NASA/TM-2008-215558

Evaluation of Acoustic Emission NDE of Kevlar Composite Over Wrapped Pressure Vessels

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December 2008

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Symbols and Abbreviations

AE	Acoustic emission
COPV	Composite Over Wrapped Pressure Vessel
FBG	Fiber Bragg Grating
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
TRI	Texas Research Institute

Abstract

Pressurization and failure tests of small Kevlar®(Dupont)/epoxy COPV bottles were conducted during 2006 and 2007 by Texas Research Institute (TRI) Austin, Inc., at TRI facilities. This is a report of the analysis of the Acoustic Emission (AE) data collected during those tests. Results of some of the tests indicate a possibility that AE can be used to track the stress-rupture degradation of COPV vessels.

1.0 Introduction

This is a report of the investigation of the Acoustic Emission (AE) data collected during the pressurization and failure tests of small Kevlar/epoxy COPV bottles. A set of these tests were conducted in the period of October 10, 2006 through March 31, 2007 by Texas Research Institute Austin, Inc., at TRI facilities and they will be called the "multi-bottle" tests. More tests conducted in May/July 2007 were "single" bottle tests "primarily focused on the evaluation of Fiber Bragg Gratings (FBG) as strain sensors either embedded between the COPV liner and overwrap or bonded to the surface of the overwrap." AE was also collected and analysis of those results is reported here. TRI provided their report, "Stress-Rupture Investigation of Composite Overwrapped Pressure Vessels (COPV) in Support of NASA NDE Working Group; FINAL REPORT, For The Period October 10, 2006 Through March 31, 2007" to us and is hereafter referred to as the "TRI final report".

In the following discussions the word "event" will be used primarily to mean one set of data recorded and captured from several sensors simultaneously in one data acquisition cycle. Following discussions focus on what qualifies each "event" as a valid acoustic emission from a potential damage event. It is the understanding of the author that the acoustic emission tests were conducted as additions to test procedures that were not primarily for AE testing. Hence, there were some limitations encumbered on the analysis and subsequent conclusions. A "lessons learned" section that addresses those concerns is included in this report. According to provided documentation 18 bottles were instrumented for AE as shown in Table 1 below. Of that set 11 (23, 32, 38, 42, 43, 64, 66, 68, 82, 84, 97) bottles were reported as failed. The rest were pulled before failure. The AE of bottles 35, 38, 43, 44, 64, 66, and the two May/July 2007 FBG single bottle tests are analyzed in this report. Bottle 35 was the shakedown pressurization test and therefore was not subjected to any accelerated aging affects. According to the TRI final report, bottle 44, and 66 were subjected to high temperature, low stress testing, while 38, 43, and 64 were subject to low temperature, high stress testing. In the TRI final report AE data are plotted for bottles 35, 44, 38 and one of the FBG bottles and are compared to AE analyses of this report.

Table 1 Bottles instrumented for AE

AE Bottles	Start Date	End Date	State
32	11/29/2006	1/3/2007	Failed
43	11/29/2006	1/20/2007	Failed
75	11/29/2006	1/31/2007	Pulled
97	11/29/2006	1/31/2007	Failed
42	12/17/2006	1/4/2007	Failed
82	12/17/2006	12/21/2006	Failed
66	12/17/2006	1/9/2007	Failed
71	12/30/2006	1/9/2007	Pulled
99	12/30/2006	1/9/2007	Pulled
85	1/7/2007	1/10/2007	Pulled
23	1/8/2007	1/10/2007	Failed
64	1/22/2007	1/26/2007	Failed
68	1/22/2007	1/31/2007	Failed
84	1/22/2007	1/30/2007	Failed
6	2/12/2007	2/15/2007	Pulled
27	2/12/2007	2/15/2007	Pulled
38	2/12/2007	2/14/2007	Failed
62	2/12/2007	2/15/2007	Pulled

2.0 Acoustic Emission Data Acquistion, Filtering, and Analysis Procedures

AE systems collect structure-borne sound generated by dynamic processes occurring in or impinging on the structure. Data from a network of sensors can be used to locate the epicenter of the process by triangulation using time-of-flight of the sound from the source to the sensors.

AE sensor channels are typically separate circuits so that each channel can complete a data collection cycle immediately without interruption, when triggered to do so. However, they do not operate independently. To be able to do event location calculations, all the channels are linked to one trigger signal. Triggering typically occurs when the signal from any channel becomes larger than a specified amplitude threshold. Then all channels simultaneously collect signal for a specified time window. Hence time t=0 is the same global time for all channels for that one “event”. The data collection cycle typically includes a delay that is designed to wait long enough for reverberations from one event to die down before re-arming for another data capture. During this time the system may be moving data to storage, but it is not “listening” to any sensor (and not acquiring data).

Other effects due to this type of triggering become apparent when a large network of sensors is being used. In the specific tests performed in this report, there were as many as six COPV bottles instrumented with four sensors each being recorded simultaneously. An event on one bottle would trigger all 24 channels, but only the four sensors on that bottle would show actual

AE data. The other 20 channels would typically show background data only. In some cases, it is possible that several bottles might be experiencing uncorrelated AE events that were recorded simultaneously. Because AE events are so asynchronous in occurrence, this effect is rare and when it does occur, the trigger time can be used to help to discriminate such events. If used for energy calculations, the channels from the bottles with no meaningful signals would result in essentially the energy of the background circuit noise.

AE data acquisition software typically has the ability to sort or filter data based on channel, amplitude, energy, or signal frequency criteria. Some systems also have the ability to easily "playback" the event waveforms for visual examination. The first step in processing the files received from TRI's AE testing was to evaluate and eliminate the events where all the channels had flat-line data. As was the case for this data, the data was sorted post-test by channel at TRI, such that each file contained sets of channels for just one bottle. In that case, it was possible to have all the channels for an event in one of these resultant files to have background data and not true AE event data. The actual event data would be found in another bottle's data file.

One can sort the events visually to manually remove false data, but this is very time consuming for files with hundreds to thousands of events and somewhat subjective. However for filtering out flat-line or small continuous data, threshold filtering can be very effective. Threshold filtering is applied, incrementally increasing the threshold and visually inspecting the results with "playback" until just the valid data is left.

Energy calculations can be applied to each waveform collected by each sensor. The results are functions of the energy of the signal collected at each sensor and are therefore related to the energy release of each event, including the effects of attenuation during propagation from source to sensor and the transfer function of the sensor. The event energy calculations can be plotted in energy vs. time plots by channel/sensor. With further filtering and manipulation it can also be plotted in event vs. time plots per event. More detailed discussions of the analyses are presented in the following sections.

3.0 Analysis and results

3.1 Bottle 35: Shakedown burst test analysis

As reported in the TRI final report, a shakedown burst test of a single bottle was undertaken prior to the multi-bottle tests. It is a good bottle to examine because it was a single bottle test and both AE and pressure (on a parametric channel) were recorded simultaneously. Hence AE analysis can be compared to definitive knowledge of when a failure occurred. The data has been re-plotted here for illustrative purposes as Figure 1. The exact calibration for pressure is unknown so the pressure data is shown here as the recorded signal voltage. An approximate calibration factor is 830 psi/volt. As seen, there were pressure fluctuations of several hundred psi during the course of the test. The AE behavior was possibly affected by that fluctuation.

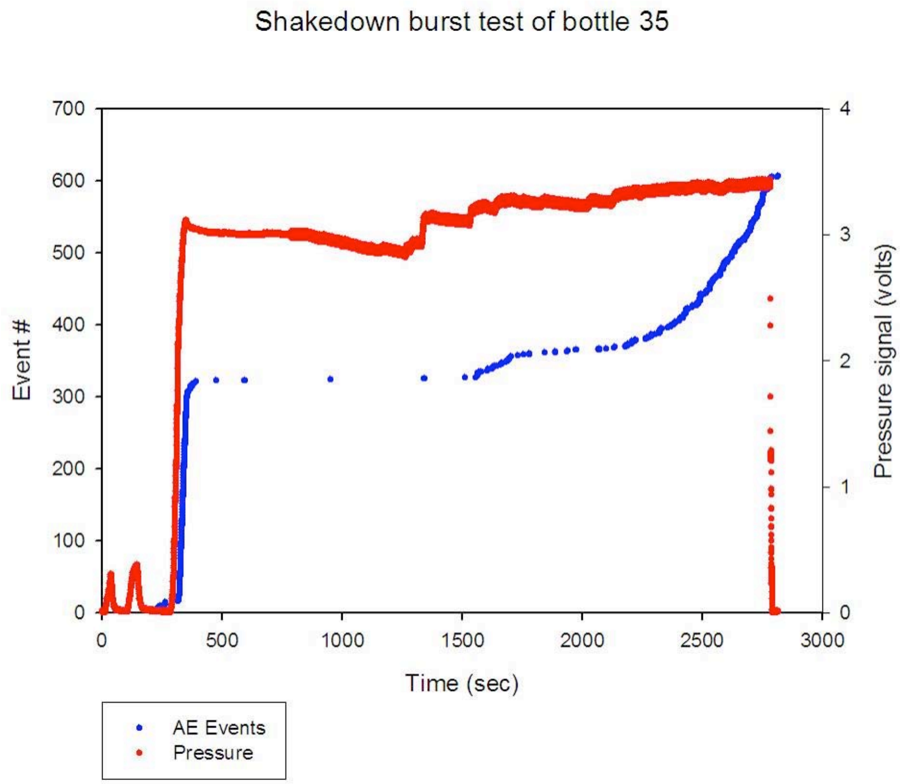


Figure 1. Bottle 35 pressurization profile and AE response.

Examination of all the recorded waveforms found that there were very few false AE events or extraneous data that needed to be filtered out. Frequency content of the data collected during pressurization was approximately centered around 75 kHz with no obvious changes as failure was approached. However, many of the signals were large enough in amplitude to be clipped by the maximum recordable voltage threshold; hence frequency analysis of those signals is less accurate.

Energy calculations also suffer when the signals are clipped. However, until there is complete saturation, where every peak and valley of the signal is clipped, calculated energy should be loosely proportional to the actual energy of the event. The following plots show the energy of the AE events vs. time of occurrence during the test. Figure 2 shows all of the events in gray (as a baseline) compared to a histogram-like approach of partitioning the data by energy. The AE software uses the following equation calculate the energy:

$$E = \int_{t_i}^{t_f} V(t)^2 dt = \sum_{i=1}^{n} V_i^2 \Delta t \ ,$$

where V_i is the voltage recorded at the ith data point in the time record and Δt is the sampling rate. The data is plotted with increasing symbol size to denote increased threshold for each dataset. Most of the original emissions were small; this plot of emissions larger than 20 V^2-μsec is approximately only 10% of all the events.

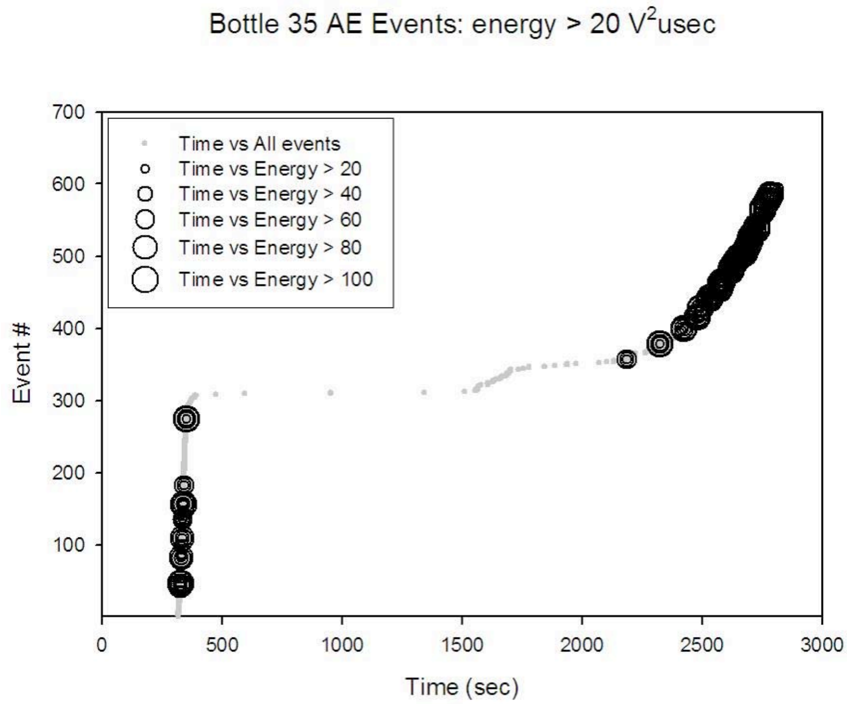


Figure 2. Bottle 35 event energy plotted on event rate.

It is unknown if this bottle was pressurized before this pressure test, so it cannot be concluded if the large emissions occurring during initial pressurization are just “settling-in” noises or actually due to significant damage. Even so, there is a strong correlation between event size and event rate for the larger events occurring after the event rate increases significantly (near 2200 seconds). In this particular plot it is not clear whether there is a significant trend in these larger events late in life that could be used for tracking life.

Many of these later events are saturated to some extent, so close examination, as noted before, should be considered as being more qualitative than quantitative. To study just the largest events, all signals whose amplitude did not pass 90% of saturation, i.e. clipping level on all eight channels, were eliminated. This eliminated the large events prior to approximately 500 seconds, which occurred when the bottle was brought up to pressure. The event with the largest energy was ascertained for scaling purposes and is plotted as a red circle. The data was filtered into bins in a manner similar to the previous plot and plotted against the “all events” baseline. As can be seen in Figure 3, in general, largest events of these sets occur later. However, the event size does fluctuate before increasing steadily to the peak value occurring near failure.

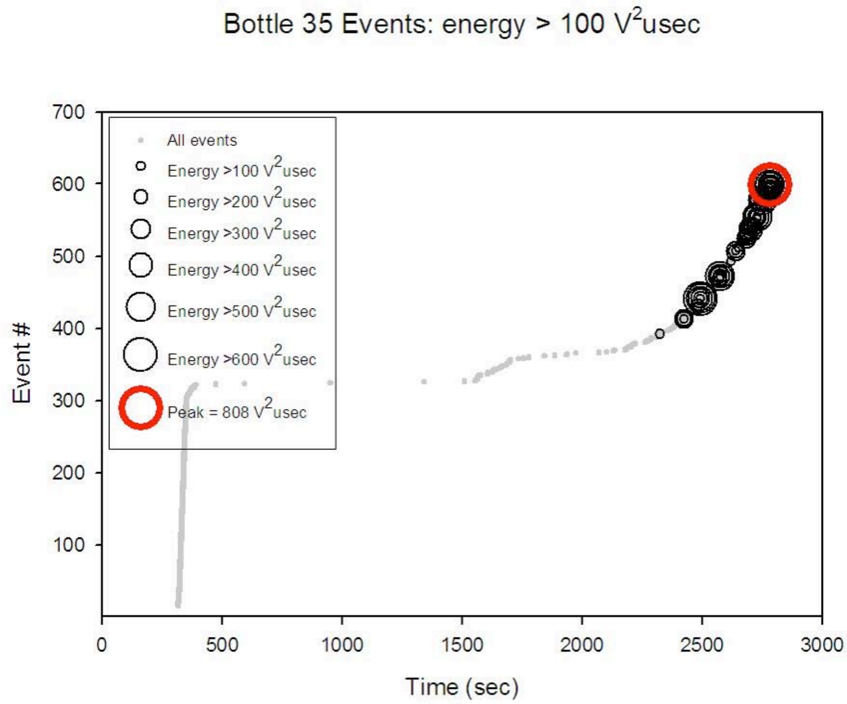


Figure 3. Bottle 35 large event energy plotted on event rate.

Even though the preceding plots clearly show a trend in the energy with time they do not differentiate by channel. The event filtering is based on the lowest energy value per event regardless of the sensor/channel that received it. To complete the picture, one can plot the energy by channel and time as seen in Figure 4. This plot shows a clear indication of energy increase for most of the channels after the increase in event rate occurring near 2200 seconds.

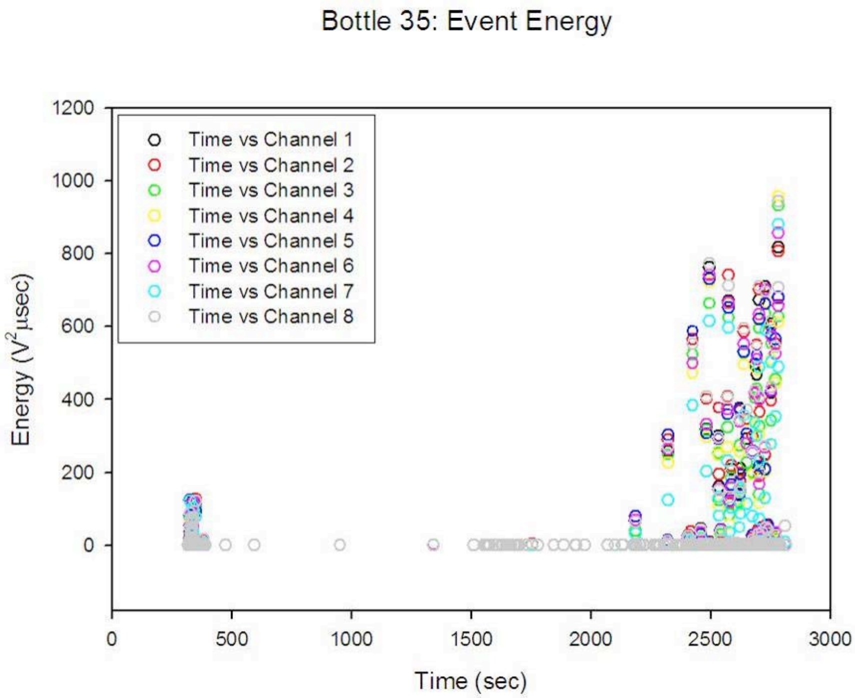


Figure 4. Bottle 35 event energy plotted by channel/sensor.

3.2 Single bottle Fiber Bragg Grating tests (May/July 2007)

Tests were also conducted in May and July 2007. As noted before, they were single bottle tests primarily focused on testing out new fiber Bragg grating strain gauges. AE was also collected during these tests. There were no flat line "events" that needed to be filtered out. There were many very small events that were filtered out, but this did not appreciably change the shape of the rate or energy plots. The pressurization profile was step-hold for several steps and the AE responded at each step as could be seen in the Figures 5 and 6.

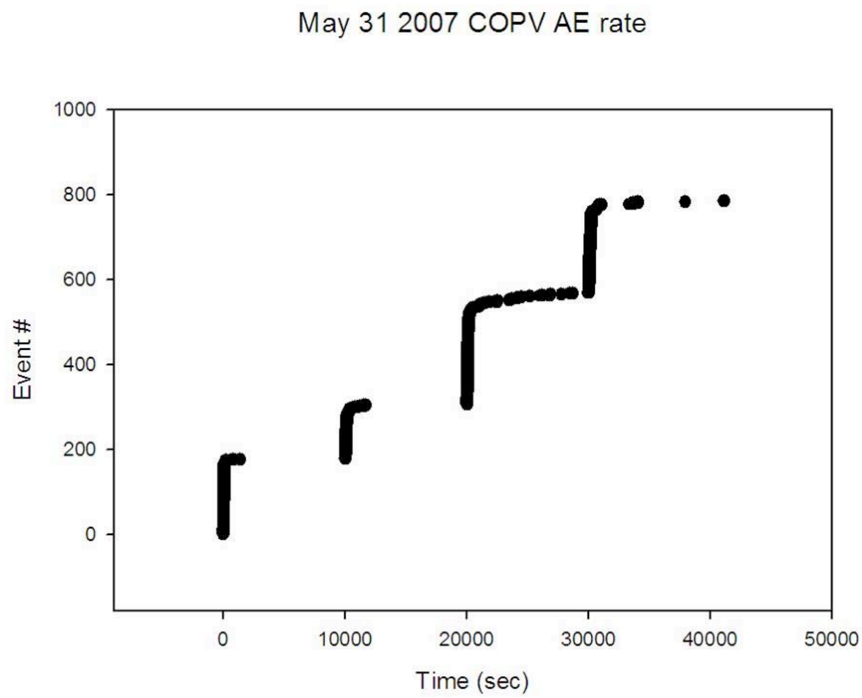


Figure 5. May 2007 AE event rate.

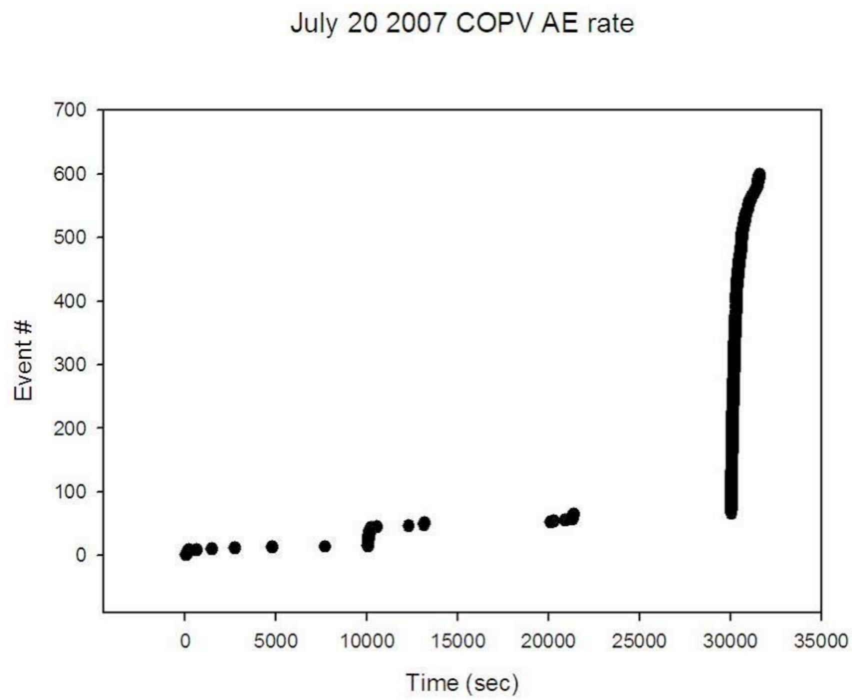


Figure 6. July 2007 AE event rate.

The calculated energy also responded to the pressure steps with increasingly larger events occurring at the steps of increasingly higher pressure as can be seen in the energy plots in Figures 7 and 8. Large events did not occur during the pressure-hold portions.

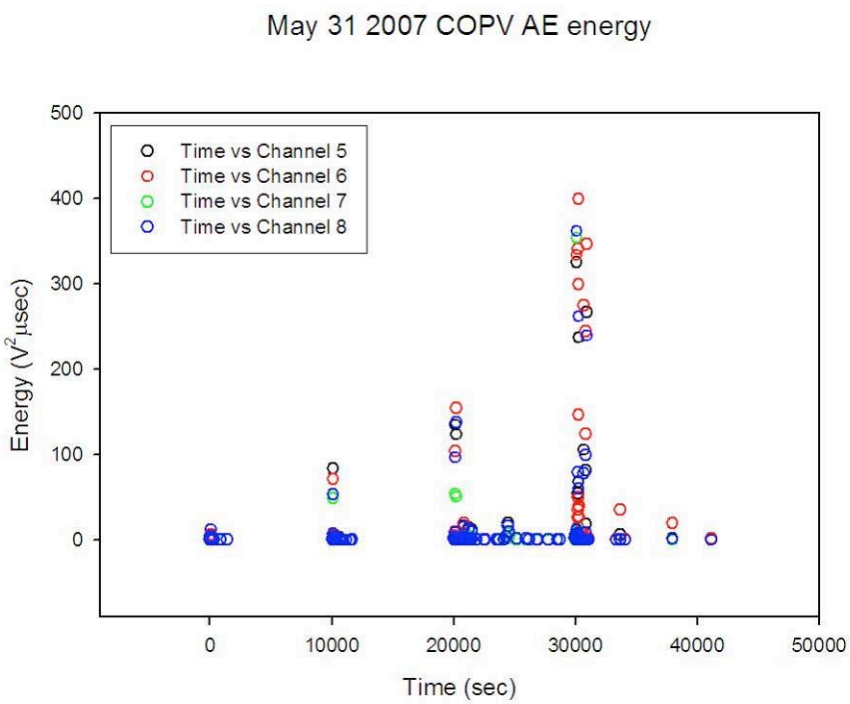


Figure 7. May 2007 AE energy.

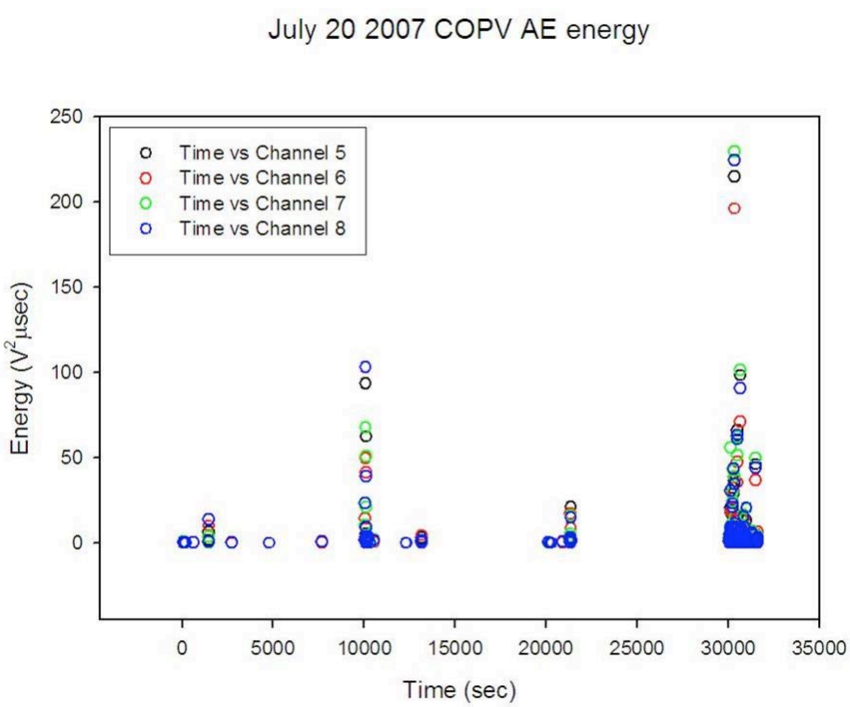


Figure 8. July 2007 AE energy

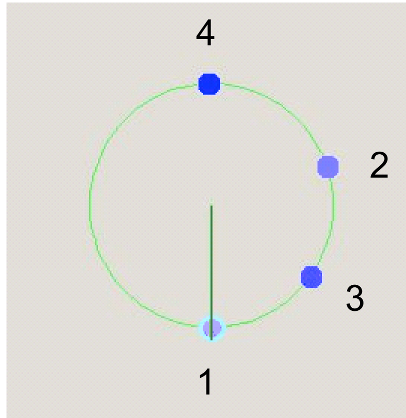
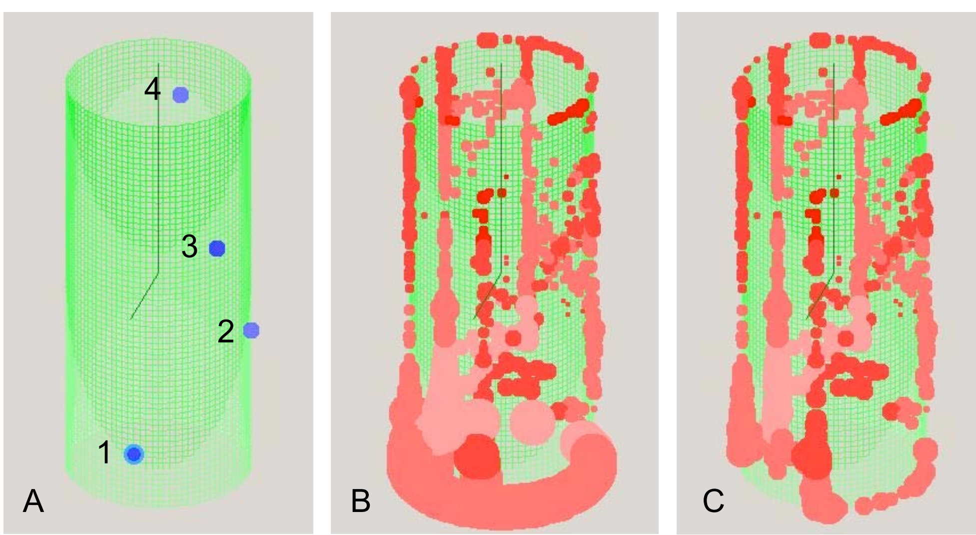


Figure 9. May/July tests: End view of sensor locations

Sensor location mapping was provided for these tests. This allowed AE location calculations to be conducted. Figure 9 shows the sensor locations as seen from the end of the bottle, the green ring symbolizing the wall of the bottle. The spots are darker, the closer they are to the viewer, so in order from near to far: 4, 3, 2, 1.

The algorithm used to calculate location of AE events can be adjusted to plot values sorted by confidence of fit. Figure 10 shows the sensor location in profile with two levels of confidence plotting for the May 31 test. Darker red spots are closer to viewer while lightest red spots would be locations on the far side of the bottle. Please also note that as confidence of fit decreases the spot size increases. Also note that the conical "structures" visible inside the cylindrical grid is just an artifact of the grid plotting. The cylindrical grid is the geometry of the composite overwrap. It does not include the spherical end caps of the aluminum liner.



a) Sensor locations b) All fits c) At least 75% fit

Figure 10. May 31 test location plots: a) sensor locations, b) All calculated locations, c) only locations with at least a 75% fit.

No conclusions have yet been made about the striped pattern of AE locations running up the side of the bottle although it is believed to be fitting failures of the nonlinear fitting algorithm due to time of arrival inconsistencies that occur with small signals. Even though these events tend to be reported as "good fits" for location they are typically small amplitude events that will have the actual "time of arrival" of the signal hidden in the noise, which will be missed by the threshold level setting. Filtering out small events and bad fits (by keeping data that has amplitude of at least 10% of maximum and 95% fit on at least one sensor) clarifies the pattern of AE locations as seen in Figure 11. A swath of calculated locations near sensor 2 that extends towards sensor 4 may corroborate the comments of a TRI employee that the failure occurred across sensor 2.

If we plot only the largest events, at least 95% of maximum, we note that some of the largest events have the worst fit and are oddly located at one end, but we still have clusters of good fit data near sensors 2 and 4 as seen in Figure 12.

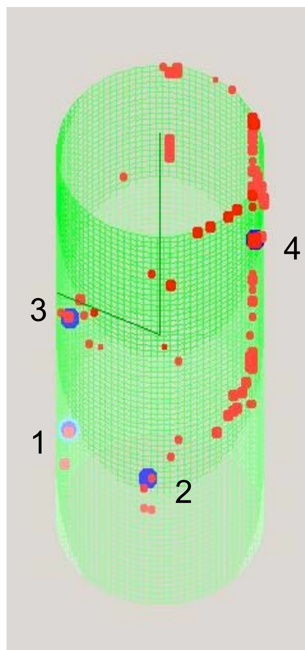


Figure 11. May 31 test: Small events and bad fits eliminated

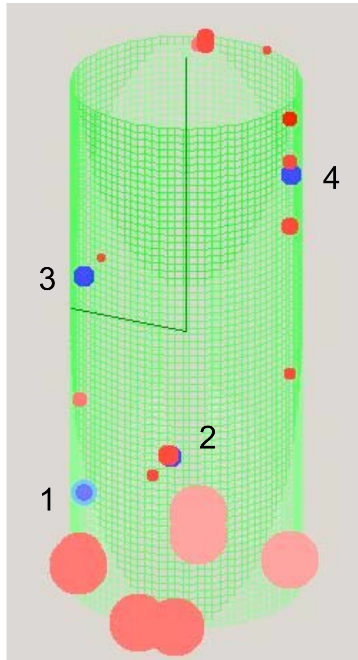


Figure 12. May 31 test: Largest events with at least 95% of maximum amplitude

Looking at the AE locations in Figure 13 for the July 20 test we still see a vertical striped pattern and also a more pronounced spiral pattern across sensors 2 and 3.

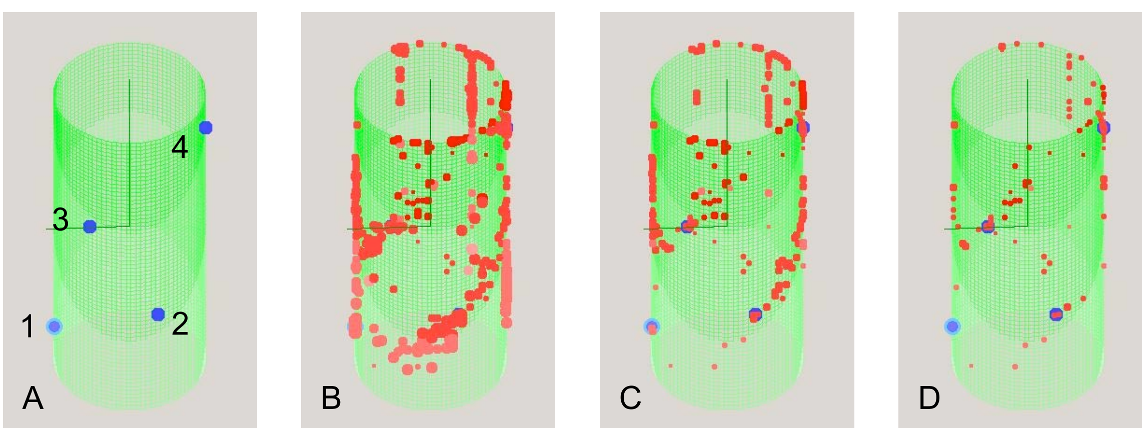


Figure 13. July 20 tests: a) sensor locations, b) 90% fit, c) 95% fit, d) 96% fit

3.3 Bottle 43 analysis

The data reported here was indicated by filename as being the AE data for the failure of bottle 43 during the first set of tests. The Event versus Time plot for unfiltered data is seen in Figure 14. Flat line data was removed and amounted to only 5% of the total number of events. The results were plotted as seen in Figure 15. The filtered behavior looks remarkably like the unfiltered results, hence there seems to be little influence from other bottle activity. After filtering again to remove events with peak amplitudes less than 50% of maximum saturation level (shown in Figure 16), the data still maintains the characteristics of the unfiltered plot, even though 77% of the data was removed.

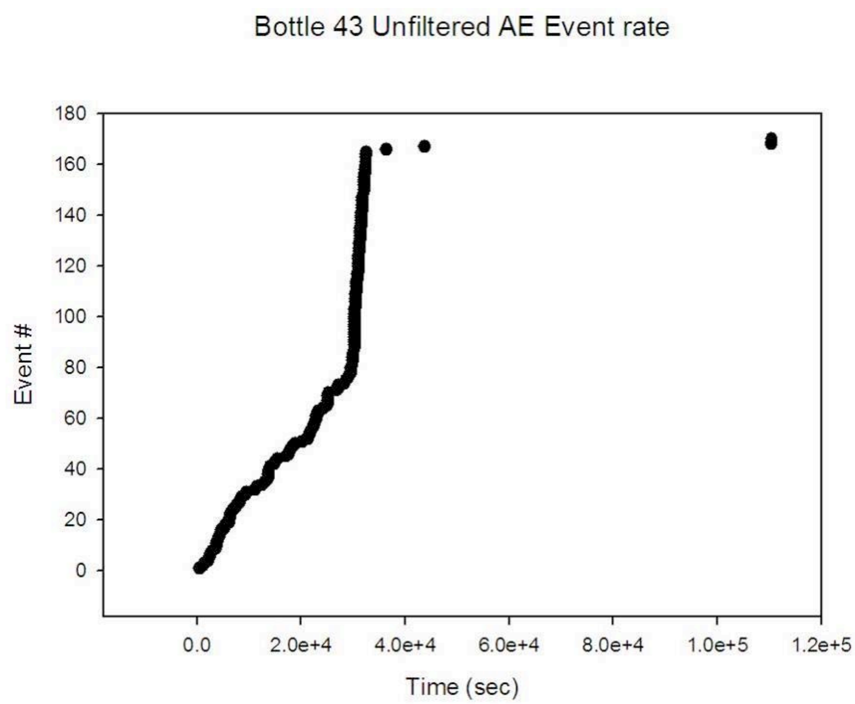


Figure 14. Bottle 43 AE event rate

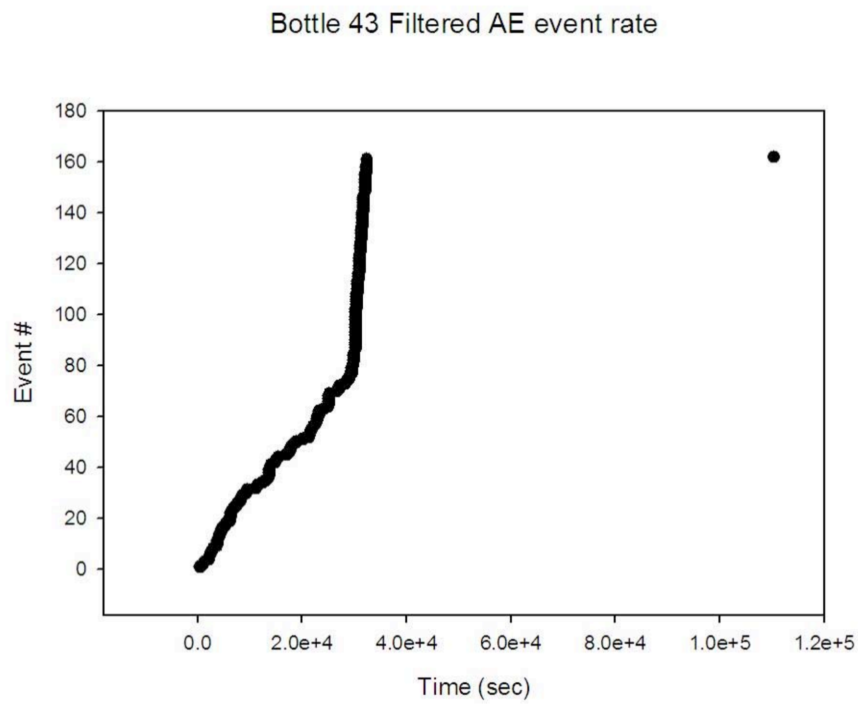


Figure 15. Bottle 43 Filtered AE event rate

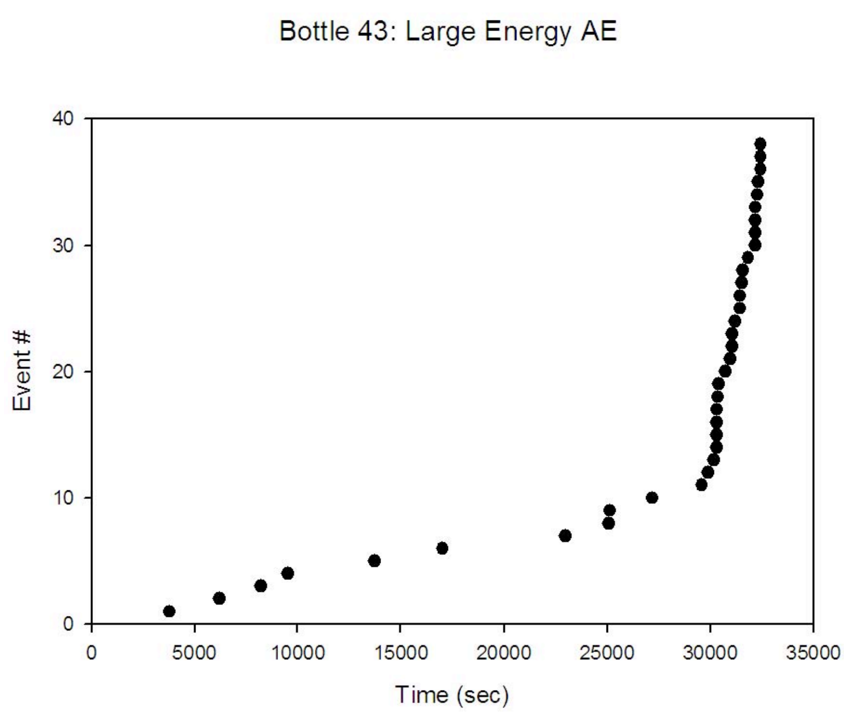


Figure 16. Bottle 43 Large energy event rate

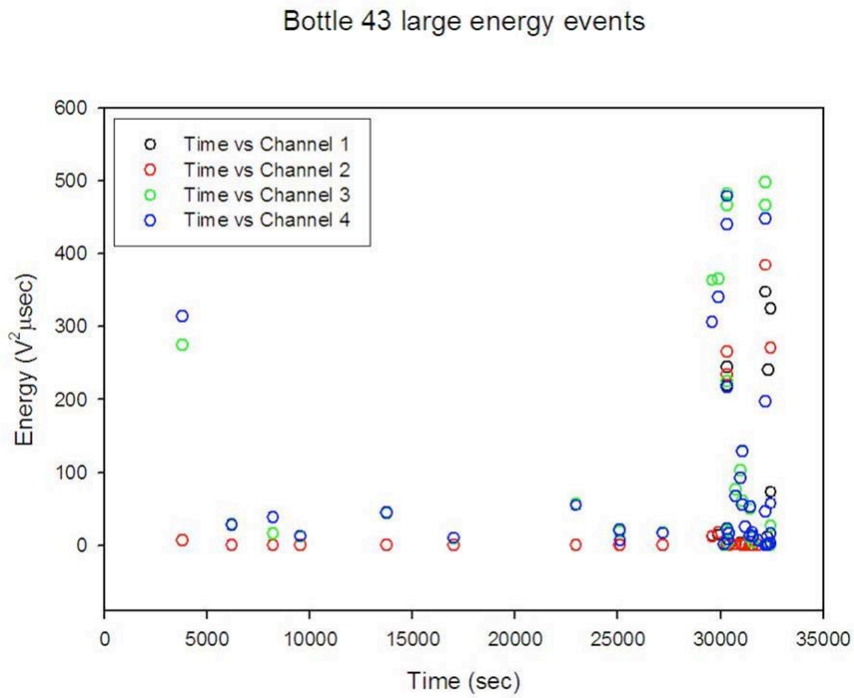


Figure 17. Bottle 43 large AE energy

Figure 17, a plot of the energy of these large energy events, shows that the majority of these events occur late in the plot. A few of the larger events of this set also occur 7 hours earlier at the beginning but it is unknown at this time what they indicate. What is also troublesome to interpret is the one small event at 1.1e5 seconds (30.5 hr). However there does seem to be correlation of event energy increase when event rate increases.

4.0 Lessons learned

- Not all AE data collected is useful or relevant. From an operational point of view AE sensors/channels are not independent. They are all linked to one trigger signal that is derived from the first input signal to cross an amplitude threshold. This is done to simultaneously start data collection on all channels and allow location calculations of the epicenter. The data collection cycle typically includes a delay that is designed to wait long enough for reverberations from one event to die down before re-arming for another data capture. During this time the system may be storing data, but it is not "listening" (and not acquiring data). If the incoming signal rate from the sensors is high enough so that subsequent signals overlap the time delay, then data is lost. So, if one bottle becomes very active and dominates the triggering, the lost data will most likely be from the less active, but not necessarily, less important behavior of other bottles. Also, the data collected from bottles that aren't active at the time of triggering is flat-line and not related to any damage events of those bottles. This fact is a weakness of taking the data in this manner, ie. recording independent bottles at the same event times. This is the cost of running a series of tests in parallel on one instrument. Tracking failure behavior of any particular bottle by tracking AE rate of that bottle must be filtered to remove any irrelevant events for that bottle, but the apparent rate may not be accurate if much data is filtered out.

- Most AE data collection systems have the capability to also capture non-AE data, simultaneously on parametric channels. Collecting parametric data, such as pressure or strain, helps make it possible to corroborate and track AE behavior with damage development.
- Monitoring AE uninterrupted (i.e. not starting and stopping the AE data acquisition system) during the entire time the experiment is conducted establishes a single time baseline. If that is not feasible, try not to start and stop the data acquisition indiscriminately and, most importantly, keep a log of when those activities occur.
- Paying attention to details is time-consuming and some details may be irrelevant. But AE is a stochastic process and it isn't always easy to know what details are relevant *a priori*. The best approach to reduce extraneous variables is to do single bottle tests. If that is not feasible, attempt to reduce the number of channels per bottle and the number of bottles per system.
- Documenting the channel # to bottle mapping makes it possible to sort the data into files for each bottle. Documenting the sensor locations makes it possible to do location calculations.

Implementing the above lessons, reduces the need to filter or eliminate data, and allows more definitive conclusions about damage development. The following discussions illustrate the issues that arise when these lessons are not implemented.

4.1 Bottle 38 Analysis

This section is a response to the data plotted in Figure 5.3.3 of the TRI final report. The following discussion is about the distinct difference that appropriate filtering can have on the apparent AE event rate and the validity of subsequent conclusions.

The as-received data file had 427 "events". A few of the events look like the plot of event 49 in Figure 18. This shows each response from all 4 sensors on the bottle and they do have the characteristics of a typical AE damage event.

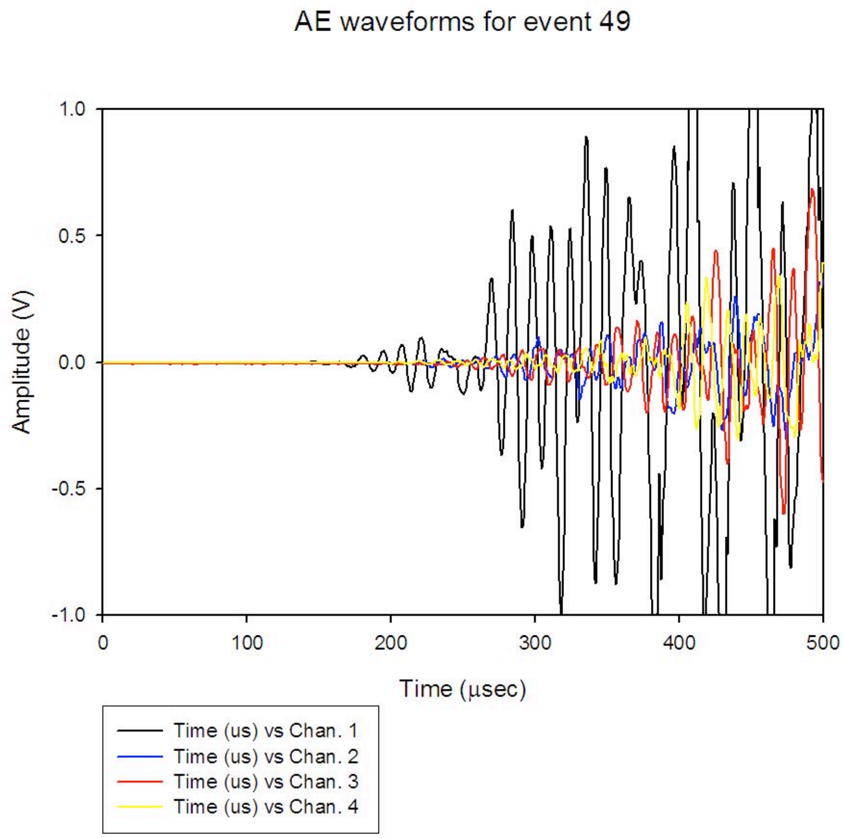


Figure 18. Bottle 38 AE waveform,s

However, the majority of the events look like the one shown in Figure 19, the "event" 48 waveform plot. This is the flat line waveform referred to previously. Filtering out this type of event resulted in only 12 events that look like the one in Figure 18.

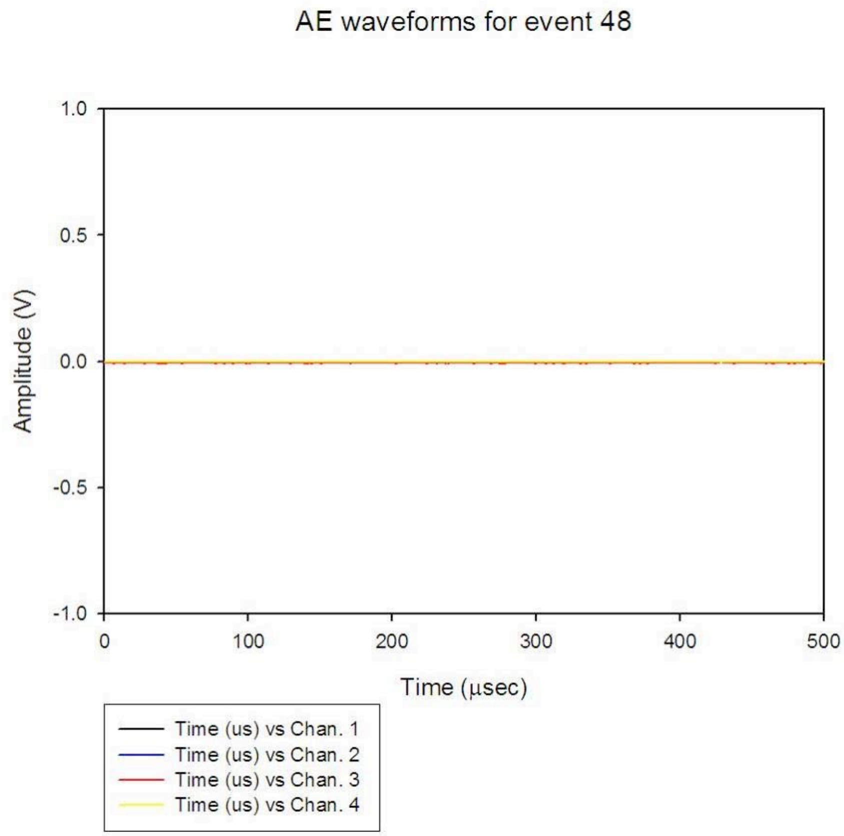


Figure 19. Bottle 38 AE waveform

To understand why this is an issue, consider Figure 20, the Event vs. Time plot. The blue circles are all the events, plotted as in the TRI figure. Each remaining event, after filtering out the flat-lined ones, is plotted as a red “x”. The apparent AE “behavior” (early low AE event rate followed by a sharp increase), as indicated by the blue events, is not supported by the shape of the plot of the filtered results.

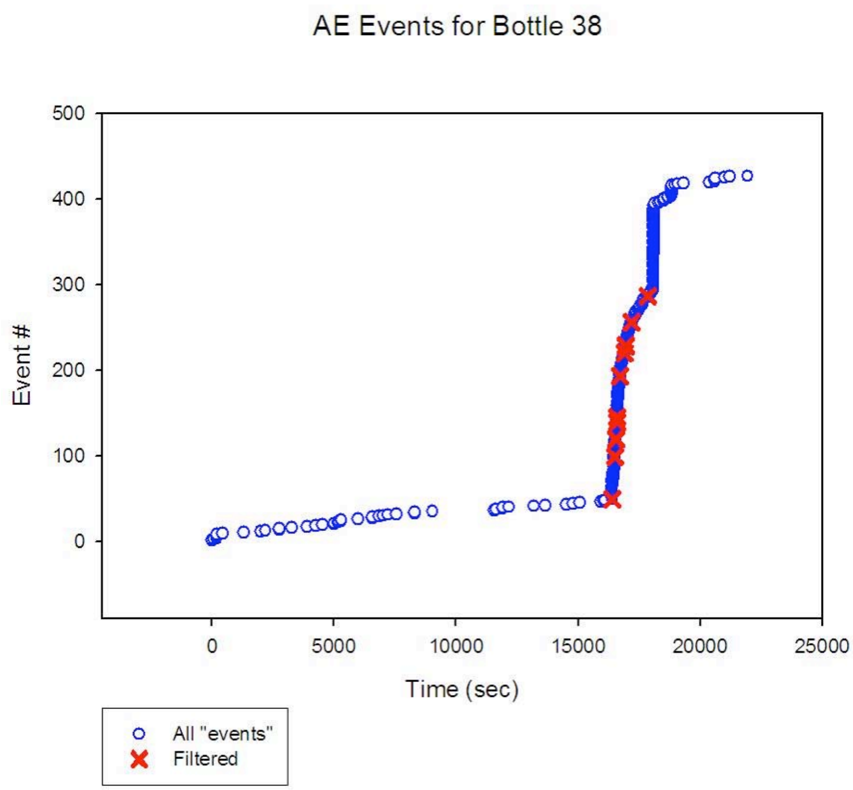


Figure 20. Bottle 38 AE event rate comparison.

If we look at the energy of those events left after filtering, we see large events occurring within a 5 minute window at the beginning, then several small ones for the next 20 minutes, as seen in Figure 21. If the large ones are the final failure event, what are the events occurring after that? If those large events are just precursor events, where is the failure? In summary, the plot in Figure 5.3.3 of the TRI final report is not indicative of the failure behavior of this particular bottle and further energy analysis also provides inconclusive results.

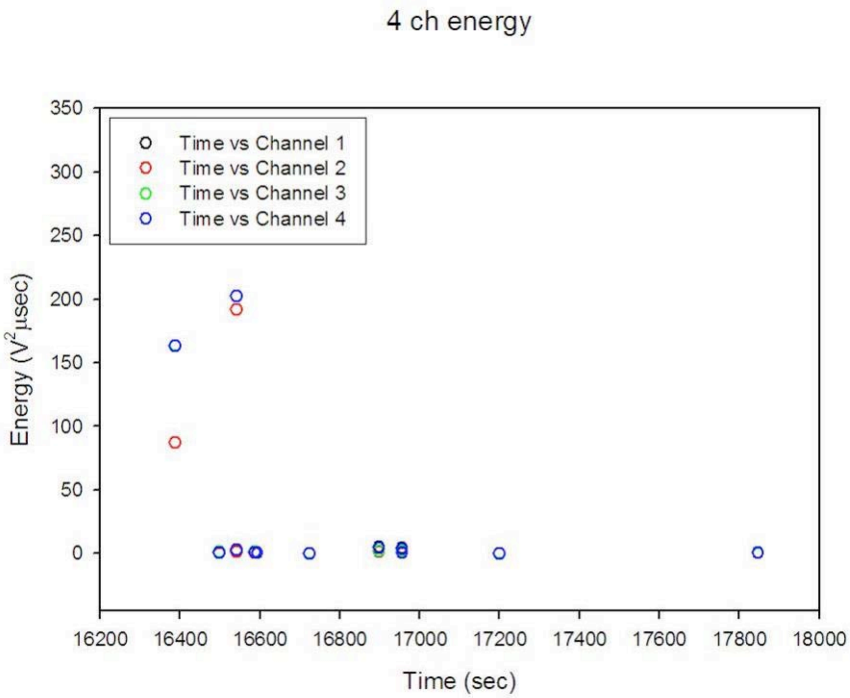


Figure 21. Bottle 38 AE energy plotted by channel

4.2 Bottle 66 Analysis

The data reported here was indicated by filename as being the AE data for the failure of bottle 66. This analysis illustrates the potential for data to be lost. The Event versus Time plot of unfiltered data is seen in Figure 22.

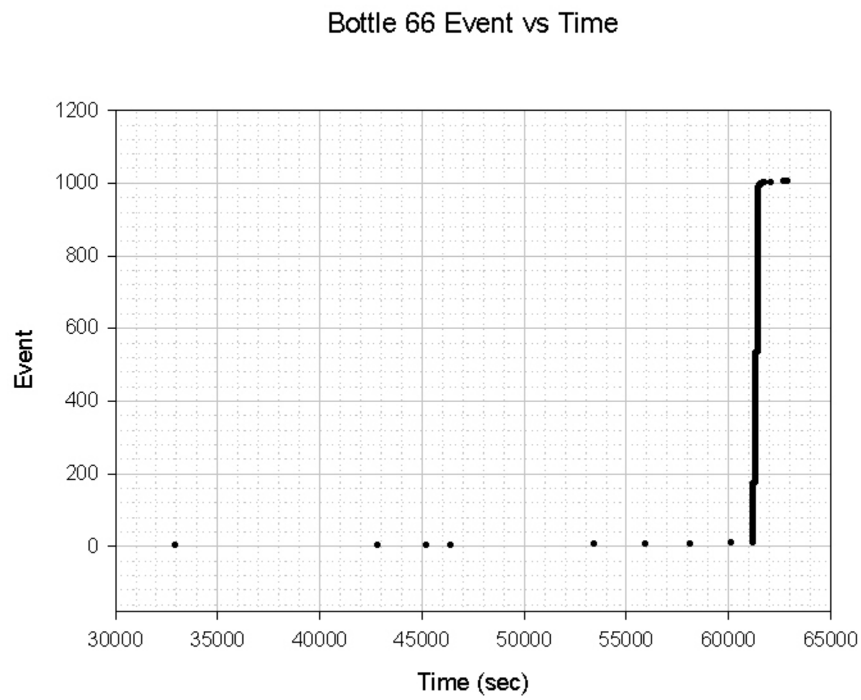


Figure 22. Bottle 66 “all” AE events vs. time

It appears to have a small number of events that occur in the 8 hours before the last burst of AE at about 61,000 seconds. That burst may seem to be the final failure of this particular bottle and the earlier AE may seem to be precursor AE that might indicate the upcoming failure.

In this section we will take a much closer look at the timing of the events and the shape of the waveforms. If we look closer at the pattern around event 270 as seen in Figure 23, we can see individual events in a pattern of pairs at close to equal time intervals. Patterns like this typically occur when the data acquisition is affected by hardware limitations. In other words the signals are occurring faster than the system can acquire. This is further supported by the typical shape of the data, as illustrated in figure 24 of event 269, which seems to have been occurring before this capture was started and continued long after it ended.

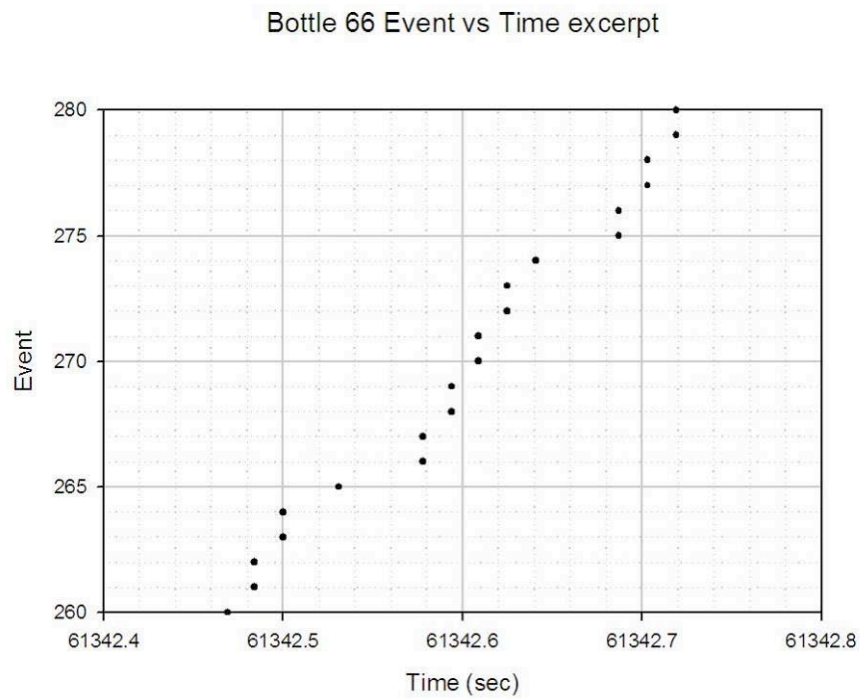


Figure 23. Bottle 66 AE event rate

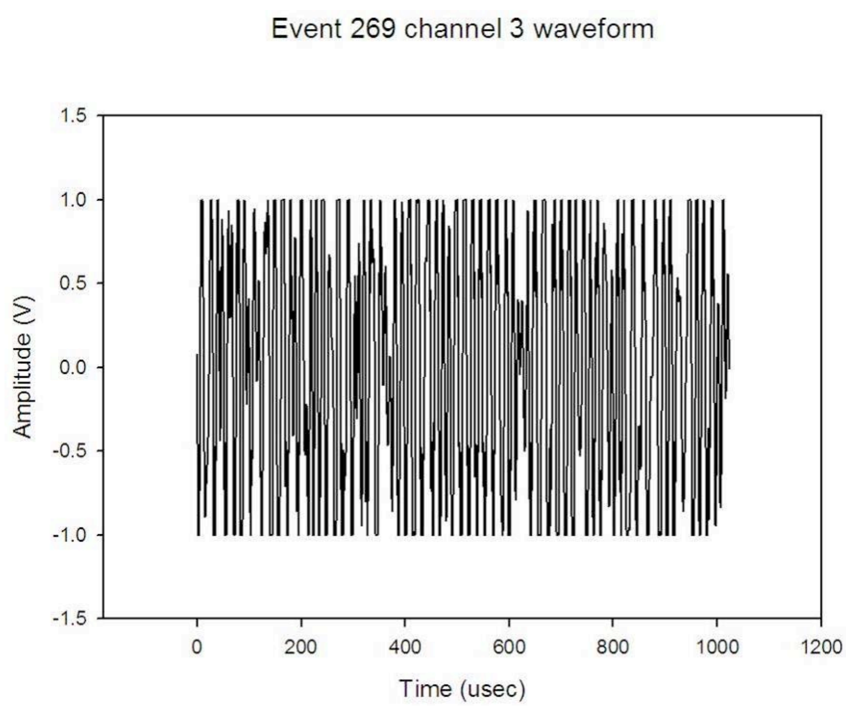


Figure 24. Bottle 66 AE waveform.

This data affords us a chance to estimate the percentage of total time the system is not listening when there is much AE activity. Let's make the assumption that the sound is mostly continuous (as supported by the character of Figure 24). Let's also look at a large statistical sample. The apparent average event rate for the events from 174-532 is about 48.9 events per second. The length of each window of the collected data is 0.001024 seconds long; hence the time footprint the data represents is 0.001024 x 48.9 = 0.05 sec of data per sec of time or 5% of the total time. Hence, 95% of the time, data was not being collected, but, judging the character of the collected data, it is very likely that there was sound impinging on the sensors during that time.

The point of the above discussion is that this may not be a large problem if all of the 24 AE channels were on a single structure where damage development in one area (and the subsequent AE response at one subset of sensors) is presumably not completely independent of damage development in another area (i.e. due to redistribution of load with damage development). In other words, events not being recorded may not be too critical if trends can be inferred from the recorded data, because the trends are all related to the failure of a single structure.

However, when every 4 channels of the 24-channel system are on separate structures that are mechanically independent (from a failure perspective), as was done for the multi-bottle tests, a very active single bottle can essentially control the triggering. Hence the design of the multi-bottle tests not only increased the potential for creating an apparent event rate profile that can be a distortion of the actual event rate, it increased the chance of missing any precursor AE on the other bottles. This is a shortcoming of the multi-bottle test mode and is a risk in the data quality that could occur, but it maybe a necessary limitation that must be lived with.

Now let's look at the waveforms of the early events in this file. Most of these events are flat-line on all channels and not due to a triggering event on those bottles. Event 8 in Figure 25 is the first and only event in this file that looks like initial AE from some type of damage event.

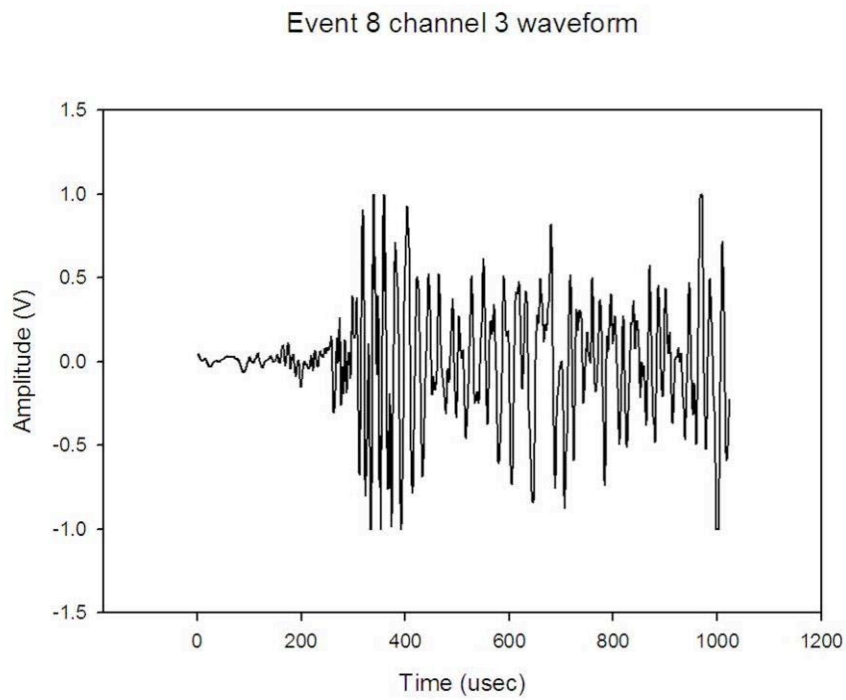


Figure 25. Bottle 66 AE event waveform.

The "final burst" of events (events 10-986) is actually three separate sets; 2, 6, and 9 seconds long separated by approximately 2 minutes. The first set is small amplitude and continuous, the second set is large amplitude saturated and continuous, and the last set is small amplitude and continuous. The characteristics of the failure of this bottle are unknown to the author and none of the events have a distinct beginning as seen in Figure 25. It could be that these are three episodes of some type of prolonged damage, but having a set of small amplitude emission both before and after the large amplitude set does seem strange.

However, if we can assume the three bursts are final failure, then event 8 occurring 17 minutes earlier is the only evidence that some precursor AE did occur for this bottle before final failure.

4.3 Bottle 64 Analysis

The data reported here was indicated by filename as being the AE data for the failure of bottle 64. This discussion illustrates that even though appropriate filtering may produce results that could be interpreted as being valid, further investigation using energy calculations creates more questions.

The Event versus Time plot for the unfiltered data is seen in Figure 26. Filtering out the flat line and reverberation data retains some of the step-like shape that is occurring at 6000 seconds as seen in Figure 27. It should be noted that this process reduced the event count by two orders of magnitude from 1917 to 18. In other words, approximately 1 percent of the data is possibly useful.

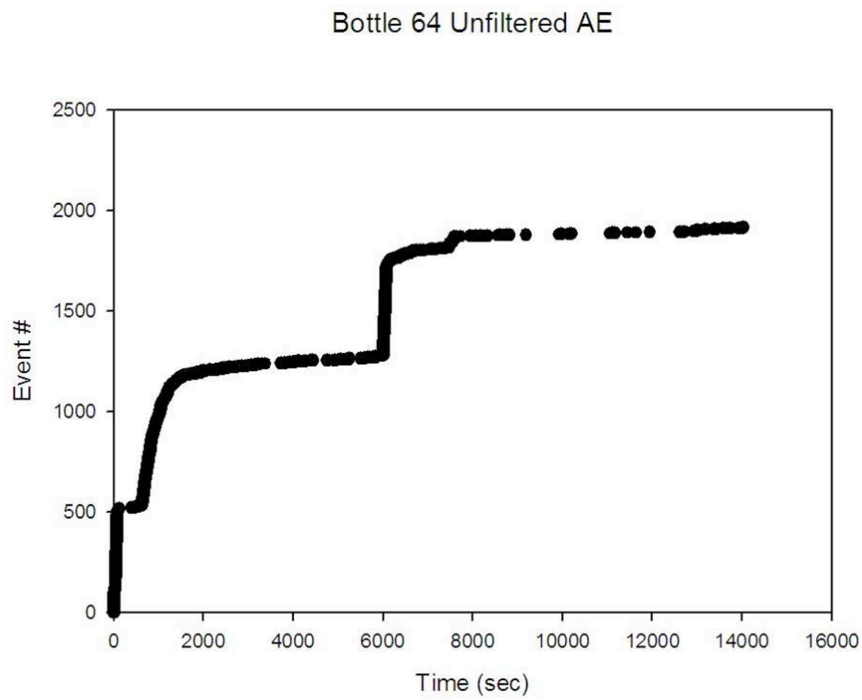


Figure 26. Bottle 64 AE event rate.

If we then look at the energy as seen in Figure 28, we see two short bursts, a few minutes each, of large events occurring at 6000 seconds and 14000 seconds. Echoing concerns of the energy analysis results for bottle 38, these results are inconclusive, although they look suspiciously like the behavior noted before in the Single bottle Fiber Bragg Grating tests (May/July 2007). The event energy jumped when event rate jumped, however, for those tests pressure was increased in steps and the AE jumps corresponded to each pressure jump. It is unknown if pressure jumps occurred during the time bottle 64 was being pressurized.

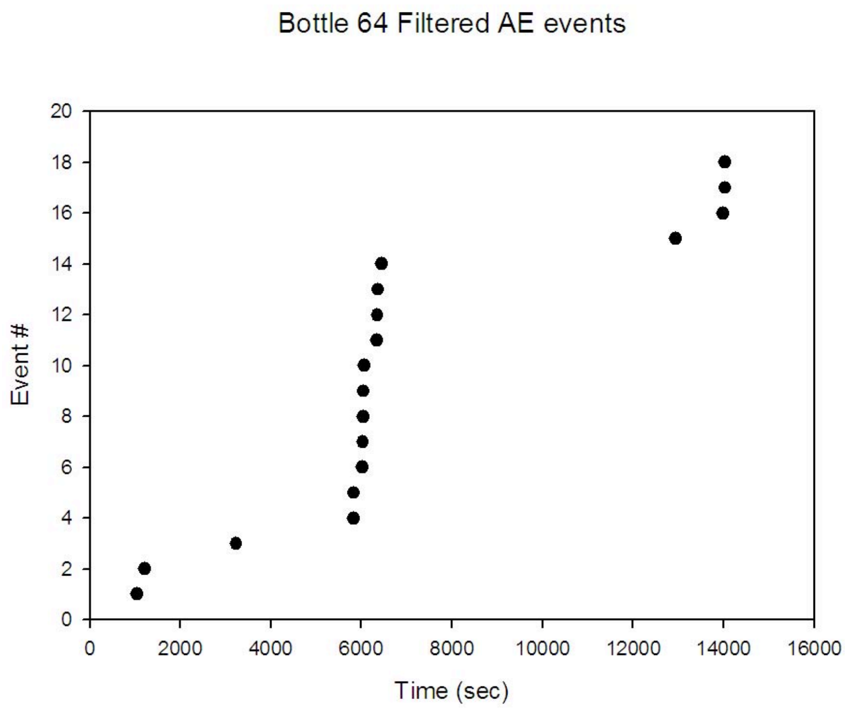


Figure 27. Bottle 64 filtered events

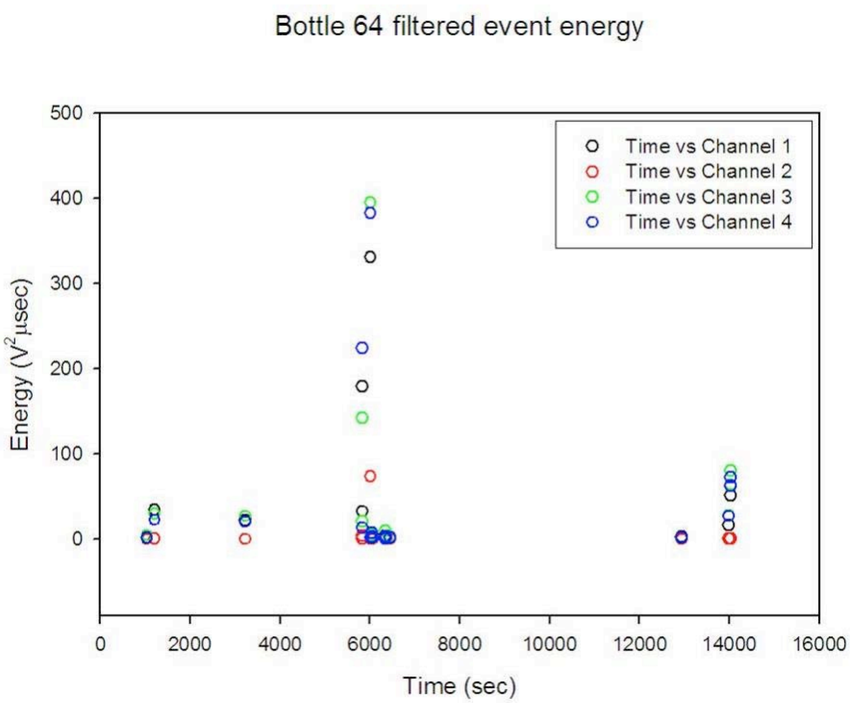


Figure 28. Bottle 64 Filtered AE event energy.

5.0 Conclusions and questions

Some of the results indicate that there is potential for AE to track stress-rupture degradation prior to failure. However, due to test design, there is not a statistically significant set of results for a more definitive conclusion. Application of the lessons learned should improve future testing, but there will always have to be trade-offs between test design and time and cost considerations.

However, even if future tests could be restricted to single bottles, which are the easiest to analyze, there may still be questions about the damage degradation rates. These tests were designed to accelerate failure and there are always questions about the relationship of an accelerated failure to the actual failure in operational bottles. About that issue the following AE questions come to mind.

- If the rate of damage development (i.e., energy release rate) for an accelerated test is greater than the available AE event capture rate (creating a situation similar to the multi-bottle tests where the potential for lost data is large), how does one compare these accelerated results to real-world situation where the damage development rate may be within the capabilities of the AE instrumentation's event capture rate? In other words, if event rate in an accelerated test allows tracking degradation, this is the best case scenario because the real-time test event rate would be even slower and easier to track. But if degradation in an accelerated test is not stretched out in time long enough for effective tracking by AE, that doesn't mean that real-time degradation is not slow enough to track with AE. In other words AE monitoring may be conclusive in a real-time test, even though results from accelerated tests are inconclusive.
- Does accelerated failure alter the failure mechanism such that energy release is rapid enough to create AE, but in a real-time test may not create AE?

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*: 01- 12 - 2008

2. REPORT TYPE: Technical Memorandum

3. DATES COVERED *(From - To)*:

4. TITLE AND SUBTITLE: Evaluation of Acoustic Emission NDE of Kevlar Composite Over Wrapped Pressure Vessels

5a. CONTRACT NUMBER:

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER:

5d. PROJECT NUMBER:

5e. TASK NUMBER:

5f. WORK UNIT NUMBER: 939904.05.07

6. AUTHOR(S): Horne, Michael R.; and Madaras, Eric I.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES): NASA Langley Research Center, Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER: L-19534

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES): National Aeronautics and Space Administration, Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S): NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S): NASA/TM-2008-215558

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 38
Availability: NASA CASI (301) 621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Pressurization and failure tests of small Kevlar/epoxy COPV bottles were conducted during 2006 and 2007 by Texas Research Institute Austin, Inc., at TRI facilities. This is a report of the analysis of the Acoustic Emission (AE) data collected during those tests. Results of some of the tests indicate a possibility that AE can be used to track the stress-rupture degradation of COPV vessels.

15. SUBJECT TERMS
Acoustic emission; COPV; Kelvar overwrapped pressure vessels

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	36	(301) 621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18