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Composite Structure Ultimate Strength Prediction from Acoustic Emission Amplitude Data

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COMPOSITE STRUCTURE ULTIMATE STRENGTH PREDICTION FROM ACOUSTIC EMISSION AMPLITUDE DATA

by

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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 School of Graduate Studies and Research and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

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ABSTRACT

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The acoustic emission (AE) given off by a structure as it is stressed provides a passive means to characterize flaw growth activity in complex structures. This thesis demonstrates how the qualitative analysis of AE data can be refined to provide a quantitative tool for predicting the ultimate strength of composite tensile test specimens. From an original sample set of only six specimens, a multivariate statistical analysis was used to generate an ultimate strength prediction equation. The variables of the multivariate statistical analysis were obtained through the mathematical modeling of the specimen's AE amplitude distributions produced during proof testing. Ultimate strengths were then accurately predicted at proof stresses less than 25% of the expected failure stress for five randomly drawn tensile coupons. The results of this and previously conducted composite pressure vessel research demonstrate the ability to accurately predict ultimate strengths in composite structures using AE amplitude distribution data.

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1.0 INTRODUCTION

Acoustic Emission (AE) technology is a rapidly maturing form of nondestructive testing. By providing accurate real time monitoring of complex structures and allowing for both the location and classification of flaw growth activity within such structures, AE nondestructive testing has proven itself to be a valuable tool in quality assurance and control. The research which has been performed here extends the AE technology from a strictly qualitative tool into a quantitative one as well.

The AE technology is based on the sounds produced as both microscopic and macroscopic flaws within the structure grow. In certain instances the flaw growth is audible, such as the crackling noise produced when wood is overstressed, but for most practical engineering materials and situations the sounds produced are of such high frequencies that they cannot be detected without special sensors and monitoring equipment. In most cases, once an audible sound is produced, sufficient damage has been done to render the structure useless or at least severely weakened.

Acoustic emission is produced by the rapid release of strain energy at localized stress concentration points within the structure. Stress wave packets which travel radially outward from each source are produced by this rapid release of energy. Piezoelectric transducers are used to monitor the acoustic activity within a structure. These transducers convert the waves impinging on the face of the piezoelectric element into electric signals which can then be analyzed. The signals produced by the piezoelectric element resemble overdamped sinusoids with a short rise-time and exponential decay (Section 2.1). The frequency of the signal is centered around the natural or resonant frequency of the crystal itself.

The characteristics of the AE signal provide a picture of how a flaw is developing within a structure. Some of the key parameters used to quantify the signal are counts, peak amplitude, rise-time, duration and energy (Section 2.1). During each test, thousands of signals (events) may be produced. Computers are normally used to quantify this large amount of data.

Of the many parameters used to quantify AE waveforms, the event amplitude and its associated events versus amplitude plot (amplitude distribution) have proven to be the most informative for assessing structural integrity.

Previous research by Hill [1] using a set of six 18 inch diameter graphite/epoxy pressure vessels has shown that burst pressures can be predicted at proof pressures less than 12.5% of the expected burst pressures using the percentage of high amplitude (>70 dB) AE events. Analyzing the AE data from a set of eleven 5.75 inch diameter graphite/epoxy pressure vessels Kalloo [2] demonstrated that burst pressures could be predicted to within ±1.0% of the actual value using the percentages of amplitude-based failure modes. The research presented herein has shown that ultimate strengths can be predicted in ASTM D-3039 unidirectional graphite/epoxy tensile specimens by correlating the parameters of a Weibull representation of AE amplitude distribution data (taken at or below 25% of the expected failure strength) to known fracture strengths. The resulting equation predicted the fracture strength of five specimens with a worst case error of 5.4%.

2.0 ACOUSTIC EMISSION PARAMETERS

To better understand how AE nondestructive testing can be used to model the complex failure modes of a growing flaw some knowledge of how the AE event is captured and characterized must be provided. The AE event begins as a result of a rapid release of strain energy at a location within a material where the magnitude of the stress is large enough to produce flaw growth activity. The energy, initially traveling in spherical stress wave packets from the source, is generally of such a magnitude that it cannot be monitored without special sensors.

Typically piezoelectric transducers, which convert the stress waves into electric signals, are used since they can detect minute surface vibrations over a wide range of frequencies. Piezoelectric transducers are commercially available in two basic forms, resonant and non-resonant. Resonant transducers are used in applications where it is important to monitor lower amplitude events, since they normally have a greater sensitivity than non-resonant transducers. Due to their flatter frequency response, non-resonant transducers are used when it is more important to analyze the true stress wave frequency [3]. Figure 1 is a schematic representation of a typical resonant type acoustic emission transducer.

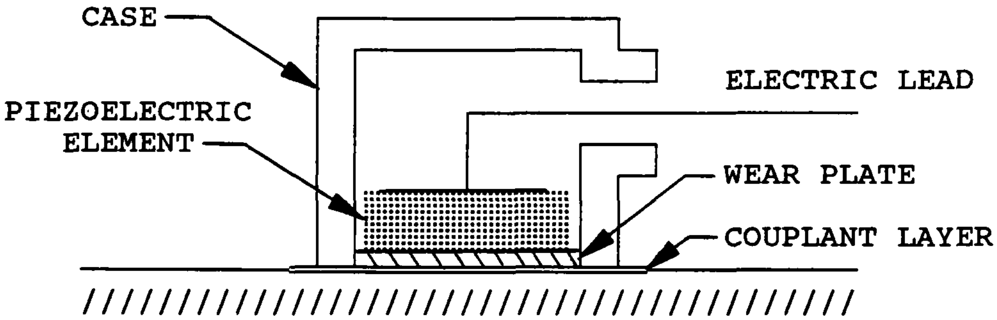


Figure 1. Resonant AE Transducer.

The electric signal generated by the resonant transducer, as shown in Figure 2, has a fast rise-time and an exponential decay resembling a damped sinusoid at the piezoelectric crystal's resonant frequency [4].
The signal produced by the sensor normally lasts for microseconds and has a peak amplitude on the order of only a few millivolts, which makes it very susceptible to electromagnetic interference. To help eliminate this problem, amplifiers are placed in the circuit as close to the transducer as possible, and shielded cables are used to connect the components. The amplifier serves to impedance match the AE signal and increase its magnitude to a usable voltage level. Usually, the amplifier is

set at 40 dB which provides a 100X magnification factor. Also, in some systems, a filter is built into the amplifier arrangement to block out unwanted mechanical, electrical and hydraulic noises. In many instances, a bandpass filter will be used to block out both low and high frequencies, such as in the Physical Acoustics Corporation (PAC) model 1220A preamplifier, which uses a 100 to 300 kHz bandpass filter.

2.1 EVENT CHARACTERISTICS

A schematic representation of an AE event waveform is shown in Figure 2 with the primary characteristics identified.

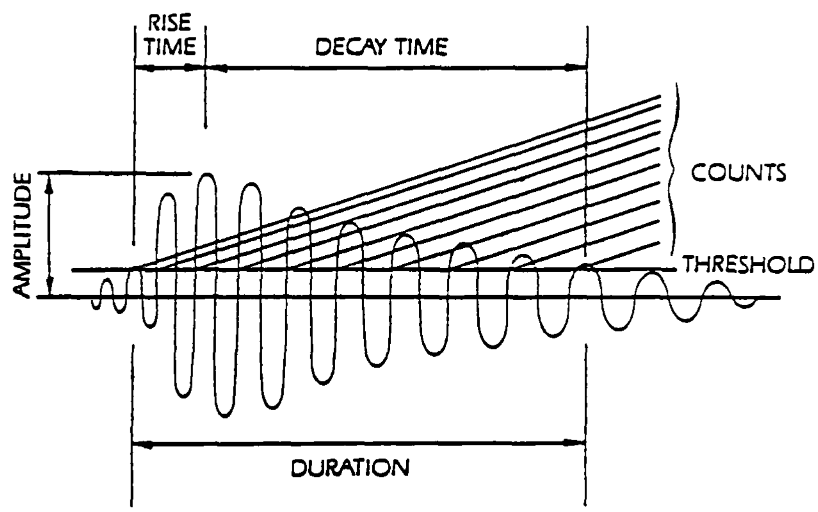


Figure 2. Event Waveform Characteristics [5].

One of the major problems encountered during an AE test is that of background noise. This background noise may come from many sources, including hydraulic, mechanical and electromagnetic interferences. The effect of the background noise on the data is reduced by setting a voltage threshold, below which no data is recorded. The AE event then begins with the first crossing of the threshold by the signal and continues until the signal drops below the threshold for a given amount of time. The remaining parameters of the event can be described as

peak amplitude : Usually referred to simply as the amplitude of an event, it is the maximum voltage the signal attains for a given event. Typically, the amplitude is measured in decibels (dB's) referenced to a given voltage level such as 1 μV.

Example: A 0.40 V signal measured after a 40 dB gain would be said to have an amplitude of 72 dB, referenced to 1 μV.

X dB = 20 log (V measured/V reference)

rise-time : The time, in microseconds, it takes the signal to reach the peak amplitude of the event.

duration : The total time, in microseconds, that the event lasts.

counts : The total number of times the signal amplitude exceeds the threshold.

energy : The area under the rectified and squared event envelope, measured in decibels.

2.2 SIGNIFICANCE OF AE PARAMETERS ON MATERIAL PROPERTIES

There is a direct relationship between the type of failure mode and the magnitudes of the AE parameters. For most composites, the three failure modes which produce the most unique AE signatures are matrix cracking, fiber breakage and delaminations.

Matrix cracking is found to occur throughout the loading cycle and is represented by low energy, short to moderate duration events with a low amplitude. The next prominent mode, fiber breakage, tends to produce the most damaging results. During proof testing it is this type of failure which can cause the destruction of the specimen on subsequent loadings below the proof stress [6]. Fiber breakage is characterized as a high energy, short duration event with a moderate to high amplitude (depending upon the type of fiber). The final mode is delamination in which the laminae begin to shear apart. Delaminations can be characterized as high energy, long duration, events with moderate to high amplitudes. This mode tends to initially "seat" the specimen and reduces the interlaminar shear stresses, thereby increasing the specimen's overall strength. The major adverse effect of delaminations is the decrease in buckling resistance of the specimen [6]. Less prominent failure modes, which can be found in varying degrees during a particular test, can cloud the distinction between the three principal failure modes, making their identification difficult. With signals varying in duration, amplitude and energy, trying to identify such sub-modes as fiber pullouts, fiber splitting, matrix crazing and fiber-matrix debonding [3] can unduly complicate the analysis.

The three principal failure modes can be observed during an AE test by plotting the number of events versus the amplitude of the emitted waves. Typical graphs of events versus amplitude for unidirectional graphite/epoxy tensile specimens are shown in Figures 3, 4 and 5. Notice that the signatures are significantly different depending upon the direction of load application. Applying the load parallel to the fiber direction produces a smooth, continuous distribution (Figure 3), whereas applying the load perpendicular to the fiber direction produces two additional humps which are probably due to longitudinal matrix cracking along the fiber direction (52 dB peak) and delaminations (65 dB peak) (Figures 4 and 5).

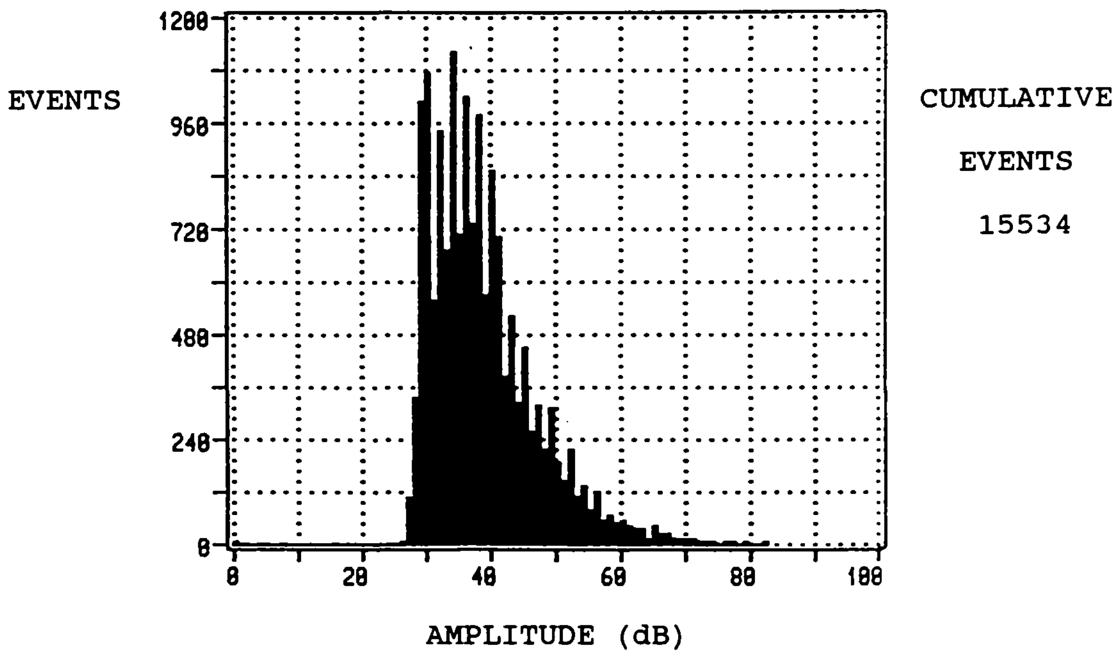


Figure 3. Events Versus Amplitude (dB) Plot for Load Applied Parallel to the Fiber Direction.

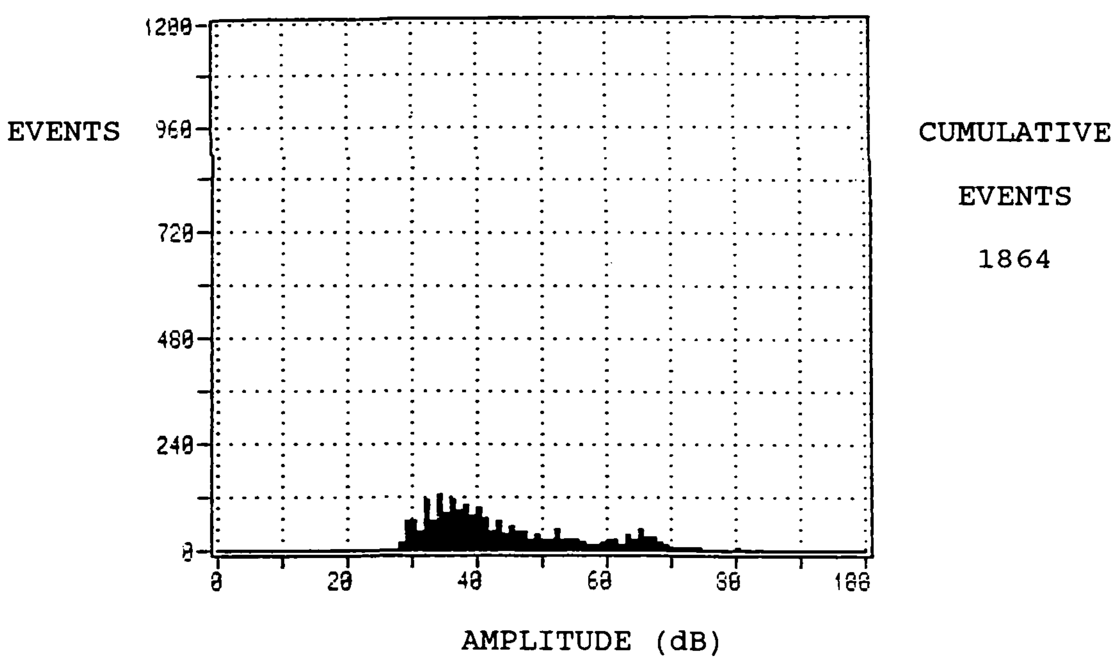


Figure 4. Events Versus Amplitude (dB) Plot for Load Applied Perpendicular to the Fiber Direction.

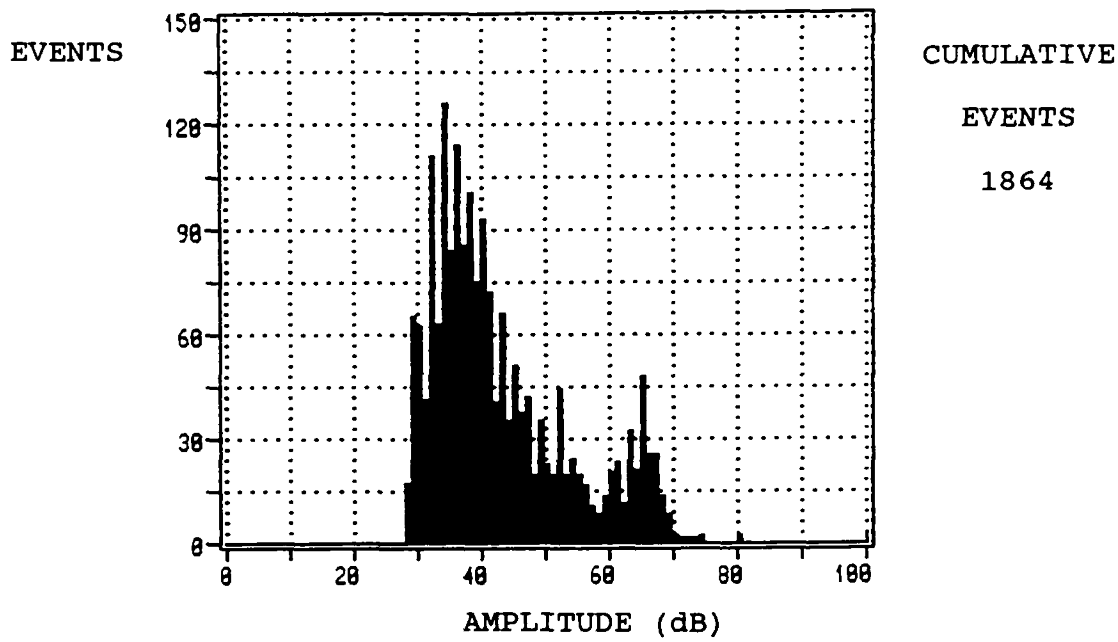


Figure 5. Events Versus Amplitude (dB) Plot of Figure 4 Enlarged.

Based upon the principal failure modes prevalent during the aforementioned tests, the amplitude distribution can, for this particular graphite/epoxy, be divided into three main regions. A large percentage of the AE data is produced by the low amplitude, 25 to 45 dB, matrix cracking; the second band, from 45 to 60 dB, consists primarily of fiber breakage; while delaminations are represented by amplitudes greater than 60 dB.

It should be noted that these values are peculiar to the material and test setup given and will vary for different test configurations.

The three principal failure modes are observed to occur cyclically. Upon initial loading, the matrix supporting the fibers cracks due to its low strength and generally brittle nature. After a considerable amount of matrix cracking, delaminations begin to form between the laminae, thereby relieving the stresses between the layers. Finally, the fibers in the most critically loaded layers begin to break. Then the cycle repeats itself. Fiber breakage and delaminations eventually become more prevalent and higher in amplitude as the load increases and the specimen cyclically progresses to failure.

2.3 COMPUTER INTERPRETATION OF AE PARAMETERS

For most practical AE research, thousands of events are produced, each of which must be categorized and interpreted. To accomplish this, data acquisition systems such as the one shown in Figure 6 are used. With this type of system timing parameters are used to control the physical interpretation of the many signals entering the unit.

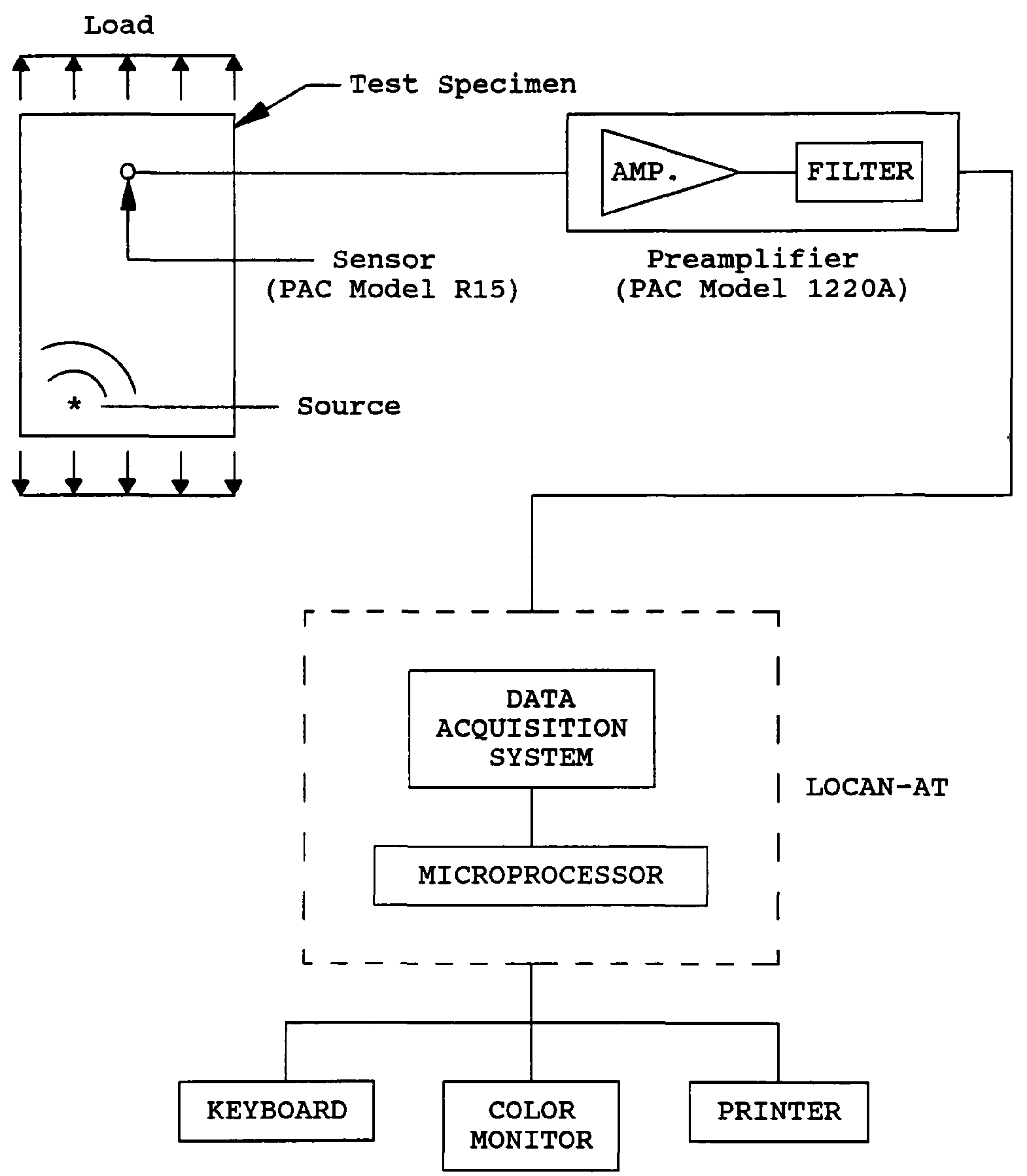


Figure 6. A Typical Test Setup and Configuration.

Independent waveforms, or hits (events), are separated by a hit delay time, HDT (Figure 7). The HDT is set such that the amount of time between the last crossing of the threshold, or count, of event "A" and the first count of event "B" is slightly larger than the HDT. It is very important to set the HDT such that each event only contains the counts which actually belong to that particular event. The HDT should not be so long as to overlap events or so short as to chop events. For graphite/epoxies, the HDT is usually set between 100 to 200 microseconds (μs) [7]. By correctly setting the HDT, the energy of the event (which is represented by the area under the amplitude envelope and may be approximated by the square of the signal amplitude [8]) may be determined.

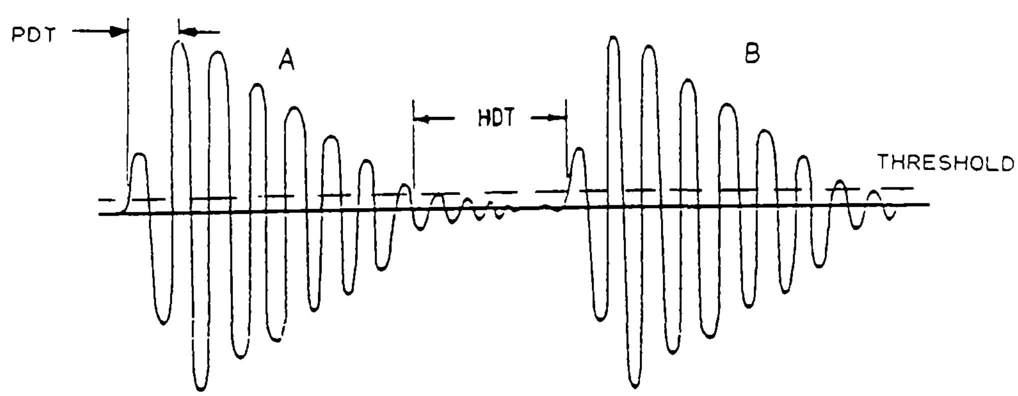


Figure 7. Timing Parameters [7].

Other important parameters to set properly in order to identify an event include the PDT and HLT. The PDT, peak detection time, ensures the correct identification of the signal peak for rise-time measurements. Nominal values for the PDT vary between 20 and 50 μs for graphite/ epoxies. The HLT, hit lock-out time, typically set at 300 μs for graphite/epoxies, eliminates false echoes and spurious measurements during the signal decay, speeding data acquisition [7].

3.0 MATHEMATICAL MODELS

Of the many parameters used to model AE activity, the distribution of the event amplitudes is one of the most informative. As previously discussed, the amplitude of a given signal provides a means to qualitatively determine the type of failure mode present. Therefore, by monitoring the distribution of the amplitudes for many signals during a particular test, insight into the overall damage state of the structure may be attained.

3.1 MODELING BASED ON LARGE AMPLITUDE EVENTS

Hill [1] has shown that by using the percentage of high amplitude (>70 dB) AE events, a burst pressure prediction equation could be generated for 18 inch diameter graphite/epoxy pressure vessels. Burst pressures were predicted using multivariate statistical analysis (with data collected at or below 12.5% of the expected burst pressure for the six bottle test set) to within ±3.0% of the actual burst pressure with a 95% prediction interval.

The approach used to develop the burst pressure prediction equation involved separating out which types of failure mechanisms produced the most structurally degrading forms of damage, and then through multivariate statistics, correlating the amount of damage accumulated during proof testing with known burst pressures.

When a composite pressure vessel is pressurized, the three principal failure mechanisms, matrix cracking, delaminations and fiber breakage, are all observed. Of these three, delaminations and fiber breakage produce the most structurally degrading forms of damage. Through experimentation, it was determined that the high amplitude (>70 dB) events were produced by delaminations and fiber breakage; thus, by monitoring these parameters, a quantitative measure of the integrity of the structure was obtained.

On plotting the number of high amplitude events versus burst pressure, two distinct trends were found (Figure 8). From the two different slopes it became apparent that some factor other than the percentage of high amplitude events was entering into the test.

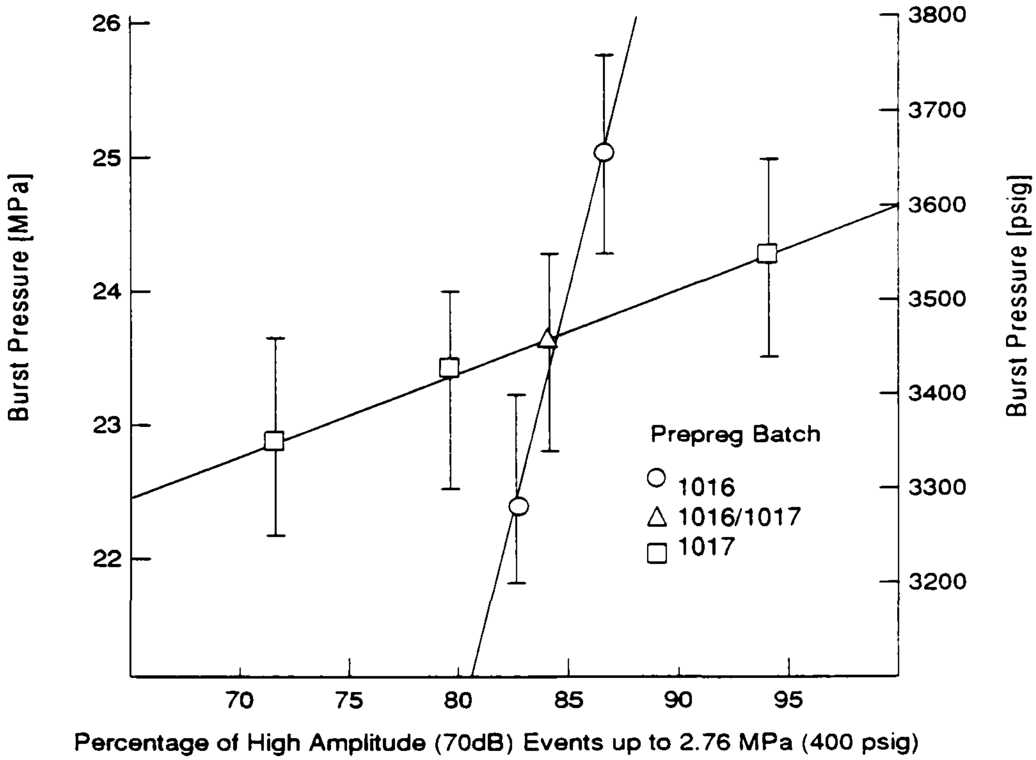


Figure 8. Burst Pressure Versus the Percentage of High Amplitude Events [1].

After performing a stepwise linear regression analysis of the data using several different test variables, it was found that only the percentage of high amplitude events and the prepreg (partially cured resin impregnated fibers) batch contributed significantly to the model.

The resulting burst pressure prediction equation thus became

$$\text{BRSTPRS} = -378.8 + 4539\ \text{PCTHAE} + 3053\ \text{PREPREG} - 3600\ \text{PCTHAE} * \text{PREPREG},$$

where BRSTRS = Burst pressure (psig)

PCTHAE = Percentage of high amplitude events

PREPREG = Prepreg batch (Note: The value of PREPREG takes on 0, 1 or -1 depending upon batch number).

It should be noted that the cross product term PCTHAE * PREPREG allows for both lines represented on Figure 8 to be generated by the single prediction equation. Physically, this says that the percentage of high amplitude events is a function of the prepreg batch, or in other words, the acoustical attenuation properties of the two resins are significantly different, and thus the amplitude distributions are also distinctly different.

Overall, the model provided for a sample standard deviation of 17.99 psig and a multiple correlation coefficient, adjusted for degrees of freedom, of $R^2(\text{adj}) = 98\%$. The value of $R^2(\text{adj})$ can be interpreted to mean that 98% of the variability in the data was taken into account by this model [1].

3.2 MODELING BASED ON PERCENTAGE OF FAILURE MODE TYPES

Through the correlation of the percentage of amplitude-based failure modes to known burst pressures in ASTM 5.75 inch diameter graphite/epoxy pressure vessels, Kalloo [2], demonstrated the techniques required to develop an accurate burst pressure prediction equation. Employing a multivariate statistical analysis, burst pressures were predicted to within ±1.0% of the expected values while using AE amplitude distribution data collected at or below 25% of the expected burst pressure for the eleven bottles tested.

The approach used to develop the burst pressure prediction equation involved using Rayleigh and Gaussian distributions to mathematically model the various humps in the AE amplitude distribution. It was postulated that by correlating the percentage of the total amplitude distribution for each of the three principle failure modes comprised with known burst pressures, a burst pressure prediction equation could be generated.

Through experimentation, Kalloo determined that the first hump in the amplitude distribution could best be modeled with a Rayleigh-type representation, while the remaining humps could best be represented by Gaussian distributions (Figure 9).

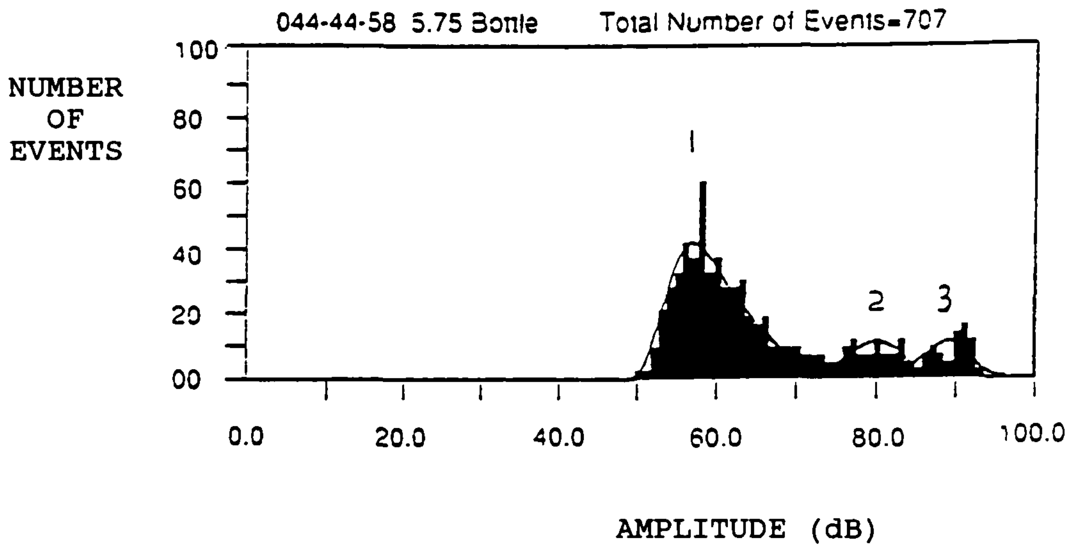


Figure 9. Failure Mode Modeling.

The percentage of the amplitude-based failure modes were found by modeling the amplitude distribution and then determining the areas under the various humps of the model. This then allowed the statistical generation of the following burst pressure equation:

$$BP = 4563.3 - 1433.6 * V1 - 3661.8 * V2 + 2864.9 * V3.$$

Here V1 represents the percentage of failure mechanisms under the first hump using the Rayleigh distribution and V2 and V3 represent the areas under the second and third humps, respectively, modeled using Gaussian representations [2].

Although this analysis technique showed that burst pressures could be predicted very accurately, some uncertainty arose concerning the repeatability of the solution algorithm. Slight errors in the statistical representations of the various humps of the AE amplitude distribution would have caused large errors in the individual failure mode percentages. Therefore, in order to reduce the possibility of introducing human error into the data analysis, research into an automated routine will be required.

3.3 AMPLITUDE DISTRIBUTION ANALYSIS BY WEIBULL REPRESENTATION

The research conducted by this author has demonstrated the ability to accurately model the events versus amplitude distributions in unidirectional graphite/epoxy tensile specimens, thereby providing a means to predict the specimen's ultimate strength.

The analysis concentrated primarily on the portion of the amplitude distribution below 45 dB. In this region, the primary failure mechanism is matrix cracking, although other source mechanisms may also exist. By modeling only the low amplitude emissions during the initial part of the loading, a quantitative measure of the integrity of the structure can be attained, while minimizing the accumulation of damage.

In general, advanced composites are brittle in nature; hence, their strength is greatly affected by the presence of flaws. Stress concentrations in the form of broken or misaligned fibers, voids, disbonds, etc., make up the vast majority of the flaws which can adversely affect the strength of a structure. During the initial portion of loading, these stress concentration areas are acoustically very active, which allows a quantitative picture of the structure's quality to be painted in the form of its amplitude distribution. The mode or maximum peak value of the amplitude distribution can be related to the stress state of the specimen in that a shift of the mode towards higher amplitudes indicates an increase in higher stress failure mechanisms and hence a more evenly distributed stress state throughout the specimen or a higher quality part. Conversely, for lower quality specimens, increased acoustic activity in the vicinity of stress concentration points at lower stresses shifts the mode towards lower amplitudes. Examining amplitude distributions in this manner is not unlike power law modeling, where the slope of the line produced by plotting the AE event's amplitudes on a log-log graph gives a measure of the extent of damage accumulated in the structure (Appendix B) [9].

This research has shown that the events versus amplitude curve can be represented by a Weibull distribution (Figure 10 and Appendix A).

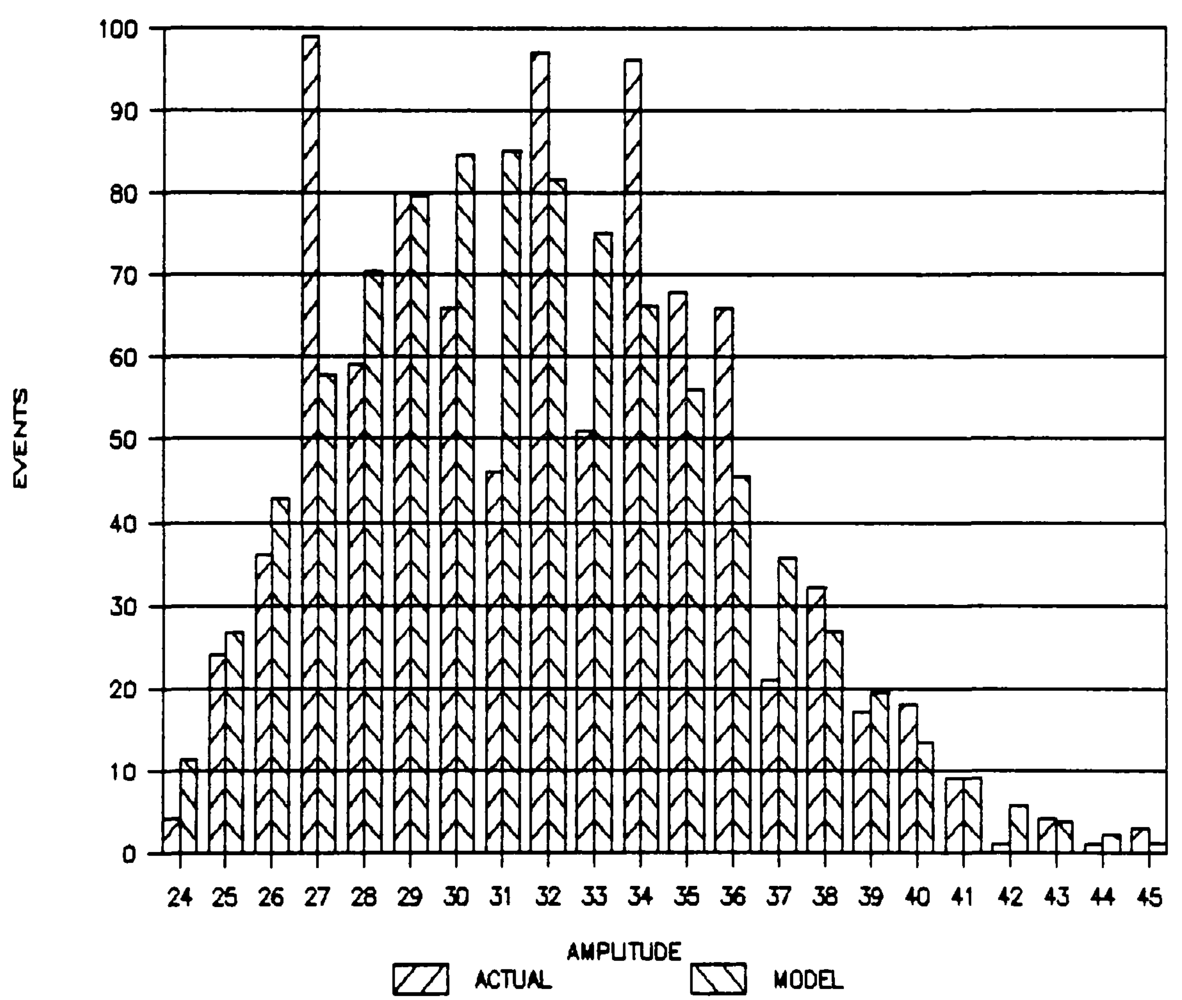
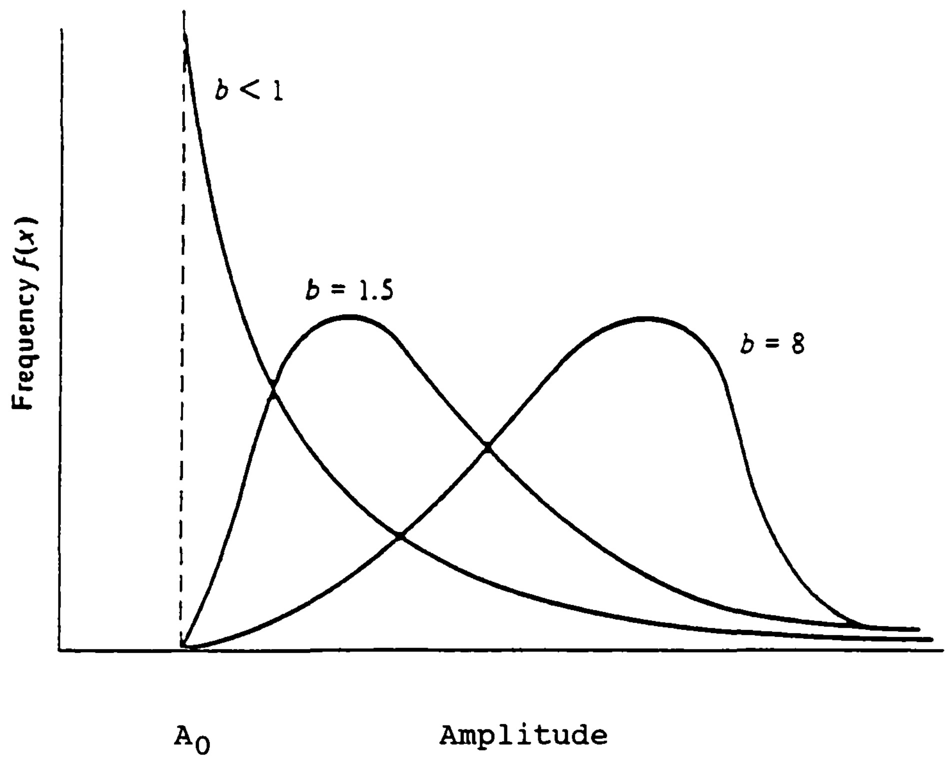


Figure 10. Amplitude Distribution Model.

Three parameters are necessary to identify the shape of the Weibull distribution: A_0, θ and b. The term "A_0" is defined as the guaranteed variate which can approximate the threshold amplitude. "θ" is defined as the characteristic variate which represents a value of "A" below which 63.2 percent of the observations occur. It is a measure of the mean amplitude, or centroid, of the AE amplitude distribution and is a function of the ductility or brittleness of the cured resin. The more ductile the resin, the greater the signal attenuation and the lower the mean signal amplitude. The term "b" is defined as a shape parameter which is a measure of the skewness or mode of the distribution (Figure 11). Here larger values of "b" (curve skewed to the left) would indicate an increase in the percentage of high amplitude or high stress events, whereas small values of "b" (curve skewed to the right) would denote an increase in the percentage of low amplitude or low stress events.

The Weibull distribution is a sort of chameleon distribution, used primarily in cases where flexibility is required, such as in reliability testing. The density function of the Weibull distribution is given mathematically as

$$f(x) = b/(\theta - A_0) * [(A - A_0)/(\theta - A_0)]^{(b-1)} * \exp\{-[(A - A_0)/(\theta - A_0)]^{b}\} \qquad (A \geq A_0).$$



A_0 = Threshold amplitude

b = Shape parameter

f(x) = Events

Figure 11. Weibull Distribution.

The statistical mean of the Weibull distribution is given as

$$\mu_x = A_0 + (\theta - A_0)\ \Gamma(1 + 1/b),$$

where Γ is the gamma function and may be found in most mathematical tables. By referring to the density function, it can be seen that the skewness of the distribution is controlled by the shape parameter, "b". For example if b = 1

$$f(x) = 1/(\theta - A_0) * \exp\{-[(A - A_0)/(\theta - A_0)]\},$$

which represents an exponential distribution with a asymptote at "A_0". It is interesting to note that for values of "b" in the range $3.3 < b < 3.5$ the distribution makes a good approximation to the normal distribution. Also, the Rayleigh distributions used by Kalloo [2] are a special case of the Weibull distribution where "b" is equal to 2.0 (Section 3.2).

The parameters A_0, θ and b are found mathematically by constructing two graphs. First by plotting lnln(1/R) against ln(A), where "R" is the reliability factor at a given amplitude "A", the threshold amplitude "A_0" can be found according to Figure 12 and Equation (1) of Table 1.

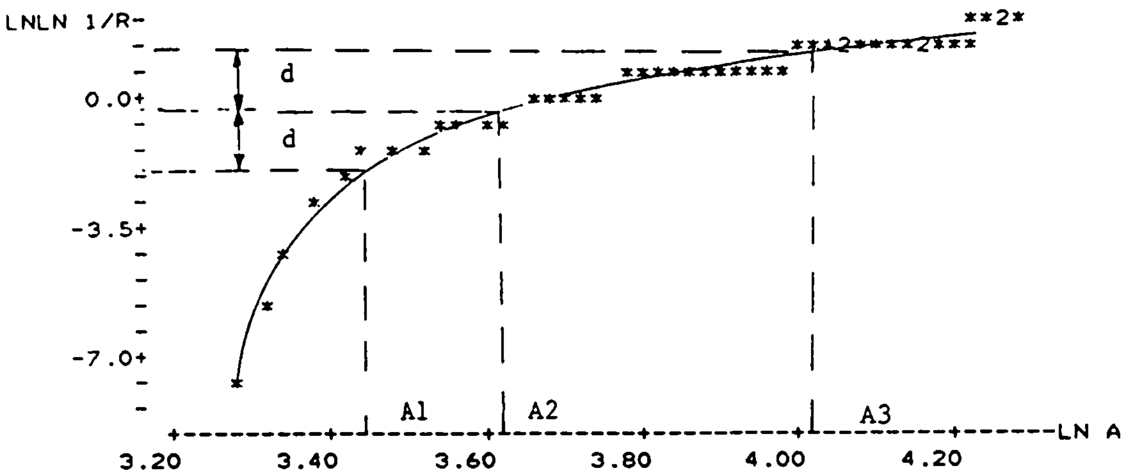


Figure 12. Plot of lnln(1/R) Versus ln(A).

Table 1. Weibull Parameter Equations.

1	$A_0 = A_2 - \dfrac{(A_3 - A_2)(A_2 - A_1)}{((A_3 - A_2) - (A_2 - A_1))}$
2	$\theta = \text{inv } \ln(\theta - A_0) + A_0$
3	$b = \Delta Y / \Delta X$

Note that "d" is an arbitrary, fixed distance which usually changes from test to test. For different values of "d", "A_0" can also change, creating a lack of repeatability in the data. Wherever possible it is advisable to fix "A_0" at a given value, such as the AE equipment test threshold, to give a common point of reference for each test.

Mathematically the value of "R" represents the cumulative density function complementary to unity at a given value of "A" and is given as

$$R(x) = \exp \; \{-[(A - A_0)/(\theta - A_0)]^b\} \qquad (A \geq A_0).$$

In layman's terms, the reliability factor is the number of events at a given amplitude divided by the total number of events under the amplitude distribution envelope.

Replacing ln(A) with ln($A-A_0$) and replotting the first graph, Figure 13, provides a means of calculating "θ" and "b" using a least squares fit and Equations (2) and (3) from Table 1. This assumes that the data is Weibullian, i.e., that the rectified graph is linear [10], which has proven to be a good assumption. Figures 12 and 13 were produced during the Weibull modeling of the AE amplitude distribution data given in Figure 3 of Section 2.2.

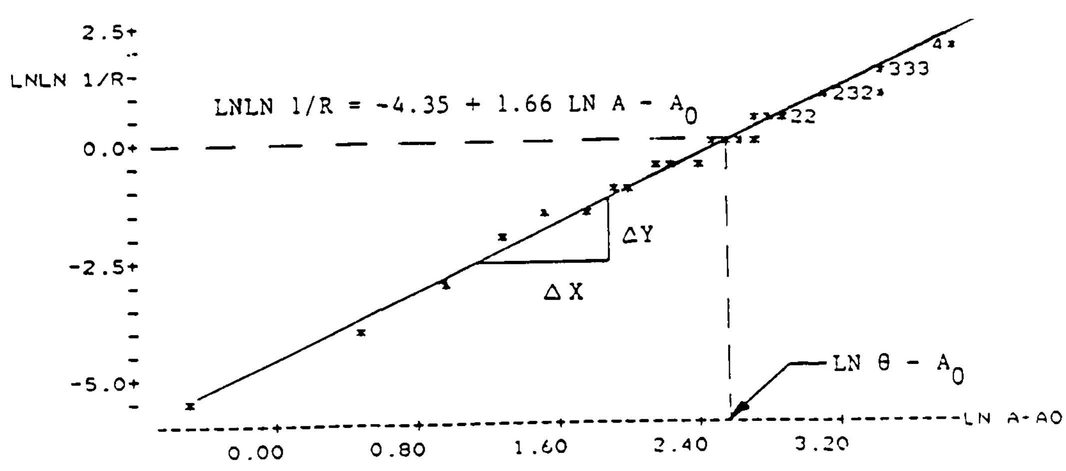


Figure 13. Plot of lnln(1/R) Versus ln($A-A_0$).

The parameters A_0, b and θ are summarized in Table 2 for both tension tests previously described in Section 2.2. The calculations for determining the Weibull parameters are given in Appendix C.

Table 2. Weibull Parameters for a Typical Test Using Unidirectional Graphite/Epoxy Tensile Specimens.

Loading With Respect to Fiber Direction	A_0	b	θ
Parallel	26.90	1.66	40.65
Perpendicular	28.13	1.44	44.44

Once the parameters A_0, θ and b are found and correlated to known ultimate strengths in a set of sample data, the constants for the ultimate stress prediction equation can be determined using multivariate statistical analysis [1,6,11]. The proposed ultimate strength equation is given as follows:

$$Su = C_0 + C_1 * A_0 + C_2 * b + C_3 * \theta + C_4 * A_0 * b + C_5 * b * \theta + C_6 * A_0 * \theta.$$

Here

Su = Predicted ultimate strength (ksi)

C_i = Parameter coefficient (i=1,...,6).

It should be noted that by fixing "A_0" to a constant value, the three terms involving "A_0" in the above ultimate strength equation will vanish.

Experiments were conducted on unidirectional graphite/epoxy tensile specimens in order to determine if an ultimate strength prediction equation could be developed by correlating the parameters of a Weibull representation of AE amplitude distribution data with known ultimate strengths.

3.3.1 EXPERIMENTAL SETUP AND TEST PROCEDURES

A series of six ASTM (American Society for Testing and Materials) D-3039 unidirectional graphite/epoxy tensile specimens were loaded to failure in an MTS (Materials Testing System) machine. The specimen's cross-sectional area was 0.025 in^2 (0.5 inches wide and 0.05 inches thick). The exact origin of the specimens was unknown, so information on the fiber (type/lot), resin (type/batch) or cure cycle is not available. The specimens were loaded at a constant rate of 500 pounds per minute until failure.

To monitor the AE released by each specimen during loading, the LOCAN-AT data acquisition system, built by Physical Acoustics Corporation (PAC), was utilized along with a PAC model R15 transducer and PAC model 1220A preamplifier. The test setup and timing parameters (discussed in section 2.3) included:

$$\begin{aligned} \text{HDT} &= 150\ \mu\text{s} \\ \text{HLT} &= 300\ \mu\text{s} \\ \text{PDT} &= 40\ \mu\text{s} \\ \text{THRESHOLD} &= 30\ \text{dB} \\ \text{TOTAL GAIN} &= 60\ \text{dB}. \end{aligned}$$

The data, which was stored on the hard drive of the LOCAN-AT, was converted to ASCII (American Standard Code for Information Interchange) format by means of PAC's computer program, called ATASC. The ASCII formatted data was then analyzed using a computer program, written in BASIC, called AESORT.

The AESORT computer program was written to provide a means of both sorting acoustic emission data and performing the Weibull distribution modeling. BASIC was chosen as the program language due to its readability and availability; plus, most computer systems will accept and run BASIC programs.

The AESORT computer program is supplied in Appendix D along with an operations guideline/flowchart.

3.3.2 RESULTS OBTAINED FROM AESORT

The Weibull parameters obtained by analyzing the AE amplitude distributions of the six unidirectional specimens (with the AESORT computer program) are given in Table 3. The cross product term "b*θ" also appears in Table 3 for reference.

The data used in the analysis were collected at or below a stress of 60 ksi (1500 lbs), which was 25% of the expected failure strength. The threshold value, "A_0", was set to 23 dB, and only the data which had amplitudes less than 45 dB were included in the analysis.

Table 3. Weibull Parameters from Experimental Data.

TEST NO.	ULTIMATE STRENGTH (ksi)	b	θ	b*θ
1	234.8	2.2663	32.89	74.539
2	227.6	2.2193	32.66	72.482
3	237.2	2.2759	32.69	74.399
4	218.8	2.1537	32.32	69.608
5	144.0	1.9041	33.09	63.007
6	176.7	2.0755	32.60	67.661

The threshold value was determined by observing the amplitude at which the number of events approached zero on the left-hand side of the amplitude distribution. The value of "A_0" was determined to be 23 dB by averaging the observed threshold values from the six tests. To verify this value, the Weibull analysis was performed using thresholds ranging from 20 dB to 30 dB. This analysis showed that the best fit to the AE amplitude distribution data, determined by the linearity of the graph of $\ln\ln(1/R)$ versus $\ln(A-A_0)$ (Section 3.3), was produced by choosing "A_0" equal to 23 dB. In all cases, a better than 99% correlation between $\ln\ln(1/R)$ and $\ln(A-A_0)$ was attained with "A_0" equal to 23 dB.

The upper limit of the modeled amplitude distribution was set at 45 dB in order to block out the higher amplitude failure mechanisms, such as fiber breakage and delaminations. This limit was determined by observing the difference in the amplitude distributions of specimens stressed with the loading parallel (matrix cracking plus fiber breakage) and perpendicular (matrix cracking plus delaminations) to the fiber axis. Examples of typical AE amplitude distributions for the two loading cases are given in Figures 3, 4, and 5 of Section 2.2. From this analysis it was determined that amplitudes below 45 dB were primarily attributable to matrix cracking. The AESORT computer program was then modified to block out long duration (>200 μs) events (delaminations), and high energy (>5 units) events (delaminations and fiber breakage) in order to determine if the events with amplitudes less than 45 dB were indeed matrix cracking. Examination of the data files indicated that the vast majority of the events with less than 45 dB amplitudes had short durations and low energy levels, which are characteristic of matrix cracking.

Figures 14, 15 and 16 are plots of the ultimate strength versus the Weibull parameters "b" and "θ" and the cross product term "b*θ". It can be seen that the parameter "b" and the cross product term "b*θ" appear to be linearly correlated with the ultimate strength, while "θ" shows no correlation with the ultimate strength. This is because "θ" is a measure of the mean amplitude of the AE signal and is related to variations in the brittleness or ductility of the cured resin and the concomitant attenuation of the AE event waveforms. Thus, "θ" functions primarily to correct the shape parameter "b" for variations in signal attenuation due to changes in the cure cycle and/or the resin batch.

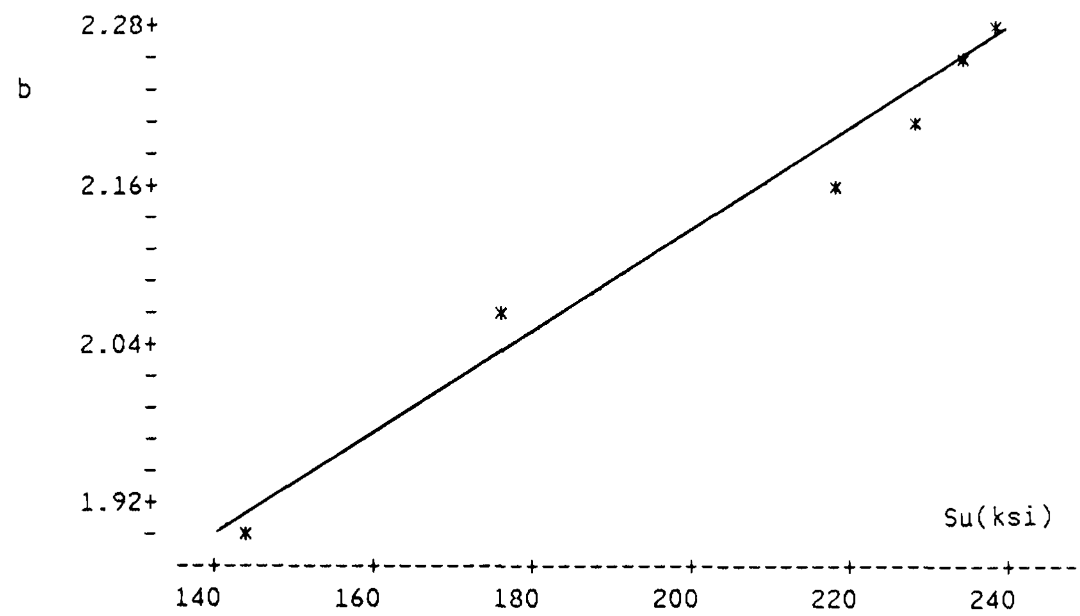


Figure 14. Plot of "b" Versus Ultimate Strength.

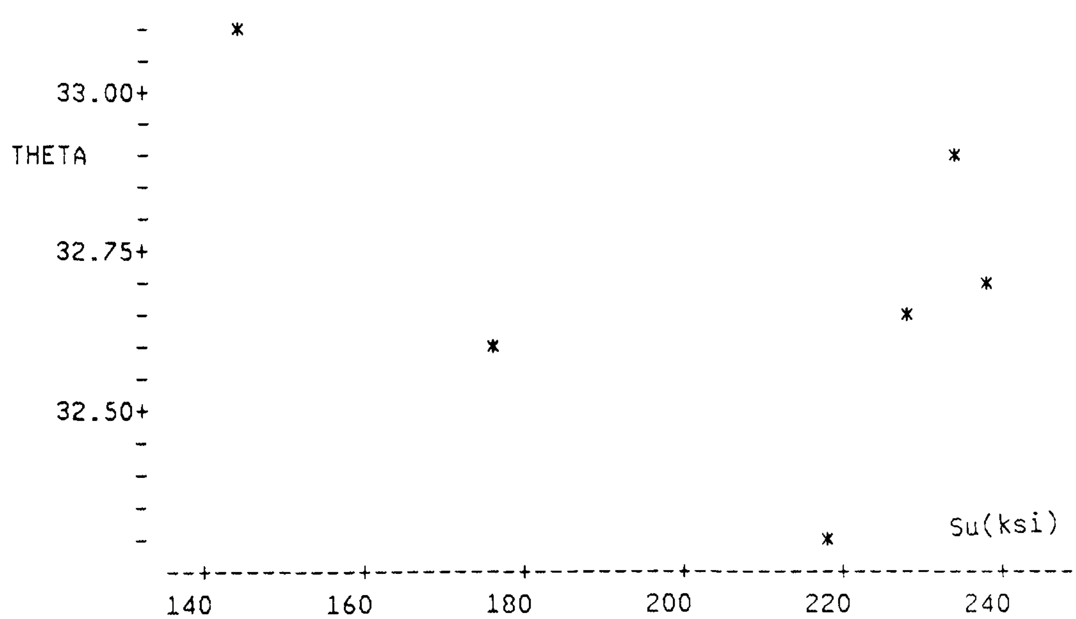


Figure 15. Plot of "θ" Versus Ultimate Strength.

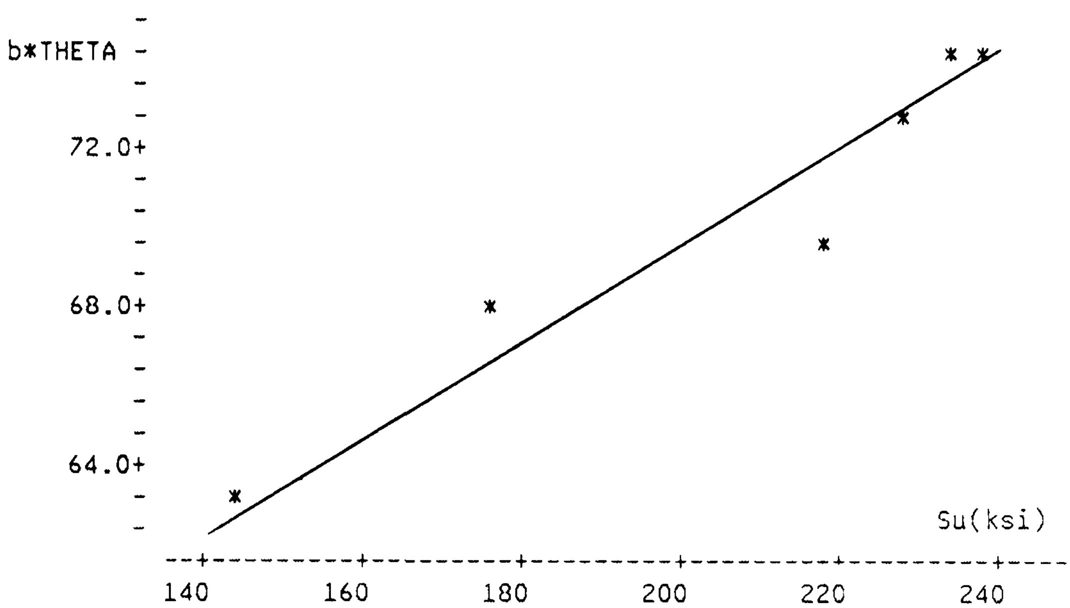


Figure 16. Plot of "b*θ" Versus Ultimate Strength.

A simple linear regression analysis was conducted using first "b" and then "b*θ" as the predictor variables. The analysis was performed using the students edition of **MINITAB** statistical software. The results of this analysis are given in Figure 17.

MODEL 1

The regression equation is
Su(ksi) = - 357 + 262 b

Predictor	Coef	Stdev	t-ratio	p
Constant	-356.58	54.46	-6.55	0.003
b	262.01	25.29	10.36	0.000

s = 8.007 R-sq = 96.4% R-sq(adj) = 95.5%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	6878.9	6878.9	107.29	0.000
Error	4	256.5	64.1		
Total	5	7135.4			

MODEL 2

The regression equation is
Su(ksi) = - 367 + 8.17 b*THETA

Predictor	Coef	Stdev	t-ratio	p
Constant	-367.35	75.24	-4.88	0.008
b*THETA	8.165	1.069	7.64	0.002

s = 10.70 R-sq = 93.6% R-sq(adj) = 92.0%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	6677.8	6677.8	58.37	0.002
Error	4	457.6	114.4		
Total	5	7135.4			

Figure 17. Statistical Output from **MINITAB**.

Statistically, the R-sq(adj) term of the ANOVA (analysis of variance) table (Figure 17) provides insight into the amount of variability taken into account by the model. For Model 1, R-sq(adj) was equal to 95.5%; therefore, 95.5% of the variability in the data was taken into account by this model, while for Model 2, 92% of the variability in the data was taken into account. In both models, the p-value is zero to two significant figures which indicates that both variables, "b" and "b*θ", contribute significantly to their respective strength prediction equations.

In Section 3.3 of this report a multiple independent variable ultimate strength equation was proposed. Due to the limited number of samples used, which restricted the degrees of freedom for error, only two predictor variables at one time could be utilized in the regression analysis. By setting "A_0" to 23 dB, the three terms involving "A_0" were immediately eliminated from the model. The remaining three terms were then analyzed, two at a time, in stepwise fashion. The MINITAB results for the three, two-variable models, are given in Figures 18, 19 and 20.

```
MTB > STEPWISE 'Su(ksi)' 'b' 'theta';
SUBC> ENTER 'b' 'theta'.

 STEPWISE REGRESSION OF Su(ksi)  ON  2 PREDICTORS, WITH N      6

    STEP        1        2
CONSTANT  -0.2841-356.5768

b             255      262
T-RATIO      8.59    10.36

THETA         -10
T-RATIO     -0.65

S            8.66     8.01
R-SQ        96.85    96.41
```

Figure 18. **MINITAB** Results for a Stepwise Regression Analysis Using "b" and "θ" as the Predictor Variables.

```
MTB > STEPWISE 'Su(ksi)' 'b*theta' 'theta';
SUBC> ENTER 'b*theta' 'theta'.

 STEPWISE REGRESSION OF Su(ksi)  ON  2 PREDICTORS, WITH N =    6

    STEP        1        2
CONSTANT    535.6   -367.3

b*THETA      7.73     8.17
T-RATIO      8.44     7.64

THETA         -27
T-RATIO     -1.71

S            8.80     10.7
R-SQ        96.75    93.59
```

Figure 19. **MINITAB** Results for a Stepwise Regression Analysis Using "θ" and "b*θ" as the Predictor Variables.

```
MTB > STEPWISE 'Su(ksi)' 'b' 'b*theta';
SUBC> ENTER 'b' 'b*theta'.

 STEPWISE REGRESSION OF Su(ksi)  ON  2 PREDICTORS, WITH N      6

    STEP          1        2
CONSTANT     -341.8   -356.6

b               429      262
T-RATIO        1.80    10.36

b*THETA        -5.3
T-RATIO       -0.70

S              8.56     8.01
R-SQ          96.92    96.41
```

Figure 20. **MINITAB** Results for a Stepwise Regression Analysis Using "b" and "b*θ" as the Predictor Variables.

The stepwise regression analysis showed that in all cases, the only Weibull parameters which entered significantly into the two variable prediction models where "b" and "b*θ". Therefore, a two term ultimate strength equation using the Weibull parameters as predictor variables does not warrant further study.

The next stage of the analysis was to verify that the prediction equations would actually predict the ultimate strength of specimens drawn at random. Five specimens were tested in the MTS machine using the same test setup as given in the previous section. Four of the specimens were ramped directly to failure, while the last specimen was ramped to 60 ksi (1500 lbs), held for 30 seconds, unloaded, and then ramped to failure. In all cases the loading rate was the same as that used in the initial testing: 500 pounds per minute. The purpose for the ramp-hold-unload-ramp to failure pattern of loading was to simulate a typical low stress proof test and determine if the damage induced in the specimen on the first loading cycle significantly affected the specimen's ultimate strength and the ability of the model to predict that strength [6].

Table 4 provides a summary of the results obtained for each of the five tests. Tables 5 and 6 provide a comparison of the predicted and actual values of ultimate strengths for Models 1 and 2, respectively.

Table 4. Results Obtained From Verification Tests.

TEST NO.	ULTIMATE STRENGTH (ksi)	b	Θ	b*Θ
7	224.4	2.1382	33.87	72.421
8	215.2	2.1683	33.56	72.768
9*	233.0	2.2537	33.09	74.575
10	192.4	2.1311	31.76	67.684
11	138.0	1.9315	32.19	62.175

* Ramp-hold-unload-ramp to failure

Table 5. Comparison of Actual Ultimate Strengths to Predicted Values for Model 1.

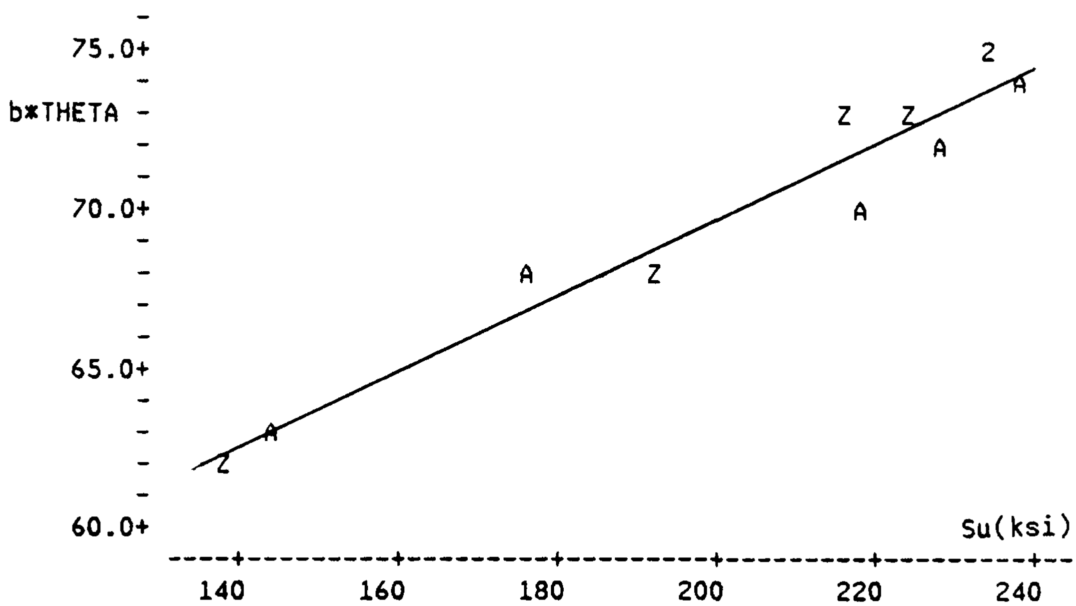
	Su(ksi) = - 357 + 262 * b		
TEST NO.	ACTUAL STRENGTH (ksi)	PREDICTED STRENGTH (ksi)	PERCENT ERROR
7	224.4	203.6	9.3
8	215.2	211.5	1.7
9	233.0	233.9	0.4
10	192.4	201.8	4.9
11	138.0	149.5	8.3

Table 6. Comparison of Actual Ultimate Strengths to Predicted Values for Model 2.

	Su(ksi) = - 367 + 8.17 * (b*θ)		
TEST NO.	ACTUAL STRENGTH (ksi)	PREDICTED STRENGTH (ksi)	PERCENT ERROR
7	224.4	224.7	0.1
8	215.2	226.8	5.4
9	233.0	241.6	3.7
10	192.4	185.3	3.7
11	138.0	140.3	1.7

The results indicate that although a better correlation between the original Weibull parameters and the ultimate strength is obtained with Model 1, a more accurate prediction is produced by using Model 2. The primary reason why the "b*θ" term of Model 2 provides for a better prediction is probably because it separates and distinguishes between the different acoustic properties and the physical differences (fiber type, resin batch, cure mode, etc.) between the various specimens. In performing the analysis, it was found that the number of events accumulated up to 60 ksi (1500 lbs) varied greatly for each test. This, along with the scattered values for "θ", gave reason to believe that the specimens tested may have been manufactured from different material batches and/or had different cure cycles. By modeling with the cross product term, the correlation between the shape of the distribution "b" and the centroidal location of the distribution "θ" was used to help predict the specimens' ultimate strength. The effect of the acoustic properties of a material on the correlation between "b" and "θ" is a topic for future research. It is thought that, by testing materials of known origin, the ultimate strength equations would be able to predict the specimen's ultimate strength with extreme accuracy.

The next logical step in the analysis was to develop a new prediction model based on the Weibull parameters collected from all eleven tests (Figure 21).



A = ORIGINAL SAMPLE SET (TABLE 3)

Z = VERIFICATION TESTS (TABLE 4)

2 = BOTH Z AND A

Figure 21. Plot of "b*θ" Versus Ultimate Strength for Model 3.

The cross product term "b*θ" was chosen to be the predictor variable of the new model (Model 3) since it had been used successfully in Model 2, the better of the two models in terms of prediction capabilities. The results obtained by performing the linear regression analysis for the eleven tests, with "b*θ" as the predictor variable, are given in Figure 22.

MODEL 3

The regression equation is
Su(ksi) = - 343 + 7.79 b*THETA

Predictor	Coef	Stdev	t-ratio	p
Constant	-343.05	42.56	-8.06	0.000
b*THETA	7.7949	0.6055	12.87	0.000

s = 8.641   R-sq = 94.8%   R-sq(adj) = 94.3%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	12374	12374	165.73	0.000
Error	9	672	75		
Total	10	13046			

Figure 22. **MINITAB** Results Obtained for Model 3.

The results indicate that 94.3% of the variability is taken into account by Model 3, and the sample standard deviation is 8.64 ksi. The ability of the resulting ultimate strength equation to accurately predict the specimen's failure strength will continue to increase as more tests are conducted and a larger data base is built.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The following conclusions can be made from the results of previous research in composite pressure vessels:

1. Statistically correlating the percentage of high amplitude (>70 dB) AE events and the prepreg batch with known burst pressures allowed the generation of a burst pressure prediction equation for 18 inch diameter graphite/epoxy bottles [1].

2. A burst pressure prediction equation was also generated by statistically correlating the percentage of amplitude-based failure modes with known burst pressures in 5.75 inch diameter graphite/epoxy pressure vessels [2].

The results of the tensile test research lead to the following conclusions:

1. The "b" and "θ" parameters of a Weibull representation of the low amplitude (matrix cracking) portion of the AE

amplitude distribution -- collected at 25% of the expected failure strength, from only six unidirectional graphite/epoxy tensile specimens -- were used to develop an ultimate strength prediction equation.

2. The shape parameter "b" was found to be the primary measure of the specimens' ultimate strengths (Figure 11). A higher value of "b" indicated an increase in high amplitude matrix cracking activity, signifying a more evenly distributed loading and thus a higher quality structure. Conversely, lower values of "b" indicated an increase in low amplitude matrix cracking activity around stress concentrations; therefore, the quality of the structure or structural efficiency, was lower. Thus, the maximum load the structure could withstand before failure was less for a lower value of "b".

3. The centroid of the AE amplitude distribution, given by the Weibull parameter "θ", provided an amplitude correction factor, i.e., it normalized the amplitude distribution such that the "b's" could be compared directly. The parameter "θ" adjusted for variations in the acoustical attenuation within the samples due to changes in the resin (type/batch), fiber(type/lot) and cure mode.

4. The capability of the model to predict ultimate strengths improved as the number of samples in the data base increased.

5. The failure strength of a specimen which was not ramped directly to failure was predicted with the same apparent accuracy as the specimens that were ramped directly to failure. This meant that the amount of damage accumulated in the structure during proof testing at 25% of the expected failure strength was probably insignificant.

The following general conclusions can be made regarding the use of AE amplitude data to predict ultimate strengths in composite structures:

1. The amount of damage created by proof testing composite structures can be reduced by predicting their ultimate strength at lower (less than 25% of the expected failure strength) stresses.

2. Statistical analysis of acoustic emission amplitude distributions provides a quantitative measure of the integrity of structural components fabricated from composite materials. It also provides a qualitative measure of variations in process variables for composite structures.

4.2 RECOMMENDATIONS

The research conducted by Hill [1] and Hill and Lewis [6], relied on information concerning the physical make-up of the structures being tested. This included such variables as resin batch, cure mode/cycle, fiber lot, etc. These added variables allowed the regression model to predict the ultimate strength of a structure with extreme accuracy, even for small sample sizes. On the other hand, the Weibull representation has demonstrated that ultimate strengths can be predicted with reasonable accuracy by simply analyzing a single failure mechanism -- the matrix cracking produced during the initial stages of loading -- without even knowing the physical make-up of the test samples.

Kalloo [2] demonstrated that sorting out the three principle failure mechanisms by hand can lead to very accurate burst pressure predictions without knowing what the material is or how it is processed. The one problem with this technique is that it required the data to be hand edited in order to separate the three characteristic humps (failure mechanisms) in the amplitude distribution. This was necessary in order to achieve the high degree of accuracy that was obtained.

What is needed here is an automated routine which will sort the AE data into specific bands based upon the event parameters. Not only will the routine be required to sort the acoustic data based on the amplitude of the signal, but it will also have to take into consideration the duration and energy levels of each event. By sorting out the individual failure mechanisms, a measure of not only the damage state of the specimen but also the material's physical properties could be determined. The AE analysis could then be used to aid in process monitoring by modeling the percentage of each failure mechanism and its progression during loading. The unique acoustic signature of the structure would then automatically be used to discriminate between different cure rates and cycles, fibers (types/lots) or resins (types/batches). This should be the subject of future research.

Because signal attenuation and dispersion are more pronounced in larger structures [3], future testing will also be required to verify that the procedures used to develop the ultimate strength and burst pressure prediction equations presented in this thesis will work for larger structures. Since the energy of an AE event is not as affected by signal attenuation and dispersion as is the AE amplitude, a predictor variable based upon the number of high energy events may prove to be advantageous in predicting the failure stress in larger structures.

Hill and Lewis [6] have previously shown that by using the number of high energy (>500 units) AE events, burst pressures could be predicted in 5.75 inch diameter fiberglass/epoxy pressure vessels to within ±1.0% at a 95% prediction interval.

The next step in the development of this technology would be to apply the techniques demonstrated in this thesis to real world applications. To further demonstrate the usefulness and accuracy of predicting ultimate strengths, future research involving scale models of aircraft structures and pressure vessels will be required. These tests should lead to the practical usage of ultimate strength prediction from acoustic emission data in aerospace structures where quality control and a high degree of certainty in predicting ultimate strengths are required.

5.0 REFERENCES

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APPENDICES

APPENDIX A

GRAPHICAL OUTPUT FROM TESTS OF UNIDIRECTIONAL GRAPHITE/EPOXY SPECIMENS

Test Set-up

Specimens - Type - ASTM D 3039

- Material - Unidirectional Graphite/Epoxy

Loading - Direction: Parallel to the fiber axis

- Rate: 500 pounds per minute

Equipment - Sensor - PAC model R15

- Preamplifier - PAC model 1220A - 40 dB gain
  - 100-300 khz filter

- Data Acquisition System - LOCAN-AT

Hardware set-up

GAIN = 20 dB

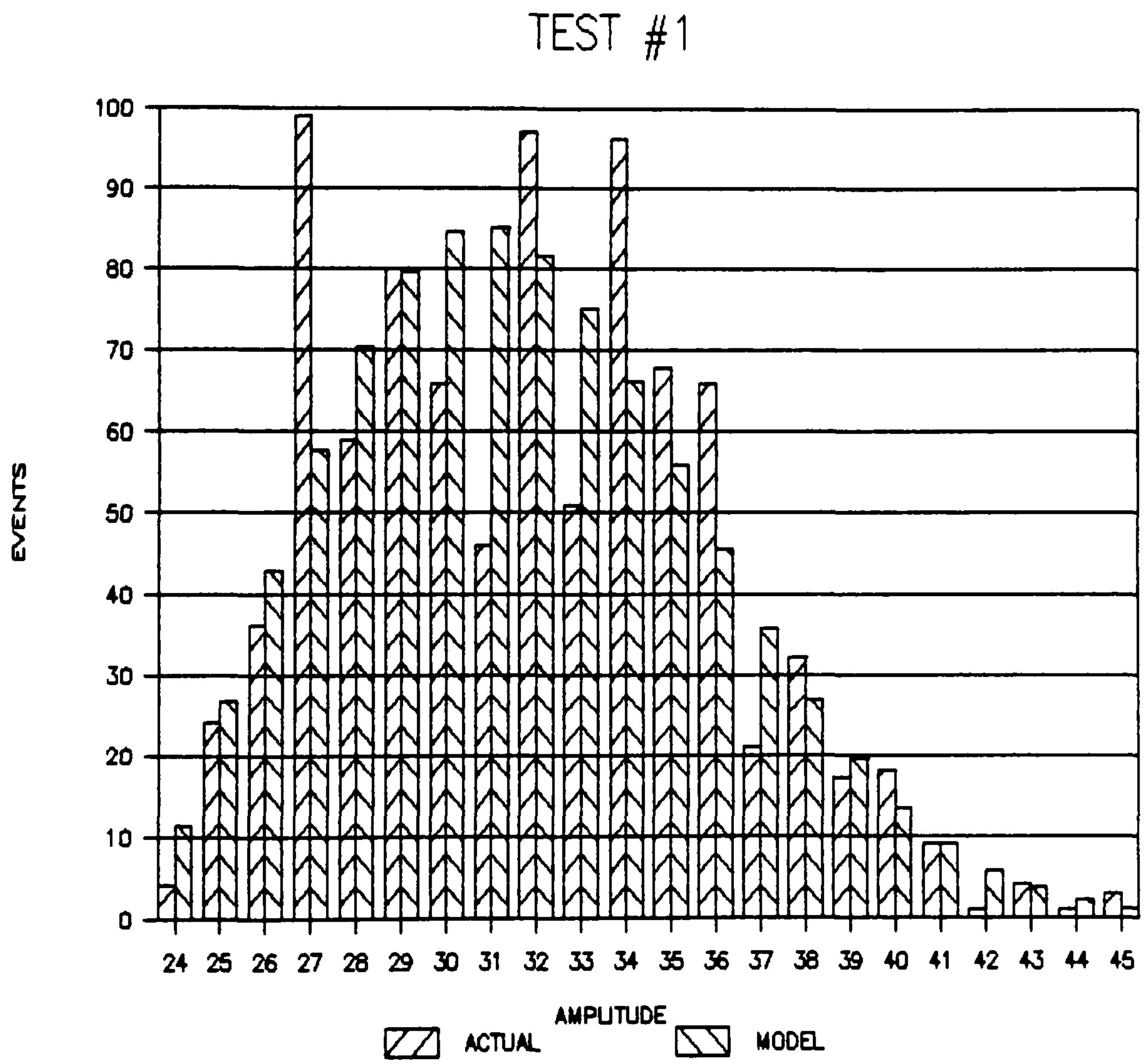
THRESHOLD = 30 dB

HDT = 150 μs

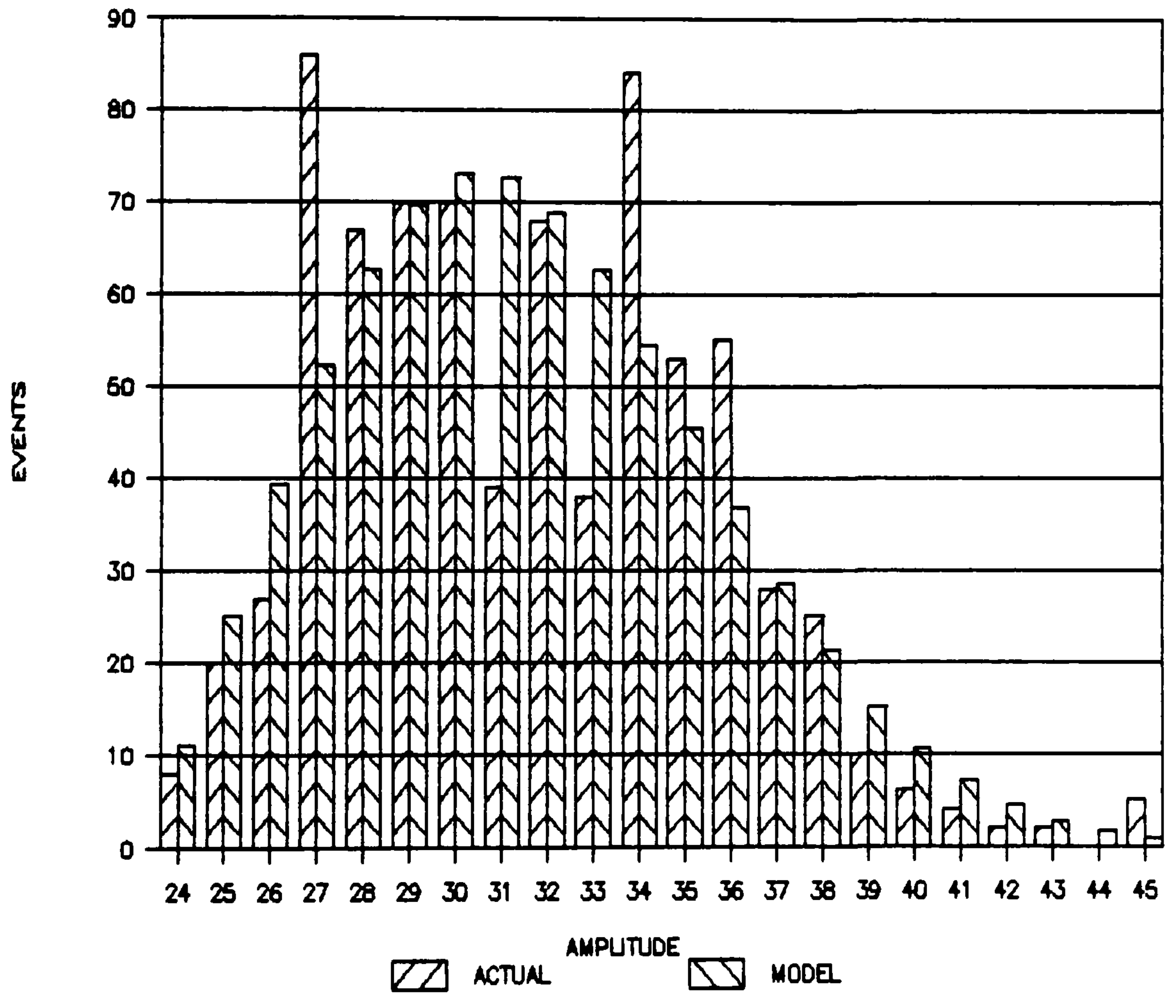
PDT = 40 μs

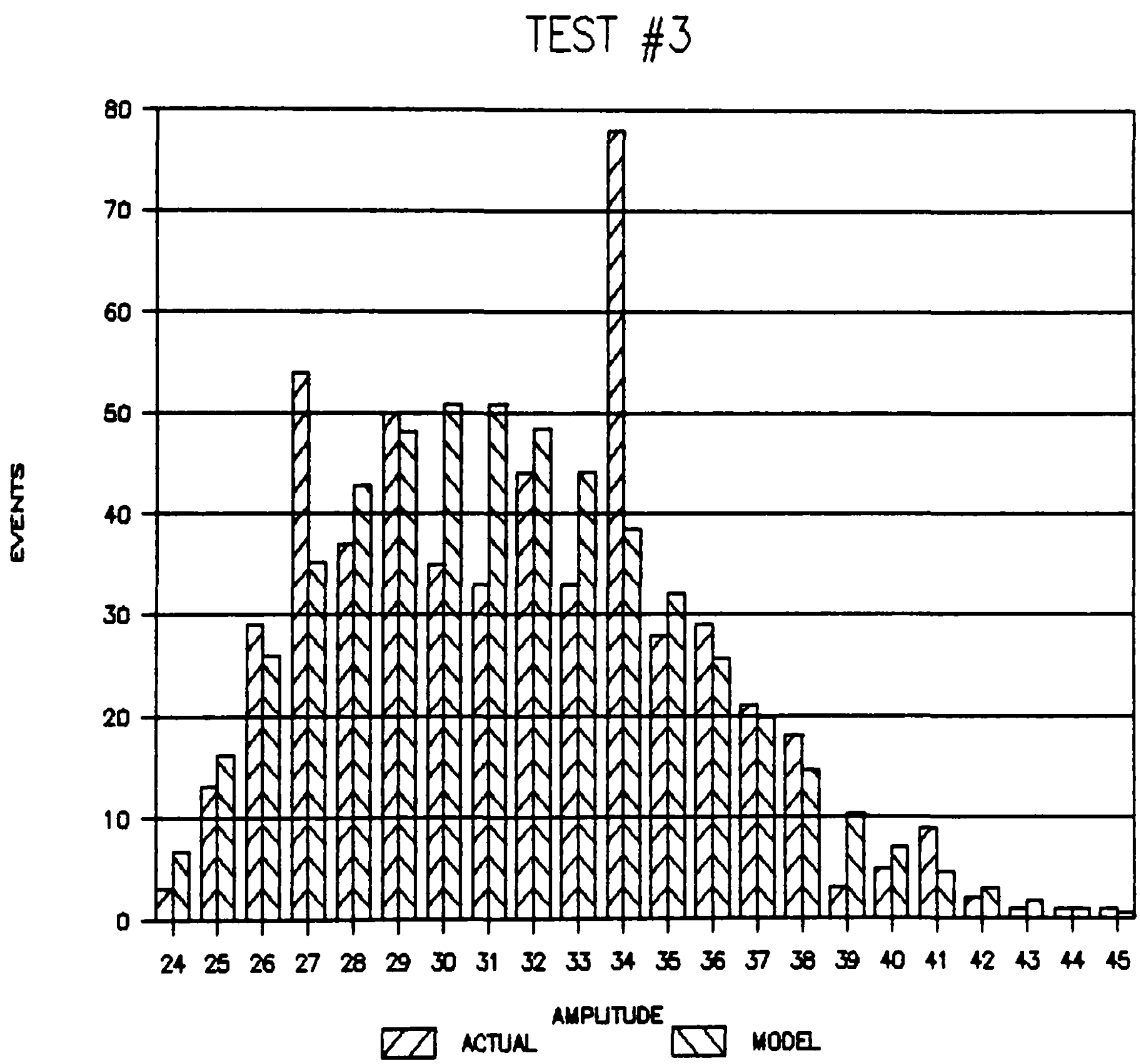
HLT = 300 μs

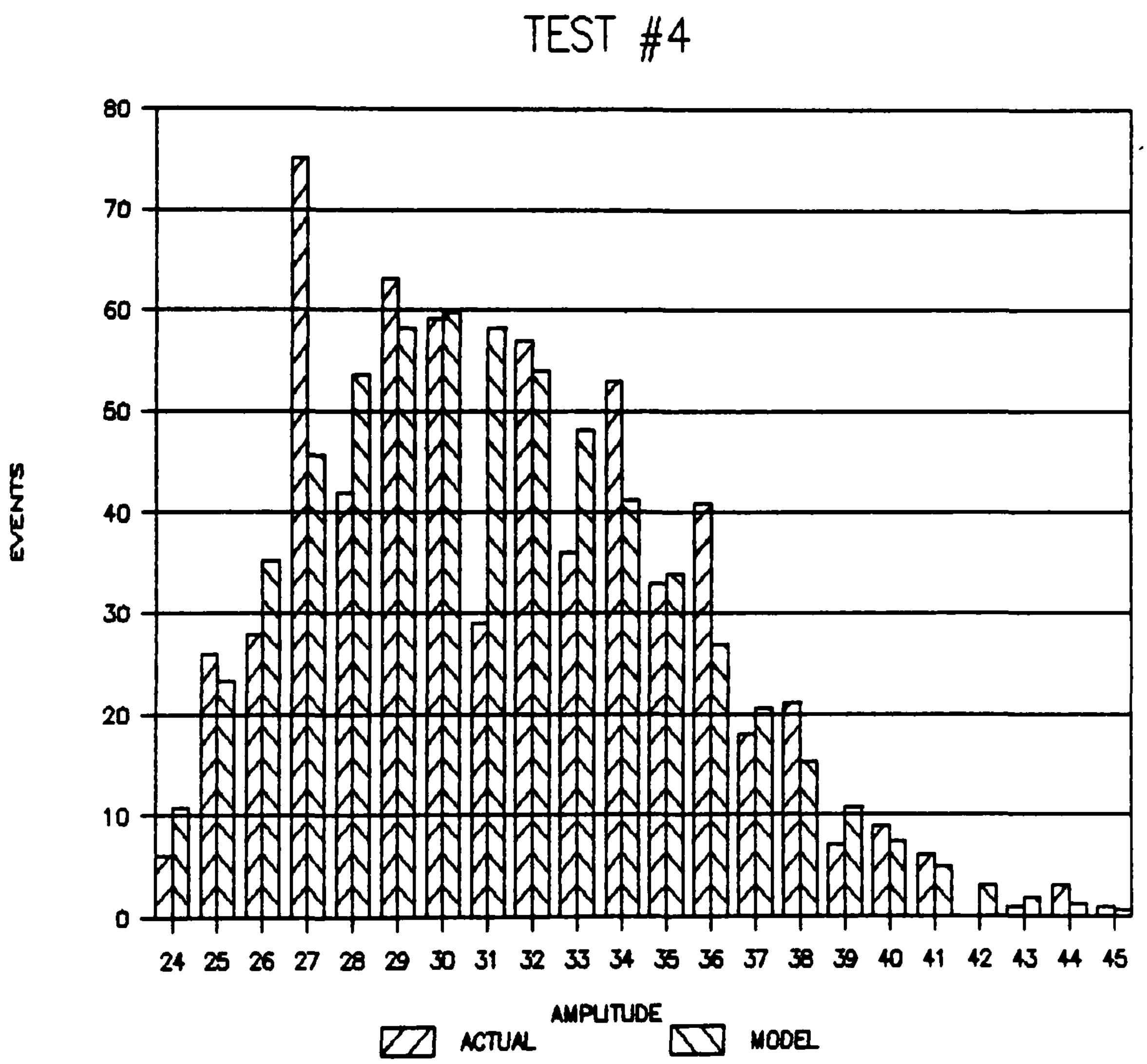
PAC = Physical Acoustic Corporation

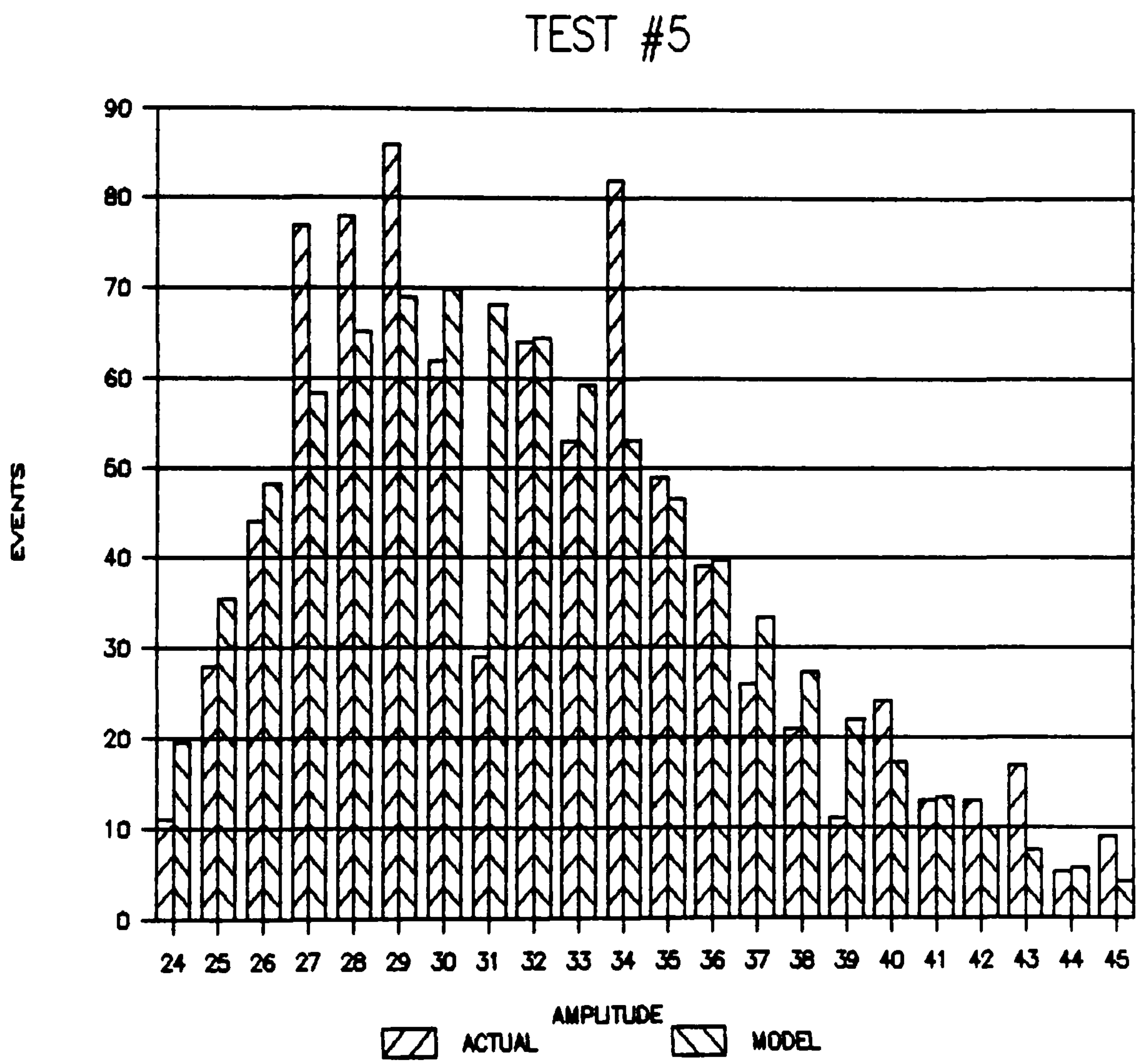

TEST #1
EVENTS
AMPLITUDE
ACTUAL
MODEL
0
10
20
30
40
50
60
70
80
90
100
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45

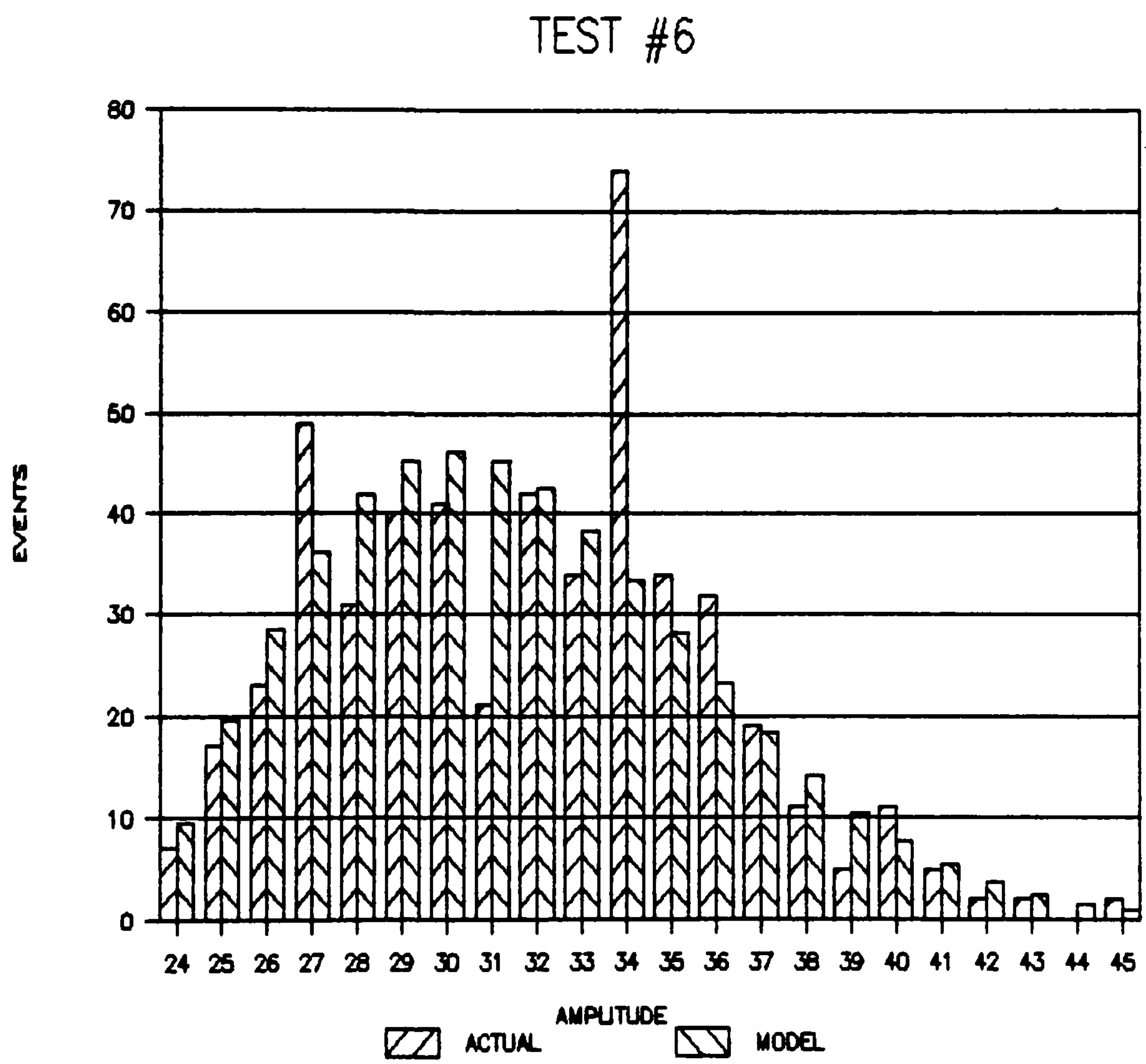
TEST #2

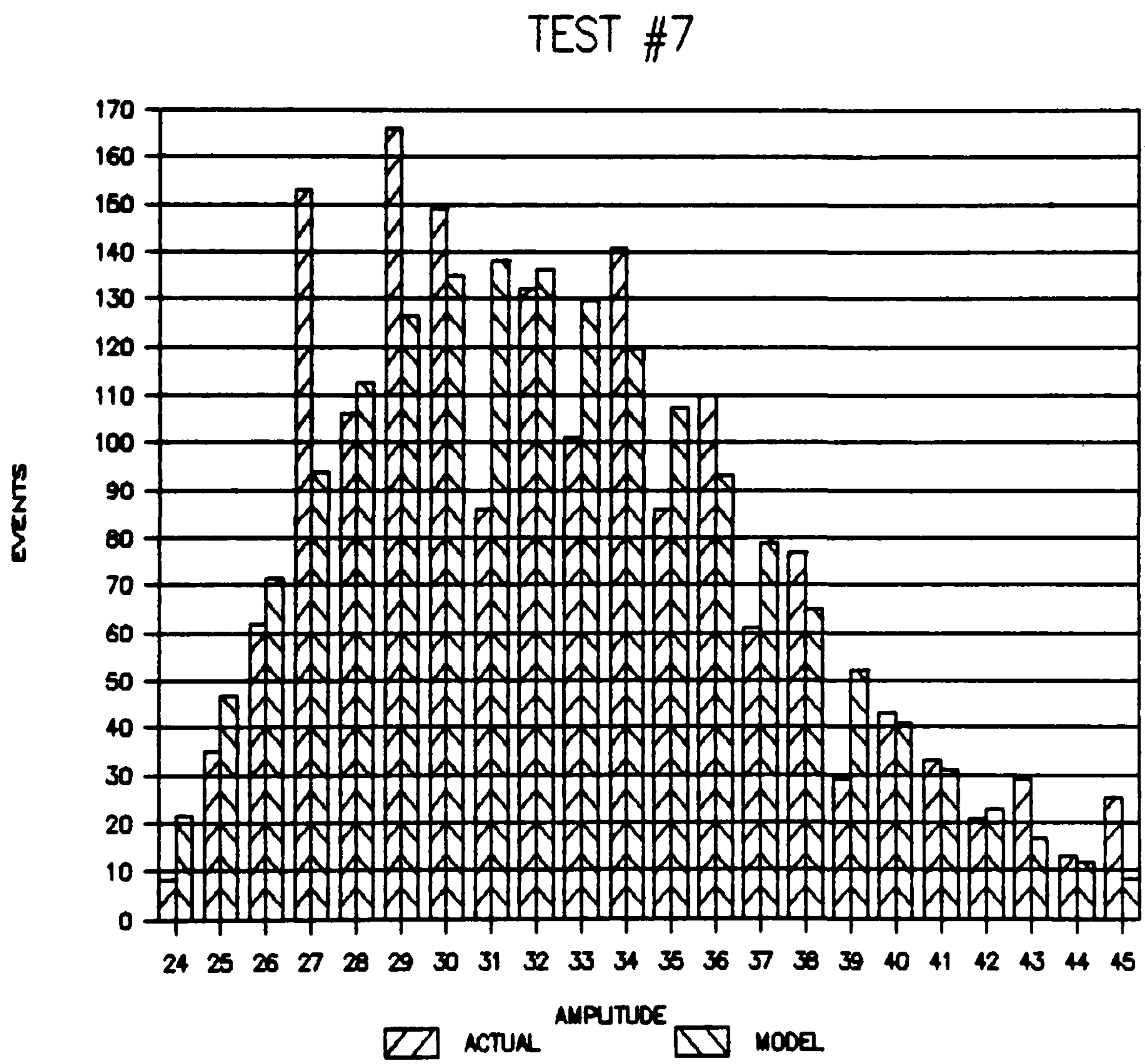

90
80
70
60
50
40
30
20
10
0
EVENTS
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
AMPLITUDE
ACTUAL
MODEL

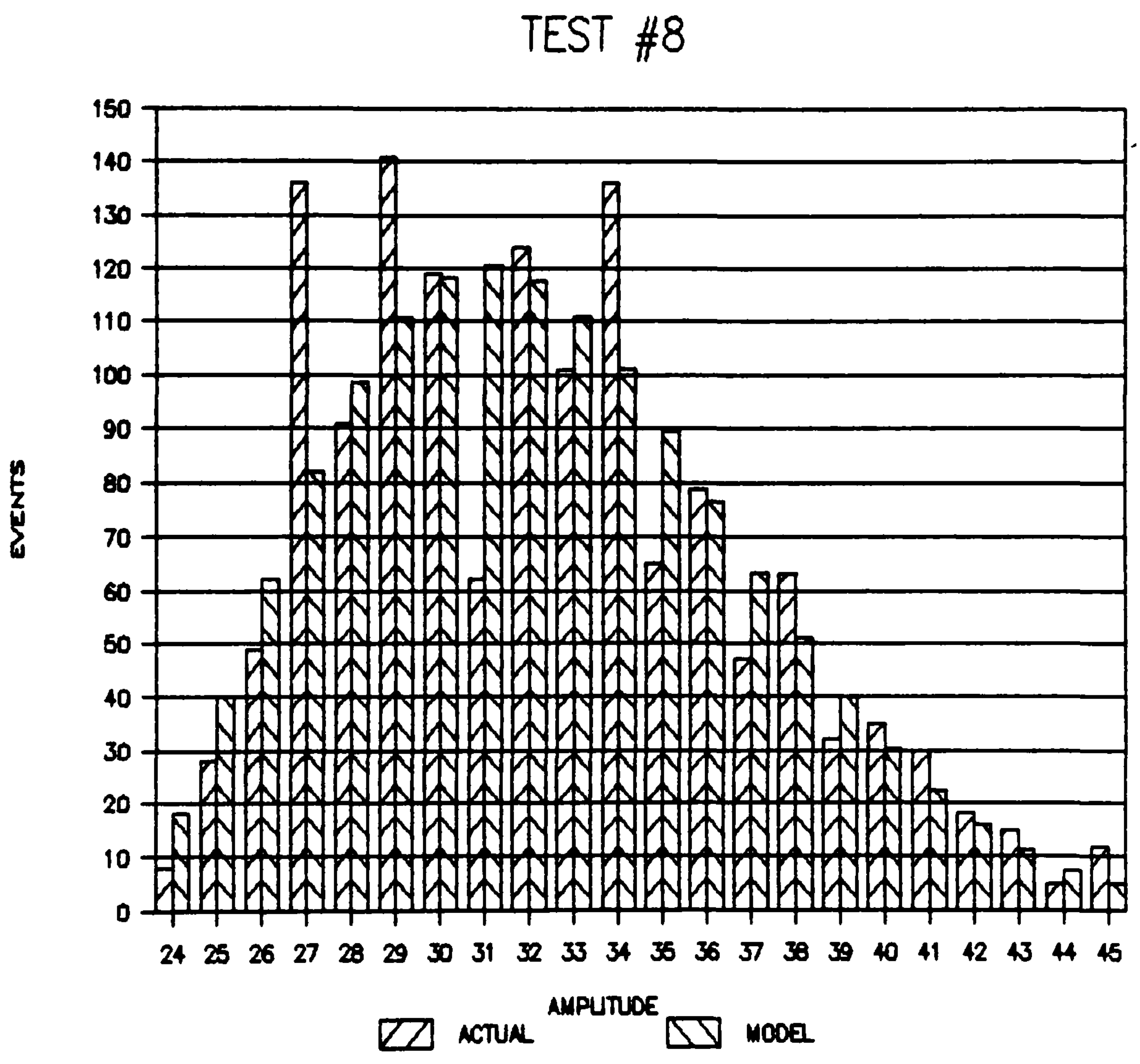

TEST #3
EVENTS
80
70
60
50
40
30
20
10
0
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL


TEST #4
EVENTS
0
10
20
30
40
50
60
70
80
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL

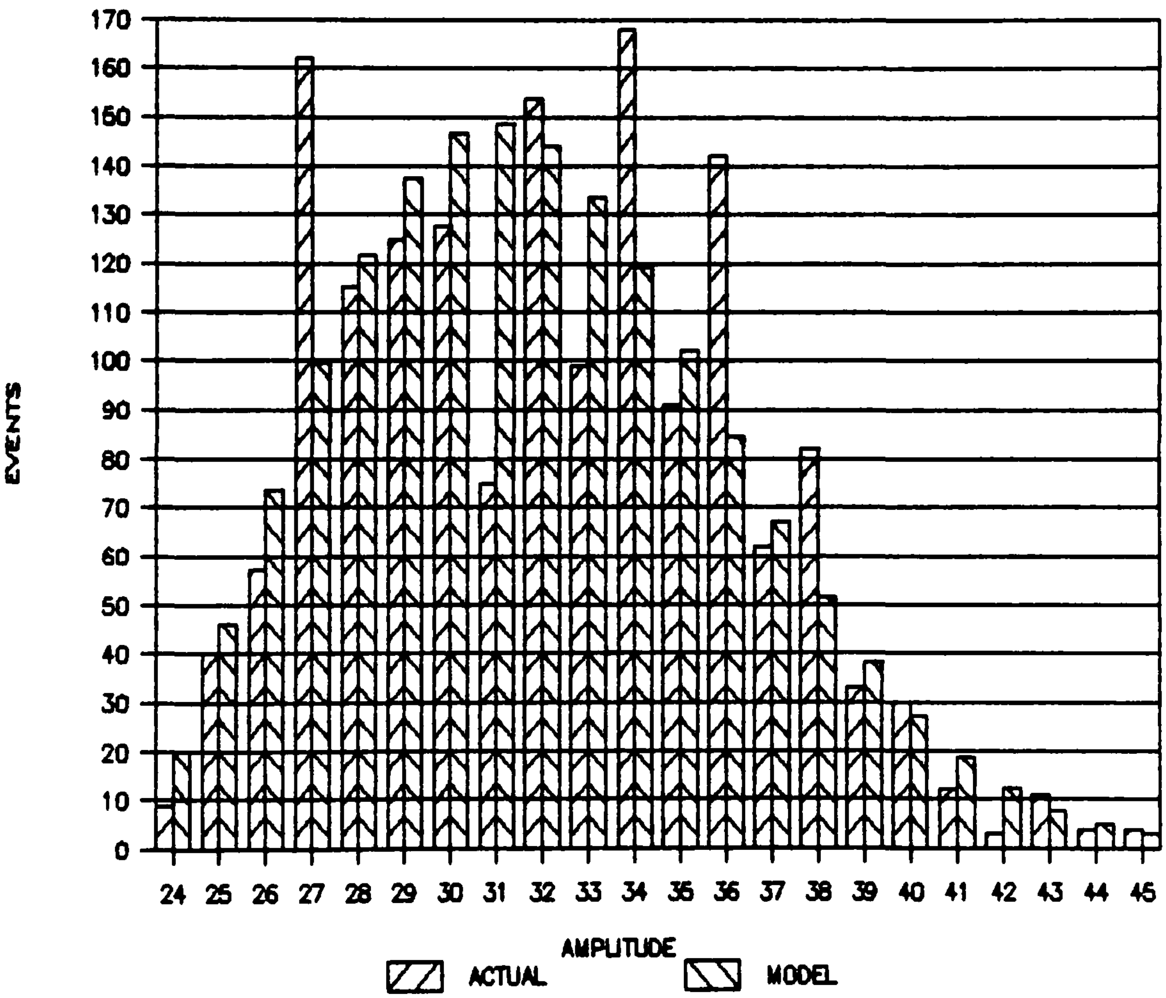

TEST #5
EVENTS
90
80
70
60
50
40
30
20
10
0
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL

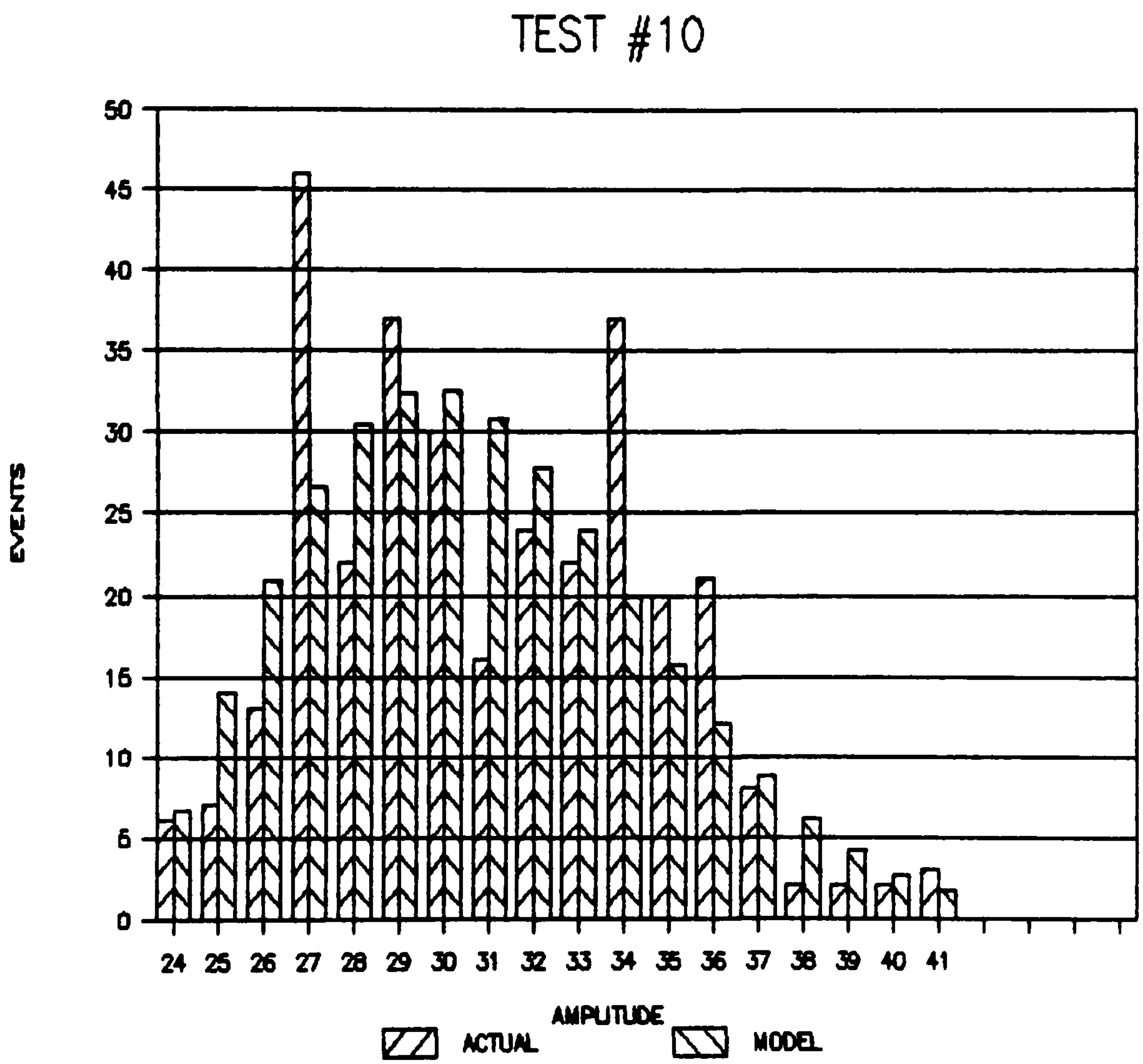

TEST #6
EVENTS
80
70
60
50
40
30
20
10
0
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL


TEST #7
EVENTS
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL

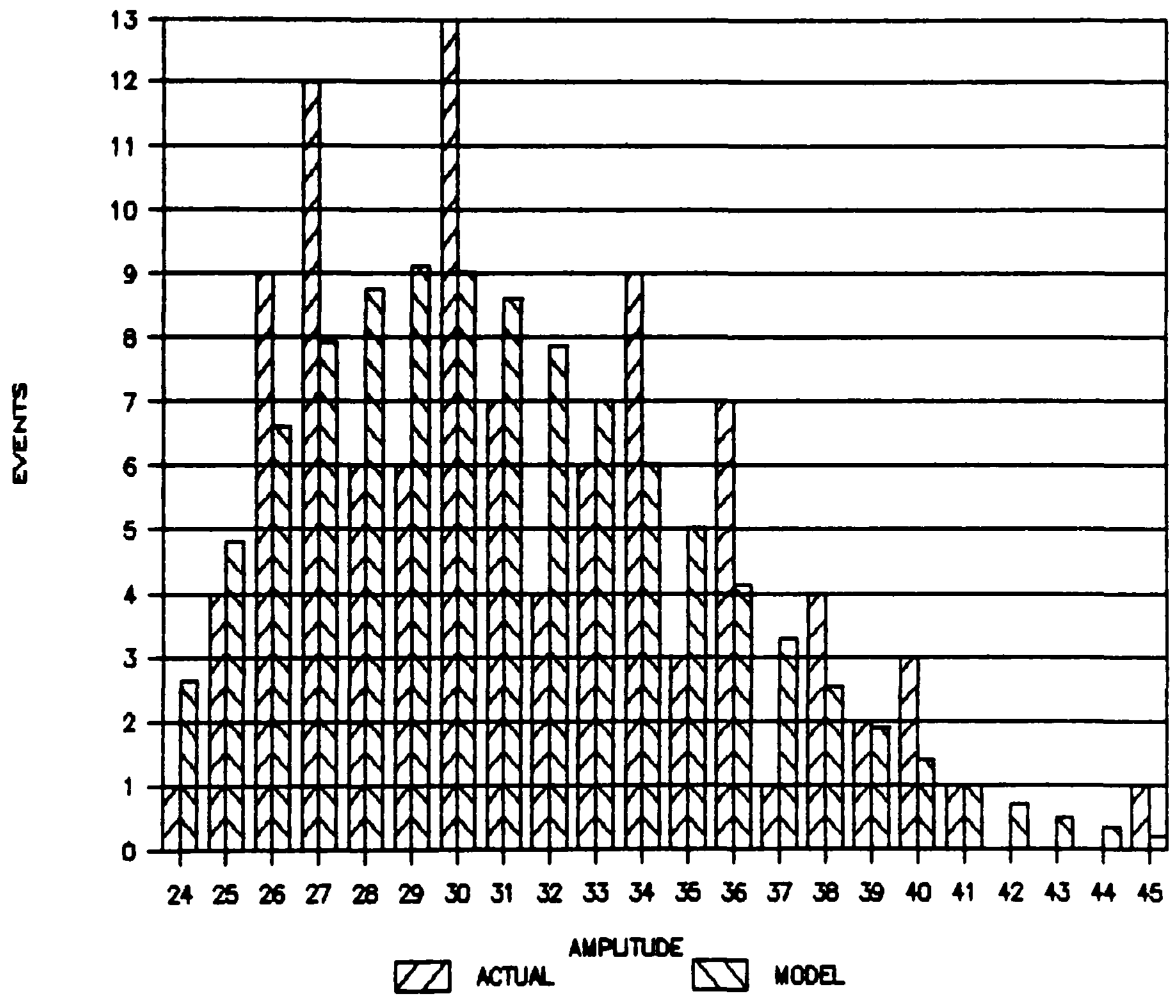

TEST #8
EVENTS
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL

TEST #9


170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
EVENTS
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL


TEST #10
EVENTS
0
5
10
15
20
25
30
35
40
45
50
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
AMPLITUDE
ACTUAL
MODEL

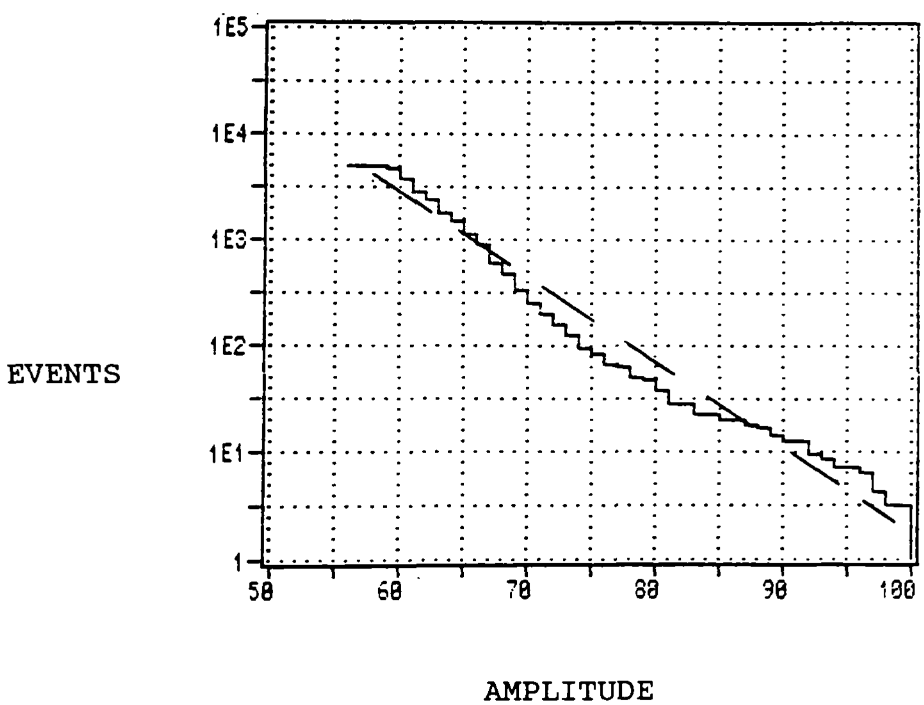
TEST #11


13
12
11
10
9
8
7
6
5
4
3
2
1
0
EVENTS
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
AMPLITUDE
ACTUAL
MODEL

APPENDIX B

POWER LAW MODELING

Power law modeling provides a valuable tool in AE amplitude distribution modeling. By plotting the amplitude distribution on Log-Log scales, oftentimes the resulting graph approximates a straight line, as shown in the figure below.



The slope of the line produced gives a measure of the type of failure mode present during the test. For instance, during the initial portion of loading for most composite materials, where the major source of AE activity is matrix cracking, the slope is large in magnitude. As the load increases, though, and the amount of AE produced by fiber breakage and delaminations increases, the slope will become smaller.

Mathematically, the normalized cumulative density function of the power law may be written as

$$\Phi(V) = (V/Vt)^{-b},$$

where "b" is the slope of the line produced by power law modeling.

Some typical examples of the values for "b" for various materials are given in the table on the following page.

The power law is not without its limitations though. Unfortunately, some distributions do not take on a "linear relationship" when plotted on a Log-Log scale. Furthermore, the power law predicts unrealistic values outside a restricted range. For low amplitudes, the power law predicts an infinitely large number of indefinitely small emissions, while at unrealistically large amplitudes it predicts a finite number of emissions [10].

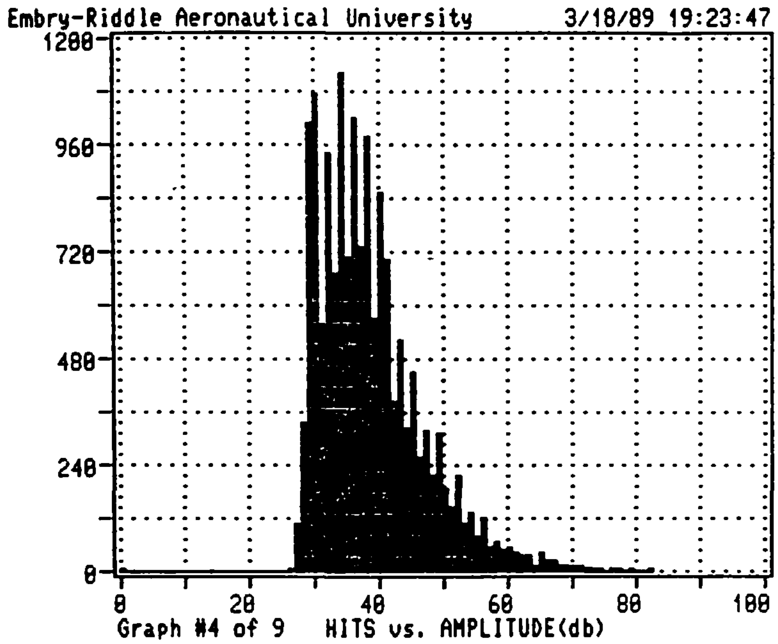
Material	Deformation Mechanism	b-value
Steels		
30 Oak (mild steel)	Plastic zone growth	0.8
A516	Plastic zone growth	4.0
A537	Plastic zone growth	1.5-2.0
X6 Cr Ni 18 11 (aust.)	Plastic zone growth, 550°C	1.5
Kromarc 55 (aust.)	Plastic zone growth, 300°C	1.0
HY-130	Subcritical crack growth	0.4
Ducol (low alloy steel)	Subcritical crack growth (-135°C)	0.4
4340	Stress corrosion cracking	0.8
Other metals		
7075-T6 Al	Growth of crack and plastic zone	1.0
Ti-13Al-22Nb	Tensile test	1.1
Non-metals		
Fiber glass	Inter-layer crack propagation	1.7
Graphite epoxy composite	Surface damage by thermal stress	2.0
Graphite epoxy composite	Internal damage by thermal stress	0.8
Wood laminate	Translaminar shear (before failure)	1.2
Wood laminate	Translaminar shear (after failure)	0.8
Rubber	Tensile test	0.7-1.3
Bone healthy	Uniaxial compression	0.7
Bone during healing	Uniaxial compression	1.0
Bone - pre-Columbian	Uniaxial compression	0.8
Other processes		
Cadmium-plated steel	Debonding of plating	1.0
Steel pipeline	Rainfall	1.2

Typical Examples of "b" Values from Power Law Modeling.

APPENDIX C

WEIBULL ANALYSIS CALCULATIONS FOR TABLE 2

The following statistical analysis was performed on **The Student Edition of MINITAB Statistical Software.**



Test Set-up

Specimens - Type - ASTM D 3039

- Material - Graphite/Epoxy unidirectional

Loading - Parallel to the fiber axis

Equipment - Sensor - PAC model R15

- Preamplifier - PAC model 1220A - 40 dB gain
  - 100-300 khz filter

- Data Acquisition System - LOCAN-AT

Hardware set-up

GAIN = 20 dB

THRESHOLD = 30 dB

HDT = 150 μs

PDT = 40 μs

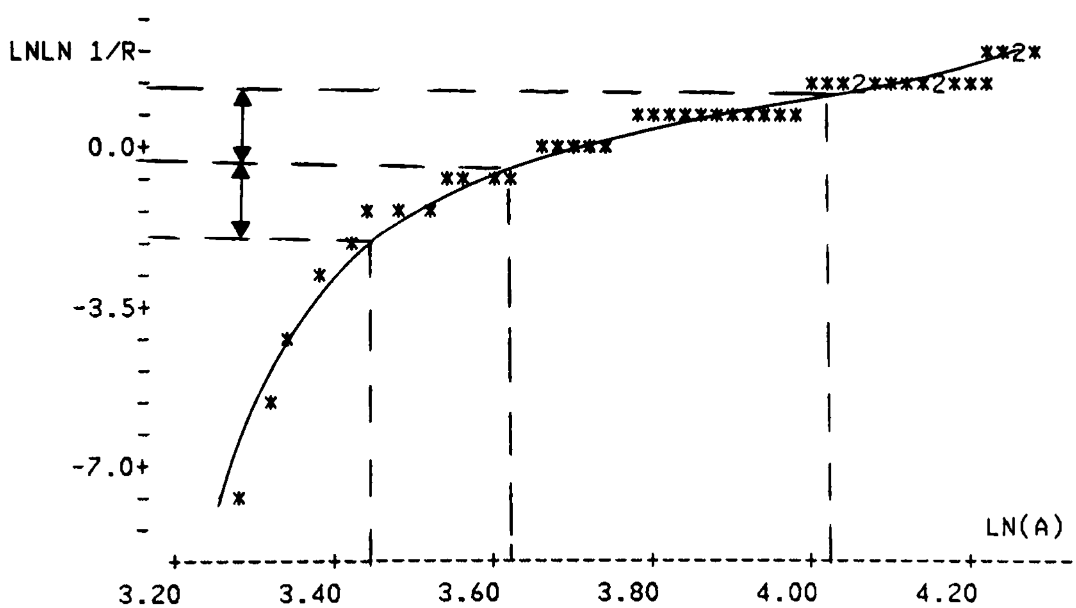
HLT = 300 μs

```
MTB > EXECUTE 'FINDAO'
MTB > LET K1 = SUM(C2)
MTB > LET C3 = C2/K1
MTB > NAME C3 'FREQ.'
MTB > LET C4 = 1 - (PARSUMS(C3) - C3/2)
MTB > NAME C4 'R'
MTB > LET C5 = LOGE(C1)
MTB > NAME C5 'LN(A)'
MTB > LET C6 = LOGE(LOGE(1/C4))
MTB > NAME C6 'LNLN 1/R'
MTB > END
MTB > PRINT C1-C6
```

ROW	C1	C2	FREQ.	R	LN(A)	LNLN 1/R
1	26.5	12	0.0007627	0.999619	3.27714	-7.87167
2	27.5	108	0.0068641	0.995805	3.31419	-5.47183
3	28.5	336	0.0213550	0.981696	3.34990	-3.99140
4	29.5	1008	0.0640651	0.938986	3.38439	-2.76533
5	30.5	1080	0.0686412	0.872633	3.41773	-1.99333
6	31.5	564	0.0358459	0.820389	3.44999	-1.61961
7	32.5	936	0.0594890	0.772722	3.48124	-1.35543
8	33.5	672	0.0427101	0.721622	3.51155	-1.12008
9	34.5	1128	0.0716919	0.664421	3.54096	-0.89443
10	35.5	708	0.0449981	0.606076	3.56953	-0.69165
11	36.5	1020	0.0648278	0.551163	3.59731	-0.51798
12	37.5	732	0.0465235	0.495488	3.62434	-0.35352
13	38.5	984	0.0625397	0.440956	3.65066	-0.19990
14	39.5	576	0.0366086	0.391382	3.67630	-0.06393
15	40.5	852	0.0541502	0.346002	3.70130	0.05950
16	41.5	696	0.0442354	0.296810	3.72569	0.19447
17	42.5	384	0.0244057	0.262489	3.74950	0.29084
18	43.5	528	0.0335579	0.233507	3.77276	0.37469
19	44.5	324	0.0205923	0.206432	3.79549	0.45602
20	45.5	456	0.0289818	0.181645	3.81771	0.53398
21	46.5	264	0.0167789	0.158765	3.83945	0.60995
22	47.5	324	0.0205923	0.140079	3.86073	0.67577
23	48.5	216	0.0137282	0.122919	3.88156	0.74014
24	49.5	312	0.0198297	0.106140	3.90197	0.80781
25	50.5	182	0.0115673	0.090441	3.92197	0.87674
26	51.5	144	0.0091522	0.080081	3.94158	0.92613
27	52.5	216	0.0137282	0.068641	3.96081	0.98539
28	53.5	108	0.0068641	0.058345	3.97968	1.04429
29	54.5	132	0.0083895	0.050718	3.99820	1.09242
30	55.5	84	0.0053388	0.043854	4.01638	1.14004
31	56.5	120	0.0076268	0.037371	4.03424	1.18993
32	57.5	60	0.0038134	0.031651	4.05178	1.23924
33	58.5	72	0.0045761	0.027457	4.06903	1.27959
34	59.5	60	0.0038134	0.023262	4.08598	1.32467
35	60.5	60	0.0038134	0.019448	4.10264	1.37118

36	61.5	48	0.0030507	0.016016	4.11904	1.41928
37	62.5	36	0.0022880	0.013347	4.13517	1.46244
38	63.5	36	0.0022880	0.011059	4.15104	1.50508
39	64.5	12	0.0007627	0.009534	4.16667	1.53750
40	65.5	48	0.0030507	0.007627	4.18205	1.58434
41	66.5	24	0.0015254	0.005339	4.19720	1.65494
42	67.5	24	0.0015254	0.003814	4.21213	1.71725
43	68.5	12	0.0007627	0.002669	4.22683	1.77933
44	69.5	12	0.0007627	0.001907	4.24133	1.83456
45	70.5	12	0.0007627	0.001144	4.25561	1.91297
46	71.5	6	0.0003813	0.000572	4.26970	2.01040
47	72.5	6	0.0003813	0.000191	4.28359	2.14768

MTB > PLOT C6 C5



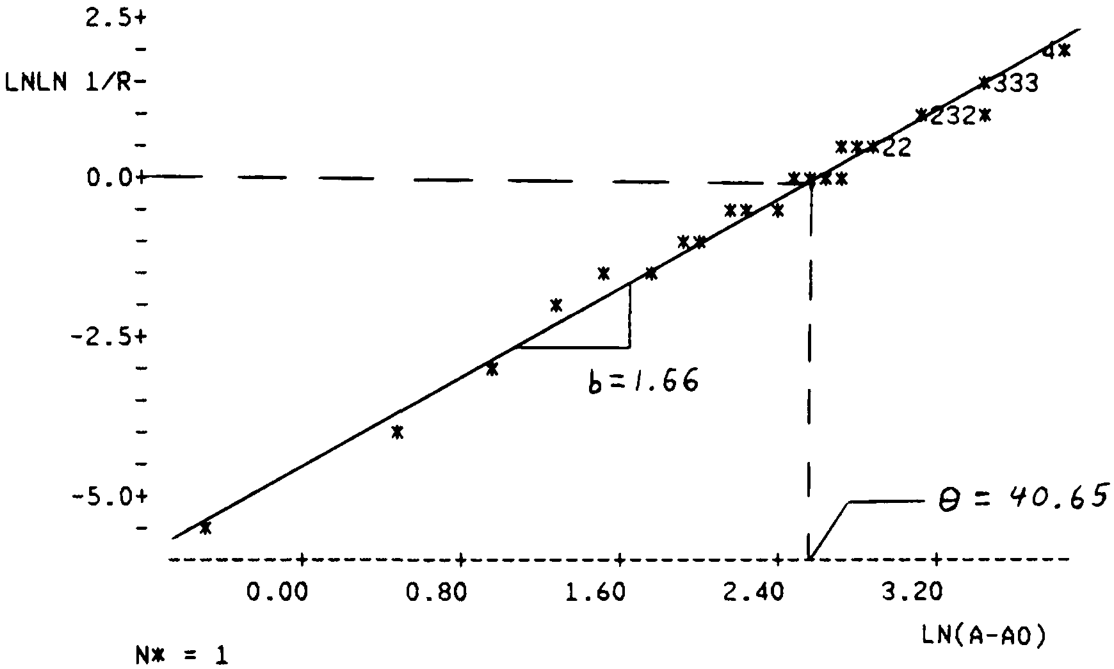

```
MTB > LET K2 = 26.9
MTB > LET C5 = LOGE(C1-K2)
MTB > LET C5 = LOGE(C1-K2)
              A
*** NEGATIVE VALUES FOR SQRT, LOG OR ** AT A
    MISSING RETURNED 1 TIMES

MTB > NAME C5 'LN(A-A0)'
```

MTB > PRINT C1-C6

ROW	C1	C2	FREQ.	R	LN(A-A0)	LNLN 1/R
1	26.5	12	0.0007627	0.999619	*	-7.87167
2	27.5	108	0.0068641	0.995805	-0.51082	-5.47183
3	28.5	336	0.0213550	0.981696	0.47000	-3.99140
4	29.5	1008	0.0640651	0.938986	0.95551	-2.76533
5	30.5	1080	0.0686412	0.872633	1.28093	-1.99333
6	31.5	564	0.0358459	0.820389	1.52606	-1.61961
7	32.5	936	0.0594890	0.772722	1.72277	-1.35543
8	33.5	672	0.0427101	0.721622	1.88707	-1.12008
9	34.5	1128	0.0716919	0.664421	2.02815	-0.89443
10	35.5	708	0.0449981	0.606076	2.15176	-0.69165
11	36.5	1020	0.0648278	0.551163	2.26176	-0.51798
12	37.5	732	0.0465235	0.495488	2.36085	-0.35352
13	38.5	984	0.0625397	0.440956	2.45101	-0.19990
14	39.5	576	0.0366086	0.391382	2.53370	-0.06393
15	40.5	852	0.0541502	0.346002	2.61007	0.05950
16	41.5	696	0.0442354	0.296810	2.68102	0.19447
17	42.5	384	0.0244057	0.262489	2.74727	0.29084
18	43.5	528	0.0335579	0.233507	2.80940	0.37469
19	44.5	324	0.0205923	0.206432	2.86790	0.45602
20	45.5	456	0.0289818	0.181645	2.92316	0.53398
21	46.5	264	0.0167789	0.158765	2.97553	0.60995
22	47.5	324	0.0205923	0.140079	3.02529	0.67577
23	48.5	216	0.0137282	0.122919	3.07269	0.74014
24	49.5	312	0.0198297	0.106140	3.11795	0.80781
25	50.5	182	0.0115673	0.090441	3.16125	0.87674
26	51.5	144	0.0091522	0.080081	3.20275	0.92613
27	52.5	216	0.0137282	0.068641	3.24259	0.98539
28	53.5	108	0.0068641	0.058345	3.28091	1.04429
29	54.5	132	0.0083895	0.050718	3.31782	1.09242
30	55.5	84	0.0053388	0.043854	3.35341	1.14004
31	56.5	120	0.0076268	0.037371	3.38777	1.18993
32	57.5	60	0.0038134	0.031651	3.42100	1.23924
33	58.5	72	0.0045761	0.027457	3.45316	1.27959
34	59.5	60	0.0038134	0.023262	3.48431	1.32467
35	60.5	60	0.0038134	0.019448	3.51453	1.37118
36	61.5	48	0.0030507	0.016016	3.54385	1.41928
37	62.5	36	0.0022880	0.013347	3.57235	1.46244
38	63.5	36	0.0022880	0.011059	3.60005	1.50508
39	64.5	12	0.0007627	0.009534	3.62700	1.53750
40	65.5	48	0.0030507	0.007627	3.65325	1.58434
41	66.5	24	0.0015254	0.005339	3.67883	1.65494
42	67.5	24	0.0015254	0.003814	3.70377	1.71725
43	68.5	12	0.0007627	0.002669	3.72810	1.77933
44	69.5	12	0.0007627	0.001907	3.75185	1.83456
45	70.5	12	0.0007627	0.001144	3.77506	1.91297
46	71.5	6	0.0003813	0.000572	3.79773	2.01040
47	72.5	6	0.0003813	0.000191	3.81991	2.14768

MTB > PLOT C6 C5



MTB > CORRELATE C6 C5

Correlation of LNLN 1/R and LN(A-A0) = 0.997

MTB > REGRESS C6 ON 1 PREDICTOR IN C5

The regression equation is
LNLN 1/R = - 4.35 + 1.66 LN(A-A0)

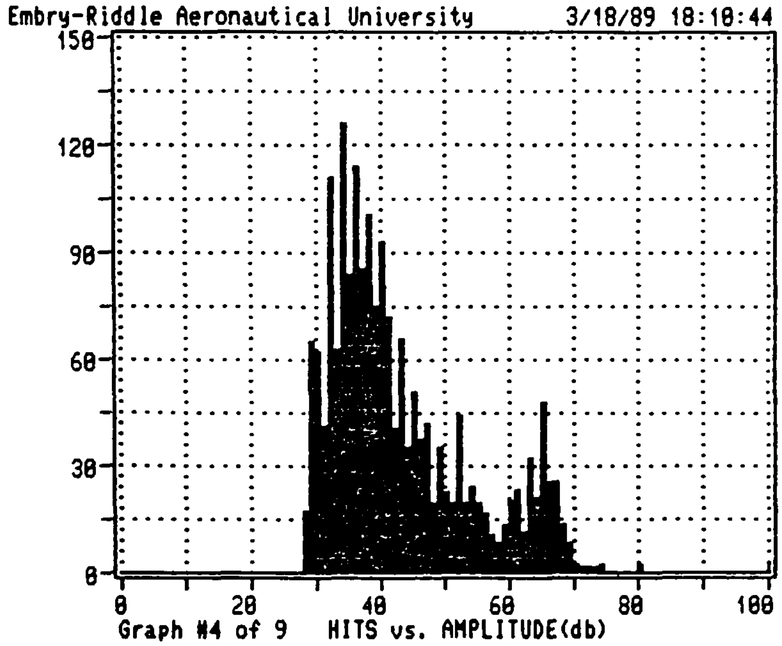
46 cases used 1 cases contain missing values

Predictor	Coef	Stdev	t-ratio	p
Constant	-4.35003	0.05609	-77.56	0.000
LN(A-A0)	1.65502	0.01870	88.50	0.000

s = 0.1192   R-sq = 99.4%   R-sq(adj) = 99.4%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	111.23	111.23	7832.48	0.000
Error	44	0.62	0.01		
Total	45	111.85			



Test Set-up

Specimens - Type - ASTM D 3039

- Material - Graphite/Epoxy unidirectional

Loading - Perpendicular to the fiber axis

Equipment - Sensor - PAC model R15

- Preamplifier - PAC model 1220A - 40 dB gain
  - 100-300 khz filter

- Data Acquisition System - LOCAN-AT

Hardware set-up

GAIN = 20 dB

THRESHOLD = 30 dB

HDT = 150 μs

PDT = 40 μs

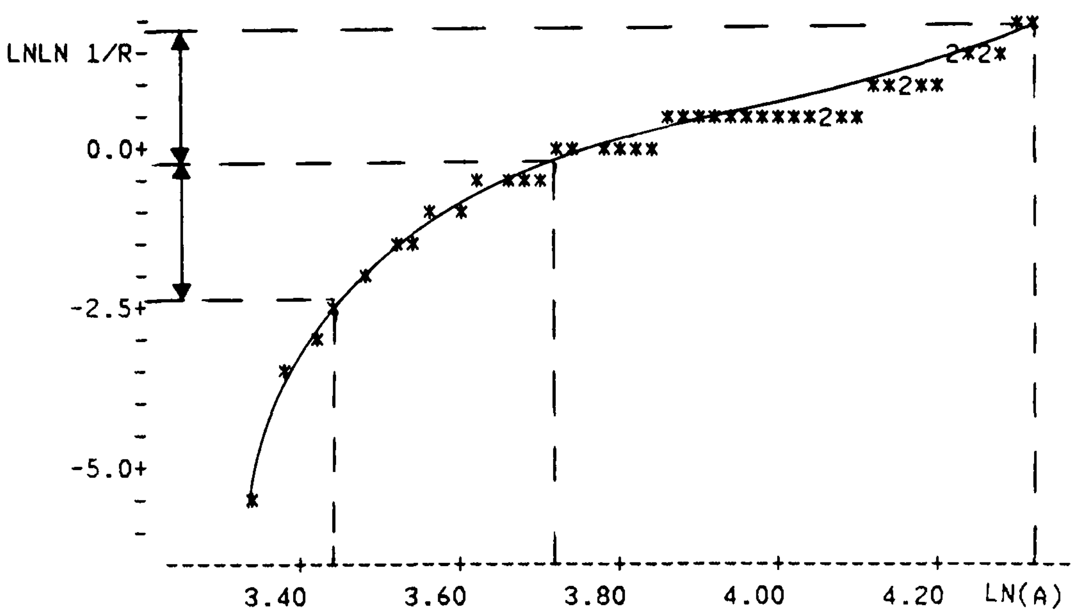
HLT = 300 μs

```
MTB > EXECUTE 'FINDAO'
MTB > LET K1 = SUM(C2)
MTB > LET C3 = C2/K1
MTB > NAME C3 'FREQ.'
MTB > LET C4 = 1 - (PARSUMS(C3) - C3/2)
MTB > NAME C4 'R'
MTB > LET C5 = LOGE(C1)
MTB > NAME C5 'LN(A)'
MTB > LET C6 = LOGE(LOGE(1/C4))
MTB > NAME C6 'LNLN 1/R'
MTB > END
MTB > PRINT C1-C6
```

ROW	C1	C2	FREQ.	R	LN(A)	LNLN 1/R
1	28.5	18	0.0095339	0.995233	3.34990	-5.34365
2	29.5	66	0.0349576	0.972987	3.38439	-3.59779
3	30.5	63	0.0333686	0.938824	3.41773	-2.76261
4	31.5	42	0.0222458	0.911017	3.44999	-2.37307
5	32.5	111	0.0587924	0.870498	3.48124	-1.97551
6	33.5	63	0.0333686	0.824417	3.51155	-1.64466
7	34.5	126	0.0667373	0.774364	3.54096	-1.36370
8	35.5	84	0.0444915	0.718750	3.56953	-1.10793
9	36.5	114	0.0603814	0.666314	3.59731	-0.90141
10	37.5	85	0.0450212	0.613612	3.62434	-0.71664
11	38.5	106	0.0561441	0.563030	3.65066	-0.55439
12	39.5	75	0.0397246	0.515095	3.67630	-0.41037
13	40.5	93	0.0492585	0.470604	3.70130	-0.28271
14	41.5	72	0.0381356	0.426907	3.72569	-0.16112
15	42.5	40	0.0211864	0.397246	3.74950	-0.07991
16	43.5	66	0.0349576	0.369174	3.77276	-0.00352
17	44.5	36	0.0190678	0.342161	3.79549	0.06997
18	45.5	48	0.0254237	0.319915	3.81771	0.13076
19	46.5	37	0.0195975	0.297405	3.83945	0.19282
20	47.5	42	0.0222458	0.276483	3.86073	0.25123
21	48.5	20	0.0105932	0.260064	3.88156	0.29775
22	49.5	36	0.0190678	0.245233	3.90197	0.34043
23	50.5	22	0.0116525	0.229873	3.92197	0.38542
24	51.5	20	0.0105932	0.218750	3.94158	0.41860
25	52.5	45	0.0238347	0.201536	3.96081	0.47112
26	53.5	20	0.0105932	0.184322	3.97968	0.52536
27	54.5	24	0.0127119	0.172669	3.99820	0.56325
28	55.5	20	0.0105932	0.161017	4.01638	0.60226
29	56.5	17	0.0090042	0.151218	4.03424	0.63606
30	57.5	11	0.0058263	0.143803	4.05178	0.66233
31	58.5	9	0.0047669	0.138506	4.06903	0.68150
32	59.5	13	0.0068856	0.132680	4.08598	0.70301
33	60.5	21	0.0111229	0.123676	4.10264	0.73721
34	61.5	24	0.0127119	0.111758	4.11904	0.78455
35	62.5	12	0.0063559	0.102224	4.13517	0.82443
36	63.5	33	0.0174788	0.090307	4.15104	0.87736
37	64.5	21	0.0111229	0.076006	4.16667	0.94660

38	65.5	48	0.0254237	0.057733	4.18205	1.04800
39	66.5	25	0.0132415	0.038400	4.19720	1.18163
40	67.5	25	0.0132415	0.025159	4.21213	1.30361
41	68.5	14	0.0074153	0.014830	4.22683	1.43772
42	69.5	9	0.0047669	0.008739	4.24133	1.55602
43	70.5	3	0.0015890	0.005561	4.25561	1.64710
44	71.5	2	0.0010593	0.004237	4.26970	1.69816
45	72.5	2	0.0010593	0.003178	4.28359	1.74947
46	73.5	2	0.0010593	0.002119	4.29729	1.81759
47	74.5	3	0.0015890	0.000794	4.31080	1.96541

```
MTB > PLOT C6 C5
```

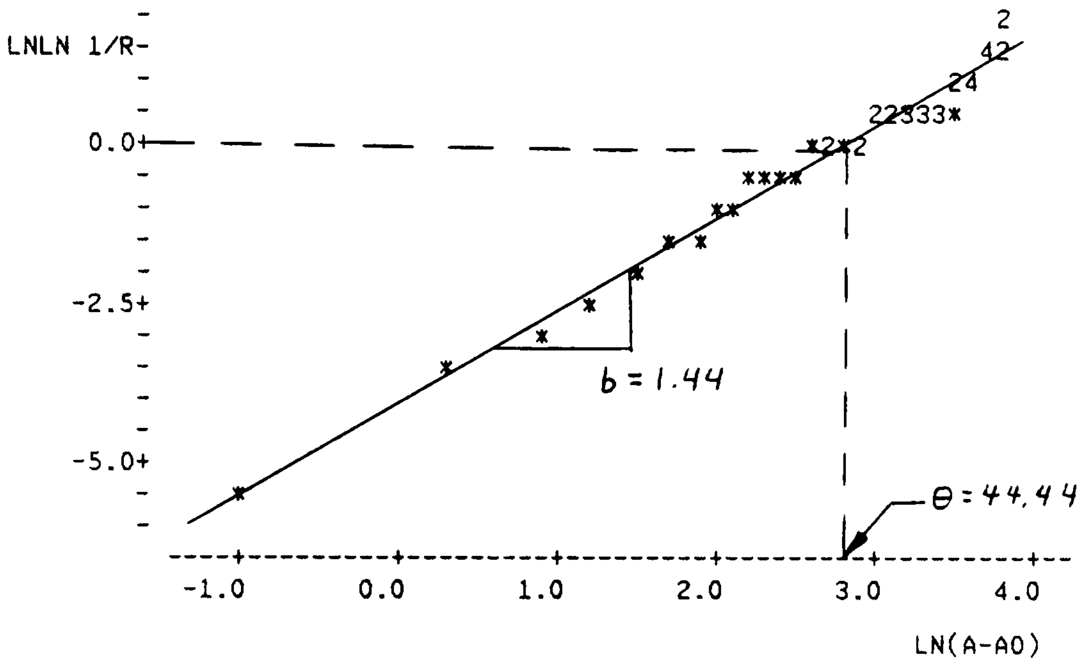



```
MTB > LET K2 = 28.13
MTB > LET C5 = LOGE(C1-K2)
MTB > NAME C5 'LN(A-A0)'
```

MTB > PRINT C1-C6

ROW	C1	C2	FREQ.	R	LN(A-A0)	LNLN 1/R
1	28.5	18	0.0095339	0.995233	-0.99425	-5.34365
2	29.5	66	0.0349576	0.972987	0.31481	-3.59779
3	30.5	63	0.0333686	0.938824	0.86289	-2.76261
4	31.5	42	0.0222458	0.911017	1.21491	-2.37307
5	32.5	111	0.0587924	0.870498	1.47476	-1.97551
6	33.5	63	0.0333686	0.824417	1.68083	-1.64466
7	34.5	126	0.0667373	0.774364	1.85160	-1.36370
8	35.5	84	0.0444915	0.718750	1.99742	-1.10793
9	36.5	114	0.0603814	0.666314	2.12465	-0.90141
10	37.5	85	0.0450212	0.613612	2.23751	-0.71664
11	38.5	106	0.0561441	0.563030	2.33892	-0.55439
12	39.5	75	0.0397246	0.515095	2.43098	-0.41037
13	40.5	93	0.0492585	0.470604	2.51527	-0.28271
14	41.5	72	0.0381356	0.426907	2.59301	-0.16112
15	42.5	40	0.0211864	0.397246	2.66514	-0.07991
16	43.5	66	0.0349576	0.369174	2.73242	-0.00352
17	44.5	36	0.0190678	0.342161	2.79545	0.06997
18	45.5	48	0.0254237	0.319915	2.85474	0.13076
19	46.5	37	0.0195975	0.297405	2.91072	0.19282
20	47.5	42	0.0222458	0.276483	2.96373	0.25123
21	48.5	20	0.0105932	0.260064	3.01406	0.29775
22	49.5	36	0.0190678	0.245233	3.06199	0.34043
23	50.5	22	0.0116525	0.229873	3.10772	0.38542
24	51.5	20	0.0105932	0.218750	3.15145	0.41860
25	52.5	45	0.0238347	0.201536	3.19335	0.47112
26	53.5	20	0.0105932	0.184322	3.23357	0.52536
27	54.5	24	0.0127119	0.172669	3.27223	0.56325
28	55.5	20	0.0105932	0.161017	3.30945	0.60226
29	56.5	17	0.0090042	0.151218	3.34533	0.63606
30	57.5	11	0.0058263	0.143803	3.37997	0.66233
31	58.5	9	0.0047669	0.138506	3.41346	0.68150
32	59.5	13	0.0068856	0.132680	3.44585	0.70301
33	60.5	21	0.0111229	0.123676	3.47723	0.73721
34	61.5	24	0.0127119	0.111758	3.50766	0.78455
35	62.5	12	0.0063559	0.102224	3.53718	0.82443
36	63.5	33	0.0174788	0.090307	3.56586	0.87736
37	64.5	21	0.0111229	0.076006	3.59374	0.94660
38	65.5	48	0.0254237	0.057733	3.62087	1.04800
39	66.5	25	0.0132415	0.038400	3.64728	1.18163
40	67.5	25	0.0132415	0.025159	3.67300	1.30361
41	68.5	14	0.0074153	0.014830	3.69809	1.43772
42	69.5	9	0.0047669	0.008739	3.72256	1.55602
43	70.5	3	0.0015890	0.005561	3.74644	1.64710
44	71.5	2	0.0010593	0.004237	3.76977	1.69816
45	72.5	2	0.0010593	0.003178	3.79256	1.74947
46	73.5	2	0.0010593	0.002119	3.81485	1.81759
47	74.5	3	0.0015890	0.000794	3.83665	1.96541

MTB > PLOT C6 C5



MTB > CORRELATE C6 C5

Correlation of LNLN 1/R and LN(A-A0) = 0.993

MTB > REGRESS C6 ON 1 PREDICTOR IN C5

The regression equation is
LNLN 1/R = - 4.02 + 1.44 LN(A-A0)

Predictor	Coef	Stdev	t-ratio	p
Constant	-4.01532	0.07535	-53.29	0.000
LN(A-A0)	1.43784	0.02503	57.44	0.000

s = 0.1710 R-sq = 98.7% R-sq(adj) = 98.6%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	96.474	96.474	3298.80	0.000
Error	45	1.316	0.029		
Total	46	97.790			

APPENDIX D

AESORT PROGRAM

```
10 CLEAR
20 GOTO 2520
30 REM
40 CLEAR
50 REM ***** DIMENSION ARRAYS *****
60 DIM A(10000),AMP(120),R(120),XAXIS(120),YAXIS(120)
70 DIM YFITTED(120), RESID(120), SQRESID(120), FX(120)
80 REM
90 REM ***** VARIABLE DESCRIPTIONS GIVEN IN README.BAS FILE *****
100 REM
110 REM ***** DATA INPUT ROUTINE *****
120 J=0
130 PRINT "ENTER THE TEST FILENAME, EXTENSION AND PATHING INSTRUCTIONS."
140 INPUT FILE$
150 PRINT
160 PRINT "ENTER THE MAXIMUM LOAD TO BE INCLUDED IN THIS STUDY."
170 INPUT MLOAD
180 PRINT
190 OPEN "I",1,FILE$
200 IF EOF(1) THEN PRINT "END OF FILE.  :GOTO 270
210 Q$=INPUT$(21,#1)
220 INPUT#1,P1
230 IF P1 > (MLOAD/1000) THEN GOTO 270
240 INPUT#1,CH,DUR,EN,PC,CO,A(I),PD
250 I=I+1
260 GOTO 200
270 PRINT "DATA TRANSFERAL COMPLETE.
280 PRINT USING "THE NUMBER OF EVENTS UP TO #### LBS. IS #####.";MLOAD,I
290 CLOSE #1
```

```
300 BEEP
310 REM
320 GOTO 380
330 REM ** RESET FOR NEW TEST BOUNDARIES **
340 EVENTS = 0
350 FOR Y = 0 TO 120
360   AMP(Y) = 0
370 NEXT Y
380 REM ***** AMPLITUDE COUNTING ROUTINE *****
390 PRINT
400 PRINT "USE THE DEFAULT VALUE FOR THE EVENT CUT-OFF POINT? Y/N"
410 INPUT Q$
420 IF Q$ = "Y" OR Q$ = "y" THEN GOTO 480
430 PRINT " "
440 PRINT "ENTER THE EVENT CUT-OFF VALUE"
450 INPUT II
460 IF II > I THEN GOTO 480
470 I = II
480 PRINT   '
490 PRINT "ENTER THE MINIMUM AMPLITUDE TO BE INCLUDED IN THIS STUDY."
500 INPUT MINAMP
510 PRINT
520 PRINT "USE THE DEFAULT VALUE FOR THE MAXIMUM AMPLITUDE? Y/N.
530 INPUT DEFAULT$
540 IF DEFAULT$ = "Y" OR DEFAULT$ = "y" THEN MAXAMP = 0 :GOTO 590
550 IF DEFAULT$ <> "N" AND DEFAULT$ <> "n" THEN GOTO 520
560 PRINT
570 PRINT "ENTER THE MAXIMUM AMPLITUDE TO BE INCLUDED IN THIS STUDY.'
```

```
580 INPUT MAXAMP
590 PRINT " '
600 PRINT "WORKING"
610 FOR Y=0 TO I
620    IF A(Y) < MINAMP THEN GOTO 670
630    AMP(A(Y)) = AMP(A(Y)) + 1
640    IF A(Y) > MAXAMP AND DEFAULT$ = "Y" OR A(Y) > MAXAMP AND DEFAULT$ = "y" T
HEN MAXAMP = A(Y)
650    IF A(Y) <= MAXAMP AND DEFAULT$ = "N" OR A(Y) <= MAXAMP AND DEFAULT$ = "n"
 THEN EVENTS = EVENTS + 1
660    IF DEFAULT$ = "Y" OR DEFAULT$ = "y" THEN EVENTS = EVENTS + 1
670 NEXT Y
680 BEEP
690 PRINT
700 PRINT USING "THERE ARE ##### EVENTS INCLUDED IN THIS STUDY.";EVENTS
710 PRINT " '
720 PRINT "CR TO RETURN TO THE MAIN MENU."
730 INPUT Q$
740 GOTO 2520
750 REM ****** OUTPUT *******
760   LPRINT                 AMPLITUDE(dB)               EVENTS"
770   FOR Y=MINAMP TO MAXAMP
780     IF AMP(Y) = 0 THEN GOTO 800
790     LPRINT USING                    ###                        ####";Y,AMP(Y)
800   NEXT Y
810 GOTO 2520
820 REM
830 REM ***** WEIBULL ANALYSIS ROUTINE *****
840 PARSUMS = 0
```

```
850 FOR Y = MINAMP TO MAXAMP
860   PARSUMS=PARSUMS + AMP(Y)/EVENTS
870   R(Y) = 1 - PARSUMS + AMP(Y)/(EVENTS*2)
880 NEXT Y
890 PRINT ' "
900 PRINT "ENTER THE THRESHOLD AMPLITUDE."
910 INPUT THRESHOLD
920 PRINT " "
930 PRINT "OUTPUT DATA FOR LN(A-A0) AND LNLN(1/R)? Y/N"
940 INPUT Q$
950 IF Q$ = "Y" OR Q$ = "y" THEN LPRINT '          LN(A-A0)             LNLN(1/
R)"
960 PRINT
970 C = 0
980 CC = 0
990 FOR Y = MINAMP TO MAXAMP
1000   IF (Y - THRESHOLD) > 0 THEN GOTO 1050
1010    XAXIS(Y) = 0
1020    YAXIS(Y) = 0
1030    C = C + 1
1040   GOTO 1120
1050    XAXIS(Y) = LOG(Y - THRESHOLD)
1060   IF R(Y) > 0 THEN GOTO 1090
1070    CC = CC + 1
1080    GOTO 1120
1090    YAXIS(Y) = LOG(LOG(1/R(Y)))
1100   IF Q$ = "N" OR Q$ = "n" THEN GOTO 1120                .
1110    LPRINT USING           ##.######            ##.###### ";XAXIS(Y),YAXIS
(Y)
```

```
1120 NEXT Y
1130 GOTO 1500
1140 PRINT "DO YOU WANT TO SAVE THE LINEAR REGRESION MODEL AND ORIGINAL DATA POI
NTS TO DISK? Y/N"
1150 INPUT QQ$
1160 IF QQ$ = "N" OR QQ$ = "n" THEN GOTO 1260
1170 PRINT
1180  PRINT "ENTER THE DISK DESTINATION CODES AND NAME. ie C:\LOTUS\FILES\NAME.P
RN"
1190  INPUT LFILE$
1200  OPEN "O",#2,LFILE$
1210  FOR Y = TMIN TO TMAX
1220     M = BOH + B1H * XAXIS(Y)
1230     WRITE #2,XAXIS(Y),YAXIS(Y),M
1240  NEXT Y
1250  CLOSE #2
1260 THETA = EXP(ABS(BOH/B1H)) + THRESHOLD
1270 CLS
1280 PRINT USING "AO=###.##     b=##.####      THETA=###.##";THRESHOLD,B1H,THETA
1290 PRINT
1300 ZZ = THETA - THRESHOLD
1310 FOR Y=TMIN TO TMAX
1320    Z = Y - THRESHOLD
1330    FX(Y) = EVENTS * (B1H/ZZ)*((Z/ZZ)^(B1H-1))*EXP(-(Z/ZZ)^B1H)
1340 NEXT Y
1350 PRINT "DO YOU WANT TO SEE THE WEIBULL DISTRIBUTION COORDINATES? Y/N"
1360 INPUT Q$
1370 IF Q$ = "Y" OR Q$ = "y" THEN GOTO 2180
1380 PRINT '
```

```
1390 PRINT "DO YOU WANT TO SAVE THE WEIBULL DISTRIBUTION DATA TO DISK? Y/N"
1400 INPUT Q$
1410 IF Q$ = "Y" OR Q$ = "y" THEN GOTO 2260
1420 PRINT
1430 PRINT "DO YOU WISH TO VIEW THE ANOVA TABLE. (Y/N)"
1440 INPUT Q$
1450 IF Q$ = "Y" OR Q$ = "y" THEN GOTO 2000
1460 PRINT ' "
1470 PRINT "CR TO RETURN TO MAIN MENU.
1480 INPUT Q$
1490 GOTO 2520
1500 REM ***** LINEAR REGRESSION ANALYSIS *****
1510 REM ** RESET PARAMETERS **
1520 N=0
1530 SX=0
1540 SY=0
1550 SXY=0
1560 SXS=0
1570 SYS=0
1580 SSXY=0
1590 SSXX=0
1600 SSYY=0
1610 TMIN = MINAMP + C
1620 TMAX = MAXAMP - CC
1630 FOR Y = TMIN TO TMAX
1640      SX = SX + XAXIS(Y)
1650      SY = SY + YAXIS(Y)
1660      SXY = SXY + XAXIS(Y) * YAXIS(Y)
1670      SXS = SXS + XAXIS(Y)^2
```

```
1680       SYS = SYS + YAXIS(Y)^2
1690       N = N + 1
1700 NEXT Y
1710  SSXY = SSXY + SXY - (SX * SY)/N
1720  SSXX = SSXX + SXS - (SX^2)/N
1730  SSYY = SSYY + SYS - (SY^2)/N
1740  SST = SSYY
1750  B1H = SSXY/SSXX
1760  B0H = SY/N - B1H * (SX/N)
1770 REM
1780 REM ***** RESIDUAL ANALYSIS *****
1790 SUMRESID=0
1800 SSE=0
1810 FOR Y = TMIN TO TMAX
1820     YFITTED(Y) = (XAXIS(Y) * B1H) + B0H
1830     RESID(Y) = YFITTED(Y) - YAXIS(Y)
1840     SQRESID(Y) = RESID(Y)^2
1850     SUMRESID = SUMRESID + RESID(Y)
1860     SSE = SSE + SQRESID(Y)
1870 NEXT Y
1880 S = SQR(SSE/(N-2))
1890 SSR = SST - SSE
1900 K = 2
1910 DFR = K - 1
1920 DFE = N - K
1930 DFT = DFR + DFE
1940 MSR = SSR/DFR
1950 MSE = SSE/DFE
1960 F = MSR/MSE
```

```
1970 RSQ = 100 * (1 - (SSE/SST))
1980 RSA = 100 * (1 - (SSE/DFE)/(SST/DFT))
1990 GOTO 1140
2000 REM ***** STATISTICAL OUTPUT *****
2010 CLS
2020 PRINT ' '
2030 PRINT USING "THE REGRESSION EQUATION IS Y= ####.#### + ####.#### X.";B0H,B1
H
2040 PRINT
2050 PRINT "ANALYSIS OF VARIANCE"
2060 PRINT " "
2070 PRINT "SOURCE        DF          SS             MS            F"
2080 PRINT USING "REGRESSION   ###      #####.####   #####.####    #####.####";D
FR,SSR,MSR,F
2090 PRINT USING "ERROR        ###      #####.####   #####.####";DFE,SSE,MSE
2100 PRINT USING "TOTAL        ###      #####.####";DFT,SST
2110 PRINT "
2120 PRINT USING "S= ####.####    R-SQ= ##.##%    R-SQa= ##.##%";S,RSQ,RSA
2130 PRINT
2140 LOCATE 22,1:PRINT "CR TO RETURN TO MAIN MENU"
2150 INPUT Q$
2160 GOTO 2520
2170 REM
2180 REM ***** WEIBULL DISTRIBUTION COORDINATES *****
2190 LPRINT                       WEIBULL DISTRIBUTION COORDINATES
2200 LPRINT                         AMPLITUDE             EVENTS
2210 LPRINT
2220 FOR Y = TMIN TO TMAX
2230    LPRINT USING                         ###.#              ####.##";Y,FX(Y
```

```
2240 NEXT Y
2250 GOTO 1380
2260 PRINT " "
2270 PRINT "ENTER THE DISK DESTINATION CODES AND NAME. ie C:\LOTUS\FILES\G1.PRN"
2280 INPUT GFILE$
2290 PRINT " "
2300 PRINT "THE DATA WILL BE SAVE IN COLUMN FORM AS AMPLITUDE, EVENTS AND"
2310 PRINT "MODEL EVENTS."
2320 OPEN "O",#3,GFILE$
2330 FOR Y = TMIN TO TMAX
2340   WRITE #3,Y,AMP(Y),FX(Y)
2350 NEXT Y
2360 CLOSE #3
2370 GOTO 1420
2380 REM ***** STATISTICS FILE INPUT/OUTPUT *****
2390 PRINT "ENTER THE NAME OF THE STATISTICS OUTPUT FILE"
2400 INPUT OUTFILE$
2410 OPEN "O",#2,OUTFILE$
2420 WRITE #2,MSR,MSE,F,RSQ,DFT,THRESHOLD,SST,B1H,B0H,SSE,S,SSR,DFR,DFE,RSA
2430 CLOSE #2
2440 GOTO 2520
2450 REM
2460 CLS
2470 PRINT "ENTER THE NAME OF THE STATISTICS FILE TO RETRIEVE"
2480 INPUT INFILE$
2490 OPEN "I",#3,INFILE$
2500 INPUT #3,MSR,MSE,F,RSQ,DFT,THRESHOLD,SST,B1H,B0H,SSE,S,SSR,DFR,DFE,RSA
2510 CLOSE #3
```

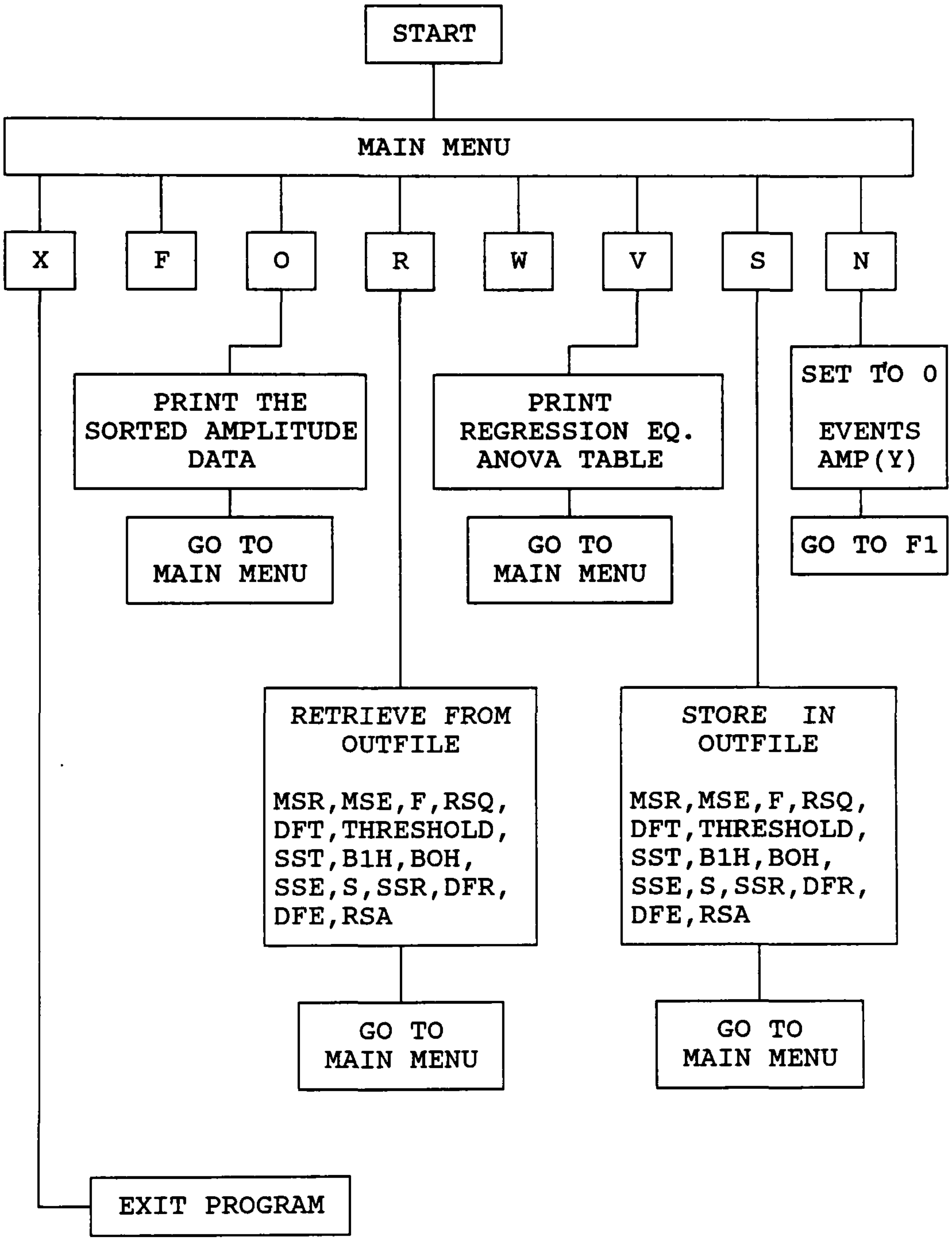
```
2520 REM ***** HEADER *****
2530 CLS
2540 LOCATE 2,21:PRINT CHR$(213);:FOR X=1 TO 38:PRINT CHR$(205);:NEXT:PRINT CHR$
(184)
2550 LOCATE 3,21:PRINT CHR$(179);"       AE-SORT MAIN PROGRAM MENU      ";CHR$(1
79)
2560 LOCATE 4,21:PRINT CHR$(198);:FOR X=1 TO 38:PRINT CHR$(205);:NEXT:PRINT CHR$
(181)
2570 LOCATE 5,21:PRINT CHR$(179) :LOCATE 5,25:PRINT CHR$(179) :LOCATE 5,60 :PRIN
T CHR$(179)
2580 LOCATE 6,21:PRINT CHR$(179); ' F   ;CHR$(179);" ENTER A NEW FILE TO ANALYZE
      ";CHR$(179)
2590 LOCATE 7,21:PRINT CHR$(179) :LOCATE 7,25:PRINT CHR$(179) :LOCATE 7,60 :PRIN
T CHR$(179)
2600 LOCATE 8,21:PRINT CHR$(179); ' O ";CHR$(179);" OUTPUT SORTED AE DATA
     ";CHR$(179)
2610 LOCATE 9,21:PRINT CHR$(179) :LOCATE 9,25:PRINT CHR$(179) :LOCATE 9,60 :PRIN
T CHR$(179)
2620 LOCATE 10,21:PRINT CHR$(179);   W   ;CHR$(179);" WEIBULL ANALYSIS ROUTINE
       ";CHR$(179)
2630 LOCATE 11,21:PRINT CHR$(179) :LOCATE 11,25:PRINT CHR$(179) :LOCATE 11,60:PR
INT CHR$(179)
2640 LOCATE 12,21:PRINT CHR$(179);   N   ;CHR$(179);" RETEST WITH NEW BOUNDARIES
       ";CHR$(179)
2650 LOCATE 13,21:PRINT CHR$(179) :LOCATE 13,25:PRINT CHR$(179) :LOCATE 13,60:PR
INT CHR$(179)
2660 LOCATE 14,21:PRINT CHR$(179);   S   ;CHR$(179);' SAVE STATISTICAL DATA TO F
ILE    ";CHR$(179)
```

```
2670 LOCATE 15,21:PRINT CHR$(195);:FOR X=1 TO 38 :PRINT CHR$(196);:NEXT:PRINT CH
R$(180)
2680 LOCATE 16,21:PRINT CHR$(179);   R ";CHR$(179);" REVIEW A STORED STATISTICAL
 FILE ";CHR$(179)
2690 LOCATE 17,21:PRINT CHR$(179) :LOCATE 17,25:PRINT CHR$(179) :LOCATE 17,60:PR
INT CHR$(179)
2700 LOCATE 18,21:PRINT CHR$(179);   V   ;CHR$(179);" VIEW ANOVA TABLE
       ";CHR$(179)
2710 LOCATE 19,21:PRINT CHR$(195);:FOR X=1 TO 38 :PRINT CHR$(196);:NEXT:PRINT CH
R$(180)
2720 LOCATE 20,21:PRINT CHR$(179); ' X ' ;CHR$(179);" EXIT PROGRAM
       ";CHR$(179)
2730 LOCATE 21,21:PRINT CHR$(198);:FOR X=1 TO 38 :PRINT CHR$(205);:NEXT:PRINT CH
R$(181)
2740 LOCATE 22,21:PRINT CHR$(179);            ENTER YOUR SELECTION        ";CHR$
(179)
2750 LOCATE 23,21:PRINT CHR$(212);:FOR X=1 TO 38 :PRINT CHR$(205);:NEXT:PRINT CH
R$(190)
2760 INPUT CHOICE$
2770 CLS
2780 IF CHOICE$ = "X" OR CHOICE$ = "x" THEN CLS:END
2790 IF CHOICE$ = "F" OR CHOICE$ = "f" THEN GOTO 30
2800 IF CHOICE$ = "O" OR CHOICE$ = "o" THEN GOTO 750
2810 IF CHOICE$ = "R" OR CHOICE$ = "r" THEN GOTO 2450
2820 IF CHOICE$ = "W" OR CHOICE$ = "w" THEN GOTO 830
2830 IF CHOICE$ = "V" OR CHOICE$ = "v" THEN GOTO 2030
2840 IF CHOICE$ = "S" OR CHOICE$ = "s" THEN GOTO 2380
2850 IF CHOICE$ = "N" OR CHOICE$ = "n" THEN GOTO 330
```

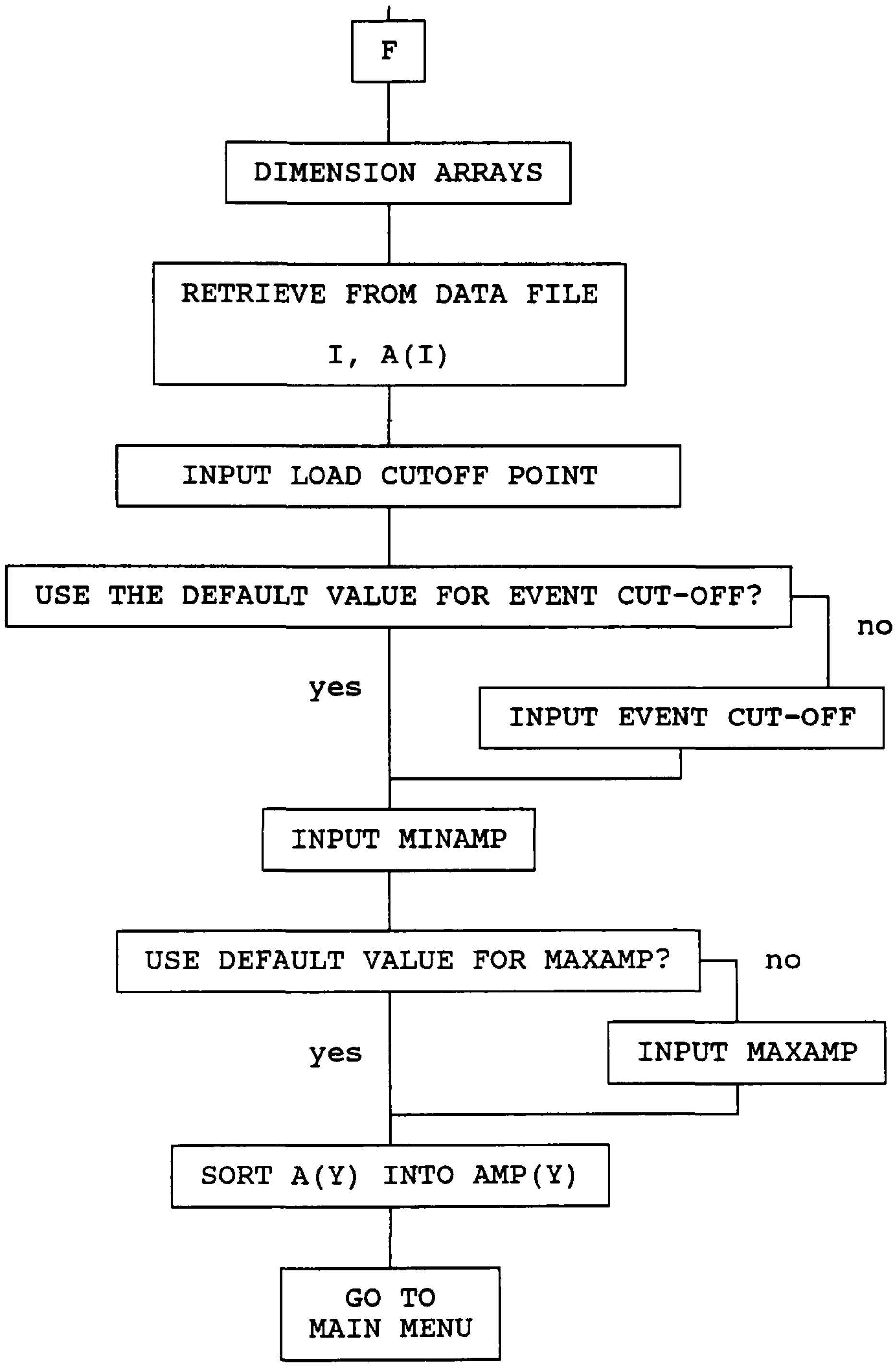
```
10 REM THIS FILE CONTAINS THE VARIABLE DESCRIPTIONS FOR "AE-SORT".
20 REM ***** ARRAYS *****
30 REM A(I) => CONTAINS THE AMPLITUDE OF EVENT NUMBER "I".
40 REM AMP(I) => CONTAINS THE SORTED AMPLITUDE DATA FOR AMPLITUDE "I".
50 REM R(I) => CONTAINS THE RELIABILITY OF A THE "I'TH" VALUE.
60 REM XAXIS(I) => CONTAINS THE VALUE OF LN(A-AO) FOR "I".
70 REM YAXIS(I) => CONTAINS THE VALUE OF LNLN(1/R(I)).
80 REM FX(I) => WEIBULL MODEL COORDINATES
90 REM YFITTED(I) => THE FITTED Y COORDINATE FOR THE LEAST SQUARES MODEL.
100 REM RESID(I) => THE DIFFERENCE BETWEEN THE YFITTED VALUE AND THE
    ACTUAL VALUE.
110 REM SQRESID(I) => THE SUM OF THE RESIDUALS SQUARED.
120 REM ***** CHARACTER VARIABLES *****
130 REM GFILE$ => WEIBULL MODEL DATA FILE.
140 REM OUTFILE$ => STATISTICS OUTPUT FILE.
150 REM INFILE$ => STATISTICS INPUT FILE.
160 REM DEFAULT$ => USED TO CONTROL DEFAULT FOR MAXAMP.
170 REM LFILE$ => LINEAR REGRESSION MODEL DATA FILE
180 REM FILE$ => THE FILENAME, EXTENSION AND PATH TO LOCATE THE FILE
    CONTAINING
190 REM          THE ASCII VERSION OF THE AE DATA.
200 REM Q$     => A DUMMY VARIABLE TO STORE THE FIRST 50 CHARACTERS OF
    FILE$.
210 REM L$     => USED TO LIST SORTED ENERGY AND AMPLITUDE DATA.
220 REM YY$    => USED TO CONTROL CONTINUATION OF LIST COMMAND.
230 REM ***** NUMERIC VARIABLES *****
240 REM MINAMP=> THE SMALLEST AMPLITUDE VALUE TO BE INCLUDED IN THE
    STUDY.
250 REM MAXAMP=> THE LARGEST AMPLITUDE TO BE INCLUDED IN THE STUDY.
260 REM MAXENERGY=> THE LARGEST VALUE OF ENERGY.
270 REM MINENERGY=> THE SMALLEST VALUE OF ENERGY.
280 REM EVENTS=> THE TOTAL NUMBER OF EVENTS INCLUDED IN THE STUDY.
290 REM PARSUMS=> THE SUM OF NUMBER OF EVENTS UP TO A GIVEN POINT.
300 REM SX => THE SUM OF ALL XAXIS(I).
```

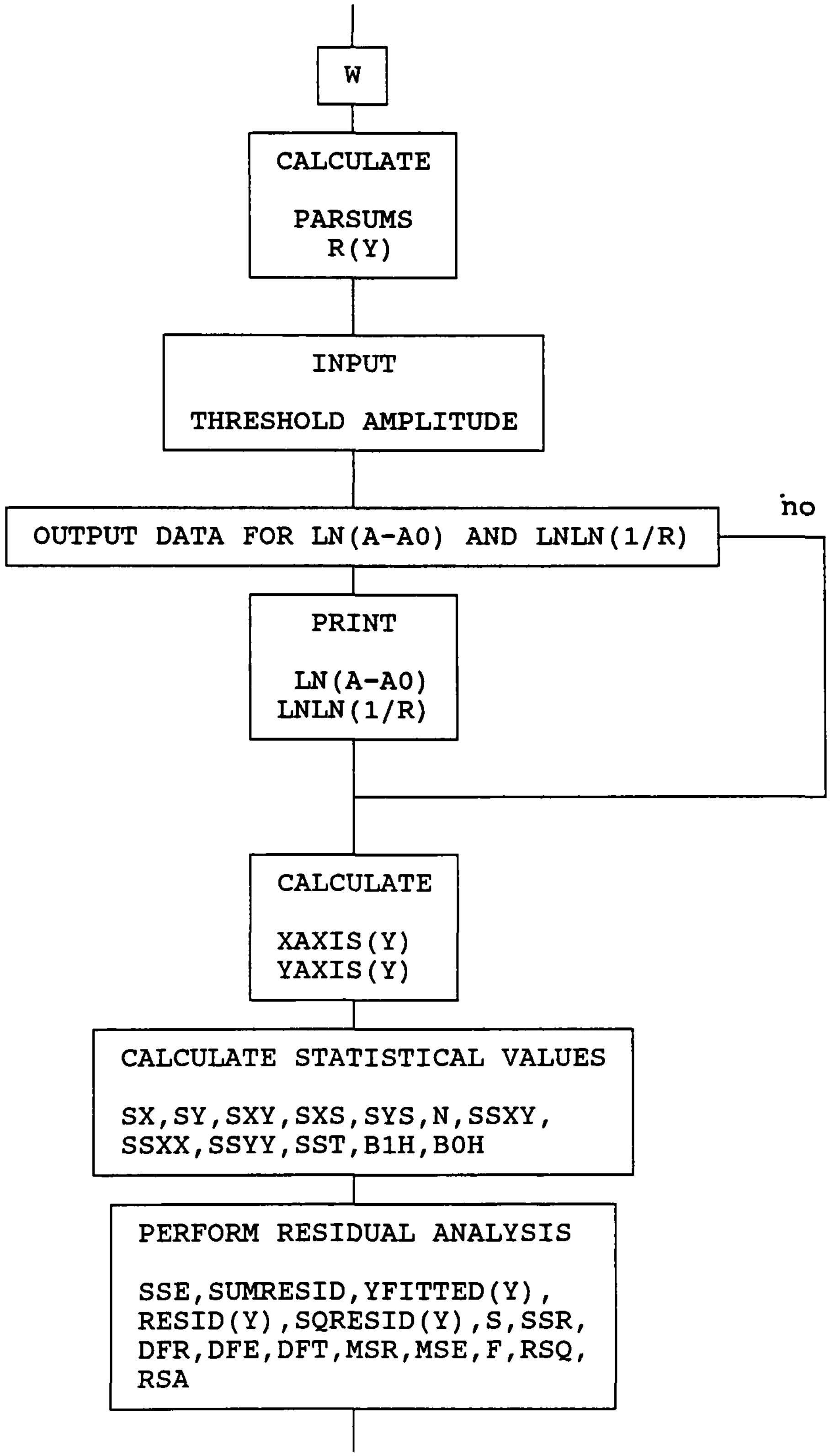
```
310 REM SY => THE SUM OF ALL YAXIS(I).
320 REM SXY => THE SUM OF ALL XAXIS(I) TIMES YAXIS(I)
330 REM SXS => THE SUM AF ALL XAXIS(I) SQUARED.
340 REM SYS => THE SUM OF ALL YAXIS(I) SQUARED.
350 REM N   => THE NUMBER OF OBSERVATIONS.
360 REM B0H => THE CONSTANT IN THE LINEAR REGRESSION MODEL.
370 REM B1H => THE SLOPE PARAMETER IN THE LINEAR REGRESSION MODEL.
380 REM S  => THE STANDARD DEVIATION.
390 REM RSQ => THE R-SQUARED VALUE USED TO PREDICT CLOSENESS OF FIT.
400 REM D => A DUMMY VARIABLE.
410 REM P => A DUMMY VARIABLE.
420 REM R2A => MULTIPLE COORELATION COEFFICIENT.
430 REM II => EVENT CUT-OFF PARAMETER.
440 REM M => Y COORDINATE OF LINEAR REGRESSION MODEL.
450 REM I => A COUNTER.
460 REM THRESHOLD => THE CUTOFF AMPLITUDE THRESHOLD.
470 REM SSXY =>
480 REM SSXX =>
490 REM SSYY =>
500 REM SST => THE SUM OF SQUARES TOTAL.
510 REM SUMRESID => THE SUM OF THE RESIDUALS.
520 REM SSE => THE SUM OF SQUARES FOR ERROR.
530 REM SSR => THE SUM OF SQUARES FOR REGRESSION.
540 REM DFR => DEGREES OF FREEDOM FOR REGRESSION.
550 REM DFE => DEGREES OF FREEDOM FOR ERROR.
560 REM DFT => DEGREES OF FREEDOM TOTAL
570 REM MSR => MEAN SQUARE FOR REGRESSION.
580 REM MSE => MEAN SQUARE FOR ERROR.
590 REM F => THE F STATISTIC.
600 REM THETA => THE WEIBULL CENTROID (63.4%) PARAMETER.
610 REM EV => THE EVENTS COORDINATE BASED ON THE WEIBULL PARAMETERS.
```

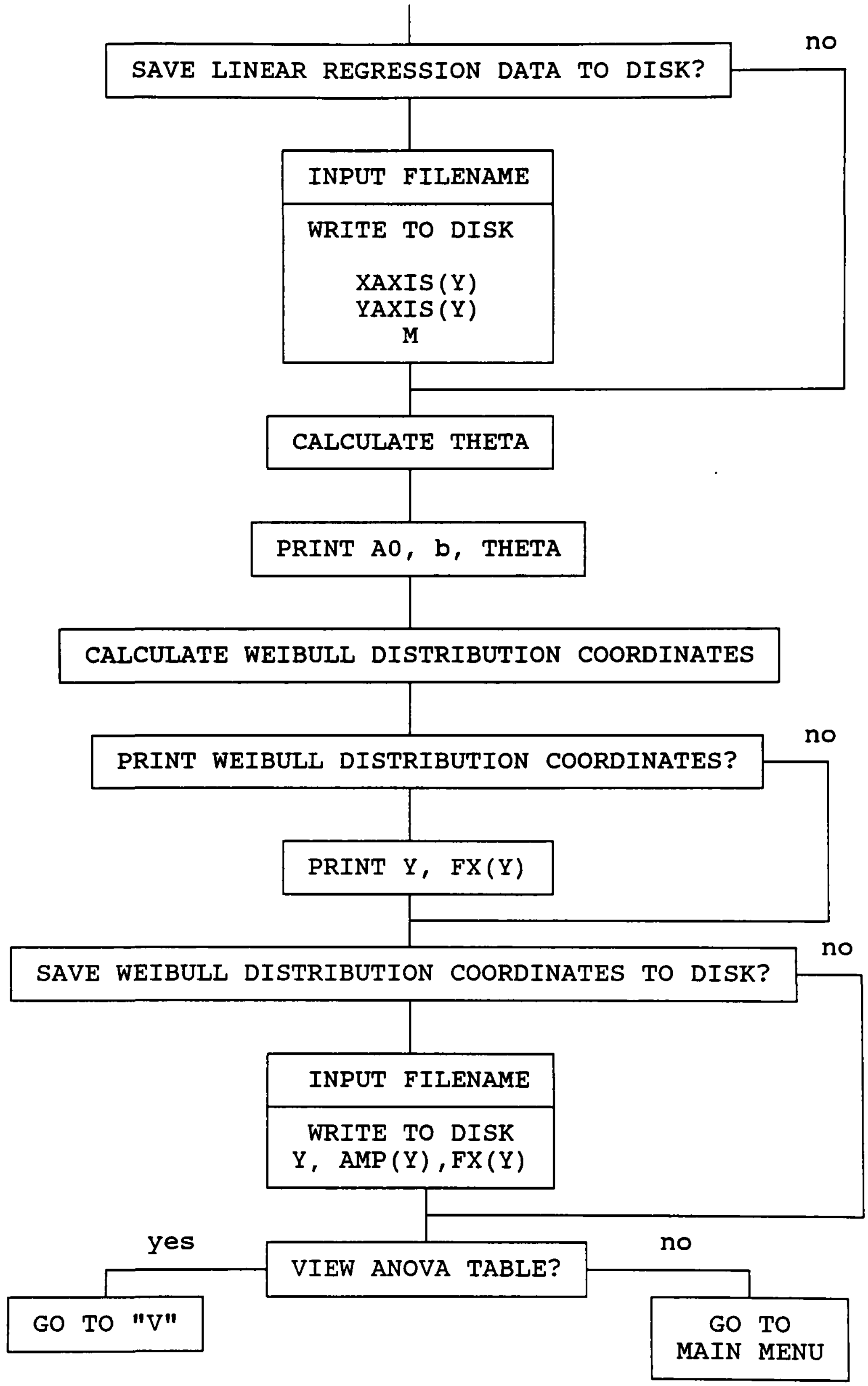
AESORT OPERATIONS GUIDLINE\FLOWCHART



NOTE: FUNCTIONS FOR "F" AND "W" CAN BE FOUND ON THE FOLLOWING PAGES.


F
DIMENSION ARRAYS
RETRIEVE FROM DATA FILE
I, A(I)
INPUT LOAD CUTOFF POINT
USE THE DEFAULT VALUE FOR EVENT CUT-OFF?
no
yes
INPUT EVENT CUT-OFF
INPUT MINAMP
USE DEFAULT VALUE FOR MAXAMP?
no
yes
INPUT MAXAMP
SORT A(Y) INTO AMP(Y)
GO TO
MAIN MENU


W
CALCULATE
PARSUMS
R(Y)
INPUT
THRESHOLD AMPLITUDE
OUTPUT DATA FOR LN(A-A0) AND LNLN(1/R)
no
PRINT
LN(A-A0)
LNLN(1/R)
CALCULATE
XAXIS(Y)
YAXIS(Y)
CALCULATE STATISTICAL VALUES
SX,SY,SXY,SXS,SYS,N,SSXY,
SSXX,SSYY,SST,B1H,B0H
PERFORM RESIDUAL ANALYSIS
SSE,SUMRESID,YFITTED(Y),
RESID(Y),SQRESID(Y),S,SSR,
DFR,DFE,DFT,MSR,MSE,F,RSQ,
RSA


SAVE LINEAR REGRESSION DATA TO DISK?
no
INPUT FILENAME
WRITE TO DISK
XAXIS(Y)
YAXIS(Y)
M
CALCULATE THETA
PRINT A0, b, THETA
CALCULATE WEIBULL DISTRIBUTION COORDINATES
PRINT WEIBULL DISTRIBUTION COORDINATES?
no
PRINT Y, FX(Y)
SAVE WEIBULL DISTRIBUTION COORDINATES TO DISK?
no
INPUT FILENAME
WRITE TO DISK
Y, AMP(Y),FX(Y)
yes
VIEW ANOVA TABLE?
no
GO TO "V"
GO TO
MAIN MENU