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Standard Guide for Nondestructive Testing 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, the 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 2 m^3 (70 ft^3), and *(2)* high pressure COPVs used for storing compressed gases at MAWPs up to 70 MPa (10,000 psia) and volumes down to 8000 cm^3 (500 $in.^3$). Internal vacuum storage or exposure is not considered appropriate for any vessel size.

1.5 The 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 must 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 (ECT, Section 8), Laser Profilometry (LP, Section 9), Leak Testing (LT, Section 10), Penetrant Testing (PT, Section 11), and Radiologic 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 Due to difficulties associated with inspecting thin-walled metallic COPV liners through composite overwraps, and the availability of the NDE methods listed in Section 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.

1.8 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.

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

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1.9 Wherever possible, the NDT procedures described shall 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 1—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.

1.10 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 E07's forthcoming Guide for Nondestructive Testing of Composite Overwraps in Filament-Wound Pressure Vessels Used in Aerospace Applications.

1.11 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.

1.12 This guide does not specify accept/reject criteria (Section 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 shall be used when available and take precedence over any acceptance criteria contained in this document.

1.13 This standard 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 standard as methods of the former type.

1.14 To insure 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.

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

1.16 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C274 Terminology of Structural Sandwich Constructions
D1067 Test Methods for Acidity or Alkalinity of Water
D3878 Terminology for Composite Materials
D5687 Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation
E165 Practice for Liquid Penetrant Examination for General Industry
E215 Practice for Standardizing Equipment for Electromagnetic Testing 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 Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode
E499 Test Methods 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 Test Method for Radiographic Examination of Weldments
E1066 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
E1316 Terminology for Nondestructive Examinations
E1416 Test Method for Radioscopic Examination of Weldments
E1417 Practice for Liquid Penetrant Testing
E1419 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
E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases
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 Computed Radiology (Photostimulable Luminescence Method)
E2261 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
E2698 Practice for Radiological Examination Using Digital Detector Arrays

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

E2736 Guide for Digital Detector Array Radiology

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

2.2 *AIA Standard:*[3]

NAS 410 NAS Certification & 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-081 Space Systems—Composite Overwrapped Pressure Vessels (COPVs)

2.4 *AMS Document:*[5]

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

2.5 *ASME Document:*[7]

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:*[8]

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:*[9]

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:*[10]

21 CFR 1040.10 Laser products

21 21 FR 1040.11 Specific purpose laser products

2.9 *ISO Document:*[11]

ISO 9712 Non-destructive testing—Qualification and certification of NDT personnel

2.10 *Compressed Gas Association Standard:*[12]

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

2.11 *LIA Document:*[13]

ANSI, Z136.1-2000 Safe Use of Lasers

2.12 *MIL Documents:*[14]

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 *National Aerospace Standard:*[15]

NAS 410 Certification & Qualification of Nondestructive Test Personnel

2.14 *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

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

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

2.15 *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)

2.16 *Governmental Document:*[18]

AFRL-ML-WP-TR-2001-4011 Probability of Detection (POD) Analysis for the Advanced Retirement for Cause

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

[4] Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA, 20191-4344.

[5] Available from SAE Aerospace, www.sae.org, Warrendale, PA 15096.

[6] 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.

[7] Available from ASME, Three Park Avenue, New York, NY 10016-5990, 800-843-2763 (U.S/Canada), email: CustomerCare@asme.org.

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

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

[10] 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.

[11] Available from ISO copyright office, Case postale 56, CH-1211 Geneva 20, Switzerland.

[12] Available from Compressed Gas Association (CGA), 4221 Walney Rd., 5th Floor, Chantilly, VA 20151-2923, http://www.cganet.com.

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

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

[15] Available from Aerospace Industries Association of America Inc., Aerospace Industries Association of America , Inc., 1000 Wilson Blvd. Arlington, VA 22209.

[16] Available from the NASA Technical Standards System at the NASA website www.standards.nasa.gov.

[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/.

(RFC)/Engine Structural Integrity Program (ENSIP) Nondestructive Evaluation (NDE) System Development Volume 2—User's Manual (DTIC Accession Number ADA393072)

3. Terminology

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

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

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

3.3.1 *cognizant engineering organization*—see Terminology E1316.

3.3.2 *defect*—see Terminology E1316.

3.3.3 *discontinuity*—see Terminology E1316.

3.3.4 *flaw*—see Terminology E1316.

3.3.5 *fracture control*—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*—see Practice D1067, Section 3, Terminology.

3.4 *Definitions of Terms Specific to This Standard:*

3.4.1 *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.

3.4.2 *capability demonstration specimens*—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, i.e., probability of detection (POD) or other methods of capability assessment, of an NDT procedure.

3.4.3 *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.

3.4.4 *cracks or crack-like flaws*—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)*—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.

3.4.6 *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 examination) throughout the life cycle of the COPV. The MDPC shall 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*—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 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*—a documented statement defining the engineering criteria for rejecting a COPV based upon NDT.

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

3.4.10 *hit*—(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)*—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*—pressure for which a vessel is rated. Normally this value is stamped on the vessel.

3.4.13 *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.

3.4.14 *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 combinations thereof, are used to control pressure, collectively they shall be two-fault tolerant from causing the pressure to exceed the MDP of the system.

3.4.15 *minimum detectable crack size*—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*—an existing discontinuity that is missed during a POD examination.

3.4.17 *NDT reliability*—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*—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)*—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*—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*—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 LLB 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 $\hat{a}$—(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 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; FM-73, urethane, West 105, Epon 862 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 E07's forthcoming Guide for Nondestructive Testing of Composite Overwraps in Filament-Wound Pressure Vessels Used in Aerospace Applications.

4.2 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 2—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. So, as a precursor to liner fatigue, attention should be paid to liner buckling.

4.3 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:

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

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

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

4.4 Per 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:

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

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

4.5 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.

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

4.5.2 Per 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 the standard.

4.5.3 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.

4.6 *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 Section 4.6 in E07's forthcoming Guide for Nondestructive Testing of Composite Overwraps in Filament-Wound Pressure Vessels Used in Aerospace Applications). 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 shall be categorized as follows:

4.6.1 Inherent material discontinuities: inclusions, grain boundaries, etc., detected during *(a)* and *(b)* of subsection 4.2.

NOTE 3—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.

4.6.2 Manufacturing-induced discontinuities: caused by welding, machining, heat treatment, etc., detected during *(b)* and *(c)* of subsection 4.2.

NOTE 4—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.

4.6.3 Service-induced discontinuities: fatigue, corrosion, stress corrosion cracking, wear, accidental damage, etc. detected during *(d)* and *(e)* of subsection 4.2 (after the COPV has been installed). In these cases, NDT shall either be made on a "remove and inspect" or "*in-situ*" basis depending on the procedure and equipment used.

4.7 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 must be detected by NDT.

NOTE 5—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.

4.8 *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.

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

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

4.8.3 *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.

4.8.4 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.

4.9 *Certification of PVs*—ANSI/AIAA S-080 defines the approach for design, analysis, and certification of metallic PVs.

4.10 *Certification of COPVs*—ANSI/AIAA S-081 defines the approach for design, analysis, and certification of COPVs. More specifically, the PV or COPV thin-walled metal liner 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 procedure 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 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 must be addressed by the cognizant engineering organization.

4.10.1 *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 shall exhibit an LBB failure mode or shall possess adequate damage tolerance life (safe-life), or both. 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.

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 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).

4.11.1 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 6—$a_{90/95}$ 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.

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

NOTE 7—NDT of fracture critical hardware shall 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.

4.11.3 *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**).[19] Accordingly, POD testing on metallic COPV liners shall be performed at the bounds of the required range of crack aspect ratios.

NOTE 8—**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.

4.11.4 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.

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

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

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

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

4.11.6 *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.

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

4.11.6.2 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.

4.12 *NDT Data Reliability*—MIL-HDBK-1823 provides nonbinding guidance for estimating the detection capability of

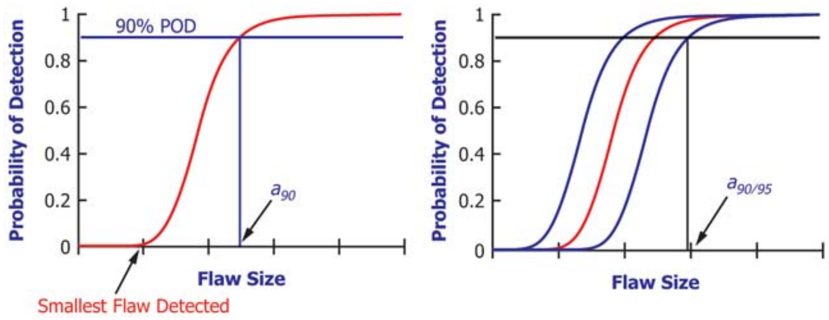

FIG. 1 Probability of Detection as a function of flaw size, POD(*a*), showing the location of the smallest detectable flaw and a_{90} (left). POD(*a*) with confidence bounds added and showing the location of $a_{90/95}$ (right).

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

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, i.e., 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 9—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 E07's forthcoming Guide for Nondestructive Testing of Composite Overwraps in Filament-Wound Pressure Vessels Used in Aerospace Applications).

4.13 *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 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 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.

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, 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. 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 shall be the responsibility of manufacturer. After receipt and installation, scheduling of NDT shall 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.

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.

For fatigue-dominated crack growth, fatigue (for example, pressure or fill) cycles shall be the metric of scheduling (Fig. 2). For time-dominated drivers of failure, such as corrosion, the examination interval shall 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 must 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 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 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 shall be followed according to Guide D5687 to ensure data reproducibility and repeatability.

5.9 *Composite Overwrap Material Naming Conventions*—Guides E1309 and E1471 shall 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 Requirements*—Regardless of the NDT procedure used, the following general minimum reporting requirements 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,

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 Requirements*—For specific reporting requirements 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 the corresponding Specific Reporting Requirements section 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

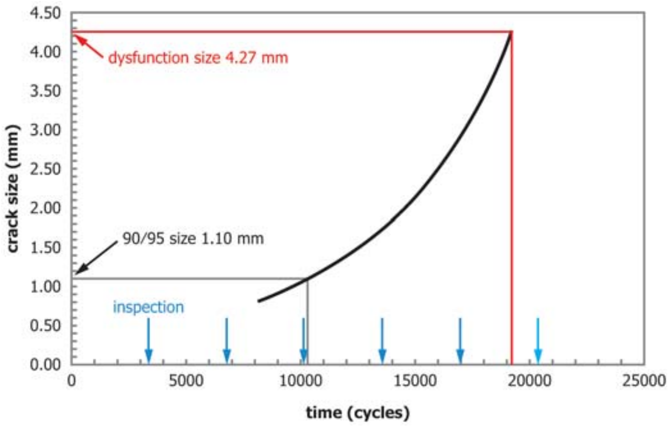

FIG. 2 Illustration of NDT scheduling to provide two examinations between the time a flaw is detectable and the time at failure for case of fatigue mechanism

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

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 (ECT–Section 8, LP–Section 9, LT–Section 10, PT–Section 11, and RT–Section 12).

NOTE 10—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.

7.2 *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 11—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 12—Gas, water, or oil pressurization media will yield vastly different results in attenuation and alternative signal paths (e.g., 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 shall receive a secondary (for example, ultrasonic) examination.

7.2.3 Maximum test pressure shall 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 13—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 shall not exceed maximum safe rate defined by the manufacturer or designer. The pressurization rate also shall 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 shall 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.

7.4 *Apparatus:*

7.4.1 The essential features of the test apparatus are discussed in Section 7 of Practice E1419. 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.

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 14—Geometric spreading and dispersion can cause a large loss of signal amplitude and will be more problematic in liners with large volumes. Amplitude losses must 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.

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., shall 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 (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 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:*

7.7.1 Monitor the AE background noise long enough to identify all extraneous sources of spurious AE. In the case of elevated background noise, identify the source(s) of the noise and eliminate or reduce it to the lowest possible level. Noise signals with an amplitude above 40 dB_{AE} may reduce reliability of the examination.

7.7.2 Begin pressurization while observing AE activity. If an unusual response is observed, interrupt pressurization and analyze the AE data or use other NDT methods, or both, to identify the reason for the unusual AE activity.

7.7.3 Check for absence of leaks. If there is an indication of a leak, interrupt pressurization and fix the leak after venting to zero.

7.7.4 Continue pressurization until the maximum test pressure is reached. Hold at this pressure for 5 minutes. Longer hold times should be approved by the manufacturer/designer. Ideally, the pressure shall be controlled with an accuracy of ±2 percent of the maximum examination pressure to ensure reproducible pressure loading of the liner.

NOTE 16—The 5-minute hold time proposed here is illustrative. The actual hold time used will require validation using the AE data generated during one or more preliminary tests.

7.7.5 If significant or abnormal exponentially growing activity is detected, interrupt the test, analyze the AE data or use other NDT methods, or both, to identify the reason for the exponentially growing AE activity.

7.7.6 In a case of large volume liners that require long fill times or when frictional noises cannot be effectively eliminated, an alternative pressurization schedule following ASME Section V Article 12 can be applied with the following modifications:

7.7.6.1 Duration of the last hold time at maximum test pressure will be 3 minutes. If longer hold times are needed, approval by the liner manufacturer/designer must be sought.

7.7.6.2 A second pressurization cycle performed at the maximum test pressure shall be unnecessary unless *(1)* significant flaw suspected activity is detected and confirmed, or *(2)* the results are inconclusive.

7.7.7 Reduce the pressure to zero and perform verification of the AE system and AE sensor performance.

7.8 *Report:*

7.8.1 Prepare a written report for each examination containing the following information:

7.8.1.1 Examination date and place,

7.8.1.2 Liner material, geometry, wall thickness, position and description of welds, their type and the welding procedure,

7.8.1.3 Loading schedule, maximum test pressure and pressurization rate,

7.8.1.4 Pressurization medium,

7.8.1.5 Position of sensors (in welded liners, report the location of the sensor(s) relative to the weld),

7.8.1.6 Couplant,

7.8.1.7 PLB data and distances,

7.8.1.8 Visual examination results,

7.8.1.9 Locations of AE sources that exceed acceptance criteria. Report the surface area used to define multiple AE events taken as being from the same location and the propagation velocity used for location calculations, and

7.8.1.10 AE examination results, including events versus location plots and cumulative events versus a pressure plot for each vessel.

7.8.1.11 Report occurrence of AE activity at pressure levels below 50 % of the maximum pressure levels even if the activity disappears at higher pressure. During the first pressurization of a liner, such activity can be a result of micro-discontinuity formation, which in some cases can have lengths of 30 to 100 µm (0.001 to 0.004 in.) and which develop in liner's welds. Such discontinuities can stop propagating at higher loads. Nevertheless, they represent a structural risk factor and can reduce liner's useful service life or pressure bearing capability in service.

7.8.1.12 Report on the presence of zones in the liner with an increased root mean square (RMS) level of noise recorded by any sensor compared with the RMS level measured before pressurization. An increased RMS level (when possibility of interference is rejected) can indicate local plastic deformation development and growth of micro-discontinuities under stress.

7.9 *Acceptance and Rejection Criteria:*

7.9.1 Acceptance and rejection criteria for metal liners can be obtained from testing a statistically significant number of liners (including burst tests) followed by nondestructive and destructive evaluations performed by other methods. The following consideration can be used as initial and non-mandatory criteria:

7.9.1.1 A small liner with one-sensor installation can be accepted for service if (during pressurization with slow pressurization rates or during pressure holds for high pressurization rates) no more than total six signals with an amplitude above 50 dB_{AE} are detected at pressure levels above 50 % of the maximum test pressure and no apparent increase of the RMS level was observed.

NOTE 17—Numerical pass/fail criteria will vary depending on metallic liner material-of-construction, and different types of liners are expected to yield different emission under test regardless of the size, orientation, or nature of the defect sources.

7.9.1.2 A liner with several sensors installed can be accepted for service if in any location there are no more than six signals detected in the same location (during pressurization with slow pressurization rates or during pressure holds for high pressurization rates) having amplitudes above 50 dB_{AE} at pressure levels above 50% of the maximum test pressure and no increase in the RMS level noise at any sensor.

NOTE 18—The area size of the calculated locations (so that the events said to come from the same location) can be defined conservatively as at least 2–3 time fold of location error obtained using PLB tests.

7.9.1.3 A liner that does not meet acceptance criteria shall be reexamined by other NDT procedures per the discretion of the cognizant engineering organization. Once a flaw-indication is confirmed and sized, evaluation of its criticality is performed to evaluate whether the flaw indication is rejectable.

7.10 *Precision and Bias:*

7.10.1 *Location accuracy* is influenced by factors that affect elastic stress wave propagation including thickness of the liner, propagation distance, leakage of elastic energy and alternate paths across the liner for hydro testing, sensor coupling, and by signal processor settings.

7.10.2 It is possible to measure AE and determine AE source locations that cannot be verified by other NDT procedures, especially in case of a system of micro-discontinuities developing in liner's welds.

8. Eddy Current

8.1 *Scope:*

8.1.1 This guide describes procedures for ECT of metallic liners used in COPVs. These procedures are capable of detecting surface-breaking and subsurface discontinuities such as cracks, pitting, and wall thinning.

8.1.2 Although ECT can be used to examine both the composite overwrap and the metallic liner of COPVs, procedures included here focus on the metallic liner. For use of ECT to interrogate the composite overwrap, consult E07's forthcoming Guide for Nondestructive Testing of Composite Overwraps in Filament-Wound Pressure Vessels Used in Aerospace Applications.

8.1.3 ECT is generally most sensitive to the liner surface that is proximate to the sensor being used. However, by selecting appropriate instrument operating parameters, the condition of both the near-surface (exterior) and far-surface (interior) can be determined. Eddy current methods can also be used to examine the liner through the composite overwrap, as long as an appropriate sensor is used to account for the thickness of the overwrap and the sensitivity of the sensor to the discontinuities of interest has been demonstrated.

8.1.4 For quantifying crack detection and crack length estimation capabilities in support of damage tolerance analyses of the liners and COPVs, a POD study should be employed.

8.2 *Summary of Procedure:*

8.2.1 The examination is performed by scanning an eddy current sensor or eddy current sensor array over the surface of the material being examined, 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 material being examined. The extent of this modification is determined by the distance between the eddy current sensor and the material being examined, as well as the dimensions and electrical properties (conductivity and magnetic permeability) of the material. The presence of local metallurgical or mechanical discontinuities 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.

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 determine the presence and characteristics of discontinuities. 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 detect and characterize the discontinuity.

8.2.3 Processing parameters, such as the operating frequency, scan rate, and standardization procedure are determined by the sensor selection, specific materials used, the nature of the part to be examined, and the type of discontinuity expected. Standardization of the sensor is performed on a reference standard having suitable discontinuities of known dimensions or, for the case of model-based sensors, on a material with uniform properties. For both types of standardization, a performance verification is required in which the signal variation due to the discontinuity as well as any background variations associated with discontinuity-free regions of the reference standard are to be within specified tolerances.

8.3 *Apparatus:*

8.3.1 *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 the sensor or 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.

8.3.2 *Eddy Current Sensor*—The eddy current sensor or sensor array shall be capable of inducing currents in the metallic liner and sensing changes in the physical characteristics (electrical conductivity, thickness, and magnetic permeability) of the liner. The eddy current sensor may be a surface probe type or a sensor array that can contain an exciter (drive) coil and one or more sensors, multiple pairs of drive/sensor coils, or an array of surface probes. The sensor face may be protected from abrasive wear during scanning by an adhesive polymeric tape or film, if so, the same film material and thickness used to scan the liner shall be used for scanning the reference standard.

8.3.3 *Reference Standard*—The reference standard used to adjust the sensitivity setting of the apparatus or to verify system operation, or both, shall be of the same nominal alloy and temper as the material to be examined. Artificial discontinuities can be made in the reference standard and can be notches made by electric discharge machining (EDM). Orientation, dimensions (width, length, and depth), and configuration of the notches affect the eddy current sensor response. Notches may be placed on the outer surface (liner surface nearest the sensor), inner surface (liner surface farthest from the sensor), or both surfaces of the reference standard. The configuration, orientation, and dimensions (width, length, and depth) of the artificial discontinuities to be used for establishing acceptance limits should be subject to agreement between supplier and purchaser. Discontinuities can also be formed by service-related usage or other fatigue procedures but must be verified using another NDT (for example, visual) procedure.

8.3.4 Specific apparatus requirements may be found in material- or application-specific standards.

8.4 *Calibration and Standardization:*

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

8.4.2 Fabricate applicable reference standards in accordance with the agreement between the user and COPV manufacturer. Reference standards should be fabricated from the same material, be the same configuration and wall thickness, and have received the same processing as the vessel liner. Artificial discontinuities should be sufficiently separated so that their signals will not interfere with each other. Reference standards should contain no discontinuities other than those intended to produce reference signals. Wear of the reference standard can play an undesirable role.

8.4.3 The instrument should be assembled, turned-on, and allowed sufficient time to stabilize in accordance with the manufacturer's instructions before use. Beware of temperature variations and their effect on instrumentation and reference standards.

8.4.4 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.

8.4.4.1 If adjustment on a reference standard is required, then the equipment is to be adjusted to obtain an optimum signal-to-noise ratio with the minimum sensitivity required to detect the discontinuities in the reference standard.

8.4.4.2 For model-based sensors, standardization using measurements in air or on a discontinuity-free reference material, or both, 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 (e.g., 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. For example, for examining nonmagnetic materials for cracks, the lift-off response can be used to ensure that the sensor array is within an acceptable range for the examination while the conductivity response can be used to indicate the presence and size of the crack.

8.5 *Procedure:*

8.5.1 Standardize the examination equipment prior to the examination. The recommended maximum interval between restandardization is 4 hours 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 all material examined since the last successful standardization.

8.5.2 Scan the sensor or sensor array over the surface of the liner in a manner which ensures complete coverage of the surface. Monitor the condition of the protective film or tape, if used, to minimize variations in lift-off.

8.5.3 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.

8.5.4 Additional guidance for examination procedures can be found in application or material specific standards.

8.5.4.1 Guidance for setting operational parameters for the examination of liners made from aluminum alloys can be found in Practice E215.

8.5.4.2 Guidance for setting operational parameters for the examination of liners made from austenitic stainless steel and similar alloys can be found in Practice E426.

8.5.4.3 Guidance for examination of welds for surface-breaking discontinuities can be found in Practice E2261.

8.5.5 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 examination to examination.

8.6 *Significance of Data:*

8.6.1 ECT methods are used for nondestructively locating and characterizing discontinuities in magnetic or nonmagnetic conducting materials.

8.6.2 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 providing a discontinuity size. This information can be used to establish a starting flaw size for damage tolerance analyses of liners and COPVs.

8.6.3 Liners that contain discontinuities that are large enough to be considered "fracture critical flaws," or that contain discontinuities that are large enough to grow to fracture critical size before a reexamination is performed, shall be removed from service.

8.6.4 Several example procedures illustrate the selection of sensors and operating conditions and provide representative results. Additional details are typically required in operational procedures.

8.6.4.1 *Example 1*—Outer surface examination of bare liner for outside diameter fatigue cracks.

(1) Target examination: Detection of 0.51 mm (0.020 in.) long × 0.25 mm (0.010 in.) deep flaw at outside diameter of 15 cm (6 in.) diameter polished cylindrical 6061-T62 aluminum alloy liners.

(2) Probe Type: 500 kHz absolute unshielded eddy current probe.

(3) Scan attributes: An automated scanning system held the probe normal to the liner surface while the probe was scanned using a 3.8 cm (1.5 in.) per second scan velocity with data acquisition rate of 60 samples per second to achieve a grid spacing of 0.64 mm (0.025 in.). The liner was rotated 0.4 degrees and the probe returned to the nozzle end of the liner before the next scan line of data was acquired. Impedance data in phase and 90º out of phase with the lift-off direction were saved as a function of position for data processing.

(4) Data Processing: C-scan plots of the eddy current data were constructed from the acquired probe impedance data, with surface defects highlighted in the component of the impedance 90º out of phase with that due to a change in the probe-to-part spacing.

(5) Results: Fig. 3 displays the C-scan results for a 3.5 cm (9 in.) × 60º section of the liner containing a 0.51 mm (0.02 in.) long × 0.25 mm (0.01 in.) deep laser notch.

8.6.4.2 *Example 2*—Outer surface examination of 2.3 mm (0.090 in.) thick bare liner for inside diameter fatigue cracks.

(1) Target examination: Partially through the thickness fatigue cracks initiating at the inside diameter of 15 cm (6 in.) diameter polished cylindrical 6061-T62 aluminum alloy liners with 2.3-mm (0.090-in.) wall thickness.

(2) Probe Type: Commercial version of the self-nulling eddy current probe (**8**) in driver pickup mode at an operating frequency of 5 kHz.

(3) Scan attributes: An automated scanning system held the probe normal to the liner surface while the probe was scanned using a 3.8 cm (1.5 in.) per second scan velocity with data acquisition rate of 30 samples per second to achieve a grid spacing of 1.3 mm (0.05 in.). The liner was rotated and the probe returned to the nozzle end of the liner before the next scan line of data was acquired, enabling the entire cylindrical region of the liner to be scanned in 2.5 hours. Impedance data in phase and 90º out of phase with the lift-off direction were saved as a function of position for data processing.

(4) Data Processing: C-scan plots of the eddy current data were then constructed from the acquired probe impedance data, with internal defects highlighted in the component of the impedance 90º out of phase with that due to a change in the probe to part spacing.

(5) Results: Fig. 4 displays C-scan results for detection of naturally occurring inside diameter fatigue cracking.

8.6.4.3 *Example 3*—Outer surface examination of wrapped COPVs for liner fatigue cracks.

(1) Target examination: Detection of 2.5 mm (0.1 in.) long by 0.64 mm (0.025 in.) deep outside diameter fatigue cracks through the overwrap in 15 cm (6 in.) diameter polished cylindrical 6061-T62 aluminum alloy liners with carbon composite overwrap thickness of approximately 1.5 mm (0.06 in.).

(2) Probe Type: Custom wound 100 kHz tangential differential eddy current probe.

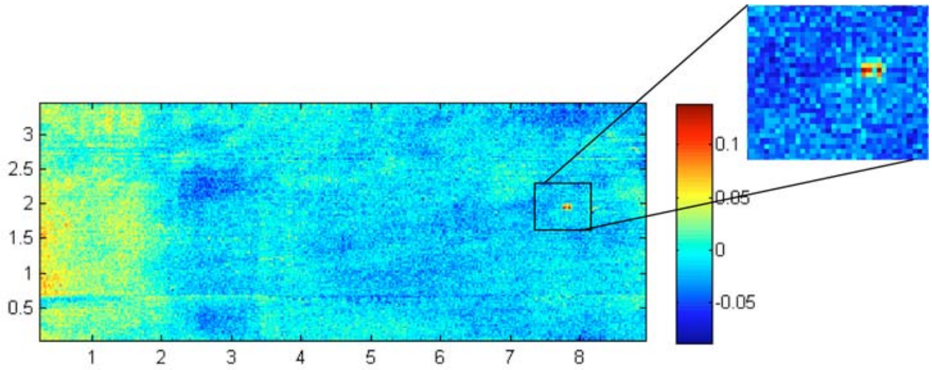

FIG. 3 Eddy current examination results for 0.51 mm (0.020 in.) long × 0.25 mm (0.010 in.) deep laser cut notch in the outside diameter of an Al6061 liner. The horizontal and vertical axes of the image are in inches.

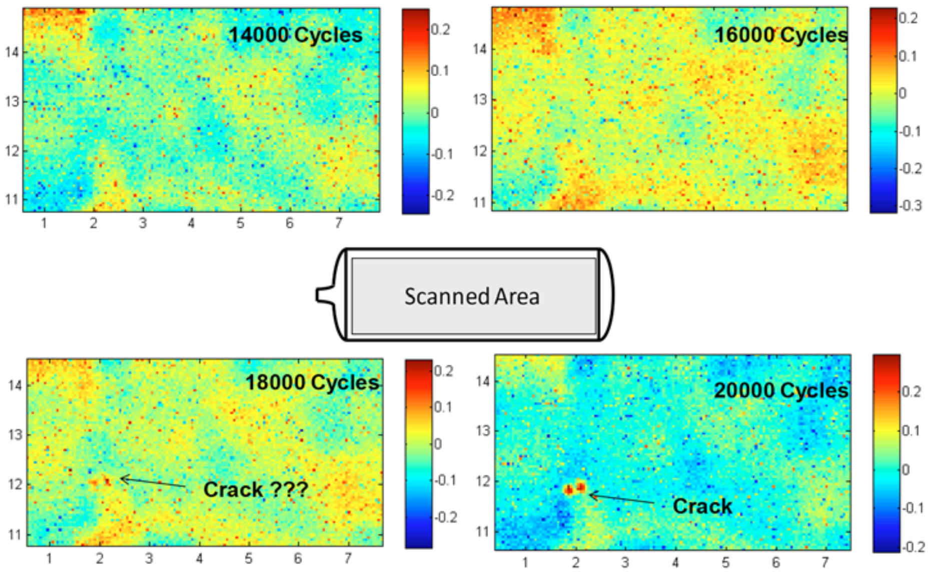

FIG. 4 The results of the eddy current scan of a bare liner. The color indicates the relative intensity of the signal. The horizontal and vertical axes of the images are in inches.

(3) Scan attributes: An automated scanning system held the probe normal to the liner surface while the probe was scanned using a 3.8 cm (1.5 in.) per second scan velocity with a data acquisition rate of 50 samples per second to achieve a grid spacing of 0.76 mm (0.030 in.). The liner was rotated and the probe returned to the nozzle end of the liner before the next scan line of data was acquired. Impedance data in phase and 90º out of phase with the lift-off direction were saved as a function of position for data processing.

(4) Data Processing: C-scan plots of the eddy current data were constructed from the acquired probe impedance data, with defects beneath the overwrap typically highlighted in the component of the impedance approximately 70º out of phase with the lift-off direction.

(5) Results: Fig. 5 displays C-scan results for detection of three outside diameter fatigue cracks beneath the carbon overwrap.

8.7 *Reporting:*

8.7.1 An examination report should contain the following information:

8.7.1.1 Date of examination and name of operator,

8.7.1.2 Instrument, probe, and sensor identification, including protective tape material and thickness, if used,

8.7.1.3 Identification of components and/or location of examination, or both,

8.7.1.4 Material(s) of the component,

8.7.1.5 Date of last instrument standardization and type and frequency of standardization,

8.7.1.6 Frequencies used,

8.7.1.7 Orientation of the probe relative to any component geometrical features,

8.7.1.8 Examination procedure identification, including scanning speed, and

8.7.1.9 Results of examinations including identification of indications and whether they fall within an acceptable range.

8.8 *Precision and Bias:*

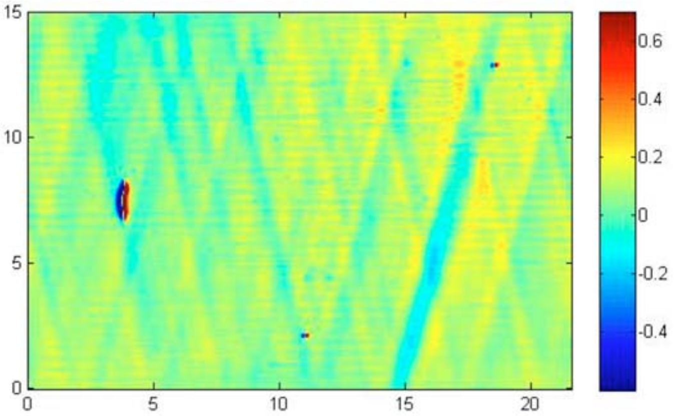

FIG. 5 The results for eddy current scan of COPV with carbon overwrap. Three features are highlighted in the image and the largest was confirmed to be a through the thickness crack. The horizontal and vertical axes of the image are in inches.

8.8.1 The accuracy of an eddy current measurement can be affected by the instrument, its standardization, its operating condition, such as frequency, as well as the material condition, such as the material properties and component geometry. The reliability of a measurement procedure for a specific examination requires demonstration through a POD study that is guided by MIL-HDBK-1823.

8.8.1.1 The selection of sensor or sensor array dimensions and operating frequency is based on the type of examination being performed and affects the type of discontinuity, surface-breaking and sub-surface, that can be observed. The depth of penetration of eddy currents into the material under examination 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.

8.8.1.2 Insulating coatings may be present between the sensor and the liner surface. The sensitivity of a measurement to a discontinuity generally decreases as the coating thickness increases.

9. Laser Profilometry

9.1 *Scope:*

9.1.1 Laser profilometry is used to examine the interior and exterior surfaces of a PV or COPV, and rapidly generate quantitative, high-resolution radial surface plots using a non-contact sensor.

9.1.2 Profilometry allows accurate evaluation of both the amplitude and periodicity of various surface features or defects.

9.1.3 Profilometers with specially articulated probes are used to examine vessels of variable shape (typically spherical or cylindrical) and size, and that can be inserted through the vessel end ports as small as 7 mm (0.25 in.). Under field conditions, measurement accuracy of 0.025 to 0.05 mm (0.001 to 0.002 in.) is typical. Accuracy is primarily limited in COPV inspection by the relatively large measurement range required to inspect irregular surfaces.

9.1.4 Profilometry can directly support examinations of flight vessels during development and qualification programs and subsequently be implemented into manufacturing examinations to screen out vessels with "out of family" surface features or defects.

9.1.5 Profilometry will not detect subsurface features and is often used before and in conjunction with more elaborate and costly NDT procedures, such as radiography, ultrasound and eddy current, that are sensitive to subsurface features.

9.2 *Summary of Procedure:*

9.2.1 Laser profilometers rapidly scan a tiny laser beam over the surface of a vessel, generating a quantitative, three-dimensional map. The results can be used to detect and accurately map defects, flaws, or dimensional variations. The laser spot size can be focused as small as 0.025 mm (0.001 in.), permitting extremely high spatial resolution with up to 100 % surface coverage, and sensors with profile depth resolutions to 0.0025 mm (0.0001 in.) are available. Operators view examination results in near-real time using computer-graphic formats. Laser profile sensors use optical triangulation to determine the distance between the sensor and the target surface. Optical triangulation requires a light source, imaging optics, and a photodetector (Fig. 6). The light source and focusing optics generate a collimated or focused beam of light that is projected onto a target surface. An imaging lens captures the scattered light and focuses it onto a photodetector. As the target surface distance changes, the imaged spot shifts due to parallax. The optical system is designed to maintain high accuracy when measuring challenging textures, such as contoured specular surfaces. To generate a three-dimensional image of the part surface, the sensor is scanned in two dimensions, thus generating a set of distance data that represents the surface topography of the part. In practice, the output voltage, V_R, which is produced by photodiode signal processor, is proportional to radial distance to the target surface.

9.3 *Significance and Use:*

9.3.1 Profilometry examination includes but is not limited to detection and examination of surface finish, cracks, pits, corrosion, superficial foreign material inclusions, depressions, dents, wrinkles, and buckling.

9.3.2 During vessel design and development it is important to compare vessel deformation under applied pressure to the

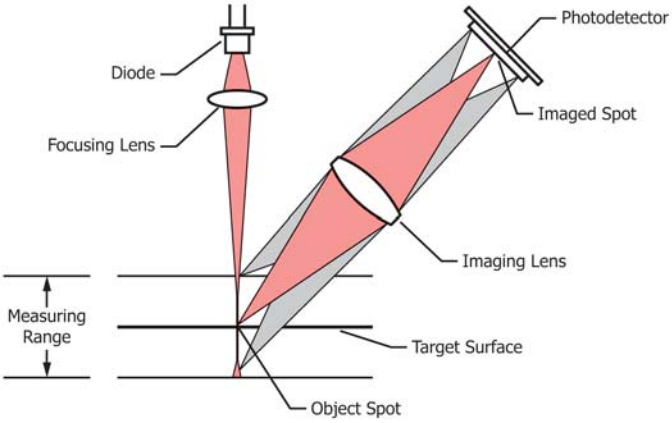

FIG. 6 Principle of Operation of a Laser Profilometer

predicted deformation. Similarly, during manufacturing, it is important to compare deformation of each vessel to nominal "in family" deformation.

9.3.3 Profilometry may involve review of a vessel's data package to verify proper materials and dimensions are maintained. It may also involve examination of quality records (autofrettage records, pressures cycles, impact control plan, certificates of material conformance, etc.) to ensure engineering design is maintained. In some instances these data review and dimensional check portions of the examination are conducted by an examiner assigned to the fabrication work area while the defect screening examination is performed by a qualified NDT specialist more familiar with defect detection and the other NDT examination processes, which may be needed to confirm profilometry examination results.

9.3.4 This procedure provides a rapid, wide field survey of a vessel to ensure design and material compliance. It also ensures that no mechanical damage has occurred to the vessel. This NDT procedure is often complemented with additional NDT to better understand the nature of the indication. For example, profilometry can be used to accept or reject large, costly aerospace structures to verify the absence of surface voids, excessive wrinkles, or buckling. Once the structure is accepted, other NDT procedures can be used for more elaborate qualification.

9.3.5 *Laser Video Imaging*—In most cases it is useful to know whether a surface has been exposed to small scratches, changes in surface roughness, or even staining. By post-processing the received signal from profilometer sensors, operators are able to obtain much more information regarding the condition of a component than if they only used dimensional information. If generated at adequate resolution, the image produced provides near photograph resolution quality.

9.4 *Basis of Application:*

9.4.1 Profilometry is performed immediately after manufacturing, and is particularly well suited for examining to interior of COPVs after autofrettage.

9.4.2 Profilometry is often required during in-service examination, especially for vessels exposed to flight environments, thermal fluctuations, and impact or handling-induced damage.

9.5 *Apparatus:*

9.5.1 The laser profilometer shall consist of a light source (sensor), imaging optics, and a photodetector.

9.5.2 Almost any light source can be used for basic optical triangulation; however, typical wavelengths ranging from as low as 375 to over 1000 nm are used.

9.5.3 The photodetector shall be either a lateral-effect detector for high-speed measurement, or a CCD for environments with high background light.

9.5.4 Lateral-effect photodetectors generate signals proportional to the position of the spot in its image plane.

9.5.5 Rotary, translational, or fixed laser profile sensors are used.

9.5.6 These sensors are normally attached to robotic arms or other scanning mechanisms. For example, an articulated sensor system is used to examine vessels with ellipsoidal heads.

9.5.7 Control and analysis software shall provide a variety of options for motion control, data acquisition, analysis, and display.

9.6 *Calibration and Standardization:*

9.6.1 Profilometers are generally standardized using a suitable two- or three-step physical reference standard that is traceable to the National Institute of Standards and Technology (NIST).

9.6.2 The normalized output voltage (V_R) is standardized by acquiring a series of distance measurements over the sensor's measuring range. The distances and associated voltage readings are then correlated using a mathematical equation. Typically a second or third-order polynomial equation will describe the sensor with sufficient accuracy to meet most needs. This Calibration Curve is unique to each probe and probe type. It is influenced by a number of factors, including total measuring range as well as the type and quality of optics being used for a given application.

9.7 *Special Safety Precautions:*

9.7.1 *Specific Requirements for Laser Safety*—Laser-based profilometry examination systems normally operate in the visible range as a Class 2 laser product, which means that operators do not have to use special eye protection and laser warning signs and barriers are not required. For information on laser safety guidelines, consult ANSI Z136.1.

NOTE 19—**Caution:** Operators should NEVER stare into the laser beam or disassemble the sensor.

NOTE 20—Class 2 diode laser operating at a 630 – 680 nm (visible) wavelength and a maximum output power rating of 5 mW have been shown to be useful for characterizing the inside of COPVs with aluminum-liners.

9.7.2 When the laser is on and there is no target within the measuring range of the sensor, it will operate in a low-power pulse mode as long as the reflected signal is below a pre-set threshold. When the system is in this mode, the total radiance and integrated radiance comply with 21 CFR 1040.10 for Class 2 operation.

NOTE 21—**Caution:** During laser service or repair, the laser will remain on continuously, and the laser source is classified as Class 3a, in which case the operator must wear protective eyewear and follow requirements as set forth in ANSI Z136.1.

9.7.3 *General Requirements for Laser Safety*—Depending on the performance demands of the application, a variety of diode laser sizes, wavelengths, and power outputs are possible. The inherent hazards associated with using non-Class 2 lasers must be known and appropriate precautions taken. With the exception of extremely low-powered laser systems, virtually all laser products pose some form of hazard; most often associated with the direct exposure of the eyes and skin to the laser light. Laser systems are classified in the United States according to the Center for Devices and Radiological Health (CDRH) division of the Food and Drug Administration (FDA). The applicable federal documents are 21 CFR 1040.10 and 21 CFR 1040.11. In the European community, laser system standards are overseen primarily by the International Electrotechnical Commission (IEC) and the British Standards Institution (BSI). The applicable European document is EN 60825-1. Additional federal, state, and local regulations may also apply to the use and classification of laser products depending on the intended location of the system. Many of these regulations are based on classification data provided by the American National Standards Institute (ANSI). ANSI Z136.1-2000 provides detailed information regarding Hazard Evaluation and Classification, Control Measures, Laser Safety Programs and Employee Training, Medical Surveillance, Non-beam Hazards, Criteria for Exposure of Eye and Skin, and Small and Extended Source Measurements. From a practical standpoint, laser profilometry systems should be classified so as to provide the most usable system for the operator with the least restrictions. To minimize hazard and restrictions, systems with classification of Class 1, 2, and 3a (3r IEC) are the preferred classifications for profilometry systems.

9.7.3.1 Systems classified as Class 1 and 2 laser systems generally do not require any special safety consideration beyond a basic understanding of the safe use of lasers. Under normal working conditions, Class 3a laser systems extend allowable output emissions of the laser system by 5 times those of Class 2 laser systems without adding additional restrictions beyond a more in-depth knowledge of safe laser operation. When using Class 3a laser systems, care must be taken not to view the laser emissions with any optical system that will increase concentration of the laser light (i.e., binoculars or telescopes). This does not include normal corrective lenses.

9.7.3.2 Class 3b and Class 4 laser systems should generally be avoided for all but laboratory systems due to required operating restrictions and the need for additional medical surveillance.

9.8 *Procedure:*

9.8.1 Set up the system, making sure all cable attachments have been made.

9.8.2 Turn on the laser and allow sufficient time for warm-up.

9.8.3 Calibrate the sensor and generate the Characteristic Curve (Section 9.6.2).

9.8.4 Select the desired scan parameters, for example, the scan type, scan rate, rotary speed of the sensor, scan length, linear resolution, and scan speed.

NOTE 22—Relatively slow scan rates are typically used (25 to 75 mm/sec).

NOTE 23—Rotary sensors, when used, rotate at a relatively high rate (e.g., 200–300 rpm).

9.8.5 Verify gain setting and scan start position.

9.8.6 Execute the scan, drawing the sensor through the vessel, and save the scan data. By encoding both the axial and radial position of the sensor as the data is acquired, a high-resolution map of the vessel ID is generated.

9.8.7 Analyze the scan data, applying any post-processing data manipulation parameters.

9.8.8 Data may also be exported for further analysis and processing using commercial scientific software packages.

9.9 *Significance of Data:*

9.9.1 Profilometry can directly support examinations of flight vessels during development and qualification programs and subsequently be implemented into manufacturing examinations to screen out vessels with “out of family” defects.

9.9.2 Depending on the size of the defects, and their growth rate under applied pressure, pass/fail criteria can be developed and remaining life estimated for a given in-service pressure schedule.

9.10 *Reporting:*

9.10.1 The examination record shall consist of the following:

9.10.1.1 Calibration data,

9.10.1.2 The scan parameters, for example, the scan type, scan rate, rotary speed of the sensor, scan length, linear resolution, and scan speed,

9.10.1.3 Post-processing data manipulation parameters,

9.10.1.4 The processed data. Processed data will typically be recorded in a binary format (for example, a bitmap);

9.10.1.5 A qualitative description of any surface features or defects (surface finish, cracks, pits, corrosion, foreign material inclusions, depressions, dents, wrinkles, or buckling), and

9.10.1.6 A corresponding quantitative description (location, number, size, size distribution).

9.11 *Precision and Bias:*

9.11.1 Precision will depend on sensor type; wavelength used, characteristics of the vessel being examined, and other examination parameters, and must be determined for each unique vessel design and examination hardware combination.

9.11.2 Measurement accuracy diminishes the larger the vessel is, and the farther away the sensor is from the surface being examined.

NOTE 24—Measured surface profile accuracy can vary from within 0.025 mm (0.001 in.) for a 66-cm (26-in.) COPV, to within 0.05 mm (0.002 in.) for a 102-cm (40-in.) diameter COPV.

10. Leak Testing

10.1 *Scope:*

10.1.1 Helium leak testing (LT) is a sensitive method for detecting through-cracks in metal PVs and thin-walled metallic liners in COPVs while the part is under pressure at a manufacturing facility.

10.1.2 For a general discussion on leak test system selection, leak location, and leakage (rate) measurement, consult Guide E432. A broader overview of LT, and more comprehensive method specific information, is found elsewhere (**9**).

10.1.3 The purpose of LT shall be *(1)* to prevent leakage loss that interferes with in-service function, *(2)* to prevent fire, explosion (including creep rupture), and environmental contamination hazards or nuisances created by accidental leakage, and *(3)* to identify unreliable components, and those whose leakage rates exceed acceptance criteria, so as to remove them from service.

NOTE 25—The LT performed here does not address installation errors or misalignment of components, but will be sensitive to small leaks having a low leakage rate less than that which ensures water tightness at about 10^{-5} Pa m^3 s^{-1} (10^{-4} std cm^3 s^{-1}).

NOTE 26—Since all COPVs or PVs will exhibit some level of leakage, and, therefore, cannot be treated as being completely leak tight, the presence of leakage shall not be construed as being a direct indicator of service reliability. For this reason, establishing practical acceptance criteria for allowable leakage rates, while difficult, is essential if unnecessary examination costs are to be avoided.

NOTE 27—Most leaks in welded, brazed, and mechanical joints tend to be large, while leaks due to material flaws such as cracks and fissures tend to be small. Therefore, the decision to opt for increasing sensitivity to detect leaks due to material flaws must be balanced by *(1)* the considerably greater examination costs, and *(2)* the probability that such leaks will in fact compromise service reliability.

10.1.4 Whenever possible and practical, the LT method chosen shall simulate leakage of the vessel in its usage condition. For example, the same gas as used in service (for example, helium or nitrogen) will be used; however, the use of a tracer gas to increase leak sensitivity is not ruled out. Also, the same temperature and differential pressure should be used in test as encountered in service.

10.1.5 Since vessels used in spacecraft applications leak to vacuum, and vessels used in terrestrial applications leak to atmosphere, it will be desirable to test under those conditions. Both scenarios (leak to vacuum or atmosphere) allow for leakage measurement; however, for leak location, only leakage to atmosphere is practical.

10.1.6 This guide has some utility for evaluating the leak tightness of vessels used to store liquids; namely, liquid propellants. However, since smaller molecular weight tracer gases are used, the number of leaks and the leakage rate will generally be overestimated by the methods described below compared to what would be expected to occur during service. For leak testing of vessels used to store aerospace media that are liquids at nominal service pressures, wherein colorimetric detection is used, and procedures for ultrasonic pretesting are described, consult Test Method E1066 for guidance.

10.1.7 This guide does not address vessels used to store cryogens, or involve leak testing at cryogenic temperatures.

10.2 *Summary of Procedure:*

10.2.1 LT can be divided into three categories: *(1)* leak detection, *(2)* leak location, and *(3)* leakage rate measurement. Each category involves using a leak tracer that is all or part of the pressurizing medium. A pressure differential is then established across the vessel wall. In general, gases and vapors are preferred when high sensitivity is required; however, liquid pressurant media can also be used, especially if present during vessel service.

10.2.2 *Leak Detection and Leak Location*—The preferred leak location method will be the detector probe technique (Fig. 7, right logic path). When applying this technique, it is important that the leak location be attempted only after the presence of a leak has been detected. The detector probe technique involves pressurizing the vessel, typically to its usage pressure (service condition) with the gas or liquid used in service. Sampling of the leaking gas or liquid is then performed at atmospheric pressure in ambient air. Leak location of individual leaks is often required when it is necessary to locate and repair unacceptable leaks so that total leakage from the vessel can be brought within acceptable limits.

NOTE 28—Since stress leaks in COPVs and PVs have a habit of growing, i.e., small leaks can become problematic later, especially after cyclic pressurization; it is desirable to locate every leak regardless of size.

NOTE 29—The use of the tracer probe technique for leak location in COPVs and PVs, wherein the vessel is evacuated, is not deemed suitable since the metal liner (and composite overwrap when present) will be under fundamentally different stress states than those encountered in service. Namely, evacuating the vessel will cause the vessel to shrink or compress due to the greater external pressure, which will potentially reduce the size of leak paths, thus making them harder to locate.

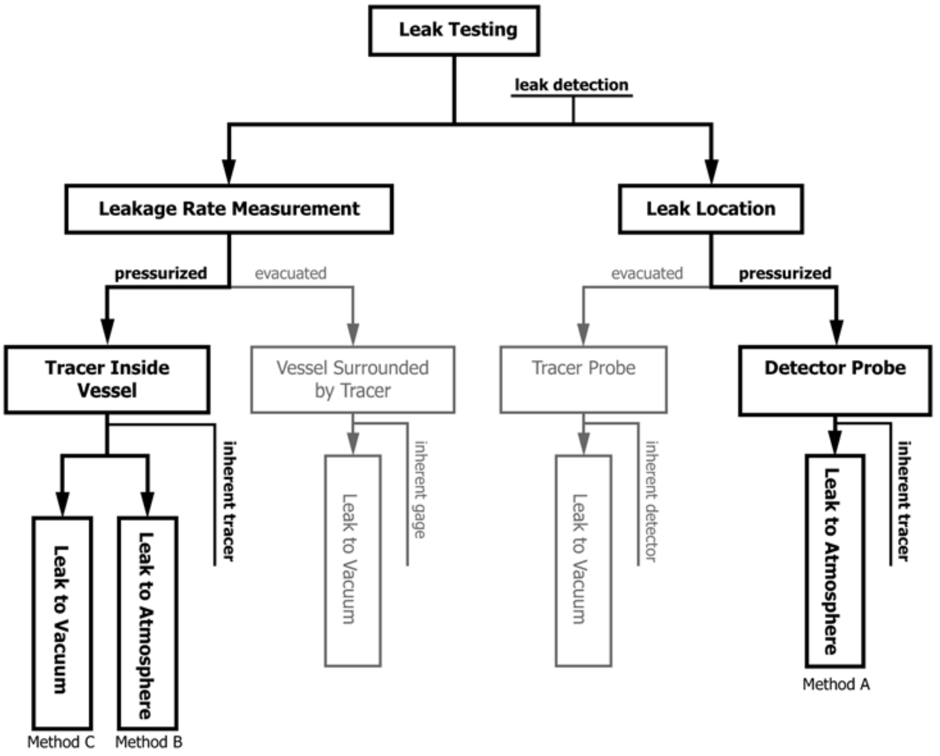

FIG. 7 Leak Testing of Composite Overwrapped and Metallic Pressure Vessels (preferred approaches in bold)

10.2.3 *Leakage Rate Measurement*—Leakage rate measurement can be divided into pressurized and evacuated vessel tests (Fig. 7, left logic path). All leak rate measurements involving a tracer gas are based on flow of gas from the high to low pressure side of the vessel pressure boundary through a presumed leak. When tracer gases are used, instruments sensitive to the tracer gas presence or concentration are used to detect outflow from the low pressure side of the leak in the vessel pressure boundary. When pressurized vessels are surrounded by vacuum or the ambient atmosphere (service condition), leakage can be detected by loss of pressure in the vessel, or by rise in pressure in an external chamber surrounding the vessel. When evacuated or low pressure vessels are surrounded by higher pressure media (nonservice condition), leakage can be detected by loss of pressure in the external chamber or by rise in pressure within the lower pressure vessel. In cases where the pressurized vessel leaks to vacuum or atmosphere, and is surrounded by an external chamber, leakage rate measurement techniques fall into two categories: *(1)* static, and *(2)* dynamic testing. In static testing of pressurized vessels, the chamber into which the tracer gas leaks is not subjected to pumping, thereby allowing the gas to accumulate. While static techniques increase the sensitivity, the time for testing is also increased. In dynamic testing, the chamber is pumped continuously or intermittently to draw the gas into the detector. A dynamic test can be performed in the shortest of time. The leakage rate measurement may consist of either placing the tracer gas inside the vessel, or by surrounding the vessel with tracer. In the former case, the vessel is pressurized and detector is connected to the lower pressure envelop surrounding the pressurized vessel. In the latter case, the vessel is evacuated and detector is connected to the evacuated vessel surrounded by a higher pressurized envelope containing the tracer gas.

10.2.4 Three test scenarios arise, one for leak location (Method A), and two for leakage rate measurement (Methods B and C):

10.2.4.1 *Leak Location (Method A)*—A pressurized vessel containing an inherent tracer leaks to atmosphere, static or dynamic testing). The vessel is then manually probed with a detector sensitive to the tracer gas.

10.2.4.2 *Leakage Rate Measurement (Method B)*—A pressurized vessel containing a tracer leaks to atmosphere inside of an external chamber, thus allowing accumulation of the tracer gas. This can increase sensitivity depending on the volume difference between the external chamber and the vessel under test, and the amount of outgassing produced by the vessel due to the presence of polymeric matrix resin, etc. Better sensitivity is expected for smooth metallic vessel, for example. In practice, leak testing down to 4.5×10^{-11} mol/s (1×10^{-6} std cm^3/s)[20] can be attained if reasonable precautions are taken to prevent release of tracer gas in the test area, and the effects of other interferences are minimized. Both static (chamber is not subjected to pumping) or dynamic (chamber is pumped continuously or intermittently) sampling techniques are used.

10.2.4.3 *Leakage Rate Measurement (Method C)*—a pressurized vessel containing a tracer gas, typically helium, leaks into an evacuated external chamber. Depending on the internal volume, the strength of the enclosure, the elapsed time of a test, and the sorption characteristics of the vessel under test and the enclosure material for helium, various degrees of sensitivity can be obtained. In general practice the sensitivity limits are from 4.4×10^{-15} to 4.4×10^{-11} mol/s (10^{-9} std cm^3/s to 10^{-5} std cm^3/s at 0°C) for helium, although these limits may be exceeded by several decades in either direction in some circumstances. Both static (chamber is not subjected to pumping) or dynamic (chamber is pumped continuously or intermittently) sampling techniques will be used.

NOTE 30—COPVs and PVs used in terrestrial applications and that leak to atmosphere can, however, be tested so they leak to vacuum (i.e., under non-service conditions) if greater leak sensitivity using a helium leak MSLD can be obtained.

NOTE 31—Helium MSLDs will not be effective for leak location or leakage rate measurement when the vessel leaks to atmosphere since they are designed to work in vacuum.

NOTE 32—Evacuation of vessels for leakage rate measurement is not deemed suitable since the metal liner (and composite overwrap when present) will be under a fundamentally different stress state than encountered in service. Namely, evacuating the vessel will cause the vessel to shrink or compress due to the greater external pressure, which will potentially reduce the size of leak paths, thus causing the leakage rate to be underestimated.

10.3 *Apparatus and Material:*

10.3.1 The equipment needed will depend on the leak Practice or Test Method used. Tracer gases, tracer gas leak standards, a leak detector, safety monitors, roughing pumps, auxiliary pumps, secondary pressure vessels or chambers (for accumulation), pressure gauges, dry air or nitrogen (for "washing" nonleaking surfaces that have sorbed tracer gas, for example), may also be needed. For example, when conducting helium gas leak detection, a mass spectrometer leak detector will be needed. Consult the appropriate Test Method or Practice for the specific equipment needed.

10.4 *Calibration and Standardization:*

10.4.1 Reference to a leak standard to ascertain detector probe response shall be made frequently.

10.4.2 The leak detectors are not standardized in the sense that they are taken to the standards laboratory, standardized, and then returned to the job. Rather, the leak detector is standardized by comparing a leak standard (set to the specified leak size), which is part of the instrumentation, and the unknown leak. However, the sensitivity of the leak detector is checked and adjusted on the job so that a leak of specified size will give a readily observable, but not off scale reading.

10.4.3 To verify sensitivity, reference to the leak standard should be made before and after a prolonged test. When rapid repetitive testing of many items is required, refer to the leak standard often enough to ensure that desired test sensitivity is maintained.

10.4.4 In cases (Method C) where an accurate leakage rate measurement is needed and a mass spectrometer leak detector (MSLD) is used, the MSLD will be standardized with a standardized leak to read directly in Pa m^3/s or standard cm^3/s of helium in accordance with the manufacturers' instructions.

10.5 *Special Safety Precaution:*

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[20] The gas temperature is referenced to 0°C. To convert to another gas reference temperature, T_{ref}, multiply the leak rate by $(T_{ref} + 273)/273$.

10.5.1 Precautions should be taken to prevent failure of the vessel during leak testing, or to ensure the operator is protected from the consequences of a failure. For example, failure of the COPV or PV may result in environmental damage, or personnel exposure and hazard due to leakage, rupture, or explosion. Environmental damage will be caused by material leaking out of the system. Personnel exposure and hazard can be caused by exposure to the pressurant, potentially resulting in a chemical exposure or an asphyxiation hazard. Tolerable concentrations of the test pressurant should be known before testing is begun, so the maximum allowable vessel leakage rate can be calculated. Rupture of the vessel may result in additional hazards such as fire, noise, flying debris.

10.5.2 To be satisfactory, the test gas shall be nontoxic, nonflammable, not detrimental to vessel materials of construction, and inexpensive. Helium, or helium mixed with air, nitrogen, or some other suitable inert gas meets the requirements. If the test specification allows leakage of 4.5×10^{-10} mol/s (1×10^{-5} std cm^3/s)[12] or more, or if large vessels are to be tested, consideration should be given to diluting the tracer gas with another gas such as dry air or nitrogen. This will avoid excessive helium input to the sensor and in the case of large vessels, save tracer gas expense.

10.6 *Interferences:*

10.6.1 For possible interferences during Methods A and B, such as atmospheric helium, outgassing of absorbed helium by nonmetallic materials, tracer gas pressurization artifacts, dirt and liquids, consult Test Method E499, Section 7.

10.6.2 For possible interferences during Method C, such as background signal from offgassing of absorbed helium by surfaces fissures, dirt, polymers (composites); or leakage rate measurement errors due to large leaks from small vessel volumes, consult Test Method E493, Section 7.

10.7 *Procedure:*

10.7.1 *Test Pressure*—The vessel under test should be tested at or above its operating pressure and with the pressure drop in the normal direction, where practical.

10.7.2 *Leak Location (Method A)*—Leak to atmosphere, direct probing:

10.7.2.1 Method A (this guide) is based on Test Method E499 Method A (Fig. 8, top).

10.7.2.2 Method A has broader application to testing large vessels versus smaller ones. Helium is normally used. The test method is used to locate leaks but cannot be used to quantify except for approximation. Care must be taken to provide sufficient ventilation to prevent increasing the helium background at the test site. Results are limited by the helium background and the percentage of the leaking trace gas captured by the probe.

10.7.2.3 For general procedural considerations (test specifications, safety factor, test pressure, recovery of test gas, detrimental effects of helium tracer gas, correlation of leakage with other gases or liquids at different operating pressures), consult Test Method E499 Section 11.1.

10.7.2.4 For specific procedural consideration (apparatus and procedure), consult Test Method E499 Section 11.2.

10.7.3 *Leakage Rate Measurement (Method B)*—Leak to atmosphere, accumulation testing:

10.7.3.1 Method B (this guide) is based on Test Method E499 Method B (Fig. 8, bottom).

10.7.3.2 Method B is used to increase the concentration of trace gas coming through the leak by capturing it within a chamber until the signal above the helium background can be detected. By introducing a standardized leak into the same volume for a recorded time interval, leak rates can be measured.

10.7.3.3 For general procedural considerations (test specifications, safety factor, test pressure, recovery of test gas, detrimental effects of helium tracer gas, correlation of leakage with other gases or liquids at different operating pressures), consult Test Method E499 Section 11.1.

10.7.3.4 For specific procedural consideration (apparatus and procedure), consult Test Method E499, Section 11.3.

10.7.4 *Leakage Rate Measurement (Method C)*—Leak to vacuum:

10.7.4.1 Method C (this guide) is based on Test Method E493 Method B (vessel preparation by prefilling) (see Fig. 8, bottom, except no fan is used).

10.7.4.2 Method C requires that the vessel under test contain helium at some calculable pressure during test. After pressurization, the vessel is then placed in an external chamber, as in Method B, except the chamber is then evacuated. The evacuated chamber is coupled to a mass spectrometer leak detector. In the event of a leak, an output signal will be obtained from the leak detector. If the actual leak rate of the vessel must be known, it is calculated from the output reading and the test parameters.

10.7.4.3 For specific procedural consideration (apparatus and procedure), consult Test Method E493 Section 11.2.

10.8 *Significance of Data:*

10.8.1 The leak test procedure, required sensitivity, and leak detection method are subject to agreement between the purchaser and supplier. Any requirement to determine leak location(s) or leakage rate, or both, shall be explicitly stated. If leak location determination is required, any requirement to perform tracer probe mode (PV or COPV can be evacuated) and detector probe mode (PV or COPV cannot be evacuated) detection shall be explicitly stated.

10.9 *Precision and Bias:*

10.9.1 *Leak Location (Method A):*

10.9.1.1 *Precision*—No statement about precision is made.

10.9.1.2 *Bias*—Due to the nature of the test no statement of bias is possible. Calibration standards are used only to ensure that the leak detector is functioning properly. No leak measurement is intended.

10.9.2 *Leakage Rate Measurement (Method B):*

10.9.2.1 *Precision*—Replicate tests by the same operator with the same equipment should not be considered suspect if the results agree within ±25 %. Replicate tests from a second facility should not be considered suspect if the results agree within ±50 %.

10.9.2.2 *Bias*—Bias of leak rates between 10^{-7} and 10^{-4} $Pa \cdot m^3/s$ (10^{-6} to 10^{-3} std cm^3/s) are typically ±25 %.

10.9.3 *Leakage Rate Measurement (Method C):*

10.9.3.1 *Precision*—Replicate tests by the same operator with the same equipment should be considered suspect if more

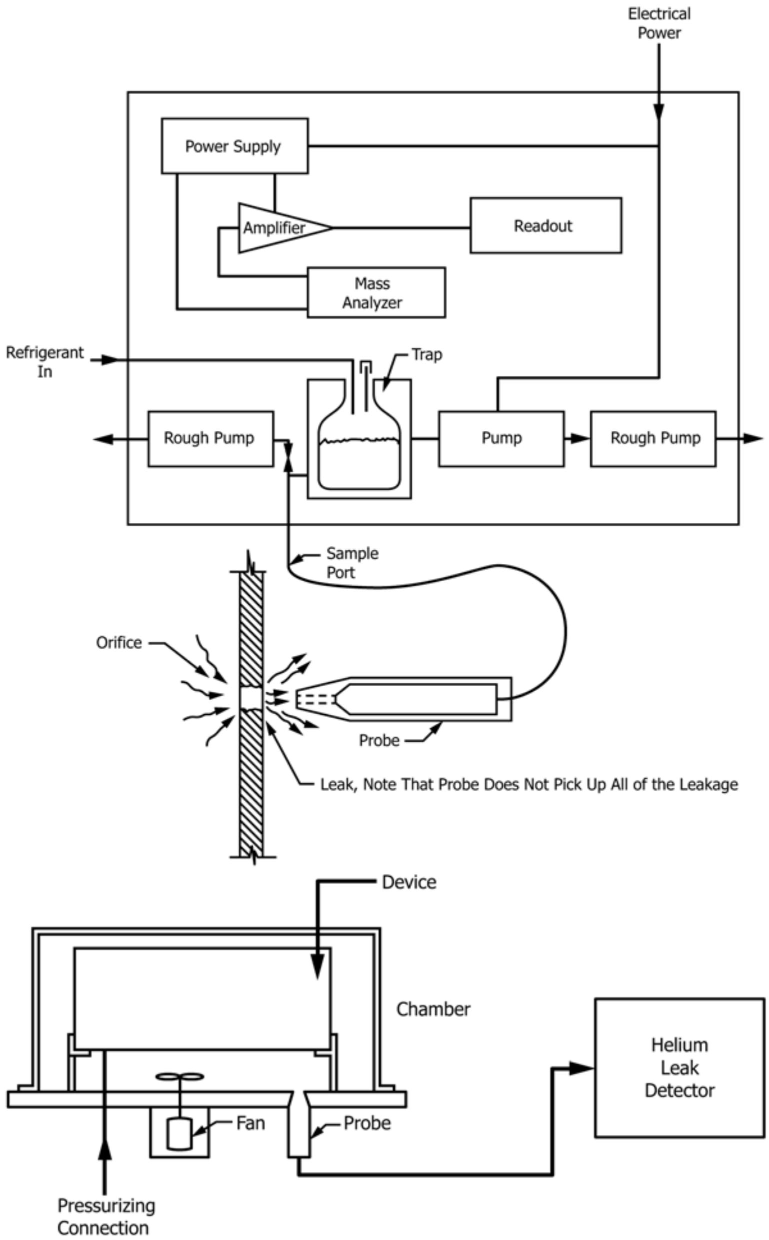

FIG. 8 Detector probe technique using (top, Method A) direct probing of a vessel leaking to atmosphere, and accumulation techniques (bottom, Method B)

than 0.1 % of the devices previously accepted are found to be rejects. The test results for this method need not be considered suspect if less than 1 % of the devices are found to be rejects on subsequent tests by another facility.

10.9.3.2 *Bias*—The bias of the test is on the order of ±25 %. The commercially available standardized leaks have stated uncertainties of ±10 % of their rated values. This test is not intended to be a measurement of actual leak rate but a determination of a leak rate in excess of a specified allowable leak rate.

11. Penetrant Testing

11.1 *Scope:*

11.1.1 This section provides a set of instructions for fluorescent penetrant examination of metallic liners used in COPVs. These fluorescent penetrant nondestructive procedures are capable of detecting surface-connected discontinuities, such as cracks, lack-of-fusion, porosity, laps, corrosion, and cold shuts.

11.1.2 Prior to fabrication into a completed liner, penetrant examination is applicable to both the interior and exterior surfaces of the individual liner segments. After fabrication into a completed liner, penetrant examination is only applicable to the liner exterior surfaces.

11.1.3 In addition to identifying, locating, sizing, and allowing for classification of surface connected discontinuities, penetrant inspections can also provide a minimum reliably detectable flaw size in support of damage tolerance life analysis of COPV liners. The latter is accomplished through POD demonstration testing by the metal PV or liner manufacturer.

NOTE 33—POD testing will limit application for sufficiently thin metallic COPV liners addressed herein and the relatively large detectable flaw sizes that would result from such POD demonstration testing.

11.2 *Summary of Procedure:*

11.2.1 Liquid fluorescent penetrant is applied over the surfaces to be examined and allowed to enter into open discontinuities. After a suitable dwell period, excess surface penetrant is removed and a developer is applied to draw the penetrant out of the discontinuity and stain the developer. The test surface is then examined visually under black light in a darkened enclosure to determine the presence or absence of indications.

11.2.2 Processing parameters such as precleaning, penetrant dwell time, and excess penetrant removal methods are determined by the specific materials used, the nature of the part examined, and the type of discontinuity expected.

11.3 *Apparatus and Materials:*

11.3.1 Penetrant processes and materials and their classifications are specified in accordance with Practice E1417 and QPL-AMS-2644. Penetrant testing shall be restricted to Type 1 fluorescent penetrants of Level 3 or 4 sensitivity, and to the penetrant procedures listed in paragraphs 11.6.1.1 through 11.6.1.3 of this guide unless otherwise agreed to by the cognizant engineering organization.

11.3.2 Equipment and facilities shall be constructed and arranged to permit uniform and controlled processes and shall be kept clean and tidy at all times per Practice E1417:

11.3.2.1 The viewing area requirements are specified in paragraph 6.6.1,

11.3.2.2 The drying oven requirements are specified in paragraph 6.6.2, and

11.3.2.3 Water washing techniques requirements are specified in paragraphs 7.3.1.1 through 7.3.1.4.

11.4 *Calibration and Standardization:*

11.4.1 Tests shall be conducted to ensure that the penetrant materials, the equipment, and the penetrant tests performed to a specific written procedure provide an acceptable and repeatable level of performance per Practice E1417:

11.4.1.1 New materials shall conform to paragraph 7.8.1 (and QPL-AMS-2644), unless otherwise approved by the cognizant engineering organization,

11.4.1.2 In-use materials shall be checked per paragraph 7.8.2, and

NOTE 34—Aerosols are not subject to the requirements of paragraph 7.8.2.

11.4.1.3 To demonstrate that the penetrant system and materials are performing satisfactorily, the penetrant system performance shall be checked per paragraph 7.8.3. Known defect standards such as TAM panels, chrome crack panels, or other test articles approved by the cognizant engineering organization require daily checks or checks prior to use if the penetrant system is not used daily.

11.4.2 If the penetrant inspection is also to be used to establish a minimum reliably detectable flaw size, then each examiner that performs liner examinations shall be required to take and pass a POD demonstration test using the specific fluorescent penetrant written procedure, which will be used to inspect the PV and liner segments and the finished product.

11.4.3 Fatigue-cracked specimens are the generally accepted standard for POD demonstration testing. Guidance on specimen preparation, the number and distribution of crack sizes, and statistical analysis methodology can be found in MIL-HDBK-1823.

11.5 *Special Safety Precautions:*

11.5.1 Specific cautionary notes regarding penetrant materials and practices can be found in Practice E165 (notes: 5, 12, 13, and 20).

11.6 *Procedure:*

11.6.1 Any of the following fluorescent penetrant Test Methods may be used to examine COPV metallic liners.

NOTE 35—Although this standard is directed to COPV liners these penetrant methods may also be used to examine monolithic metallic pressure vessels.

NOTE 36—Surface condition and pre-penetrant cleaning requirements are very important.

11.6.1.1 The water washable penetrant procedure shall be performed in accordance with Practice E1209.

11.6.1.2 The hydrophilic post-emulsification penetrant procedure shall be performed in accordance with Practice E1210.

11.6.1.3 The solvent removable penetrant procedure shall be performed in accordance with Practice E1219.

NOTE 37—The solvent removable process is effective as a small area, spot check penetrant testing, but should not be used for large area full size liners, unless otherwise approved by the cognizant engineering organization.

11.6.2 Although penetrant examination may be employed at any time during liner manufacturing, some manufacturing steps such as machining and grinding can cause smearing of metal surfaces, which can mask tightly closed discontinuities; particularly, crack-like discontinuities. Therefore, it is essential that a final penetrant examination be performed after all potential metal smearing operations on the liner have been completed and the potentially smeared metal has been removed. Etching is routinely used to remove such smeared metal. Generally, a minimum of 5 to 15 µm (0.0002 to 0.0006 in.) of metal per surface must be removed by etching to ensure smeared metal removal.

11.6.3 A specific written procedure shall be developed for each liner. Liners of similar configuration and materials shall be covered by a single specific written procedure. Each written procedure shall provide sufficient details such that the procedure can be consistently repeated from examination to examination. Details shall include precleaning and etching processes, penetrant and material classifications, penetrant application procedures, dwell times, excess penetrant removal procedures, and drying time procedures. Additional details required include developer application procedures; examination and discontinuity evaluation steps; discontinuity location, measurement, and documentation procedures; and final part cleaning procedures.

11.7 *Significance of Data:*

11.7.1 Fluorescent penetrant testing indicates the presence, location, and, to a limited extent, the type (for example, cracking and porosity) and surface dimension of surface breaking discontinuities.

11.7.2 Penetrant test results are used to assess the quality and acceptability of liners and can, to some extent, be used to establish a starting flaw size for damage tolerance life analysis of liners and the COPVs.

11.8 *Reporting:*

11.8.1 The results of all penetrant testing shall be recorded. All recorded results shall be identified, filed, and made available to the cognizant engineering organizations upon request. Records shall provide traceability to the specific part examined. As a minimum, the records shall include: a reference to the specific written procedure used, location, classification, and disposition of relevant indications, the examiner's stamp, electronic identification or signature, and the date of examination. Records shall be kept for a minimum of 3 years or as otherwise agreed to by the cognizant engineering organizations.

12. Radiology

12.1 *Scope:*

12.1.1 This section describes two radiologic procedures for detecting buckling defects and weld discontinuities in COPV metal liners.

12.1.1.1 The first radiologic procedure involves detecting internal buckling in COPVs using a tangential X-ray procedure.

NOTE 38—The critical flaw size for liner buckling, both in terms of magnitude and periodicity, has not been established and will depend on the type of metal or metal alloy used to construct the liner.

12.1.1.2 The second radiologic procedure involves detecting liner weld defects by examining the weld from several directions, such as perpendicular to the weld surface and along both weld bevel angles. For the COPV liner sizes considered, only single wall viewing shall be performed.

NOTE 39—Depending on the thickness of the metal liner it is acknowledged that the critical flaw size specified for a weld discontinuity can be less than the minimum detectable flaw size. In this case, any flaws detected shall be grounds for immediate rejection. Also, the critical flaw size for weld defects will depend on the type of weld and the metal or metal alloy used to construct the liner.

NOTE 40—As the angle of penetration is important for the flaw detection, real-time imaging with radioscopy or digital detector systems with real-time capability may be required for some applications.

12.1.2 The procedures described provide uniform procedures for radiologic examination for internal damage using industrial radiographic film, radioscopy, computed radiography (CR) or digital detector array (DDA) based X-ray detection technology. Requirements expressed in these procedures are intended to control the quality of the radiographic film or digital X-ray images and are not intended for controlling acceptability or quality of the components.

12.1.3 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.

12.1.4 The radiographic 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 than those specified may be required. In these cases, the use of alternative radiologic techniques shall be as agreed upon between purchaser and supplier.

12.2 *Summary of Procedures:*

12.2.1 *Buckling*—Radiologic methods may be utilized to detect the internal buckling of metallic liners in COPVs. This section describes X-ray film, CR and DDA based methods that utilize a tangential X-ray technique to detect internal liner buckling. EN 16407-1 may be used for measurement of thicknesses by tangential radiography.

12.2.2 *Welds*—Radiologic examination of weldments shall be in accordance with Practice E2104 and Test Methods E1416 and E1032, or NASA fracture control and NASA NDT engineering-approved contractor internal specifications with the following additional requirements:

12.2.2.1 The minimum radiologic examination sensitivity level shall be 2-1T.

12.2.2.2 Film density shall be 2.5 to 4.0.

12.2.2.3 The center axis of the radiation beam shall be within ±5 degrees of the assumed crack plane orientation.

12.2.2.4 Nonfilm radiology may be performed per the requirements of Practices E1255 (Radioscopy), E2033 (CR), or E2698 (Digital Detector Arrays) as agreed upon between the supplier and contractor (or NDT Agency).

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

12.3 *Apparatus:*

12.3.1 *Radiation Source*—Selection of the appropriate source is dependent upon variables regarding the components being examined (material composition and thickness). The suitability of the source shall be demonstrated by attainment of the required sensitivity and compliance with all other requirements stipulated herein (for example, focal spot size, tube energy and current, angle of the beam, etc.). In those cases where the X-ray process is being employed to identify material issues or conditions such as gaps or voids, an X-ray technique shall be developed to meet the sensitivity requirements.

12.3.2 *Film Systems*—Only film systems having cognizant engineering organization approval or meeting the requirements of Test Method E1815 shall be used to meet the requirements of this guide. Digital image enhancement techniques applied to scanned radiographic images in some cases have shown the ability to resolve doubts regarding the true nature of indications shown in the original radiograph. Where applicable, these techniques may be used in an effort to resolve questions regarding the nature of indications.

12.3.3 *Phosphor Imaging Plates of Computed Radiography Systems*—May be used in lieu of film systems if the quality of the image meets the intent and requirements of the cognizant engineering function. Guide E2007 and Practice E2033 may be used for non-film computed radiologic examination.

12.3.4 *Radioscopic Systems*—May be used in lieu of film systems if the quality of the image meets the intent and requirements of the cognizant engineering function. Guide E1000 and Practice E1255 may be used as guidance for real-time radiologic examination. Guide E1000 is a radioscopy standard for real-time imaging (image intensifier and other analogue techniques).

12.3.5 *Digital Detection Systems*—Digital Detector Arrays may be used in lieu of film systems if the quality of the image meets the intent and requirements of the cognizant engineering function. Guides E1000 and E2736, and Practice E2698 may be used as guidance for non-film radiologic examination.

NOTE 41—The guide for Digital Detector Arrays is E2736 and some important information can be found there for COPV composite overwrap inspection.

12.4 *Calibration and Standardization:*

12.4.1 *Buckling*—The contractor or NDT agency will develop an X-ray technique utilizing reference standards or cut-away sections of COPV, or both, with either known or artificially induced buckling conditions. The capability of the tangential X-ray process will be validated by using those test articles. The capability assessment may include the degree of buckling based upon radial deflection or displacement measurements of the buckle, area of buckling, or a combination of these parameters. Spacer devices of known dimensions may be inserted into the buckled regions and imaged to determine the extent of buckling present in the test articles. The test data obtained from the test articles may be used as estimates to quantify buckling on production components when alternative standards are not available.

12.4.2 *Welds*—Shims, separate blocks, or like sections made of the same or radioscopically similar materials as defined in Test Method E1416 or in Practices E1032 or E2104 may be used to facilitate image quality indicator positioning. The like section should be geometrically similar to the object being examined.

12.5 *Procedures:*

12.5.1 *Procedure Requirement*—Unless otherwise specified by the applicable job order or contract, radiologic examination 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 radiologic images.

12.5.2 *Time of Examination, Buckling*—Unless otherwise specified by the applicable job order or contract, radiography shall be performed post autofrettage on the COPV component or at any other stage in the processing that can induce internal damage (i.e., proof pressure test) as required by the engineering function.

12.5.3 *Time of Examination, Welds*—Unless otherwise specified by the applicable job order or contract, perform radioscopy or digital imaging prior to heat treatment and before composite wrapping and subsequent autofrettage.

12.5.4 *Surface Preparation, Buckling*—Unless otherwise agreed upon, the surface of the COPV shall be free of any items that may mask internal damage within the COPV. Interpretation can be optimized if surface irregularities are removed such that the image of the irregularities is not discernible on the radiologic image.

12.5.5 *Surface Preparation, Welds*—Unless otherwise agreed upon, remove the weld bead ripple or weld-surface irregularities on both the inside and outside (where accessible) by any suitable process so that the image of the irregularities cannot mask, or be confused with, the image of any discontinuity.

12.5.6 *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. Digital images shall contain the same information in the name of the image or in image tags (TIFF or DICONDE).

12.5.7 *Radiographic Location and Identification Markers*—Lead numbers and letters 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. 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.

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

12.5.9 *Tangential Technique*—The X-ray source shall be positioned relative to the detector to image the OD of the inner (liner) wall of the COPV.

12.5.10 *Direction of the Radiation*—The central beam of radiation shall be directed perpendicularly toward the center of the effective area of the detector or to a plane tangent to the center of the detector to the maximum extent possible.

12.5.11 *Radiologic Coverage, Buckling*—Unless otherwise specified by purchaser and supplier agreement, the extent of radiologic coverage shall be determined by engineering direction.

12.5.12 *Radiologic Coverage, Welds*—Unless otherwise specified by purchaser and supplier agreement, the extent of radiologic coverage shall include 100 % of the volume of the weld and the adjacent base metal.

12.5.13 *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 Test Method E1815.

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

12.5.15 *Radiologic Density Limitations*—The density through the body of the area of interest shall be sufficient to determine the areas of buckling, weld defects, and damage within the component.

12.5.16 *Radiation Source (X-ray)*—Selection of the appropriate source is dependent upon variables regarding the COPV or weld being examined, such as material composition(s) and thickness(es). A microfocus or minifocus tube shall be used and the required magnification shall be determined as described in Practice E2698, Section 10.19.

12.5.17 *Specific Requirements, Buckling*—The schematic diagram (Fig. 9) shows a real-time X-ray technique to accomplish detection of liner buckling. The contractor or NDT agency may utilize similar procedures to detect and assess the severity of buckling based upon their specific program requirements including the use of a conventional radiologic tubehead and multiple film or digital detector views to image the internal liner of the COPV. If radioscopy or real-time imaging with DDA is not used, the number of views required for sufficient coverage when using radiographic film or digital detector arrays shall be agreed upon between the supplier and engineering function.

NOTE 42—Fig. 9 shows a microfocus X-ray tubehead. In most cases a conventional radiologic system will suffice. Specifying a microfocus system will increase the cost of implementation.

12.5.18 *Tangential X-ray Process, Buckling*—The tangential X-ray process is based upon positioning an X-ray source in an orientation that permits the outer circumference of the COPV to be imaged onto a recording medium. The COPV may be rotated or the X-ray set-up translated to provide 360-degree coverage of the circumference of the liner. Since COPVs vary in size, shape, configurations, and thicknesses, the contractor or NDT agency shall verify that their X-ray technique will provide coverage of all areas of interest including regions such as the domes (heads), cylindrical side walls, inlet/outlet port openings, etc. The key elements of the tangential X-ray process are the X-ray source, tooling to position and rotate the COPV, and an image capture medium with real-time capability with image intensifier or DDA, or X-ray film, or imaging plate. The degree of automation and type of detection system utilized will be determined by the contractor or NDT agency and will be documented on an X-ray technique form.

NOTE 43—Real-time capability that allows examination of all of the images will increase the POD since detection of buckling and weld flaws will depend very much on the angle of penetration.

12.5.19 *Written X-ray Technique Requirements*—The X-ray technique should include the following items as a minimum:

(1) Program
(2) Part name
(3) Part number
(4) Serial number
(5) Date
(6) Brief description of the type of examination
(7) Test description
(8) Set-up requirements
(9) X-ray kV setting
(10) X-ray mA setting
(11) X-ray source to COPV or liner (object) distance (SOD)
(12) Focal spot size

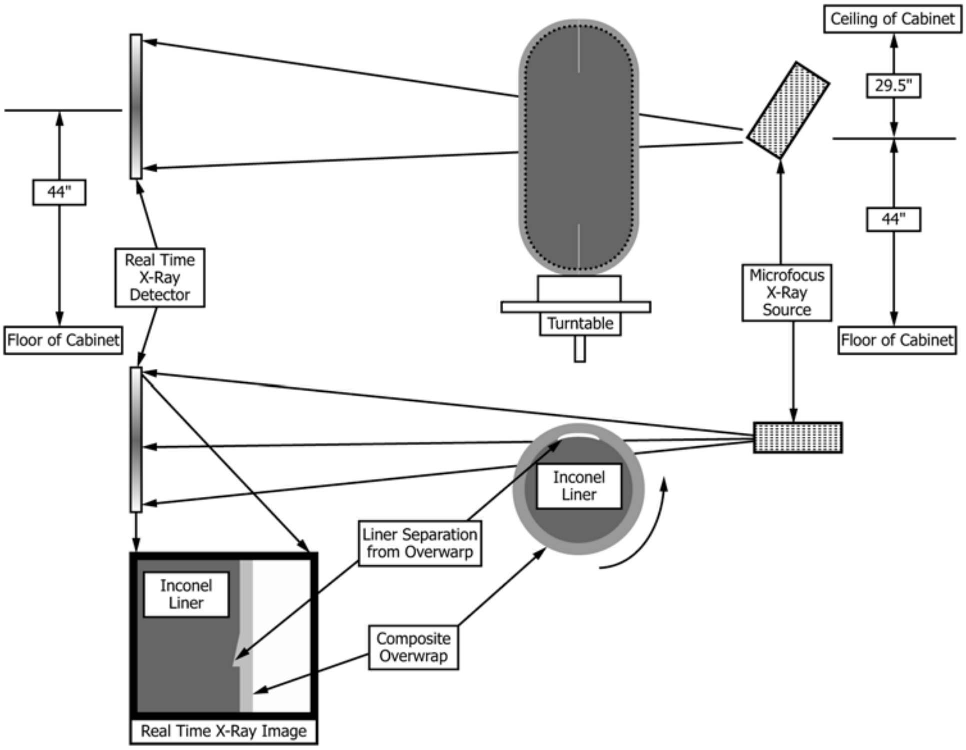

FIG. 9 Schematic diagram of a composite overwrapped pressure vessel being examined for the presence of liner buckling using a tangential X-ray procedure.

(13) Exposure duration, frame rate and frame number of DDAs

(14) X-ray source to recording detector (film, image intensifier, imaging plate or DDA) distance (SDD) and magnification

(15) Identification markers on the COPV or liner

(16) Type, size, basic spatial resolution and fidelity of recording medium for digital X-ray images

(17) Speed of COPV or liner rotation for real time X-ray viewing applications

(18) Number of images necessary for required coverage when using film X-ray or imaging plate or DDA in still mode

(19) Imaging and data acquisition software; critical settings and type of scanner or detector; type of imagining plate

(20) Image processing parameters if applied (e.g., digital filters)

(21) Applicable specifications

(22) Name of individual preparing technique and approval signature as required

12.6 *Significance of Data:*

12.6.1 *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.

12.7 *Reporting and Records:*

12.7.1 The results of all radiologic examinations shall be documented. The examination report shall reference the acceptance criteria and revision, provide traceability to the specific part or the lot of parts examined, the disposition of the part(s) (accept/reject), the reason for rejection of any items, and shall include the name and/or signature of the interpreter(s), or their acceptance stamp when applicable. The record for real-time imaging shall follow the description in Test Method E1416, Section 10.

12.7.2 Disposition of each radiograph or digital image (acceptable or rejectable).

12.7.3 *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 real-time examination a (digital) film (video) will be stored.

12.7.4 *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.

13. Keywords

13.1 acoustic emission (AE); composite overwrapped pressure vessel (COPV); composite pressure vessel; eddy current testing (ECT); filament-wound pressure vessel; laser profilometry; leak testing (LT); metallic liner; nondestructive testing (NDT); penetrant testing (PT); pressure vessel; profilometry; radiography; radiologic testing (RT); radiology

REFERENCES

(1) Bell, M., Capability Demonstrations for Penetrant Nondestructive Evaluation (NDE) of Metallic Tanks and Composite Overwrapped Pressure Vessel (COPV) Liners, NASA Engineering and Safety Center Technical Bulletin No. 09-04, 2009.

(2) Rummel, W. D., “Recommended Practice for a Demonstration of Nondestructive Evaluation (NDE) Reliability,” *Materials Evaluation*, 40, 1982.

(3) Berens, A. P., “NDE Reliability Data Analysis,” *Metals Handbook*, ASTM International, 9th Edition, Volume 17, 689, 1989.

(4) Rummel, W. D., et al, “Recommended Practice for a Demonstration of Nondestructive Evaluation Reliability on Aircraft Production Part,” *Materials Evaluation*, 40, 922, 1982.

(5) Rummel, Hardy, G. L., Cooper, T. D., “Applications of NDE Reliability to Systems,” *Metals Handbook*, 9th Edition, 17, 674, ASM International, 1989.

(6) Rummel, W. D., “Considerations for Quantitative NDE and NDE Reliability Improvement,” *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 2A, Plenum Press, New York, 19, 1983.

(7) Yee, B. G. W., Chang, F. H., Couchman, J. C., Lemon, G. H., and Packman, P. F., “Assessment of NDE Reliability Data,” *NASA-CR-134991*, 1975.

(8) “Self-Nulling Eddy Current Probe for Surface and Subsurface Flaw Detection,” *Materials Evaluation*, 1994.

(9) *ASNT Nondestructive Testing Handbook*, Volume 1, Leak Testing.