Designation: E2981 − 15

Standard Guide for
Nondestructive Testing of the Composite Overwraps in Filament Wound Pressure Vessels Used in Aerospace Applications[1]

This standard is issued under the fixed designation E2981; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide discusses current and potential nondestructive testing (NDT) procedures for finding indications of discontinuities and accumulated damage in the composite overwrap of filament wound pressure vessels, also known as composite overwrapped pressure vessels (COPVs). In general, these vessels have metallic liner thicknesses less than 2.3 mm (0.090 in.), and fiber loadings in the composite overwrap greater than 60 percent by weight. In COPVs, the composite overwrap thickness will be of the order of 2.0 mm (0.080 in.) for smaller vessels and up to 20 mm (0.80 in.) for larger ones.

1.2 This guide focuses on COPVs with nonload-sharing metallic liners used at ambient temperature, which most closely represents a Compressed Gas Association (CGA) Type III metal-lined composite tank. However, it also has relevance to *1)* monolithic metallic pressure vessels (PVs) (CGA Type I), *2)* metal-lined hoop-wrapped COPVs (CGA Type II), *3)* plastic-lined composite pressure vessels (CPVs) with a nonload-sharing liner (CGA Type IV), and *4)* an all-composite, linerless COPV (undefined Type). This guide also has relevance to COPVs used at cryogenic temperatures.

1.3 The vessels covered by this guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points will in general be different and more stringent than for vessels used in non aerospace applications.

1.4 This guide applies to *1)* low pressure COPVs used for storing aerospace media at maximum allowable working pressures (MAWPs) up to 3.5 MPa (500 psia) and volumes up to 2 m^3 (70 ft^3), and *2)* high pressure COPVs used for storing compressed gases at MAWPs up to 70 MPa (10,000 psia) and volumes down to 8000 cm^3 (500 $in.^3$). Internal vacuum storage or exposure is not considered appropriate for any vessel size.

1.5 The composite overwraps under consideration include but are not limited to ones made from various polymer matrix resins (for example, epoxies, cyanate esters, polyurethanes, phenolic resins, polyimides (including bismaleimides), and polyamides) with continuous fiber reinforcement (for example, carbon, aramid, glass, or poly-(phenylenebenzobisoxazole) (PBO)). The metallic liners under consideration include but are not limited to aluminum alloys, titanium alloys, nickel-chromium alloys, and stainless steels.

1.6 This guide describes the application of established NDT methods; namely, Acoustic Emission (AE, Section 7), Eddy Current Testing (ECT, Section 8), Laser Shearography (Section 9), Radiologic Testing (RT, Section 10), Thermographic Testing (TT, Section 11), Ultrasonic Testing (UT, Section 12), and Visual Testing (VT, Section 13). These methods can be used by cognizant engineering organizations for detecting and evaluating flaws, defects, and accumulated damage in the composite overwrap of new and in-service COPVs.

NOTE 1—Although visual testing is discussed and required by current range standards, emphasis is placed on complementary NDT procedures that are sensitive to detecting flaws, defects, and damage that leave no visible indication on the COPV surface.

NOTE 2—In aerospace applications, a high priority is placed on light weight material, while in commercial applications; weight is typically sacrificed to obtain increased robustness. Accordingly, the need to detect damage below the visual damage threshold is more important in aerospace vessels.

NOTE 3—Currently no determination of residual strength can be made by any NDT method.

1.7 All methods discussed in this guide (AE, ET, shearography, RT, TT, UT, and VT) are performed on the composite overwrap after overwrapping and structural cure. For NDT procedures for detecting discontinuities in thin-walled metallic liners in filament wound pressure vessels, or in the bare metallic liner before overwrapping; namely, AE, ET, laser profilometry, leak testing (LT), penetrant testing (PT), and RT; consult Guide E2982.

1.8 In the case of COPVs which are impact damage sensitive and require implementation of a damage control plan, emphasis is placed on NDT methods that are sensitive to

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[1] This test method is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

Current edition approved July 1, 2015. Published September 2015. DOI: 10.1520/E2891-15.

detecting damage in the composite overwrap caused by impacts at energy levels and which may or may not leave any visible indication on the COPV composite surface.

1.9 This guide does not specify accept-reject criteria (subsection 4.9) to be used in procurement or used as a means for approving filament wound pressure vessels for service. Any acceptance criteria specified are given solely for purposes of refinement and further elaboration of the procedures described in this guide. Project or original equipment manufacturer (OEM) specific accept/reject criteria shall be used when available and take precedence over any acceptance criteria contained in this document. If no accept/reject criteria are available, any NDT method discussed in this guide that identifies broken fibers shall require disposition by the cognizant engineering organization.

1.10 This guide references both established ASTM methods that have a foundation of experience and that yield a numerical result, and newer procedures that have yet to be validated and are better categorized as qualitative guidelines and practices. The latter are included to promote research and later elaboration in this guide as methods of the former type.

1.11 To ensure proper use of the referenced standard documents, there are recognized NDT specialists that are certified according to industry and company NDT specifications. It is recommended that an NDT specialist be a part of any composite component design, quality assurance, in-service maintenance, or damage examination.

1.12 The values stated in SI units are to be regarded as standard. The English units given in parentheses are provided for information only.

1.13 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. Some specific hazards statements are given in Section 7 on Hazards.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D3878 Terminology for Composite Materials

D5687 Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation

E114 Practice for Ultrasonic Pulse-Echo Straight-Beam Contact Testing

E317 Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Instruments and Systems without the Use of Electronic Measurement Instruments

E543 Specification for Agencies Performing Nondestructive Testing

E569 Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation

E650 Guide for Mounting Piezoelectric Acoustic Emission Sensors

E750 Practice for Characterizing Acoustic Emission Instrumentation

E976 Guide for Determining the Reproducibility of Acoustic Emission Sensor Response

E1001 Practice for Detection and Evaluation of Discontinuities by the Immersed Pulse-Echo Ultrasonic Method Using Longitudinal Waves

E1065 Practice for Evaluating Characteristics of Ultrasonic Search Units

E1067 Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels

E1106 Test Method for Primary Calibration of Acoustic Emission Sensors

E1118 Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)

E1316 Terminology for Nondestructive Examinations

E1416 Test Method for Radioscopic Examination of Weldments

E1781/E1781M Practice for Secondary Calibration of Acoustic Emission Sensors

E1815 Test Method for Classification of Film Systems for Industrial Radiography

E2104 Practice for Radiographic Examination of Advanced Aero and Turbine Materials and Components

E2191 Practice for Examination of Gas-Filled Filament-Wound Composite Pressure Vessels Using Acoustic Emission

E2033 Practice for Computed Radiology (Photostimulable Luminescence Method)

E2338 Practice for Characterization of Coatings Using Conformable Eddy-Current Sensors without Coating Reference Standards

E2533 Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications

E2580 Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications

E2581 Practice for Shearography of Polymer Matrix Composites and Sandwich Core Materials in Aerospace Applications

E2582 Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications

E2661/E2661M Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications

E2662 Practice for Radiographic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications

E2698 Practice for Radiological Examination Using Digital Detector Arrays

E2884 Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays

E2982 Guide for Nondestructive Testing of Thin-Walled Metallic Liners in Filament-Wound Pressure Vessels Used in Aerospace Applications

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

2.2 *AIA Standard:*[3]

NAS 410 NAS Certification and Qualification of Nondestructive Test Personnel

2.3 *ANSI/AIAA Standards:*[4]

ANSI/AIAA S-080 Space Systems—Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

ANSI/AIAA S-0801 Space Systems—Composite Overwrapped Pressure Vessels (COPVs)

ANSI NGV2-2007 American National Standard for Natural Gas Vehicle Containers

2.4 *ASME Standard:*[5]

ASME Boiler and Pressure Vessel Code

2.5 *ASNT Standards:*[6]

ASNT CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel

SNT-TC-1A Recommended Practice for Nondestructive Testing Personnel Qualification and Certification

2.6 *BSI Documents:*[7]

EN 4179 Aerospace Series — Qualification and Approval of Personnel for Non-Destructive Testing

2.7 *Compressed Gas Association Standards:*[8]

CGA Pamphlet C-6.2 Standard for Visual Inspection and Requalification of Fiber Reinforced High Pressure Cylinders

CGA Pamphlet C-6.4 Methods for Visual Inspection of AGA NGV2 Containers

2.8 *Federal Standards:*[9]

21 CFR 1040.10 Laser Products

21 CFR 1040.11 Specific Purpose Laser Products

2.9 *ISO Document:*[10]

ISO 9712 Non-destructive Testing—Qualification and Certification of NDT Personnel

2.10 *LIA Document:*[11]

ANSI, Z136.1-2000 Safe Use of Lasers

2.11 *MIL Documents:*[12]

MIL-HDBK-17 Composite Materials Handbook, Guidelines for Characterization of Structural Materials

MIL-HDBK-6870 Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts

MIL-HDBK-340 Test Requirements for Launch, Upper-Stage, and Space Vehicles, Vol. I: Baselines

MIL-HDBK-787 Nondestructive Testing Methods of Composite Materials—Ultrasonics

MIL-HDBK-1823 Nondestructive Evaluation System Reliability Assessment

2.12 *NASA Documents:*[13]

KNPR 8715.3 (Kennedy NASA Procedural Requirements) Chapter 13: NASA KSC Requirements for Ground-Based Vessels and Pressurized Systems (PV/S), Rev. G.

NASA/TM-2012-21737 Elements of Nondestructive Examination for the Visual Inspection of Composite Structures

NASA-STD-(I)-5019 Fracture Control Requirements for Spaceflight Hardware

2.13 *Air Force Documents:*[12]

AFSPCMAN 91-710 v3 Range Safety User Requirements Manual Volume 3 - Launch Vehicles, Payloads, and Ground Support Systems Requirements

AFSPCMAN 91-710 v6 Range Safety User Requirements Manual Volume 6 - Ground and Launch Personnel, Equipment, Systems, and Material Operations Safety Requirements

3. Terminology

3.1 *Abbreviations*—The following abbreviations are adopted in this guide: acoustic emission (AE), eddy current testing (ET), radiologic testing (RT), ultrasonic testing (UT), and visual testing (VT).

3.2 *Definitions:* Terminology in accordance with Terminologies E1316 and D3878 shall be used where applicable.

3.2.1 *active source*—see Test Method E569, Section 3, Terminology.

3.2.2 *AE activity*—see Test Method E569, Section 3, Terminology.

3.2.3 *AE counts (N)*—the number of times the acoustic emission signal exceeds a preset threshold during any selected portion of a test.

3.2.4 *AE source*—a region of impact damage in the composite overwrap or growing crack in the metallic liner of a COPV that can be classified as active, critically active, intense, or critically intense.

3.2.5 *AE source intensity*—see Test Method E569, Section 3, Terminology.

3.2.6 *AE test pressure*—see Test Method E2191, Section 3, Terminology

3.2.7 *cognizant engineering organization*—the company, government agency, or other authority responsible for the design or end use of the system or component for which NDT is required. This, in addition to the design personnel, may include personnel from engineering, materials and process engineering, stress analysis, NDT, or quality groups and other, as appropriate.

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[3] Available from Aerospace Industries Association (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

[6] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[7] Available from British Standards Institution (BSI), 389 Chiswick High Rd., London W4 4AL, U.K., http://www.bsigroup.com.

[8] Available from Compressed Gas Association (CGA), 14501 George Carter Way, Suite 103, Chantilly, VA 20151, http://www.cganet.com.

[9] Available from U.S. Food and Drug Administration (FDA), 10903 New Hampshire Ave., Silver Spring, MD 20993, http://www.fda.gov.

[10] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

[11] Available from the Laser Institute of America, 13501 Ingenuity Drive, Suite 128, Orlando, FL 32826.

[12] Available from Standardization Documents Order Desk, Bldg 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

[13] Available from National Aeronautics and Space Administration, Technical Standards Program, 300 E. Street SW, Suite 5R30, Washington, D. C. 20546. https://standards. nasa.gov/documents/nasa.

3.2.8 *critically active source*—see Test Method E569, Section 3, Terminology.

3.2.9 *critically intense source*—see Test Method E569, Section 3, Terminology.

3.2.10 *defect*—see Terminology E1316.

3.2.11 *discontinuity*—see Terminology E1316.

3.2.12 *flaw*—see Terminology E1316.

3.2.13 *Felicity effect*—the presence of acoustic emission, detectable at a fixed, predetermined sensitivity level at stress levels below those previously applied. **E1106**

3.2.14 *Felicity ratio*—the ratio of the stress at which the Felicity effect occurs to the previously applied maximum stress. **E1106, E1118**

NOTE 4—The fixed sensitivity level will usually be the same as was used for the previous loading or test (E1118).

3.2.15 *high-amplitude threshold*—a threshold for large amplitude AE events. (See A2.3 of Annex A2, Practice E1106)

3.2.16 *intense source*—see Test Method E569, Section 3, Terminology.

3.2.17 *low-amplitude threshold*—the threshold above which AE counts (N) are measured. (See A2.2 of Annex A2, Practice E1106).

3.2.18 *operating pressure*—alternatively known as the service pressure, see Practice E1067, Section 3, Terminology.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *active thermography*—active thermography refers to the examination of an object upon intentional application of an external energy source. The energy source (active or passive) may be a source of heat, mechanical energy (vibration or fatigue testing), electrical current, or any other form of energy.

3.3.2 *aspect ratio* —the diameter to depth ratio of a flaw. For irregularly shaped flaws, diameter refers to the minor axis of an equivalent rectangle that approximates the flaw shape and area.

3.3.3 *burst-before-leak (BBL)* —an insidious failure mechanism exhibited by composite materials usually associated with broken fibers caused by mechanical damage, or with stress rupture at an applied constant load (pressure), whereby the minimum time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environment is exceeded, resulting in a sudden, catastrophic event.

3.3.4 *coherent light source*—a monochromatic beam of light having uniform phase over a minimum specified length known as the coherent length.

3.3.5 *composite overwrapped pressure vessel (COPV)*—an inner shell overwrapped with multiple plies of polymer matrix impregnated reinforcing fiber wound at different wrap angles that form a composite shell. The inner shell or liner may consist of an impervious metallic or nonmetallic material. The vessel may be cylindrical or spherical and be manufactured with a minimum of one interface port for pressure fitting or valve attachment (synonymous with filament wound pressure vessel), or both.

3.3.6 *critical Felicity ratio*—the lower threshold of the Felicity ratio at which rupture has been previously observed, regardless of what the current applied load or pressure is.

3.3.7 *damage control plan (DCP)*—a control document that captures the credible damage threats to a COPV during manufacturing, transportation and handling, and integration into a space system up to the time of launch/re-launch, reentry and landing, as applicable, and the steps taken to mitigate the possibility of damage due to these threats, as well as delineation of NDT performed (for example, visual testing) throughout the life cycle of the COPV. The DPC shall be provided by the design agency and made available for review by the applicable safety/range organization per AIAA S 081, KNPR 8715.3, and AFSPCMAN 91 710.

3.3.8 *de-correlation*—loss of shearography phase data caused by test part deformation exceeding the resolution of the shearing interferometer sensor or motion between the test object and shearing interferometer during data acquisition.

3.3.9 *discrete discontinuity*—a thermal discontinuity whose projection onto the inspection surface is smaller than the field of view of the inspection apparatus.

3.3.10 *emissivity (ε)*—the ratio of the radiance of a body at a given temperature to the corresponding radiance of a blackbody at the same temperature.

3.3.11 *extended discontinuity*—a thermal discontinuity whose projection onto the inspection surface completely fills the field of view of the inspection apparatus.

3.3.12 *field of view (FOV)*—The shape and angular dimensions of the cone or the pyramid that defines the object space imaged by the system; for example, rectangular 4 degrees wide by 3 degrees high.

3.3.13 *hit—(in reference to probability of detection (POD), not AE)* an existing discontinuity that is identified as a find during a POD demonstration examination.

3.3.14 *indication* —The response or evidence from a nondestructive examination. An indication is determined by interpretation to be relevant, non-relevant, or false.

3.3.15 *inspection surface*—the surface of the specimen that is exposed to the FT apparatus.

3.3.16 *Kaiser effect*—the absence of detectable acoustic emission at a fixed sensitivity level, until previously applied stress levels are exceeded.

3.3.17 *leak-before-burst (LBB)*—a design approach in which, at and below MAWP, potentially pre-existing flaws in the metallic liner, should they grow, will grow through the liner and result in more gradual pressure-relieving leakage rather than a more abrupt Burst-Before-Leak (BBL) rupture.

3.3.18 *Level I indication*—a defect/discontinuity/flaw that doesn't involve broken tow(s) or known reductions in component residual burst pressure. A Level I indication does not require a problem report (PR) or discrepancy report (DR) and resulting Material Review Board disposition.

3.3.19 *Level II indication*—a defect/discontinuity/flaw that does involve broken tow(s) or known reductions in component residual burst pressure. A Level II indication requires a problem report (PR) or discrepancy report (DR) and resulting Material Review Board disposition.

3.3.20 *maximum allowable working pressure (MAWP)*—The maximum operating pressure, to which operational personnel may be exposed, for a pressure vessel. This pressure is synonymous with Maximum Expected Operating Pressure (MEOP), as used and defined in ANSI/AIAA S-080 or ANSI/AIAA S-081.

3.3.21 *maximum design pressure (MDP)*—The highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures shall be considered. When determining MDP, the maximum temperature to be experienced during a launch abort to a site without cooling facilities shall also be considered. In designing, analyzing, or testing pressurized hardware, loads other than pressure that are present shall be considered and added to the MDP loads as appropriate. MDP in this standard is to be interpreted as including the effects of these combined loads when the non-pressure loads are significant. Where pressure regulators, relief devices, or a thermal control system (e.g., heaters), or a combination thereof, are used to control pressure, collectively they shall be two-fault tolerant from causing the pressure to exceed the MDP of the system.

3.3.22 *miss*—an existing discontinuity that is missed during a POD examination.

3.3.23 *non-relevant or false indications*—defined as thermography system signals whose source or sources are from conditions not associated with defects, degradations or discontinuities of interest to the inspection process.

3.3.24 *probability of detection (POD)*—the fraction of nominal discontinuity sizes expected to be found given their existence.

3.3.25 *shearogram*—is the resulting image from the complex arithmetic combination of interferograms made with an image shearing interferometer showing target surface out-of-plane deformation derivatives and presented for interpretation in various image processing algorithms including static or real-time wrapped phase maps, unwrapped phase maps, integrated images or Doppler shift map.

3.3.26 *shearography camera, shear camera*—an image shearing interferometer capable of imaging the test part surface for out-of-plane deformation derivatives when the test part is subjected to a change in stress, used for shearography nondestructive testing, usually including features for adjustment of image focus, iris, shear vector adjustment and for the projection of coherent light onto the test object area to be examined.

3.3.27 *shear vector*—in Shearography, the separation vector between two identical images of the target in the output of an image shearing interferometer. The shear vector is expressed in degrees of angle from the X axis, with a maximum of 90°, with + being in the positive Y direction and – in the negative Y direction and the shear distance between identical points in the two sheared images expressed in inches or mm. (See Figure 15, Shear Vector Convention.)

3.3.28 *soak period* —the time during which a thermal image is acquired, beginning with the introduction of a gas or liquid into the COPV.

3.3.29 *stressing method*—the application of a measured and repeatable stress to the test object during a shearography examination, is selected for a particular defect type. The applied stress changes may be in the form of a partial or full vacuum, pressure, heat, vibration, magnetic field, electric field, microwave, or mechanical load, and is timed with respect to the shear camera image acquisition in order to obtain the highest probability for defect detection. The applied stress method is engineered to develop a surface differential strain at the site of an anomaly. Also referred to as the "excitation method."

3.3.30 *thermal conductivity*—The time rate of steady heat flow through the thickness of an infinite slab of a homogeneous material perpendicular to the surface, induced by unit temperature difference. The property must be identified with a specific mean temperature, since it varies with temperature.

3.3.31 *thermal diffusivity*—the ratio of thermal conductivity to the product of density and specific heat; a measure of the rate at which heat propagates in a material; units [length^2/time].

3.3.32 *thermal discontinuity* —a change in the thermophysical properties of a specimen that disrupts the diffusion of heat.

3.4 *Symbols:*

3.4.1 a—the physical dimension of a discontinuity, flaw or target—can be its depth, surface length, or diameter of a circular discontinuity, or radius of semi-circular or corner crack having the same cross-sectional area.

3.4.2 a_0—the size of an initial, severe, worst case discontinuity, also known as a rogue flaw.

3.4.3 a_{crit}—the size of a severe discontinuity that causes LLB or BBL failure, often caused by a growing rogue flaw.

3.4.4 a_p—the discontinuity size that can be detected with probability p.

3.4.5 a_{pc}—the discontinuity size that can be detected with probability p with a statistical confidence level of c.

3.4.6 $\hat{a}$—(pronounced a-hat) the measured response of an NDT system, to a target of size a. Units depend on testing apparatus, and can be scale divisions, counts, number of contiguous illuminated pixels, millivolts, etc.

4. Significance and Use

4.1 The COPVs covered in this guide consist of a metallic liner overwrapped with high-strength fibers embedded in polymeric matrix resin (typically a thermoset) (Fig. 1). Metallic liners may be spun-formed from a deep drawn/extruded monolithic blank or may be fabricated by welding formed components. Designers often seek to minimize the liner thickness in the interest of weight reduction. COPV liner materials used can be aluminum alloys, titanium alloys, nickel-chromium alloys, and stainless steels, impermeable polymer liner such as high density polyethylene, or integrated composite materials. Fiber materials can be carbon, aramid, glass, PBO, metals, or hybrids (two or more types of fibers). Matrix resins include epoxies, cyanate esters, polyurethanes, phenolic resins, polyimides (including bismaleimides), polyamides and other high performance polymers. Common bond line adhesives are FM-73, urethane, West 105, and Epon 862 with

FIG. 1 Typical Carbon Fiber Reinforced COPVs (NASA)

thicknesses ranging from 0.13 mm (0.005 in.) to 0.38 mm (0.015 in.). Metallic liner and composite overwrap materials requirements are found in ANSI/AIAA S-080 and ANSI/AIAA S-081, respectively.

NOTE 5—When carbon fiber is used, galvanic protection must be provided for the metallic liner using a physical barrier such as glass cloth in a resin matrix, or similarly, a bond line adhesive.

NOTE 6—Per the discretion of the cognizant engineering organization, composite materials not developed and qualified in accordance with the guidelines in MIL-HDBK-17, Volumes 1 and 3 shall have an approved material usage agreement.

4.2 The as-wound COPV is then cured and an autofrettage/proof cycle is performed to evaluate performance and increase fatigue characteristics.

4.3 The strong drive to reduce weight and spatial needs in aerospace applications has pushed designers to adopt COPVs constructed with high modulus carbon fibers embedded in an epoxy matrix. Unfortunately, high modulus fibers are weak in shear and therefore highly susceptible to fracture caused by mechanical damage. Mechanical damage to the overwrap can leave no visible indication on the composite surface, yet produce subsurface damage.

NOTE 7—The impact damage tolerance of the composite overwrap will depend on the size and shape of the vessel, composite thickness (number of plies), and thickness of the composite overwrap relative to that of the liner.

4.4 Per MIL-HDBK-340 and ANSI/AIAA S-081, the primary intended function of COPVs as discussed in this guide will be to store pressurized gases and fluids where one or more of the following apply:

4.4.1 Contains stored energy of 19 310 J (14 240 ft-lbf) or greater based on adiabatic expansion of a perfect gas.

4.4.2 Contains a gas or liquid that would endanger personnel or equipment or create a mishap (accident) if released.

4.4.3 Experiences a design limit pressure greater than 690 kPa (100 psi).

4.5 According to NASA-STD-(I)-5019, COPVs shall comply with the latest revision of ANSI/AIAA Standard S-081. The following requirements also apply when implementing S-081:

4.5.1 Maximum Design Pressure (MDP) shall be substituted for all references to Maximum Expected Operating Pressure (MEOP) in S-081.

4.5.2 COPVs shall have a minimum of 0.999 probability of no stress rupture failure during the service life.

4.6 Application of the NDT procedures discussed in this guide is intended to reduce the likelihood of composite overwrap failure, commonly denoted "burst before leak" (BBL), characterized by catastrophic rupture of the overwrap and significant energy release, thus mitigating or eliminating the attendant risks associated with loss of pressurized commodity, and possibly ground support personnel, crew, or mission.

4.6.1 NDT is done on fracture-critical parts such as COPVs to establish that a low probability of preexisting flaws is present in the hardware.

4.6.2 Following the discretion of the cognizant engineering organization, NDT for fracture control of COPVs shall follow additional general and detailed guidance described in MIL-HDBK-6870 not covered in this guide.

4.6.3 Hardware that is proof tested as part of its acceptance (i.e., not screening for specific flaws) shall receive post-proof NDT at critical welds and other critical locations.

4.7 *Discontinuity Types*—Specific discontinuity types are associated with the particular processing, fabrication, and service history of the COPV. Metallic liners can have cracks, buckles, leaks, and a variety of weld discontinuities (see Section 4.5 in E2982). Non-bonding flaws (voids) between the liner and composite overwrap can also occur. Similarly, the composite overwrap can have preexisting manufacturing flaws introduced during fabrication, and damage caused by autofrettage or proof testing before being placed into service. Once in service, additional damage can be incurred due to low velocity or micrometeorite orbital debris impacts, cuts/scratches/abrasion, fire, exposure to aerospace media, loading stresses, thermal cycling, physical aging, oxidative degradation, weathering, and space environment effects (exposure to atomic oxygen and ionizing radiation). These factors will lead to complex damage states in the overwrap that can be visible or invisible, macroscopic or microscopic. These damage states can be characterized by the presence of porosity, depressions, blisters, wrinkling, erosion, chemical modification, foreign object debris (inclusions), tow termination errors, tow slippage, misaligned tows, distorted tows, matrix crazing, matrix cracking, matrix-rich regions, under and over-cure of the matrix, fiber-rich regions, fiber-matrix debonding, fiber pull-out, fiber splitting, fiber breakage, bridging, liner/overwrap debonding, and delamination. Often these discontinuities can placed into four major categories: *1)* manufacturing; *2)* scratch/scuff/abrasion; *3)* mechanical damage; *4)* discoloration.

4.8 *Effect of Defect*—The effect of a given composite flaw type or size ("effect of defect") is difficult to determine unless test specimens or articles with known types and sizes of flaws are tested to failure. Given this potential uncertainty, detection of a flaw is not necessarily grounds for rejection (i.e., a defect) unless the effect of defect has been demonstrated. Even the detection of a given flaw type and size can be in doubt unless physical reference specimens with known flaw types and sizes undergo evaluation using the NDT method of choice. The suitability of various NDT methods for detecting commonly occurring composite flaw types is given in Table 1 in Guide E2533.

4.9 *Acceptance Criteria*—Determination about whether a COPV meets acceptance criteria and is suitable for aerospace service must be made by the cognizant engineering organization. When examinations are performed in accordance with this guide, the engineering drawing, specification, purchase order, or contract shall indicate the acceptance criteria.

4.9.1 Accept/reject criteria shall consist of a listing of the expected kinds of imperfections and the rejection level for each.

4.9.2 The classification of the articles under test into zones for various accept/reject criteria shall be determined from contractual documents.

4.9.3 *Rejection of COPVs*—If the type, size, or quantities of defects are found to be outside the allowable limits specified by the drawing, purchase order, or contract, the composite article shall be separated from acceptable articles, appropriately identified as discrepant, and submitted for material review by the cognizant engineering organization, and given one of the following dispositions: *1)* acceptable as is, *2)* subject to further rework or repair to make the materials or component acceptable, or *3)* scrapped (made permanently unusable) when required by contractual documents.

4.9.4 Acceptance criteria and interpretation of result shall be defined in requirements documents prior to performing the examination. Advance agreement should be reached between the purchaser and supplier regarding the interpretation of the results of the examinations. All discontinuities having signals that exceed the rejection level as defined by the process requirements documents shall be rejected unless it is determined from the part drawing that the rejectable discontinuities will not remain in the finished part.

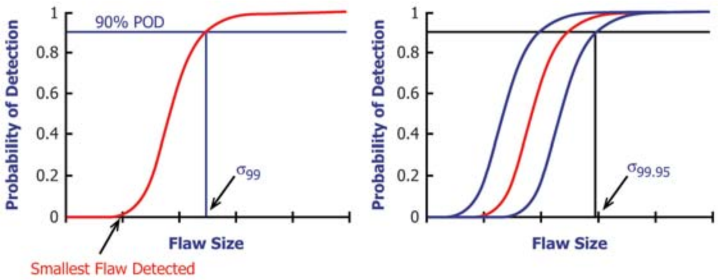
4.10 *Certification of COPVs*—ANSI/AIAA S-081 defines the approach for design, analysis, and certification of COPVs. More specifically, the COPV shall exhibit a leak before burst (LBB) failure mode or shall possess adequate damage tolerance life (safe-life), or both, depending on criticality and whether the application is for a hazardous or nonhazardous fluid. Consequently, the NDT method must detect any discontinuity that can cause burst at expected operating conditions during the life of the COPV. The Damage-Tolerance Life requires that any discontinuity present in the liner will not grow to failure during the expected life of the COPV. Fracture mechanics assessments of flaw growth are the typical method of setting limits on the sizes of discontinuities that can safely exist. This establishes the defect criteria: all discontinuities equal to or larger than the minimum size or have *J*-integral or other applicable fracture mechanics based criteria that will result in failure of the vessel within the expected service life are classified as defects and must be addressed by the cognizant engineering organization.

4.10.1 *Design Requirements*—COPV design requirements related to the composite overwrap are given in ANSI/AIAA S-081. The key requirement is the stipulation that the COPV shall exhibit a LBB failure mode or shall possess adequate damage tolerance life (safe-life), or both, depending on criticality and application. The overwrap design shall be such that, if the liner develops a leak, the composite will allow the leaking fluid (liquid or gas) to pass through it so that there will be no risk of composite rupture. However, under use conditions of prolonged, elevated stress, assurance must be made that the COPV overwrap will also not fail by stress (creep) rupture, as verified by theoretical analysis (determination of risk reliability factors) or by test (coupons or flight hardware).

4.11 *Probability of Detection (POD)*—Detailed instruction for assessing the reliability of NDT data using POD of a complex structure such as a COPV is beyond the scope of this guide. Therefore, only general guidance is provided. More detailed instruction for assessing the capability of an NDT method in terms of the POD as a function of flaw size, *a*, can be found in MIL-HDBK-1823. The statistical precision of the estimated POD(*a*) function (Fig. 2) depends on the number of inspection sites with targets, the size of the targets at the inspection sites, and the basic nature of the examination result (hit/miss or magnitude of signal response).

4.11.1 Given that $a_{90/95}$has become a de facto design criterion it is more important to estimate the 90th percentile of the POD (*a*) function more precisely than lower parts of the curve. This can be accomplished by placing more targets in the region of the a_{90} value but with a range of sizes so the entire curve can still be estimated.

NOTE 8—$a_{90/95}$ for a composite overwrap and generation of a POD(*a*) function is predicated on the assumption that effect of defect has been demonstrated and is known for a specific composite flaw type and size,



NOTE 1—POD(*a*), showing the location of the smallest detectable flaw and a_{90} (left). POD(*a*) with confidence bounds added and showing the location of $a_{90/95}$ (right).

FIG. 2 Probability of Detection as a Function of Flaw Size and that detection of a flaw of that same type and size is grounds for rejection, i.e., the flaw is a rejectable defect

4.11.2 To provide reasonable precision in the estimates of the POD(a) function, experience suggests that the specimen test set contain at least 60 targeted sites if the system provides only a binary, hit/miss response and at least 40 targeted sites if the system provides a quantitative target response, $\hat{a}$. These numbers are minimums.

4.11.3 For purposes of POD studies, the NDT method shall be classified into one of three categories:

4.11.3.1 Those which produce only qualitative information as to the presence or absence of a flaw, i.e., hit/miss data.

4.11.3.2 Those which also provide some quantitative measure of the size of the target (for example, flaw or crack), i.e., $\hat{a}$ versus a data.

4.11.3.3 Those which produce visual images of the target and its surroundings.

5. Basis of Application

5.1 *Personnel Certification*—NDT personnel shall be certified in accordance with a nationally or internationally recognized practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS 410, ISO 9712, or a similar document. The practice or standard used and its applicable revisions shall be specified in any contractual agreement between the using parties.

5.2 *Personnel Qualification*—NDT personnel shall be qualified by accepted training programs, applicable on-the-job training under a competent mentor or component manufacturer. Cognizant engineering organization and manufacturer qualification will only be applied to the components under direct training experience or production.

5.3 *Qualification of Nondestructive Test Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Practice E543. The applicable edition of Practice E543 shall be specified in the contractual agreement.

5.4 *Selection of NDT*—Choice of the proper NDT procedure (outside of those required per AIAA S 081, KNPR 8715.3, and AFSPCMAN 91 710) is based on the following considerations: *a)* the flaw to be detected and the sensitivity of the NDT method for that given flaw, *b)* any special equipment and/or facilities requirements, *c)* cost of examination, and *d)* personnel and facilities qualification.

5.4.1 The desired NDT output must be clearly separated from responses from surrounding material and configurations and must be applicable to the general material conditions, environment and operational restraints.

5.5 *Life Cycle Considerations*—NDT has been shown to be useful during: *a)* product and process design and optimization, *b)* on-line process control, *c)* after manufacture examination, *d)* in service examination (including re-certification), and *e)* health monitoring. After the COPV has been installed (stages *d* and *e*), NDT measurements shall be made on a "remove and inspect" or "in-situ" basis depending on the processing area controls, pressure system accessibility, and the procedure and equipment used.

5.5.1 Visual testing between stages *a* through *e* through decommissioning, during which the partially assembled or completed COPV is handled must also be considered and is required prior to flight per AIAA S 081, KNPR 8715.3, and AFSPCMAN 91 710.

5.5.2 The applicability of NDT methods to evaluate the composite overwrap in COPVs during their life cycle is summarized in Table 1.

5.6 *Timing of NDT and Responsibilities*—NDT conducted before delivery or owner buy-off to ensure safety and reliability of the COPV shall be the responsibility of the manufacturer. After receipt and installation, scheduling of NDT shall be the responsibility of the prime contractor and shall be listed in the program Damage Control Plan (DCP) per AIAA S-081 and various other range documents (KNPR 8715.3 or AFSPCMAN 91 710). For example, the in-service inspection interval is determined based upon the growth of composite discontinuities and the POD of the selected NDT technique, such that there is a negligible possibility of failure of the component in service. For fatigue-dominated flaw growth, fatigue (for example, pressure or fill) cycles shall be the metric of scheduling (Figure 2 in E2982). For time-dominated drivers of failure, such as physical aging, oxidation, and creep, the examination interval shall be calendar-based. For mixed time and usage modes of failure such as space environmentally assisted degradation under sustained stresses (for example, accelerated stress rupture) the schedule must be based on a combined analysis by the cognizant engineering organization. In case of fatigue, assuming a severe initial discontinuity (often called the "rogue flaw") denoted a_0, the amount of usage for this to grow a flaw to some critical size (denoted a_{crit}) is estimated. As per the previous text, usage could be fatigue cycles, time, or both depending upon the driving forces. Examinations are scheduled based on the threshold of NDT capability (denoted $a_{p/c}$, see 4.6) to have one or more opportunities in this usage interval to detect the defect and repair/replace the COPV before failure (Figure 2 in E2982).

TABLE 1 Application of Composite Overwrap-Specific NDT Methods During the Life Cycle of Composite Overwrapped Pressure Vessels

Method	Product and Process Design and Optimization	On-Line Process Control	After Manufacture Inspection	In-Service Remove and Inspect	*In-situ* Structural Health Monitoring
Acoustic Emission			X	X	X
Eddy Current^A			X	X	
Radiology			X	X	
Radioscopy	X	X	X	X	
Shearography			X	X	X
Thermography			X	X	
Ultrasound^B			X	X	
Visual	X	X	X	X	X

^{A}Applicable to (semi)conductive composites; for example, carbon, graphite or metal fiber reinforced composites

^{B}Performed after composite wrapping and curing, after or during autofrettage/proof cycling. Also consists of many separate techniques such as laser guided wave UT, water immersion UT, water column microfocus UT, each with specific attributes.

5.7 *COPV Mapping Convention*—All NDT techniques covered in this guide require establishment of a coordinate convention allowing the location of indications detected to be located on the outside surface of the COPV. Accurate mapping is especially important when applying multiple NDT techniques for corroborative analysis. Use an indelible off-axis mark (such as label or boss serial number) or scribe on a pre-defined end boss fitting to determine an arbitrary 0°, then mark the 90° clocking position. For greater accuracy mark a point with a greater radial distance from the axis of the COPV. The longitudinal location can be determined (using a flexible tape measure) along an arch length line from the base of the pre-determined boss fittings and the composite overwrap. Follow guideline for mapping conventions described in NASA/TM-2012-21737.

5.8 *Vessel Preparation*—Prior to NDT, considerations for vessel conditioning and preparation shall be followed according to Guide D5687 to ensure data reproducibility and repeatability.

5.9 *General Reporting Requirements*—Regardless of the NDT procedure used, the following general minimum reporting requirement exist and are used to establish the traceability of vessel under test:

5.9.1 Date and name of operator,

5.9.2 Vessel manufacturer,

5.9.3 Vessel model number and serial number,

5.9.4 Vessel geometry and dimensions,

5.9.5 Materials of construction,

5.9.6 Fiber volume fraction,

5.9.7 Resin content,

5.9.8 Applicable material certifications (when available),

5.9.9 Description of process (autoclave or out-of-autoclave temperature-pressure-time profile),

5.9.10 Date of cure (thermosetting matrices) or molding (thermoplastic matrices),

5.9.11 Location of any witness or reference marks/mapping convention,

5.9.12 Results of examination including location and description of all indications, and

5.9.13 Special notes (for example, service media, damage control plan).

5.10 *Specific Reporting Requirements*—For specific reporting requirements that pertain to the NDT procedure, equipment, sensor(s), and special test conditions, and that ensure the data acquired on the vessel under test is reproducible and repeatable, consult the corresponding Specific Reporting Requirements in Sections 7 to 10, 12, and 13.

6. General Safety Precautions

6.1 *Pressure Vessels*—As in any pressurization of pressure vessels, ambient temperature should not be below the ductile-brittle transition temperature of the metallic liner or above the glass-transition temperature of the matrix.

6.2 *Gas Pressurization*—In case of pressurization using gases special precautions shall be taken to avoid hazards related to catastrophic BBL failure of the pressure vessel. It is accepted practice to perform leak/integrity pressure checks of COPVs remotely and/or behind concrete or metal walls prior to any hand-on method(s) to avoid injury to personnel, death, and excessive damage to equipment and facilities in the event of a burst failure.

SPECIFIC PROCEDURES

7. Acoustic Emission

7.1 *Scope*

7.1.1 Guidelines are provided for acoustic emission examination of COPVs after composite wrapping and curing. The procedures described, therefore, have application to COPVs during and after manufacturing, during in-service examination, after repair, and during health monitoring (parts *a* through *e* in subsection 5.5.)

7.1.2 The primary goal of an AE examination is the overall assessment of COPVs' structural integrity and removal from service of vessels that exhibit abnormal or out of family activity due to materials and process variations, or flaw initiation and growth in the composite shell due to handling, damage, and use.

7.1.3 The procedures described, detect and possibly locate acoustic emission sources generated by flaws such as matrix cracking, fiber-matrix debonding, fiber pullout, fiber splitting, fiber fracture, and delamination.

7.1.4 When special methods of data acquisition and analysis are used, it is possible in some cases to identify the nature of AE indications and their severity.

7.1.5 Other NDT methods may be used to characterize AE sources when it is required, as long as the location of the sources have been determined. Procedures for other corroborative NDT methods are covered elsewhere in this guide (ECT (Section 8), Laser Shearography (Section 9), UT (Section 10), TT (Section 11), RT (Section 12), and VT (Section 13)).

7.1.6 The procedures described are not intended to assess damage in welded or spin formed metallic COPV liners. For AE procedures specific to detecting flaw initiation and growth in the metallic liner or its welds, or both, consult Guide E2982.

7.2 *Summary of Procedure*

7.2.1 AE sensors are mounted on a COPV and acoustic emission measurements are performed while the COPV is pressurized with gas, water, or oil, to the target AE test pressure(s).

NOTE 9—Normally, gas is heated when compressed during the filling process; hence, tanks are filled to more than the rated service pressure. After filling, the pressure should settle to the rated service pressure as gas temperature within the tank approaches ambient temperature.

NOTE 10—For safety reasons, water is the preferred medium for pressurizing COPVs during AE examination. Safe means for hydraulically controlling the pressure under prescribed conditions shall be provided.

7.2.2 Typical pressurization schedules (Fig. 3) include: *1)* a slow fill ramp and hold pressurization schedule (Fig. A3.1 in Test Method E2191); *2)* a fast fill stepped load pressurization schedule (Fig. A2.1 in Test Method E2191); *3)* an intermittent load hold pressurization schedule (Fig. 4 in Practice E1067); and *4)* re-pressurization to 98 % of the hydrostatic test or autofrettage pressure (ASME Section X, Appendix 8-600.2.7,

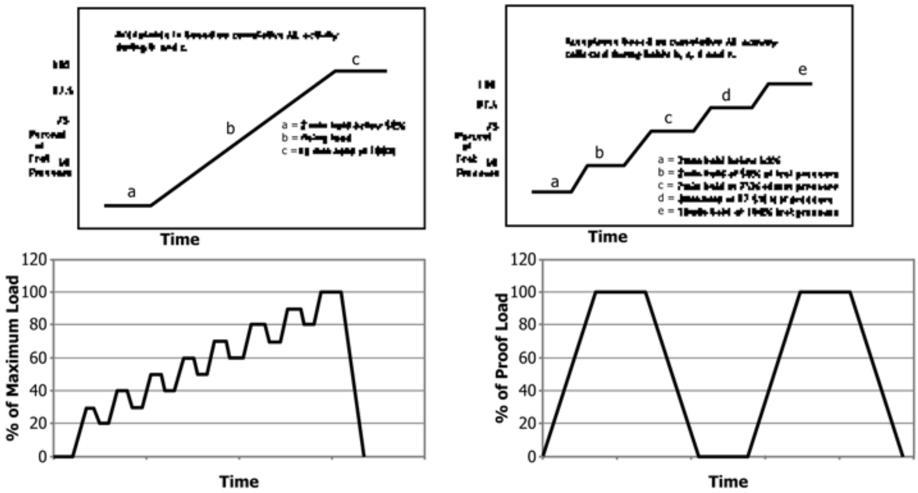


FIG. 3 Pressure Schedules Used for AE Testing of Composite Overwrapped Pressure Vessels (load-bearing liner) or Composite Pressure Vessels (linerless or nonload bearing liner): (a) Slow Fill Ramp (Schedule 1, top left), (b) Fast Fill Stepped Load (Schedule 2, top right), (c) Intermittent Load Hold (Schedule 3, bottom left), and (d) Double Cycle to 100 and 98 % of the Proof Pressure (Schedule 4, bottom right)

also see Fig 2 in Practice E2661/E2661M). Other pressurization schedules may be used if proven to be more effective in detecting and locating flaw indications.

NOTE 11—The pressure ramp needs to be at a constant rate (feedback control) and the same from one vessel to the next to allow comparisons. This is required since the matrix has viscoelastic time-dependent properties. Furthermore, the holds occur at a constant pressure, which entails that a correction be made to compensate for the relaxation of the COPV.

7.2.3 The pressurization rate shall not exceed the maximum safe rate defined by the manufacturer/designer. The pressurization rate also shall be low enough to minimize or avoid frictional sources produced by the vessel expansion/movement, or that are otherwise produced by turbulent flow of the pressurization medium. The potentially deleterious effects of excessively high strain rates on the mechanical performance of composite overwrap fiber and matrix resin must also be considered. Also, it is recommended that pressurization will be slow enough so that the AE events do not overlap in time.

7.2.4 If the measured acoustic emission exceeds the acceptance criteria then such locations or regions shall receive secondary examination by other appropriate NDT method(s) or the vessel is rejected.

7.2.5 Any number of COPVs may be examined simultaneously as long as the appropriate number of sensors and instrumentation channels are used, and AE from each vessel is isolated from the AE from neighboring vessels. It also requires that the hit rate processing speed of the AE measurement system be able to process all of the hits even when many vessels are active at the same time. As a practical consideration, a maximum of 20 COPVs may be interrogated simultaneously.

7.2.6 Other accepted guidance and practice for AE of polymer matrix composites can be found in Guide E2533 and Practice E2661/E2661M.

7.3 *Significance and Use*

7.3.1 COPVs used in aerospace applications typically have lower design margins than those used in commercial applications. Also, most of the pressure load is exerted on the composite overwrap, not the metal or plastic liner. Failure of the composite shell, therefore, has more severe ramifications than failure of the liner.

NOTE 12—The risk of catastrophic burst before leak (BBL) failure in COPVs manufactured with aramid and carbon fibers due to stress rupture of the reinforcing fiber in the composite is well-documented. For this reason, the consequences of BBL overwrap failure of gas-filled COPVs are much more severe than leak before burst (LBB) failure caused by liner failure.

7.3.2 The goal of AE examination is to evaluate the overall condition of the composite overwrap after wrapping and cure. In addition to AE produced by the composite overwrap, AE is also produced by liner yielding, friction between the liner and overwrap upon (de)pressurization, and by weld lines or other inclusions or discontinuities in the liner. Depending on the AE configuration, every effort should be made to determine AE originating from the overwrap versus AE originating from the liner or liner welds. However, most of the AE activity in COPVs will typically originate from the composite overwrap.

7.3.3 The AE examination is also used to evaluate the overall condition of COPV after manufacturing or in-service.

7.3.4 This procedure can be used to detect and locate flaw indications in the composite overwrap, such as those caused by impact damage, pressure cycling, over-pressure, and physical and environmental aging. Damage mechanisms and processes that are detected by AE in composite materials include matrix cracking, fiber-matrix debonding, fiber pullout, fiber splitting, fiber fracture, bundle failure, tow slippage, delamination and friction between damaged surfaces. In COPVs, AE can also result from movement between the overwrap and liner (disbond). Detectability of composite damage during pressurization depends on many factors such as prior pressure history, fiber lot modulus variation, matrix crosslink density, and tension during wrapping. AE will be generated if the resulting local stress is high enough to activate one or several of the above mentioned mechanisms or processes.

7.3.5 In spin formed or welded metallic liners, AE examination may be used to detect micro and macro-cracks, local plastic deformation development around discontinuities and fracture and de-bonding of hard non-metallic inclusions (Guide E2982).

7.3.6 When special methods of data acquisition and analysis are used, it is possible to characterize and identify flaw indications, including but not limited to some of the above mentioned failure mechanisms and processes. Such methods are beyond the scope of this document.

7.3.7 When an intermittent load hold pressurization is used (Practice E1067), the Felicity ratio (FR) can be used to estimate the severity of previously induced damage. This technique is particularly effective for assessing COPVs with known damage or suspected flaw indications revealed by previous AE examination or by other NDT methods. Prediction of a COPV's burst pressure based on the FR is out of scope of this guide but can be found elsewhere (**1-3**).[14] Use of the FR as an analytical damage parameter does, however, require a means to subject the vessel to a highly controlled and reproducible pressure schedule.

7.3.8 Based on the results of an AE examination, COPVs can be accepted for service. COPVs that do not meet acceptance criteria should be evaluated further by other applicable NDT methods.

7.3.8.1 Acceptance of a COPV must be based on comparison of AE data of a suspect vessel to data acquired on nominal vessels under identical strain rate conditions, data acquisition settings, and on vessels that are also equivalent in terms of design, materials of construction, and process method. Furthermore, to assess behavior of suspect versus nominal vessels at failure, the AE database must include results on failed (burst) vessels.

7.3.9 AE examination can be used to evaluate significance of flaw indications revealed by other NDT methods, and vice versa.

7.3.10 Unlike other NDT methods, AE does not "size" flaws in composites the same way flaws (typically cracks) are sized in metals by RT, UT, PT, etc. In metals, the flaw size is determined by direct measurement of the crack size, usually expressed by the crack's depth (*a*) and length (*c*). In composites, more complex empirical relationships must be derived that relate the type of damage (fiber breakage, breaking of covalent bonds in the matrix, or fiber/matrix debonding and pull-out) with a measured AE quantity (for example, the amount of energy released within a specified frequency band). No such empirical relationships are provided in this guide. It can be inferred; however, that AE measured quantities such as event rate and amplitude, or related qualitative features such as criticality and intensity, do correlate with the type and severity of damage in composites in a way that is similar to the way flaws are sized in metals.

7.4 *Apparatus*

7.4.1 For an overview of personnel training/test requirements, the essential features of the AE apparatus, use of sensor couplant, attenuation characterization and sensor positioning, consult Test Method E2191. For a general overview, see Section 5.

7.4.2 Additional information on AE sensor surface preparation and mounting can be found in Guide E650.

7.4.3 Additional information on AE instrumentation can be found in Practice E750.

7.4.4 Detection of composite damage in COPVs may be done by use of resonance sensors with peak frequency between 100 to 300 kHz. High fidelity sensors with nearly flat frequency response between 100 kHz to 1 MHz, as determined by Practice E1781/E1781M or Test Method E1106, are recommended when it is necessary to perform frequency differentiation of different damage mechanisms. For example, higher frequency damage events, most notably fiber breakage, has been measured in the 300 to 600 kHz range (**4-6**).

NOTE 13—The AE frequency depends on the total vessel wall thickness (liner plus composite shell) and the propagation distance between the source and the sensor(s).

7.5 *Calibration and Standardization*

7.5.1 General guidelines for calibration and standardization, including routine electronic evaluations, system performance verification using a pencil lead break can found in Practices E569 and E650, and Test Method E2191.

7.5.2 The preferred technique for conducting performance verification is a pencil lead break (PLB). All PLBs shall be done at a fixed distance from the center of the sensor, and at an angle of approximately 30 degrees to the test surface, with a 2.5-mm (0.1-in.) lead extension using 0.3 mm diameter 2H lead (see Guide E976). It is recommended that PLBs be performed at a fixed distance, for example 150 mm (6.0 in.), from the sensor center to one of the principal wrap directions of the surface fiber (if applicable). The PLB data, distances, etc., shall be documented as part of the examination report.

7.5.3 The optimum number of sensors and their position should be determined for a given vessel design prior to actual collection of data.

NOTE 14—COPVs are anisotropic with respect to propagation of the transient elastic stress wave, with more attenuation observed in the direction perpendicular to the outermost wrap direction. Sensor spacings must, therefore, be tailored to the specific design/wrapping pattern.

7.5.4 To examine with PLBs whether sources can be located with sufficient accuracy, first create a grid inside the sensor array with spacing at one-quarter to one-fifth the spacing of the sensors. Then PLBs can be done at each grid point with a series of different thresholds. Start with a threshold about 3 or 4 dB above the background noise level (typically electronic noise). Increase the threshold with increments of about 4 to 6 dB until the peak amplitude of the PLB is reached. The information from these tests can be used to make an estimate about whether real sources can be located with sufficient accuracy based on a single velocity used for the location calculation.

7.5.5 If the locations cannot be determined with sufficient accuracy, then either use more sophisticated methods (e.g. wavelet transformations to obtain arrival times at a fixed frequency of the flexural mode) or use first hit sensors to determine the region of origin of the sources.

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[14] The boldface numbers in parentheses refer to a list of references at the end of this standard.