SUPPLEMENT 9

INSPECTION OF STATIONARY HIGH PRESSURE (3000-15000 psi)(21-103 MPa) COMPOSITE PRESSURE VESSELS

S9.1 SCOPE

This supplement provides specific guidelines for inspection of high pressure composite pressure vessels, hereafter referred to as vessels. This supplement is applicable to pressure vessels with a design pressure that exceeds 3000 psi (21 MPA) but no greater than 15000 psi (103 MPa), and is applicable to the following four types 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) Fully wrapped FRP vessel with a non-load sharing non-metallic liner.

d) Fully wrapped FRP vessel with load sharing metallic liner.

This supplement is intended for inspection of ASME Section X, Class III vessels and ASME Section VIII, Division 3 Composite Reinforced Pressure Vessels (CRPVs). However, it may be used for inspection of similar vessels manufactured to other construction codes with approval of the jurisdiction in which the vessels are installed.

S9.2 GENERAL

a) High pressure composite vessels are used for the storage of fluids at pressures up to 15000 psi (103 MPa). Composite vessels consist of the FRP laminate with load sharing or non-load sharing metallic shells/liners, or nonmetallic 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 nonmetallic liners. The purpose of the non-load sharing metallic and the nonmetallic liners is to minimize the permeation of fluids through the vessel wall.
b) Fluids stored in vessels are 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

S9.3 INSPECTOR QUALIFICATIONS

a) The inspector referenced in this supplement is a National Board Commissioned Inspector.
b) The Inspector shall be familiar with vessel 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 vessels to be inspected. The Inspector should have basic knowledge of the vessel material types and properties. Refer to Part 2 Para. S4.2 and S4.5.
c) The acoustic emission technician conducting the examination required per S9.5(c) and in accordance with S9.10 shall be certified per the guidelines of ASNT SNT-TC-1A or CP-189 AE Level II or III. A technician performing this test shall have training in and experience with measuring C_e and C_f in composites and identifying wave modes.

S9.4 INSPECTION FREQUENCY

a) Initial inspection

The vessel shall be given an external visual examination by the Inspector or the Authority having jurisdiction where the vessel is installed and during the initial filling operation. The examination 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 visually examine the vessel exterior 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 examined by the Inspector or the Authority having jurisdiction where the vessel is installed. Internal inspections shall only be required if any of the conditions of S9.9(a) are met. These examinations are in addition to the periodic acoustic emission examination requirements of S9.5(c).

S9.5 INSERVICE INSPECTION

a) Section 1 of this Part shall apply to inspection of high pressure vessels, except as modified herein. This supplement covers vessels, and is not intended 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 vessels shall be in accordance with Part 2, Section 2.3 of this Code.

c) All composite vessels shall have an initial acoustic emission examination per S9.10 after the first 3 years from the date of manufacture. Thereafter, vessels shall have a maximum examination interval of 5 years which may be more frequent based on the

results of any external inspection per paragraph S9.8 or internal inspections per paragraph S9.9.
All vessels shall be subject to the periodic inspection frequency given in S9.4.

S9.6 ASSESSMENT OF INSTALLATION

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

The causes of damage to vessels 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 supports.

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

S9.7 VISUAL EXAMINATION

a) Acceptable Damage

Acceptable damage or degradation is minor, normally found in service, and considered to be cosmetic. This level of damage or degradation does not reduce the structural integrity of the vessel. This level of damage or degradation should not have any adverse effect on the continued safe use of the vessel. 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 vessel, any damage or degradation should be limited to this layer. Damage or degradation of the structural wall shall not exceed the limits specified in Tables 1a or 1b.

b) Rejectable Damage (Condemned—Not Repairable)

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

c) Acceptance Criteria

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

d) Fitness-for-service

1) If a visual examination reveals that a vessel does not meet all criteria of Table 1a or 1b 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 or legal successor who must also hold a National Board R certificate. When the vessel is taken out of service, its contents shall 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 vessel manufacturer shall be contacted as soon as possible after the rejectable defects have been found. The manufacturer shall then determine the vessel fitness-for-service by applicable techniques, i.e., acoustic emission testing, ultrasonic 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 vessel. Repairs to the outer protective layer may be made by a R certificate holder other than the original manufacturer following the original manufacturer's instructions.

(3) Determination of fitness-for-service is restricted to original Manufacturer or legal successor.

S9.8 EXTERNAL INSPECTION

a) Vessel Service Life

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

b) Identification of External Damage

The external surface should be inspected for damage to the laminate. Damage is classified into two levels as shown in Table 1a or Table 1b of this supplement. The acceptance/rejection criteria shown in Table 1a or Table 1b of this supplement shall be followed, as a minimum.

The external surface of the vessel is subject to mechanical, thermal, and environmental damage. The external surface of a vessel may show damage from impacts, 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 shall be noted. Vessel 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 vessels 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 1a or Table 1b of this supplement.

2. Abrasion Damage

Abrasion damage is caused by grinding or rubbing away of the exterior of the vessel. Minor abrasion damage to the protective outer coating or paint will not reduce the structural integrity of the vessel. Abrasion that results in flat spots on the surface of the vessel 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 qualified fit for service using an acoustic emission examination.

7. Structural Damage

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

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 vessels. Long-term contact with water can also contribute to corrosive damage. Chemicals can dissolve, corrode, remove, or destroy vessel 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. If there is any suspicion of damage, the vessel shall be re-qualified using acoustic emission examination.

S9.9 Internal Examination

a) Requirements for Internal Visual examination

Internal visual examination is normally not required. When vessels have been filled only with pure fluids, corrosion of the interior of the liner should not occur. Internal visual examination of the tanks should only be carried out when:

1. There is evidence that any commodity except a pure fluid 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 vessel will require an internal visual examination.
2. There is evidence of structural damage to the vessel, such as denting or bulging.
3. The vessel valve is removed for maintenance or other reason. Internal examination in this case is limited to examination of the threads and sealing surface. When an internal visual examination is conducted, the following procedures should be followed.

b) Identification of Internal Damage

1. Vessels with Metallic Liners

For vessels with metallic liners, the objective of the internal visual examination is primarily to detect the presence of any corrosion or corrosion cracks.
The internal surface of the vessel shall be examined with adequate illumination to identify any degradation or defects present. Any foreign matter or corrosion products should be removed from the interior of the vessel to facilitate inspection. Any chemical solutions used in the interior of the vessel should be selected to ensure that they do not adversely affect the liner or composite overwrap materials. After cleaning the vessel should be thoroughly dried before it is examined.
All interior surfaces of the vessel should be examined for any color differences, stains, wetness, roughness, or cracks. The location of any degradation should be noted.

Any vessel showing significant internal corrosion, dents or cracks should be removed from service.

2. Vessels with Non-metallic Liners or No Liners

Vessels with non-metallic liners may show corrosion on the plastic liner or metal boss ends. Vessels 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 vessels should be examined with adequate illumination to identify any degradation or defects present. Any foreign matter or corrosion products should be removed from the interior of the vessel to facilitate examination. Chemical solutions used in the interior of the vessel should be selected to ensure they do not adversely affect the liner or composite overwrap materials. After cleaning the vessel should be thoroughly dried before it is examined.

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.

S9.10 ACOUSTIC EMISSION EXAMINATION

a) Use and Test Objectives

All high pressure composite pressure 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 (13 mm) 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 (0.0000381 mm), within 0.0001 inch (0.0025 mm) of actual size and sphericity within 0.000025 inch (0.00064 mm). The plate shall be made of 7075 T6 aluminum, be at least 4 ft x 4 ft (1200 mm X 1200 mm) in size, the larger the better to avoid reflections, be 1/8 inch (3.2 mm) in thickness and be simply supported by steel blocks. The inclined plane shall be aluminum with a machined square groove 3/8 inch (9.5 mm) 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 inch (305 mm) 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 12 inches (305 mm) 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 ± 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.

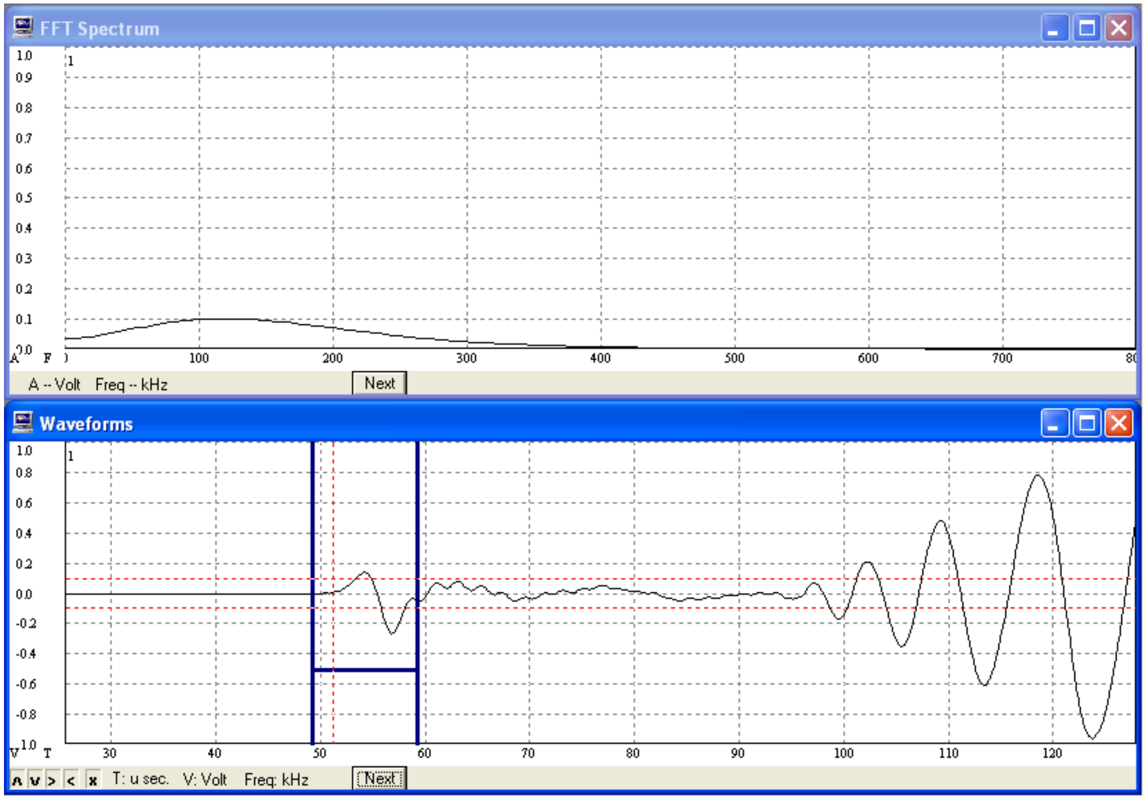

Figure 2. Front End Waveform

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 (203, 305, and 406 mm). 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 microsecond (µs) 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./µs (5080 m/s) and C_F = 0.05 in./µs (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 µs. This is when the first part of the direct E wave will arrive.
L / C_F = T2 µs. This is when the last part of the direct F wave will arrive.
(T2 – T1) x.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 S9.10 (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 $U = \frac{V^2 NT}{2Z}$ 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 electromagnetic interference (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 (610 mm). Adjacent rings of sensors shall be offset by ½ 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 (610 mm), until the other end of the vessel is reached. See Figure 3. The diameter referred to is the external diameter of a vessel.

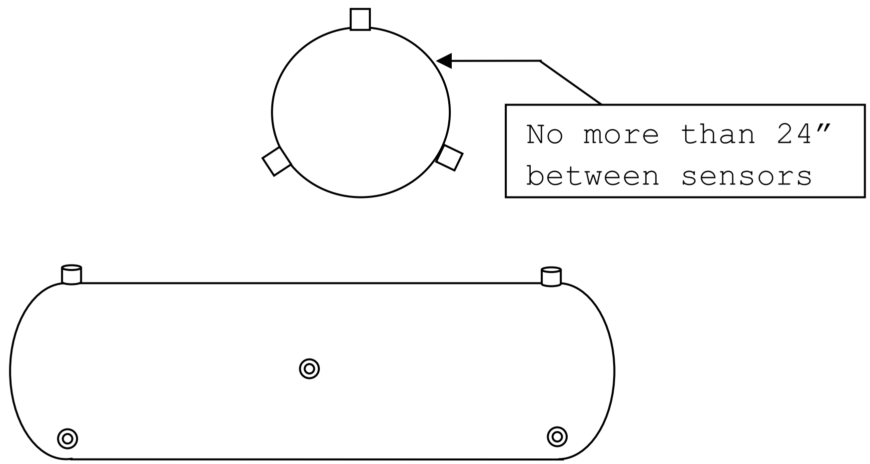

Figure 3. Sensor spacing and pattern.

Maximum distance between sensors in the axial and circumferential directions shall not exceed two feet (609 mm) unless it is demonstrated that the essential data can still be obtained using a greater distance and the authority having the jurisdiction concurs.

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 ASME 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 be 60 dB ref 1 µV at the transducer.

Performance checks shall be carried out by pencil lead breaks (Pentel 0.3 mm, 2H) six inches (150 mm) 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. 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) and 120°F (49°C).

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

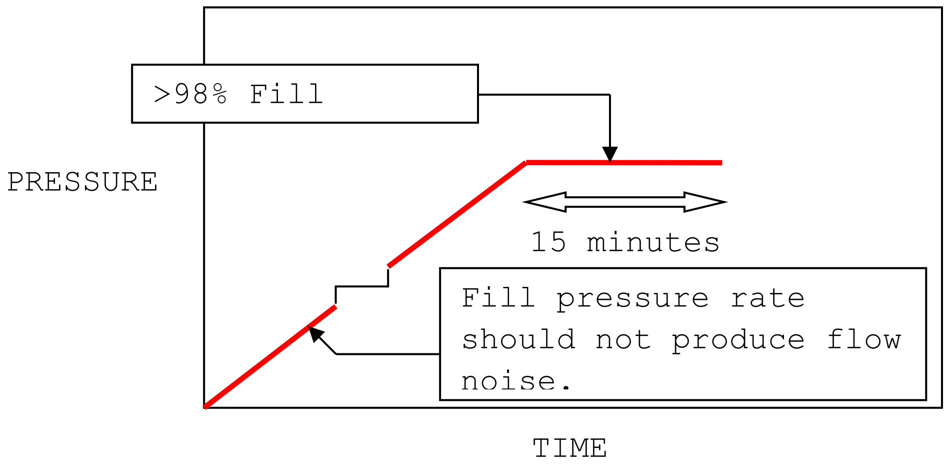

Figure 4. Typical Pressurization Plan When Filling Vessels.

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 examiner 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 from the manufacturer's data or independent test data. The manufacturer's data shall be used if available. 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. Set $U_{FBB} = 100 \times U_{FB}$, 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 shall be removed from service.

3. Example of Fiber Break Energy Calculation

Suppose d = 7 μm, E = 69.6 GPa and ε = 0.01 (average breaking strain) for some carbon fiber. Using $A = \pi d^2/4$ and $l = 4d$,

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

$$UFB = \frac{(69.6)(0.01)^2}{2} \pi \frac{\left[7(10)^{-6}\right]^2}{4} \left[4(7)(10)^{-6}\right]$$

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

4. Example of Scaling Calculation

Suppose that the rolling ball impact (RBI) acoustical energy measured by a particular high fidelity AE transducer is U^{AE}_{RBI} = 5 x 10^{-10} J and the impact energy U_{RBI} = 1.9 x 10^{-3} J (due to gravity). Suppose d = 7 µm, E = 69.6 GPa and ε = 0.01 (average breaking strain) for some carbon fiber. Using $A = \pi d^2/4$ and l = 4d, U_{FB} = 3x10^{-8} J. A carbon fiber with a break energy of U_{FB} = 3x10^{-8} J would correspond to a wave energy

$$U^{AE}_{FB} = U_{FB} \text{ x } U^{AE}_{RBI} / U_{RBI}$$

$$U^{AE}_{FB} = 3\text{x}10^{-8} \text{ J x } 5 \text{ x } 10^{-10} \text{ J / } 1.9 \text{ x } 10^{-3} \text{ J}$$

$$U^{AE}_{FB} = 7.9 \text{ x } 10^{-15} \text{ J.}$$

This is the number that is used to calculate the value of U_{FBB} that is used in the fiber break criterion in 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.

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 be acceptable no AE event shall have an energy greater than (F) x 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.

S9.11 DOCUMENT RETENTION

a) The vessel owner shall retain a copy of the Manufacturer’s Data Report for the life of the vessel.
b) After satisfactory completion of the periodic in-service inspection, vessels shall be permanently marked or labeled with date of the inspection, signature of the Inspector, and date of the next periodic in-service inspection.
c) The vessel owner shall retain a copy of the in-service inspection report for the life of the vessel.

Table 1a-Visual Acceptance/Rejection Criteria for Composite Pressure Vessels (U.S. Customary Units)

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.	$\geq$ 0.050 in. depth in the pressure bearing thickness
Cuts	Linear indications flaws caused by an impact with a sharp object	Less than 0.050 in. depth in the pressure bearing thickness.	$\geq$ 0.050 in. depth in the pressure bearing thickness
Impact Damage	Damage to the vessel caused by striking the vessel 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 vessel or damaged filaments

Type of Degradation or Damage	Description of Degradation or Damage	Acceptable Level of Degradation or Damage	Rejectable Level of Degradation or Damage
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 vessel 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.

Type of Degradation or Damage	Description of Degradation or Damage	Acceptable Level of Degradation or Damage	Rejectable Level of Degradation or Damage
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	$\geq$ 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

Type of Degradation or Damage	**Description of Degradation or Damage**	**Acceptable Level of Degradation or Damage**	**Rejectable Level of Degradation or Damage**
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 vessel caused by impact or dropping	< 1/16 in. in depth	Any dents with a depth ≥ 1/16 in. Or with a diameter greater than 2 inches
Reported collision, accident, or fire	Damage to the vessel 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*

Type of Degradation or Damage	Description of Degradation or Damage	Acceptable Level of Degradation or Damage	Rejectable Level of Degradation or Damage
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 not exceed the thickness of the protective or sacrificial layer plus 0.050 inch.	The depth of any damage to the protective or sacrificial layer that exceeds the thickness of the protective or sacrificial layer plus 0.050 inch.
Crazing	Hairline surface cracks only in the composite resin	Light hairline cracks only in the resin	Any damage to the filaments

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 the affected area should be cleaned and painted with a UV tolerant paint. If broken, frayed, or separated fibers to the non sacrificial layer, are discovered during the cleaning process then the vessel shall be condemned.

Table 1b-Visual Acceptance/Rejection Criteria for Composite Pressure Vessels (SI Units)

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 1.3 mm. depth in the pressure bearing thickness.	≥ 1.3 mm depth in the pressure bearing thickness
Cuts	Linear indications flaws caused by an impact with a sharp object	Less than 1.3 mm. depth in the pressure bearing thickness.	≥ 1.3 mm depth in the pressure bearing thickness
Impact Damage	Damage to the vessel caused by striking the vessel 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 vessel or damaged filaments

Type of Degradation or Damage	Description of Degradation or Damage	Acceptable Level of Degradation or Damage	Rejectable Level of Degradation or Damage
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 vessel 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.

Type of Degradation or Damage	Description of Degradation or Damage	Acceptable Level of Degradation or Damage	Rejectable Level of Degradation or Damage
Cracks	Sharp, linear indications	None	None
Scratches/Gouges	Sharp, linear indications caused by mechanical damage.	Less than 1.3 mm depth in the pressure bearing thickness No structural fibers cut or broken	≥ 1.3 mm 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

Type of Degradation or Damage	**Description of Degradation or Damage**	**Acceptable Level of Degradation or Damage**	**Rejectable Level of Degradation or Damage**
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 vessel caused by impact or dropping	< 1.6 mm depth	Any dents with a depth $\geq$ 1.6 mm Or with a diameter greater than 51 mm
Reported collision, accident, or fire	Damage to the vessel 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*

Type of Degradation or Damage	**Description of Degradation or Damage**	**Acceptable Level of Degradation or Damage**	**Rejectable Level of Degradation or Damage**
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 not exceed the thickness of the protective or sacrificial layer plus 1.3 mm	The depth of any damage to the protective or sacrificial layer that exceeds the thickness of the protective or sacrificial layer plus 1.3 mm
Crazing	Hairline surface cracks only in the composite resin	Light hairline cracks only in the resin	Any damage to the filaments

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 the affected area should be cleaned and painted with a UV tolerant paint. If broken, frayed, or separated fibers to the non sacrificial layer, are discovered during the cleaning process then the vessel shall be condemned.