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ACOUSTIC EMISSION EXAMINATION

OF FIBER REINFORCED PLASTIC PRESSURE VESSEL

TA-301

UNDER CONTROLLED HYDROSTATIC

PRESSURIZATION

AT

COPIISA OFFSHORE, S.A. DE C.V.

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NOTICE

CONTENT

1. INTRODUCTION

A new fiber reinforced plastic (FRP) pressure Vessel TA-301 (Figure 1) was examined by acoustic emission technology during controlled hydrostatic pressurization. The vessel was not pressurized before. The test was conducted in accordance with the following standards:

[1] ASME Section X, Article RT-6. Acceptance Test Procedure for Class II Vessels, Edition 2013.

[2] ASME Section V, Article 11. Acoustic Emission Examination of Fiber-Reinforced Plastic Vessels, Edition 2013.

Other standards that were used or considered during the tests included:

[3] ASTM E 2374-10 Guide for Acoustic Emission System Performance Verification.

[4] ASTM E 569-13 Standard Practice for Acoustic Emission Monitoring of Structures during Controlled Stimulation.

[5] ASTM E 650-12 Guide for Mounting Piezoelectric Acoustic Emission Sensors.

[6] ASTM E 750-10 Standard Practice for Characterizing AE Instrumentation.

[7] ASTM E 1316-14 Terminology for Nondestructive Examinations.

[8] ASTM E 1067-07 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels.

The FRP vessel was designed and manufactured based on ASME Section X Edition 2013 Class II Method A from type E glass fibers and Derakane 411-350 epoxy VE resin. It had internal diameter of 1.473 meters and 3.099 meter height of the cylindrical body (between the top and the bottom ellipsoidal heads). The minimum design wall thickness of the shell was 58.5 mm. Specified maximum allowable pressure was 10.55 kg/cm^2 and hydrostatic test pressure 11.60 kg/cm^2. Maximum operational pressure was 10.55 kg/cm^2. For the detailed design and operational information refer fabrication drawings CO-VFS TA-301.

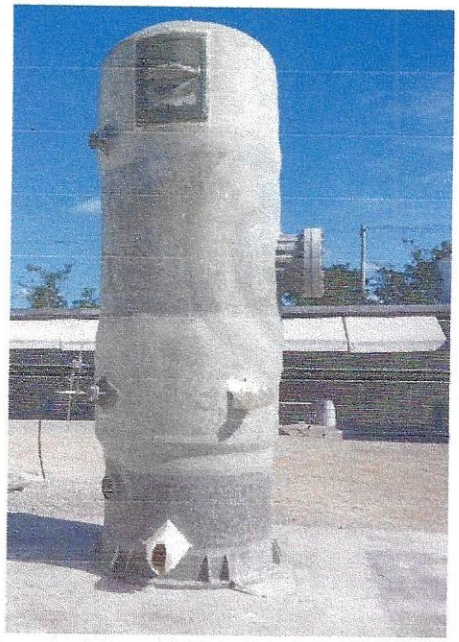

Figure 1. Pressure vessel TA-301.

In order to monitor structural integrity of the vessel during pressurization, a multichannel acoustic emission system (Figure 2) was installed. The acoustic emission system included 16 channels with AE sensors installed as shown in Figures 3-4. Sensors were mounted using cyano-acrylic adhesive for the best sensitivity and repeatability of installation. Two types of AE sensors were used per [2] including two low frequency sensors for monitoring the central part of the vessel and 14 high frequency sensors for monitoring the bottom and the top parts as well as the main nozzle in the central part (Figures 3-4). Channel characteristics including sensors resonance frequency, bandwidth of preamplifiers and AE device (Mistras PCI8 boards) frequency setup were selected in accordance with [2].

Acoustic emission parameters (see Terminology Section) of detected and measured signals during the tests included:

- Time of AE wave arrival.
- Peak amplitude.
- Energy.
- Signal strength.
- Rise time.
- Duration.
- Counts.
- Average frequency.
- RMS (root-mean-square).
- ASL (average signal level), a similar parameter to RMS measured in dB_{AE}.

Signal detection was performed using fixed threshold at all channels. For each detected signal, a corresponding waveform has been recorded.

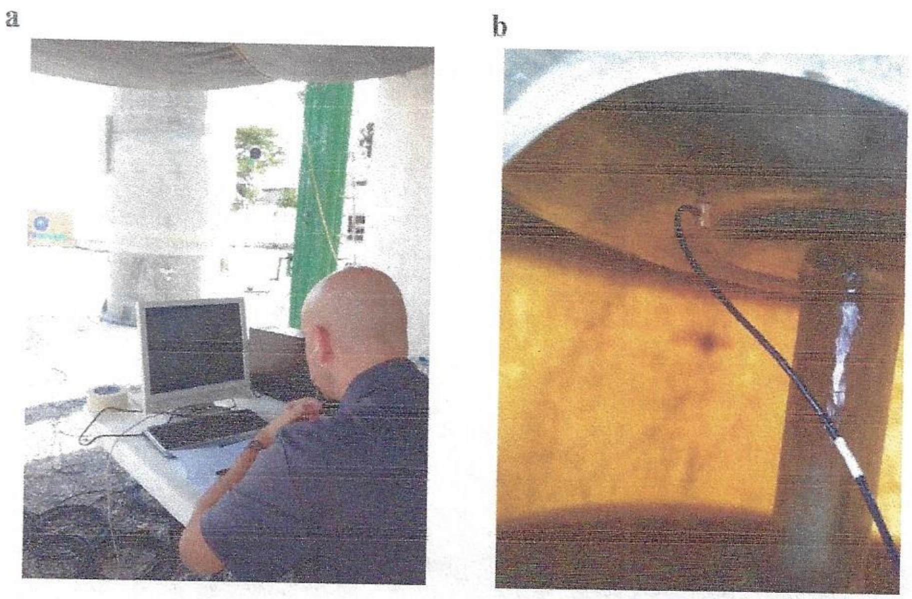

Figure 2. Multichannel AE system (a), AE sensor installed near AE point 1 on Vessel 301 (b).

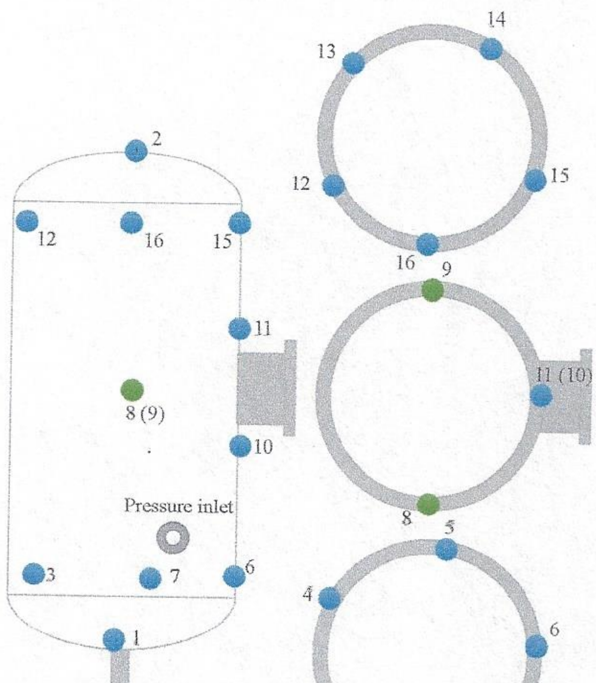

Figure 3. Schematic position of AE sensors along Vessel 301 during the first pressurization.

COPIISA OFFSHORE VITRODISEÑOS. CREATIVIDAD EN FIBRA DE VIDRIO	Vitro Fibras del Sureste, S.A. de C.V A Division of Copiisa Offshore, S.A. de C.V. SENSOR LOCATIONS

Date 12/01/2016
Quality Assurance Manager: Jesús Gamboa

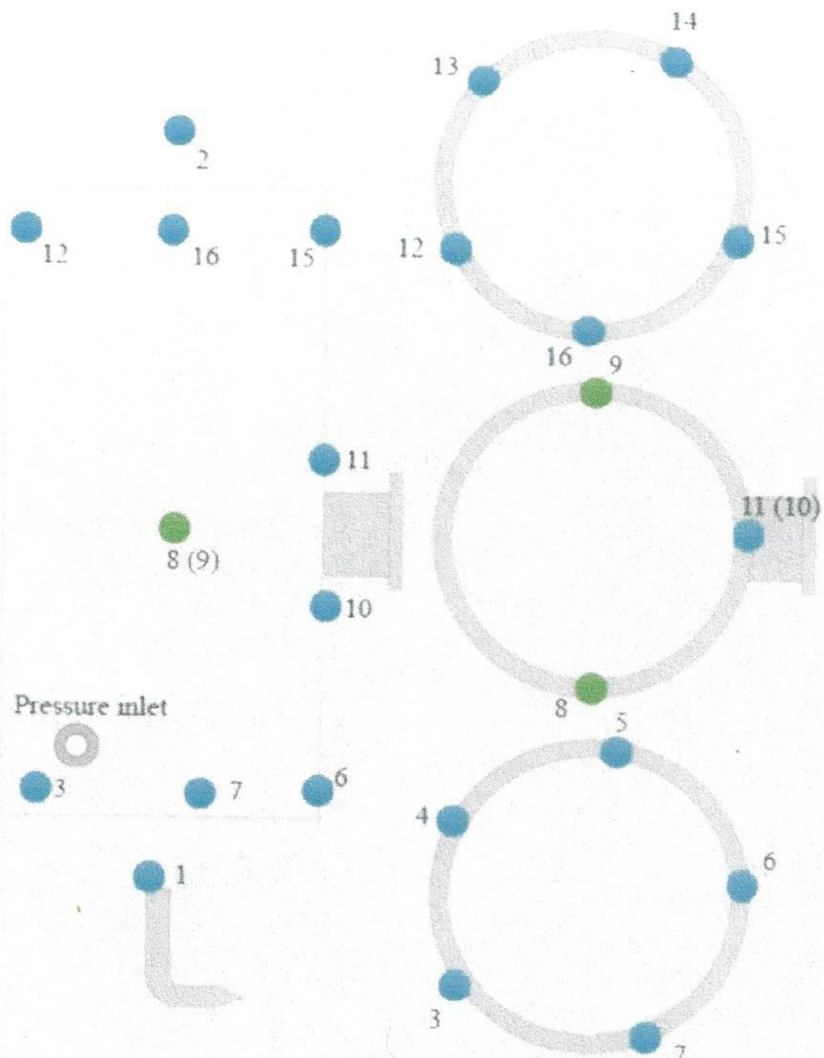

Figure 3. Schematic position of AE sensors on Vessel 901 during the test.

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SENSOR LOCATIONS

Date: 11/01/2016
Quality Assurance Manager: Jesús Gamboa

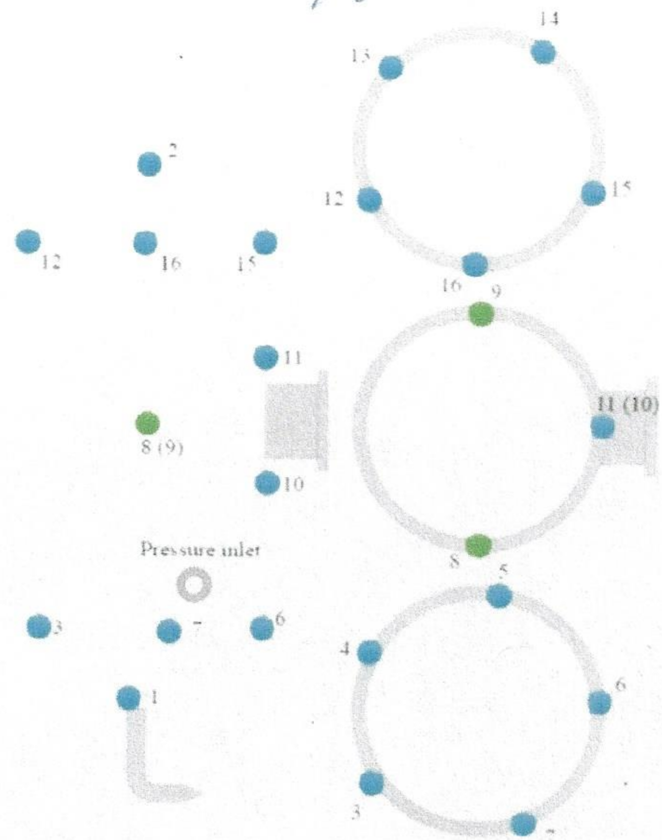


Figure 3. Schematic position of AE sensors along Vessel 301 during the first pressurization.

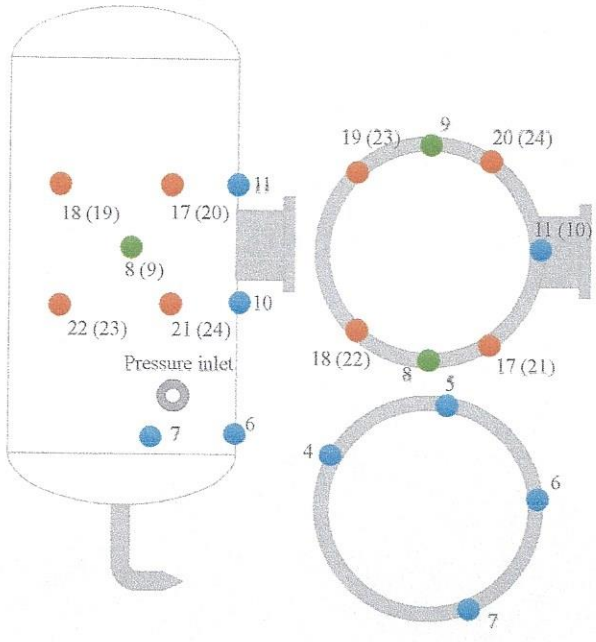


Figure 4. Schematic position of AE sensors on Vessel 301 during the second pressurization.

2. SENSITIVITY, VELOCITY AND ATTENUATION TESTS

After installation of the AE system was completed, a series of tests were conducted in order to evaluate sensitivity of the system, velocity of AE waves propagation and their attenuation characteristics in the vessel in different principle directions.

The tests were performed by generating artificially AE waves using pencil lead break at different positions near AE sensors per [2] (Figure 5). The results showed that:

1. All sensors maintain required level of sensitivity.
2. AE system maintains optimal sensitivity with adequately selected sensors position and acquisition scheme.

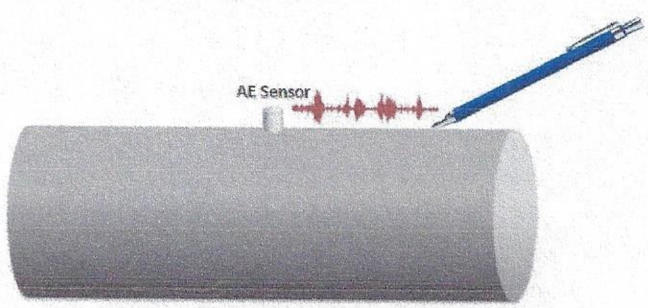


Figure 5. Illustration of pencil lead breaks used to generate AE waves.

3. AE EXAMINATION

3.1. Analysis and evaluation procedure

Analysis and evaluation were performed per [1] and [2]. In addition, special proprietary methods of data analysis were applied for additional flaw-indication characterization.

Analysis of acoustic emission data measured during the tests had the following principle steps:

1. ***Detection:*** Detection of AE activity was done by application of fixed amplitude threshold, equal in all measurement channels.
2. ***Filtering*** frictional and other mechanical noises. Flaw suspected activity was selected based on signal's rise time, duration, peak amplitude, counts, energy and frequency values.
3. ***Location:*** 2D time-difference of wave arrival locations were performed to evaluate source location whenever was practical. In other cases zone location was performed.
4. ***Indication assessment:*** Analysis of total number of AE hits during pressure rise and hold periods, their energy, amplitude, duration, counts and frequency characteristics and AE activity vs. location vs. pressure and calculation of Felicity ratio were performed to assess revealed indications.

3.2. Results

3.2.1. First pressurization

During the first cycle, pressure was raised in a stepwise manner (Figures 6 and 7) per requirements in [2] to the test pressure of 176 psi (specified by the customer) and then released to zero. Analysis of examination data performed according to [1]-[2] and the procedure described in Section 3.1., established that:

1. Loading was accompanied by AE activity in several zones of the vessel. Most of this activity had low energy and low amplitude below minimum detectability threshold required in [2] (Figure 8).
2. The highest level of AE events with peak amplitudes above A_M (see for definition and specifications in [1] and [2]) were detected near AE points 2, 5, 7, 8, 9 and 10 (Figures 7 and 9). Correspondingly in high frequency AE points 2, 5 and 7 there were 5 or more events. Further analysis established that:
    a. In all these 3 zones, AE events with amplitude above A_M were released during a period of up to 30 seconds after 2 hours and 3 minutes from the beginning of the test. This period corresponds to the end of pressurization to 159 psi and the very beginning of the corresponding hold time.
    b. Nevertheless, acoustic emission activity during this and all other load holds between the second and the 4th minute was below 5 events per minute with amplitude above A_M and the acceptance criteria based on hold time activity was met.

   c. Most of AE activity (but not all) detected near AE point 7 was related to AE waves that propagated through water from AE point 5 (Figures 8 and 9).

3. It is important to note that small drops of pressure were observed at the beginnings of almost all pressure holds and small leaks were detected in the main nozzle (AE points 10-11) and in the pressurization nozzle locating near AE point 7 during pressurization. There is a possibility that at least some of the detected activity was related to leaks.
4. Felicity ratio calculated for each pressurization step was above 1 during the entire test in all locations.
5. Number of events E_A with amplitude above reference amplitude threshold (see for definition and specifications [1] and [2]) has not exceeded 10 events at all locations.
6. Total number of counts was not excessive in all locations during pressure rise and hold periods.
7. No signals with high energy and prolong duration suspected to delamination, adhesive bond failure or major crack growth (*M* criteria, see for definition and specifications [1] and [2]) were detected.

Based on the results of the test and despite that the acceptance criteria (see [1]) was met, it was decided to perform a repetitive pressurization. The main reasons for that were:

1. Presence of AE activity in the central part of the vessel near low frequency AE points 8 and 9 as well as activity near AE points 2, 5 and 10-11.
2. Installation of additional high frequency sensors in the central part of the vessel for better indication location.

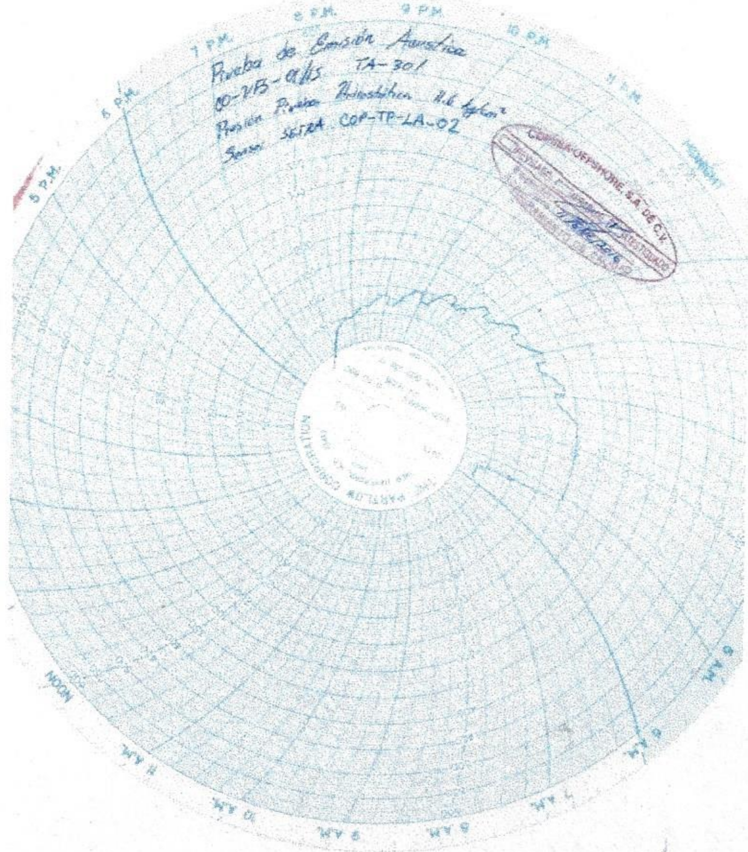


Figure 6. First pressurization schedule of Vessel 301.

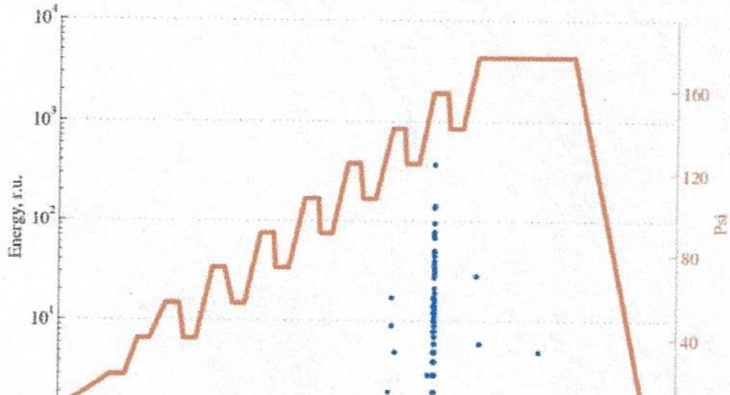


Figure 7. Acoustic emission Energy, r.u. vs. Time, sec vs. Pressure, psi during the first pressure cycle at AE point 5.

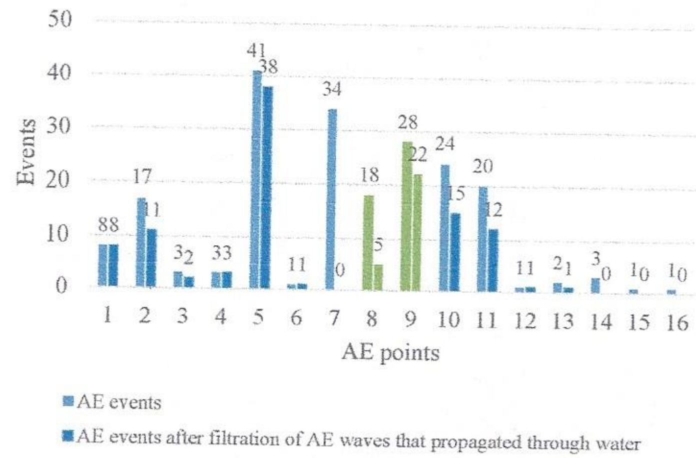


Figure 8. Acoustic emission events with Amplitude **below** minimum required detectability threshold **during the entire first pressurization**.

Note: Low frequency AE sensors 8 and 9 were not used in criteria evaluation per [2].

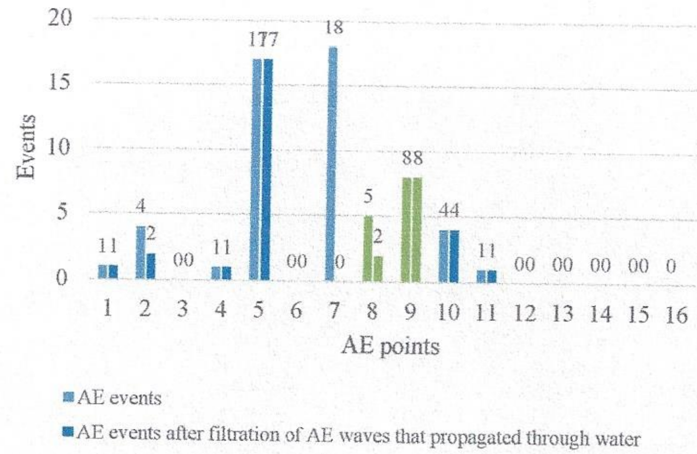


Figure 9. Acoustic emission events with Amplitude above A_M detected **during the entire first pressurization**.

Note: Low frequency AE sensors 8 and 9 are not used in criteria evaluation per [2].

3.2.2. Second pressurization

During the second test performed one day after the first pressurization, pressure was raised in a stepwise manner specified by an ASME inspector (Figure 10) to 176 psi test pressure and then released to zero. Analysis of examination data established that:

1. Loading was accompanied by AE activity in several zones of the vessel. Most of this activity had low energy and low amplitude below minimum detectability threshold required in [2] (Figure 11).
2. The highest level of AE events with peak amplitude above A_M were detected near AE points 5 and 7 (Figure 12) and initiated mostly at 42 minutes and 50 seconds from the beginning of the test at pressure of 155 psi (Felicity ratio above 1) just before reaching 159 psi pressure hold. During next unloading and pressure hold at 142 psi pressure this activity was not observed anymore.
3. Further analysis established that most of AE activity (but not all) detected near AE point 7 was related to AE waves that propagated through water from AE point 5 (Figures 11 and 12).

4. After 2 minutes and to the end of the load hold at 159 psi, there were detected 11 AE events with peak amplitude above A_M near AE point 5 which is above acceptance criteria [1], but Felicity ratio calculated for this pressurization step was above 1.
5. After 2 minutes and to the end of the load hold of 176 psi, there were detected 5 AE events with peak amplitude above A_M near AE point 5 which is above acceptance criteria [1], but Felicity ratio calculated for this pressurization step was above 1.
6. Felicity ratio calculated for all pressurization steps was above 1 during the entire test in all locations. Felicity ratio for initiation of significant AE activity near AE point 5 calculated relatively to the first pressurization cycle was with the first 155/159=0.975 which meets acceptance criteria in [1].
7. Number of events E_A with amplitude above reference amplitude threshold that remained after the first hit filtration has not exceeded 5 events at all high frequency sensors.
8. Total number of counts has not exceeded N_C (see for definition and specifications [1] and [2]) however it was close to limit numbers near AE points 5.
9. No signals with high energy and prolong duration suspected to delamination, adhesive bond failure or major crack growth (M criteria, see for definition and specifications [1] and [2]) were detected.

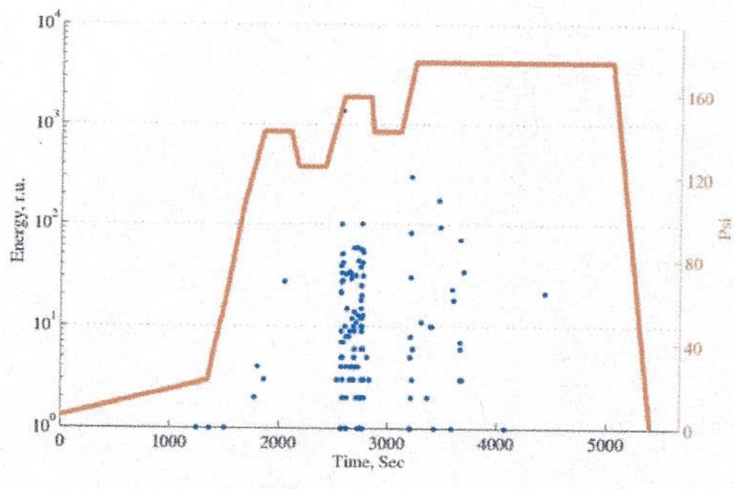


Figure 10. Acoustic emission Energy, r.u. vs. Time, sec vs. Load, psi during the second pressure cycle at AE point 5.

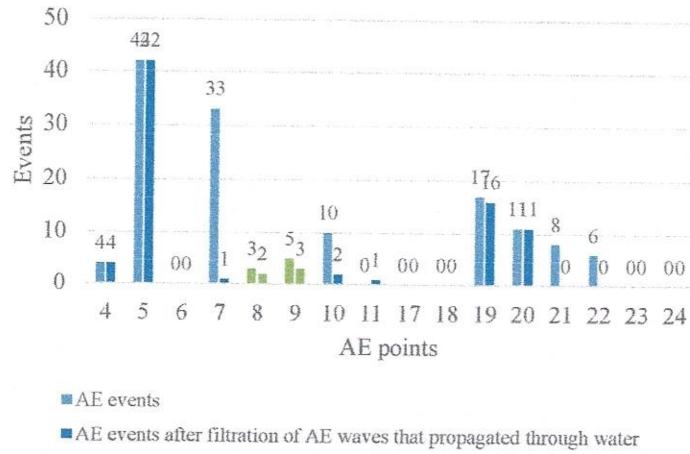


Figure 11. Acoustic emission events with Amplitude **below** minimum required detectability threshold **during the entire second pressurization**.

Note: Low frequency AE sensors 8 and 9 were not used in criteria evaluation per [2].

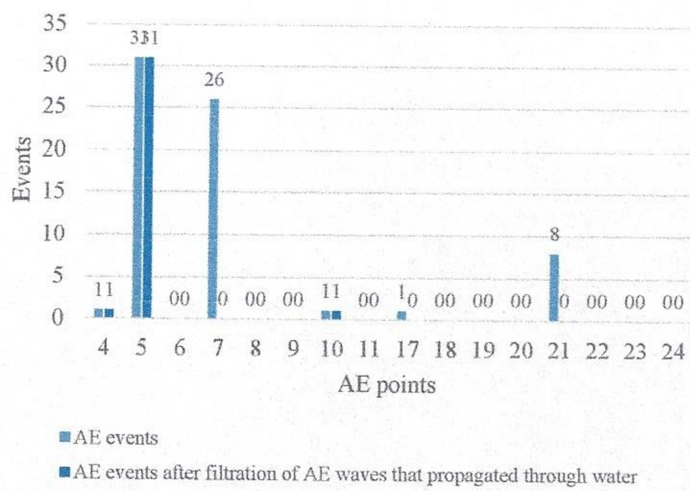


Figure 12. Acoustic emission events with Amplitude above A_M detected **during the entire second pressurization**.

Note: Low frequency AE sensors 8 and 9 are not used in criteria evaluation per [2].

Figure 13. Position of AE indication revealed in Vessel 301 near AE point 5.

4. CONCLUSIONS

Based on the results of the tests it is possible to conclude that Vessel 301 has met acceptance criteria per ASTM Section X Article RT-6 [1] during the first pressurization. However, a repetitive pressurization was performed due to borderline indications near AE point 5 (Figure 13). AE results from the second pressurization have not met acceptance criteria for AE activity during load holds at 159 and 176 psi. Additional special analysis of AE data from the second pressurization established that:

1. No significant AE activity at pressure below maximum operation pressure of 10.55 kg/cm^2 (150 psi).
2. Revealed indication near AE point 5 at 159 psi and higher pressure was characterized by a relatively low activity level and low energy during load holds and was not characteristic of major/severe structural damage. There were not detected indications suspected to delamination development, adhesive bond failure or major crack growth. Also, Felicity ratio was above 1 during all loading steps indicating absence of severe structural damage. Based on these findings, we consider the indication near AE point 5 as a borderline indication which was not a structure critical at the time of examination.

5. RECOMMENDATIONS

It is recommended to:

1. Perform a follow up test of Vessel 301 (can be tested in operation) after 12 month of service. Consider to perform other local NDT examinations and/or a visual inspection and/or a tap testing in the area near AE point 5.
2. Re-inspect vessels regardless recommended interval in case of suspected in-service damage from impact, over pressurization, overheating, deformation or other reason that can affect their structural integrity in a short-term.

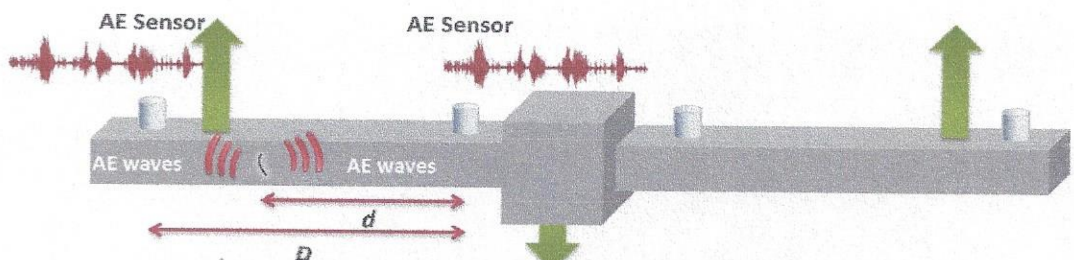
APPENDIX

1. ACOUSTIC EMISSION TECHNOLOGY

Different methods have been developed and applied during recent decades for non-destructive evaluation of composite structures. Among these methods, ***acoustic emission*** technology is unique as it is not only detects, locates and assesses flaws but also is used for on-line, real time monitoring of flaw-development under real operational/stress conditions.

Application of acoustic emission testing for aerospace structures has started in 1960s after failure of motor cases that passed shop proof-pressure hydro tests but failed during fire tests. Since then acoustic emission technology is widely applied for inspection of composite aerospace structures over the world and especially for composite structures of planes, rocket bodies, radomes, motor cases and composite overlapped pressure vessels.

Acoustic emission is a phenomenon of sound and ultrasound (stress) wave radiation in materials that undergo deformation or fracture processes.



$d = \frac{1}{2}(D - \Delta T \cdot V)$

d = distance from first hit sensor

D = distance between sensors

V = wave velocity

Figure I. Location of AE sources on a composite beam.

Crack propagation in loaded solid materials such as metal and composites results in a fast release of potential energy in form of stress waves with frequencies typically between 50 kHz and 1 MHz. These waves propagate along the structure for distances of several meters and are detected by piezoelectric sensors. Special analysis of detected AE waves is then performed to locate acoustic emission flaw sources, identify flaw type, evaluate rate of flaw propagation and it sensitivity to load/stress/operational changes.

Main sources of AE in composite structures are matrix cracking, delamination, fiber cracking and fiber pullout. In addition, other sources of acoustic emission due to impact and leaks are readily detected and assessed by AE technology.

2. ACOUSTIC EMISSION STANDARDS

Acoustic Emission non-destructive test method has several dozens of standards, procedures and test methods issued by various international organizations such as ASTM, ASME and others. The following standards were applicable partially or at whole for examination of composite structures:

1. ASTM E 569 Standard Practice for Acoustic Emission Monitoring of Structures during Controlled Stimulation.
2. ASTM E 2076 Standard Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission.
3. ASTM E 650 Guide for Mounting Piezoelectric Acoustic Emission Sensors.
4. ASTM E 750 Standard Practice for Characterizing AE Instrumentation.
5. ASTM E 976 Guide for Determining the Reproducibility of Acoustic Emission Sensor Response.
6. ASTM E 1316 Terminology for Nondestructive Examinations.
7. ASTM E 2374 Guide for Acoustic Emission System Performance Verification.
8. ASTM E 2533 Standard Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications.
9. ASTM E 2661 / E 2661M-10 Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications.
10. ASME Section V, Article 11 Acoustic Emission Examination of Fiber-Reinforced Plastic Vessels, Edition 2013.
11. ASME Section V, Article 13, Boiler & Pressure Vessel Code, Continuous Acoustic Emission Monitoring.

3. TERMINOLOGY

This report use standard terminology from ASTM E 1316 *Terminology for Nondestructive Examinations*.

Selected terms from ASTM E 1316 11B edition:

acoustic emission (AE)—the class of phenomena whereby transient stress/displacement waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated.

NOTE 3—Acoustic emission is the recommended term for general use. Other terms that have been used in AE literature include: (*1*) stress wave emission, (*2*) microseismic activity, and (*3*) emission or acoustic emission with other qualifying modifiers.

attenuation, *n*—the gradual loss of acoustic emission wave energy as a function of distance through absorption, scattering, diffraction and geometric spreading.

DISCUSSION—Attenuation can be measured as the decrease in AE amplitude or other AE signal parameter per unit distance.

defect, *n*—one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.

discontinuity, *n*—a lack of continuity or cohesion; an intentional or unintentional interruption in the physical structure or configuration of a material or component.

flaw, *n*—an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.

Other terms used in this report are:

fracture critical flaw – a flaw that exhibit unstable growth at service conditions.

AE activity, *n*—the presence of acoustic emission during a test.

AE amplitude—the peak voltage of the largest excursion attained by the signal waveform from an emission event. AE Amplitude is normally reported in dB_{AE} - a logarithmic measure of acoustic emission signal amplitude, referenced to 1 µV at the sensor, before amplification. Signal peak amplitude ($dBAE$) = $20 \log_{10}(A_1/A_0)$, where

$A0$ = 1 µV at the sensor (before amplification), and

A_1 = peak voltage of the measured acoustic emission signal (also before amplification).

AE average frequency – signal counts divided on signal's duration.

AE rms, *n*—the rectified, time averaged AE signal, measured on a linear scale and reported in volts.

AE signal duration—the time between AE signal start and AE signal end.

AE signal end—the recognized termination of an AE signal, usually defined as the last crossing of the threshold by that signal.

AE signal rise time—the time between AE signal start and the peak amplitude of that AE signal.

AE signal start—the beginning of an AE signal as recognized by the system processor, usually defined by an amplitude excursion exceeding threshold.

count, acoustic emission (emission count) (N)—the number of times the acoustic emission signal exceeds a preset threshold during any selected portion of a test.

energy, acoustic emission signal—the energy contained in an acoustic emission signal, which is evaluated as the integral of the volt-squared function over time.

signal strength—the measured area of the rectified AE signal with units proportional to volt-sec.