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Standard Guide for Nondestructive Examination of Thin-Walled Metallic Liners in Filament-Wound Pressure Vessels Used in Aerospace Applications[1]

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1. Scope

1.1 This guide discusses current and potential nondestructive testing (NDT) procedures for finding indications of discontinuities in thin-walled metallic liners in 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 COPV. However, it also has relevance to *(1)* monolithic metallic pressure vessels (PVs) (CGA Type I), and *(2)* metal-lined hoop-wrapped COPVs (CGA Type II).

1.3 The vessels covered by this guide are used in aerospace applications; therefore, examination 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 and PVs used for storing aerospace media at maximum allowable working pressures (MAWPs) up to 3.5 MPa (500 psia) and volumes up to 2000 L (70 ft^3), and *(2)* high pressure COPVs used for storing compressed gases at MAWPs up to 70 MPa (10 000 psia) and volumes down to 8 L (500 $in.^3$). Internal vacuum storage or exposure is not considered appropriate for any vessel size.

NOTE 1—Some vessels are evacuated during filling operations, requiring the tank to withstand external (atmospheric) pressure.

1.5 The metallic liners under consideration include, but are not limited to, ones made from aluminum alloys, titanium alloys, nickel-based alloys, and stainless steels. In the case of COPVs, the composites through which the NDT interrogation should be made after overwrapping include, but are not limited to, various polymer matrix resins (for example, epoxies, cyanate esters, polyurethanes, phenolic resins, polyimides (including bismaleimides), polyamides) with continuous fiber reinforcement (for example, carbon, aramid, glass, or poly-(phenylenebenzobisoxazole) (PBO)).

1.6 This guide describes the application of established NDT procedures; namely, Acoustic Emission (AE, Section 7), Eddy Current Testing (ET, Section 8), Laser Profilometry (LP, Section 9), Leak Testing (LT, Section 10), Penetrant Testing (PT, Section 11), and Radiographic Testing (RT, Section 12). These procedures can be used by cognizant engineering organizations for detecting and evaluating flaws, defects, and accumulated damage in metallic PVs, the bare metallic liner of COPVs before overwrapping, and the metallic liner of new and in-service COPVs.

1.7 All methods discussed in this guide (AE, ET, LP, LT, PT, and RT) are performed on the metallic liner of COPVs before or after overwrapping and structural cure. The same methods may also be performed on metal PVs. For NDT procedures for detecting discontinuities in the composite overwrap in filament wound pressure vessels; namely, AE, ET, Shearography Testing (ST), RT, Ultrasonic Testing (UT) and Visual Testing (VT); consult Guide E2981.

1.8 Due to difficulties associated with inspecting thin-walled metallic COPV liners through composite overwraps, and the availability of the NDE methods listed in 1.6 to inspect COPV liners before overwrapping and metal PVs, ultrasonic testing (UT) is not addressed in this standard. UT may still be performed as agreed upon between the supplier and customer. Ultrasonic requirements may utilize Practice E2375 as applicable based upon the specific liner application and metal thickness. Alternate ultrasonic inspection methods such as Lamb wave, surface wave, shear wave, reflector plate, etc. may be established and documented per agreed upon contractual requirements. The test requirements should be developed in conjunction with the specific criteria defined by engineering analysis.

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[1] This guide 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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1.9 In general, AE and PT are performed on the PV or the bare metallic liner of a COPV before overwrapping (in the case of COPVs, AE is done before overwrapping to minimize interference from the composite overwrap). ET, LT, and RT are performed on the PV, bare metallic liner of a COPV before overwrapping, or on the as-manufactured COPV. LP is performed on the inner and outer surfaces of the PV, or on the inner surface of the COPV liner both before and after overwrapping. Furthermore, AE and RT are well suited for evaluating the weld integrity of welded PVs and COPV liners.

1.10 Wherever possible, the NDT procedures described should be sensitive enough to detect critical flaw sizes of the order of 1.3 mm (0.050 in.) length with a 2:1 aspect ratio.

NOTE 2—Liners often fail due to improper welding resulting in initiation and growth of multiple small discontinuities of the order of 0.050 mm (0.002 in.) length. These will form a macro-flaw of 1-mm (0.040-in.) length only at higher stress levels.

1.11 For NDT procedures that detect discontinuities in the composite overwrap of filament-wound pressure vessels (namely, AE, ET, shearography, thermography, UT and visual examination), consult Guide E2981.

1.12 In the case of COPVs which are impact damage sensitive and require implementation of a damage control plan, emphasis is placed on NDT procedures that are sensitive to detecting damage in the metallic liner caused by impacts at energy levels which may or may not leave any visible indication on the COPV composite surface.

1.13 This guide does not specify accept/reject criteria (4.10) used in procurement or used as a means for approving PVs or COPVs for service. Any acceptance criteria provided herein are given mainly for purposes of refinement and further elaboration of the procedures described in the guide. Project or original equipment manufacturer (OEM) specific accept/reject criteria should be used when available and take precedence over any acceptance criteria contained in this document.

1.14 This guide references established ASTM test methods that have a foundation of experience and that yield a numerical result, and newer procedures that have yet to be validated which 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.

1.15 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 thin-walled metallic component design, quality assurance, in-service maintenance, or damage examination.

1.16 *Units*—The values stated in metric units are to be regarded as the standard. The English units given in parentheses are provided for information only.

1.17 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.18 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C274 Terminology of Structural Sandwich Constructions (Withdrawn 2016)[3]
D1067 Test Methods for Acidity or Alkalinity of Water
D3878 Terminology for Composite Materials
D5687/D5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation
E165/E165M Practice for Liquid Penetrant Testing for General Industry
E215 Practice for Standardizing Equipment and Electromagnetic Examination of Seamless Aluminum-Alloy Tube
E426 Practice for Electromagnetic (Eddy Current) Examination of Seamless and Welded Tubular Products, Titanium, Austenitic Stainless Steel and Similar Alloys
E432 Guide for Selection of a Leak Testing Method
E493/E493M Practice for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode
E499/E499M Practice for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode
E543 Specification for Agencies Performing Nondestructive Testing
E976 Guide for Determining the Reproducibility of Acoustic Emission Sensor Response
E1000 Guide for Radioscopy
E1032 Practice for Radiographic Examination of Weldments Using Industrial X-Ray Film
E1066/E1066M Practice for Ammonia Colorimetric Leak Testing
E1209 Practice for Fluorescent Liquid Penetrant Testing Using the Water-Washable Process
E1210 Practice for Fluorescent Liquid Penetrant Testing Using the Hydrophilic Post-Emulsification Process
E1219 Practice for Fluorescent Liquid Penetrant Testing Using the Solvent-Removable Process
E1255 Practice for Radioscopy
E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases (Withdrawn 2015)[3]
E1316 Terminology for Nondestructive Examinations
E1416 Practice for Radioscopic Examination of Weldments
E1417 Practice for Liquid Penetrant Testing
E1419/E1419M Practice for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission
E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases (Withdrawn 2015)[3]

[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.

[3] The last approved version of this historical standard is referenced on www.astm.org.

E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases (Withdrawn 2015)[3]
E1742/E1742M Practice for Radiographic Examination
E1815 Test Method for Classification of Film Systems for Industrial Radiography
E2007 Guide for Computed Radiography
E2104 Practice for Radiographic Examination of Advanced Aero and Turbine Materials and Components
E2033 Practice for Radiographic Examination Using Computed Radiography (Photostimulable Luminescence Method)
E2261/E2261M Practice for Examination of Welds Using the Alternating Current Field Measurement Technique
E2338 Practice for Characterization of Coatings Using Conformable Eddy Current Sensors without Coating Reference Standards
E2375 Practice for Ultrasonic Testing of Wrought Products
E2445/E2445M Practice for Performance Evaluation and Long-Term Stability of Computed Radiography Systems
E2446 Practice for Manufacturing Characterization of Computed Radiography Systems
E2597/E2597M Practice for Manufacturing Characterization of Digital Detector Arrays
E2698 Practice for Radiographic Examination Using Digital Detector Arrays
E2736 Guide for Digital Detector Array Radiography
E2737 Practice for Digital Detector Array Performance Evaluation and Long-Term Stability
E2884 Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays
E2981 Guide for Nondestructive Examination of Composite Overwraps in Filament Wound Pressure Vessels Used in Aerospace Applications

2.2 *AIA Standard:*[4]
NAS 410 NAS Certification & Qualification of Nondestructive Test Personnel

2.3 *ANSI/AIAA Standards:*[5]
ANSI/AIAA S-080 Space Systems—Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
ANSI/AIAA S-081 Space Systems—Composite Overwrapped Pressure Vessels (COPVs)

2.4 *AMS Document:*[6]
Qualified Products List (Military) of Products Qualified Under Detail Specification SAE-AMS 2644 Inspection Material, Penetrant[7]

2.5 *ASME Document:*[8]
ASME Boiler and Pressure Vessel Code, Section V Nondestructive Examinations, Article 12, Rules for the Construction & Continued Service of Transport Tanks

2.6 *ASNT Documents:*[9]
ASNT CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel
SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing
Leak Testing, Volume 1, Nondestructive Testing Handbook

2.7 *CEN Documents:*[10]
EN 60825-1 Safety of Laser Products—Part 1: Equipment Classification, Requirements and User's Guide
EN 16407-1 Non-destructive testing—Radiographic inspection of corrosion and deposits in pipes by X- and gamma rays—Part 1: Tangential radiographic inspection

2.8 *Federal Standards:*[11]
21 CFR 1040.10 Laser products
21 CFR 1040.11 Specific purpose laser products

2.9 *ISO Document:*[12]
ISO 9712 Non-destructive testing—Qualification and certification of NDT personnel

2.10 *Compressed Gas Association Standard:*[13]
CGA Pamphlet C-6.4 Methods for Visual Inspection of AGA NGV2 Containers

2.11 *LIA Document:*[14]
ANSI, Z136.1-2000 Safe Use of Lasers

2.12 *MIL Documents:*[15]
MIL-HDBK-6870 Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts
MIL-HDBK-340 Test Requirements for Launch, Upper-Stage, and Space Vehicles, Vol. I: Baselines
MIL-HDBK-1823 Non-destructive Evaluation System Reliability Assessment

2.13 *NASA Documents:*[16]
JSC 25863B Fracture Control Plan for JSC Space-Flight Hardware
NASA-STD-5003 Fracture Control Requirements for Payloads Using the Space Shuttle
NASA-STD-5009 Nondestructive Evaluation Requirements for Fracture Control Programs

[4] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.
[5] Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA, 20191-4344.
[6] Available from SAE International (SAE), 400 Commonwealth Dr., Warrendale, PA 15096, http://www.sae.org.
[7] The activity responsible for this qualified products list is the Air Force Materiel Command, ASC/ENOI, 2530 Loop Road West, Wright-Patterson AFB, OH 45433-7101. The qualifying activity responsible for qualification approval is AFRL/RXSA, 2179 Twelfth St, Ste 1, Wright-Patterson AFB OH 45433-7809.
[8] Available from ASME, Three Park Avenue, New York, NY 10016-5990, 800-843-2763 (U.S/Canada), email: CustomerCare@asme.org.
[9] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.
[10] Available from British Standards Institution (BSI), 389 Chiswick High Rd., London W4 4AL, U.K., http://www.bsigroup.com.
[11] Published by the Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration (FDA) , available from Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401.
[12] Available from ISO copyright office, Case postale 56, CH-1211 Geneva 20, Switzerland.
[13] Available from Compressed Gas Association (CGA), 4221 Walney Rd., 5th Floor, Chantilly, VA 20151-2923, http://www.cganet.com.
[14] Available from the Laser Institute of America, 13501 Ingenuity Drive, Suite 128, Orlando, FL 32826.
[15] Available for Standardization Documents Order Desk, Bldg 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.
[16] Available from the NASA Technical Standards System at the NASA website www.standards.nasa.gov.

NASA-STD-5014 Nondestructive Evaluation (NDE) Implementation Handbook for Fracture Control Programs
NASA-STD-(I)-5019 Fracture Control Requirements for Spaceflight Hardware
NASA-TM-2012-21737 Elements of Nondestructive Examination for the Visual Inspection of Composite Structures
MSFC-RQMT-3479 Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures
SSP 30558 Fracture Control Requirements for Space Station
SSP 52005 Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures
NSTS 1700.7B ISS Addendum, Safety Policy and Requirements for Payloads Using the International Space Station, Change No. 3, February 1, 2002

2.14 *Non-Governmental Documents:*[17]
NTIAC-DB-97-02 Nondestructive Evaluation (NDE) Capabilities Data Book
NTIAC-TA-00-01 Probability of Detection (POD) for Nondestructive Evaluation (NDE)

2.15 *Governmental Document:*[18]
AFRL-ML-WP-TR-2001-4011 Probability of Detection (POD) Analysis for the Advanced Retirement for Cause (RFC)/Engine Structural Integrity Program (ENSIP) Nondestructive Evaluation (NDE) System Development Volume 2—User's Manual (DTIC Accession Number ADA393072)

2.16 *ECSS Document:*[19]
ECSS-E-30-01A Space Engineering Fracture control

3. Terminology

3.1 *Abbreviations*—The following abbreviations are adopted in this guide: acoustic emission (AE), eddy current testing (ET), laser profilometry (LP), leak testing (LT), penetrant testing (PT), and radiographic testing (RT).

3.2 *Applicable Document*—Documents cited in the body of this guide that contain provisions or other pertinent requirements directly related and necessary to the performance of the activities specified by this guide.

3.3 *Definitions*—Terminology in accordance with Terminologies D3878, E1316, and C274 should be used where applicable. Definition of terms related to NDT, and composites appearing in Terminologies C274, E1316, and D3878, respectively, should apply to the terms used in this guide.

3.3.1 *cognizant engineering organization, n*—see Terminology E1316.

3.3.2 *defect, n*—see Terminology E1316.

3.3.3 *discontinuity, n*—see Terminology E1316.

3.3.4 *flaw, n*—see Terminology E1316.

3.3.5 *fracture control, n*—the rigorous application of those branches of design engineering, quality assurance, manufacturing, and operations dealing with the analysis and prevention of crack propagation leading to catastrophic failure.

3.3.6 *operating pressure, n*—see Practice D1067, Section 3, Terminology.

3.4 *Definitions of Terms Specific to This Standard:*

3.4.1 *burst-before-leak (BBL), n*—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.

3.4.2 *capability demonstration specimens, n*—a set of specimens made from material similar to the material of the hardware to be examined with known flaws used to estimate the capability of flaw detection, that is, probability of detection (POD) or other methods of capability assessment, of an NDT procedure.

3.4.3 *composite overwrapped pressure vessel (COPV), n*—an inner shell overwrapped with multiple plies of polymer matrix impregnated reinforcing fiber wound at different wrap angles that form a composite shell.

3.4.3.1 *Discussion*—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.

3.4.4 *cracks or crack-like flaws, n*—flaws (for example, planar discontinuities) that are assumed to behave like cracks and may be initiated and grow during material production, fabrication, and service life of the part.

3.4.5 *critical-initial flaw size (CIFS), n*—the largest crack that can exist at the beginning of the service life of a structure that has an analytical life equal to the service life times the service life factor.

3.4.5.1 *Discussion*—For example, a factor of 4 is used by NASA.

3.4.6 *damage control plan (DCP), n*—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 examination) throughout the life cycle of the COPV.

3.4.6.1 *Discussion*—The DPC should be provided by the design agency and made available for review by the applicable safety/range organization per ANSI/AIAA S-081.

3.4.7 *damage-tolerance life, n*—the required period of time or number of cycles that the metallic liner of a COPV, containing the largest undetected crack shown by analysis or

[17] Available from Advanced Materials, Manufacturing, and Testing Information Analysis Center, 201 Mill Street, Rome, NY 13440, Phone 315-339-7117, Fax 315-339-7107.

[18] Copies are available from Defense Technical Information Center (DTIC), 8725 John J. Kingman Road, Fort Belvoir VA 22060-6218 or online http://www.dtic.mil/dtic/.

[19] Available from ESA Publications Division, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands.

testing, will survive without leaking or failing catastrophically in the expected service load and environment; also referred to as safe-life.

3.4.8 *defect criteria, n*—a documented statement defining the engineering criteria for rejecting a COPV based upon NDT.

3.4.9 *fracture critical flaw, n*—a flaw that exhibits unstable growth at service conditions.

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

3.4.11 *leak-before-burst (LBB), n*—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.

3.4.12 *marked service pressure, n*—pressure for which a vessel is rated; normally this value is stamped on the vessel.

3.4.13 *maximum allowable working pressure (MAWP), n*—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.

3.4.14 *maximum design pressure (MDP), n*—the highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature.

3.4.14.1 *Discussion*—Transient pressures should be considered. When determining MDP, the maximum temperature to be experienced during a launch abort to a site without cooling facilities should also be considered. In designing, analyzing, or testing pressurized hardware, loads other than pressure that are present should 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 (for example, heaters), or combinations thereof, are used to control pressure, collectively they should be two-fault tolerant from causing the pressure to exceed the MDP of the system.

3.4.15 *minimum detectable crack size, n*—the size of the smallest crack-like discontinuity that can be readily detected by NDT procedures and which is assumed to exist in a part for the purpose of performing a damage tolerance safe-life or POD analysis of the part, component, or assembly.

3.4.16 *miss, n*—an existing discontinuity that is missed during a POD examination.

3.4.17 *NDT reliability, n*—the reliability of an NDT procedure is determined by: *(1)* the reproducibility—NDT system standardization; *(2)* the capability—POD; and *(3)* the repeatability—process control of the applied NDT procedure.

3.4.18 *normal fill pressure, n*—level to which a vessel is pressurized; this may be greater, or may be less, than *marked service pressure*.

3.4.19 *probability of detection (POD), n*—the mean fraction of flaws at a given size or other characteristic such as stress intensity factor expected to be detected.

3.4.20 *special NDT, n*—nondestructive examinations of fracture critical hardware that are capable of detecting cracks or crack-like flaws smaller than those assumed detectable by standard NDT or do not conform to the requirements for standard NDT.

3.4.21 *standard NDT, n*—well established nondestructive examination methods for which a statistically based flaw detection capability has been established for a specific application or groups of similar applications, for example, such as the methods discussed in NASA-STD-5009.

3.5 *Symbols:*

3.5.1 *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.

3.5.2 a_0—the size of an initial, severe, worst case crack-like discontinuity, also known as a rogue flaw.

3.5.3 a_{crit}—the size of a severe crack-like discontinuity that causes LBB or BBL failure often caused by a growing rogue flaw.

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

3.5.5 $a_{p/c}$—the discontinuity size that can be detected with probability *p* with a statistical confidence level of *c*.

3.5.6 *â*—(pronounced a-hat) measured response of the 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 goal of the NDT is to detect defects that have been implicated in the failure of the COPV metal liner, or have led to leakage, loss of contents, injury, death, or mission, or a combination thereof. Liner defects detected by NDT that require special attention by the cognizant engineering organization include through cracks, part-through cracks, liner buckling, pitting, thinning, and corrosion under the influence of cyclic loading, sustained loading, temperature cycling, mechanical impact and other intended or unintended service conditions.

NOTE 3—Liners made from stainless steel and nickel-based alloys exhibit a higher damage resistance to impact than those made from aluminum.

NOTE 4—Safe life is the goal for any COPV so that a through crack in the liner will not develop during the service life.

NOTE 5—The use a material with good fatigue and slow crack growth characteristics is important. For example, nickel-based alloys are better than precipitation-hardened stainless steel. Aluminum also has good ductility and crack resistance.

4.2 The COPVs covered in this guide consist of a metallic liner overwrapped with high-strength fibers embedded in polymeric matrix resin (typically a thermoset). 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 fiber). Matrix resins include epoxies, cyanate esters, polyurethanes, phenolic resins, polyimides (including bismaleimides), polyamides and other high performance polymers. Common bond line adhesives are generally epoxies (FM-73, West 105, and Epon 862) or urethanes with thicknesses ranging from 0.13 mm (0.005 in.) to 0.38 mm (0.015 in.). Metal liner and composite overwrap materials requirements are found in ANSI/AIAA S-080 and ANSI/AIAA S-081, respectively. Pictures of representative COPVs are shown in Guide E2981.

4.3 The operative failure modes COPV metal liners and metal PVs, in approximate order of likelihood, are: *(a)* fatigue cracking, *(b)* buckling, *(c)* corrosion, *(d)* environmental cracking, and *(e)* overload.

NOTE 6—For launch vehicles and satellites, the strong drive to reduce weight has pushed designers to adopt COPVs with thinner metal liners. Unfortunately, this configuration is more susceptible to liner buckling. Therefore, as a precursor to liner fatigue, attention should be paid to liner buckling.

4.4 Per MIL-HDBK-340, 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 Per NASA-STD-(I)-5019, COPVs should comply with the latest revision of ANSI/AIAA S-081. The following requirements also apply when implementing S-081:

4.5.1 Maximum Design Pressure (MDP) should 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 of the composite shell during the service life.

NOTE 7—For other aerospace applications, the cognizant engineering organization should select the appropriate probability of survival, for example, 0.99, 0.999, 0.9999, etc., depending on the anticipated failure mode, damage tolerance, safety factor, or consequence of failure, or a combination thereof. For example, a probability of survival of 0.99 means that on average, 1 in 100 COPVs will fail. COPVs exhibiting catastrophic failure modes (BBL composite shell stress rupture versus LBB liner leak), lower damage tolerance (cylindrical versus spherical vessels), lower safety factor, and high consequence of failure will be subject to more rigorous NDT.

4.6 Application of the NDT procedures discussed in this standard is intended to reduce the likelihood of liner failure, commonly denoted leak before burst (LBB), characterized by leakage and loss of the pressurized commodity, thus mitigating or eliminating the attendant risks associated with loss of the pressurized commodity, and possibly 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 Per the discretion of the cognizant engineering organization, NDT for fracture control of COPVs should follow additional general and detailed guidance described in MIL-HDBK-6870, NASA-STD-5019, MSFC-RQMT-3479, or ECSS-E-30-01A, or a combination thereof, not covered in this guide.

4.6.3 Hardware that is proof tested as part of its acceptance (that is, not screening for specific flaws) should 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. COPV composite overwraps can have a myriad of possible discontinuity types, with varying degrees of importance in terms of effect on performance (see 4.7 in Guide E2981). As for discontinuities in the metallic liner, the primary concern from an NDT perspective is to detect discontinuities that can develop cracks or reduce residual strength of the liner below the levels required, within the context of the life cycle. Therefore, discontinuities should be categorized as follows:

4.7.1 Inherent material discontinuities: inclusions, grain boundaries, etc., detected during *(a)* and *(b)* of 5.5.

NOTE 8—Inherent material discontinuities are generally much smaller than the damage-tolerance limit size. Any design that does not satisfy this statement should be revised. Quality control procedures in place in the manufacturing process should eliminate any source materials that do not satisfy specifications.

4.7.2 Manufacturing-induced discontinuities: caused by welding, machining, heat treatment, etc., detected during *(b)* and *(c)* of 5.5.

NOTE 9—Manufacturing-induced discontinuities depend on the manufacturing process, and can include machining marks, improper heat treatment, and weld-related discontinuities such as lack of fusion, porosity, inclusions, zones of local material embrittlement, shrinkage, and cracking.

4.7.3 Service-induced discontinuities: fatigue, corrosion, stress corrosion cracking, wear, accidental damage, etc. detected during *(d)* and *(e)* of 5.5 (after the COPV has been installed). In these cases, NDT should either be made on a "remove and inspect" or "*in-situ*" basis depending on the procedure and equipment used.

4.8 A conservative damage-tolerance life assessment is made by assuming the existence of a crack-like discontinuity or system of discontinuities, and determining the maximum size or other characteristic of this discontinuity(s) that can exist at the time the vessel is placed into service but not progress to failure under the expected service conditions. This then defines the dimensions or other characteristics of the crack or crack-like discontinuity or system of crack-like discontinuities that should be detected by NDT.

NOTE 10—Welding or machining may result in non-crack like flaws/imperfections/conditions that may be important, and NDT choices for these flaws/imperfections/conditions may be different than for crack-like ones.

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

4.9.1 Accept/reject criteria should 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 should 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 should 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 should 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 should 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 PVs*—ANSI/AIAA S-080 defines the approach for design, analysis, and certification of metallic PVs.

4.11 *Certification of COPVs*—ANSI/AIAA S-081 defines the approach for design, analysis, and certification of COPVs, while ANSI/AIAA S-080 defines the approach for design, analysis, and certification of PVs. More specifically, the PV or COPV thin-walled metal liner should 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 procedure should 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 assessment of crack growth is the typical approach used for 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 should be addressed by the cognizant engineering organization.

4.11.1 *Design Requirements*—COPV design requirements related to the metallic liner are given in ANSI/AIAA S-080. The key requirement is the stipulation that the PV or COPV thin-walled metal liner should exhibit an LBB failure mode or should possess adequate damage tolerance life (safe-life), or both. The overwrap design should 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.

4.12 *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 procedure 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. 1) depends on the number of examination sites with targets, the size of the targets at the examination sites, and the basic nature of the examination result (hit/miss or magnitude of signal response).

4.12.1 Given that $a_{90/95}$ has become a de facto design criterion, it is 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 11—$a_{90/95}$ for a metallic liner and generation of a POD(*a*) function is predicated on the assumption that critical initial flaw size (CIFS) for a liner of a given thickness can be detected with a capability of 90/95 (90 percent probability of detection at a 95 percent confidence level). This is problematic for COPVs with very thin metallic liners where the CIFS will be smaller than the minimum detectable flaw sizes given in Table 1 in NASA-STD-5009. At this limit of detection (CIFS < $a_{90/95}$), $a_{90/95}$ will have no validity for a thin-walled COPV.

4.12.2 NASA-STD-5009 defines typical limits of NDT capability for a wide range of NDT procedures and applications. Given the defect criteria established by the Damage-Tolerance Life requirements and the potential discontinuities to

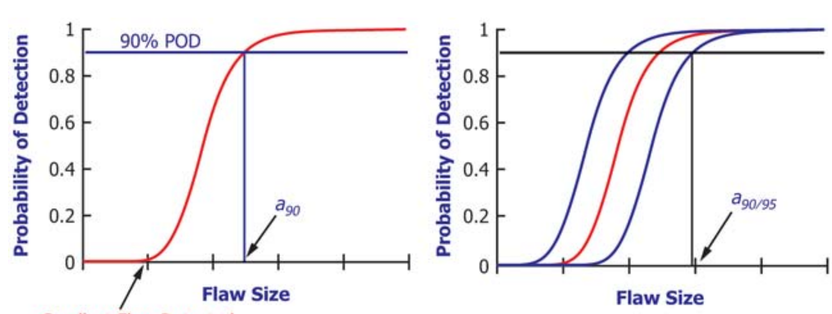

FIG. 1 Probability of Detection as a Function of Flaw Size, POD(*a*), Showing the Location of the Smallest Detectable Flaw and a_{90} (Left); POD(*a*) With Confidence Bounds Added and Showing the Location of $a_{90/95}$ (Right)

be detected, NASA-STD-5009 can be used to select NDT procedures that are likely to achieve the required examination capability.

NOTE 12—NDT of fracture critical hardware should detect the initial crack sizes used in the damage tolerance fracture analyses with a capability of 90/95. The minimum detectable crack sizes for the standard NDT procedures shown in Table 1 of NASA-STD-5009 meet the 90/95 capability requirement. The crack size data in Table 1 of NASA-STD-5009 are based principally on an NDT capability study that was conducted on flat, fatigue-cracked 2219-T87 aluminum panels early in the Space Shuttle program. Although many other similar capability studies and tests have been conducted since, none have universal application, neither individually or in combination. Conducting an ideal NDT capability demonstration where all of the variables are tested is obviously unmanageable and impractical.

4.12.3 *Aspect Ratio and Equivalent Area Considerations*—Current standards governing aerospace metallic pressure vessels (ANSI/AIAA S-080) and COPV liners (ANSI/AIAA S-081) require that fracture analysis be performed to determine the CIFS for cracks having an aspect ratio ranging from 0.1 to 0.5. However, there is insufficient data to support the approach of testing at only one aspect ratio and then using an equivalent area approach to extend the results to the required range of aspect ratios (**1-9**).[20] Accordingly, POD testing on metallic COPV liners should be performed at the bounds of the required range of crack aspect ratios.

NOTE 13—**Caution:** To minimize mass, designers of aerospace systems are reducing the wall thickness for metallic pressure vessels and COPV liners. This reduction in wall thickness produces higher net section stresses, for a given internal pressure, resulting in smaller CIFS. These smaller crack sizes approach the limitations of current NDT. Failure to adequately demonstrate the capabilities of a given NDT procedure over the required range of crack aspect ratios may lead to the failure to detect a critical flaw resulting in a catastrophic tank failure.

4.12.4 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.

4.12.5 For purposes of POD studies, the NDT procedure should be classified into one of three categories:

4.12.5.1 Those which produce only qualitative information as to the presence or absence of a flaw, that is, hit/miss data,

4.12.5.2 Those which also provide some quantitative measure of the size of the target (for example, flaw or crack), that is, $\hat{a}$ versus *a* data, and

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

4.12.6 *Detailed POD Guidance*—For detailed guidance on how to conduct a POD study, including system definition and control, calibration, noise, demonstration design, demonstration tests, data analysis, presentation of results, retesting, and process control plan, consult MIL-HDBK-1823.

4.12.6.1 For detailed guidance on how to conduct a POD study for ET, PT, and UT, consult MIL-HDBK-1823, Appendices A through D, respectively.

4.12.6.2 For detailed test program guidance; specimen design, fabrication, documentation, and maintenance; statistical analysis of NDT data; model-assisted determination of POD; special topics; and related documents, consult MIL-HDBK-1823, Appendices E through J, respectively.

4.13 *NDT Data Reliability*—MIL-HDBK-1823 provides nonbinding guidance for estimating the detection capability of NDT procedures for examining either new or in-service hardware for which a measure of NDT reliability is needed. Specific guidance is given in MIL-HDBK-1823 for ET, PT, and UT. MIL-HDBK-1823 may be used for other NDT procedures, such as RT or Profilometry, provided they provide either a quantitative signal, $\hat{a}$, or a binary response, *hit/miss*. Because the purpose is to relate POD with target size (or any other meaningful feature like chemical composition), "size" (or feature characteristic) should be explicitly defined and be unambiguously measurable, that is, other targets having similar sizes will produce similar output from the NDT equipment. This is especially important for amorphous targets like corrosion damage or buried inclusions with a significant chemical reaction zone. Other literature on NDT data reliability is given elsewhere (**2-7**).

NOTE 14—AE as generally practiced does not yield the size of a flaw in a metallic liner of a COPV; however, can be used for accept-reject of COPVs (see Section 7 in both this guide and Guide E2981).

4.14 *Further Guidance*—Additional guidance for fracture control is provided in other governmental documents (NASA-STD-5003, SSP 30558, SSP 52005, NSTS 1700.7B), and non-government documents (NTIAC-DB-97-02, NTIAC-TA-00-01).

5. Basis of Application

5.1 *Personnel Certification*—NDT personnel should 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 should be specified in any contractual agreement between the using parties.

5.2 *Personnel Qualification*—NDT personnel should 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 should be qualified and evaluated as described in Specification E543. The applicable edition of Specification E543 should be specified in the contractual agreement.

5.4 *Selection of NDT*—Choice of the proper NDT procedure (outside of those required per ANSI/AIAA S-081, KNPR 8715.3 and AFSPCMAN 91 710) is determined primarily by the flaw to be detected and the sensitivity of the NDT procedure for that given flaw. Secondary considerations include *(a)* any special equipment or facilities requirements, or both, *(b)* cost of examination, and *(c)* personnel and facilities qualification.

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

5.4.1 The desired NDT output should be clearly separated from responses from surrounding material and configurations and should 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, and *(e)* health monitoring. After the COPV has been installed (stages *d* and *e*), NDT measurements should 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. During in-service examination, the vessel is removed and examined, while during health monitoring, the vessel is examined *in-situ*. Currently, none of the NDT procedures listed in this standard are capable of *in-situ* health monitoring of metal liners of COPVs.

5.5.1 On-line process control NDT during welding or spin forming operations (column 2 in Table 1), can be used for feedback process control, since all tests are based upon measurements which do not damage the article under test.

5.5.2 The applicability of NDT procedures to evaluate metallic liners 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 should be the responsibility of manufacturer. After receipt and installation, scheduling of NDT should be the responsibility of the end user or designated subcontractors, or both. For example, in-service examination interval is determined based upon the growth of metallic liner 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 crack growth, fatigue (for example, pressure or fill) cycles should be the metric of scheduling (Fig. 2). For time-dominated drivers of failure, such as corrosion, the examination interval should be calendar-based. For mixed time and usage modes of failure such as environmentally assisted cracking under sustained stresses (for example, hydrogen embrittlement and stress corrosion cracking) the schedule should be based on analysis by the cognizant engineering organization. In case of fatigue, assuming a severe initial crack-like discontinuity (often called the "rogue flaw") denoted a_0, the amount of usage for this to grow a crack 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 4.8) to have one or more opportunities in this usage interval to detect the crack defect and repair or replace the COPV before failure (Fig. 2).

5.7 *COPV Mapping Convention*—All NDT techniques covered in this guide entail 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 predefined 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 predetermined 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 should be followed according to Guide D5687/D5687M to ensure data reproducibility and repeatability.

5.9 *Composite Overwrap Material Naming Conventions*—Guides E1309 and E1471 should be followed to ensure material traceability and uniform nomenclature are adopted for the fiber-reinforced polymer-matrix composite materials and constituent fibers and fillers, respectively.

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

5.10.1 Date and name of operator,

5.10.2 Vessel manufacturer,

5.10.3 Vessel model number and serial number,

5.10.4 Vessel geometry and dimensions,

5.10.5 Materials of construction and any applicable material certifications,

5.10.6 Date of cure,

TABLE 1 Application of Liner-Specific NDT Procedures during the Life Cycle of Composite Overwrapped Pressure Vessels

Procedure^A	Product and Process Design and Optimization	On-Line Process Control^B	After Manufacture Examination^C	In-Service Examination	Health Monitoring
Acoustic Emission	X	X		X	X
Eddy Current	X		X^D	X^D	
Laser Profilometry	X	X	X	X	
Leak Testing	X	X	X		
Penetrant Testing	X				
Radiography, buckling	X		X	X	
Radiography, welding	X	X	X	X	

^{A} Ultrasound also has utility but is not covered in this guide.
^{B} NDT performed during spin forming or welding operations.
^{C} NDT performed after composite wrapping or autofrettage operations.
^{D} Limited utility unless composite thickness is 0.25 mm (0.010 in.) or less.

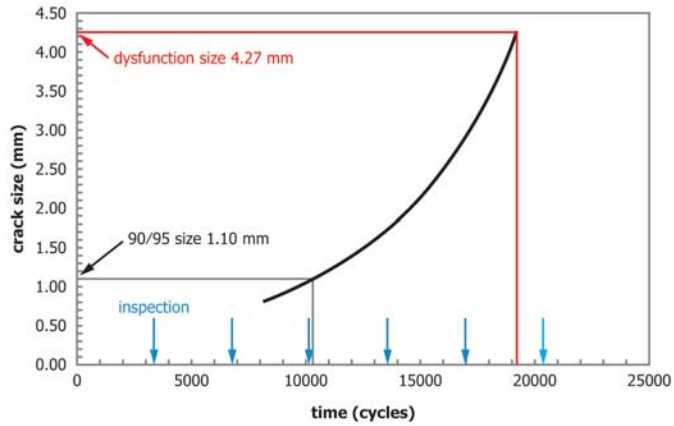

FIG. 2 Illustration of NDT Scheduling to Provide Two Examinations Between the Time a Flaw is Detectable and the Time at Failure for Case of Fatigue Mechanism

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

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

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

5.11 Additional provisions in Guide E1434 can be followed to further ensure uniform data recording procedures are followed for each of the NDT techniques discussed in this standard.

5.12 *Specific Reporting Recommendations*—For specific reporting recommendations that pertain to the NDT procedure, the equipment and sensor(s), special test conditions, and that ensure the data acquired on the vessel under test is reproducible and repeatable, consult any Specific Reporting Recommendations that appear in Sections 7 to 11.

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 metal 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 or behind concrete or metal walls, or both, 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 Testing

7.1 *Scope:*

7.1.1 This procedure describes application of acoustic emission for examination of thin-walled metallic liners in COPVs.

7.1.2 The primary purpose of this procedure is examination of welded liners after manufacturing. This practice can also be applied for examination of seamless liners.

7.1.3 AE examination is performed on metallic liners before composite wrapping. Examination of metallic liners in fabricated COPVs is beyond the scope of this procedure.

7.1.4 The AE measurements are used to detect, locate and assess the overall condition of metal liners, and to detect flaws in liner weldments, in their heat affected zones and in the base metal.

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. Possible NDT methods are covered elsewhere in this guide (ET–Section 8, LP–Section 9, LT–Section 10, PT–Section 11, and RT–Section 12).

NOTE 15—Ultrasonic Testing (UT) is commonly used to establish circumferential position and dimensions of flaw-indications detected by AE examination. Use of UT to corroborate AE measurement on welded or seamless metal liners is beyond the scope of this guide.

7.1.6 The procedures described are not intended to assess damage in the composite overwrap in COPVs. For AE procedures specific to detecting flaw initiation and growth in the COPV composite overwraps, consult Guide E2981.

7.2 *Summary of Procedure:*

7.2.1 AE measurements are conducted during pressurization and load holds of metal liners. Pressurizations are performed using the service gas, water, or oil. It is recommended that the AE examination be conducted during the first hydrostatic test.

NOTE 16—AE examination performed during the first pressurization provides important information about the condition of liner's welds, including presence of weld discontinuities that may grow and later cease propagating (in some cases temporarily) after application of initial load. AE examination during consecutive pressurizations can be less sensitive for detection of flaws, especially if it is performed under the same pressure levels or too soon after the previous pressurization, or both.

NOTE 17—Gas, water, or oil pressurization media will yield vastly different results in attenuation and alternative signal paths (for example, with liquid media, propagation from a source directly through the water to a sensor on the opposite side of the liner), which affect both signal characteristics and source location accuracy.

7.2.2 If measured emission exceeds acceptance criteria (7.8) then such locations should receive a secondary (for example, ultrasonic) examination.

7.2.3 Maximum test pressure should be defined by the manufacturer or designer in order to avoid any permanent damage or deformation of the liner due to overload. At a first approximation, the maximum AE test pressure is such that resulting maximum stresses are within the elastic limit of the metallic liner. However, defining the elastic limit of a weld, or of a seamless liner with geometric stress concentrations and biaxial stresses with complex yielding criteria is not trivial, and can result in an undefined elastic limit.

NOTE 18—By allowing testing up to the 'elastic limit,' which is a macroscopically defined quantity, it is possible AE can be generated from the yielding of multiple grains that have a favorable alignment of their slip systems. The resulting local yielding and corresponding AE could lead to the incorrect conclusion that the liner is defective, which may not be the case in actuality.

7.2.4 Pressurization rate should not exceed maximum safe rate defined by the manufacturer or designer. The pressurization rate also should be low enough to minimize/avoid frictional sources produced by the vessel expansion/movement, or that are otherwise produced by turbulent flow of the pressurization medium.

7.2.5 The pressurization should be slow enough so that the AE events do not overlap in time.

7.3 *Significance and Use:*

7.3.1 The goal of AE examination is to evaluate overall condition of thin-walled welded or seamless liner after their fabrication and before composite wrapping. For example, AE is used to identify events produced by metal yielding or damage leading to stress concentrations, or other unusual activity.

7.3.2 AE measurements can be used to detect, locate and assess flaw indications in liners.

7.3.3 Based on results of AE examination, liners can be accepted for service. Liners that do not meet acceptance criteria should be evaluated further by other NDT procedures.

7.3.3.1 Conversely, AE examination can be used to evaluate significance of flaw indications revealed by other NDT procedures covered in this guide.

7.3.4 Performing AE on COPVs after composite overwrapping will mask flaw indications attributable to the metallic liner, rendering detection of pre-existing flaws in the liner after manufacturing, or flaws produced during service due to microcracking and local plastic deformation of the metallic liner. For AE to detect per-existing flaws in the composite overwrap, and damage and flaw growth in the composite overwrap, consult Guide E2981.

7.4 *Apparatus:*

7.4.1 The essential features of the test apparatus are discussed in Section 7 of Practice E1419/E1419M. Specific instrument specifications for sensors, signal cables, couplant, preamplifiers, power/signal cables, power supply, and signal processor are given in the Annex (Mandatory Information) of Practice E1419/E1419M.

7.5 *Examination Preparation:*

7.5.1 Perform a visual examination of the liner and document any unusual or abnormal visual indications.

7.5.2 Install the liner in the test stand while isolating its surfaces from contact with other hardware using rubber, plastic, or other insulating materials.

7.5.3 Connect the pressurization equipment to the liner.

7.5.4 Mount AE sensor(s) on the liner so that the face of the sensor(s) is parallel to the tangent plane to the surface of the liner at the desired installation location. One sensor is normally enough for a small volume (less than two liter) liner for detecting flaw-development suspected activity, and to assess overall condition to guide other NDT procedures for additional examination of the liner when necessary. In cases where evaluation of precise location of AE source(s) is required, or where the liner and weld circumference is large, an appropriate number of sensors should be installed over the liner in order to allow accurate source location.

NOTE 19—Geometric spreading and dispersion can cause a large loss of signal amplitude and will be more problematic in liners with large volumes. Amplitude losses should be small enough so that detection of a source is not precluded at the maximum distance a source could be located from the sensor.

7.5.5 Use a couplant to acoustically connect the sensors to the liner. Sensor mounting hardware and couplant should be selected so that all channels will maintain their equivalent sensitivity and the sensors do not detach even after significant liner expansion (or contraction if repressurization is necessary).

7.5.6 Install additional sensor(s), when practical or needed, on the test stand holding the liner in order to filter out extraneous or spurious AE due to friction, impact, vibration, etc., originating outside of the liner.

7.6 *Calibration and Standardization:*

7.6.1 Perform standardization of the AE apparatus according to Section 9 of Practice E1419/E1419M.

7.6.2 The preferred technique for conducting performance verification is a pencil lead break (PLB) according to Guide E976; however, a piezoelectric pulser can also be used. The PLB data, distances, etc., should be documented as part of the examination report.

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

7.6.4 To examine with PLBs whether sources can be located with sufficient accuracy, first create a grid inside the sensor array with spacing at 1/4th to 1/5th 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.

7.6.5 If the locations cannot be determined with sufficient accuracy, then either use more sophisticated methods (for example, 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 20—PLB-generated AE signals are about 20 dB (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 metal liner.

7.7 *Procedure:*