



Standard Guide for Nondestructive Testing of the Composite Overwraps in Filament Wound Pressure Vessels Used in Aerospace Applications¹

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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 m³ (70 ft³), and 2) high pressure COPVs used for storing compressed gases at MAWPs up to 70 MPa (10,000 psia) and volumes down to 8000 cm³ (500 in.³). Internal vacuum storage or exposure is not considered appropriate for any vessel size.

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.

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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

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](#)

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, Non-destructive 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.

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 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 Arlington 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.

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 black-body 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 non-destructive 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 [length²/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 be 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

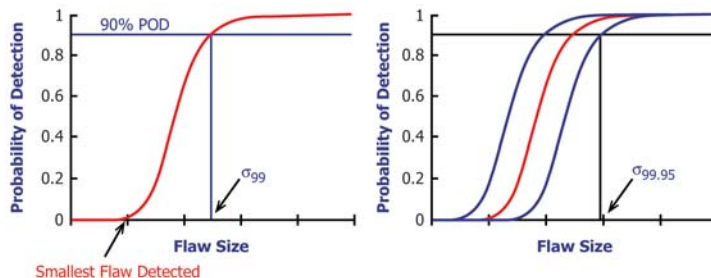
during the life of the COPV. The Damage-Tolerance Life requires that any discontinuity present in the liner will not grow to failure during the expected life of the COPV. Fracture mechanics assessments of flaw growth are the typical method of setting limits on the sizes of discontinuities that can safely 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

^AApplicable to (semi)conductive composites; for example, carbon, graphite or metal fiber reinforced composites

^BPerformed 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,

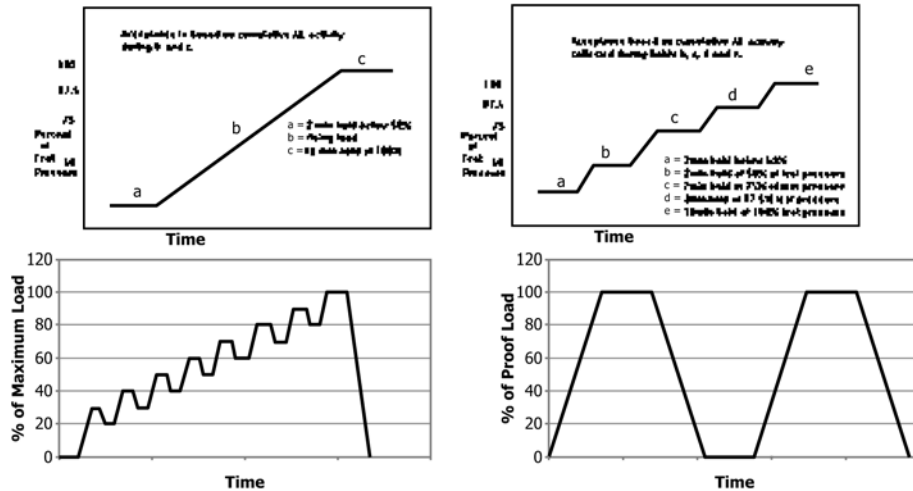


FIG. 3 Pressure Schedules Used for AE Testing of Composite Overwrapped Pressure Vessels (load-bearing liner) or Composite Pressure Vessels (linerless or nonload bearing liner): (a) Slow Fill Ramp (Schedule 1, top left), (b) Fast Fill Stepped Load (Schedule 2, top right), (c) Intermittent Load Hold (Schedule 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 applica-

tions. 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

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

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.

NOTE 15—PLB generated AE signals are on the order of 20dB or more higher in amplitude than real AE and they are strongly dominated by the flexural mode not representative of the real AE in a composite.

7.6 Safety Precautions

7.6.1 **Warning!** The energy release associated with failure of a COPV pressurized with gas is extremely high compared to a liquid and can result in injury or death of personnel or severe damage to facilities and equipment, or both.

7.6.2 Allowances shall always be made to account for the possibility of unanticipated, premature vessel failure. Additional precautions shall be taken to protect against the consequences of catastrophic failure, for example, flying debris (sensors for example) and impact of escaping liquid or gases. It is recommended that vessels are pressurized remotely with adequate burst shielding/protection.

7.6.3 Water is the preferred medium for pressurizing vessels during AE examination. Safe means for hydraulically increasing the pressure under controlled conditions shall be provided.

NOTE 16—Trace impurities that may cause or accelerate stress corrosion cracking of metallic liners must be avoided, for example, halogenated species from (per)halogenated softgoods used in COPV sealing and filling applications.

7.6.4 The test temperature should not be below the ductile brittle transition temperature of the metallic liner or above the glass-transition temperature of the composite matrix.

7.6.5 Special safety precautions shall be taken when pneumatic testing is required; for example, safety valves, etc.

7.7 Examination Preparation

7.7.1 Install the vessel in the test stand while insulating its surfaces from contact with other hardware using rubber, plastic or other insulating material (for example, foam). Remove any external objects that come into contact with the vessel and isolate the vessel. External objects can also extract wave energy and thus reduce the sensitivity to monitor the real AE. If the vessel cannot be completely isolated, record in the test report the external objects which could produce AE.

NOTE 17—AE from external sources that produce electromagnetic interference (EMI) or vibration must be accounted for and isolated.

7.7.2 Before AE measurements are made, visually examine the accessible exterior surfaces of the COPV per Section 13. Note observations in the test report (see CGA Pamphlet C-6.2).

7.7.3 Connect the fill hose (and pressure transducer). Eliminate any leaks.

7.7.4 Mount the acoustic emission sensors according to Test Method E2191 (Section 7), and Guide E650. One sensor is normally enough for a small volume (less than two liters) COPV for detecting activity due to flaw initiation and growth, and to assess the overall condition in order to guide examination by other appropriate NDT methods. No surface preparation is allowed, for example, sanding to smooth the region where a sensor will be mounted. Sensors are mounted so that the face of the sensor(s) is parallel to the tangent plane of the surface of the COPV at the desired installation location.

NOTE 18—A two-liter sphere can have AE sources 50 cm (20 in.) from a single sensor, which can result in non-detection of events due to geometric spreading and dispersion-based loss of amplitude.

7.7.5 Install additional sensor(s), when practical or needed, on the test stand holding the COPV in a manner to filter out frictional/impact noises originating outside of the COPV.

7.7.6 Perform an AE system performance/verification check using PLB(s) in accordance with Guide E976. A piezoelectric pulser can also be used for this purpose. When source location shall be performed, use the PLB method (see subsection 7.5.4) to verify the accuracy of any source location algorithms.

7.7.7 Select one of the following pressurization schedules:

7.7.7.1 A slow fill ramp and hold pressurization schedule (Schedule 1, similar to Fig. A3.1 in Test Method E2191),

7.7.7.2 A fast fill stepped load pressurization schedule (Schedule 2, similar to Fig. A2.1 in Test Method E2191),

7.7.7.3 An intermittent load hold pressurization schedule (Schedule 3, Fig. 4 Practice E1067), or

7.7.7.4 Repressurization to 98 % of the hydrostatic test or autofrettage pressure (Schedule 4, ASME Section X, Appendix 8-600.2.7).

7.7.8 Other pressurization schedules may be used if proven to be more effective in detecting and locating flaw indications. For examination of newly manufactured vessels or in-service examination of vessels without known or suspected flaws, one can use Schedule 1, 2, or 4. The target test pressure(s) depend on the COPV design and can be referenced against known values of the proof pressure, autofrettage pressure, normal operating pressure, and burst pressure, for example. The goal of the AE examination will be to assess damage during pressurization and at discrete pressures holds and times.

7.7.8.1 Schedule 1 is selected whenever the duration of slow fill pressurization is practical and reduction of background noise can be achieved by reducing the pressurization rate.

7.7.8.2 Schedule 2 is used as an alternative to Schedule 1 whenever shorter fill times are requested or when reduction of the pressurization rate does not provide the necessary reduction of background noise produced by friction, flow turbulence from the pressurization medium, or adjacent machinery, or combinations thereof.

7.7.8.3 Schedule 3 is recommended for examination of vessels with apparent/suspected impact damage, or vessels that produce inconclusive results during other AE examinations or when a flaw-indication is detected by another NDT method and additional characterization by AE is needed.

7.7.8.4 Schedule 4 is recommended as a manufacturer's test of virgin, as-manufactured vessels with no apparent or suspected damage, and is typically performed in conjunction with the initial hydrostatic pressure test and volumetric expansion test of the vessel, including an autofrettage or proof pressurization. Schedule 4 is used to assess in-family or out-of-family composite stability, to detect hidden flaws, and to provide an initial signature of the vessel. ASME also requires that the AE test described in ASME Section X, Appendix 8-600.2.7 be performed on all Class III production and qualification vessels.

7.8 Procedure

7.8.1 *Background Noise Check*—Perform a background noise measurement in order to evaluate the average AE event rate and variability of the event rate over a time period of at least 5 minutes. If the AE background noise level is changing

significantly, increase the noise monitoring period to 30 minutes. In the case of elevated or varying background noise, identify the source of the noise and eliminate or reduce it to the lowest minimum possible. Record/note the root-mean square (RMS) or Average Signal Level (ASL) of noise recorded by any sensor. Also, record the hit rate of noise in each channel at the test AE threshold.

7.8.2 Begin pressurizing the COPV according to the selected pressurization Schedule 1, 2, 3, or 4 and monitor and record the AE data.

7.8.3 If significant/abnormal AE activity is detected and appears to be growing in a nonlinear or exponential manner during pressurization, during Schedule 1, 2, 3, or 4, terminate the test. If, during pressurization according to the Schedule 3, the FR falls below a critical Felicity ratio at which prior failure has been observed, terminate the test.

NOTE 19—The critical Felicity ratio should be determined for each type of vessel separately as it depends on factors related to the vessel (design, materials, and processing), the AE apparatus (sensors, signal conditioning unit, data acquisition parameters including threshold and high and low pass filters), and the analytical methods used during data reduction (onset of significant AE, partial powers analysis, pattern recognition, etc.). If no such criterion is yet elaborated or available, one can use 0.96 as an initial value of critical Felicity ratio for a carbon-epoxy composite based on results obtained on uniaxial single tow (1). It must be noted that this value is only approximate and was not determined from a significant database of COPVs. COPVs respond to pressure by exhibiting a more complex biaxial stress state, resulting in greater shear degradation than observed in uniaxial tow or laminate. The Felicity ratio is also strongly dependent on 1) the sensitivity as determined by the threshold and sensor used, and 2) how close to the actual residual vessel strength the peak value of the pressure value is for the denominator in the calculation of the Felicity ratio.

7.8.4 Check for the absence of leaks after the pressurization equipment is connected to the vessel. If indications of leakage are identified, interrupt pressurization and fix the leak.

7.8.5 Reduce the pressure to zero and perform system verification checks and sensor sensitivity checks (see Test Method **E2191**, Section 9.4).

7.8.6 New or as-manufactured vessels subjected to initial pressurization (virgin loading) may exhibit normal but significant acoustic emission due to creation of the characteristic damage state (Practice **E2661/E2661M**). Such AE is typically noticeable at the start of pressurization and gradually declines with pressure rise. For such vessels, in order to ensure that no flaw-related activity was masked, a second pressurization cycle should always be done immediately after the first one.

7.9 Interpretation of Results

7.9.1 There are several steps in data interpretation of AE examination results including; isolation of suspected composite flaw signals from noise, source location, defect identification (7.9.6) classification (7.9.7) (whenever it is possible) and quantitative or qualitative assessment (7.9.8).

7.9.2 *Detection of Suspected Flaw Signals*—This is performed in order to select signals relevant for assessing a COPVs structural integrity and to remove background AE due to leaks, mechanical vibration, friction, turbulent flow of the pressurization medium, impacts or electrical noise. This can be accomplished, for example, by removing recorded AE signals with signatures matching known noise sources. Removing

signals with long rise times may result in errors since delamination sources can have long rise times and should not be removed. Signals that cannot be reliably attributed to flaw-related or non-related activity should be considered as flaw-related until proven otherwise.

7.9.3 Criteria for selecting flaw-related signals that are specific to the vessel design are not part of the interpretation of results produced by this procedure.

7.9.4 Evaluation based on emissions during pressure holds is particularly significant. Continuing emissions indicate continuing damage. Fill and other background noise will generally be at a minimum during a pressure hold. The opportunity to interpret hold data is particularly important during Schedules 3 and 4; however, can also be integrated in Schedule 1 or 2 assessment.

7.9.5 *Source Location*—Source location is performed on flaw- and non-flaw-related activity to determine the origin and global distribution of possible flaw indications and noise sources. Dense locations indicate localized damage. In small vessels with one or a few sensors, accurate source location may not be possible and recorded AE signals are used for the overall assessment of structural integrity. Source location is performed normally by considering time of arrival detected by fixed thresholds and effective velocity as determined by arrival time data at three (two for linear location) or more sensors. However, more sophisticated methods of source location can be used to improve location accuracy by taking into consideration the anisotropy of COPVs and specific velocities at fixed frequencies of wave propagation modes in specific directions relative to the principle composite wrap angles. In the AE examination report, source location results should include the surface area used to define multiple AE events taken as being from the same location and the propagation velocity used for location calculations.

7.9.6 *Indication Identification*—This is performed whenever reliable methods of data analysis, including clustering and pattern recognition techniques, can be used and have proven utility for specific vessels. For example, in many cases it is possible to distinguish activity due to fiber breakage, delamination and matrix cracking in a composite structure by considering the duration, amplitude, and frequency characteristics of acoustic emission detected by high fidelity sensors.

7.9.7 *Indication Classification*—Rapid flaw development, such as that caused by impact damage, is usually distinguished by the AE activity (event rate) and its intensity (energy per event) or an FR test, or both.

7.9.7.1 A source's acoustic emission activity is normally measured by event count or hit count. A source in the overwrap or metallic liner is considered to be "active" if its AE activity continues to increase with increasing or constant pressure. A source is considered to be "critically active" if the rate of change of its AE activity with respect to applied pressure increases with increasing pressure, or alternatively, if the rate of change of its AE activity with respect to time increases with time at constant pressure (see Fig. 1 in Practice **E569**).

7.9.7.2 The preferred intensity measures of a source in the overwrap or metallic liner are its 1) average detected energy per event, 2) average emission count per hit, or 3) average

amplitude per hit. A source is considered to be “intense” if it is both active and its intensity measure consistently exceeds, by a specified amount, the average intensity of active sources. The intensity of a source, such as an impact-damaged area can be calculated for increments of the pressure stimulus or of hits. A “critically intense” source is one in which the AE source intensity increases with increasing stimulus or with time under constant stimulus. It is noted that, if there is only one active source, the intensity measure of the source is the average intensity of all sources, and therefore the intrinsic comparison no longer is applicable. In this case, it is necessary to classify the source through comparison with results from similar examinations.

7.9.8 Indication Assessment—One of the goals of an AE examination is to use signal analysis to ascertain the damage mechanism whenever suspected flaw activity is detected.

7.9.8.1 Evaluation based on high-amplitude and high-energy events is important for COPVs. These events are often associated with breakage of fiber bundles or are indicative of major structural damage due to impact or other severe accumulated damage. Presence of high amplitude and high-energy events is a condition on which acceptance criteria (7.11) can be based. Source location, duration, frequency, pattern recognition and partial powers analysis (in addition to amplitude) can be used to further characterize high amplitude events.

7.9.8.2 For COPVs examined under Schedule 3, the FR provides a measure of the severity of previously induced damage. The onset of “significant” emission for determining measurement of the FR is a matter of experience. The following are offered as guidelines to determine if the emission is significant:

- (1) Multiple bursts of emission during an increase in load.
- (2) Emission continues at a load hold.
- (3) FR is a condition on which acceptance criteria (7.11) can be based.

7.9.8.3 For vessels examined under Schedule 4, numerical fits to exponential AE event and energy decay curves during a specified load hold of an as-manufactured, virgin vessel held for a period of time at a given percent of the target test pressure (typically the autofrettage or proof pressure), provides a measure of composite stability and further serves as a useful indicator of out-of-family behavior. During Schedule 4 pressure holds, both the decay rate and coefficient of variance of its exponential fit are conditions on which acceptance criteria can be based.

NOTE 20—ASME Section X, Appendix 8-600.2.7 specifies 30 min at 98 % of the autofrettage or proof pressure.

7.10 Specific Reporting Requirements

7.10.1 In addition to the general reporting requirements listed in Section 5.9, follow the reporting guidelines given in Section 11 of Test Method E2191. The following also shall become part of the data record:

7.10.1.1 Visual test observations (see Sections 7.7.2 and 13.10).

7.11 Acceptance and Rejection Criteria—Acceptance and rejection criteria are still evolving for COPVs and currently no universal criteria exist for the variety in COPVs in use. General

nonmandatory guidance for AE based acceptance and rejection of COPVs; however, is provided in Appendix X1. This guidance is included so as to promote development of more rigorous and universal acceptance and rejection criteria than are currently available.

8. Eddy Current Testing

8.1 Scope

8.1.1 This guide describes procedures for eddy current examination of composite overwraps used in aerospace COPVs. Eddy current methods can be used with composite overwraps that include electrically conducting or magnetic component materials, such as metallic or carbon fibers in a polymer matrix, or both.

8.1.2 Although eddy current methods can be used to examine both the composite overwrap and the metallic liner, this guide is aimed at the overwrap itself. For use of eddy current to interrogate the metallic liner through the composite overwrap, consult Guide E2982.

8.1.3 The procedure described here does not pertain to the use of magnetic stress gages on aerospace COPVs.

8.2 Summary of Practice

8.2.1 The examination is performed by scanning an eddy current sensor or eddy current sensor array over the surface of the overwrap, with the sensor energized with alternating current of one or more frequencies. The electrical response from the sensor is modified by the proximity and local condition of the overwrap. The extent of this modification is determined by the distance between the eddy current sensor and the overwrap material being examined, the dimensions (such as layer thicknesses) and electrical properties (electrical conductivity and magnetic permeability) of the overwrap, and the sensor orientation with respect to the fibers in the overwrap. Scans are typically performed in each orientation corresponding to the fiber wrap directions. The presence of local mechanical discontinuities or material variations in the material alters the measured electrical signal from the sensor. This signal can be processed and used to actuate visual or audio signaling devices or a mechanical marker to indicate the position of the discontinuity or material variation.

8.2.2 If an eddy current sensor array is used, the position at each measurement location is recorded along with the response of each element in the sensor array. The measured responses and location information are then used, typically in the form of a displayed image, to display the sensor response and material condition over an area. For sensors or sensor arrays used with models for the sensor response, the measured responses are converted into dimensional or electrical properties, or both. Baseline values for these properties ensure proper operation during the examination while local variations in one or more of these properties are used to assess the overwrap condition.

8.2.3 Processing parameters, such as the operating frequency, scan rate, and standardization procedure are determined by the sensor selection and the type and layup of the materials used in the overwrap. Standardization of the sensor is performed on a reference standard having overwrap electrical properties and thickness comparable to the material under

examination, or for the case of model-based sensors, on a material with uniform properties.

8.3 Significance and Use

8.3.1 Eddy current sensors can respond to the composite overwrap if it contains electrically conducting or semiconducting fibers. The procedures described here are suitable for detecting and locating material property variations in the composite overwrap. Example material conditions are winding uniformity of the fibers, fiber rich and matrix rich regions, fiber orientation, impact damaged areas, and mechanical stress associated with pressurization.

8.3.2 The eddy current sensor responds to the electrical conductivity of the fibers, the volume fraction of the fibers, and electrical interconnections between the fibers. Variations in the fiber volume fraction, for example from fiber-rich or matrix-rich regions, can be imaged as spatial variations in the material properties. Fiber breakage, for example from impact damage, reduces the effective fiber conductivity and appears as a change in the eddy current sensor response. Often the response to damage is comparable to the material property variations within the composite. A baseline image can be subtracted from an examination image to remove the inherent material property variations from service-induced changes and to improve the detectability of damage.

8.3.3 Some eddy current sensors are directional and only have a substantial response when aligned with the fibers in a particular layer of the overwrap. This type of sensor can be used to verify the fiber orientation and uniformity in a wrapped vessel.

8.3.4 The eddy current sensor can be sensitive to the properties of the metallic liner if the sensor dimensions are larger than the thickness of the composite. When using a sensor that responds to both the overwrap and the liner, care must be exercised to isolate the overwrap response from that of the liner.

8.4 Apparatus

8.4.1 *Instrumentation*—The electronic instrumentation shall be capable of energizing the eddy current sensor or sensor array with alternating current of one or more suitable frequencies and shall be capable of measuring changes in the impedance of each element in the sensor array. The equipment may include a capability to convert the impedance information into physical property values for the material under examination.

8.4.2 *Eddy Current Sensor*—The eddy current sensor or sensor array shall be capable of inducing currents in the composite overwrap and sensing changes in the physical characteristics (electrical conductivity, thickness, and magnetic permeability) of the composite overwrap. The eddy current sensor may be a surface probe type or a sensor array that contains an exciter (drive) coil and one or more absolute sensors.

8.4.3 *Reference Standard*—The standard used to adjust the sensitivity setting of the apparatus or to verify system operation, or both, shall have a similar electrical conductivity to the composite overwrap being examined. The standard may be a uniaxial composite or a laminate with two or more fiber orientations. The reference standard may need a metallic backing layer of known electrical properties to simulate the

presence of the liner if the composite overwrap is thin compared to the sensor dimensions.

8.5 Calibration and Standardization

8.5.1 Select the apparatus, operating frequency or frequencies, sensor or sensor array, examination speed, and instrument-specific circuitry, if necessary.

8.5.1.1 The selection of sensor or sensor array dimensions is based on the type of examination being performed. For sensitivity to composite material properties near the surface, sensors with small dimensions should be used, such that the sensor diameter or the distance between the drive winding and sense element is small compared to the overwrap thickness. For sensitivity through the thickness of the overwrap, sensors with large dimensions should be used, such that the sensor diameter or the distance between the drive winding and sense element is large compared to the overwrap thickness.

8.5.1.2 The selection of the operating frequency depends upon the frequency of the signal, the conductivity and magnetic permeability of the material, and some dimensions of the sensor. The depth of penetration is equal to the conventional skin depth at high frequencies but is related to the sensor size at low frequencies. For carbon fiber composites, the excitation frequency is typically greater than 1 MHz.

8.5.1.3 The sensitivity of a measurement to fibers within a specific layer of the composite generally decreases with the distance below the composite surface.

8.5.2 Fabricate applicable reference standards in accordance with the agreement between the user and COPV manufacturer.

8.5.3 The instrument should be assembled, turned on, and allowed sufficient time to stabilize in accordance with the manufacturer's instructions before use.

8.5.4 Adjust the apparatus through standardization measurements in accordance with the manufacturer's instructions before use. This adjustment is followed by a performance verification measurement to ensure that the equipment is operating at the proper level of sensitivity.

8.5.4.1 If adjustment on reference standards is required, then the equipment is to be adjusted so that the signal obtained from composite to obtain an optimum signal-to-noise ratio with the minimum sensitivity required to detect the discontinuities in the reference standard.

8.5.4.2 For model-based sensors, standardization using measurements in air or on a discontinuity-free reference material should be performed in accordance with Practice [E2338](#) and Guide [E2884](#). Performance verification is performed through measurements on a discontinuity-free reference material for one or more lift-offs to ensure that the measured property values (for example, electrical conductivity for nonmagnetic materials or magnetic permeability for magnetic materials) are not affected by the lift-off. A performance verification on a reference standard may also be performed to ensure that the response to the discontinuity as well as the background variation in the property value associated with discontinuity-free regions of the reference standard are within specified tolerances.

8.6 Procedure

8.6.1 Standardize the examination equipment prior to the examination. The recommended maximum interval between

restandardization is 4 h, although more or less frequent restandardization may be done by agreement between using parties or whenever improper functioning of the examination apparatus is suspected. If improper functioning occurs, restandardize the apparatus and reexamine at material examined since the last successful standardization.

8.6.2 Scan the sensor or sensor array over the surface of the composite in a manner which ensures complete coverage of the surface. One scan should be performed for each fiber orientation in the composite.

8.6.3 Analyze the data to determine if any measured signals exceed a threshold level set for discontinuity and to verify that background variations are within specified tolerances.

8.6.4 A specific written procedure shall be developed for each part. Parts of similar configuration may be covered by a single specific procedure. Each written procedure shall provide sufficient details such that the procedure can be consistently repeated from test to test.

8.7 Significance of Data

8.7.1 ECT methods are used for nondestructively locating and characterizing discontinuities in magnetic or electrically conductive materials.

8.7.2 Processing of the measurement data may be performed to highlight the presence of discontinuities, to reduce background noise, and to characterize detected discontinuities, such as provide a discontinuity size.

8.8 Specific Reporting Requirements

8.8.1 In addition to the general reporting requirements listed in Section 5.9, the following information shall be recorded to ensure the reproducibility and repeatability of the data acquired on the vessel under test:

8.8.1.1 Instrument, probe, and sensor identification,

8.8.1.2 Date of last instrument calibration and type and frequency of calibration,

8.8.1.3 Frequencies used,

8.8.1.4 Orientation of the probe relative to any component geometrical features, and

8.8.1.5 Examination procedure identification.

9. Laser Shearography

9.1 Scope

9.1.1 This section provides guidelines for shearography testing of COPVs with metallic liners as well as linerless CPVs, for latent manufacturing anomalies as well as handling or operational damage.

9.1.2 This guide does not specify accept-reject criteria and is not intended to be used as a means for approving COPV or CPV for service.

9.1.3 To ensure proper use of the referenced standards, there are recognized NDT specialists who 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 activity.

9.2 Significance and Use

9.2.1 Latent manufacturing anomalies in COPV detectable with the shearography methods described here include fiber

bridging (Fig. 4), broken fibers (Fig. 5), poor fiber consolidation and porosity (Fig. 6), disbonds between the liner and the composite overwrap (Fig. 7) and the detection of liner wrinkles or buckles without need to penetrate the vessel as is required with borescope or profilometry (Fig. 8). Shearography is also highly effective for COPV evaluation for detecting both visible and non-visible impact damage (Fig. 9) and cracks (Fig. 10). These techniques have been used for a “last look” before or after COPV installation in flight vehicles. Anomalies detectable with shearography may cause a significant reduction in vessel fatigue life, stress rupture, and pressure performance.

9.2.2 The presence of fiber bridging in COPV at transitions or over poorly prepared welds in welded liners represents an extremely dangerous condition that can lead to liner cracks, low cycle fatigue failure, leaks, or even a low burst pressure.

9.2.3 Shearography can be used with any metallic liner including aluminum, stainless steel, or titanium fabricated by spin forming or welding. Shearography techniques described herein are also applicable to liner-less, or plastic lined carbon fiber pressure vessels, liquid propellant tanks, and tubular structures such as composite struts.

9.2.4 Other accepted guidance and practice for laser shearography of polymer matrix composites can be found in Guide E2533 and Practice E2581.

9.3 Apparatus

9.3.1 Equipment required for shearography COPV testing includes:

9.3.1.1 Shearography camera with a laser light source and means for steering both the camera and laser light over the surface of the COPV surface. Independent steering and control of the laser is needed for uniform illumination of the complex curved surfaces;

9.3.1.2 Real-time, native-resolution phase map imaging of deformation derivatives, with a minimum real-time resolution of 12 bit, 1200 × 1200 pixels at 18 mps (30 fps);

9.3.1.3 Remote calibration system using structured light for shearography image calibration of COPV surfaces;

9.3.1.4 Capability to map the defect image or feature onto the COPV surface;

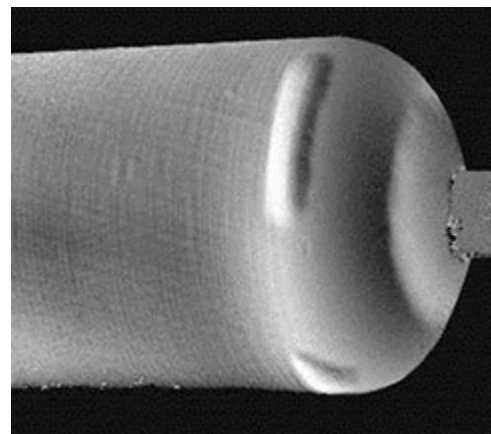


FIG. 4 Fiber Bridging Defects, an Extremely Dangerous Condition, at the Transition from the Barrel Section to the End Dome

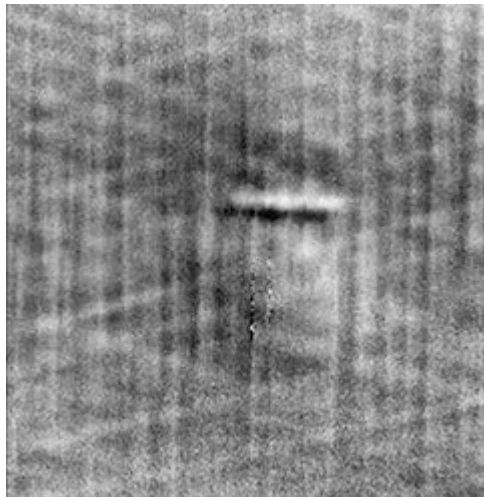


FIG. 5 Broken Fibers

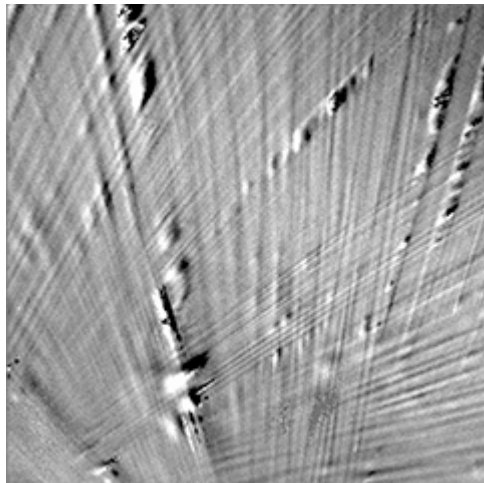


FIG. 6 Porosity, Voids, and Poor Fiber Consolidation

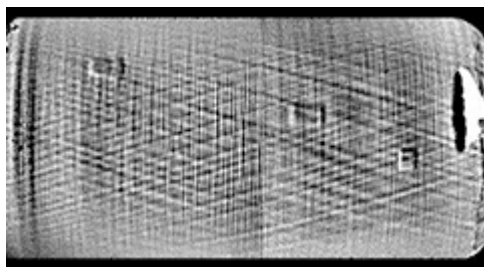


FIG. 7 Intentionally Introduced Disbands Between the Liner and the Consolidation Carbon Fiber composite overwrap

sec) and uniform heating of the composite COPV test area within the field of view. (Note the use of hot air guns is not recommended);

9.3.1.8 Stable COPV support or structure allowing axial vessel rotation around its longitudinal axis for complete coverage; and

9.3.1.9 A process control and reference standard.

9.4 Safety Precautions

9.4.1 Procedures for the protection of personnel, equipment, and the COPV from any injury or consequential damage of any kind are an integral part of this procedure.

9.4.2 *Pressure Safety*—Pressure shearography is generally performed in a pressure range inversely proportional to the COPV diameter. Pressures of only 0.7 kPa (0.1 psi) have been used to examine very large, 4 m (13 ft.) diameter COPV (Fig. 11) and for small diameter thick walled vessels, pressures typically applied are less than 620 kPa (90 psi). Appropriate safety procedures must be followed for the pressure range applied to the COPV during the test to prevent injury and damage if an unexpected failure were to occur. Precautions must include determination of a safe pressure limit for the test equipment and facility. Hose restraints and appropriate safety restraints on the COPV should be used to prevent injury to personnel or damage to equipment or the COPV from unintended hose disconnection or rupture. Shearography COPV testing can usually be accomplished with pressures from 0.1 to 0.5 % of the maximum allowable working pressure, depending on diameter, volume, liner and composite thickness and material strength. Generally, pressures up to 620 kPa (90 psi) may allow the use of gas as the pressure medium. All federal, state, and facilities safety procedures for safe personnel exposure to pressure vessel must be applied.

9.4.3 *Personnel Protection*—If gaseous nitrogen is used to pressurize the COPV during shearography testing, personnel will be provided a well-ventilated work area with nominal oxygen partial pressure, free from accumulated gaseous nitrogen (GN₂) (or other hazardous gases). In any confined space or inside a vehicle, where examinations may occur, vented gases may accumulate and create a dangerous, life-threatening depletion of oxygen. All federal and facilities safety procedures must be followed. Sensors with alarms measuring oxygen concentrations shall be used in all shearography testing in confined spaces.

9.4.4 *Laser Safety*—Shearography cameras with built-in lasers are classified as laser systems. The emitted laser radiation must meet required state regulations and those outlined in federal standards 21 CFR 1040.10 and 21 CFR 1040.11 for labeling and safety procedures for the given classification. The laser shall emit visible light and at a power density meeting the requirements of Center for Devices and Radiological Health (CDRH) Class IIIa. The use of non-visible laser radiation shall not be permitted. All personnel shall be warned to refrain from staring into the laser light emitted directly from the shear camera. For additional guidance for safe use of laser, consult ANSI Z136.1.

9.4.5 COPV Protection and Foreign Object Debris (FOD):

9.4.5.1 *Damage Prevention*—Protection from damage is a priority for all equipment and hardware handling procedures.

9.3.1.5 Image Processing Computer outputting and full native resolution data to a high resolution monitor of at least 1200(v) × 1900(h) pixels;

9.3.1.6 Manual- or computer-controlled valves and regulator to perform repeatable pressurize of the COPV and safely vent the pressurizing gas or fluid;

9.3.1.7 Computer-controlled thermal stress equipment to provide a repeatable application of radiant heat (within ±0.05

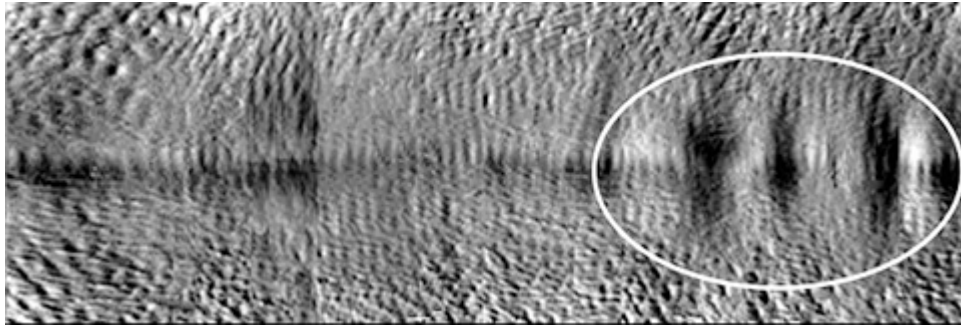


FIG. 8 Metallic Liner Wrinkles (circled) Detected from the Outside Surface of the COPV Without Need for COPV Interior Access

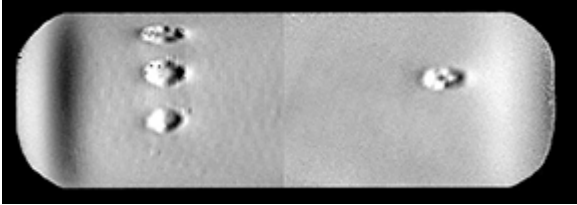


FIG. 9 Pressure Shearogram of a 15 x 45 cm (6 x 18 in.) Carbon Fiber COPV with Barely Visible Impact Damage and Delamination

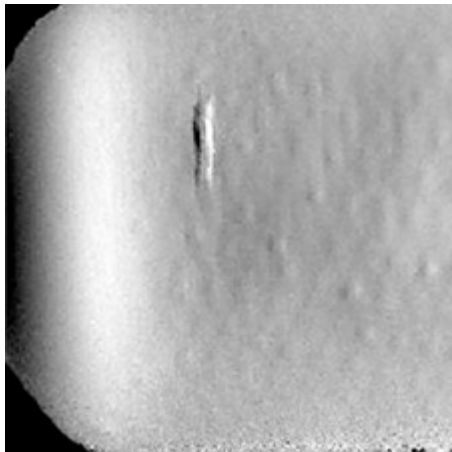


FIG. 10 A Small Crack Due to Impact in a 5 x 45 cm (6 x 18 in.) Carbon Fiber COPV Overwrap

Handling test equipment or support fixtures in close proximity to flight hardware requires diligent care to prevent damage.

9.4.5.2 *FOD*—At all times, procedures must prevent contamination of the COPV, within allowable limits. The use of pure, filtered GN2 may be required for flight hardware. Non-flight hardware may require oil and water separators if standard quality industrial GN2 or shop air is used.

9.5 Calibration and Standardization

9.5.1 *Shearography Image Calibration*—Calibrate the shearography camera image scale (pixels/inch) and the shear vector on the surface of the part to be performed after every change in the camera distance to the COPV surface, camera zoom or shear vector. Recalibration can be automatic or the camera system can reset to the programmed magnification, shear vector, image scale, if the distance to target has remained unchanged.

9.6 Procedure

9.6.1 Follow the camera system OEM Manual for all system set ups and operation.

9.6.2 *COPV Scan Plan*—Develop a scan plan based on the COPV geometry to cover the entire surface to allow the location of indications on the COPV surface. Fig. 12 shows a 15 x 45 cm (6 x 18 in.) COPV, examined in two bands of four 90° sectors. The end domes are examined in quadrants, with sixteen total shearography images.

9.6.3 *COPV Preparation*—The dark color, gloss finish and compound curvature of carbon fiber wrapped COPV can pose challenges to shearography testing. The COPV surface color may absorb rather than reflect the laser light, reducing the signal. The color of the laser light should generally match the color of the surface being examined. Green lasers (532 nm wavelength) usually offer the greatest overall reflection from carbon fiber surfaces while red laser light will be more highly absorbed. The gloss finish produces glare, especially on surfaces with compound curves. Glare and low light reflection for the COPV surface can be substantially overcome by using 12-bit, sensitive shearography cameras. Aiming the camera off the axis normal to the COPV surface and reducing the field of view (FOV) can reduce or eliminates glare and yield good imaging of highly curved compound surfaces, such as the COPV end domes. However, shearography data should be deemed invalid from any area on the COPV where the angle between the camera and a line normal to the surface, in any direction, is greater than 75°.

9.6.3.1 If allowable, a light, even coating of dye penetrant developer produces improved surface characteristics for both thermal and pressure shearography.

9.6.3.2 COPVs can frequently be manufactured with a non-gloss and a brighter, more reflective surface that can substantially improve inspectability, reduce preparation time, and clean up.

9.6.3.3 The COPV shall to be supported in a test fixture (Fig. 13 and Fig. 14) providing mechanical stability and the ability to easily roll the vessel manually or automatically, around the longitudinal axis for full coverage. The fixture cannot allow any noticeable motion or rocking. Use shims to stabilize. A simple alternative for small light weight COPV is a section of metal channel.

9.6.4 Set the camera position and the distance to the COPV in a range within recommended limits defined in the camera manual. Typical camera-to-target distances of 0.9 to 1.2 m (36 to 46 in.) are recommended (Fig. 13).



NOTE 1—The shearography camera is positioned to examine the aft end dome at left. The maximum safe test pressure is a function of volume, diameter and the pressure rating of the vessel. Test pressures are typically between 0.1 and 0.5 % of the maximum allowable working pressure.

FIG. 11 A Large Carbon Fiber Reinforced Propellant Tank with a 4-m (13-ft.) Diameter Tested with a Maximum Pressure Loading of 0.7 kPa (0.1 psi)

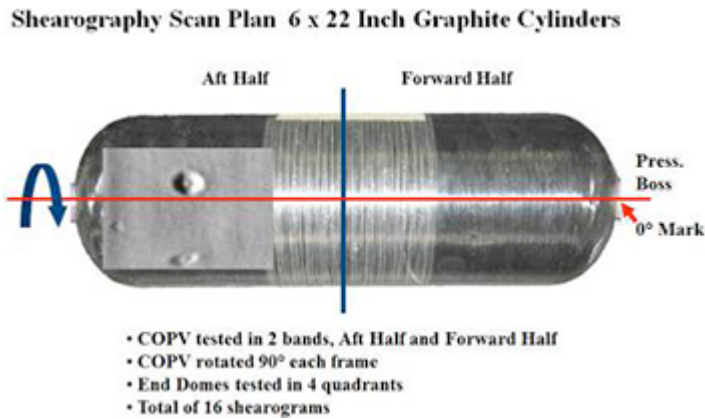


FIG. 12 Scan Plan for a COPV Involving Testing of the End Domes in Four Quadrants



NOTE 1—The camera can be positioned to view “off-normal” to reduce glare from the surface finish.

FIG. 13 Shear Camera Positioned Approximately 0.9 to 1.2 m (36 to 46 in.) from the Target COPV

9.6.5 *Set Field of View (FOV)*—The FOV is determined by target illumination and resolution sufficient to image small anomalies for a given camera pixel count. Set the field of view and angle to the surface for a given area on the COPV to reduce



NOTE 1—The test uses a pneumatic control unit to provide repeatable pressure/vent load cycles to the COPV. The COPV is placed on any stable platform or table.

FIG. 14 Test Set Up for Shearography Inspection of a 15 x 45 cm (6 x 18 in.) COPV

glare to ensure sufficient laser light reflects back to the camera.

Laser light striking the COPV near the top and bottom of the barrel section, as viewed by the shear camera, is more highly scattered away from the camera. Adjust the camera zoom to a FOV that will produce an acceptable image quality at the image edges.

9.6.5.1 The maximum FOV must provide a resolution on the target surface of no less than 100 pixels/cm (40 pixels/in.). For a 6 mm (0.25 in.) void or crack, this provides a minimum of 40/4=10 pixels over the Maximum Allowable Defect Length (MaxADL), exceeding the 10 pixels over the MaxADL recommended resolution (7).

9.6.6 *Shear Vector (Sv) Convention*—By applying the shear vector convention (Fig. 15) consistently, determination of test part out-of-plane deformation direction can be determined. The shear camera software must generate an output for the unwrapped phase map showing positive slope on the left image of the deformation derivative image with known deformation towards the shear camera. Starting with the shear camera adjusted for a 0 in. at 0° shear vector, the sheared image is moved to the right (+X) or up/down, never adjusted in the direction of -X. For a +45° shear vector, the second image is moved in the +X and +Y direction. For 60° shear vector, the second image is adjusted in the +X and -Y directions.

9.6.7 *Focus Camera*—Set the camera focus with the iris as wide open as possible (to reduce the depth of field) and still resolve dark features in the field of view, adjust the focus, then close the iris until the image has no saturated pixels in the image. If the shear camera has auto focus or focus assist features, follow recommended procedures in the OEM Manual.

9.6.8 *Process Control Physical Reference Standard Test*—Select a process control physical reference standard, such as a COPV with known anomalies and surface finish or preparation for system calibration and operation verification. This standard must be examined and images saved as Master Images. Place the standard at the same distance from the shear camera with the same field of view. The standard must be examined at the beginning and end of each shift or test session. If the image does not match all indications seen in the master image, do not conduct the examination. Correct the malfunction issue(s)

before continuing. Save all test images of the process control physical reference standard to the system hard drive with the test data. The process control physical reference standard is again run at the conclusion of the test, or at the end of the work shift, or if the system is shut down during the testing, for any reason.

9.6.9 *Shearography Test Parameters*—The shear vector direction is oriented with respect to the COPV position in the FOV. The following typical shearography test procedures assume the COPV is oriented with the longitudinal axis (the line through the end boss fittings) horizontal, at 0°. Spherical COPV would also be oriented horizontal (equator oriented in a vertical plane).

9.6.9.1 The shearography shear vector and stress procedures change with different defect types and composite thickness. Typical test parameters by defect type are shown in Table 2 and Table 3. For example, composite-to-liner disbonds are much more likely to be detected using thermal stress than pressure shearography. Fiber bridging defects can be detected with both thermal and pressure (Fig. 16 and Fig. 17). Broken fibers are better detected with pressure stress (Fig. 18 and Fig. 19).

9.6.10 *Thermal Shearography*—The induced temperature changes, ΔT, are for the COPV surface. Differences in emissivity over the COPV surface, such as from paint or coatings, will affect the rate of thermal absorption. Typical temperature changes shown are for dark, glossy carbon composite surfaces with a typical emissivity of 0.95 in the 3-5 μm wavelength.

9.6.11 *Pressure Shearography*—The test pressure for COPV or CPV is typically 0.001 to 0.005 times the MAWP of the vessel, never exceeding safe limits and facility rules.

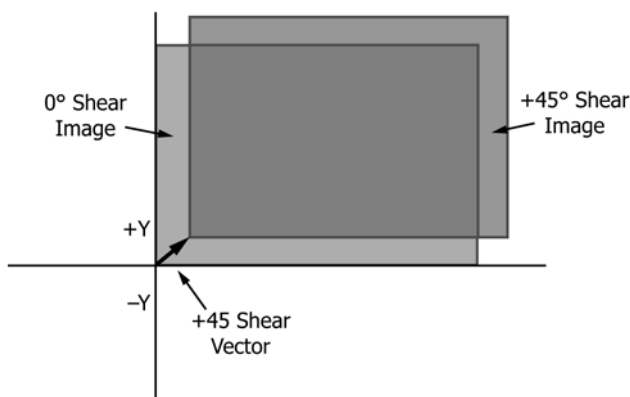
9.6.12 *COPV Pressure Shearography Test Sequence*—With the test set-up complete and the camera adjusted to the recommended Sv setting in given in Table 2, perform the following steps:

9.6.12.1 Click on the “refresh” button with the image shear camera computer.

9.6.12.2 With zero pressure in the COPV, increase the gas pressure to the full test pressure. Close the gas supply valve, verify the test pressure has been reach and press “Freeze/Process.” The wrapped and/or unwrapped image will appear on the monitor. Evaluate the shearogram in both the wrapped and unwrapped images and the real-time phase map observed during pressurization.

9.6.12.3 COPV stressing may result in deformation or movement of COPV or hoses resulting in image decorrelation

Shear Vector Angle Convention



NOTE 1—A shear vector of 6 mm (0.25 in.) with a 45° image displacement is designated as Sv = 6 mm (0.25 in.) at +45°.

FIG. 15 Shear Vector Convention

TABLE 2 Typical Shear Vector and Thermal Stress Procedures by Defect Type for Carbon-epoxy COPVs with Aluminum Liners

Defect Type	Typical Shear Vector	Typical Application Temperature
composite-to-liner disbond	6 mm (0.25 in.) at 0°	ΔT= 8°C (15°F) RBH ^A
fiber bridging	Larger of 6 mm (0.25 in.) at 0°, or 3 times the composite overwrap thickness.	ΔT=5°C (10°F) RAH ^A
porosity, voids, and poor fiber consolidation	(0.12 to 0.25 in.) at 0°	ΔT=5°C (10°F) RAH

^AShearography data acquisition sequence designations: RBH denotes Refresh Before Heating, RAH denotes Refresh After Heating

TABLE 3 Typical Shear Vector and Pressure Stress Procedures by Defect Type for Carbon-epoxy COPVs with Aluminum Liners, 15 cm (6 in.) in Diameter, Designed for 50 MPa (7200 psi) MAWP

Defect Type	Recommended Shear Vector	Typical Pressure Differential
impact damage	3 to 6 mm (0.125 to 0.25 in.) at 0°	Δ 70 to 175 kPad (10 to 25 psid)
cracks	3 mm (0.125 in.) at 0°, +45°, -45°	Δ 35 to 105 kPad (5 to 15 psid)
broken fiber	3 to 6 mm (0.125 to 0.25 in.) at 90°	Δ 70 kPad (10 psid)
liner wrinkles	Cylinder: 13 mm (0.5 in.) at 0° Sphere: 13 mm (0.5 in.) at 90°	Δ 175 to 350 kPad (25 to 50 psid)
fiber bridging	6 mm (0.25 in.) at 0°	Δ 175 kPad (25 psid)

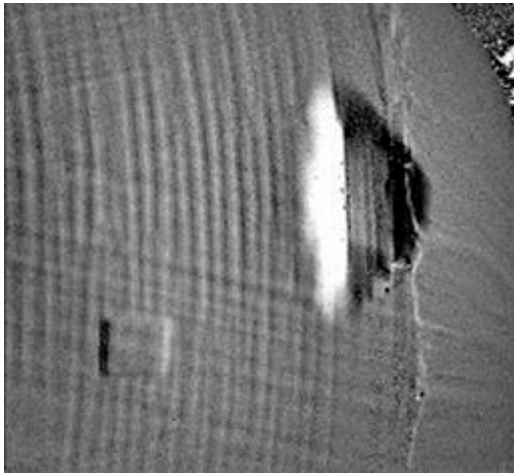


FIG. 16 Thermal Shearogram of a 15 x 45 cm (6 x 18 in.) Carbon-epoxy COPV Showing a 45 mm (1.8 in.) (circumferential length) Fiber Bridge Defect and a 13 mm (0.5 in.) (edge length) Square Polytetrafluoroethylene Insert Between the Liner and the Composite Wrap (no visible indication of these defects can be detected)

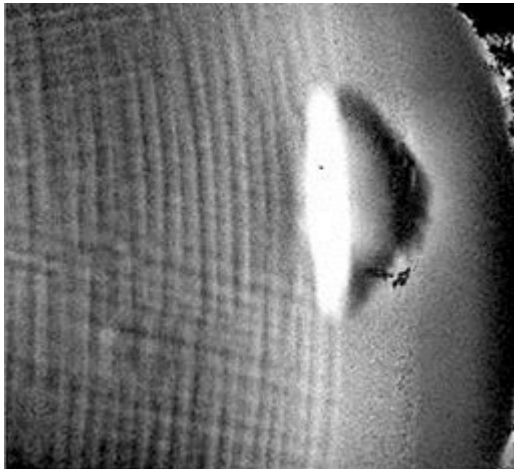


FIG. 17 Pressure Shearogram of the Same Area as in Fig. 16 showing the 45 mm (1.8 in.) (circumferential length) Fiber Bridge Defect. The square 13 mm (0.5 in.) (edge length) polytetrafluoroethylene insert is seen only very faintly with pressure stress loads.

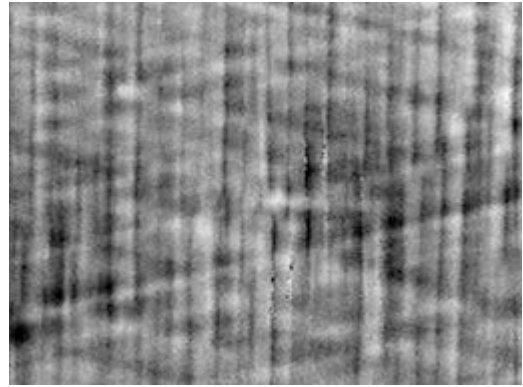


FIG. 18 Thermal Shearogram of a 15 x 45 cm (6 x 18 in.) Carbon-epoxy COPV Showing a Weak Indication of a Cut Fiber

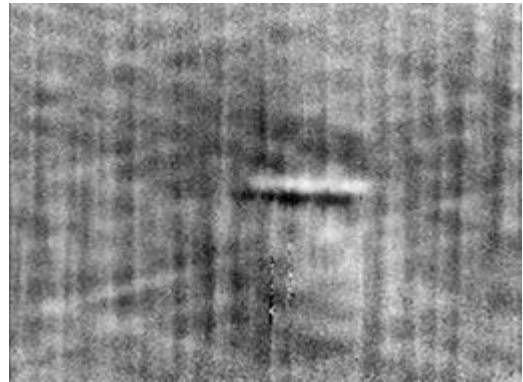


FIG. 19 Pressure Shearogram of the Same Area as in Fig. 18 Showing the Cut Fiber Clearly Using the Same Shear Vector, (S_v) = 3 mm (0.12 in.) at 90°

improve the COPV mechanical stability. The final image must be of sufficient quality to allow detection of indications 50 % of the rejection size limit

9.6.12.4 Save the image to the hard drive along with position data based on the scan plan.

9.6.12.5 Use the video caliper or image overlay box and size any defect indication(s). Measure each defect indication's major and minor axis, location from an identifiable feature and angle. For each defect, note in the sequential defect number, location position, number in a cluster and size.

9.6.12.6 Rotate the COPV to the next area and repeat the test.

9.6.12.7 Move the camera to examine the end domes as required in the scan plan.

9.6.12.8 Perform visual testing of shearography indication sites for any anomalies.

9.6.13 *COPV Thermal Shearography Test Sequence*—Perform the same test sequence as in subsection 9.6.12, substituting for subsection 9.6.12.2, thermally stress the vessel using the stress application and S_v settings shown in Table 2.

9.6.14 *Image Overlap*—Index the camera to provide at least 15 % overlap with adjacent test images. Repeat the test described in subsection 9.6.12 (Pressure Shearography) or 9.6.13 (Thermal Shearography) until all areas of the test surface are covered.

to the point that no meaningful data can be obtained. If image decorrelation occurs below the test pressure, stop the test and

9.6.15 *Geometric Correction of Indication Dimensions*— Except for indications located in the center of the FOV and in a plane normal to the shearography camera, anomalies will be seen at angles up to 75°, distorting measurements. The indication measurement L can be corrected (to first approximation) for geometric distortion by measuring the angle α between a line, N , normal to the measurement L and a line from the center to the center of the indication to the shearography camera (Fig. 20). L_c , the corrected measurement length is then given by: $L_c = L/\sin(\alpha)$.

9.6.16 Scans of COPV shall ensure complete and overlapping circumferential and longitudinal coverage of required test areas. Overlapping each image at each edge of at least 10 percent minimum is recommended. Indication location shall be determined using the shearography Indication Mapping Tool.

9.7 *Significance of Data*

9.7.1 *Fiber Bridging*—Fiber bridging (Fig. 21) is caused by improper weld finishing, misalignment of welded liner components, or improper fiber tension during winding. There is usually no visible indication. Both thermal and pressure shearography techniques can detect and size fiber bridging, which represents an extremely dangerous condition that can lead to liner cracks, low cycle fatigue failure, leaks, or even a low burst pressure. The test set up is simple and the results are immediate.

9.7.2 *Other Defects*—Shearography has also been proven to detect other latent manufacturing anomalies in COPVs including impact damage, cracks, broken fibers, poor fiber consolidation, porosity, disbonds between the liner and the composite overwrap, and liner wrinkles or buckles without need to inspect the inside surface of the vessel.

9.8 *Specific Reporting Requirements*

9.8.1 In addition to the general reporting requirements listed in Section 5.9, the following minimum information shall be recorded to ensure the reproducibility and repeatability of the data acquired on the vessel under test:

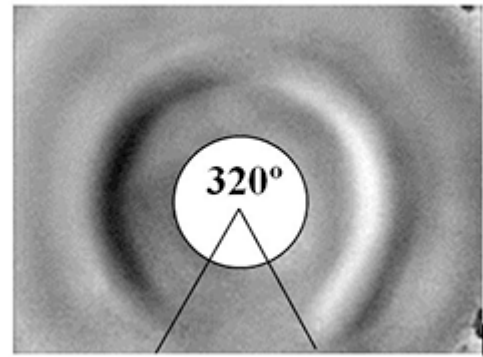


FIG. 21 Fiber Bridging at a Poorly Finished Weld is Seen in this Helium Pressurization COPV (top view), Extending Approximately 320° Around the Axis of the COPV (a boss fitting is located in the center (circle))

- 9.8.1.1 Shearography test procedure, shear vector, distance from camera to COPV,
- 9.8.1.2 Pressure shearography parameters,
- 9.8.1.3 Thermal shearography parameters,
- 9.8.1.4 Table of all shearography indications, size, location on COPV surface,
- 9.8.1.5 Optional map of COPV showing defect locations, and
- 9.8.1.6 Corroborating visual testing results (see Section 13).

10. Radiologic Testing

10.1 *Scope*

10.1.1 Radiologic testing is performed as double wall inspection with single image or double image viewing.

10.1.2 The procedures described provide uniform procedures for radiologic examination for internal damage using industrial radiographic film, computed radiography (CR) or digital detector array (DDA) or radioscopy based X-ray detection technology. Requirements expressed in these procedures

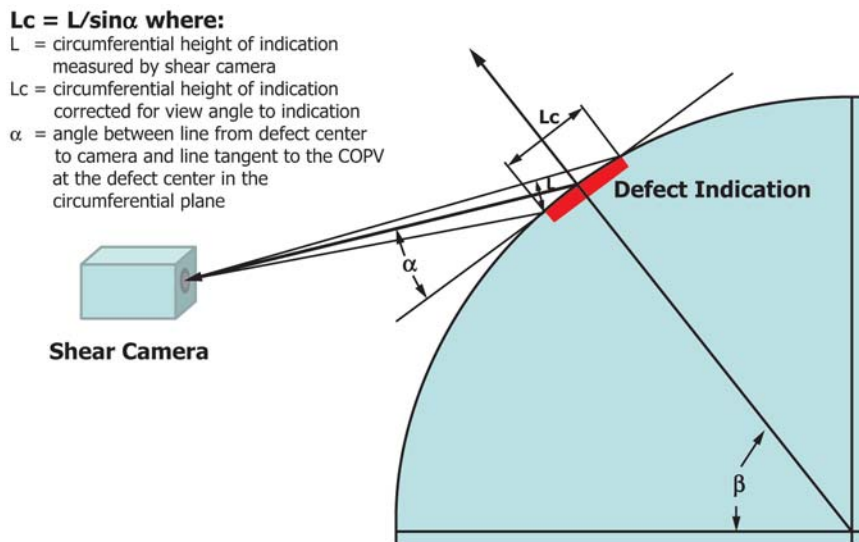


FIG. 20 Correction of measured indication circumferential dimensions located away from the COPV centerline, $L_c = L/\sin(\alpha)$

are intended to control the quality of the radiographic film or digital radiographic images and are not intended for controlling acceptability or quality of the components.

10.2 Summary of Procedure

10.2.1 The radiologic extent, the quality level, and the acceptance criteria to be applied shall be specified in the contract, purchase order, product specification, or drawings.

10.2.2 The radiologic techniques stated herein provide adequate assurance for defect detectability; however, it is recognized that, for special applications, specific techniques using more or less stringent requirements may be required than those specified. In these cases, the use of alternative radiologic techniques shall be as agreed upon between purchaser and supplier.

10.2.3 Radiographic examination with film shall be in accordance with Practice **E2104** or NASA fracture control and NASA NDT engineering-approved contractor internal specifications with the following additional requirements:

10.2.3.1 The minimum radiographic examination sensitivity level shall be 2-1T;

10.2.3.2 Film density shall be 2.5 to 4.0;

10.2.4 Digital radiography or radioscopy may be performed per the requirements of Practices **E2104**, **E2033**, **E2662**, or **E2698** (digital detector arrays), or Test Method **E1416** (radioscopy) as agreed upon between the supplier and contractor (or NDT agency); and

10.2.5 Any additional deviations from these specifications shall be agreed upon between the supplier and contractor (or NDT agency).

10.2.6 Other accepted guidance and practice for radiography of polymer matrix composites can be found in Guide **E2533** and Practice **E2662**.

10.3 Procedures

10.3.1 *Procedure Requirement*—Unless otherwise specified by the applicable job order or contract, radiographic examination or radioscopy shall be performed in accordance with a written procedure. Specific requirements regarding the preparation and approval of the written procedures shall be dictated by purchaser and supplier agreement. The production procedure shall address all applicable portions of this document and shall be available for review during interpretation of the radiographic or radioscopy images.

10.3.2 *Radiograph Identification*—A system of positive identification of the film shall be provided for production applications. As a minimum, the following shall appear on the radiograph: the name or symbol of the company performing radiography, the date, and the component identification number traceable to part and contract. Subsequent radiographs shall utilize a similar identification method such that regions can be accurately mapped. No lead numbers or letters are required for digital images as this information shall be stored in the name of the image or in image tags.

10.3.3 *Radiographic Location and Identification Markers*—Lead numbers and letters, if required, should be used to designate the part number and location number, appearing as radiographic images. The size and thickness of the markers shall depend on the ability of the radiographic technique to discern the markers on the radiographic image.

10.3.4 *Radiographic Density Measurement*—Radiographic density on film shall be consistent for discerning the area of interest based upon engineering evaluation criteria.

10.3.5 *Radiographic Film Quality*—All radiographs shall be free of mechanical, chemical, handling-related, persistent images, or other blemishes which could mask or be confused with the image of any other anomalous condition in the area of interest on the radiograph. If any doubt exists as to the true nature of an indication exhibited by the film, the radiograph shall be rejected and the view retaken. Used film systems should be T2 or better in accordance with Practice **E1815**.

10.3.6 *Radiographic Quality Level*—Radiographic quality level shall be determined upon agreement between the purchaser and supplier and shall be specified in the applicable job order or contract.

10.3.7 *Radiographic Density Limitations*—The density through the body of the area of interest shall be sufficient to determine the areas of interest (for example, buckling, weld defects, and damage within the component).

10.3.8 *Radiation Source*—Selection of the appropriate source is dependent upon variables regarding the COPV or weld being examined, such as material composition(s) and thickness(es).

10.3.9 *Specific Reporting Requirements*—The radiological technique should include the following items as a minimum:

- 10.3.9.1 Program,
- 10.3.9.2 Part name,
- 10.3.9.3 Part number,
- 10.3.9.4 Serial number,
- 10.3.9.5 Date,
- 10.3.9.6 Brief description of the type of examination,
- 10.3.9.7 Test description,
- 10.3.9.8 Set-up requirements,
- 10.3.9.9 Radiology kV setting,
- 10.3.9.10 Radiology mA setting,
- 10.3.9.11 Radiation source to COPV or liner (object) distance (SOD),
- 10.3.9.12 Focal spot size,
- 10.3.9.13 Exposure time (film, CR), frame time, and frame number for DDAs,
- 10.3.9.14 Radiation source-to-recording-detector (film, imaging plate, or DDA) distance (SDD) and magnification,
- 10.3.9.15 Identification markers on the COPV or liner,
- 10.3.9.16 Type, size, basic spatial resolution, and fidelity of recording medium for digital radiographic images,
- 10.3.9.17 Speed of COPV or liner rotation for real time radiological viewing applications,
- 10.3.9.18 Number of images necessary for required coverage when using film radiology,
- 10.3.9.19 Imaging and data acquisition software; critical settings and type of CR scanner; and type of imaging plate, DDA, or image intensifier,
- 10.3.9.20 Image processing parameters if applied (for example, digital filters),
- 10.3.9.21 Applicable specifications, and
- 10.3.9.22 Name of individual preparing technique and approval signature as required.

10.4 Significance of Data

10.4.1 *Acceptance Level*—Accept and reject levels shall be stipulated by the applicable contract, job order, drawing, or other purchaser and supplier agreement. In the case of liner buckling, the acceptance level will define the type of buckling permissible in specific locations such as the domes, barrel sections, welded regions and inlet/outlet ports to the COPV. In the case of weld discontinuities, the acceptance level will define the type and amount of weld fusion permissible across the entire circumference and volume of the weld.

10.5 *Reporting and Records*

10.5.1 The following radiographic or radioscopy records shall be maintained as agreed upon between purchaser and supplier and include the radiographic technique and component identification records. Film or digital image interpretation records shall contain as a minimum the following information:

10.5.1.1 Disposition of each radiograph or digital image (acceptable or rejectable);

10.5.1.2 *Storage of Radiographs*—When storage is required by the applicable job order or contract, the radiographs should be stored in an area with sufficient environmental control to preclude image deterioration or other damage. The radiograph storage duration and location shall be as agreed upon between purchaser and supplier. In case of digital examination a digital image (or video for real time examination) will be stored.

10.5.1.3 *Storage of Digital Images*—Storage of digital images shall be agreed upon between the supplier and contractor (or NDT agency) and shall be provided in a recognized format. These images will become part of the permanent record as determined by the engineering function.

11. Thermographic Testing

11.1 *Scope*

11.1.1 This section describes a procedure for detecting near surface, subsurface, or liner-to-overwrap flaws in COPVs using TT. The process consists of injecting a hot or cooled gas or liquid into the COPV while the external surface of the COPV is monitored using a thermographic camera to detect thermal variations. Alternatively, the COPV can be tested in a reflection configuration with external heating using flash lamps or other heat sources, allowing detection of defects (for example, impacts) which have been introduced from outside.

11.1.2 This section describes TT procedures that are currently used by industry and have demonstrated utility in quality assurance of the liner-to-composite structures during post manufacturing and in-service examinations.

11.1.3 This practice applies to polymer or ceramic matrix composite structures with inspection surfaces that are sufficiently optically opaque to absorb incident light, and that have sufficient emissivity to allow monitoring of the surface temperature with an IR camera. Excessively thick samples and sections or samples with low thermal diffusivities require long acquisition periods and yielding weak signals that approach background or noise levels, or both, and therefore may be impractical for this technique.

11.1.4 This practice applies to detection of flaws in a composite structure at the bonded interfaces between the external surface of the overwrap and internal liner.

11.1.5 This practice does not specify accept-reject criteria and is not intended to be used as a basis for approving composite overwrap pressure vessels for service.

11.2 *Summary of Practice*

11.2.1 During COPV TT, a gas such as nitrogen or suitable liquid is injected into the vessel while the external surface of the component is monitored using an IR camera. Alternatively, the COPV can be heated using external flash lamps or other heat sources. The surface temperature typically varies dependent upon the thermal conductivity properties of the liner and composite overwrap. Internal thermal discontinuities such as voids, delaminations, liner-to-overwrap disbonds, etc., change the localized heating or cooling rates at the surface and are correlated to internal variations within the COPV.

11.2.2 Fundamental detectability of a flaw will depend on its size and the degree to which its thermal properties differ from the surrounding materials. For a given flaw-host combination detectability is a function of the aspect ratio of the flaw. The minimum detectable flaw size increases with thinner materials and detectability is highest for larger flaws that have thermal properties significantly different from the surrounding materials.

11.2.3 Operational parameters affecting detectability include component surface emissivity and optical reflectivity, data acquisition period and camera wavelength, frame rate, sensitivity, optics, and spatial resolution.

11.2.4 This section describes a through-transmission examination, in which the gas or fluid injected into the COPV (excitation source) and IR camera (temperature sensor) are located on opposite sides of the component or material under examination.

11.2.5 In common practice, signal processing algorithms or numerical analysis techniques can be used to enhance detectability of flaws that are not detectable in the raw IR camera signal image and to assist in evaluation and characterization of indications.

11.2.6 Other accepted guidance and practice for thermography of polymer matrix composites can be found in Guide [E2533](#) and Practice [E2582](#).

11.3 *Significance and Use*

11.3.1 TT is typically used to identify flaws that occur either in the manufacture of composite overwrap pressure vessels or to track flaw development during service. Flaws detected with TT include liner-to-overwrap disbonds, delaminations, voids, impact damage or the presence of other discontinuities that interrupt the heat transfer path from the inner diameter to the outer diameter of the COPV.

11.3.2 Since through-transmission TT is based on the diffusion of thermal energy from the inner surface of the COPV to the outer surface, the practice requires that data acquisition allows sufficient soak time for this process to occur and that at the completion of the acquisition process, the radiated surface temperature signal collected by the IR camera is strong enough to be distinguished from spurious IR contributions from background sources or system noise.

11.3.3 This method is based on accurate detection of changes in the emitted IR energy emanating from the inspection surface during the heating or cooling process. As the

emissivity of the inspection surface deviates from ideal black-body behavior (emissivity = 1) the signal detected by the IR camera may include components that are reflected from the inspection surface. Most composite materials can be examined without special surface preparation; however, it may be necessary to coat low emissivity, optically translucent inspection surfaces with an optically opaque, high-emissivity water-washable paint or a similar material.

11.3.4 This practice is based on the thermal response of a specimen to a heat source that is uniformly distributed inside of the COPV.

11.3.5 This practice applies to COPV and is intended to be used for monitoring COPV barrel sections, domes, and bulkhead sections where the local surface normal is less than 30 degrees from the IR camera optical axis. Barrel sections and domes are typically inspected in quadrants using this technique.

11.4 *Equipment and Materials*

11.4.1 *IR Camera*—The camera should be capable of uninterrupted monitoring of the sample surface for the entire duration of the acquisition. Cameras with automatic internal shuttering mechanisms should allow the shuttering to be disabled during the data acquisition period. The camera should provide real-time digital output of the acquired signal. The camera output signal should be approximately linear over the temperature range of the sample during the soak period. The camera wavelength should be in either the 2-5 micron range or the 8-14 micron range, selected such that the test material is not IR translucent in the spectral range of the camera. The optics and focal plane should be sufficient so that the projection of nine contiguous pixels onto the sample plane is less than or equal to the minimum flaw area that is to be detected.

11.4.2 *Injection Medium*—The injection medium can be comprised of either gas or liquid. The medium is heated or cooled to a temperature either well above or below the median surface temperature of the COPV and is then rapidly injected, during which time the external thermal image is captured. A reference standard with known defects is typically used to develop the injection technique and to establish the temperature of the medium.

11.4.3 *Injection Dispersion Device*—The injection dispersion device is a device that is used to uniformly disperse the medium inside the COPV such that thermal hot or cold spots are not created on the interior wall.

11.4.4 *Acquisition System*—The acquisition system includes the IR camera and a dedicated computer that is interfaced with the camera. The system should allow data to be acquired before, during and after the medium's injection into the COPV.

11.4.5 *Analysis Software*—The computer software should allow acquired sequences to be archived and retrieved for subsequent evaluation. The software should allow viewing of the temperature or time, or both, during the acquisition period along with a real time display of the data. Additional processing operations (for example, averaging, image subtraction, noise-reduction, numerical analysis, etc.) may be performed to improve detection capability.

11.5 *Physical Reference Standards*

11.5.1 *Detectability Standard*—A reference standard with known thermal discontinuities is used to establish operating parameters of the apparatus and limits of detectability for a particular application and to periodically verify proper performance of the apparatus.

11.5.2 Known discontinuities may be actual flaws or artificial features that simulate the thermo-physical behavior of typical flaws that are known to occur in the area of interest.

11.5.3 A series of flaw sizes should be included in the reference standard. The known flaws should represent the range of aspect ratios for anticipated flaws and should include the minimum required detectable flaw size for a given application as determined by the cognizant engineering organization.

11.5.4 If the minimum detectable flaw size requirement is not known, the reference standard should include a group of known flaws of a given type spanning the range of aspect ratios from 0.5 to 10.

11.5.5 If different types of known flaws are to be used, a representative sample of each type should be included.

11.5.6 Known flaws should be arranged so that edge-to-edge separation of adjacent flaws is at least one diameter of the larger neighboring flaw.

11.5.7 Known flaws should be arranged so that the edges of each flaw are at least one diameter from the edge of the test sample.

11.5.8 If a test standard containing actual or simulated flaws is not available one may be constructed using defects implanted into the structure. Defects such as pull-out tabs, polytetrafluoroethylene (PTFE) inserts or release agent may be used to simulate defects in the COPV.

11.6 *Calibration and Standardization of Apparatus*

11.6.1 *Calibration*—The IR camera should be calibrated and maintained at regular intervals following the procedure recommended by the manufacturer. Non-uniformity or flat field correction should be performed according to the manufacturer's instructions or more frequently if required to achieve optimum camera performance.

NOTE 21—A temperature calibration is required for reproducible and repeatable detection of flaws having a known size and depth; however, is not as critical for routine screening inspections.

11.6.2 Measure the dimensions of a single pixel field of view at the sample plane by placing an object with known dimensions in the field of view at the sample plane and determining the number of pixels that span the object in either the horizontal or vertical direction.

11.6.3 *Standardization*—Operating parameters for the through transmission TT will vary with the thickness, surface characteristics, and composition of the component under test as well as the geometry and thermo-physical characteristics of a rejectable flaw as determined by the cognizant engineering organization. Standardization should be performed prior to examination of a component or material on a detectability reference standard (See Section 11.5) that is representative of the structure to be examined to establish appropriate operating parameters.

11.6.3.1 Acquire data for the reference standard using the normal through transmission TT procedure.

11.6.4 The sample surface may be coated with a water-washable black paint to increase the optical absorption and emissivity of the sample.

11.6.5 The sample may be IR translucent in the spectral range of the camera and a camera that operates in a different spectral range may be required.

11.6.6 The sample may be too thin or heat transfer through the sample may be too fast to be detected at the IR camera frame rate and an IR camera capable of operation at a higher frame rate may be required.

11.6.6.1 The frame rate of the IR camera shall be specified in the test request when lower or higher frame rates are needed.

11.7 Procedure

11.7.1 Position the apparatus so that the inspection surface is in the field of view of the IR camera. The sample should be mounted to minimize thermal conduction to the mounting apparatus.

11.7.2 Focus the IR camera by placing a thermally reflective object (for example, foil marker or tape) on the sample surface and adjusting the camera lens until the edges of the object appear distinctly.

11.7.3 The inspection surface should be clean and free of dirt or grease. Obvious visual indications or features should be noted.

11.7.4 Begin data acquisition and recording with the IR camera.

11.7.4.1 The data sequence should contain at least one frame acquired prior to injection of the medium (gas or liquid) into the COPV. During procedure development, the optimal soak time should be determined to maximize image contrast.

11.7.5 Inject the medium into the COPV.

11.7.6 Terminate the IR camera data acquisition after an image sequence of appropriate duration has been acquired. See inspection flow diagram in Fig. 22. Repeat for each quadrant or field of view to ensure coverage of area of interest.

11.8 Interpretation of Results

11.8.1 The raw captured data sequence may be viewed as a sequence of images so that the entire volume of interest of the test material is interrogated.

11.8.2 Analysis—Analysis of the raw captured sequence is based on visual examination of the contrast between flaw indications and intact areas in the field of view. Discrete flaws that are smaller than the inspection field of view but larger than the minimum detectable flaw size may be detected using this technique.

11.8.2.1 Subsurface flaws that obstruct the flow of heat (for example, disbonds, voids, or delaminations) will appear cooler than nearby intact areas. Conversely, flaws that act as heat sinks (for example, water or metal inclusions) will appear warmer than surrounding intact areas. The temperature of the gas or liquid used to fill the COPV will also affect whether flaws appear cooler or warmer than surrounding areas.

11.8.2.2 Software Analysis—Contrast or numerical analysis may be used to identify flaws.

11.8.2.3 Contrast Analysis—Discrete flaws will appear during the sequence and typically have different amplitudes than flaw-free regions in the field of view.

11.8.3 Post-Processing Analysis—The acquired frames of the data set may be processed using mathematical techniques that maximize the contrast between adjacent regions.

11.8.4 Flaw Sizing—The lateral dimensions of a discrete flaw may be determined by measuring the raw or post-analyzed full-width at half maximum amplitude, along a line segment that bisects the flaw (or traces the major and minor axes of an equivalent rectangle). The pixel field of view size may be used to convert the defect dimensions measured in pixels to appropriate physical units.

11.8.5 The location, size, and nature of indications detected in either the raw or derivative data sequences should be recorded.

11.8.6 In the event that an indication is detected, the inspection surface should be visually examined to determine whether the indication is superficial, for example, due to dirt or markings on the surface.

11.9 Safety Precautions

11.9.1 TT involves the use of heated or electrically energized equipment.

NOTE 22—In cases where the COPV is filled with hot or cool gas or liquid, other heating or cooling equipment is used with different inherent precautions.

11.9.2 Injection of a medium such as gas or fluid may not be permitted in some situations.

11.9.3 High or low temperature materials that are injected into the COPV may be hazardous to the operator.

11.10 Specific Reporting Requirements

11.10.1 To ensure test validity including reproducibility and repeatability, essential information about the test method shall be recorded, including specimen geometry, condition and preparation, test equipment, optics, camera frame rate and integration period, soak times, working distance between apparatus and specimen, and data processing methods.

12. Ultrasonic Testing

12.1 Scope

12.1.1 This section provides ultrasonic techniques entering from the outside diameter of the overwrap for the evaluation of

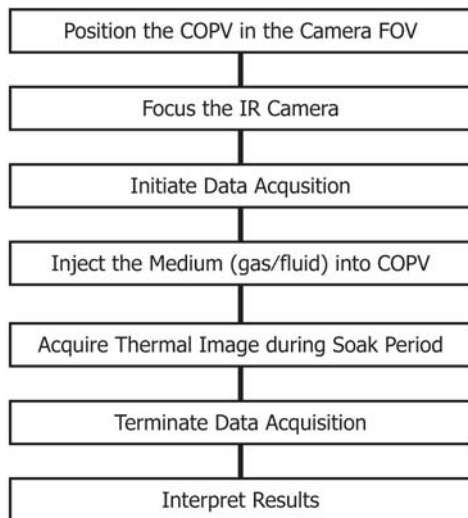


FIG. 22 COPV Thermography Data Acquisition Procedure

composite materials found on COPVs. This also includes the verification of the overwrap to liner bond.

12.1.2 The more frequently used Ultrasonic Testing (UT) technique is pulse-echo testing (non-contacting or contacting). Through transmission testing, requiring access to both sides of the vessel is generally not feasible. Angle-beam techniques using shear waves have generally not been applicable, and surface-angle beam techniques using Lamb waves are not discussed.

NOTE 23—Shear wave testing in anisotropic composite overwrap is difficult, with highly variable results, and therefore is not recommended.

12.1.3 For procedures that detect discontinuities in the metallic liner of COPVs, for example, fractures, inclusions, weld anomalies (incomplete or excessive penetration, cracks in the weld fusion zone, incomplete fusion, burn through), porosity (isolated, clustered, aligned), undercut, laminations, and thickness variations, consult Guide E2982.

12.2 Summary of Procedures

12.2.1 Ultrasonic testing involves introducing controlled ultrasonic energy into the vessel under test, and observing how the passage of sound is affected in transit. Any discontinuity can reflect, disperse, or attenuate the amount of reflected energy in a pulse-echo configuration. The ultrasonic energy for testing is generated in a short burst or a pulse by piezoelectric transducers driven by appropriate electronic circuitry. Test frequencies used for composites are usually between 0.5 to 20 MHz. Since air is not very efficient at propagating this ultrasonic energy at higher frequencies, a liquid such as water or oil is often used as a couplant between the transducer and the article under test.

12.2.2 Non-contact, contact, and immersion testing are commonly used in ultrasonic testing of COPVs and CPVs. Regardless of the technique chosen, the vessel under test should be cleaned to remove loose particles or debris prior to testing.

12.2.3 For a discussion of the advantages and applications, and limitations and interferences of pulse-echo (contact and non-contact) and immersion testing, consult Section 14.3.5 in Guide E2533.

12.2.4 Detailed Ultrasonic C-scans (Fig. 23) are possible with the automated digital ultrasonic scan systems. Interpretation of these scans is the responsibility of the vessel manufacturer. The vessel manufacturer must establish engineering acceptance requirements and the ultrasonic data interpretation procedures. Ultrasonic C-scan interpretation is usually accomplished by comparison of the scans or responses from physical reference standards used during system calibration to the scans or responses from the ultrasonic test of the actual part.

12.2.5 The surface texture of the composite overwrap generally precludes efficient contact scanning of the outside diameter of vessels once fabrication is complete. When this is evident, non-contacting techniques such as laser ultrasound or squirter may be applicable.

12.2.6 Other accepted guidance and practice for ultrasonic testing of polymer matrix composites can be found in Guide E2533 and Practice E2580.

12.2.7 Guided Wave—Laser UT guided waves in composite laminate media are complex and the propagation of the stress waves is governed by mechanical interface boundary conditions and the overall geometry/dimensions of the structure. Sensing of the guided wave modes requires careful selection of the transducers, test configurations, and appropriate transducer response to the guided waves. The laser ultrasonic guided (LUG) wave test configuration (Fig. 24) enables direct sensing of composite damage and modulus changes in the composite overwrap. Because of the laser source time and spatial reproducibility (short laser impulse of less than 10 ns), it is possible to accurately measure the ultrasonic signal propagation time. This feature entails high fidelity measurements of ultrasonic velocity that is a direct indicator of material mechanical modulus. In its simplest isotropic form, velocity (V) is related to modulus (E) and density (ρ) by relation:

$$V = (E / \rho)^{1/2} \tag{1}$$

Guided wave signal changes, including velocity and velocity amplitude, can be used to assess composite damage of the COPV.

12.3 Significance and Use

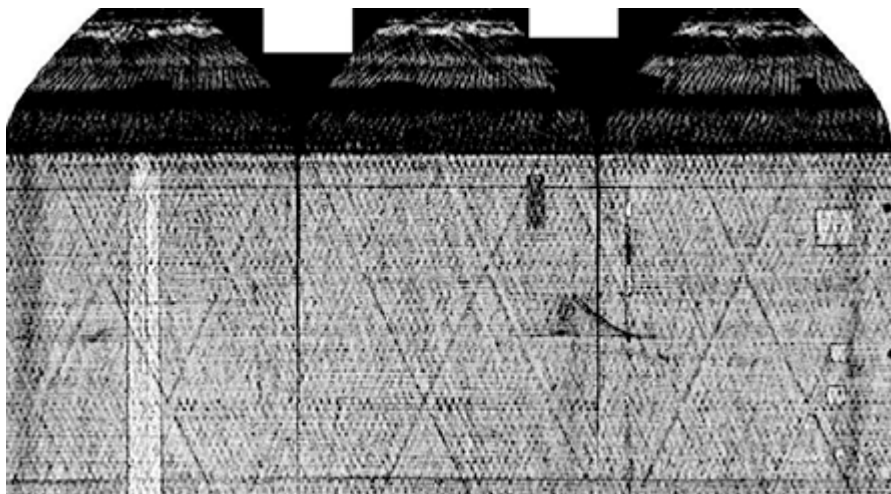


FIG. 23 C-scan Image of the Helical Layer of a COPV Composite Overwrap

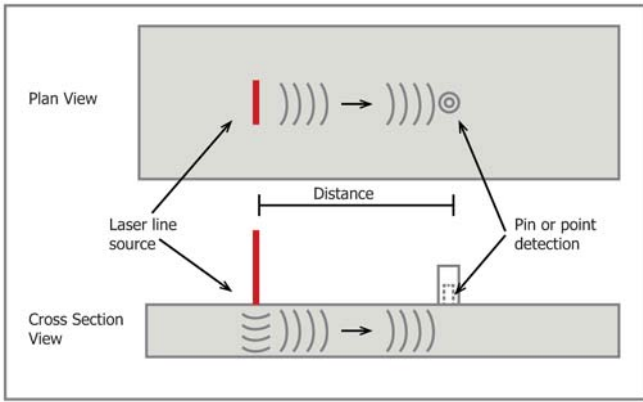


FIG. 24 Test Configuration for the Laser UT Guided Wave Measurements of In-plane Velocity Directly Related to Composite Modulus and Composite Damage

12.3.1 UT can detect and size sub-surface imperfections or discontinuities either revealed by surface disruptions seen visually. Discontinuities that have been source located by AE may also be verified and sized using ultrasonic.

12.3.2 In-process ultrasonic testing of vessels can be for the detection of foreign materials, inclusions, delaminations, wrap misalignment, voids, porosity, and proof/autofrettage cycle induced separation of the overwrap from the liner (disbond/un-bond). Automatic recording systems allow vessels to be removed from a processing line when defect severity exceeds established limits.

12.3.3 In-service ultrasonic testing of vessels can be for the detection of damage such as delaminations, fiber fracturing, and impact-induced separation of the overwrap from the liner (disbond/un-bond).

12.3.4 Measurement of ultrasonic attenuation in composite materials is useful in applications such as comparison of fiber loading in different lots, or the assessment of environmental degradation.

12.3.5 Ultrasonic wave transmission requires a relatively flat and smooth surface for acoustic coupling. Material type can also affect inspectability. The surface texture of the composite overwrap generally precludes efficient contact scanning of vessels.

12.3.6 Composite overwrap materials tend to be relatively inhomogeneous, anisotropic, and attenuative in comparison to the metal alloys used for liners. Thus, attenuation can be an issue when testing composite overwraps with thicknesses at the upper end of range of interest (20 mm (0.80 in.)). As attenuation increases, frequency may need to be lower to allow penetration. However, low frequency will result in reduced inspection sensitivity, i.e. larger “minimum detectable” flaw sizes.

12.3.7 On larger vessels and tanks, a phased array probe coupled with low frequency and increased gain can improve material penetration for a given frequency, increase scanning speed, and assist in orienting the beam orthogonal to the reflecting surface. It also allows for surface imaging B-scans and C-scans in both automated and manual scanning configurations. However, due to the directional properties of the composite overwrap, phased array transducer focusing is not a reproducible method for overwrap testing unless precise alignment of the transducer with respect to the primary ply directions is maintained.

12.3.8 Acoustic couplants are normally required to couple the ultrasonic energy to the test surface (notable exceptions are air-scanning and laser UT – see subsections 12.2.7 and 12.3.9). The couplant will vary depending on the ultrasonic technique used. Ultrasonic testing of as-manufactured vessels can be done in an immersion water bath (Fig. 25) or using water-jet coupling scan methods (Fig. 26). In both these systems water is used as the acoustic couplant. Ultrasonic testing can be done using water or a more viscous couplant to allow for manual movements of the search probe. Ensure any proposed couplants are approved for application on the vessel surface prior to use. In the water bath method, the water must be degassed to eliminate bubbles in bath or on part surface. When water

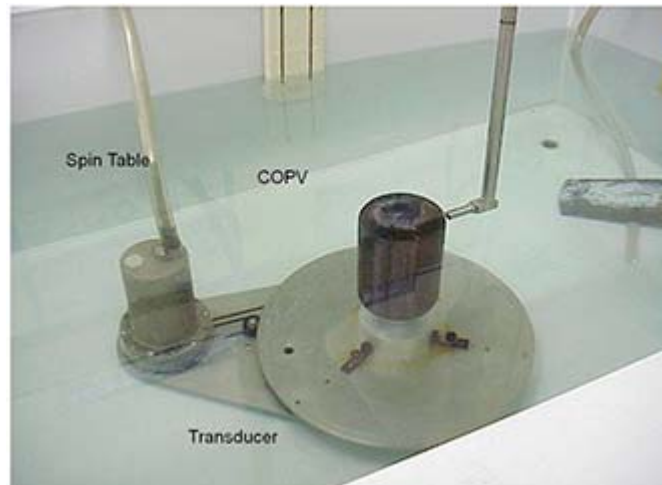


FIG. 25 Full Surface Ultrasonic “C-Scan” (NASA)



FIG. 26 Carbon-epoxy COPV in UT C-scan Pulse Echo Test Configuration using Water-jet Probes

baths and squirters are used, care must be exercised to avoid undue moisture or water ingress.

NOTE 24—During manufacturing, if a vessel is subsequently processed in an autoclave after exposure to water, high pressure steam could be released in a near-explosive event.

12.3.9 Emerging non-contact ultrasonic techniques including air coupled and laser acoustic ultrasonic are also available when contact and exposure to couplants must be avoided.

12.3.10 During ultrasonic testing of metal-lined COPVs, the effect of water on the liner must be considered. For example, metallic liner materials are generally considered corrosion-resistant alloys; however, they are often susceptible to a particularly insidious form of environmental degradation known as stress corrosion cracking. Classic examples include sensitized microstructures in austenitic stainless steels exposed to dilute aqueous chlorides, nickel alloys, sulfur compounds, titanium alloys, halogens, and light alcohols. Commercially available liquid couplants are manufactured with stringent quality controls to ensure the desired chemical purity. The effect of biocides or corrosion inhibitors that may be added to an immersion tank must also be considered.

12.3.11 Consult MIL-HDBK-787 for discussions on ultrasonic determination of fiber orientation, void content, delaminations, strength-related properties (for example, ultimate strength) using a stress wave factor, fatigue damage, impact damage, and elastic constants within a stiffness matrix.

12.3.12 *Guided Wave*—Laser UT guided wave technology can perform detailed ultrasonic examinations of the COPV composite material layers (8-11). The laser-generated ultrasonic guided wave propagates in the plane of the material and is sensitive to in-plane composite material mechanical condition. Sensing changes in the guided wave propagation time enables direct assessment of the mechanical modulus of the composites. Additionally, guided stress waves strongly interact

with typical structural damage such as delaminations or disbonds (laminate-to-laminate or laminate-to-core), broken fibers, thermal damage, resin cure temperatures, microcracking, and other mechanical degradation conditions. Laser UT guided wave test methods enable in-plane composite material measurements that cannot be observed using traditional through thickness ultrasonic test configurations.

12.4 Calibration and Standardization

12.4.1 The cognizant engineering organization should approve the required calibration procedure and interval.

12.4.2 During the calibration procedure a comparison or adjustment of the ultrasonic instrument to a known reference standard is conducted. This provides the inspector assurance the instrument is functioning properly. The standardization procedure is similar to the calibration procedure but with the objective of preparing the instrument for the specific testing requirements. Standardization uses reference standard(s) that simulate the test piece in configuration and contains the required reflectors to adjust instrument sensitivity.

12.4.2.1 If quantitative information is to be obtained, vertical or horizontal linearity of both should be checked in accordance with Practice E317 or other procedures approved by the examining agency and the customer. An acceptable linearity performance may be agreed upon between the examining agency and customer.

12.5 Physical Reference Standards

12.5.1 Ultrasonic testing requires fabrication of physical reference standards from similar acoustic material with built-in, known defects that closely resemble the defects for which information is sought.

12.5.2 Consult Guide E2533 for a discussion on pulse echo reference standards and blocks.

12.5.3 In the event vessels are autofrettaged or proof-tested, it is also important to fabricate physical reference standards that represent both pre- and post-pressurization conditions since UT signal responses can change. This is especially true for disbond/un-bond detection between the composite overwrap to liner interface.

12.6 Geometry and Size Considerations

12.6.1 Ultrasonic transducers, often called search units, are typically less than 25 mm (1 in.) in diameter. These transducers may have different exit sound characteristics. Thus, when examining large objects, it is necessary to scan the object with consideration to the effective sound beam dimension associated with the transducer. See Practice E1065 for sound beam dimension procedure.

12.6.2 If the vessel under test is sufficiently thick to resolve successive back reflections, then one can resort to a pulse echo scanning technique utilizing a single transducer.

12.6.3 For rounded surfaces, geometry must be considered when using contact pulse-echo methods. For example, reference blocks with flat surfaces may be used for establishing gain settings for examinations on test surfaces with radii of curvature of the order of 100 to 130 mm (4 to 5 in.) or greater. For test surfaces with radii of curvature less than 100 to 130 mm, reference blocks with the same nominal curvature should be used, unless otherwise agreed upon by the purchaser and supplier.

12.6.4 *Geometric Similarity*—When comparing the apparent attenuations in different composite materials or layups, the vessel under examination must be geometrically similar, and of course is relative to the transducer and technique applied. For example: a focused transducer used on a thin overwrap with a small diameter sound beam may tolerate curvature differences. On the other hand, a large sound beam will have greater beam modification with smaller radii vessels.

12.7 Safety Precautions

12.7.1 Precautions must be taken to preclude the possibility of electrical shock when performing UT.

12.8 Procedures

12.8.1 *Metallic Liner*—Consult Guide **E2982** for details on UT of the metallic liner raw material and the liner after spin forming or welding operations.

12.8.2 *Composite Overwrap to Liner*—Several techniques have been successful in detecting damage caused by low energy level impacts that leave no visible damage indication to the vessel. A pulse-echo technique, using a reflection rod, was inserted into the center position receiving the signal after passing through the vessel and reflecting back. Use the amplitude of the received signal in both techniques after passing through the wall(s) of the vessel. Application and results of this method are strongly tied to service life and if the vessel has been pressurized after damage occurred.

12.8.3 Composite Overwrap

12.8.3.1 *Pulse Echo*—Consult Practice **E114** for ultrasonic examination of articles under test by the pulse-echo method using straight beam longitudinal waves introduced by direct contact of the search unit with the material being examined. Consult Practice **E1001** for procedures for detecting discontinuities in the overwrap using instruments that transmit and receive pulsed longitudinal ultrasonic waves introduced into the material to be examined while immersed in or impinged upon by a liquid coupling agent.

12.8.3.2 *Guided Wave*—Laser UT guided wave technology can perform detailed ultrasonic examinations of the COPV composite material layers. For detailed procedures, consult the literature (**8-11**).

(1) *Advantages*—Laser UT guided wave test methods enable in-plane composite material measurements that cannot be made using traditional through thickness ultrasonic test configurations.

(2) For all guided wave methods, vessel manufacturers should create appropriate written test procedures, specify required defect detection limits/sizes and specific instrumentation guidelines. Because of the significantly broad possible test configurations options, UT guided wave examinations need to be customized to the specific product engineering requirements.

NOTE 25—Performing a reliable handheld ultrasonic scan of the entire outside of a suspect COPV might be difficult if access to the vessel is limited or if the outside surface has a rough texture.

12.9 Significance of Data

12.9.1 Accept/reject criteria are determined by the COPV manufacturer.

12.10 Specific Reporting Requirements

12.10.1 In addition to the general reporting requirements listed in Section **5.9**, the following information shall be recorded to ensure the reproducibility and repeatability of the data acquired on the vessel under test:

12.10.1.1 UT instrument and model number,

12.10.1.2 UT transducer and model number,

12.10.1.3 UT transducer frequency,

12.10.1.4 UT technique: pulse-echo, guided wave,

12.10.1.5 UT procedure: non-contact or contact, and

12.10.1.6 Couplant (if used): water jet/squirter, water immersion, oil, air.

13. Visual Testing

13.1 Scope

13.1.1 This section provides guidelines for visual testing of the external surface of a COPV. These guidelines are for “flight” weight COPVs used for fluid storage on satellites and launch vehicles. Similar guidelines are currently in use per CGA, ISO, and ANSI documentation. This procedure when properly applied to the entire composite surface provides wide field screening for indications that could potentially reduce the residual strength of the COPV. Indications may be observed at any time during the life of the component and may occur during manufacturing, handling (shipping, integration, etc.), or use, therefore visual testing shall occur at numerous pre-defined points throughout the service life of the COPV (see Section **5.5**). The credible threat analysis, inspection points, approved NDT techniques and any associated accept/reject criteria are defined in the COPV DCP as required per existing range documents (ANSI/AIAA S-081, KNPR 8715.3, or AF-SPCMAN 91-710). The examination shall be performed by individuals that are qualified to visually examine and document flaws or damage on the composite surface of aerospace vessels.

13.1.2 Examples and criteria for evaluation of the visible damage level are provided and are a function of damaged fibers requiring disposition by the cognizant engineering organization.

NOTE 26—Multiple engineering approaches (NDT methods, comparable test data, and modeling) should be applied when interpreting the effect of visual indications when data about the COPV’s residual strength are lacking or absent.

13.2 Summary of Practice

13.2.1 These guidelines will provide direction to perform a detailed visual testing of the external composite surface of an aerospace COPV. Reference documents specific to the vessel being examined must be reviewed and understood prior to performing a detailed visual testing. Work authorizing documents, examination tools, and reports shall be gathered and reviewed. Approach the visual testing initially from a global/far field of view and then examine from the local/near field of view. Evaluate and report any suspect observation according to any known, quantitative accept/reject criteria, otherwise report the qualitative damage level (Level I or II) on the examination report. Upon completion of visual testing the visual test reports shall be signed, dated, and filed as required by the DCP and/or program.

13.3 Significance and Use

13.3.1 Visual testing is inexpensive and is the only accepted wide-field NDT procedure required by ANSI/AIAA S-081, KNPR 8715.3, or AFSPCMAN 91-710. It shall be performed in all stages of the COPV life from manufacturing to retirement in order to ensure a high level of confidence in safety and mission assurance. As required in the DCP examination shall be performed at various pre-determined points starting at the manufacturer and continuing through all phases of handling and service life.

13.3.2 Personnel certified to ANSI NGV2 for visual testing are not inherently qualified to perform adequate examination of “flight” weight vessels. The methodology of a visual testing is the same but the extent of allowable damage presented in CSA Pamphlets C-6.2 and 6.4 are not identical. Careful consideration should be applied when evaluating the qualifications of such personnel. Although personnel certification in visual testing per NAS 410 and SNT-TC-1A may meet some range requirements, the qualification of the examiner should be reviewed to ensure proper training with respect to composite structure.

13.3.3 *Advantages and Applications:* This procedure provides an effective, wide field examination of a composite structure to ensure design and material compliance is maintained for the entire service life of the manufactured component. By application of this technique any mechanical damage that could affect component residual strength can be identified and a disposition reached prior to a potentially catastrophic event. This procedure is non-contact and as required shall be applied at all stages of the vessel’s service life. It can be performed in all stages of integration, use, and re-use without altering the stress state or contents of the component. Additionally, visual testing is required to be performed in all service environments and stages of process and use until decommission and removal from service. This NDT procedure should be complemented with additional NDT to best understand the nature of the observed visual indication. Follow-on NDT as outlined and discussed in this guide will aid in the final disposition of the vessel.

13.3.4 *Limitations and Interferences:* Visual testing is insensitive to subsurface, bulk features and characteristics and cannot yield information on the depth and extent of discontinuities caused by impact or anomalous fabrication. Familiarity with the manufacturing process and damage tolerance must be understood to provide adequate visual testing screening. Inspections performed after integration or instrumentation, or both, yield areas inaccessible by the inspectors. These areas must be visually examined and the results reported before final “close out” prior to any areas being obscured from view.

13.4 Apparatus

13.4.1 The primary sensors for visual testing are the eyes of the inspector and shall be evaluated to ensure a minimum level defined in **Table 4**. Visual testing is assisted mainly by proper illumination and COPV accessibility. Characterization of indications are supported by the use of specialty tools and evaluated against COPV-specific accept/reject criteria. Proper lighting is essential for visual testing. Lighting at a minimum intensity of 160 lx (15 ftc) is recommended for general or global examination. Lighting at a minimum intensity of 500 lx

TABLE 4 Visual Requirements

Exam	Examination Requirements
Near Vision	Jaeger No. 1 or equivalent, not less than 30 cm/12 in. in at least one eye, natural or corrected
Color Perception	Personnel shall be capable of adequately distinguishing and differentiating colors used in the process involved

(50 ftc) is recommended for local, critical inspection. Direct and oblique lighting should be used during examination to distinguish between protruding or concave surface features. A mixture of florescent, incandescent, and LED light sources should be used during examination to aid the inspector in detection. A borescope may be employed if required for internal visual testing of the liner. Jeweler’s loupes and low level magnifiers should be used to further investigate and evaluate visual indications. A soft flexible measuring tape should be used to locate the coordinates of the indication. If depth or length measurements are required for the evaluation of an indication against accept/reject criteria, a calibrated device shall be used. The calibrated devices include depth gages, calipers, and micrometers.

13.5 Safety Precautions

13.5.1 Extended exposure to elevated/depressed light sources may cause fatigue and strain to the inspector and should be mitigated by appropriate illumination levels. Extended fixed focal lengths may also cause fatigue and strain to the inspector and can be mitigated by shortening the examination duration or by using fixed focal length interruptions. The general application of this technique does not warrant other specific safety precautions but based on the typical amount of stored energy, lack of damage tolerance and use environments the inspector shall attempt to gain a full understanding of the examination scenario prior to performing VE. The surface of the vessel may have sharp edges resulting from the manufacturing process or mechanical damage. Inspectors should use caution when handling or tactically evaluating the vessel surface. A pre-task work sheet shall be completed before the first visual testing to ensure overall safety and mission assurance. This will help identify and mitigate potentially hazardous situations (i.e. atmospheric, hypergolic, stored energy, etc.) while providing invaluable data to the visual inspector.

13.6 Calibration and Standardization

13.6.1 Personnel performing visual testing shall be trained and qualified in the field of composite structure examination. Examination for visual acuity for all ASNT qualification levels shall assure the near vision and color perception meets the requirements of **Table 4**. Near vision shall be administered annually and color perception tests shall be administered prior to certification or re-certification. The near vision test should be repeated annually and the color perception test every three years. These eye examinations should be administered by personnel designated by the responsible National Aerospace NDT Board (NANDTB), SNT-TC-1A, or outside agency used for the qualification examination of personnel. Any limitations in color perception shall be evaluated prior to certification and must be approved in writing. Any measurement devices

(calipers, depth gage, etc.) used to assess accept/reject criteria shall be calibrated or demonstrated to be within allowable tolerances.

13.7 Procedure

13.7.1 Visual testing of a COPV follows generic guidelines prescribed for visual testing. The inspector shall have experience or training specific to the manufactured COPVs including methods of construction and material selection/performance. The inspector shall review all available OEM records, program design requirements, damage control plans, and all previous reports prior to the visual testing. Work authorizing documents shall be reviewed to identify test requirements/limitations, hardware identification, accept/reject criteria, component accessibility, area access controls, and personal protective equipment.

13.7.2 Gather approved examination/reporting apparatuses in the examination area.

13.7.3 Locate and positively identify the COPV that requires examining. Lack of proper and positive identification/traceability is generally a condition for vessel rejection.

13.7.4 Determine the orientation of the vessel as determined by the mapping convention. If this is not provided or cannot be determined, a new mapping convention must be established and documented on the examination report.

13.7.5 Evaluate the entire examination environment with special attention to available lighting and vessel accessibility. Evaluate COPV accessibility to determine an approach ensuring that 100 % of the surface is examined. If vessel is still in the shipping container or has protective covers installed a general inspection of the exterior surface shall be performed. Any areas that are hidden or obscured from view that should have been accepted prior to close-out shall be noted by the inspector.

13.7.6 Perform a global/far field examination looking for obvious/gross indications. This will give the inspector a good idea of the general condition of the vessel. This should be performed in adequate lighting over the entire surface of the vessel at roughly an arm's length (45 to 60 cm (18 to 24 in.)).

13.7.7 Some observations are more apparent during global/far field examination and should be noted before a more detailed interrogation occurs during local/near field examination.

13.7.8 Perform and document the detailed local/near field visual testing on examination report. Local/near field examination may be aided by minor magnification, mirrors, and a movable light source. The inspector should change the vantage point with respect to the vessels orientation and light source to increase the ability to detect indications.

13.7.9 The examination focal length should vary from the surface to a distance of no greater than 45 cm (18 in.). Inspect a high-gloss surface at an off-nominal angle less than 45 degrees and a rough textured surface(s) at a normal viewing angle.

13.7.10 Near field indications shall be evaluated against documented accept/reject criteria.

13.7.11 When possible, examine composite surfaces in conjunction with available linear surfaces on the vessel such as the hoop section.

13.7.12 Inspect composite surface for Level I or level II damage. If a significant indication is observed it shall be characterized and recorded on the inspection report. The location shall be measured and located using the established mapping convention. Important characteristics should include type of indication, affected area, and measured depth. This should also be accompanied by a sketch or photographic documentation of the indication. Most types of indications are best described by one of the following:

13.7.12.1 Scratch/scuff/abrasion,

13.7.12.2 Impact,

13.7.12.3 Discoloration, or

13.7.12.4 Manufacturing defect (reject) or flaw (non-reject).

13.7.13 Compare the physical dimensions of the indication to the accept/reject criteria established by first the cognizant engineering organization/program documentation, second by the OEM documentation, and third by CGA Pamphlet 6.4 (if applicable). If no accept/reject criteria exist for the specific vessel design, any Level II damage that involves a broken, cracked, or cut fiber/tow will require a cognizant engineering organization disposition. If significant mechanical damage is observed on a pressurized vessel it is highly recommended to terminate the examination immediately. Secure the surrounding area until program and safety personnel have been notified.

13.7.14 If the vessel is unpressurized, the visual testing shall continue until 100 % of the exposed composite surface is examined.

13.7.15 Damage shall be classified as Level I or II damage as follows:

13.7.15.1 *Level I Damage*—Manufacturing artifacts (tow terminations, excess resin, resin bubbles, entrained fibers, etc.), scratch/scuff/abrasion limited to the resin, resin micro-cracking, or minor ply disorientation (see **Figs. 27-30**).

13.7.15.2 *Level II Damage*—Scratch/scuff/abrasion that affects the fiber, impact damage, broken fibers, obvious discoloration, gross ply disorientation, lack of proper component identification (see **Figs. 31-33**). All Level II damage is potentially a basis for rejection that must be reported and evaluated by the cognizant engineering organization for final



FIG. 27 Level I Manufacturing Artifact (Tow Termination)



FIG. 28 Level I Resin Outgassing/Bubbling



FIG. 31 Level II Scratch



FIG. 29 Level I Scratch



FIG. 32 Level II Broken Fiber Tows



FIG. 30 Level I Abrasion

13.7.16 As required, photo document all of the indications as listed on the visual test report. Follow proper lighting requirements and traceability of images similar to those spelled out in the document.

13.7.17 Return the COPV to its pre-examination configuration. The visual test report shall then be signed and dated by the approved visual inspector. The visual test report shall then be filed as a quality document. This report may be required for vessel close-out and flight readiness review, therefore it should be copied and placed with the vessel, sub-system, or vehicle data pack.

13.8 Significance of Data

13.8.1 Visual testing of COPVs by a trained visual inspector is the most widely accepted and only NDT technique currently required by ANSI/AIAA S-081, KNPR 8715.3, and AFSPC-MAN 91-710. This is a result of the USAF/NASA COPV program generating a significant amount of data that has been incorporated in the various requirements.

disposition, which includes the implementation of follow-on NDT as discussed in this guide.



FIG. 33 Level II Discoloration (Propellant Exposure)

13.9.2 The examination technique is capable of detecting discontinuity sizes corresponding to a 90 % probability of detection at a 95 % confidence level; however, for such a measurement to be meaningful, destructive testing is required to link accept/reject criteria based on discontinuity size and type to actual reductions in vessel strength. This method should be applied to all forms of NDT as applied to the specific COPV in review.

13.10 *Specific Reporting Requirements*

13.10.1 In addition to the general reporting requirements listed in this guide in Section 5.9, the following information shall be recorded to ensure the reproducibility and repeatability of the data acquired on the vessel under examination:

- 13.10.1.1 Damage control plan number,
- 13.10.1.2 Type of lighting, and
- 13.10.1.3 Intensity of illumination.

13.10.2 Vessel-specific reporting requirements shall be defined in the program DCP. The DCP is required by various range documents and is the responsibility of the prime contractor. Inspection reports shall be maintained by the program, OEM or appropriate cognizant engineering department, as required, for the life of the COPV.

13.10.3 Qualitative description of any defects (cracks, ply delamination, blisters, depressions, foreign material inclusions, tow distortions, surface features, or wrinkles) should be provided, along with corresponding quantitative details (location, number, size (length and depth), and size distribution).

13.10.4 For archival and reference purposes, photos or video documentation is recommended as part of the visual testing record. Follow the guidelines for photo documentation described in NASA/TM-2012-21737.

13.10.5 In most cases the records shall be maintained for three years after the program is complete.

13.10.6 Visual testing results shall also be part of the Shearography test record (see subsection 9.8), and can also be used to corroborate AE source location (Section 7) and UT discontinuity location (Section 12).

14. **Keywords**

14.1 accumulated damage; acoustic emission; carbon epoxy; composite; composite overwrapped pressure vessel; composite pressure vessel; COPV; Felicity ratio; fiber bridging; filament wound pressure vessel; graphite-epoxy; impact damage; IR; Kaiser effect; latent defects; nondestructive; shearography; source location; ultrasound; radiography; radiology; thermography; visual testing

13.8.2 Visual NDT involves qualitative physical inspection of a composite material or component assuring compliance to the engineered design requirements to ensure that no mechanical damage has occurred during handling or field service. Accept/reject criteria for such defects are given in the applicable engineering drawing(s), specification, purchase order, DCP or contract. If no accept/reject criteria exist provisions of this guide can be applied to initiate disposition by the cognizant engineering organization.

13.8.3 Complete visual testing involves review of a material or component’s data package to verify proper materials and dimensions are maintained. It should also involve review of quality records (damage control plan, prior visual test reports, certificates of material conformance, etc.) to verify inspection points, required documentation, and to ensure engineering design is maintained.

13.8.4 Visual testing that is specific to a particular vessel design may or may not apply to any other vessel design.

13.8.5 If accept/reject criteria exist they must be documented at the program level with concurrence of the OEM.

13.9 *Precision and Bias*

13.9.1 Since visual NDT procedures can be highly subjective, repeatability and reproducibility errors must be known and controlled. These errors shall be minimized and controlled through proper training using actual COPVs, review of reference material and associated certification programs.

APPENDIX
(Nonmandatory Information)
X1. SUPPLEMENTARY INFORMATION FROM CORRESPONDING SECTIONS OF GUIDE (NOTE SECTION NUMBERS REFER TO PARTS OF THE GUIDE)
X1.1 (Section 7) Comments Relative to AE-based Acceptance and Rejection Criteria

X1.1.1 Acceptance and rejection criteria can be determined from tests of a statistically significant number of COPVs (including burst tests) followed by non-destructive and destructive evaluations performed by other methods. The following consideration can be used as initial and non-mandatory criteria.

X1.1.2 The numerical values associated with specific acceptance criteria can be design-, materials-, and process-specific and should be evaluated for every new design, and when material and processes are significantly changed. The validity of the acceptance criteria used is also predicated on the analytical consistency of the compiled AE results used to assess in-family or out-of-family behavior. Possible acceptance and rejection criteria, applied as a whole or in part, that can be used to approve or remove a COPV from use are as outlined in the following subsections:

X1.1.2.1 *Excessive Fiber Breakage*—Excessive rupture of the fiber reinforcement in COPVs is indicative of a major structural damage that can compromise a COPV’s load-bearing capability. However, without a valid specification of required sensor sensitivity, it is not possible to specify a threshold amplitude, for example, 60 dBAE, above which excessive structural damage is inferred and the COPV rejected if a sufficient number of AE events are observed. Also, amplitude-distance correction is very complicated in a composite since amplitudes decay differently in different propagation directions (particularly for cylindrical vessels) and also vary with different source depths in the vessel’s composite wall. For these reasons, establishing rejection criteria based on observation of a fixed number of AE events greater than a fixed amplitude, or observation of a fixed number of events observed at a specific location (with amplitude–distance correction) for a vessel configured with multiple sensors and pressurized above MEOP is very difficult and requires trial and error.

X1.1.2.2 *Critical Felicity Ratio*—In the case of Schedule 3 pressurization, an FR below a critical value can be used for

COPV acceptance and rejection. For example, an FR of 0.96 can be used as an initial value in absence of criteria delivered for the examined COPVs (see **Note 19** in subsection **7.8.3**).

X1.1.2.3 Critically active flaws present in the metallic liner can be used for COPV acceptance and rejection.

X1.1.2.4 Critically intense flaws present in the metallic liner can be used for COPV acceptance and rejection.

X1.1.2.5 *Composite Instability*—Deviation of exponential decay curve-fitting parameters obtained by use of Schedule 4, ASME Section X, Appendix 8-600.2.7, or the observation of a poor “goodness of fit” parameter or coefficient of variance, R^2 , either for fitting of AE event rate decay curve or AE energy decay curve data, can be used for COPV acceptance and rejection.

NOTE X1.1—Deviation of exponential decay curve fitting parameters or the observation of a poor “goodness of fit” parameter or coefficient of variance has not been established using Schedules 1, 2, or 4.

X1.1.3 A COPV that does not meet acceptance criteria in **X1.1.2** can be re-examined by other NDT methods given in this guide per the discretion of the cognizant engineering organization. Once a flaw is confirmed by a collaborating NDT method, its significance can be established by stress analysis. Once a flaw-indication is confirmed and its significance is established by a corroborating NDT method, the validity of the original AE acceptance criteria can be re-evaluated to determine conservatism and to ensure that false positives are not being rejected unnecessarily.

X1.1.4 *Precision and Bias*—Location accuracy is influenced by factors that affect AE wave propagation, for example, the source amplitude, propagation distances, the orientation of the composite plies relative to the source and sensor, sensor coupling, and signal processor settings.

X1.1.5 *Verification*—It is possible to measure AE and produce AE source locations that cannot be verified by other NDT methods. This can be due to incorrect source location, or in case of micro-discontinuities or incipient flaws, sources that are below the detection threshold of other NDT methods.

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