantify acoustic emission waveforms. Amplitude is the largest voltage peak in the AE signal waveform, customarily expressed in decibels [dB] relative to 1 microvolt at the transducing element. The threshold serves as a dividing line, determining which signals will be recorded, and which will be neglected, based on their peak amplitudes. The threshold level is usually set by the operator, and it is a key variable that determines test sensitivity. Counts (sometimes called ringdown counts) is one of the oldest and easiest ways of quantifying the AE signal. It is the number of times the voltage
of the signal crosses a threshold set by the operator of the data acquisition system. MARSE, also known as energy counts, is the measured area under the rectified signal envelope. The risetime is the time it takes for the signal to reach its maximum amplitude (after crossing the detection threshold), while the duration is the time that the signal remains above the detection threshold.

2.1 AE GENERATION IN FIBER COMPOSITES

Most composite structures do not exhibit the same elastic-plastic behavior found in metal structures. The failure mechanisms associated with fiber matrix composites, such as matrix cracking, delaminations, fiber fracture, etc, result in AE characteristics that are different from those of metal structures. To begin with, it is well known that a large number of AE events are generated during the first stressing of a fiber composite sample. The uniformly distributed damage, which is created during the virgin stressing of a composite, has been called the "characteristic damage" [Hamstad]. Subsequent stress cycles often show a significant drop in the number of AE hits that are generated. This is due to the fact that the characteristic damage has already formed.

Another fundamental of AE generation in fiber composites is that during a second load cycle, very little AE is generated until the previous peak level of the load is approached. Such an observation is called the Felicity effect and leads to the Felicity ratio [Hamstad]: The lower the Felicity ratio, the lower the residual strength of the structure. The other fundamental of AE generation in fiber matrix composites is based upon friction between damaged portions of a composite. It has been observed that friction or rubbing between such surfaces can be a significant source of AE [Awerbuch, et. al]. Such
friction-based AE generation has been observed to increase with increased level of damage as the structure is loaded and unloaded.

A fourth fundamental of AE generation in fiber composites relates to fact that catastrophic failure occurs due to a concentration and accumulation of damage in a local region of the composite [Hamstad]. Thus, the AE associated with this local accumulation of damage has a relatively small region of origin. Finally, generation of AE has also been observed to occur while the composite is at a constant load [Hamstad and Chicio]. The intensity of such AE emission depends on the materials from which the structure is constructed. Glass fiber composites are known to generate larger amounts of AE than graphite fibers. Unless a structure is approaching catastrophic failure, under the hold-at-fixed-load stress conditions, this hold-based AE decreases with increasing time at a fixed load.
CHAPTER 3
WAVEFORM ANALYSIS

In order to fully understand acoustic emission or “stress waves” from a material, it is important to first understand the acoustic properties of the material. In order to study the acoustic properties of the cylinders, a suitable AE sensor had to be selected. This chapter presents the work done to arrive at a decision on the best sensor to be used for acoustic emission testing of the cylinders. In addition the nature of the waveforms in a pressurized vessel, as opposed to an unpressurized one, is also discussed. This was prompted by the results obtained from earlier studies of carbon fiber composite gas cylinders with aluminum liners at Lockheed Martin Company (LMCO), Littleton, CO [Beattie].

The LMCO work showed that at atmospheric pressure, the aluminum liner was not necessarily in good contact with the composite layer. This could have a significant effect on the characteristics of acoustic waves propagating in the cylinders. LMCO found that by pressurizing the cylinders to 50 psi or higher, the acoustic waveforms became independent of further increases in pressure up to near the failure pressure of the cylinder. In light of the fact that acoustic properties of these FRP vessels were investigated while the vessels were in an unpressurized state, it was felt imperative to investigate if the findings of LMCO are applicable in the pressurized state. The obvious differences between the LMCO cylinders and the cylinders used in this study are that the LMCO cylinders were designed for use at lower pressures and that their construction was resin lean compared to the cylinders studied herein.
An appropriate simulator to generate stress waves with characteristics similar to those of a crack was selected: namely, the Pencil Lead Break (PLB) method using a 0.3 millimeter diameter Pentel pencil. Data from the PLB experiments were used to determine acoustic wave propagation velocities in the cylinders. Wave attenuation characteristics in the cylinders were also determined from PLB data. Knowledge of the attenuation characteristics of acoustic waves is also important information in the determination of the minimum spacing between AE sensors. The waveforms were studied in the time domain and frequency domain (power spectra). Looking at the waves in the time domain shows how the amplitude of a waveform decreases with time. The power spectrum, on the other hand, enables us to view how the energy in the signal is distributed among the various frequencies.

3.1 CHOICE OF SENSOR

The experimental setup shown in Figure 3.1.1 was used to determine both the suitable sensor and the effect of internal pressure on the bonding between the aluminum liner and the composite wrap. To examine whether the same effect discovered at LMC was present in these cylinders, a low-pressure system was set up to pressurize the cylinder to 100 psi with air. A cylinder was instrumented with six sensors at various locations plus a drive sensor, which was driven by a square wave. The sharp transitions of the square waves are fast enough to drive an AE sensor and produce an acoustic wave. These waveforms are completely reproducible except that the phase changes 180 degrees between the ascending and descending edge of the square wave. The six receiving sensors consisted of two 150 kHz resonant frequency sensors, two 60 kHz resonant
frequency sensors, one 500 kHz resonant frequency sensor, and a 300 kHz resonant frequency sensor. These sensors were located on the cylinder as shown in Figure 3.1.1(a).

![Figure 3.1.1(a): Relative Positions of the Sensors](image)

Figure 3.1.1(a): Relative Positions of the Sensors

![Longitudinal cross-section and Circumferential cross-section](image)

Figure 3.1.1(b): Coordinate system used for sensor location description.

The coordinates of the sensors are given in radians in a spherical coordinate system. Theta (θ) is the angle between the horizontal axis of the cylinder and a vector to the location from the center of the cylinder, and phi (ϕ) is the radial angle measured from the apex of the top surface of the cylinder. Table 3.1.1 presents the sensor number, coordinates, and distance from the drive sensor and signal peak amplitudes in volts [V], while Table 3.1.2 gives the frequency specifications of the sensors used. It is worth
noting from Table 3.1.2 that the sensors investigated have wide ranges of both resonant and operating frequencies.

Table 3.1.1 Sensor positions and peak amplitudes of acoustic waves

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Theta (radians)</th>
<th>Phi (radians)</th>
<th>Distance to Driver (mm)</th>
<th>Peak Signal Amplitude (V)</th>
</tr>
</thead>
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<tr>
<td>D</td>
<td>0.574</td>
<td>6.022</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.686</td>
<td>5.784</td>
<td>51</td>
<td>0.28</td>
</tr>
<tr>
<td>2</td>
<td>2.573</td>
<td>4.033</td>
<td>465</td>
<td>0.0024</td>
</tr>
<tr>
<td>3</td>
<td>0.187</td>
<td>0.0</td>
<td>182</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>1.492</td>
<td>0.872</td>
<td>234</td>
<td>0.021</td>
</tr>
<tr>
<td>5</td>
<td>2.923</td>
<td>0.0</td>
<td>559</td>
<td>0.0070</td>
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<tr>
<td>6</td>
<td>2.459</td>
<td>2.459</td>
<td>352</td>
<td>0.032</td>
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Table 3.1.2 Sensor specifications summary

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Operating Frequency Range (kHz)</th>
<th>Peak Frequency (kHz)</th>
</tr>
</thead>
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<tr>
<td>D</td>
<td>20-175</td>
<td>160</td>
</tr>
<tr>
<td>1 and 6</td>
<td>70-200</td>
<td>153</td>
</tr>
<tr>
<td>2</td>
<td>125-750</td>
<td>300</td>
</tr>
<tr>
<td>3 and 5</td>
<td>40-100</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>20-1000</td>
<td>500</td>
</tr>
</tbody>
</table>

Observing the amplitude values for sensors 1 and 6, a 19 dB difference in amplitude over a distance of 301 mm is seen. This yields an attenuation of 0.63 dB/cm. The waveforms for the other sensors differ enough that a simple amplitude measurement for the attenuation does not make any sense. Table 3.1.3 shows the maximum amplitude frequency components for the six sensors investigated.
Table 3.1.3: Maximum amplitude frequency components of the sensors investigated

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Maximum Amplitude Frequency (kHz)</th>
</tr>
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<tbody>
<tr>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 3.1.3 summarizes the maximum amplitude frequency components of the waveforms shown in Figures 3.1.2 through 3.1.7. It can be seen from Table 3.1.3 that sensor 4 has its maximum frequency component at 10 kHz, which is in the audible range. This makes sensor 4 unsuitable for acoustic emission testing of FRP vessels, since low frequencies are susceptible to background noise contamination. Sensor 2 signals have their maximum amplitude frequency components at 100 kHz. This is a reasonable value; however, the peak signal amplitudes from the sensors on both sides of sensor 2 (sensors 5 and 6) are much higher, that is, sensor 2 possesses an unacceptably high value of wave attenuation. The attenuation measured for the 60 kHz (3 and 5) and 150 kHz (1 and 6) sensors are comparable. A look at the maximum amplitude frequency components for sensors 3 and 5 shows a shift downwards from 95 kHz to 20 kHz. This undesirable behavior is certainly not seen in the case of the 150 kHz resonant frequency sensors (1 and 6). It can be seen that (Figures 3.1.2 and 3.1.3) the maximum amplitude frequency components for sensors 1 and 6 are in the same range (150 and 145 kHz).
Figure 3.1.2 Waveform in the time (a) and frequency (b) domain for sensor number 1

Figure 3.1.3 Waveform in the time (a) and frequency (b) domain for sensor number 6
Figure 3.14 Waveform in the time (a) and frequency (b) domain for sensor number 3

Figure 3.15 Waveform in the time (a) and frequency (b) domain for sensor number 5
Figure 3.1.6 Waveform in the time (a) and frequency (b) domain for sensor number 2

Figure 3.1.7 Waveform in the time (a) and frequency (b) domain for sensor number 4
Figures 3.1.2 through 3.1.7 show huge effects on the apparent waveform with the type of detecting sensor used and the bandwidth of the preamplifier. The same signal detected by two different sensors situated reasonably close to each other can have an apparent signal duration that varies from 0.3 milliseconds to over 70 milliseconds. Thus, the choice of a sensor to be used in the tests was a trade off between very high attenuation at the high frequency end to extremely long duration signals. The long signals have considerable superposition leading to almost continuous emission signals, which necessitates very low data rates. The best trade off is provided by the 150 kHz resonant frequency sensor.

3.2 EFFECT OF PRESSURE ON ACOUSTIC PROPERTIES

To examine the effect of pressure on the acoustic properties of the cylinders, the waveform and frequency spectrum for each sensor in Figure 3.1.1(a) were analyzed at both 0 and 100 psi. Careful examination showed no significant differences between waveforms at the different internal pressures. Thus, the liner appears to be well bonded to the composite layer in these bottles, and there should be no change in the wave propagation in the bottle as a function of pressure until extensive damage in the composite has occurred.

3.3 WAVE VELOCITY AND ATTENUATION MEASUREMENTS

Acoustic wave velocity measurements were made by mounting two 150 kHz resonant frequency sensors approximately 10 inches from each other. Measurements were made at alpha values of 0, 22.5, 45, 67.5, and 90 degrees to the cylinder longitudinal
axis. In this case, alpha is the angle between the acoustic path and the cylinder longitudinal axis, in radians.

The results of the velocity measurements are shown in Figure 3.3.1. The values measured varied from 4.4 mm/microsecond along the cylinder longitudinal axis to 6.0 mm/microsecond perpendicular to the axis. A numerical regression was used to fit to the data as shown in Figure 3.3.1. Attenuation was also measured by plotting peak amplitudes of the sound waves as a function of distance from the sensor. The attenuation from top to bottom was 0.55 dB/cm. It was also noted that attenuation from the bottom of the cylinder to the top was 40% higher than from top to bottom. This difference is due to the way the cylinders are manufactured.

\[ V = 4.40 + (e^{0.3407\alpha^2} - 1) \]

**Figure 3.3.1 Wave velocity as a function of angle alpha**
4.1 BACKGROUND

The location of acoustic emission sources, by calculation from signal arrival times at multiple sensors on a specimen, is a well-established technology for metallic structures. Composite structures present a more difficult problem. The three main deviations from properties of a metallic structure are a much higher acoustic attenuation, anisotropic acoustic velocities, and small-scale inhomogeneties in the materials.

The high acoustic attenuation produces a rapid decrease in signal amplitude with distance, which can result in the triggering circuitry of the acoustic emission system firing at different points on the acoustic waveform detected at different sensors. This is especially true when the signal peak amplitude at a sensor is near the trigger threshold setting. The result is that the measured transit time of a signal from source to detector may be longer than the actual transit time. When such measurements are incorporated in a source location calculation using the minimum required number of sensors, the calculated locations can be off by inches.

Anisotropic acoustic velocities result in measured transit times that vary as a function of the acoustic path between the source and the sensors and an axis of the structure. The degree of anisotropy will vary with the number of layers and the lay-up pattern of the composite. The errors in the calculated locations produced by an anisotropic velocity are not as large as the errors produced by high attenuation, but they can produce significant distortions in the apparent AE source position on a structure.
Small-scale inhomogeneities in the composite (and on its surface) distort the acoustic wave as it propagates from its source. The propagating waveform will vary as a function of angle. However, unlike the anisotropic acoustic velocity, the angular variation will differ for every microscopic point in the structure. This applies not only to real signals produced by flaws, but also to injected signals for calibration purposes. A series of lead breaks with the lead tip always in the same small spot can produce relatively large location errors on some composite cylinders. Even a signal-injecting sensor can produce noticeably different waveforms if it is moved slightly. The magnitude of the errors will depend upon the details of the structure. A coarse fiber, or a coarse or variable winding pattern on the surface, seems to produce the largest errors. Variations as large as \( \pm 20\% \) on a 15 microsecond difference in the time of arrival have been observed in lead break data.

4.2 INTRODUCTION

Both the methods of linear and planar location are currently used for determining the position of simulated and real sources using acoustic emission. The use of linear location for source position determination on a cylindrical structure, such as the pressure vessel, might introduce errors in locating the source. These types of errors occur in any type of material and can be caused by two main factors:

1. An AE source does not produce a single wave type, but several of them, each traveling with a particular velocity and attenuation. Therefore, depending on the position of the source in relation to each of the sensors, different wave modes will trigger different sensors.
2. When a source is located off the line along which the sensors are mounted, the arrival
times of the signal produced in an event will define a family of hyperbolae with the
foci located on the sensors. Thus, the position of the source could be at any point
along the hyperbola on which the source is located.

The effects of different wave modes arriving with different velocities at different
sensors cannot be avoided. However, using a large enough number of sensors on the
bottle can reduce such effects. The latter effect (factor 2 above) can normally be avoided
by using planar location instead of the linear location method. The problem with linear
location is that it only gives location positions in one dimension, which is acceptable for
very long, slender structures, but not when the aspect ratio is on the order of 1. This is the
case for these FRP cylinders, which have a circumference of 31 inches and a length of
29.2 inches.

A location program developed by Dr. Alan Beattie (PAC, Albuquerque, NM) for
a previous project involving steel airline halon bottles and oxygen cylinders was modified
and applied to the composite cylinders. This program was modified to take into account
earlier findings that the wave velocity is a function of direction. An anisotropic velocity
formula was built into the location program so that location accuracy was improved. The
difference between this method and the common source location techniques is that it first
uses different velocities to determine the location of the acoustic source, while the other
approaches use only a single previously determined velocity value fed into the program
manually.
4.3 EXPERIMENTAL SETUP

The experimental source location set-up consisted of six sensors (three sensors on two different rings) on the cylinder surface. The sensors were spaced on each ring at 0°, 120° and 240° from an arbitrary reference line drawn on the cylinder surface, parallel to the cylinder axis. The edge of each sensor was touching the transition line between the cylindrical section and the end cap on each end. All locations on the cylinder are defined in a spherical coordinate system (Figure 4.1(b)). The angle \( \theta \) is the angle between the axis of the cylinder and the vector from the center of the cylinder to the point on the surface. \( \theta = 0.0 \) for the vector going to the top of the cylinder and \( \theta = \pi \) for the vector to the bottom. The angle \( \phi \) goes from 0.0 to 2.0 \( \pi \) starting from the reference line. The length of the vector is variable and defined so that each point is on the surface of the bottle.

![Figure 4.1(a) Approximate positions of sensors along the circumference of the cylinder.](image)

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Data were generated either by pencil lead breaks at various points on the surface of the cylinder or by coupling a piezoelectric sensor to various points on the surface and driving it by a square wave. An acoustic signal is generated each time the wave reverses polarity. A calibrated attenuator allowed precise control of the acoustic amplitude. Waveform data showed very good repeatability of the acoustic signal as long as the coupling between the sensor and cylinder was not disturbed.

4.4 LOCATION PROGRAM

The location program was originally developed for steel airline oxygen cylinders and was modified for use in these cylinders. It calculates the most probable location of an emission source on the cylinder by using an over-determined data set from six sensors. Only three arrival times from three sensors are needed to calculate the location of an event on a surface, but if one of these times is not completely accurate, the location calculation can give highly erroneous answers. The program uses a nonlinear least squares fitting routine to calculate the location. The only approximation in the program is
the assumption that the end caps are hemispherical. Errors due to this assumption are small. Spherical geometry is used, and a numerical subroutine calculates the distances between any two points on the cylinder. Errors in the distance calculation arise mostly from small deviations of the composite cylinder from a cylindrical center section and hemispherical end caps and not from the numerical calculation. These errors are generally small compared to the errors in the arrival time measurements. The output is a file containing the calculated theta and phi coordinates and the occurrence time of the event.

The location program reads a Physical Acoustics Corporation MISTRAS or DiSP data file and calculates the delta time for each sensor (the difference between the arrival time at a sensor and the arrival time at the first sensor excited by the event). The program then calculates the most probable location using the delta times from all sensors hit. By using an over-determined data set from six sensors, the effect of one bad measurement is minimized, and the calculated location, while not exact, will generally be in the near proximity of the actual source. The program uses the anisotropic velocity formula that was given in Chapter 3. The program also calculates an estimate of the goodness of fit. The use of the anisotropic velocity formula increased the coefficient of determination ($R^2$) from about 90% to 99%.

4.5 EXPERIMENTAL RESULTS

Three different source location experiments were conducted. In the first, a sensor was bonded to the cylinder with hotmelt glue and excited with a square wave. The square wave could be attenuated. For zero attenuation, the signal amplitude was 79 dB at the nearest sensor and 58 dB at the farthest. For 20 dB of attenuation, the signal amplitudes
were 59 and 37 dB. As the attenuation increased, the delta time at the farthest sensor also increased. This time was 96 microseconds for 0 dB attenuation of the drive signal, 119 microseconds for 10 dB attenuation, and 126 microseconds at 20 dB attenuation. For 30 dB attenuation, the amplitude at the nearest sensor was 49 dB as expected, but with a 30 dB threshold, the farthest sensor did not detect a signal, and the delta time of the next farthest sensor showed a value of 60 microseconds more than that sensor had measured with the 20 dB attenuated signal. Figure 4.5.1 shows the plotted results for this set of experiments. These location graphs are projections of the curved cylinder surfaces onto a flat surface with a resulting shrinking of the apparent distance between points near the edges of the projection. In Figure 4.5.1, it can be seen that the delta time increases with attenuation, placing the source further from its actual location. It is also seen that even the 0 dB data is not located precisely at the measured location: there is a displacement of about 15 millimeters. This may be caused by local variations in the acoustic velocity, a possibility that cannot be measured on these cylinders. Figure 4.5.1 does show that for the same waveform, the source location program is quite consistent. It also shows that there is a minor effect due to the polarity of the signal. Whether the first cycle is positive or negative appears to be detectable in this data.

The second experiment consisted of five lead breaks at one point on the cylinder. Care was taken that each lead break was at the same point on the cylinder. However, the angle of the pencil with respect to the cylinder axis was varied. These data are shown in Figure 4.5.2 where there is a larger spread than in Figure 4.5.1. The maximum distance between two locations is approximately 25 mm. This is consistent with earlier findings
showed that it is very difficult to generate identical signals with lead breaks on these cylinders.

The third experiment consisted of breaking pencil lead every 20 mm on a straight line drawn on the cylinder surface parallel to the cylinder axis from about the middle of the cylinder to the center of the bottom end cap. As can be seen in Figure 4.5.3, there are noticeable deviations from the straight line. These deviations appear to follow a pattern, which again suggests local variations in the acoustic velocity.
Figure 4.5.1 Plotted results of square wave pulser source location on the cylinder with varying attenuation
Figure 4.5.2 Plotted results of PLB location on the cylinder. Angle of pencil with respect to the cylinder axis varies.
source - 0.3 mm Pentel pencil lead breaks

location of signals - lead breaks every 2 cm on a straight line parallel to axis drawn from middle of cylinder to bottom of cylinder.

Figure 4.5.3 Plotted PLB source location on the cylinder. Leads were broken every 20 mm on a straight line parallel to the cylinder axis.
CHAPTER 5

AE TESTING OF CYLINDERS - PHASE I

5.1 TEST SETUP

Several acoustic emission tests were conducted in this phase of the research. A Physical Acoustics Corporation 24-Channel DiSP system was used for data acquisition in all the testing. The testing procedure used is the one proposed by the draft ASTM standard E070403-95/1. Two PAC resonant frequency piezoelectric transducers were used to monitor each of the cylinders during AE tests. Parametric input from a pressure transducer was fed into the AE system for the instantaneous recording of pressure and acoustic emission with time. The AE sensors were attached to the vessels by duct tape. Vacuum grease was used as a couplant in all sensor mountings. A study of the coupling efficiency of several couplants resulted in vacuum grease being the couplant of choice.

The pressurization schedule was selected so that it was in accordance with the slow-fill pressurization schedule of the proposed ASTM standard E070403-95/1. According to this procedure (Figure 5.1), acoustic emission data are recorded from the end of the first hold period to the end of the test with no intermediate hold periods. Acoustic emission hits with amplitudes 40 dB or higher were recorded in each test and saved for later analysis. During AE testing, the cylinders were pressurized to 3300 psi, which represents 110 % of the operating pressure.
5.2 THE FLOW-NOISE PROBLEM

Pressurization of the cylinders during AE testing was accomplished either by a 25 CFM compressor or from already pressurized flasks of much greater volume that the ones under investigation. During the testing of the cylinders, it was observed that flow noise was dominant when the pressure difference between the test bottles and the pressure-applying bottles was significant. The flow noise was especially dominant in AE activity when the test bottles were empty. Flow noise will cause problems when interpreting acoustic emission data. Thus, it was important to remove this noise from the data before any meaningful data analysis could be done. To accomplish this, a pattern recognition
and neural network program "NOESIS", (developed by Physical Acoustics Corporation), was used. A noise filter was built based on a principal component analysis (PCA). In this analysis, AE data were chosen from a few of the tests and projected along eigenvectors 0 and 2 as shown in Figure 5.2.1.

Figure 5.2.1 Principal Component Analysis plot

Figure 5.2.1 is a plot of PCA axes with the maximum variance of the data. Analysis of the waveforms associated with the AE hits was done in order to determine the part of the PCA plot that represents flow noise. A neural network was then trained using the PCA so that it could recognize and filter out flow noise from new data in the future. After the classifier was developed, the filter was applied to data from the other AE tests. Figure 5.2.2 shows some of the results obtained using the classifier. This classifier can be implemented in real time to filter off flow noise during AE testing.
5.3 CYCLING OF CYLINDERS

Three cylinders were chosen at the beginning of the research to undergo pneumatic cycling in order to simulate service life over a long period of time. Three AE tests were performed on the three cylinders at this stage in the research. The three cylinders (A, B, and C) were subjected to pressurization and depressurization cycles, a cycling history of which is summarized in Table 5.3.1.

**Table 5.3.1 Summary of the cycling status and AE tests**

<table>
<thead>
<tr>
<th>Test #</th>
<th>Date</th>
<th>Total Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22 Feb 01</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>4 May 01</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>10 Aug 01</td>
<td>62</td>
</tr>
</tbody>
</table>
5.3.1 DATA ANALYSIS

The AE data collected in the three test sets were analyzed using NOESIS. As explained in section 5.2, a flow-noise filter was developed to process AE data acquired during the first two tests. In Test 3, the data did not contain hits due to flow noise since an air compressor was used for pressurization rather than filling from the big bottles.

Figure 5.3.1.1 represents the AE activity of the three bottles during the different tests by plotting the cumulative AE counts vs. time of test. It is clear from Figure 5.3.1.1 that the three bottles generated different AE activity levels during each of the tests. Comparing curve (a) in the three subplots, corresponding to A, B, and C in the new (as received) condition, respectively, one finds that C had about an order of a magnitude higher total cumulative counts than the other two bottles. Since the three bottles were essentially in the same condition, deviations in the manufacturing of the vessels are suggested as a possible explanation for the differences. A further comparison between plots (a) and plots (c) for the three cylinders in Figure 5.3.1.1 shows more cumulative AE counts after 15 cycles (plots (c)). This is attributable to the "characteristic damage", discussed in Chapter 2, Section 2.1. It can also be seen from Figure 5.3.1.1 that when the cylinders were tested after 62 cycles, they showed more AE activity than they did at 15 cycles. It is important, however, to mention that no conclusions can be drawn at this point. Further testing would be required to confirm any trends.
Figure 5.3.1.1 Cumulative counts vs. time for all three tests and cylinders (a = new), (b = 15 cycles), and (c = 62 cycles)
5.4 IMPACT DAMAGE OF CYLINDERS

Cylinder D was the first bottle to be subjected to impact forces. A pendulum style impactor was constructed and used to produce controlled impact damage. The system consisted of a long slender aluminum beam as the pendulum arm with a mass attached to the beam. Damage was induced by a 0.59-inch diameter blunt tip impactor with an energy of 34 N-m. It was expected that the blunt impactor would produce a wide damaged zone with some localized delaminations.

AE tests after the cylinder was impacted showed that the cumulative AE counts increased from 1900 before impact to 4500 after impact. While there was an increase in AE activity, analysis of the waveforms from the post damage data showed that the cylinder might have only suffered very minor damage. Furthermore, an acousto-ultrasonic inspection of the impacted region did not show any evidence of structural damage.

5.4.1 FURTHER DAMAGE OF CYLINDERS

To damage cylinder F, the cylinder was placed in the compression test-section of an Instron machine at Physical Acoustics Corporation. Two sensors were mounted on the cylinder 12 inches from each other in the longitudinal direction, each being 6 inches from the mid-hoop point. A 0.55 inch diameter rounded-end hemispherical impactor was attached to the Instron to be used for producing the damage. The two sensors were then connected to the DiSP system to monitor AE during compression of the bottle. Monitoring AE in real time during compression was important because the idea was to stop the test at a point where significant damage had been done to the composite wrap.
A parametric input was also connected and the system calibrated such that the compressive force applied by the impactor was then lowered onto the top of the bottle at a speed of 0.05 inches per minute. AE activity was monitored during compressive loading, and the experiment was stopped as soon as there was evidence that the cylinder was actually damaged. That determination was made based on the presence of the "knee in the curve", which is a characteristic of damaged composites [Fultineer and Mitchell]. A graph of cumulative AE counts versus the compression load for damage production is shown in Figure 5.4.1.1. Notice that the knee in the curve occurs at approximately 1650 lbf.

Figure 5.4.1.1 Cumulative counts vs. compression force during damage of F
Since it was concluded earlier that the 34 N-m energy impact by means of a pendulum style impactor did not cause any significant structural damage to cylinder D, it was subjected to further damage. This time cylinder D was dropped from a height of 12 feet onto the aft dome on a concrete surface.

The two damaged bottles (D and F) were then instrumented, together with three other undamaged cylinders, for AE testing while being pneumatically pressurized. Figure 5.4.1.2 shows graphs of cumulative counts versus pressure for all five bottles. From Figure 5.4.1.2, it can be seen that the graph for Channels 11 and 12, which is the bottle (D) that was damaged by dropping it onto the aft dome from a height of 12 feet, shows considerably more AE counts than the rest of the bottles. While the counts for Channels 17 and 18 (F) are more than for the undamaged cylinders, one can argue that the difference is not sufficient to prove that the bottle is really damaged without any other information. In light of the high acoustic emission activity exhibited by cylinder D, this cylinder was considered to be the best candidate of the two damaged bottles for a burst test.

For the burst test, cylinder D was instrumented with two sensors and two 40 dB pre-amplifiers. The bottle was then filled with water and placed in a pressurization chamber. Pressure was applied up to 1000 psi and held for 5 minutes in order to ensure that there were no leaks. A test plan was then designed using the different pressure values for these cylinders, which are as follows:

- Normal Service Pressure > 3000 psi
- Maximum Service Pressure > 3295 psi
- Maximum Hydrotest Pressure > 5492 psi
Figure 5.4.1.2 Cumulative counts vs. pressure. Channels 5-10 are for the undamaged bottles, channels 11 and 12 are for D, while channels 17 and 18 are for F.
To start the test, the cylinder was pressurized from 2000 psi to 3000 psi (Normal Service Pressure) followed by a five minute load hold. Next, pressure was increased to 110% of the Maximum Service Pressure (3625 psi), followed by yet another five-minute load hold. Then the load was increased to 110% of the Maximum Hydrotest Pressure (6041 psi) with a five-minute load hold. The cylinder was then loaded until it burst at 12,032 psi. Figure 5.4.1.2 shows a graph of cumulative counts as a function of pressure during the burst test.

Figure 5.4.1.3: Cumulative counts vs. pressure for D during the burst test
The "knee in the curve", which is a characteristic of damaged composites [Fultineer and Mitchell], is seen at about 6000 psi in Figure 5.4.1.3. Also noteworthy is the fact that the burst pressure of 12,032 psi for this cylinder is over the minimum expected burst pressure of 11,203 psi by 829 psi. It is clear that cylinder D was damaged enough to cause failure at a location where a good cylinder would not fail (dome). However, the damage was still not enough to make the cylinder burst below the minimum acceptance pressure.

After damaging D and F and subsequently subjecting D to a burst test, the following conclusions were drawn:

1) A cylinder damaged by dropping from 12 feet onto the aft dome produces at least four times as many AE counts as the one subjected to a compressive force of 1900 lbf using a 0.55 inches diameter impactor.

2) Impact damage to a cylinder by dropping from a height of 12 feet onto the dome caused the cylinder to fail in the dome region during a burst test.

3) However, the damage sustained by D was not enough to cause the bottle to burst below the minimum acceptance pressure during burst tests. Future work will include further damage to F followed by a burst test.

5.5 INTERNAL LINER CORROSION

Internal corrosion of the metal liner is one of the types of damages that can disrupt the normal service life of a pressure vessel. In order to understand the significance of the damage that chemical corrosion has on the performance of the FRP cylinders, a controlled chemical corrosion was performed on cylinder E. Controlled chemical
corrosion was achieved with a saturated salt solution. The solution was left in the FRP cylinder for 40 hours before it was removed and rinsed. Photos of the aluminum liner were taken before and after the chemical corrosion. A comparison between those photos showed that the aluminum liner had suffered at least minor corrosion.

After analyzing AE data from a corroded cylinder, the following observations were made:

- The corroded FRP cylinder generated more AE activity after it was corroded than it did before it was corroded.
- The frequency spectrum of AE signals from the corroded cylinder displayed slightly higher frequency components than it did before the corrosion.
- This study was limited to only one cylinder, but the results indicate that using AE to classify corrosion is feasible.
- Further research should focus on characterizing AE data from cylinders with corroded liners and the determination of accept/reject criteria.
CHAPTER 6

AE TESTING OF CYLINDERS - PHASE II

6.1 OVERVIEW

This phase of the research was designed to build on the findings of the previous phase. A total of eight cylinders were used for AE testing in this phase, and some questions that the previous testing phase did not cover are addressed here. First is the question of whether low-cycle fatigue initiates flaws in good cylinders. This was answered through monitoring the cylinders with acoustic emission before, during, and after fatigue cycling and comparing the data. The significance of this finding is that, if fatigue does not initiate flaws in the cylinders, then periodic AE testing is needed primarily to detect externally inflicted damage to the cylinders and/or corrosion of the liner.

Another aim of the test plan was to determine whether low cycle fatigue produces growth in damage that was induced before application of the cyclic pressure. To accomplish this, six of the eight cylinders were subjected to external damage, pressurized to 8000 psi while being monitored with AE, cycled for 780 cycles, and then pressurized again to 8000 psi. If low cycle fatigue produces growth of such flaws, the program was also aimed at determining the number of cycles necessary to increase the severity of the worst flaw to the point where it would show significant emission in a single loading to 1.5 x MEOP (Maximum Expected Operating Pressure). It was expected that the results of this test would allow for an intelligent determination of the interval between tests.
Finally, the determination of accept/reject criteria will be made by analyzing the acoustic emission profile with increasing pressure to the point where AE activity evidences significant growth in each of the cylinders.

6.2 TEST PROGRAM

This program employs six sensors per bottle and uses source location of acoustic emission bursts in order to determine whether the bursts are occurring in small clusters or randomly over the cylinder. Clusters are a definite indication of damage, and their rate of growth as a function of load defines the severity of the damage. In low numbers, randomly located emissions do not indicate structural problems. A damage onset pressure can be defined as a pressure where a cluster reaches a certain number of located events. Previous research has determined this number to be about 20 events in all-metal spheres [Beattie]; therefore, this is the number that will be used herein to indicate the onset of damage.

The testing program used a total of eight bottles, identified with letters the F through M. Two of the bottles (K and M) were in new condition. Three bottles (H, I, and L) were damaged on the bottom hemisphere by dropping from a height of 15 feet onto a concrete surface. The last three cylinders (F, G and J) were indented by an Instron machine in the upper half of the cylindrical section. Acousto-ultrasonic inspection of the Instron damaged cylinders was performed, and the results indicated that the bottles were indeed damaged. Table 6.11 presents a summary of the initial state of the bottles.
Table 6.1.1 Damage type induced in the cylinders

<table>
<thead>
<tr>
<th>Cylinder ID</th>
<th>Damage Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Instron Pressing</td>
</tr>
<tr>
<td>G</td>
<td>Instron Pressing</td>
</tr>
<tr>
<td>H</td>
<td>15 ft. Drop</td>
</tr>
<tr>
<td>I</td>
<td>15 ft Drop</td>
</tr>
<tr>
<td>J</td>
<td>Instron Pressing</td>
</tr>
<tr>
<td>K</td>
<td>----</td>
</tr>
<tr>
<td>L</td>
<td>15 ft Drop</td>
</tr>
<tr>
<td>M</td>
<td>----</td>
</tr>
</tbody>
</table>

After damage was induced on the cylinders, they were subjected to five tests. In all five tests, the cylinders were monitored with AE while being pressurized. Test 1 consisted of pressurizing the bottles to a pneumatic proof loading of 3300 psi. Test 2 involved pressurizing each cylinder to 8000 psi while monitoring it with the source location program. In Test 3, the cylinders were subjected to cyclic loading between 1000 psi and 3000 psi for a total of 780 cycles. Seven hundred eighty cycles represents the current lifetime of the cylinders at an average cycling rate of one cycle per week. After fatigue cycling, the cylinders were again subjected to the 3300 psi pneumatic pressurization test (Test 4), followed by another set of 8000 psi tests (Test 5). The rest of this chapter presents and discusses the results of these tests.

6.3 RESULTS

6.3.1 PRESSURIZATION TO 3300 PSI

The bottles were first subjected to pneumatic pressurization up to 3300 psi in accordance with the procedure outlined in Chapter 5. Acoustic emission results from the
test are shown in the form of cumulative AE counts versus time of test in Figure 6.3.1. Figure 6.3.2 shows the results of a similar test done after the cylinders had each undergone a high pressure hydrostatic pressurization followed by the cycling procedure. The results of the two tests are also summarized in Table 6.3.1 including those from an earlier test that included the two control (undamaged) bottles.

From Figure 6.3.1, 6.3.2, and Table 6.3.1, it can be seen that, while the damaged cylinders consistently give more emissions than the undamaged ones, the second pneumatic test showed the cylinders to be very quiet. This phenomenon was certainly not expected, and appears to be a result of the hydrostatic proof load of 8000 psi that the cylinders were subjected to before the second set of high pressure tests.

![Figure 6.3.1 Cumulative AE counts vs. time (seconds) for the damaged bottles (before pressurization to 8000 psi & cyclic loading)](image)

Figure 6.3.1 Cumulative AE counts vs. time (seconds) for the damaged bottles (before pressurization to 8000 psi & cyclic loading)
Figure 6.3.2 Cumulative counts vs. pressure after the first high pressure test and cyclic loading (test pressure is 3300 psi)

Table 6.3.1 AE activity of the eight test cylinders (test pressure is 3300 psi)

<table>
<thead>
<tr>
<th>Cylinder ID</th>
<th>Cumulative Counts (8000 psi and cycling)</th>
<th>Cumulative Counts (after 8000 psi and cycling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>111,669</td>
<td>253</td>
</tr>
<tr>
<td>G</td>
<td>118,005</td>
<td>1773</td>
</tr>
<tr>
<td>H</td>
<td>25,739</td>
<td>388</td>
</tr>
<tr>
<td>I</td>
<td>18,611</td>
<td>5,402</td>
</tr>
<tr>
<td>J</td>
<td>40,787</td>
<td>793</td>
</tr>
<tr>
<td>K</td>
<td>508</td>
<td>101</td>
</tr>
<tr>
<td>L</td>
<td>16,631</td>
<td>320</td>
</tr>
<tr>
<td>M</td>
<td>1,286</td>
<td>202</td>
</tr>
</tbody>
</table>

The hypothesis that damage would be grown by the 780 pressure cycles and that the cylinders would recover from the 8000 psi loading during cycling did not hold true, and this imposed a limitation in evaluating the data for the 3300 psi load pneumatic tests. It was therefore not possible to determine accept/reject criteria with a proof load of 3300 psi.
6.3.2 HIGH-PRESSURE TESTS TO 8000 PSI

The bottles were instrumented with six sensors, as was done for source location (Chapter 4) and were individually hydrostatically pressurized with AE monitoring to identify the pressure where damage can first be detected using event clustering. The procedure was to pressurize each of the eight bottles to 8000 psi while monitoring with the source location system. The expected result was for the undamaged bottles to go the full 8000 psi without developing an acoustically active cluster, while the damaged bottles would develop a cluster somewhere between 6000 and 8000 psi. The pressure of 8000 psi was decided upon after analyzing AE data from the burst test of cylinder D in Phase I of this research.

After the cylinders were pressure-cycled for a total of 780 cycles, each cylinder was tested again using the same procedure. It was expected that there would be a decrease in damage initiation pressure for the damaged bottles, and that analysis of the data would enable the determination of a test pressure and accept/reject criteria for monitoring with two sensors. The results from the two sets of high pressure tests are summarized in Tables 6.3.2 and 6.3.3.
As expected, the undamaged cylinders reached 8000 psi without a detected cluster in the first set of high pressure tests. While cylinder J showed a cluster around the damaged point, the final number of events in the cluster were less than 10. Table 6.3.3 gives the results of the second set of high pressure tests.

**Table 6.3.3 Results from the second set of high pressure tests to 8000 psi**

<table>
<thead>
<tr>
<th>Cylinder ID</th>
<th>Final Pressure (psi)</th>
<th>Total Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>8000</td>
<td>10</td>
</tr>
<tr>
<td>G</td>
<td>8000</td>
<td>36</td>
</tr>
<tr>
<td>H</td>
<td>8000</td>
<td>50</td>
</tr>
<tr>
<td>I</td>
<td>7111</td>
<td>25</td>
</tr>
<tr>
<td>J</td>
<td>8000</td>
<td>4</td>
</tr>
<tr>
<td>K</td>
<td>8000</td>
<td>45</td>
</tr>
<tr>
<td>L</td>
<td>8000</td>
<td>38</td>
</tr>
<tr>
<td>M</td>
<td>8000</td>
<td>71</td>
</tr>
</tbody>
</table>

The initial high pressure tests showed clusters in the damaged areas. During the second set of high-pressure tests, no clusters were formed in any of the damaged cylinders. The events that were located were randomly spread throughout the whole
surface of the cylinder for all tests except cylinder I. In the case of I, all but two events were in the aft dome, but not close enough to be in one cluster. This observation is an indication of the ability of these bottles to re-distribute loads when they are damaged.

Two sensors were used on each cylinder for further analysis of the data acquired during the high pressure tests. The analysis entailed comparing acoustic emission activity at 4500 psi (1.5 X MEOP) for the two high pressure tests. Examining AE activity while loading a structure to 150% of the maximum load it experiences in normal operation is a common practice in acoustic emission testing. The comparison of these data is presented in Table 6.3.4. Except for one outlier (cylinder F), damaged cylinders generated more than 10,000 AE counts in both tests, while the undamaged cylinders had counts of less than 10,000.

**Table 6.3.4 Cumulative AE counts at 4500 psi for the two high pressure tests**

<table>
<thead>
<tr>
<th>Cylinder ID</th>
<th>Before Cycling</th>
<th>After Cycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>19,510</td>
<td>3,082</td>
</tr>
<tr>
<td>G</td>
<td>17,027</td>
<td>16,486</td>
</tr>
<tr>
<td>H</td>
<td>56,325</td>
<td>15,540</td>
</tr>
<tr>
<td>I</td>
<td>49,043</td>
<td>-----</td>
</tr>
<tr>
<td>J</td>
<td>14,939</td>
<td>15,135</td>
</tr>
<tr>
<td>K</td>
<td>638</td>
<td>3,260</td>
</tr>
<tr>
<td>L</td>
<td>12,516</td>
<td>21,125</td>
</tr>
<tr>
<td>M</td>
<td>8,197</td>
<td>6,117</td>
</tr>
</tbody>
</table>
6.3.3 PRESSURE CYCLING

In between the two high pressure tests, the cylinders were hydrostatically cycled between 1000 psi and 3000 psi for a total of 780 cycles. This procedure simulates normal use of the cylinders over a 15 year lifetime. Acoustic emissions from cylinders G, K, and L, which represent one Instron damaged cylinder, an undamaged cylinder, and one dropped cylinder, were recorded during portions of the cycling. The object of this test was to try to determine how fast a flawed cylinder degrades under normal cyclic usage and to compare the results with those from an undamaged cylinder. In order to understand AE response with increasing number of cycles, data were taken in four stages as summarized in Table 6.3.5. Stage I represents the first 28 cycles, Stage II represents cycles 227 to 308, Stage III is for cycles 539 to 618, and Stage IV is for cycles 681 to 780.

Table 6.3.5 AE counts per cycle during cyclic loading

<table>
<thead>
<tr>
<th>Cylinder ID</th>
<th>Stage I (0 - 28 cycles)</th>
<th>Stage II (227 - 308 cycles)</th>
<th>Stage III (539 - 618 cycles)</th>
<th>Stage IV (681 - 780 cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>240</td>
<td>622</td>
<td>1911</td>
<td>4022</td>
</tr>
<tr>
<td>K</td>
<td>2738</td>
<td>2669</td>
<td>672</td>
<td>263</td>
</tr>
<tr>
<td>L</td>
<td>165</td>
<td>541</td>
<td>1141</td>
<td>195</td>
</tr>
</tbody>
</table>

It can be seen from Table 6.3.5 that the number of AE counts per cycle for the undamaged cylinder (K) decreases with the number of cycles, whereas the number of counts per cycle for the cylinder damaged by a compressive force on the Instron (G) increases with the number of cycles. For the cylinder damaged by dropping from 12 feet (L), the number of counts per cycle initially rises and then drops as 780 cycles is approached. However, the counts per cycle value in Stage IV is still greater than the
initial value. In summary, damaged cylinders are evidenced by increasing count rates with increased loading, whereas undamaged cylinders display decreasing count rates with increasing loading.
CHAPTER 7.0
CONCLUSIONS & RECOMMENDATIONS

7.1 CONCLUSIONS

- The acoustic emission nondestructive testing method proposed by the ASTM standard E070403-95/1 was successfully employed for AE testing of Type 3 filament-wound graphite/epoxy FRP vessels.

- An accept/reject criterion of 10,000 AE counts has been determined for AE testing with a proof pressure of 4500 psi (136% of the design pressure).

- A proof pressure of 3300 psi did not provide sufficient AE data to enable the determination of an accept/reject criterion. The 8000 psi tests adversely affected the chances of determining failure criteria at 3300 psi.

- Damaged cylinders are evidenced by increasing count rates with increased cyclic loading, whereas undamaged cylinders display decreasing count rates with increased cyclic loading.

- These cylinders are very over-designed, and have shown evidence of extensive load distribution when damaged. Damage sites that were very acoustically active during AE tests at proof loads of 8000 psi were very quiet when a similar test was done after they had undergone 780 cyclic loads between 1000 and 3000 psi.

- A noise classifier has been developed and was successfully used to remove flow noise from AE data. The classifier can be modified for implementation in the AE data acquisition program so that noise filtering is accomplished in real time.

- The frequency spectrum of AE signals from the corroded cylinder displayed slightly higher frequency components than it did before the corrosion. Although the study was
limited to only one cylinder, the results indicate that using AE to classify corrosion is feasible.

- A source location procedure using the anisotropic velocity formula has been developed. This technique increased the location coefficient of determination \( R^2 \) from about 90% to 99%.

7.2 RECOMMENDATIONS

- Since pressurization of the cylinders to 4500 psi was accomplished hydrostatically, the next step should be to verify the results with pneumatic pressurization at 4500 psi. In line with this recommendation, there is need for further research to determine if accept/reject criteria can be established with proof loads lower than 4500 psi.

- The first stressing of these cylinders (after factory acceptance testing) generated a lot of activity. For successful in service testing of a cylinder using acoustic emission, the cylinder should have already had a first stressing so as to allow for the formation of the "characteristic damage".

- Further corrosion should be done to the internal liner of cylinder E in order to study the acoustic characteristics of a corroded cylinder. The research should focus on characterizing AE data from cylinders with corroded liners and the determination of accept/reject criteria.
REFERENCES


