

LETTER BALLOT 10-601

Subj: Supplement 9 Inservice Inspection of High Pressure
Composite Vessels

Explanation: The manufacturer of this type of vessels was added to Section X in the 2010 Edition. This supplement provides the requirements for inspecting the vessels.

PM: B. Shelley

Background: This supplement is for the inspection of a new class (Class 3) of vessels to be manufactured per Section X.

Existing Text: None

Proposed Revision: None. All new.

Rationale: Inspection requirements to determine the adequacy of the vessel for continued service.

Notes during discussion:

NB10-0601

SUPPLEMENT 9

INSPECTION OF STATIONARY HIGH PRESSURE COMPOSITE PRESSURE VESSELS

S9.1 SCOPE

This supplement provides specific guidelines for inspection of high pressure composite pressure vessels. This supplement is applicable to pressure vessels with a design pressure that exceeds 3000 psi but no greater than 15000 psi, and is applicable to the following four classes of pressure vessels:

- a) Metallic vessel with a hoop Fiber Reinforced Plastic (FRP) wrap over the straight shell cylindrical part of the vessel (both load sharing).
- b) Fully wrapped FRP vessel with a non-load sharing metallic liner.
- c) FRP vessel with a non-load sharing non-metallic liner.
- d) Fully wrapped FRP vessel with load sharing metallic liner.

S9.2 INSERVICE INSPECTION

- a) Section 1 of this Part shall apply to inspection of high pressure composite pressure vessels, except as modified herein. This supplement covers vessels and tanks only, and was not written to cover piping and ductwork, although some of the information in this supplement may be used for the inspection of piping and ductwork.
- b) The inspection and testing for exposed load sharing metallic portions of composite pressure vessels shall be in accordance with Part 2, Section 2.3 and 4 of this Code.
- c. All vessels shall have an initial acoustic emission examination **per S9.11** after the first 3 years from the date of manufacture. Thereafter, vessels shall have a maximum examination interval of 5 years which shall be shortened **based on the results of any external inspection per paragraph S9.7.**
- d. All vessels shall be subject to the periodic inspection frequency given in S9.9.

S9.3 GENERAL

a) High pressure composite vessels are used for the storage of hydrogen and other gases at pressures up to 15000 psi. Composite vessels consist of the FRP laminate with load sharing or non load sharing metallic shells/liners, or non metallic liners. The FRP laminate with load sharing metallic liners form the pressure retaining system. The FRP laminate is the pressure retaining material for composite vessels with non-load sharing metallic and non metallic liners. The purpose of the non-load sharing metallic and the non metallic liners is to minimize the permeation of hydrogen through the vessel wall.

b) The hydrogen gas stored in the composite vessels is 99.9999% pure, and is considered to be non corrosive to the materials used for vessel construction. The laminate is susceptible to damage from:

- 1) External Chemical attack
- 2) External Mechanical damage (i.e. abrasion, impact, cuts, dents, etc.)
- 3) Structural damage (i.e. over pressurization, distortion, bulging, etc.)
- 4) Environmental degradation [i.e. ultraviolet (if there is no pigmented coating or protective layer), ice, etc.]
- 5) Fire or excessive heat

S9.4 VISUAL EXAMINATION

a) Acceptable Damage

Acceptable damage or degradation is minor and is normally found in service and is considered to be cosmetic. This level of damage or degradation does not reduce the structural integrity of the tank. This level of damage or degradation should not have any adverse effect on the continued safe use of the tank. This level of damage or degradation does not require any repair to be performed at the time of in-service inspection. When there is an external, non load bearing, sacrificial layer of filaments on the tank, any damage or degradation should be limited to this layer. There should be no evidence of any cut filaments in the structural wall.

b) Rejectable Damage (Condemned—Not Repairable)

Rejectable damage or degradation is so severe that structural integrity of the tank is sufficiently reduced so that the tank is considered unfit for continued service and must be condemned and removed from service. No repair is authorized for tanks with rejectable damage or degradation.

c) Acceptance Criteria

Certain, specific types of damage can be identified by the external in-service visual inspection. Indications of certain types and sizes may not significantly reduce the structural integrity of the tanks and may be acceptable so that the tanks can be left in service. Other types and larger sizes of damages may reduce the structural integrity of the tanks and the tanks must be condemned and removed from service. Table 1 table is a summary of the acceptance/rejection criteria for the indications that are found by external visual inspection of the tanks.

d) Fitness-for-service

1) If a visual inspection reveals that a hydrogen cylinder does not meet all criteria of Table 1 satisfactorily, it shall be taken out of service immediately and either be condemned or a fitness-for-service examination be conducted by the original vessel manufacturer who must also hold a National Board R stamp. When the vessel is taken out of service its contents must be immediately safely vented or transferred to another storage vessel per the owner's written safety procedures.

2) If a fitness-for-service examination is to be conducted, the original hydrogen cylinder manufacturer shall be contacted as soon as possible after the rejectable defects have been found. The manufacturer shall then determine the cylinder's fitness-for-service by applicable techniques, i.e., acoustic emission testing, ultra-sonic testing, and/or other feasible methods. The manufacturer shall have documentation that the evaluation method(s) used is satisfactory for determining the condition of the cylinder and whether repairs are feasible for any permissible structural defects. All repairs to the structural laminate shall only be made by the original manufacturer. Repairs

to the outer protective layer may be made by a R stamp holder other than the original manufacturer following the original manufacturer's instructions.

Table 1 - Visual Acceptance/ Rejection Criteria for Composite Pressure Vessels

Type of Degradation or Damage	Description of Degradation or Damage	Acceptable Level of Degradation or Damage	Rejectable Level of Degradation or Damage
Abrasion	Abrasion is damage to the filaments caused by wearing or rubbing of the surface by friction	Less than 0.050 in. depth in the pressure bearing thickness.	≥ 0.050 in. depth in the pressure bearing thickness
Cuts	Linear indications flaws caused by a impact with a sharp object	Less than 0.050 in. depth in the pressure bearing thickness.	≥ 0.050 in. depth in the pressure bearing thickness
Impact Damage	Damage to the tank caused by striking the tank with an object or by being dropped. This may be indicated by discoloration of the composite or broken filaments and/or cracking.	Slight damage that causes a frosted appearance or hairline cracking of the resin in the impact area	Any permanent deformation of the tank or damaged filaments
Delamination	Lifting or separation of the filaments due to impact, a cut, or fabrication error.	Minor delamination of the exterior coating	Any loose filament ends showing on the surface. Any bulging due to interior delaminations
Heat or Fire Damage	Discoloration, charring or distortion of the composite due to temperatures beyond the curing temperature of the composite	Merely soiled by soot or other debris, such that the cylinder can be washed with no residue	Any evidence of thermal degradation or discoloration or distortion
Structural Damage - bulging, distortion, , depressions	Change in shape of the tank due to sever impact or dropping	None	Any visible distortion, bulging, or depression
Chemical attack	Environmental exposure that causes a change in the composite or failure of the filaments	Any attack that can be cleaned off and that leaves no residue	Any permanent discoloration or loss or softening of material under the exterior coat.

Cracks	Sharp, linear indications	None	None
Scratches/Gouges	Sharp, linear indications caused by mechanical damage.	Less than 0.050 in. depth in the pressure bearing thickness No structural fibers cut or broken	≥ 0.050 in. depth in the pressure bearing thickness or structural fibers cut or broken
Soot	A deposit on the composite caused by thermal or environmental exposure	Soot that washes off and leaves no residue	Any permanent marking that will not wash off the surface under the exterior coating
Over pressurization	Excessive pressure due to operational malfunction	None reported	Any report of pressurization beyond the MAWP or any indication of distortion
Corrosion	Degradation of the composite due to exposure to specific corrosive environments	None visible	Any surface damage to structural identified as corrosion
Dents	A depression in the exterior of the tank caused by impact or dropping	$< 1/16$ in. in depth	Any dents with a depth $\geq 1/16$ in. Or with a diameter greater than 2 inches
Reported collision, accident, or fire	Damage to the tank caused by unanticipated excursion from normally expected operating conditions	None reported	Any indication or report of impact or heat damage
Environmental Damage or Weathering	Ultraviolet or other environmental attack under the exterior coating.	None	Any discoloration that can not be washed off*
Crazing	Hairline surface cracks only in the composite resin	Light hairline cracks only in the resin	Any damage to the filaments
Damage to a protective or sacrificial layer	Abrasion, cuts, chemical attack, scratches/gouges, corrosion, environmental damage, or crazing that are limited only to the protective or sacrificial layer.	The depth of any damage to the protective or sacrificial layer that does <u>not exceed</u> the thickness of the protective or sacrificial layer plus 0.050 inch.	The depth of any damage to the protective or sacrificial layer that <u>exceeds</u> the thickness of the protective or sacrificial layer plus 0.050 inch.

Note: Only damage beyond the sacrificial or coated layer should be considered, and that any damage to sacrificial or coated layers should be repaired by suitable techniques (i.e. epoxy filler). Refer to ASME data report for sacrificial layer thickness.

* - Washing off UV scale will accelerate attack into lower composite layers. For this reason, if there is superficial UV damage we recommend persons to clean and paint the affected area with a UV tolerant paint. If broken, frayed, or separated fibers, to the non sacrificial layer, are discovered during the cleaning process then the cylinder must be condemned.

S9.5 INSPECTOR QUALIFICATIONS

The Inspector shall be familiar with composite tank construction and qualified by training and experience to conduct such inspections. The Inspector should have a thorough understanding of all required inspections, tests, test apparatus, inspection procedures, and inspection techniques and equipment applicable to the types of tanks to be inspected. The Inspector should have basic knowledge of the container material types and properties. Refer to Part 2 para. S4.2

The acoustic emission technician conducting the examination required per S9.2(c) and in accordance with S9.11 shall be certified per the guidelines of ASNT SNT-TC-1A or CP-189 AE Level II or III. A technician performing this test should have training in and experience with measuring C_e and C_f in composites and identifying wave modes.

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S9.6 ASSESSMENT OF INSTALLATION

a) The visual examination of the tanks requires that all exposed surfaces of the tank are examined to identify any degradation, defects, mechanical damage, or environmental damage on the surface of the tank.

The causes of damage to the tanks that may be found are: (1) abrasion damage, (2) cut damage, (3) impact damage, (4) structural damage, (5) chemical or environmental exposure damage or degradation, and (6) heat or fire damage.

The types of damage found are: (1) cracks, (2) discolored areas, (3) gouges and impact damage, (4) leaks, (5) fiber exposure, (6) blisters, (7) delaminations, (8) surface degradation, and (9) broken tank supports.

b) The visual examination of the tanks requires that the identity of the tank must be verified. This should include the ASME Code to which the tank was constructed, the tank serial number, the maximum allowed operating pressure, the date of manufacture, the tank manufacturer, the date of expiration of the service life of the tank, and any other pertinent information shown on the tank or available from tank documents. The overall condition of the tank should be noted.

S9.7 EXTERNAL INSPECTION

a) Tank Service Life

Composite tanks have been designed and manufactured for a limited lifetime; this is indicated on the tank marking. This marking should first be checked to ensure that such tanks are within their designated service lifetime.

b) Identification of External Damage

The external surface should be inspected for damage to the composite. Any damage is classified into two levels of damage as shown in Section 9 of these guidelines. The acceptance/rejection criteria shown in section 10 of these guidelines should be followed, as a minimum.

The external surface of the tank is subject to mechanical, thermal, and environmental damage. The external surface of the tank may show damage from impact, gouging, abrasion, scratching, temperature excursions, etc. Areas of the surface that are exposed to sunlight may be degraded by ultraviolet light which results in change in the color of the surface and may make the fibers more visible. This discoloration does not indicate a loss in physical properties of the fibers.

Overheating may also cause a change in color.

The size (area or length and depth) and location of all external damage should be noted.

Tank support structures and attachments should be examined for damage such as cracks, deformation, or structural failure.

c) Types of External Damage

1. General

Several types of damage to the exterior of composite tanks have been identified. Examples of specific type of damage are described below. The acceptance/rejection criteria for each type of damage are described in Table 1 of this supplement.

2. Abrasion Damage

Abrasion damage is caused by grinding or rubbing away of the exterior of the tank. Minor abrasion damage to the protective outer coating or paint will not reduce the structural integrity of the tank. Abrasion that results in flat spots on the surface of the tank may indicate loss of composite fiber overwrap thickness

3. Damage from Cuts

Cuts or gouges are caused by contact with sharp objects in such a way as to cut into the composite overwrap, reducing its thickness at that point.

4. Impact Damage

Impact damage may appear as hairline cracks in the resin, delamination, or cuts of the composite fiber overwrap.

5. Delamination

Delamination is a separation of layers of fibers of the composite overwrap. It may also appear as a discoloration or a blister beneath the surface of the fiber.

6. Heat or Fire Damage

Heat or fire damage may be evident by discoloration, charring or burning of the composite fiber overwrap, labels, or paint. If there is any suspicion of damage, the vessel shall be re-qualified using an acoustic emission examination.

7. Structural Damage

Structural damage will be evidenced by bulging, distortion, or depressions on the surface of the tank.

8. Chemical Attack

Some chemicals are known to cause damage to composite materials. Environmental exposure or direct contact with solvents, acids, bases, alcohols, and general corrosives can cause damage to composite tanks. Long-term contact with water can also contribute to corrosive damage. Chemicals can dissolve, corrode, remove, or destroy tank materials. Chemical attack can result in a significant loss of strength in the composite material. Chemical attack can appear as discoloration and in more extreme cases the composite overwrap can feel soft when touched.

S9.8 INTERNAL INSPECTION

a) Requirements for Internal Visual Inspection

Internal visual inspection is normally not required. ~~The purpose of an internal visual inspection is to determine if corrosion has occurred on the metal liner (for tanks having a metal liner) or on the plastic liner/metal boss assembly (for fully wrapped tanks with non-metallic liners).~~ When the tanks have been filled only with pure, dry hydrogen, corrosion of the interior of the liner should not occur. Internal visual inspection of the tanks should only be carried out when:

1. There is evidence that any commodity except pure dry hydrogen has been introduced into the tank. In particular, any evidence that water, moisture, compressor cleaning solvents, or other corrosive agents have been introduced into the tank will require an internal visual inspection.
2. There is evidence of structural damage to the tank, such as denting or bulging.
3. The tank valve is removed for maintenance or other reason.

When an internal visual inspection is conducted, the following procedures should be followed.

b) Identification of Internal Damage

1. Tanks with Metallic Liners

For tanks with metallic liners, the objective of the internal visual inspection is primarily to detect the presence of any corrosion or corrosion cracks. The

internal surface of the tank should be inspected with adequate illumination to identify any degradation or defects present. Any foreign matter or corrosion products should be removed from the interior of the tank to facilitate the inspection. If any chemical solutions are used in the interior of the tank they should be selected to ensure that they do not adversely affect the liner or composite overwrap materials. After cleaning the tank should be thoroughly dried before it is inspected. . All interior surface of the tank should be inspected for any color differences, stains, wetness, roughness, or cracks. The location of any degradation should be noted. Any tank showing significant internal corrosion, dents or cracks should be removed from service.

2. Tanks with Non-metallic Liners or No Liners

Tanks with non-metallic liners may show corrosion on the plastic liner or metal boss ends. Tanks with non-metallic liners or no liners may also show internal degradation in the form of cracks, pitting, exposed laminate, or porosity. The internal surface of the tank should be inspected with adequate illumination to identify any degradation or defects present. Any foreign matter or corrosion products should be removed from the interior of the tank to facilitate the inspection. If any chemical solutions are used in the interior of the tank they should be selected to ensure that they do not adversely affect the liner or composite overwrap materials. After cleaning the tank should be thoroughly dried before it is inspected. The inspector should look for cracks, porosity, indentations, exposed fibers, blisters, and any other indication of degradation of the liner and/or laminate. Deterioration of the liner may include softening of the matrix or exposed fibers.

SX.9 INSPECTION FREQUENCY

a) Initial inspection

The vessel shall be inspected by the Inspector or the Authority having jurisdiction after vessel has been installed

and during the initial filling operation. The inspection shall check for any damage during installation prior to initial filling and for any leaks or damage during and at the conclusion of filling.

b) Subsequent Filling Inspections

Before each refilling of the vessel, the manager of the facility shall inspect the vessel for damage or leaks. Refilling operations shall be suspended if any damage or leaks are detected and the vessel shall be emptied and subsequently inspected by the Inspector to determine if the vessel shall remain in service.

c) Periodic Inspection

Within 30 days of the anniversary of the initial operation of the vessel during each year of its service life, the vessel shall be externally inspected by the Inspector or the Authority having jurisdiction. Internal inspections shall only be required if any of the conditions of S9.8 are met. **These inspections are in addition to the periodic acoustic emission examination requirements of S9.2(c).**

SX.10 DOCUMENT RETENTION

A detailed record of external and internal inspections shall be retained by the owner of the tank for the life of the tank. After satisfactory completion of the periodic in-service inspection, the tanks should be permanently marked or labeled with the date of the inspection, the mark of the Inspector, and the date of the next periodic in-service. ASME data report shall be kept on file for the life of the vessel.

S9.11 ACOUSTIC EMISSION EXAMINATION

a) Use and Test Objectives

All Section X Class III vessels shall be subject to an acoustic emission examination to detect damage that may occur while the vessel is in service. This method may be used in conjunction with the normal filling procedure.

b) Test Procedure

AE transducers shall be acoustically coupled to the vessel under test and connected to waveform recording equipment. Waveforms shall be recorded and stored on digital media as the

vessel is pressurized. All analysis shall be done on the waveforms. The waveforms of interest are the E (Extensional Mode) and F (Flexural Mode) plate waves.

Prior to pressurization, the velocities of the earliest arriving frequency in the E wave and the latest arriving frequency in the F wave shall be measured in the circumferential direction in order to characterize the material and set the sample time (the length of the wave window).

The E and F waves must be digitized and stored for analysis. The test pressure shall be recorded simultaneously with the AE events. Permanent storage of the waveforms is required for the life of the vessel.

c) Equipment

1. Testing System

A testing system shall consist of 1) sensors, 2) preamplifiers, 3) high pass and low pass filters, 4) amplifier, 5) A/D (analog-to-digital) converters, 6) a computer program for the collection of data, 7) computer and monitor for the display of data, and 8) a computer program for analysis of data. Examination of the waveforms event by event must always be possible and the waveforms for each event must correspond precisely with the pressure and time data during the test. The computer program shall be capable of detecting the first arrival channel. This is critical to the acceptance criteria below.

Sensors and recording equipment shall be checked for a current calibration sticker or a current certificate of calibration.

2. Sensor Calibration

Sensors shall have a flat frequency response from 50 kHz to 400 kHz. Deviation from flat response (signal coloration) shall be corrected by using a sensitivity curve obtained with a Michelson interferometer calibration system similar to the apparatus used by NIST (National Institute for Standards and Technology). Sensors shall have a diameter

no greater than 0.5 inches for the active part of the sensor face. The aperture effect must be taken into account. Sensor sensitivity shall be at least 0.1 V/nm.

3. Scaling Fiber Break Energy

The wave energy shall be computed by the formula

$$U = \int V^2 dt / Z ,$$

which is the formula for computing energy in the AE signal, where V is the voltage and Z is the input impedance.

A rolling ball impactor shall be used to create an acoustical impulse in an aluminum plate. The measured energy in the wave shall be used to scale the fiber break energy. This scaling is illustrated later on.



Figure 1. Rolling Ball Impact Calibration Setup.

The impact setup, an example of which is shown in Figure 1, shall be arranged as follows. The steel ball shall be ½ inch in diameter. The steel ball is a type typically used in machine shops for measuring taper and is commercially available. The ball shall made of chrome steel alloy hardened to R/C 63, ground and lapped to a surface finish

of 1.5 micro-inch, within .0001 of actual size and sphericity within 0.000025 inch. The plate shall be made of 7075 T6 aluminum, be at least 4' x 4' in size, the larger the better to avoid reflections, be 1/8" in thickness and be simply supported by steel blocks. The inclined plane shall be aluminum with a machined square groove 3/8" wide which supports the ball and guides it to the impact point. The top surface of the inclined plane shall be positioned next to the edge of the plate and stationed below the lower edge of the plate such that the ball impacts with equal parts of the ball projecting above and below the plane of the plate. A mechanical release mechanism shall be used to release the ball down the plane.

The ball roll length shall be 12" and the inclined plane angle shall be six degrees. The impact produces an impulse that propagates to sensors coupled to the surface of the plate twelve inches away from the edge. The sensors shall be coupled to the plate with vacuum grease. The energy of the leading edge of the impulse, known as the wave front shall be measured. The vertical position of the ball impact point shall be adjusted gradually in order to "peak up" the acoustical signal, much as is done in ultrasonic testing where the angle is varied slightly to peak up the response. The center frequency of the first cycle of the E wave shall be confirmed as 125 kHz \pm 10 kHz. See Figure 2. The energy value in joules of the first half cycle of the E wave shall be used to scale the fiber break energy in criterion 2, as illustrated there. This shall be an "end to end" calibration meaning that the energy shall be measured using the complete AE instrumentation (sensor, cables, preamplifiers, amplifiers, filters and digitizer) that are to be used in the actual testing situation.

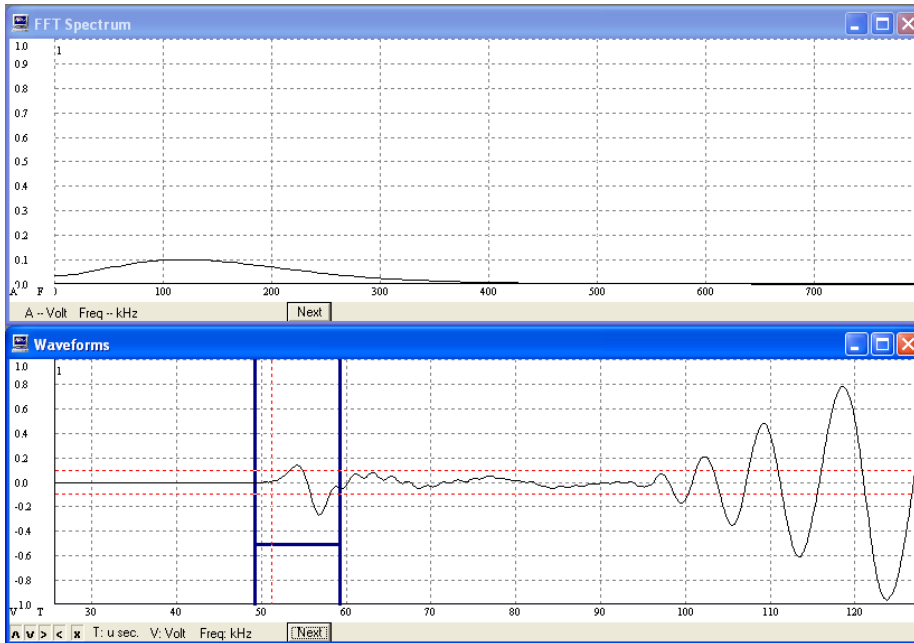


Figure 2. Front End Waveform

Front end of waveform created by rolling ball impact calibration setup described herein. FFT shows center frequency of first cycle is approximately 125kHz.

The energy linearity of the complete AE instrumentation (sensor, cables, preamplifiers, amplifiers, filters and digitizer) shall be measured by using different roll lengths of 8, 12 and 16 inches. The start of the E wave shall be from the first cycle of the waveform recognizable as the front end of the E wave to the end of the E wave which shall be taken as 10 μ s later. (The time was calculated from the dispersion curves for the specified aluminum plate.) A linear regression shall be applied to the energy data and a goodness of fit $R^2 > 0.9$ shall be obtained.

4. Preamplifiers and Amplifiers - See ASME Sec. V Article 11.

5. Filters

A high pass filter of 20 kHz shall be used. A low pass filter shall be applied to prevent digital aliasing that

occurs if frequencies higher than the Nyquist frequency (half the Sampling Rate) are in the signal.

6. A/D

The sampling speed and memory depth (wave window length) are dictated by the test requirements and calculated as follows: Vessel length = L inches (meters). Use $C_E = 0.2$ in./ μ s (5080 m/s) and $C_F = 0.05$ in./ μ s (1270 m/s), the speeds of the first arriving frequency in the E wave and last arriving frequency in the F wave, respectively, as a guide. The actual dispersion curves for the material shall be used if available.

$L / C_E = T1$ μ s. This is when the first part of the direct E wave will arrive.

$L / C_F = T2$ μ s. This is when the last part of the direct F wave will arrive.

$(T2 - T1) \times 1.5$ is the minimum waveform window time and allows for pretrigger time.

The recording shall be quiescent before front end of the E wave arrives. This is called a "clean front end". Clean is defined in SX.11(f) (2) (b) below.

The sampling rate, or sampling speed, shall be such that aliasing does not occur.

The recording system (consisting of all amplifiers, filters and digitizers beyond the sensor) shall be calibrated by using a 20 cycle long tone burst with 0.1 V amplitude at 100, 200, 300, and 400 kHz. The system shall display an energy of $U = (V^2 \cdot N \cdot T) / 2Z$ joules at each frequency, where $V = 0.1$ volts, $N = 20$, Z is the preamplifier input impedance and T is the period of the cycle.

d) Sensor Placement

At least two sensors shall be used in any AE test regardless of vessel size so that EMI is easily detected by simultaneity of arrival.

Sensors shall be placed at equal distances around the circumference of the vessel on the cylindrical portion of the

vessel adjacent to the tangent point of the dome such that the distance between sensors does not exceed 24 inches. Adjacent rings of sensors shall be offset by $\frac{1}{2}$ a cycle. For example if the first ring of sensors is placed at 0, 120 and 240 degrees, the second ring of sensors is placed at 60, 180 and 300 degrees. This pattern shall be continued along the vessel length at evenly spaced intervals, such intervals not to exceed two feet, until the other end of the vessel is reached. See Figure 3. The diameter referred to is the external diameter of a vessel.

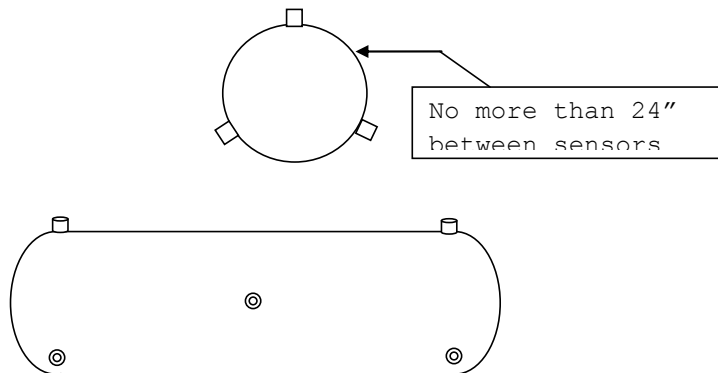


Figure 3. Sensor spacing and pattern.

Maximum distance between sensors in the axial and circumferential directions shall not exceed two feet.

This spacing allows for capturing the higher frequency components of the acoustic emission impulses and high channel count wave recording systems are readily available.

e) Test Procedure

Couple sensors to vessel and connect to the testing equipment per Section V Article 11. Connect pressure transducer to the recorder. Conduct sensor performance checks prior to test to verify proper operation and good coupling to the vessel. The E and F waveforms shall be observed by breaking pencil lead at approximately 8 in. (20 cm) and 16 in. (40.6 cm)

from a sensor along the fiber direction. All calibration data shall be recorded.

Recording threshold shall 60 dB re 1 μ V at the transducer.

Performance checks shall be carried out by pencil lead breaks (Pentel 0.3 mm, 2H) six inches from each transducer in the axial direction of the cylinder and a break at the center of each group of four sensors.

Pressurize vessel to >98% of normal fill pressure and monitor AE during pressurization and for 15 minutes after fill pressure is reached. See Figure 4 for a schematic of the pressurization scheme. The gas filler shall have the equipment necessary to deliver the gas at a controllable fill rate. The fill rate shall be greater than 5 psi/sec but less than the rate at which flow noise first appears. If at any time during fill the fill rate is too high in that it causes flow noise, decrease fill rate until flow noise disappears. Record events during pressurization and for 15 minutes after fill pressure is reached and save the data. Then conduct a post-test performance check and save data. Test temperature shall be between 50°F (10°C) 120°F (49°C).

A threshold of 60 dBAE ref 1 μ V at the sensor shall be used during all phases of testing.

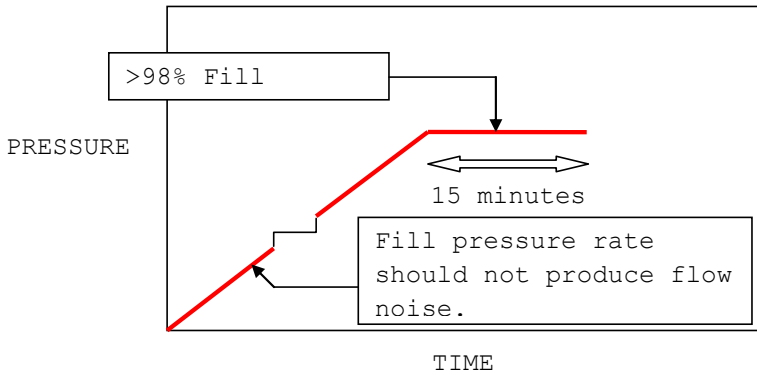


Figure 4. Typical Pressurization Plan When Filling Vessels.

AE shall be monitored for 15 min after operating fill pressure is reached.

f) Accept/Reject Criteria

1. Stability Criterion

Theory of AE Monitoring of high pressure composite pressure vessels for stability - A stable vessel will exhibit cumulative curves with exponentially decaying curvature. The shape of the cumulative events curve is similar for pressure vessels made of fiberglass, aramid and carbon fiber that exhibit a fiber dominated failure mode. This is essentially a test that demonstrates the composite is not progressing to failure at the hold pressure.

2. Analysis Procedure

Data will include matrix splits, matrix cracks, fiber breaks, and matrix chirps due to fracture surface fretting, and fiber/matrix debonding. Extraneous noise, identified by waveform characteristics, may also be included in the data.

- a.** Filter data to eliminate any external noise such as electromagnetic interference (EMI), mechanical rubbing, flow noise, etc. Identify noise events by their shape, spectral characteristics, or other information known about the test such as a temporally associated disturbance due to the pressurization system or test fixturing. EMI is characterized

by a lack of any mechanical wave propagation characteristics, particularly a lack of dispersion being apparent. EMI can be further identified by simultaneity of arrival on more than one channel. The two criteria shall be considered together to ensure it's not simply an event that happened to be centered between the sensors. Mechanical rubbing frequencies are usually very low and can be determined by experiment. There should be no flow noise. If the vessel, or a fitting, leaks, this will compromise the data as AE is very sensitive to leaks. Leak noise is characterized by waves that look uniform across the entire length of the waveform window. If a leak occurs during the load hold, the test must be redone. Flow noise is characterized by waves that fill the waveform window.

b. Use only events that have clean front ends and in which first arrival channel can be determined. Clean means having a pre-trigger energy of less than 0.01×10^{-10} joules. Energy is computed by the integral of the voltage squared over time.

c. Plot first arrival cumulative events versus time. Plots shall always show the pressure data.

d. Apply exponential fits by channel for pressure hold time and display both data and fit. The values are determined by the fit to $y = Ae^{Bt} + C$.

The B value is the shape factor of the cumulative curves. C is an intercept and A is a scale factor. The time t shall be equal intervals during the hold with events binned by time interval. Record exponents and goodness of fit (R^2). Plot energy decay curves. One third or one fourth of hold time shall be used for event energy binning (cumulative energy). The formula is $y=Ae^{Bt}$.

The sequence of energy values must monotonically decrease. This is similar to using other energy criteria, such as Historic Index. A sequence that is not properly decreasing will be indicated by a low R^2 value.

e. Save all plots (all channels) to report document.

f. Record exponents and R^2 values.

g. i) Vessel B values shall be tracked and compiled in order to develop a statistically significant database.

ii) B is the critical value that measures the frequency of occurrence of events during pressure hold.

iii) Not every vessel will have the exact same B value.

iv) Data on B values should cluster.

The criteria given below apply to each individual sensor on the vessel.

1. The stability criteria as described above shall be met. (Also see ASME Section X Mandatory Appendix 8.) Any vessel that does not meet the stability criteria must be removed from service. The criteria are:

a. Cumulative Event Decay Rate $-0.1 < B < -0.0001$, $R^2 \geq 0.80$

b. Cumulative Energy Decay Rate $-0.2 < B < -0.001$, $R^2 \geq 0.80$

If these criteria are not met, the vessel does not pass. The vessel may be retested. An AE Level III inspector must review the data from the initial testing and the subsequent loading test before the vessel can be passed. Retest loadings shall follow the original pressurization rates and pressures and use a threshold of 60 dBAE. If the vessel fails the criteria again, the vessel shall not be certified by the Inspector as meeting the provisions of this Section.

2. Events that occur at the higher loads during pressurization having significant energy in the frequency band $f > 300$ kHz are due to fiber bundle, or partial bundle, breaks. These should not be present at operating pressure in a vessel that has been tested to a much higher pressures and is now operated at the much lower service pressure. For fiber bundles to break in the upper twenty percent of load during the test cycle or while holding at operating pressure, the vessel has a severe stress concentration and shall be removed from service.

g) Fiber Breakage Criterion

1. Analysis Procedure

In order to determine if fiber bundle breakage has occurred during the filling operation the frequency spectra of the direct E and F waves shall be examined and the energies in certain frequency ranges shall be computed as given below.

2. Definitions

Energies (U) in the ranges are defined as

50 - 400 kHz: U_0

100 - 200 kHz: U_1

250 - 400 kHz: U_2

The criteria for determining if high frequency spectrum events have occurred is given by the following formulas:

$$U_0 / (U_{FBB}) \geq 10\%$$

$$U_2 / (U_1 + U_2) \geq 15\%$$

$$U_2 / U_0 \geq 10\%$$

U_{FBB} is the energy of a fiber bundle break calculated using the average breaking strength found in the literature, either from the manufacturer's data or independent test data. The formula that shall be used for calculating average fiber break energy is

$$U_{FB} = \frac{E\varepsilon^2}{2} Al,$$

where ε is the strain to failure of the fiber, E the Young's modulus of the fiber, A is area of the fiber and l is the ineffective fiber length for the fiber and matrix combination. If the ineffective length is not readily available, four (4) times the fiber diameter shall be used. We take $U_{FBB} = 100 \times U_{FB}$, where U_{FB} has been calculated and scaled by the rolling ball impact energy as in the examples below. If these criteria are met, fiber bundle break damage has occurred during the test and the vessel should be removed from service. Common fiber bundle sizes are 1000 and 3000 fibers per tow so 100 fibers represents a partial bundle break.

3. Example of Fiber Break Energy Calculation

Suppose $d = 7 \text{ } \mu\text{m}$, $E = 69.6 \text{ GPa}$ and $\varepsilon = 0.01$ (average breaking strain) for some carbon fiber. Using $A = \pi d^2/4$ and $l = 4d$,

$$U_{FB} = 3 \times 10^{-8} \text{ J}.$$

4. Example of Scaling Calculation

Suppose that the rolling ball impact (RBI) acoustical energy measured by a particular high fidelity AE transducer is $U_{RBI}^{AE} = 5 \times 10^{-10} \text{ J}$ and the impact energy $U_{RBI} = 1.9 \times 10^{-3} \text{ J}$ (due to gravity). Fiber break energy of T300 carbon fiber $U_{FB} = 3 \times 10^{-8} \text{ J}$ would correspond to a wave energy

$$\begin{aligned} U_{FB}^{AE} &= U_{FB} \times U_{RBI}^{AE} / U_{RBI} \\ &= 3 \times 10^{-8} \text{ J} \times 5 \times 10^{-10} \text{ J} / 1.9 \times 10^{-3} \text{ J} \\ &= 7.9 \times 10^{-15} \text{ J}. \end{aligned}$$

This is the number that is used to calculate the value of U_{FBB} that is used in the fiber break criterion in this the second acceptance criterion and the energy acceptance criterion in the third criterion below.

5. Amplifier Gain Correction

All energies shall be corrected for gain. (20 dB gain increases apparent energy 100 times and 40 dB gain 10,000 times.)

Fiber break waves may look similar to matrix event waves in time space but in frequency space the difference is clear. A fiber break is a very fast source, while a matrix crack evolves much more slowly due to greater than ten to one difference in their tensile moduli. The speed of the fiber break produces the high frequencies, much higher than a matrix crack event can produce. Frequencies higher than 2 MHz have been observed in proximity to a fiber break, however these very high frequencies are attenuated rapidly as the wave

propagates. Practically speaking, the observation of frequencies above 300 kHz, combined with certain other characteristics of the frequency spectrum and pressure level, is enough to confirm a fiber break. It should also be noted that it is fiber bundle breaks that are usually detected in structural testing and not the breaking of individual fibers. The energies of individual fiber breaks are very small, about 3×10^{-8} Joules for T-300 carbon fibers for example.

If fiber breakage is determined to have occurred, the vessel shall be removed from service.

h) Friction between Fracture Surfaces

Friction between fracture surfaces plays a very important role in understanding AE in fatigue testing. It is an indicator of the presence of damage because it is produced by the frictional rubbing between existing and newly created fracture surfaces. Even the presence of fiber bundle breakage can be detected by examining the waveforms produced by frictional acoustic emission or FRAE. Increasing FRAE intensity throughout a pressure cycle means more and more damage has occurred.

Therefore, for a vessel to pass, no AE event shall have an energy greater than $(F) \times U_{FB}$ at anytime during the test. F is the acoustic emission allowance factor. The smaller the allowance factor, the more conservative the test. An $F = 10^4$ shall be used in this testing. It is the equivalent of three plus fiber tows, each tow consisting of 3,000 fibers, breaking simultaneously near a given transducer.

i) Background Energy

Background energy of any channel shall not exceed 10 times the quiescent background energy of that channel. After fill pressure is reached, any oscillation in background energy with a factor of two excursions between minima and maxima shows that the vessel is struggling to handle the pressure. Pressure shall be reduced immediately and the vessel removed from service.