Designation: E2533 – 17

Standard Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

This standard is issued under the fixed designation E2533; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 This guide provides information to help engineers select appropriate nondestructive testing (NDT) methods to characterize aerospace polymer matrix composites (PMCs). This guide does not intend to describe every inspection technology. Rather, emphasis is placed on established NDT methods that have been developed into consensus standards and that are currently used by industry. Specific practices and test methods are not described in detail, but are referenced. The referenced NDT practices and test methods have demonstrated utility in quality assurance of PMCs during process design and optimization, process control, after manufacture inspection, in-service inspection, and health monitoring.

1.2 This guide does not specify accept-reject criteria and is not intended to be used as a means for approving composite materials or components for service.

1.3 This guide covers the following established NDT methods as applied to PMCs: Acoustic Emission (AE, 7), Computed Tomography (CT, 8), Leak Testing (LT, 9), Radiographic Testing, Computed Radiography, Digital Radiography, and Radioscopy (RT, CR, DR, RTR, 10), Shearography (11), Strain Measurement (contact methods, 12), Thermography (13), Ultrasonic Testing (UT, 14), and Visual Testing (VT, 15).

1.4 The value of this guide consists of the narrative descriptions of general procedures and significance and use sections for established NDT practices and test methods as applied to PMCs. Additional information is provided about the use of currently active standard documents (an emphasis is placed on applicable standard guides, practices, and test methods of ASTM Committee E07 on Nondestructive Testing), geometry and size considerations, safety and hazards considerations, and information about physical reference standards.

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

1.6 This guide summarizes the application of NDT procedures to fiber- and fabric-reinforced polymeric matrix composites. The composites of interest are primarily, but not exclusively limited to those containing high modulus (greater than 20 GPa (3×10^6 psi)) fibers. Furthermore, an emphasis is placed on composites with continuous (versus discontinuous) fiber reinforcement.

1.7 This guide is applicable to PMCs containing but not limited to bismaleimide, epoxy, phenolic, poly(amide imide), polybenzimidazole, polyester (thermosetting and thermoplastic), poly(ether ether ketone), poly(ether imide), polyimide (thermosetting and thermoplastic), poly(phenylene sulfide), or polysulfone matrices; and alumina, aramid, boron, carbon, glass, quartz, or silicon carbide fibers.

1.8 The composite materials considered herein include uniaxial laminae, cross-ply laminates, angle-ply laminates, and sandwich constructions. The composite components made therefrom include filament-wound pressure vessels, flight control surfaces, and various structural composites.

1.9 For current and potential NDT procedures for finding indications of discontinuities in the composite overwrap in filament-wound pressure vessels, also known as composite overwrapped pressure vessels (COPVs), refer to Guide E2981.

1.10 For a summary of the application of destructive ASTM standard practices and test methods (and other supporting standards) to continuous-fiber reinforced PMCs, refer to Guide D4762.

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

1.12 *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.*

---

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

Current edition approved June 1, 2017. Published June 2017. Originally approved in 2009. Last previous edition approved in 2016 as E2533–16a. DOI: 10.1520/E2533-17.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D3878 Terminology for Composite Materials

D4762 Guide for Testing Polymer Matrix Composite Materials

E543 Specification for Agencies Performing Nondestructive Testing

E1316 Terminology for Nondestructive Examinations

E1742 Practice for Radiographic Examination

E2981 Guide for Nondestructive Testing of the Composite Overwraps in Filament Wound Pressure Vessels Used in Aerospace Applications

2.2 *ASNT Standard:*

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing[3]

2.3 *ASTM Adjuncts:*

Curing Press Straining Block (13 Drawings)[4]

3. Terminology

3.1 *Abbreviations*—The following abbreviations are adopted in this guide: Acoustic Emission (AE), Computed Radiography (CR), Computed Tomography (CT), Digital Radiography (DR), Leak Testing (LT), Radiographic Testing (RT), Radioscopy (RTR), and Ultrasonic Testing (UT).

3.2 *Definitions*—Definitions of terms related to NDT of aerospace composites which appear in Terminology E1316 and Terminology D3878 shall apply to the terms used in the guide.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *aerospace*—any component that will be installed on a system that flies.

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

3.3.3 *composite material*—see Terminology D3878.

3.3.4 *composite component*—a finished part containing composite material(s) that is in its end use application configuration, and which has undergone processing, fabrication, and assembly to the extent specified by the drawing, purchase order, or contract.

3.3.5 *disbond*—see Terminology D3878.

3.3.6 *in-service*—refers to composite components that have completed initial fabrication and are in use (or in storage) for their intended function.

3.3.7 *microcrack*—invisible cracks (< 50 to 100 µm size) that are precursors to visible cracks. In angle-ply continuous fiber-reinforced composites, for example, microcracks form preferentially under tensile loading in the matrix in off-axis plies. Since most microcracks do not penetrate the reinforcing fibers, microcracks in a cross-plied tape laminate or in a laminate made from cloth prepreg are usually limited to the thickness of a single ply.

3.3.8 *reference standards*—objects that provide a known, reproducible and repeatable response to a specific stimulus. May be in the form of hardware or software.

3.3.9 *sandwich construction*—see Terminology D3878.

4. Summary of Guide

4.1 This guide describes and provides references for the practice and utilization of the following established NDT procedures as applied to polymeric matrix composites:

4.1.1 Acoustic Emission (Section 7).

4.1.2 Computed Tomography (X-ray Method) (Section 8).

4.1.3 Leak Testing (Section 9).

4.1.4 Radiography, Computed Radiography, Digital Radiography with Digital Detector Array Systems, and Radioscopy (Section 10).

4.1.5 Shearography (Section 11).

4.1.6 Strain Measurement (Strain Gauges) (Section 12).

4.1.7 Infrared Thermography (Non-Contact Methods Using Infrared Camera) (Section 13).

4.1.8 Ultrasonic Testing (Section 14).

4.1.9 Visual Testing (Section 15).

4.2 *NDT Method Selection*—Composite components such as laminates, moldings, and subassemblies may be inspected by simple procedures consisting of dimensional and tolerance measurements, weight and density determinations, cure determinations by hardness measurements, visual testing for defects, and tapping for void determinations. If the integrity of the subassembly warrants a more complete inspection, this can be accomplished by using various NDT procedures discussed in this guide. Nondestructive tests can usually be made rapidly. However, nondestructive testing will, in general, add to component cost and should be used only when warranted on critical applications. Also, the extent of NDT on composite parts depends on whether the part is a primary structure safety of flight part, or secondary structure non-safety of flight part. The type or class of part is usually defined on the engineering drawing. Some of the flaws that can be detected by NDT are given in Table 1.

4.3 Other critical defect characteristics not mentioned in Table 1 that need to be considered when establishing NDE procedures include defect size, defect shape, defect depth, defect orientation, fiber volume fraction, resin rich regions,

---

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

[3] Available from American Society for Nondestructive Testing, P. O. Box 28518, 1711 Arlington Lane, Columbus, OH 43228-0518.

[4] Available from ASTM International Headquarters. Order Adjunct No. ADJf1364.

TABLE 1 Flaws Detected By NDT Procedures

Defect	Acoustic Emission	Computed Tomography	Leak Testing	Radiography with DDA; Radiography, CR, Radioscopy	Shearography	Strain Measurement	Thermography	Ultrasonic Testing	Visual Testing
Contamination		X		X				X	X
Damaged Filaments	X	X		X					
Delamination	X	X			X		X	X	X
Density Variation		X		X			X	X	
Deformation under Load					X	X			
Disbond		X			X		X	X	X
Fiber Debonding	X	X[A]					X	X	
Fiber Misalignment		X		X			X		
Fractures	X	X		X			X	X	X
Inclusions		X		X			X	X	X
Leaks	X		X					X	
Loose or Moving Parts	X								
Microcracks	X	X[B]		X[B,C]	X			X	
Moisture		X		X[D,E]			X		
Porosity	X	X		X			X	X	
Thickness Variation		X		X[F]	X		X	X	
Undercure								X	
Volumetric Effects		X							
Voids	X	X	X	X			X	X	

[A] Can detect after impact (voids).
[B] Depends on opening/size of crack.
[C] Depends on angle of beam relative to planar defect and opening.
[D] Only in central projection (Radiography, CR).
[E] Radioscopic mode (Radiography with DDA).
[F] For Radiography, applicable to CR and digitized films only.

resin poor regions, cure state, fiber sizing, fiber-matrix bonding, crazing (cracking of amorphous matrix resins due to exposure to stress or the service environment), residual and internal stress, degradation (chemical and physical attack), and impact damage.

4.4 *General Facility and Personnel Qualification*—Minimum general requirements for NDT facilities and personnel qualification are given in Practice E543. This practice can be used as a basis to evaluate testing or inspection agencies, or both, and is intended for use for the qualifying or accrediting, or both, of testing or inspection agencies, public or private.

4.5 *General Equipment and Instrumentation Considerations*—General equipment and instrumentation considerations are provided in Practice E543. NDT method specific considerations are discussed in the appropriate section of this guide (Sections 7 to 15).

4.6 *Reference Standards*—Physical reference standards simulating target imperfections or discontinuities are used to validate NDT results. The use of physical reference standards also helps to ensure reproducibility and repeatability of measurements. Certified physical reference standards calibrated by accepted government or industrial agencies may be used.

4.7 *Extent of Examination*—Specific applications may require local regions or the entire component to be examined. Examination may be real time or delayed based upon the availability of data. Examination may be direct, or indirect, on site or remote as specified in the contractual agreement or established requirements documents.

4.8 *Timing of Examination*—Examinations shall be performed in accordance with the contractual agreement or established requirements documents, and may be performed during the life cycle of the article under test.

4.9 *Type of Examinations*—Many different NDT system configurations are possible due to the wide range of system components available. It is important for the purchaser of NDT to understand the capability and limitations of the applicable configuration. Selection of the NDT procedure and system shall be at the discretion of the testing agency unless specified by the purchaser in a contract or requirements document (that is, engineering drawing, specifications, etc.).

4.10 A tabular comparison of most of the established NDT procedures discussed in the guide is given in Appendix X1 of Practice E543; namely, acoustic emission, leak testing, radiography, strain measurement, thermography (infrared), and ultrasound are covered. The comparison summarizes properties sensed or measured, typical discontinuities detected, representative application, applicable ASTM standards, and advantages and limitations. A similar overview is provided in Table 2.

5. Significance and Use

5.1 This guide references requirements that are intended to control the quality of NDT data. The purpose of this guide, therefore, is not to establish acceptance criteria and therefore approve composite materials or components for aerospace service.

5.2 Certain procedures referenced in the guide are written so they can be specified on the engineering drawing, specification, purchase order, or contract, for example, Practice E1742 (Radiography).

TABLE 2 General Overview of Established NDT Procedures

NDT Method	Applications	Advantages	Limitations	What Is Seen and Reported?	Other Considerations
Acoustic Emission	Global monitoring of composite structures to detect and locate active sources in real time.	Remote and continuous monitoring on an entire composite article in real time is possible. Can also detect growth of active imperfections or discontinuities, and detect and determine the location of discontinuities and defects that may be inaccessible by other NDT procedures.	The part being inspected must be stressed by mechanical, load, pressure, temperature, or other stimulus. With the exception of certain imperfections or discontinuities that AE detects by friction-generated AE (for example, delamination surfaces rubbing), AE-inactive (non-propagating) imperfections or discontinuities cannot be detected and structurally insignificant imperfections or discontinuities may produce AE. Therefore, the significance of a detected AE source cannot be assessed unambiguously.	The AE technique records transient elastic waves produced by applied stress or resulting stress relaxation of the composite material or component. The mechanical waves are produced as either burst or continuous AE. AE activity, intensity and severity correlated with applied stress yield information on the degradation within the article under test.	Inspection tests and results are unique to each application and should be conducted with expert oversight.
Computed Tomography	Detects sub-surface volumetric imperfections or discontinuities. Provides quantitative, volumetric analysis of imperfections or discontinuities detectable by other NDT procedures. Also suitable for measuring geometric characteristics.	Produces clear cross-sectional image slices of an object. Obtains 3D imperfection or discontinuity data. Extensive image processing capability.	Requires access to all sides of the article under test. Not very applicable to the inspection of large areas, or objects with high (>15) aspect ratios.	A digitized cross-sectional CT-density map (tomogram) of the article under test. Allows full, three dimensional CT-density maps to be obtained for sufficiently small composite parts.	Tooling and/or part-handling fixtures may be required.
Leak Testing	Any composite material or component across which a differential pressure exists and where through-leakage or in-leakage of product, air, water vapor, or other contaminant over the projected service life are of concern.	Less ambiguous than liquid penetrant testing; more sensitive than AE or UT.	Test equipment costs increase as the required leak test sensitivity increases.	Qualitative indications, for example bubbles, or quantitative measurements, for example, detector deflections, that ascertain the presence or location, or concentration or leak rate of a leaking fluid.	Different techniques are available for characterization of large leaks (with rates as high as 10^{-2} Pa m^3 s^{-1} (10^{-1} std cm^3 s^{-1})) and small leaks (rates less than 10^{-5} Pa m^3 s^{-1} (10^{-4} std cm^3 s^{-1})).
Radiography, Computed Radiography, Radiography with Digital Detector Arrays, Radioscopy	Primarily detects sub-surface imperfections or discontinuities such as porosity & inclusions. Planar imperfections or discontinuities are detected if the beam is directed along the imperfection or discontinuity and the unsharpness is less than the imperfection or discontinuity opening/size.	Film and some imaging plates can be cut and placed almost anywhere on the part. Digital images can be processed for additional information and automated defect recognition. In radioscopy, techniques using an image intensifier and DDA can be automated by interfacing with a robot or part manipulator thus allowing the potential for a faster inspection.	Requires access to both sides of the article under test. Accessibility may need to be evaluated. Unable to determine depth of imperfections or discontinuities; sometimes possible from digital images after calibration or with additional X-ray exposures from different directions.	Projected area and density variation of subsurface imperfections or discontinuities.	Part may need to be moved to an X-ray lab; Film RT requires film storage and disposal of chemicals which can be expensive. Digital techniques (CR, DDA) are usually faster. Radiation safety. In radioscopy, radiation safety more problematic if a moving source is used, versus movement of part.

5.3 *Acceptance Criteria*—Determination about whether a composite material or component meets acceptance criteria and is suitable for aerospace service must be made by the cognizant engineering organization. When examinations are performed in accordance with the referenced documents in this guide, the

TABLE 2 *Continued*

NDT Method	Applications	Advantages	Limitations	What Is Seen and Reported?	Other Considerations
Shearography	Detects subsurface imperfections or discontinuities or changes in modulus or out-of-plane deformation.	Well suited for high speed, automated inspection in production environments.	Subsurface imperfection or discontinuity must be sufficiently large to cause measurable surface deformation under load. Surface condition, especially glossiness, can interfere with accurate shearographic detection, thus requiring the use of surface dulling agents (exception: thermal shearography).	An interference pattern created by subtracting or superimposing images of the article under test taken before and after loading, thus revealing localized strain concentrations.	Additional equipment is required to determine surface derivative slope changes, and thus uses the method as a quantitative tool.
Strain Measurement	Can be used to measure static and dynamic tensile and compressive strain, as well as shearing, Poisson, bending, and torsional strains.	Relatively inexpensive, and less bulky and better resolution than extensometers (can achieve an overall accuracy of better than ± 0.10% strain).	Individual strain gauges cannot be calibrated and are susceptible to unwanted noise and other sources of error such as expansion or contraction of the strain-gauge element, change in the resistivity, and hysteresis and creep caused by imperfect bonding.	The output of a resistance measuring circuit is expressed in millivolts output per volt input.	Depending on desired sensitivity, resistance to drift, insensitivity to temperature variations, or stability of installation, a variety of strain gauges are available (for example, semiconductor wafer sensors, metallic bonded strain gauges, thin-film and diffused semiconductor strain gauges).
Thermography	Detects disbonds, delaminations, voids, pits, cracks, inclusions, and occlusions, especially in thin articles under test having low thermal conductivity, low reflectivity/high emissivity surfaces, and in materials which dissipate energy efficiently,	Quick observation of large surfaces and identification of regions that should be examined more carefully.	Composites have temperature limits beyond which irreversible matrix and fiber damage can occur. Imperfection or discontinuity detection depends on orientation of an imperfection or discontinuity relative to the direction of heat flow. In thicker materials, only qualitative indications of imperfections or discontinuities are possible.	The areal temperature distribution is measured by mapping contours of equal temperature (isotherms), thus yielding a heat emission pattern related to surface and subsurface defects.	Both contact (requires application of a coating) and noncontact methods (relies on detection of infrared blackbody radiation) are available. Thermography is either passive or active, active thermography can be further subdivided into pulse or lock-in techniques.
Ultrasonic Testing	Detects sub-surface imperfections or discontinuities. There are two primary techniques; pulse echo for one sided inspections and through transmission for two sided inspections.	Detects sub-surface imperfections or discontinuities including porosity, inclusions, and delaminations.	Requires a relatively flat and smooth surface. Material type can affect inspectability.	Imperfections or discontinuities are directly recorded on amplitude images.	Possible fluid entrapment; possible fluid absorption into porous materials such as composites. Numerous techniques available including longitudinal, shear or surface waves. Attenuation can be comparatively high in PMCs compared to metallic articles.
Visual Testing	Detects disruptions on surfaces being viewed.	Low cost. Detect surface imperfections or discontinuities including delaminations, fiber breakage, impact damage.	Requires direct line of sight.	Imperfections or discontinuities are directly recorded on inspection documentation sometimes photographs.	Can find imperfections or discontinuities on inside diameters if a central conductor can be inserted and satisfactory electrical contact made.

engineering drawing, specification, purchase order, or contract shall indicate the acceptance criteria.

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

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

5.3.3 *Rejection of Composite Articles*—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 dispositioned as *(1)* acceptable as is, *(2)* subject to further rework or repair to make the materials or component acceptable, or *(3)* scrapped when required by contractual documents.

5.3.4 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.

5.4 *Life Cycle Considerations*—The referenced NDT practices and test methods have demonstrated utility in quality assurance of PMCs during the life cycle of the product. The modern NDT paradigm that has evolved and matured over the last twenty–five years has been fully demonstrated to provide benefits from the application of NDT during: *(a)* product and process design and optimization, *(b)* on-line process control, *(c)* after manufacture inspection, *(d)* in-service inspection, and *(e)* health monitoring.

5.4.1 In-process NDT can be used for feedback process control since all tests are based upon measurements which do not damage the article under test.

5.4.2 The applicability of NDT procedures to evaluate PMC materials and components during their life cycle is summarized in Tables 3 and 4.

5.5 *General Geometry and Size Considerations*—Part contour, curvature, and surface condition may limit the ability of certain tests to detect imperfections with the desired accuracy.

5.6 *Reporting*—Reports and records shall be specified by agreement between purchaser and supplier. It is recommended that any NDT report or archival record contain information, when available, about the material type, method of fabrication, manufacturers name, part number, lot, date of lay-up and/or of cure, date and pressure load of previous tests (for pressure vessels), and previous service history (for in-service and failed composite articles). Forwards and backwards compatibility of data, data availability, criticality (length of data retention), specification change, specification revision and date, software and hardware considerations will also govern how reporting is performed.

6. Procedure

6.1 When NDT produces an indication of a material discontinuity, the indication is subject to interpretation as false, nonrelevant, or relevant (Fig. 1). If the indication has been interpreted as relevant, the necessary subsequent evaluation will result in the decision to accept or reject the composite material or component.

TABLE 3 Application Examples of Established NDT Procedures During Life Cycle

NDT Method	Application
Acoustic Emission	May be used for quality control of production and fabrication processes (for example, to evaluate adhesive bonding after lay-up winding or curing), for proof-testing of pressure vessels after fabrication, and for periodic in-service and health monitoring inspections prior to failure.
Computed Tomography	May be used as a post-fabrication metrological method to verify engineering tolerances.
Leak Testing	May be used to validate leak tightness following fabrication, and in-service re-qualification of pressure vessels. For example, helium leak detection can be used during composite article fabrication to detect and seal leaks permanently (preferable) or temporarily in such a manner to allow repair at a later time. Similarly, halogen gas leak detection has been used in production examination.
Radiography and Radioscopy	May be used during fabrication inspection to evaluate honeycomb core imperfections or discontinuities such as node bonds, core-to-core splices, core-to-structure splices, porosity, included material as well as verification of structural placement.
Shearography	May be used in quality assurance, material optimization, and manufacturing process control.
Strain Measurement	May be used during proof testing before placement into service, or during periodic re-qualification. Can be destructive depending on the strain thresholds reached during test.
Thermography	May be used to follow imperfection or discontinuity growth during service. If video thermographic equipment is used, systems that are being dynamically tested or used can be examined in real-time.
Ultrasonic Testing	Automatic recording systems allow parts to be removed from a processing line when defect severity exceeds established limits. Measurement of the apparent attenuation in composite materials is useful in applications such as comparison of crystallinity and fiber loading in different lots, or the assessment of environmental degradation. The most common method is applied for laminar oriented defect detection such as impact damage causing delamination fiber fracturing, included material, and porosity.
Visual Testing	Used primarily for quality inspections of composite materials and components upon receipt (after fabrication and before installation).

TABLE 4 Application of Established NDT Procedures During the Life Cycle of Polymeric Matrix Composites

Defect	Product and Process Design and Optimization	On-Line Process Control	After Manufacture Inspection	In-Service Inspection	Health Monitoring
Acoustic Emission	X	X	X	X	X
Computed Tomography	X		X		
Leak Testing	X	X		X[A]	
Radiography and Radioscopy	X	X	X	X	
Shearography	X	X	X	X	
Strain Measurement			X		X
Thermography			X	X	
Ultrasonic Testing	X	X	X	X	X
Visual Testing	X	X	X	X	X

[A] Applicable to composites used in storage and distribution of fluids and gases, for example, filament-wound pressure vessels.

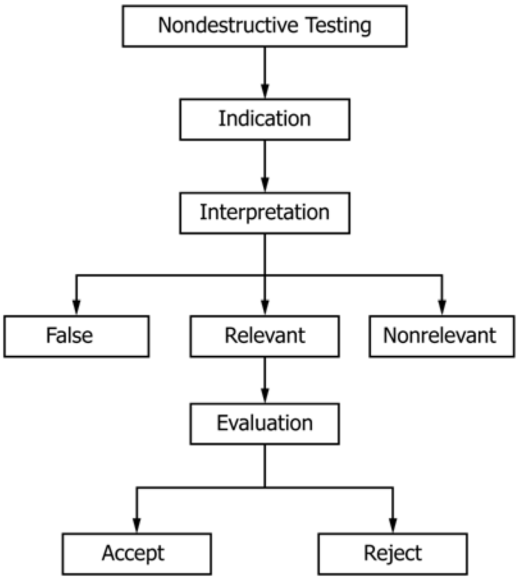

FIG. 1 Consequences of Detecting a Material Discontinuity (Indication) by NDT

7. Acoustic Emission

7.1 *Referenced Documents*

7.1.1 *ASTM Standards:*[2]

E569 Practice for Acoustic Emission Monitoring of Structures during Controlled Simulation

E650 Guide for Mounting Piezoelectric Acoustic Emission Sensors

E750 Practice for Characterizing Acoustic Emission Instrumentation

E976 Guide for Determining the Reproducibility of Acoustic Emission Sensor Response

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

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

E1211 Practice for Leak Detection and Location Using Surface-Mounted Acoustic Emission Sensors

E1419 Test Method for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission

E1932 Guide for Acoustic Emission Examination of Small Parts

E2076 Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission

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

7.1.2 *Compressed Gas Association Standard:*[5]

Pamphlet C-6.4 Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Gas Vehicle (HGV) Fuel Containers and Their Installations

7.1.3 *Military Handbooks and Standard:*[6]

MIL-HDBK-732A Nondestructive Testing Methods of Composite Materials—Acoustic Emission

7.2 *General Procedure*

7.2.1 Specially designed sensors (transducers) are used to detect transient elastic stress waves (AE) in a material produced as a result of applied stress (tension, compression, torsion, internal pressure, or thermal). The sensors are coupled to the article under test with a suitable couplant (for example, grease), or by means of an epoxy cement or other adhesive. The output from the sensor is amplified and filtered to

---

[5] Available from Compressed Gas Association, 14501 George Carter Way, Suite 103, Chantilly VA 20151.

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

TABLE 5 Summary of Acoustic Emission

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Global monitoring of composite structures to detect and locate active sources. Evaluation of the structural integrity of finished composite components such as pipes, tubes, tanks, and pressure vessels. Quality control of production and fabrication processes (for example, during lay-up winding, or curing). Proof-testing after fabrication. Also can be used as an alternative method to periodic hydrostatic proof testing. Periodic monitoring of regions of interest or concern during service. Continuous, real-time monitoring of structures (health monitoring). Evaluation of adhesive bonding. Monitoring crack growth prior to failure. Leak detection.	AE transducers are coupled to the article under test to detect transient elastic stress waves (or AE) produced during application of stress (mechanical, thermal or pressure). The location of the source is located by triangulation or area (zonal) location methods.	Remote and continuous monitoring of the entire article under test in real time is possible. Can detect growing of active imperfections or discontinuities. Can detect discontinuities and defects that may be inaccessible to other NDT procedures, and determine their location. Can be used for proof testing of new or in-service composite material components. Can be used for periodic or continuous (in situ) health monitoring.	The part or article under test must be stressed by mechanical load, pressure, or temperature, or other stimulus. Inactive (nonpropagating) imperfections or discontinuities cannot be detected and structurally insignificant imperfections or discontinuities may produce AE. Therefore, the significance of a detected AE source cannot be assessed unambiguously. Nonrelevant noise must be filtered out. Transducers must be placed on the part or article under test. Usually requires other NDT procedures to characterize detected imperfections or discontinuities.	The AE technique monitors transient elastic stress waves generated by various local processes that occur in a short time period in a structure under stress. The lack of sensed AE signals can be an indication of a composite structure having structural integrity. Alternatively, if increasing AE activity is detected, that can be an indication of damage occurring in the structure and of a potential loss of structural integrity. The AE signal from composites often consists of both continuous AE (qualitative description of a sustained signal level produced by rapidly occurring AE events) and burst AE (qualitative description of discrete signals of varying duration that are usually of higher amplitude than continuous AE).

eliminate unwanted frequencies. The conditioned AE signal is then digitized and segmented into discrete AE waveform packets through a process of threshold detection. Digital signal processing converts the transient waveform packets into extracted time and frequency features which describe the transient waveform's shape, size and frequency content. In sophisticated approaches, these features are sometimes analyzed together using artificial intelligence, pattern recognition and/or neural network techniques to distinguish true AE sources from noise. When multiple sensors in an array detect the same AE transient, location determination can be accomplished using arrival time analysis (triangulation) techniques. When multiple events are located close together they form an event cluster indicating continuing activity which is indicative of an active growing source. In addition to AE activity generated by growing imperfections or discontinuities, activity can also originate from preexisting imperfections or discontinuities that are not growing (for example, delamination surfaces rubbing together during depressurization of a pressure vessel).

7.3 *Significance and Use*

7.3.1 Acoustic emission is a term used to describe transient elastic stress waves produced in solids as a result of the application of stress. The applied stress may include mechanical forces (tension, compression or torsion), internal pressure, or thermal gradients (can often be accomplished by use of a hot-air gun). The applied stress may be short to long, random, or cyclic. The applied stress may be controlled by the examiner, or may already exist as part of the process. In either case the applied stress is measured along with the AE activity.

7.3.2 The resulting AE stress waves are produced by the rapid release of energy within the material from a localized source. The AE signal from composites often consists of both continuous AE (qualitative description of a sustained signal level produced by rapidly occurring AE events) and burst AE (qualitative description of discrete signals of varying duration that are usually of higher amplitude than continuous AE).

7.3.3 The AE technique records transient elastic stress waves produced by applied stress or resulting stress relaxation of the composite material or component. The stress waves are produced as either burst or continuous AE. AE activity, intensity, and severity correlated with applied stress yield information on the degradation within the article under test. Lack of AE activity is an indication of a sound structure, while more activity is an indication that the structure is degraded. The source is located by triangulation or zone location methods.

7.3.4 In fiber-reinforced composites, AE is generated by release of stored elastic energy during processes such as cracking of the matrix, or fracture or splitting of fibers.

Irreversible viscoelastic processes such as crazing of amorphous matrices or plastic (irreversible) deformation of either the matrix or fiber are not detectable under normal measurement conditions with commercial AE systems.

7.3.5 Interfacial sources of AE in fiber-reinforced composites include debonding of the matrix from the fibers, subsequent fiber pull-out (rubbing), and interlaminar debonding.

7.3.6 AE can also be produced by other acoustic sources in the composite not directly related to the matrix or fiber. These sources include leakage of gas or liquid through a crack, orifice, seal break or other opening (for example, in composite-overwrapped pressure vessels); and by movement or loosening of parts (thread failure in assembled composite piping systems, for example).

7.3.7 Most AE signals that are useful in NDT have frequencies that are above the audible range. Ordinarily they are between 20 kHz and 1 MHz, depending on application. The rate and amplitude of acoustic emission signals are noted and correlated to structure or composite article characteristics. Lower and higher frequencies are filtered out to avoid interferences from unwanted sources of noise such as machine vibrations or electrical equipment generated noise.

NOTE 1—When detecting leaks using low frequencies generally lower than 100 kHz, it is possible for the leak to excite mechanical resonances within the article under test that may enhance the acoustic signal used to detect leakage.

7.3.8 In addition to immediate evaluation of the emissions detected during application of the stimulus, a permanent record of the number and location of emitting sources and the relative amount of AE detected from each source provides a basis for comparison with sources detected during the examination and during subsequent stimulation.

7.3.9 The basic functions of an AE monitoring system are to detect, locate, and possibly classify emission sources. Other NDT procedures (for example, visual testing, ultrasonic testing, and eddy current testing) should be used to further evaluate the damage detected in an AE-located region.

NOTE 2—Determining the significance of damage with respect to residual strength or remaining life in a composite sample is presently not possible at the same level as is done with a crack in a metallic sample, for example, where facture mechanics can be used to determine the significance of damage.

7.3.10 *Felicity Ratio*—The Felicity ratio is the numerical value of the applied stress at which "significant AE" begins divided by the applied stress during the previous cycle. The term "significant AE" has no quantitative definition at this time, and is open to interpretation by the AE practitioner. However, Practice E1067 suggests three guidelines for determining the onset of significant AE:

7.3.10.1 More than 5 bursts during a 10 % increase in applied stress.

7.3.10.2 More than 20 counts during a 10 % increase in applied stress.

7.3.10.3 Increasing AE at constant applied stress.

7.3.11 *Effect of Variables on the Felicity Ratio*—Rate of application and removal of stress, time at peak applied stress, AE system sensitivity, time between load cycles, stress state during loading, AE source mechanism, test environment, and the applied stress relative to the ultimate strength of the article under test (stress ratio) can all affect the Felicity ratio. Composite materials and components which have rate dependent properties, such as fiber-reinforced composites with plastic matrices, will be affected to a greater extent.

7.3.12 *Kaiser Effect*—If a composite material or component is loaded to a given stress level and then unloaded, usually no AE will be observed upon immediate reloading until the previous load has been exceeded. This is known as the Kaiser effect. The Kaiser effect is said to hold when the Felicity ratio is ≥ 1.0, and violated when the Felicity ratio is ≤ 1.0. Therefore, the Kaiser effect holds when no new AE sources are operating, or when there are no reversible AE sources present during subsequent load cycling. Alternatively, when the Kaiser effect is violated, then either or both of these cases have occurred.

7.3.13 *Advantages and Applications*—AE is used to evaluate to structural integrity of composite pipes, tubes, tanks, pressure vessels, and other finished composite parts. Remote and real time surveillance of structures is possible. Inaccessible imperfections or discontinuities can be detected, and their location determined. In addition to imperfection or discontinuity or defect detection, AE can be used to detect leaks (see Practice E1211) and as an alternative to periodic hydrostatic proof testing (see Practice E1419). AE can also be used in quality control evaluation of production processes on a sampled or 100 % inspection basis, in-process examination during a period of applied stress in a fabrication process (lay-up, winding, pressing, curing, etc.) proof-testing after fabrication, monitoring regions of interest or concern, and re-examination after intervals in service. AE is particularly useful for measuring adhesive bond integrity, and monitoring the growth of a crack in order to give a warning of impending failure. Compared to other common NDT procedures, some of the advantages AE are as follows:

7.3.13.1 AE is a global monitoring technique, capable of detecting and locating imperfections or discontinuities a distance away from the sensors without the need to scan the sensors.

7.3.13.2 Can perform continuous monitoring on a complete composite article in real time.

7.3.13.3 Is very sensitive to detecting the growth of active imperfections or discontinuities compared to other NDT techniques; however, usually requires these other methods to characterize these imperfections or discontinuities.

7.3.13.4 Can detect discontinuities and defects that may be inaccessible to other NDT procedures.

7.3.13.5 Can be used for proof testing of new or in-service composite pressure vessels.

7.3.14 *Limitations and Interferences*—Some of the disadvantages AE are as follows:

7.3.14.1 The part or article under test must be stressed.

7.3.14.2 With the exception of friction-generated AE (for example, delamination surfaces rubbing together), AE-inactive (nonpropagating) imperfections or discontinuities cannot be detected and structurally insignificant imperfections or discontinuities may produce AE. Therefore, the significance of a detected AE source cannot be assessed unambiguously.

7.3.14.3 Nonrelevant noise must be filtered out.

7.3.14.4 Transducers must be placed on the part or article under test.

7.4 *Use of Referenced Documents*

7.4.1 *Applications:*

7.4.1.1 *Testing of Composite Pipe, Fittings, Tanks and Small Parts:*

(1) Consult Practice E1067 for AE examination of new and in-service fiberglass-reinforced plastic (FRP) tanks and vessels to determine structural integrity. Practice E1067 is limited to tanks and vessels with fiber loadings greater than 15 % by weight, and that are designed to operate at an internal pressure no greater than 0.44 MPa (65 psia) above the static pressure due to the internal contents, or at vacuum service differential pressures levels between 0 and 0.06 MPa (0 and 9 psi).

(2) Consult Practice E1118 for AE examination of new and in-service reinforced thermosetting resin pipe (RTRP) to determine structural integrity. Practice E1118 is limited to lined and unlined pipe, fittings, joints, and piping systems up to and including 0.6 m (24 in.) in diameter, fabricated with fiberglass or carbon fiber reinforcement at fiber loadings greater than 15 % by weight, and is applicable to tests below pressures of 35 MPa absolute (5000 psia).

(3) Consult Guide E1932 for techniques for conducting AE examination on small parts.

7.4.1.2 *Testing of Pressure Vessels:*

(1) Consult Compressed Gas Association (CGA) Pamphlet C6.4 for training of personnel conducting AE on pressure vessels.

(2) Consult Practice E569 for guidelines for AE examination and monitoring of structures such as pressure vessels that are stressed by mechanical or thermal means.

(3) Consult Test Method E1419 for guidelines for AE examination of noncryogenic seamless pressure vessels (tubes) of the type used for distribution or storage of industrial gases at pressures greater than encountered in service, as an alternative to periodic hydrostatic proof examination.

(4) Consult Test Method E2076 for measurement of AE during simulation of bending loads.

(5) Consult Test Method E2191 for guidelines for AE of new and in-service filament-wound composite pressure vessels at pressures equal to or greater than what is encountered in service, as an alternative to CGA-mandated three-year visual testing.

NOTE 3—Slow-fill pressurization must proceed at flow rates that do not produce background noise from flow of the pressurizing medium. During proof testing of composite pressure vessels, AE energy from a particular AE event reaching the AE sensor will vary depending on the liquid level in the vessel. Furthermore, AE wave propagation characteristics will be affected by whether the vessel has a metal or rubber liner, for example.

NOTE 4—In general, fast-fill pressurization can be used if hold periods are used. In this case, AE data are recorded only during hold periods. While this hold period technique may be suitable for characterization of glass or aramid-reinforced composites, the same technique may not be suitable for carbon and graphite-reinforced composites.

NOTE 5—For composites made by certain fabrication routes (for example, filament-winding), the composite surface may not be as smooth as is normally the case. To have a relatively uniform coupling from article to article, the best amount of couplant to use may have to be determined experimentally by applying different amounts and ascertaining which amount gives the most uniform AE signal from pencil lead breaks, for example.

7.4.1.3 *Leak Testing*—Consult Practice E1211 for description of a passive method utilizing *(1)* surface-mounted AE sensors, or *(2)* sensors attached by means of acoustic waveguides that allow detection and location of the steady state source of gas and liquid leaking out of a pressurized system. Application examples to illustrate the use of AE to detect leaks in a relief valve, ball valve, and a transfer line are also given in Appendix X1 of Practice E1211.

7.4.2 *Acoustic Emission Equipment and Instrumentation:*

7.4.2.1 Consult Guide E650 for guidelines about mounting piezoelectric AE sensors.

7.4.2.2 Consult Practice E750 for required tests and measurements on AE equipment components and units, determination of instrument bandwidth, frequency response, gain, noise level, threshold level, dynamic range, signal overload point, dead time, and counter accuracy.

7.4.2.3 Consult Appendix X1 of Practice E750 for a discussion of AE electronic components or units including sensors, preamplifiers, filters, power amplifiers, line drive amplifiers, threshold and counting instrumentation, and signal cables. Also, most modern AE systems use computers to control collection, storage, display, and data analysis. Features of computer-based system include waveform collection as well as a wide selection of measurement parameters relating to the AE signal.

NOTE 6—AE signals from composites are typically of high amplitude, so sensor sensitivity is usually not an issue except in cases where the sensors are spaced too far apart or if the threshold is set too high. The use of non-resonant wideband (versus resonant sensors) is useful in detecting signals over a range of frequencies and is relevant when wave propagation theory is being used to understand the AE signal and to more accurately locate the AE source. Otherwise, both resonant and non-resonant sensors can be used as long as they are spaced appropriately on the composite material or component to maintain sensitivity to AE sources distributed across the article under test. Typical AE signals generated in composites are of higher amplitude near the source compared to the AE generated in metals. In contrast to metals, the higher frequencies in the AE signal are absorbed by the composite after relatively short propagation distances. Thus, often lower frequency sensors and filters are used for composites. Due to the fact that AE sources typically occur throughout composites when they are stressed, it is not unusual for AE sources to occur in the composite directly below sensors. This situation can result in a signal of very high amplitude. Such cases are not likely in metal samples as it is unlikely that a sensor will be directly over a crack tip. Due to the amplitude of the composite AE signals, in some cases it is necessary to use a preamplifier with only 20 dB of gain to avoid saturation of the signal. Most commercial AE preamplifiers saturate at 10 to 20 volts peak-to-peak voltage output. For these reasons, preamplifiers with a 20 to 40 dB gain, 10 volt peak-to-peak output voltage, and an 80–100 dB dynamic range are common.

7.4.2.4 Consult Appendix X2 of Practice E750 for an explanation of suggested measurements (for example, preamplifier input impedance, wave shaping, gain measurements).

7.4.2.5 Consult Appendix X3 of Practice E750 about the electrical circuit configuration for measurement of input impedance.

7.4.2.6 Consult Appendix X4 of Practice E750 about acoustic and electrical noise sources.

7.4.2.7 Consult Appendix A1 of Practice E1067 or Appendix A1 of Practice E1118 for instrumentation performance requirements for sensors, signal cable, couplant, preamplifier, filters, power-signal cable, main amplifier, and the main processor.

7.4.2.8 Consult Appendix A2 of Practice E1067 or Appendix A1 of Practice E1118 for baseline calibration of AE equipment, including low-amplitude threshold, high-amplitude threshold, and count value instrument calibration.

7.4.2.9 Consult Appendix A3 of Practice E1067 for sensor placement guidelines for atmospheric, atmospheric-pressure, and atmospheric-vacuum tanks.

7.4.2.10 Consult Appendix A1 of Practice E1419 for specifications for AE components; namely, sensors, signal cable, couplant, preamplifier, power-signal cable, power supply, and signal processor used as an alternative to periodic hydrostatic proof testing.

7.4.2.11 Consult MIL-HDBK-732A for useful applications details on test installation and test fixturing (Section 4); couplants and waveguides (Section 5); type, location, and application of sensors (Section 6); cables (Section 7); preamplifiers (Section 8); secondary amplifiers and filters (Section 9); time domains of burst and continuous AE (Section 10); AE sources in composites (Sections 11–14); wave propagation characteristics (Section 15); source or imperfection or discontinuity location (Section 16); Kaiser effect/Felicity ratio (Section 17); factors of significance in AE data (Section 18); in-situ calibration of AE tests (Section 19); extraneous AE (Section 20); and control checks on AE testing (Section 21).

7.4.3 *Acoustic Emission Calibration and Standardization:*

7.4.3.1 Consult Practice E569 for performing a location sensitivity check (includes a zone location sensitivity check and a source location algorithm sensitivity check).

7.4.3.2 Consult Guide E976 for performing sensor checks or system performance checks using a pencil lead break.

7.5 *Geometric and Size Considerations*

7.5.1 Wave propagation signal losses are more considerable in composites than in metals. There are three primary causes of amplitude attenuation of AE signals in composites during AE wave propagation: *(1)* geometric spreading (same as in metals, but metals do not typically have sensors directly over AE sources; thus this can be quite large), *(2)* material absorption (much higher in composites than in metals), and *(3)* dispersion (different propagation velocities of different frequencies). In addition, depending on the geometry and size of the article under test, reflections can also alter the expected attenuation.

7.5.2 In larger composite articles, significant manpower economies using sensors with integrated preamplifiers may preclude the need to connect separate preamplifiers.

7.5.3 Since composites are in general anisotropic and of varying thicknesses, the signal (wave) propagation losses may vary in different parts of the composite.

7.6 *Safety and Hazards*

7.6.1 *Pressure Vessels*—When conducting AE examination of pressure vessels and reinforced thermosetting resin pipe (RTRP), the following safety guidelines shall be followed:

7.6.1.1 When testing in-service pressure vessels, all safety requirements unique to the examination location shall be met. Protective clothing and equipment that is normally used in the area in which the examination is conducted shall be worn.

7.6.1.2 The test temperature should not be below the ductile-brittle transition temperature (β-relaxation) of the semicrystalline matrix, or above the glass-rubber transition temperature (α-relaxation or glass transition temperature) of the amorphous matrix used in the pressure vessel composite overwrap.

7.6.1.3 Precautions shall be taken to protect against the consequences of catastrophic failure when pressure testing, for example, flying debris and impact of escaping liquid. Pressurizing under pneumatic conditions is not recommended except when normal service loads include either a superposed gas pressure or gas pressure only. Care shall be taken to avoid overstressing the lower section of the vessel when liquid test loads are used to simulate operating gas pressures.

7.6.1.4 Pneumatic testing is extremely dangerous. Special safety precautions shall be taken when pneumatic testing is required (safety valves, etc).

7.7 *Calibration and Standardization*

7.7.1 Periodically perform calibration and verification of pressure transducers, AE sensors, preamplifiers (if applicable), signal processors (particularly the signal processor time reference), and AE electronic waveform generators. Equipment should be adjusted so that it conforms to equipment manufacturer's specifications. Instruments used for calibration must have current accuracy certification that is traceable to the National Institute for Standards and Technology (NIST) or equivalent national or regional (multinational) standards institute.

7.7.2 Routine electronic checks must be performed any time there is concern about signal processor performance. A waveform generator should be used in making evaluations.

7.7.3 Routine sensor checks must be performed at any time there is concern about sensor performance. Peak amplitude and electronic noise level should be recorded. Sensors can be stimulated by a mechanical device such as a pencil lead break or piezoelectric transducer. The object is to induce stress waves into the article under test at a specified distance from each sensor. Induced stress waves stimulate a sensor in a manner similar to emission from an imperfection or discontinuity. Sensors should be replaced if they have peak amplitudes or electronic noise greater than the average, or sensitivities lower than the average of the group of sensors being used.

7.7.4 A system verification must be performed immediately before and immediately after each examination. A system verification uses a mechanical device such as a pencil lead break or piezoelectric transducer to induce stress waves into the article under test. The induced stress wave must be nondestructive. System verification validates the sensitivity of each system channel (including the couplant and test fixture).

7.8 *Physical Reference Standards*

7.8.1 Not Applicable.

8. Computed Tomography (X-ray Method)

8.1 *Referenced Documents*

8.1.1 *ASTM Standards:*[2]

E1441 Guide for Computed Tomography (CT) Imaging

TABLE 6 Summary of Computed Tomography

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Allows the depth of subsurface imperfections or discontinuities to be measured. Quantitative analysis of feature size and shape, feature density contrast, wall thickness, coating thickness, absolute material density, and average atomic number. Can perform, to a limited extent, chemical characterization of the internal structure of materials.	A penetrating X-ray radiation beam is passed through the article under test along many paths to compute a cross-sectional CT-density image called a tomogram. The CT system acquires many sets of projected X-ray data (also called views) from a DDA (either 1D or 2D), converts measured signal to a digital format, and then performs a reconstruction to compute a tomogram or 3D volume image set. The CT systems today are not limited to generating tomograms. They can also generate volume data, 3D visualization and reformatted, multi-planar reconstructions.	Produces clear cross-sectional image slices of an object. Because of the absence of structural noise from detail outside the thin plane of inspection, images are much easier to interpret. Ideally suited for locating and sizing planar and volumetric detail in three dimensions, for example, imperfection or discontinuity distribution. Applies equally well to metallic and non-metallic specimens, solid and fibrous materials, and smooth and irregularly surfaced objects. Extensive image processing possible.	CT scanners usually have an upper limit on the part size, however specialized scanners can be built for large parts. Larger parts (composite fan blades) may require the use of linear accelerator X-ray sources (1 MeV and higher). Not very applicable to inspection of large areas. CT scans may take a long time to both acquire and reconstruct the data. Scanning time is dependent on the size of the part, the X-ray source output, required resolution and the detector geometry. Difficulty obtaining sufficient contrast between low atomic number composite substructures (for example, matrix, fiber, laminates), especially for flat panel based CT systems. (Obtaining sufficient contrast is not a problem for a high dynamic range CT system). Possibility of artifacts in the data. Tooling and/or multi-axis part-handling fixtures may be required.	A digitized cross-sectional CT-density map (tomogram) of the article under test. Allows full, three dimensional CT-density maps to be obtained for sufficiently small articles under test.

E1570 Practice for Computed Tomographic (CT) Examination

E1672 Guide for Computed Tomography (CT) System Selection

E1695 Test Method for Measurement of Computed Tomography (CT) System Performance

E1935 Test Method for Calibrating and Measuring CT Density

8.2 *General Procedure*

8.2.1 Computer Tomography is a radiographic inspection method that uses a computer to reconstruct an image of a cross-sectional plane (slice) through the article under test. CT consists of making penetrating radiation measurements of the X-ray opacity of the article under test along many paths to compute a cross-sectional CT-mass attenuation density image called a tomogram. The resulting cross-sectional image is a quantitative map of the linear X-ray mass attenuation coefficient at each point in the plane. The linear mass attenuation coefficient characterizes the local instantaneous rate at which X-rays are attenuated during the scan, by scatter or absorption, from the incident radiation as it propagates through the article under test.

8.3 *Significance and Use*

8.3.1 CT is usually performed after two dimensional X-ray imaging.

8.3.2 CT, as with conventional radiography and radioscopic examinations, is broadly applicable to any material or examination object through which a beam of penetrating radiation may be passed and detected, including composite materials and components. The new user can learn quickly (often upon first exposure to the technology) to read CT data because the images correspond more closely to the way the human mind visualizes three-dimensional structures than conventional projection radiography. Further, because CT images are digital, they may be enhanced, analyzed, compressed, archived, input as data into performance calculations, compared with digital data from other NDT modalities, or transmitted to other locations for remote viewing. Additionally, CT images exhibit enhanced contrast discrimination over compact areas larger than 20 to 25 pixels. This capability has no classical analog. Contrast discrimination of better than 0.1 % at three-sigma confidence levels over areas as small as one-fifth of one percent the size of the object of interest is common.

8.3.3 CT images are well suited for use in making quantitative measurements. The magnitude and nature of the error in CT-based measurements strongly depends on the particulars of the scanner apparatus, the scan parameters, the object, and the features of interest. Among the parameters which can be estimated from CT images are feature size and shape, feature density contrast, wall thickness, coating thickness, absolute material density, and average atomic number.

8.3.4 The use of such quantitative measurements requires that errors associated with them be known. The precision of the measurement can best be determined by seeing the distribution of measurements of the same feature under repeated scans, preferably with as much displacement of the object between scans as is expected in practice. This ensures that all effects which vary the result are allowed for, such as photon statistics, detector drift, alignment artifacts, spatial variation, variation of the point-spread-function, object placement, etc.

8.3.5 One source of such variation is uncorrected systematic effects such as gain changes or offset displacements between different images. Such image differences can often be removed from the measurement computation by including calibration materials in the image, which is then transformed so that the calibration materials are at standard values.

8.3.6 In addition to random variation, measurements of any particular feature may also have a consistent bias. This may be due to artifacts in the image or to false assumptions used in the measurement algorithm. When determined by measurement of articles under test, such biases can be removed by allowing for them in the algorithm.

8.3.7 Examination of the distribution of measurement results from repeated scans of articles with known features similar to those which are the target of the NDT investigation is the best method for determining precision and bias in CT measurements. Once such determinations have been made for a given system and set of objects and scanning conditions; however, they can be used to give well-based estimates of precision and bias for objects intermediate in size, composition and form, as long as no unusual artifact patterns are introduced into the images.

8.3.8 With proper calibration, absolute density determinations can also be made very accurately. Attenuation values can be related accurately to material densities. If details in the image are known to be pure homogeneous elements, the density values may still be sufficient to identify materials in some cases. For the case in which no *a priori* information is available, CT densities cannot be used to identify unknown materials unambiguously, since an infinite spectrum of compounds can be envisioned that will yield any given observed attenuation. In this instance, the exceptional density sensitivity of CT can still be used to determine part morphology and highlight structural irregularities.

8.3.9 Because CT scan times are typically on the order of minutes per image, complete three-dimensional CT examinations can be time consuming. Complete part examinations demand large storage capabilities or advanced display techniques, or both, and equipment to help the operator review the huge volume of data generated. This can be compensated for by state-of-the-art graphics hardware and automatic examination software to aid the user. Thus, less than 100 % CT examinations are often necessary or must be accommodated by complementing the inspection process with digital radiographic screening.

8.3.10 CT examination procedures are generally part and application specific. Industrial CT usage is new enough that in many cases consensus methods have not yet emerged. The situation is complicated further by the fact that CT system hardware and performance capabilities are still undergoing significant evolution and improvement.

8.3.11 *Advantages and Applications:*

8.3.11.1 Unlike radiography or radioscopy, CT allows the depth of defects to be observed. It can show small, specific clusters of defects that give information not available in conventional radiography.

8.3.11.2 CT is ideally suited for locating and sizing planar and volumetric detail in three dimensions.

8.3.11.3 Because of the sensitivity of absorption cross sections to atomic chemistry, CT permits, to a limited extent, the chemical characterization of the internal structure of materials.

8.3.11.4 Also, since the method is X-ray based, it applies equally well to metallic and non-metallic specimens, solid and fibrous materials, and smooth and irregularly surfaced objects. When used in conjunction with other NDT procedures, such as ultrasound, CT data can provide evaluations of material integrity that cannot currently be provided nondestructively by any other means.

8.3.11.5 The principal advantage of CT is that it nondestructively provides quantitative densitometric (that is, density and geometry) images of thin cross sections through an object. Because of the absence of structural noise from detail outside the thin plane of inspection, images are much easier to interpret than conventional radiographic data.

NOTE 7—The linear mass attenuation coefficient also carries an energy dependence that is a function of material composition. This feature may or may not (depending on the materials and the energies of the X-rays used) be more important than the basic density dependence. In some instances, this effect can be detrimental, masking density differences in a CT scan; in other cases, it can be used to advantage, enhancing the contrast between different materials of similar density.

8.3.12 *Limitations and Interferences:*

8.3.12.1 As in the case for radiography and radioscopy, perhaps the biggest challenge in X-ray CT as applied to composite materials and components is to obtain sufficient contrast between low atomic number composite substructures (for example, matrix, fiber, laminates). Obtaining sufficient contrast is not a problem for high dynamic range CT systems.

8.3.12.2 As with any modality, CT has its limitations. The most fundamental is that candidate objects for examination must be small enough to be accommodated by the handling system of the CT equipment available to the user and radiometrically translucent at the X-ray energies employed by that particular system. Furthermore, high-resolution CT reconstruction algorithms require collection of more than 180 degrees of data by the scanner. Object size or opacity limits the amount of data that can be taken in some instances. While there are methods to compensate for incomplete data that produce diagnostically useful images, the resultant images are necessarily inferior to images from complete data sets.

8.3.12.3 Another potential drawback with CT imaging is the possibility of artifacts in the data. As used here, an artifact is any feature in the image that does not accurately reflect true structure in the part being inspected. Because they are not real, artifacts limit the user's ability to quantitatively extract mass attenuation coefficients, density, dimensional, or other data from an image. Therefore, as with any technique, the user must learn to recognize and be able to discount common artifacts subjectively. Some image artifacts can be reduced or eliminated with CT by improved engineering practice; others are inherent in the methodology. Examples of the former include scattered radiation and electronic noise. Examples of the latter include edge streaks and partial volume effects. Some artifacts are a little of both. A good example is the cupping artifact, which is due as much to radiation scatter (which can in principle be largely eliminated), as to the polychromaticity of the X-ray flux (which is inherent in the use of bremsstrahlung sources). Specific artifacts for composite parts, especially ones that have a large aspect ratios (like fan blades), and ways to minimize artifacts by acquiring more projections or using different scanning geometries or adding X-ray compensating material, are not discussed here.

8.4 *Use of Referenced Documents*

8.4.1 *General:*

8.4.1.1 Consult Guide E1441 for a general description of X-ray CT (including a discussion of the theoretical basis of CT imaging), CT system capabilities (spatial resolution, statistical noise, artifacts), and a glossary of terms that have meaning or carry implications unique to CT. Potential users and buyers, as well as experienced CT inspectors, will find Guide E1441 a useful source of information for determining the suitability of CT for particular examination problems, for predicting CT system performance in new situations, and for developing and prescribing new scan procedures.

8.4.1.2 Consult Guide E1672 when translating application requirements into computed tomography (CT) system requirements/specifications, or to establish a common terminology to guide both purchaser and supplier in the CT system selection process.

8.4.2 *Computed Tomography Equipment and Instrumentation:*

8.4.2.1 Consult Guide E1441 and Practice E1570 for types of subsystems present in modern CT systems.

8.4.2.2 Consult Guide E1441 for a description of modern CT system subsystems (radiation sources, ionization and scintillation detectors, mechanical scanning equipment, computer systems, operator interfaces, image display, and image processing).

8.4.3 *Computed Tomography Calibration and Standardization:*

8.4.3.1 Consult Guide E1441 for verification of CT performance parameters and interpretation of CT results.

8.4.3.2 Consult Practice E1570 for requirements that are intended to control the reliability and quality of CT images, whether by means of calibration, standardization, use of physical reference standards, or inspection plans. Control of reliability and quality is also achieved by adopting uniform procedures for CT system configuration, setup, optimization, and performance measurement.

8.4.3.3 Consult Test Method E1695for determining the spatial resolution and contrast sensitivity in X-ray CT images. The spatial resolution measurement is derived from an image analysis of the sharpness at the edge of the disk. The contrast sensitivity measurement is derived from an image analysis of the statistical noise at the center of the disk. This test method may also be used to evaluate other performance parameters such as: the mid-frequency enhancement of the reconstruction kernel; the presence (or absence) of detector crosstalk; the undersampling of views; and the clipping of unphysical (that is, negative) CT numbers.

8.4.3.4 Consult Test Method E1935 for density calibration of CT systems and for using this information to measure material densities from CT images.

8.5 *Geometry, Size, and Weight Considerations*

8.5.1 *Size*—Aside from weight and material makeup, the most basic consideration will be the article's size. The maximum height and diameter of the article under test that can be examined on a CT system defines the equipment examination envelope. Size, and therefore weight, will govern the type of mechanical subsystem that will be needed to move the article relative to the beam (article rotated or translated relative to a stationary beam and source), or move the beam relative to the article (beam source and detector system rotated around the article). For example, a very different mechanical subsystem will be required to support and accurately move a large, heavy article than move a small, light article. Similarly, the logistics and fixturing for handling a large number of similar items will be a much different problem than for handling a one-of-a-kind item. Larger articles, depending on material makeup, will in general attenuate the beam more, which will in turn govern the type of radiation source and detectors, or both, that are needed.

8.5.2 As a metrological tool, most CT systems provide a pixel resolution of roughly 1 part in 2000 (since, at present, 2048 × 2048 pixel images are standard), and metrological algorithms can often measure dimensions with acceptable accuracy down to the subpixel range. For small objects (less than 10 cm (4 in.) in diameter), this translates into accuracies of approximately 0.1 mm (0.003 to 0.005 in.) at three-sigma. For much larger objects, the corresponding figure will be proportionally greater.

NOTE 8—Systems with 0.01 mm voxel resolution are currently available.

8.5.3 The maximum height and diameter of a test article that can be examined on a CT system defines the equipment examination envelope. The weight of the object and any associated fixturing must be within the manipulation system capability. For example, a very different mechanical subsystem will be required to support and accurately move a large, heavy test article than move a small, light test article. Similarly, the logistics and fixturing for handling a large number of similar items will be a much different problem than for handling a one-of-a-kind item.

8.6 *Safety and Hazards*

8.6.1 CT examination procedures shall be carried out under protective conditions so that personnel will not receive radiation dose levels exceeding that permitted by company, city, state, or national regulations. All hazards and safe operating procedures that apply shall be identified, including:

8.6.1.1 Federal regulations,

8.6.1.2 State/local regulations,

8.6.1.3 Posting of area,

8.6.1.4 Personnel monitoring,

8.6.1.5 Positioning table lockout, and

8.6.1.6 Area evacuation.

8.6.2 For additional information pertaining to radiation safety and hazards associated with the use of X-ray equipment, refer to subsection 10.2.8.

8.7 *Calibration and Standardization*

8.7.1 CT examinations system performance parameters must be determined and monitored regularly to ensure consistent results. The best measure of CT system performance can be made with the system in operation, using the article under test under actual operating conditions.

8.7.2 System performance measurement techniques should be standardized so that performance measurement tests may be readily duplicated at specified intervals. The CT examination system performance should be evaluated at sufficiently frequent intervals, as may be agreed upon by the supplier and the user of the CT examination services, to minimize the possibility of time dependent performance variations.

8.7.3 Quantitative measurement of spatial resolution, signal-to-noise resolution, contrast sensitivity, contrast-detail-dose curves shall be conducted in accordance with Practice E1570.

8.7.4 Density calibration of CT systems using disks of material with embedded specimens of known composition and density shall be performed in accordance with Test Method E1935. The measured mean CT values of the known standards are determined from an analysis of the image, and their linear mass attenuation coefficients are determined by multiplying their measured physical density by their published mass attenuation coefficient. The density calibration is performed by applying a linear regression to the data. Once calibrated, the linear attenuation coefficient of an unknown feature in an image can be measured from a determination of its mean CT value. Its density can then be extracted from knowledge of its mass attenuation coefficient, or one representative of the feature.

8.8 *Physical Reference Standards*

8.8.1 Performance measurements involve the use of a simulated composite article (also known as a test phantom) containing actual or simulated features that must be reliably detected and measured. A test phantom can be designed to provide a reliable indication of the CT system's capabilities. Test phantom categories currently used in CT and simulated features to be imaged can be classified in accordance with Table 1 in Practice E1570.

9. Leak Testing

9.1 *Referenced Documents*

9.1.1 *ASTM Standards:*[2]

E427 Practice for Testing for Leaks Using the Halogen Leak Detector (Alkali-Ion Diode)

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

E498 Test Methods for Leaks Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Tracer Probe Mode

E499 Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode

E515 Test Method for Leaks Using Bubble Emission Techniques

E1002 Test Method for Leaks Using Ultrasonics

E1003 Test Method for Hydrostatic Leak Testing

E1066 Test Method for Ammonia Colorimetric Leak Testing

E1211 Practice for Leak Detection and Location using Surface-mounted Acoustic Emission Sensors

E1603 Test Methods for Leakage Measurement Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Hood Mode

E2024 Test Methods for Atmospheric Leaks Using a Thermal Conductivity Leak Detector

9.1.2 *Military Handbooks and Standard:*[6]

MIL-L-25567D Leak Detection Compound, Oxygen Systems

9.1.3 *ASNT Handbook:*[3]

Leak Testing, Volume 1, Nondestructive Testing Handbook

9.2 *General Procedure*

9.2.1 *Leak Detection and Location Determination*—Tracer gas tests for purposes of leak location determination can be divided into tracer probe and detector probe techniques. When choosing either technique, it is important that the leak location be attempted only after the presence of a leak has been ascertained. The tracer probe technique is used when the article under test is evacuated and the tracer gas is applied to the outside of the pressure boundary of the article. The detector probe technique is used when the article under test is pressurized with gases including the tracer gas (if used), and sampling of the leaking gas is 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 article under test can be brought within acceptable limits.

9.2.2 *Leak Rate Measurement*—All leak rate measurements involving a tracer gas are based on flow of gas from the high to low pressure sides of a 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 pressure boundary. Where leak measurements of change in pressure or volume of gas are within a pressurized enclosure, the loss of internal gas pressure or volume indicates the leakage has occurred through the pressure boundary. When evacuated or low pressure composite articles are surrounded by higher pressure media (for example, the atmosphere of a test chamber containing gases at higher pressure), leakage can be detected by loss of pressure in the external chamber or by rise in

TABLE 7 Summary of Leak Testing

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Can be performed on any composite material or component (for example, filament-wound pressure vessels) in which a differential pressure exists (by means of evacuation or pressurization) and where through-leakage or in-leakage of product, air, water vapor, or other contaminants over the projected service life are of concern. Leak testing involves either 1) detection and location of leaks, or 2) leak rate measurement. Used to 1) prevent material leakage loss, 2) prevent hazards and nuisances caused by leakage, and 3) detect unreliable components whose leakage rates exceed acceptance criteria. Used detect material imperfections or discontinuities such as cracks and fissures. Leak testing is complementary to other NDT procedures that are sensitive to material discontinuities. Can be used to measure the leak rate of articles under test that are open (both test surfaces are accessible) or sealed (only the external surface is accessible).	A flow of a fluid (liquid or gas) through a leak produces a pressure or concentration differential. However, because the leak is not manufactured intentionally, the leak hole dimensions are unknown; therefore, the quantity used to describe the leak is the measured leak rate. To improve sensitivity, a tracer gas is often used in conjunction with a detector. Leak Detection and Location—When articles under test have pressure boundaries accessible on both sides, either tracer probe (pressurized components) or detector probe (evacuated components) techniques can be used for leak location determination. Leak Rate Measurement—Leak rate measurement techniques fall into two categories: 1) static, and 2) dynamic testing. In static testing, the chamber into which the tracer gas leaks is allowed to accumulate, while in dynamic testing, the chamber is pumped continuously or intermittently to draw the gas into the detector.	For method-specific advantages of bubble, chemical penetrant, halogen gas, hydrostatic, mass loss and pressure change, mass spectrometer, thermal conductivity, and ultrasonic leak testing, refer to the appropriate subsection. Gives irrefutable evidence of through leaks compared to more ambiguous methods such as liquid penetration. More sensitive than volumetric leak detection techniques such as AE or UT, for example. Different techniques are available for characterization of large leaks (with rates as high as 10^{-2} Pa m^3 s^{-1} (10^{-1} std cm^3 s^{-1})) and small leaks (rates less than 10^{-5} Pa m^3 s^{-1} (10^{-4} std cm^3 s^{-1})).	For method-specific limitations of bubble, chemical penetrant, halogen gas, hydrostatic, mass loss and pressure change, mass spectrometer, thermal conductivity, and ultrasonic leak testing, refer to the appropriate subsection. Test equipment costs increase as the required leak test sensitivity increases.	Qualitative indications, for example bubbles, or quantitative measurements, for example, detector deflections, that ascertain the presence or concentration of a leaking fluid, either with or without the presence of a tracer gas, are made on the low pressure or low concentration side of the article under test. Depending on the technique chosen, leak locations can be precisely determined, or leak rates from 0.05 to 10^{-13} Pa m^3 s^{-1} (0.5 to 10^{-12} std cm^3 s^{-1}) can be measured.

pressure within the lower pressure composite article under test. Leak rate measurement techniques fall into two categories: *(1)* static, and *(2)* dynamic testing. In static testing, 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 within or around the article under test. In the former case, the article is pressurized and detector is connected to the lower pressure envelope surrounding the pressurized article. In the latter case, the article is evacuated and detector is connected to the evacuated article surrounded by a higher pressurized envelope containing the tracer gas.

9.2.3 *Choice of a Leak Testing Method*—The correct leak testing method optimizes sensitivity, cost, and reliability of the test. The best suited method will ultimately depend on the *(1)* desired sensitivity, *(2)* type of leak test (leak detection and location determination versus leak rate measurement), and *(3)* type of article under test (open versus sealed) (Fig. 2). Methods are listed in the order of sensitivity (the higher a method is in a given listing, the more sensitive it is).

9.3 *Significance and Use*

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

9.3.2 The equipment needed will depend on the leak practice or test method used. Chemical penetrants, tracer gases, tracer gas leak standards, a leak detector, safety monitors, roughing pumps, auxiliary pumps, secondary pressure vessels

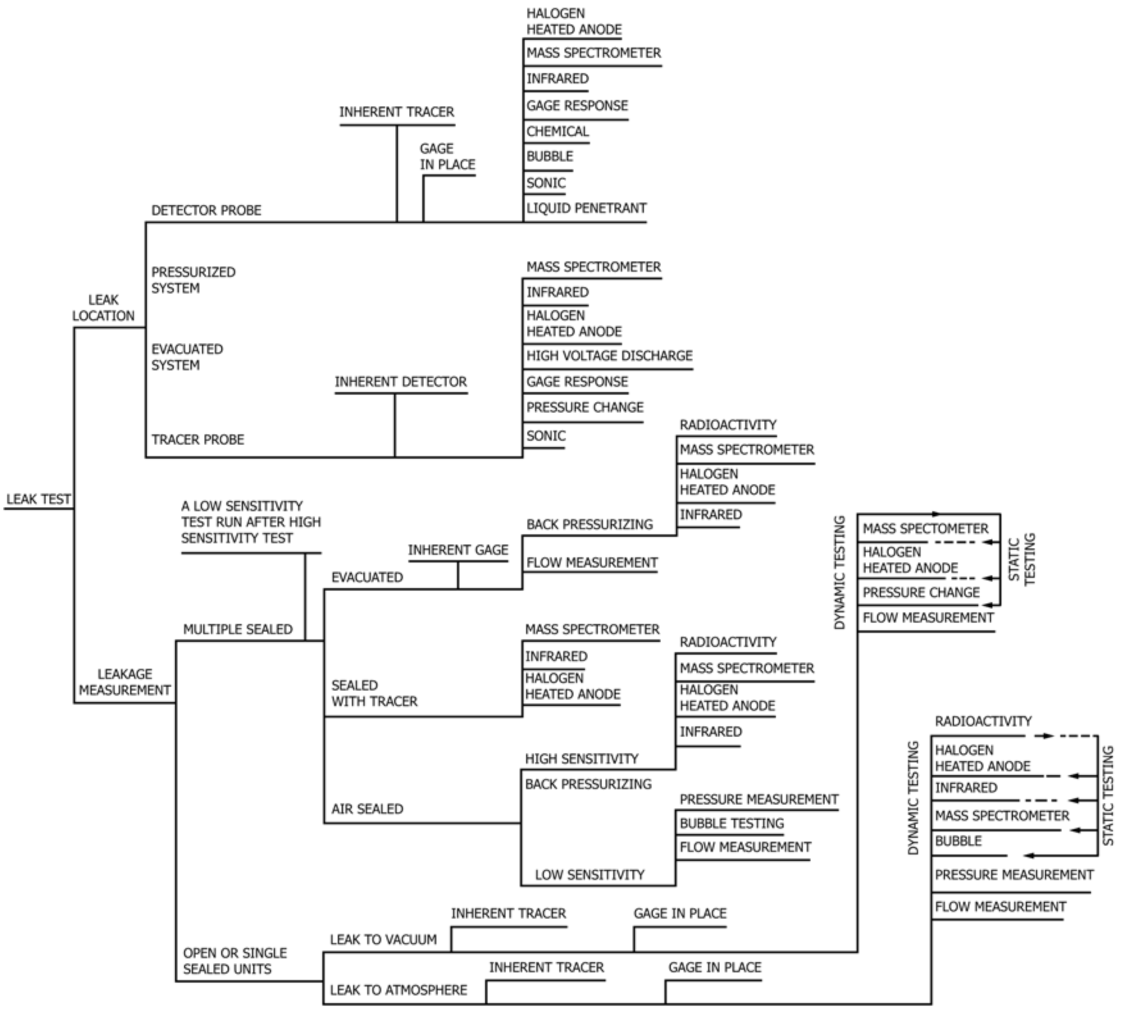

FIG. 2 Guide for Selection of a Leak Test Method

or chambers (for bombing), 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 practice or test method for the specific equipment needed.

9.3.3 Leak testing allows determination of the existence of leak sites and, under proper conditions, the quantity of material passing through the leak sites.

9.3.4 Leakage rate depends on pressure, volume, and time, so more than one set of test parameters can yield the same leakage rate. In general, the pressure used should simulate the pressure the article under test would see in service; however, this is not a requirement. If, for example, the test pressure exceeds that seen in service, elastic deformation of the article under test can cause uncharacteristically excessive leakage.

9.3.5 Leak testing of composite materials and components is primarily limited to "closed" articles under test which can be sealed and then pressurized or evacuated, for example, filament-wound pressure vessels.

9.3.6 Leak testing of composite materials and components that are "open" and cannot be sealed with a known pressure with gas or liquid inside is also possible. In this case, it is necessary to either "bomb" the article under test in a pressure chamber in order to introduce tracer gas into the article under test; or otherwise expose the article under test to tracer or penetrant liquid to determine if a leak exists.

9.3.7 It is important to distinguish between the sensitivity of the instrument used to measure leakage and the sensitivity of the test system using the instrument. The sensitivity of various test systems differ. For example, a test using a mass spectrometer leak detector normally has an ultimate sensitivity of 4.5×10^{-15} mole/s (10^{-10} standard cm^3/s) when the procedures involve the measurement of a steady-state gas leakage rate. This sensitivity can be increased to 4.5×10^{-19} mole/s (10^{-14} standard cm^3/s) by allowing an accumulation of the leakage before a leakage measurement is made. Conversely, if the test system uses the mass spectrometer leak detector in the detector-probe mode, the sensitivity can be 10^2 to 10^4 smaller than that of the mass spectrometer itself.

9.3.8 Leak location using tracer gases such as helium can be subdivided into tracer probe and detector probe modes. The tracer probe mode is used when the article under test is evacuated, and the tracer gas comes from a probe located outside the article. The detector probe mode is used when the article under test is pressurized with a tracer gas and testing is done at atmospheric pressure. Usually the tracer probe technique is more rapid because the gas reaches the detector at a higher concentration, despite any streaming effects, than it does with a detector probe which detects tracer gas that is highly diluted by atmospheric gases. In the detector probe mode, a higher pressure differential across the system may be used, and therefore leaks of a smaller conductance can be found. In using either mode it is important that leak location be attempted only after the presence of a leak has been verified.

9.3.9 To measure leakage accurately using tracer gas methods, all parts of the article under test must contain the same amount of tracer gas. When the article under test contains air prior to introduction of the tracer gas, or when a tracer gas and inert gas are added separately, uniform distribution of tracer gas may not be achieved.

9.3.10 There is no composite component or material across which a differential pressure exists (either due to pressurization or vacuum) that does not leak to some extent. Absolute leak tightness is not possible. Any vessel must, therefore, have a maximum leakage rate specified. To determine the leakage rate that can be tolerated, one must decide whether to consider the total component or system leakage, or the maximum allowable leakage from a single leak. Additional factors include shelf life, product contained, its toxicity, legal requirements, consequences of excessive leakage, product cost, LT cost, and customer requirements.

9.3.11 While it is more common to base accept/reject criteria on a specified value for the maximum allowable leakage rate for either the whole system or a single leak, go no-go accept/reject criteria can also be used, for example, as determined by Test Method E515 using bubble emission techniques.

9.3.12 Significance and use will also depend on the leak test procedure used:

9.3.12.1 *Bubble LT*—The bubble emission technique is not intended to measure leakage rates, rather, it is intended to locate leaks on a go, no-go basis. It is also useful in situations when a when a quantitative measurement is not practical. The basic procedure involves creating a pressure differential across a leak and observing for bubbles in a liquid medium on the low pressure side. Leak size can be approximated by the size of the bubble. Leakage rate can be approximated by the frequency of bubble formation. Procedurally, the article under test is fixtured (to nullify buoyancy) and pressurized; then the indicating liquid (film or immersion) is brought into contact with the component. This precludes the liquid from temporarily blocking a small leak which could cause acceptance of a leaking article. As long as they are not detrimental to the article under test, the following fluids may be used: water with wetting agent, methyl alcohol, ethylene glycol, mineral oil, fluorocarbons, and glycerin. Precleaning of the article under test is required because surface contaminants also may cause temporary blockage of leaks. From a practical standpoint, any gas may be used to pressurize the article under test. Changing the gas to a lower molecular weight and/or lower the surface tension of the liquid relative to the surface of the article under test will generally enhance sensitivity. If air is used, it must be pure to preclude contamination and temporary blockage of leak. Shop air is unsuitable to use in this application (contains too much dirt, water, and/or oils).

NOTE 9—The immersion fluid used for bubble testing must not cause crazing, environmental stress cracking, or swelling. Even reversible swelling may interfere with detection of leaks.

NOTE 10—The immersion fluid used for bubble testing of composite materials and components used in oxygen systems must meet the requirements of MIL-L-25567D.

9.3.12.2 *Chemical Penetrant LT*—Two classes of chemical penetrants are available: liquid tracers (tracer dye in suitable solvent), and gaseous tracers (gases such as ammonia or carbon dioxide with an appropriate color indicating agent). As a general rule, white light liquid tracer systems are inferior in terms of sensitivity compared to fluorescent liquid tracer systems. Test Method E1066 discusses the use of 1 to 100 % ammonia between 34.5 and 689.5 kPa (5 and 100 psig). The ammonia flows through leaks and reacts with a colorimetric developer that is applied on the outside of the container producing a visible indication.

9.3.12.3 *Halogen Gas LT*—Halogen LT can be used to indicate the pressure, location, and magnitude of leaks in closed vessels and is normally used for production examination. The use of halogen gas as the pressuring medium may take several forms: heated anode (most common), electron capture, and halide torch (least expensive). Operationally, ions are emitted from a hot plate to a collector. These positive ions increase in proportion to the amount of halogen present.

9.3.12.4 *Hydrostatic LT*—Hydrostatic testing requires a composite component to be completely filled with a liquid such as water. Pressure is slowly applied to the liquid until the required pressure is reached. This pressure is held for a required time at which point the component is inspected visually to locate leaks or pressure on a gauge is recorded to determine the component's total leakage rate. As a precautionary procedure to save time, ultrasonic pretesting is recommended before hydrostatic testing to locate leaks larger than 4.5×10^{-7} mole/s (10^{-2} standard cm^3/s).

9.3.12.5 *Mass Loss and Pressure Change*—Methods to determine mass loss and pressure change are generally used for large leaks. Pressure change methods are usually applicable to gaseous systems. No information is provided about the leak site.

9.3.12.6 *Mass Spectrometer LT*—One of the most sensitive types of LT equipment is the mass spectrometer. A mass spectrometer operates on the principle of sorting ionized gases in an electric field in accordance with molecular weight. In a helium mass spectrometer, baffles with slits allow He^+ ions to pass through the detector while others are blocked. The number of He^+ ions reaching the detector per unit time corresponds to the leakage rate. Test Methods E493 is used for hermetically-sealed devices with internal volumes, and is used primarily to determine in-leakage of air, water vapor, or other contaminant over the projected service life using prefilling (article under test can be sealed with a known pressure of helium) or bombing (article under test cannot be sealed with a known pressure of helium). Test Methods E498 and E1603 both are conducted on any composite article that can be evacuated and to the other side of which helium or other tracer gas may be applied. The main difference between Test Methods E498 and E1603 is that a small amount of helium is sprayed on the evacuated article under test in Test Methods E498, whereas the entire evacuated article under test is exposed to an envelope of helium tracer gas in Test Methods E1603.

9.3.12.7 Bombing (back pressurization with tracer gas) has special relevance for composite articles under test when it is necessary to ensure that performance characteristics will not be affected by in-leakage of air, water vapor, or other contaminants over the projected service life.

9.3.12.8 *Thermal Conductivity Testing*—These methods are based on the principle that certain gases have markedly different thermal conductivities compared to air. Equipment consists of two heated filaments in a bridge circuit. One filament is cooled by air, the other by the test gas. Any differences unbalance the bridge and can be related to leakage. The two gases with the greatest difference in thermal conductivity are hydrogen and helium, but testing can be performed using argon, carbon dioxide, neon, or Freon R-12. The procedures described in Test Methods E2024 are useful for locating and estimating the size of pressurized gas leaks, either as quality control tests or for documenting inspection procedures. Also, they are valuable as pretests before more time consuming and sensitive LTs are used. Thermal conductivity leak checks are semi-quantitative in that location of leaks is possible, but not precise leak rate measurement (only an approximation is possible). Like bubble emission techniques, thermal conductivity-based techniques are also useful in a go, no-go accept-reject test mode.

9.3.12.9 *Acoustic Emission LT*—Consult Practice E1211 for description of a passive method utilizing *(1)* surface-mounted AE sensors, or *(2)* sensors attached by means of acoustic waveguides that allow detection and location of the steady state source of gas and liquid leaking out of a pressurized system. Application examples to illustrate the use of AE to detect leaks in a relief valve, ball valve, and a transfer line are also given in Appendix X1 of Practice E1211.

9.3.12.10 *Ultrasonic LT*—This method is especially useful for detecting large leaks that are great enough to produce turbulent flow. Turbulent flow in a gas occurs when the velocity approaches the speed of sound in that gas, which is of the order of 4.5×10^{-6} to 10^{-7} mole/s (10^{-1} to 10^{-2} standard cm^3/s). This method is based on the fact that turbulent flow generates sound frequencies from audible up to 60 kHz. Ultrasonic LT is applicable for both pressurized leaks (Test Method E1002, Method A) and leaks in unpressurized or evacuated systems (Test Method E1002, Method B).

9.3.13 Method-specific advantages and applications and limitations and interferences are as follows:

9.3.13.1 *Bubble LT:*

(1) Advantages and Applications—Bubble LT can detect and locate leak sites accurately. The advantages of bubble testing are simplicity of operation, low cost, and relatively good sensitivity. The immersion technique is especially well suited for containers that can be sealed before test and completely immersed. The liquid application technique is especially well suited for pressure vessels, tanks, spheres, or other large apparatus on which the immersion techniques are impractical.

(2) Limitations and Interferences—Neither immersion nor liquid film bubble emission techniques per Test Method E515 can be used to measure leakage rate or total leakage. Disadvantages include the need for cleanup, and the fact that leaks may not be detected due to lack of time, or the possibility of clogging. Immediate application of high pressure may cause large leaks to be missed in the liquid application (film) technique. Last, since bubble testing is based on visual observation, it is subject to operator interpretation and visual acuity.

9.3.13.2 *Chemical Penetrant LT:*

(1) Advantages and Applications—One of the chief advantages of liquid and gaseous tracer is the low cost of use since little or no equipment is needed. This method gives a clear indication of leakage site location.

(2) Limitations and Interferences—Chemical penetrant leak tests are incapable of providing leakage rate information. Furthermore, liquid tracers can temporarily clog a leak, thus masking leak detection. Use of liquid tracers also necessitates cleaning of the article under test after application. Care must be taken during application so as not to create false indications. Precise leak location determination may also be hampered by liquid spread. The dyes or chemical used may also require special safety precautions. Some tracer gases such as ammonia may attack polymeric matrices and fibers to varying degrees, potentially resulting in the loss of physical and mechanical properties.

9.3.13.3 *Halogen Gas LT:*

(1) Advantages and Applications—This test may be conducted on any device or component across which a pressure differential of halogen tracer gas may be created, and on which the effluent side of the area to be leak tested is accessible for probing with the halogen leak detector. Halogen gas detectors have high sensitivity and can operate in air.

(2) Limitations and Interferences—The use of halogen gas LT has been declining because of concerns about the effect of these gases on the ozone layer. Disadvantages include spurious indications due to halogen-containing sources like cigarette smoke and cleaning compounds. The decomposed products are toxic and corrosive. Furthermore, the anode operates at 900°C (1650°F), which makes this method unsuitable for flammable environments. There is a need to recalibrate regularly as calibration changes with time. Many of these problems are obviated using electron capture detectors and sulfur hexafluoride as a tracer gas.

9.3.13.4 *Hydrostatic LT:*

(1) Advantages and Applications—Hydrostatic LT is useful for quality control testing of containers (pressure vessels, tanks) that are used to retain liquids.

(2) Limitations and Interferences—The interior and exterior weld and joint where leaks often occur must be free of oil, grease, or other contaminants that might temporarily block or mask the leak. Hydrostatic testing should not be performed before a leak test using tracer gas or air; the liquid media may clog small leaks and cause later leaks to be inaccurate. The test liquid must be equal to or above the ambient test temperature, or droplets will form on the outside of the article under test.

9.3.13.5 *Mass Loss and Pressure Change:*

(1) Advantages and Applications—Traditionally, mass loss and pressure change measurements are used to determine large leakage rates. Pressure changes are usually measured on gaseous systems.

(2) Limitations and Interferences—No information is provided about the leak site. Also, since pressure is temperature dependent, the test temperature must either remain constant, or be compensated for by the use of ideal gas laws.

9.3.13.6 *Mass Spectrometer LT:*

(1) Advantages and Applications—This test may be conducted on any object to be tested that can be evacuated and to the other side of which helium or other tracer gas may be applied.

NOTE 11—Articles under test that can be evacuated to a reasonable test pressure in an acceptable length of time require the article to be clean and dry and usually no larger the a few cubic feet in volume. To accommodate larger volumes or "dirty" components, auxiliary vacuum pumps having a greater capacity than those used in the mass spectrometer leak detector (MLSD) may be used in conjunction with the MSLD. The leak test sensitivity will be reduced under these conditions.

(2) Limitations and Interferences—As with any tracer gas system, care should be taken to minimize false signals. For example, using helium tracer gas, the natural background (5 ppm) must be "zeroed out" before leak testing can proceed. Surface fissures, paint, grease, oil, dirt, exposed elastomeric seals or plastic matrices, blind cavities or threads, etc., can sorb helium during bombing or pressurization, which can contribute to the background signal, thus reducing sensitivity. Either one of both procedures of dry air or nitrogen "washing" or baking parts for 30 min between bombing and testing will sometimes help reduce this background signal. Care must be taken to also control the pressure, time, and dwell time after bombing or pressurization with tracer gas or results can vary substantially. Series leak with an unpumped volume between them represents a difficult, if not impossible problem in helium leak detection. This type of leak occurs with double lap joints, double o-rings, flat polymer gaskets, ferrule and flange fittings.

9.3.13.7 *Thermal Conductivity LT:*

(1) Advantages and Applications—These methods provide highly sensitive leakage rate information and can locate leak sites accurately. Advantages include cost of equipment, reduced sensitivity to contaminants in the ambient atmosphere, and simplicity of operation. Thermal conductivity leak testing may be used as a go, no-go accept-reject test.

(2) Limitations and Interferences—Disadvantages include the limited types of gases that can be successfully used. Also, leak rates can only be approximated. Since thermal conductivity detectors are sensitive to all gases that have a thermal conductivity value different from air, test sensitivity to a particular tracer gas can be significantly altered by the presence of background gases. The degree of sensitivity reduction will be proportional to the difference between the thermal conductivity of the tracer gas versus interfering background gases. Areas to be tested must be free of oil, grease, paint, water, and other contaminants that might mask a leak or be drawn into the detector and clog the probe.

9.3.13.8 *Ultrasonic LT:*

(1) Advantages and Applications—By using only the ultrasonic component that is generated by turbulent flow, fewer false signals are detected. Because of the highly directional nature of ultrasound, the leak can usually be located accurately. Ultrasound equipment is also easy to operate; measurements can be made with the probe removed from the leak; and materials which could clog a leak and mask detection or otherwise necessitate post-test cleaning are not needed. Ultrasonic LT is also a valuable pretest before other more time-consuming and more sensitive leak tests are employed, such as helium leak detection or chemical penetrant leak detection.

(2) Limitations and Interferences—The chief disadvantage of ultrasound is the lack of sensitivity to small leakage rates (less than 10^{-2} standard cm^3/s). Ultrasonic leak testing should not be used to leak highly toxic or explosive gas leaks. Under certain conditions background noise produced by equipment vibration and air movement due, for example, to wind, air-cooled motors, aircrafts engines, pneumatic systems, etc., can prevent detection of relevant leakage.

9.4 *Use of Referenced Documents*

9.4.1 Consult Guide E432 for assistance in selecting a LT method depending on the type of item to be tested and information sought (leakage rate measurement or leak location determination). Suitable leak test procedures are ranked in the order of increasing sensitivity.

9.4.2 Numerous LT methods have been devised to detect, locate, and/or measure leakage. Most but not all methods considered in this guide have corresponding ASTM Practices, Test Methods, or Guides. The primary LT test methods and practices are:

9.4.2.1 *Bubble LT*—Consult Test Method E515 for procedures for detecting or locating leaks, or both, by bubble emission techniques in situations when a quantitative measurement is not practical. The normal limit of sensitivity for this test method is 4.5×10^{-10} mole/s (10^{-5} standard cm^3/s). Two techniques are considered: *(1)* an immersion technique, and *(2)* a liquid application technique.

9.4.2.2 *Chemical Penetrant LT*—Consult Test Method E1066 for LT of large single- and double-walled tanks, pressure and vacuum vessels, laminated, lined- or double-walled parts using an ammonia colorimetric method. This method can be used on containers with welded, fitted, or laminated sections that can be sealed at their ends or between their outer and inner walls and that are designed for internal pressures of 34.5 kPa (5 psig) or greater. Although Test Method E1066 is designed primarily for components that inherently contain or will contain ammonia (large tonnage refrigeration systems or fertilizer storage systems, it can be used to test critical parts or containers that will hold toxic or explosive gases or liquids or as a quick test for other containers. Basic procedures are described based on the type of inspection used. These procedures should be limited to finding leakage indications of 4.5×10^{-12} mole/s (10^{-7} standard cm^3/s) or larger. There are no applicable ASTM practices, test methods, or guides for chemical penetrant leak testing using other gaseous tracers such as carbon dioxide.

9.4.2.3 *Halogen Gas LT*—Consult Practice E427 for testing and locating the sources of gas leaking at the rate of 2.2×10^{-14} mole/s (5×10^{-10} standard cm^3/s) using a halogen leak detector (alkali-ion diode). The test may be conducted on any device or component across which a pressure differential of halogen tracer gas may be created, and on which the effluent side of the area to be leak tested is accessible for probing with the halogen leak detector. Five methods are described: *(1)* direct probing with no significant halogen contamination in the atmosphere, *(2)* direct probing with significant halogen contamination in the atmosphere, *(3)* shroud test, *(4)* air-curtain shroud test, and *(5)* a high sensitivity accumulation test.

9.4.2.4 *Hydrostatic LT*—Consult Test Method E1003 for testing of components for leaks by pressurizing them inside with a liquid. This test method can be used on containers which can be sealed at their ends and which are designed for internal pressure. Basic procedures are described based on the type of inspection used. These procedures should be limited to finding leakage indications of 4.5×10^{-9} mole/s (10^{-4} standard cm^3/s) or larger.

9.4.2.5 *Mass Loss and Pressure Change*—There are no applicable ASTM standard practices, test methods, or guides.

9.4.2.6 *Mass Spectrometer LT*—Five ASTM test methods are cited:

(1) Consult Test Methods E493 (tracer probe mode) for procedures for determining leakage through the walls of enclosures that can be sealed prior to leak testing. In the procedures cited, both involve mass spectrometer helium leak detection and have varying degrees of sensitivity depending on the internal volume, the strength of the enclosure, the time available for preparation of test, and on the sorption characteristics of the enclosure material for helium. After the article under test has been subjected to helium pressurization, it is placed in an evacuated chamber and the output signal is obtained from an MSLD. In general practice, the sensitivity limits are from 4.5×10^{-14} to 4.5×10^{-10} mole/s (10^{-9} to 10^{-5} standard cm^3/s at 0°C) for helium, although these limits may be exceeded by several decades in either direction in some circumstances. Two methods are described: test part preparation by bombing, and test part preparation by prefilling.

(2) Consult Test Methods E498 (tracer probe mode) for sensitive procedures for procedures for testing and locating the sources of gas leaking at the rate of 4.5×10^{-14} mole/s (10^{-9} standard cm^3/s) or greater using an MSLD or Residual Gas Analyzer. The test may be conducted on any object to be tested that can be evacuated and to the other side of which helium or other tracer gas may be applied. The article under test must be capable of withstanding 0.1 Pa (approximately 10^{-3} torr).

NOTE 12—Composite articles that can be evacuated to a reasonable test pressure in an acceptable length of time require the article to be clean and dry and usually no larger than a few cubic feet in volume. To accommodate larger volumes or "dirty" components, auxiliary vacuum pumps having a greater capacity than those used in the MSLD may be used in conjunction with the MSLD. The leak test sensitivity will be reduced under these conditions.

(3) Consult Test Methods E499 for procedures for testing and locating the sources of gas leaking at a rate of 4.5×10^{-13} mole/s (10^{-8} standard cm^3/s at 0°C) for helium. The procedures cited in Test Methods E499 differ from those cited in Test Methods E493, E498, and E1603 in that the effluent side of the article under test is accessible for atmospheric probing with a MSLD sampling probe. Both direct probe and accumulation testing methods are described.

(4) Consult Test Methods E1603 (hood mode) for sensitive procedures for testing and locating the sources of gas leaking at the rate of 4.5×10^{-14} mole/s (10^{-9} standard cm^3/s) or greater using an MSLD or Residual Gas Analyzer. The test may be conducted on any object to be tested that can be evacuated and to the other side of which helium or other tracer gas may be applied. The article under test must be capable of withstanding 0.1 Pa (approximately 10^{-3} torr).

(5) Consult Test Methods E2024 for procedures for detecting the sources of gas leaking at the rate of 4.5×10^{-9} mol/s (10^{-4} standard cm^3/s) or greater. The tests may be conducted on any article under test that can be pressurized with a tracer gas that is detectable by a thermal conductivity detector. The test sensitivity will vary widely depending on the tracer gas used. Both scanning (nominal sensitivity) and accumulation (high sensitivity) methods better suited to leak testing of complex-shaped articles under test are described.

9.4.2.7 *Thermal Conductivity Testing*—Consult Test Methods E2024 for procedures for detecting the sources of gas leaking at the rate of 4.5×10^{-9} mole/s (10^{-4} standard cm^3/s) or greater. The tests may be conducted on any object that can be pressurized with a tracer gas that is detectable by a thermal conductivity detector. The test sensitivity will vary widely depending on the tracer gas used.

9.4.2.8 *Ultrasonic Leak Testing*—Consult Test Method E1002 for procedures for determining the location and/or estimating the size of gas leakage to atmosphere by the airborne ultrasonic technique (ultrasonic translation). In general practice, both Class I and Class II instruments are used with minimum detectable leak rates of 6.7×10^{7} to 6.7×10^{6} mole/s (1.5×10^{2} to 1.5×10^{1} standard cm^3/s at 0°C). Two methods are described: *(1)* measurement of leak location and estimation of leak size in articles under test that can be pressurized, and *(2)* location of leak location in articles under test that are not capable of being pressurized but capable of having ultrasonic tone placed/injected into the test area to act as an ultrasonic leak trace source.

9.5 *Geometry and Size Considerations*

9.5.1 Articles under test that are amenable to leak testing fall into two categories: *(1)* open units that are accessible on two sides, and *(2)* sealed units that are accessible on one side. For practical considerations, filament-wound pressure vessels belong to the latter category.

9.5.2 Articles under test in which the diameter and length are not greatly different (such as composite tanks) may be tested satisfactorily by simply adding a tracer gas. However, when system with long or restricted geometries are tested, more uniform tracer distribution will be achieved by first evacuating to a few torr, and then filling with the test gas. The latter must be premixed if it does not consist of 100 % tracer gas.

9.5.3 In the case of small internal volumes or large leaks, allowances must be made to perform leak testing immediately after filling (vessel filled with tracer gas and sealed), pressurization (vessel pressurized with tracer gas and sealed), or bombing (sealed pressure vessel exposed to pressurized tracer gas and outside-in leakage detected); or an alternate procedure for large leaks must be used, for example, bubble testing or liquid bombing and subsequent weight change.

9.5.4 There are no size limitations for atmospheric pressure direct probe helium leak detection (see Test Methods E499 Test Method A). For parts up to several cubic meters in volume, or portions of larger composite components, atmospheric pressure accumulation testing can be performed (for example, see Test Methods E499 Test Method B).

9.5.5 Liquid film bubble emission techniques are widely applied to components that cannot easily be immersed because of size, and can be used with a vacuum box to test vessels that cannot be pressurized or where only one side is accessible.

9.6 *Safety and Hazards*

9.6.1 Regardless of the type of leak testing being done, safety considerations for personnel performing these tests must be a paramount concern.

9.6.2 Reasonable precautions against releasing tracer gases in the test area must be observed. For example, radioactive tracer gases are normally not used because of hazards associated with their use. Unique hazards are associated with the use of ammonia and halogen gases. Consult the appropriate Material Safety Data Sheet (MSDS) to determine what safety measures must be used to ensure personnel exposure does not exceed mandated exposure limits.

9.6.3 Gross leak test detection methods such as hydrostatic testing, mass and pressure change methods, and ultrasonic testing are not sensitive enough for quality control leak testing of containers used to retain toxic or explosive liquids and gases.

9.6.4 *Safety Factor*—Where feasible, ensure that a reasonable safety factor has been allowed between the actual operational leak requirement for the article under test and the maximum leak rate that can be measured during test. Usually a factor of 10 is adequate. For example, if the maximum leak rate for an article under test for satisfactory operation is 4.5×10^{-11} mole/s (10^{-6} standard cm^3/s), the measurement requirement during test should be 4.5×10^{-12} mole/s (10^{-7} standard cm^3/s) or less.

9.7 *Calibration and Standardization*

9.7.1 *Bubble LT*—Since leak size and leak rate are not quantitatively measured no equipment calibration is needed or warranted. However, operator skill and training must be sufficient to minimize repeatability and reproducibility errors.

9.7.2 *Chemical Penetrant LT*—By varying penetrant concentration, test pressure, and development time, leak rate sensitivity can vary significantly. Depending on whether the minimum detectable leak rate or maximum test pressure is more important, that variable is fixed and the remaining variable is measured.

9.7.3 *Halogen Gas LT*—Any leak detectors used in making leak tests by these procedures are not calibrated in the sense that they are taken to a standards laboratory, calibrated, and returned to the job. Rather, the leak detector is used as a comparator between a leak standard 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. To verify sensitivity, reference to the leak standard should be made before and after a prolonged test. When rapid repetitive testing is required, refer to the leak standard often enough to ensure that desired test sensitivity is maintained.

9.7.4 *Hydrostatic LT*—Since no actual measurement is made of the leak rate, calibration is not needed. However, sensitivity will depend on operator experience and training. If ultrasonic pre-testing is performed, refer to 9.7.8 for ultrasonic instrument calibration and sensitivity validation.

9.7.5 *Mass Loss and Pressure Change*—Mass and pressure measurement equipment shall be calibrated at periodic intervals in accordance with the contractual agreement or established internal procedure.

9.7.6 *Mass Spectrometer LT*—Calibrate the MSLD with a calibrated leak to read directly in Pa m^3/s, or standard cm^3/s of helium, in accordance with the manufacturer's instructions. Any leak detectors used in making leak tests by these procedures are not calibrated in the sense that they are taken to a standards laboratory, calibrated, and returned to the job. Rather, the leak detector is used as a comparator between a leak standard 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. To verify sensitivity, reference to the leak standard should be made before and after a prolonged test. When rapid repetitive testing is required, refer to the leak standard often enough to ensure that desired test sensitivity is maintained.

9.7.7 *Thermal Conductivity LT*—Calibration shall be performed prior to, during, and at completion of testing at intervals not to exceed 1 h. Failure of a calibration check to obtain the same or greater response as the previous check shall require an evaluation or retest of all tested articles. The leak detector shall be turned on and allowed to warm up and zeroed as specified by the manufacturer. The probe (sensor) then shall be moved across the standard leak at a distance not more than 1 mm (0.04 in.) from the standard leak orifice and moved not faster than 20 mm/s (0.8 in./s), and the detector's response observed. The standard shall be scanned several times and the average indicated leakage rate will be the test acceptance reading. The scanning distance and speed may have to be adjusted during calibration to improve the detector response; however, under no circumstances shall the scanning parameters used during calibration differ from this used during test. For the accumulation method, the detector needs to be checked against a known standard concentration of the tracer gas in air into the test volume during the accumulation time. For volumes different from the test volume, a proportional adjustment shall be made. Leak detector response will change when test parameters such as scanning distance and speed are altered, thus changing the gas concentration the leak detector measures. Any change in the scanning parameters from those used for calibration may cause a deduction in the test sensitivity and instrument response.

9.7.8 *Ultrasonic LT*—The ultrasonic instrument should be calibrated or have the sensitivity validated before each initial use. This will in turn require the use of an appropriate leak standard and nitrogen regulator for calibration the air probe. Recalibration shall be conducted at the beginning of each shift or designated work period interval or when abnormalities are observed using the same sensing frequency as used in the initial calibration. When using the ultrasonic transmitter method (Test Method E1002, Method B), the sensitivity and generated amplitude shall be verified before each use. This can be done by placing the ultrasonic transmitter in a container with a known leak that is equivalent to the leaks that are being detected.

9.8 *Physical Reference Standards*

9.8.1 Not applicable.

TABLE 8 Summary of Radiography and Computed Radiography

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Used to detect sub-surface imperfections or discontinuities such as cracks, foreign material, inclusions, porosity, fiber misalignment, lack of bonding and other two and three dimensional imperfections or discontinuities where the major axis of the imperfection or discontinuity is oriented parallel to the incident beam. Additional Information: Can effectively be used to find foreign materials or foreign object debris (FOD) in assemblies or composite parts. Can be used to verify completeness of assembly of finished parts, for example, look for missing parts, broken connections, etc. Used to detect three dimensional defects that have a size in the direction of the incident radiation that is equal to or greater than 1 to 2 % of the thickness of the article under test. Two dimensional cracks are detectable only if present an effective thickness equal to or greater than 1 to 2 % of the thickness of the article under test, and are in proper alignment with the incident beam.	A high voltage electric charge is applied to a cathode to generate electrons. The electrons are then accelerated through a vacuum to a positively charged anode. The point at which the electrons strike the anode (target) is made of a dense material, (for example, tungsten or copper.) When this electron beam strikes the target, the rapid deceleration of the electrons generates X-ray radiation which is directed toward the article under test. The amount of transmitted radiation that penetrates the part depends on the energy of the incident beam and on material thickness, density, and scattering effects. The transmitted radiation exposes a sheet of radiographic film creating a two dimensional image of the part (in digital X-ray, a digital imaging plate is used instead of X-ray film). Discontinuities show up on the film or digital image as changes in density relative to continuous regions. For polymeric matrix composite materials and components, soft X-rays having energies of the order of 50 kV are generally used.	General Overview: Film and some imaging plates can be cut and placed almost anywhere on part. Additional Information: Provides volumetric inspection method (it inspects the entire volume of the material as opposed to just the surface). Energy levels (penetrating ability) can be adjusted by changing the accelerating voltage. High sensitivity to material thickness and density changes. Part geometry does not affect direction of the X-ray beam to a great extent. Provides a permanent visual record of the inspection results (that is, film or digital images). Can be portable with appropriate equipment and adequate safety precautions. CR allows inspection in a shorter time and without any chemical processing and waste.	General Overview: Not generally sensitive to small surface cracks except under perfect conditions. Requires crack-like defects to be relatively deep and/or wide for reliable detection. Additional Information: Radiation safety, particularly in portable applications, is a concern. Ideally, parts should be moved to an X-ray facility. Transporting parts consumes time and exposes parts to the risk of damage. Depth of defects not indicated (see next column). Sensitivity decreases with increased part thickness. Difficult to obtain sufficient (2 % or better) contrast between low to medium atomic number composite substructures. Access to both sides of the article under test is necessary. Orientation of linear imperfections or discontinuities in the part may not be favorable. To be detected, the crack plane must be nearly parallel to the X-ray beam. Not sensitive to laminar imperfections or discontinuities (for example, delamination). High initial cost including X-ray machine, lead rooms or portable shields, film processing and reading facilities, and positioning equipment. High recurring film (which contains silver bromide) and chemical costs, and associated disposal issues.	General Overview: Actual imperfections or discontinuities are imaged, usually in actual size. Unable to determine depth of imperfections or discontinuities without additional X-ray exposures from different directions. Depth of volumetric imperfections and discontinuities can be determined from digital images after calibration. Additional Information: Imperfection or discontinuity depth can be determined by taking additional “parallax” X-ray shots. Such shots can be time consuming and expensive, however. Imperfections or discontinuities are generally reported by length for linear imperfections or discontinuities, diameter for rounded imperfections or discontinuities, and by length and width for odd-shaped imperfections or discontinuities. Clusters or touching voids or porosity may also be reported if not acceptable by the acceptance criteria.

TABLE 9 Summary of Radioscopy

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Widely used for rapid scanning of articles with gross internal imperfections or discontinuities, conducted before radiographic inspection, for example. In-motion or continuous imaging during process or production line inspection. Provides a rapid check of dimensions and the internal configuration within composite materials and components. Through manipulation, radioscopy can provide information about the three-dimensional distribution of imperfections, defects, and discontinuities within a composite material or component.	The physical principles behind radioscopy and radiography are the same. Radioscopy differs, however, in that it consists of real-time or near real-time non-film detection. Three-dimensional information can be obtained using both static and dynamic radioscopic systems. Both manual and automated systems are available. Remote viewing systems—An X-ray sensitive vidicon television pickup tube and an X-ray intensifier camera system or a real time DDA in connection with a computer and/or video monitor is used instead of film which converts X-rays to electrons thus allowing instant image reproduction on a TV or computer monitor. Compared to film imaging, greater brightness is achieved using the above mentioned systems. Direct viewing systems—The X-ray image is produced on a fluorescent screen instead of film as in radiographic systems, and viewed indirectly using a mirror or radiation barrier window to prevent direct eye exposure to hazardous radiation.	Real-time and near real-time radiographic images are obtained. In-motion or continuous imaging is possible (well suited for process or production line requirements. A permanent digital or photographic record can be obtained. Much lower operating costs than radiography in terms of time, manpower, and material. For example, film processing costs are eliminated. Allows the observer to be out of the range of hazardous radiation. Radioscopy has advantages over radiography for characterization of nonsymmetrical articles under test because of the three-dimensional capability when using mechanical motion of the articles relative to the X-ray beam. Computer-aided automated systems can incorporate software that allow automated defect recognition and accept/reject decisions to be made.	Cannot be used in real time mode with articles under test that are thick or overly dense due to excessive beam attenuation. The combination with computer based integration allows the improvement of image quality. Sensitivity and resolution of real-time systems are not as good as can be obtained with film radiography. Radioscopic systems tend to be more specialized and less versatile than those used in film radiography. Fluoroscopic and electronic imaging systems require additional expensive equipment. Permanent records usually suffer from loss of detail if not acquired with a computer because they are made on secondary recording media (for example, a video tape or photograph). In dynamic systems, a higher X-ray flux level is required to develop a suitable image compared to static systems. Also, control of scatter and careful alignment of the source, article under test, and detector is required. In dynamic systems, radiation handling requirements, additional shielding requirements, and article under test positioning devices usually result in greater capital equipment costs.	Long-term records can be obtained through motion picture recording, video recording, or “still” photographs. Remote viewing systems—A TV or computer monitor allow remote viewing. Permanent records are made on secondary recording media (for example, a computer hard drive, video tape hardcopy or photograph). Actual flaws imaged, usually in actual size or known ratio after correction of magnification. Depth of flaw is usually not indicated. Direction of planar defects can be determined if X-ray exposures from different directions are analyzed or from calibrated digital images. Direct viewing systems—The X-ray image is viewed indirectly using a mirror or radiation barrier window to prevent direct eye exposure to hazardous radiation.

10. Radiographic Testing (RT), Computed Radiography (CR), Digital Radiography (DR) with Digital Detector Array Systems (DDA), and Radioscopy (RTR)

10.1 *Referenced Documents*

10.1.1 *ASTM Standards Applicable to Radiography, Computed Radiography, Radioscopy and Digital Radiology:*[2]

E94 Guide for Radiographic Examination

E747 Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiography

E1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole Type Image Quality Indicators (IQI) Used For Radiography

E1647 Practice for Determining Contrast Sensitivity in Radiology

E1742 Practice for Radiographic Examination

E1815 Test Method for Classification of Film Systems for Industrial Radiography

E1817 Practice for Controlling Quality of Radiography Examination by Using Representative Quality Indicators (RQIs)

E2002 Practice for Determining Total Image Unsharpness and Basic Spatial Resolution in Radiography and Radioscopy

E2007 Guide for Computed Radiography (Photostimulable Luminescence (PSL) Method)

TABLE 10 Summary of Digital Radiography with Digital Detector Arrays

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Used to detect sub-surface imperfections or discontinuities such as cracks, foreign material, inclusions, porosity, fiber misalignment, lack of bonding and other two and three dimensional imperfections or discontinuities. DDAs work better than film radiography in applications requiring low dose/fast sampling, where high throughput inspections are required, and in 3D studies including CT (see Section 8). Used to detect three dimensional defects that have a size in the direction of the incident radiation that is ≥0.5 % of the thickness of the article under test being examined. Also used for rapid scanning of articles with internal imperfections or discontinuities. Provides a check of dimensions and the internal configuration within composite materials and components. Through manipulation, DR systems can provide information about the three-dimensional distribution of imperfections, defects, and discontinuities within a composite material or component. May detect surface features and imperfections.	The physical principles behind DR systems, radioscopy and radiography are similar to DR systems DR combines the advantages of radioscopy and radiography systems: near real-time non-film detection with a geometrical and contrast resolution of film or even better. Three-dimensional information can be obtained using multiple view imaging and DDAs can also be used as part of a computed tomographic system. Both manual and automated systems are available. Remote viewing systems—an X-ray sensitive real-time DDA in connection with a computer and/or video monitor is used instead of film which converts X-rays to electrons thus allowing instant image reproduction on a TV or computer monitor. Compared to film imaging, greater brightness and contrast is achieved using the above mentioned systems. A DDA captures X-rays by means of a scintillator which generates visible light and then detects that light by a photo diode array. The diode array quantizes the signal for storage on a PC and display on a computer monitor. DR intrinsically has lower spatial resolution than film; however, magnification techniques can be used when higher resolution is needed.	Radiographic images can be seen quickly (less than 15 s) after the end of the X-ray exposure. High signal-to-noise ratio (SNR) images can be obtained over a large dynamic range with one DDA read. The SNR may be significantly increased by averaging the results of multiple images on a PC. Near real-time radiographic images are obtained. Images can be accumulated on the PC; with this technology a very high SNR can be obtained. Contrast sensitivity of <0.1% is achievable. A large range of material thickness can be inspected within one image. Digital image processing can extract the important information (Filter, Zoom, Contrast/Brightness Adjust). A perfect copy of the images can be obtained by storing the images on the PC and/or a CD/DVD. Much lower operating costs than radiography in terms of time, manpower, and material. For example, film processing costs are eliminated. DR systems have advantages over radiography for characterization of nonsymmetrical composites articles because of the three-dimensional capability when using mechanical motion of the articles relative to the X-ray beam. Imperfection or discontinuity volume can be calculated of geometrical size and difference in grey values on the PC. DR systems enable the use of computer-aided systems to which automate defect recognition and may incorporate software that automates accept/reject decisions. Software can control image quality of the DR system and ensure a permanent sufficient quality level. DR systems usually require less X-ray exposure than a comparable film or CR image.	DR systems tend to be more specialized and less versatile than those used in film radiography. DR systems require additional expensive equipment.	General Overview: Actual imperfections or discontinuities, internal structure /geometries, internal/external damage, and manufacturing variability are imaged; size can be adjusted in software with calibration. Able to determine depth of imperfections or discontinuities with second (additional) X-ray image. Long-term records can be obtained through CD and DVD recording media. Images should be viewed on a high contrast, high resolution and high brightness thin film translator (TFT) or digital monitor.

E2033 Practice for Computed Radiography (Photostimulable Luminescence Method)

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

E2445 Practice for Qualification and Long-Term Stability of Computed Radiography Systems

E2446 Practice for Classification of Computed Radiography System

10.1.2 *ASTM Standards Applicable to Radioscopy:*[2]

E1000 Guide for Radioscopy

E1255 Practice for Radioscopy

E1411 Practice for Qualification of Radioscopic Systems

10.1.3 *ASTM Standards Applicable to Digital Radiography:*[2]

E2597 Practice for Manufacturing Characterization of Digital Detector Arrays

E2736 Guide for Digital Detector Array Radiology

E2737 Practice for Digital Detector Array Performance Evaluation and Long-Term Stability

10.1.4 *Federal Standards:*[6]

NBS Handbook 114 General Radiation Safety Installations Using Nonmedical X-ray and Sealed Gamma Sources up to 10 MeV[7]

Title 10, Code of Federal Regulations (CFR), Part 20, Standards for Protection Against Radiation

Title 21, Code of Federal Regulations (CFR), 1020.40, Safety Requirements of Cabinet X-ray Systems

Title 29, Code of Federal Regulations (CFR), 1910.96, Ionizing Radiation (X-rays, RF, etc.)

10.1.5 *Military Handbooks and Standards:*[6]

MIL-HDBK-728/5A Radiologic Testing

MIL-HDBK-733 Nondestructive Testing Methods of Composite Materials—Radiography

10.1.6 *National Council on Radiation Protection and Measurement (NCRP) Documents:*[8]

NCRP 49 Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV

NCRP 51 Radiation Protection Design Guidelines for 0.1–100 MeV Particle Accelerator Facilities

NCRP 91 Recommendation on Limits for Exposures to Ionizing Radiation

10.1.7 *SAE Standards:*[9]

SAE-ARP 1611, Revision A, Quality Inspection Procedures, Composites: Tracer Fluoroscopy and Radiography

10.1.8 *European Standards:*[10]

EN 14784-1, Non-Destructive Testing—Industrial Computed Radiography with Storage Phosphor Imaging Plates—Part 1: Classification of Systems

EN 14784-2, Non-Destructive Testing—Industrial Computed Radiography with Storage Phosphor Imaging Plates—Part 2: General Principles for Testing of Metallic Materials Using X-Rays and Gamma Rays

EN 13068-1, Non-Destructive Testing—Radioscopic Testing—Part 1: Quantitative Measurement of Imaging Properties

EN 13068-2, Non-Destructive Testing—Radioscopic Testing—Part 2: Check of Long Term Stability of Imaging Devices

EN 13068-3, Non-Destructive Testing—Radioscopic Testing—Part 3: General Principles of Radioscopic Testing of Metallic Materials by X- and Gamma Rays

10.2 *Radiography and Computed Radiography*

10.2.1 *General Procedure*—X-ray radiography is a process whereby transmitted X-ray radiation is converted directly into an image that gives subsurface information about the imperfection or discontinuity distribution within an article under test. To produce this image, a current is applied to a cathode to generate electrons by thermal emission. These electrons are then accelerated by high voltage through a vacuum to a positively charged anode (target). The target is made of a dense material such as tungsten or copper. When this electron beam strikes the target, the rapid deceleration of the electrons generates radiation (X-rays in this case), which is directed toward the part. The penetrating ability of X-ray radiation depends on material thickness, density, and scattering effects. In passing through matter, some of the X-rays are absorbed in proportion to the atomic mass of the material being traversed. In normal transmission, the attenuated (modulated) beam that has traversed an article under test contains very useful macroscopic information about the types of defects and discontinuities present in the matter that was traversed. The penetrating radiation exposes a sheet of radiographic film or imaging plate (IP), creating an image of the part (in digital X-ray, a digital imaging plate is used instead of X-ray film). With modern equipment and instrumentation, it is generally agreed that discontinuities can be detected which present to the axis of the incident beam a minimum dimension of 1 to 2 % of the thickness of the article under test. Discontinuities show up on the film or IP as changes in density or grey value relative to continuous regions such as matrix material.

10.2.2 *Significance and Use*—The principles discussed in this guide apply broadly to penetrating radiation systems. Although this section is written specifically for use with X-ray systems, the general concepts can be used for other penetrating radiation systems, such as those employing gamma-rays and neutrons, which involve equipment and application details unique to those systems. By far the most widely used radiographic technique for the inspection of polymeric matrix composite materials and components is the straightforward X-ray radiographic method, versus more specialized methods such as microradiography, stereo-radiography, fluoroscopy, and neutron radiography.

NOTE 13—Microradiography is particularly well-suited for obtaining images of thin articles under test of low density; for this reason it has utility in composite material and component investigations. Modern systems are based on micro or nanofocus tubes combined with film or digital detectors. The detail and radiographic quality produced by this technique can be extremely good. However, there can be inherent difficulties when using low energy (soft) X-rays. One difficulty, depending

---

[7] Available from National Technical Information Service (NTIS), U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

[8] Available from NCRP Publications, 7010 Woodmont Ave., Suite 1016, Bethesda, MD 20814.

[9] Available from Society of Automotive Engineers, Inc., 400 Commonwealth Dr., Warrendale, PA 15096-0001.

[10] Available from European Committee for Standardization (Electrotechnical), CENELEC Customer service (info@cenelec.org).

on the thickness of the article under test, and source-to-film or IP distance, is that exposure times can be very long (on the order of hours) if no special soft beam tubes with high anode current are chosen.

10.2.3 *Advantages and Applications*—Some of the types of defects detected by X-ray radiography of polymeric matrix composites include fiber/matrix debonding, impact or fatigue damage, fabrication imperfections or discontinuities, voids, porosity, inclusions, splice imperfections or discontinuities (for example, honeycomb core-to-core or core-to-structure splice imperfections or discontinuities), fiber orientation, resin content variation, fiber breaks, and crushed core. Two-dimensional defects such as cracks and delaminations are not detectable unless they present an effective thickness of at least 1 to 2 % of the thickness of the article under test, and are in appropriate alignment with the X-ray beam.

10.2.3.1 X-ray radiography can also provide information about imperfection or discontinuity content and growth, resin content, fiber orientation (when boron or glass fiber markers or tracers are used, for example), thermal effects, and failure mechanisms. Composite defects are classified in accordance with imperfection or discontinuity size. Small and large imperfections or discontinuities are readily detectable radiographically. (Very small scale defects cannot be detected radiographically without the use of radiopaque tracers):

(1) Large scale defects and discontinuities affecting wide areas or even the entire component attributable to fabrication anomalies (for example, omission of prepreg layers during lay-up, faulty cure, incorrect compaction due to failure to close the mold correctly). Such large scale defects and discontinuities can lead to catastrophic failure.

(2) Smaller scale defects that may be precursors of catastrophic failure can also be introduced during fabrication (for example, voidage, local fiber misorientation, local variation on resin content, matrix shrinkage upon cure and/or aging, and unavoidable macrostructural features such as joints in prepreg sheet).

10.2.4 *Limitations and Interferences*—Perhaps the biggest challenge in X-ray radiography as applied to composite materials and components is to obtain sufficient contrast between low to medium atomic number composite substructures (for example, matrix, fiber, laminates). Normally, a 2 % contrast is a reasonable minimum. It is often necessary to enhance contrast by using radiopaque materials or contrast agents.

10.2.4.1 In radiography of composites comprised of low and medium density materials, diffuse internally scattered radiation forms a high percentage of the total radiation reaching the film or IP. This is due to the nature of the soft, low voltage radiation (as low as 20 kV) used to image composites, which is inherently less penetrating. While lower accelerating voltages can be successfully used without excessive scattering in thin specimens, the use of higher, more penetrating voltages in thicker specimens can also result in excessive overall film density or IP grey value, reducing contrast and making the radiograph unreadable in terms of imperfection or discontinuity identification. Scattering is a major problem when radiographing polymeric matrix composites. In general, lower voltage will improve contrast by reducing the signal from scattered radiation. Consequently, lower energy is better for inspection as long as the energy is high enough to penetrate the article under test. Depending on composite article thickness and composition, use of low accelerating potentials may also increase the exposure time.

NOTE 14—There are several ways to potentially reduce scattering, hence "fogging' of radiographic images: *1)* use the lowest practical accelerating voltage, *2)* limit the incident beam so that the beam only penetrates the area of inspection, *3)* increase the distance from the object to the detector (ODD) while maintaining sufficient geometric sharpness (e.g., a 10 cm (4 in.) ODD will reduce scattering), and *4)* filter the beam so it is more monochromatic.

10.2.4.2 Another limitation of radiography is that access to both sides of the article under test is required. The film or IP is placed on one side and the X-ray source is placed on the opposite side. High cost is the chief objection to film radiography. One-half of the average inspection cost may be for the radiographic film, corresponding film processing chemicals (for example, silver bromide), and their disposal. Computed radiography (CR) does not need any chemicals and requires limited consumption of imaging plates only, since they are reusable after scanning and erasure for several hundred times. Exposure of imaging plates can typically be performed using lower keV X-rays and reduced exposure time compared to film.

10.2.5 *Use of Referenced Documents: Application:*

10.2.5.1 Consult Guide E94 for preferred radiographic examination techniques and production methods related to radiographic film recording (that is, energy selection, filters, masking, back-scatter protection, screens, exposure calculations); radiographic film selection, handling, processing (automatic or manual), viewing (image quality, distortion), and storage; maintenance of inspection records; and a list of available reference radiograph documents. Guide E2007 describes the basics of computed radiography and its applications.

10.2.5.2 Consult Practice E1742 for the application and control of the radiographic film method and Practice E2033 for computed radiography. These practices are also written so that they can be specified on the engineering drawing, specification or contract. It is not a detailed how-to procedure to be used by the NDT facility and must therefore be supplemented by a detailed written procedure.

10.2.5.3 Consult Practices E1742, E2033, E2445 or E2104 for minimum requirements for the application and control of the radiographic and CR method. For example, specific requirements are given for qualification (personnel and test agency), safety (exposure areas, darkroom, viewing areas, long-term stability tests), materials (film and non-film), equipment (radiation sources, film holders, screens, film viewers, film system classes, CR system classes, densitometers, film viewing aids), and image quality indicators (IQIs), that, together, are intended to control the quality of radiographic and digital images.

10.2.5.4 Consult Society of Automotive Engineers (SAE) ARP1611, Revision A for a radiopaque tracer inspection procedure that has demonstrated utility in characterizing imperfections or discontinuities in composite materials and components which are introduced inadvertently by cutting, machining, or drilling operations during fabrication. The types of imperfections or discontinuities detected by this procedure are delamination, breakout (usually splintering on exit side of a drilled hole or cut), microcracks (including matrix cracking), fiber/resin pullout, and shredding (tearing of one or more plies).

10.2.5.5 Consult MIL-HDBK-728/5A for a general discussion about the basic principles behind radiographic testing (generation of penetrating radiation beams, beam attenuation and absorption characteristics, detection systems), basic procedures and techniques, IQIs, applications, guidelines for use by personnel (design engineers, production engineers, QA personnel, NDT engineers and technicians), and safety.

10.2.5.6 Consult MIL-HDBK-733 for information on X-ray radiographic techniques for examining defects and discontinuities in reinforced composites (including delamination, fiber/matrix debonding, impact or fatigue damage, fabrication imperfections or discontinuities, fiber misorientation, resin content variation, and fiber breaks), computer-based image enhancement techniques (including electronic enhancement, signal processing, removal of unwanted features), and use of opaque additives (impregnation procedures).

10.2.5.7 Consult MIL-HDBK-733 for information on microradiographic imaging of thin specimens of polymeric matrix composites, including discussion about techniques, effects of low voltage radiation, and X-ray tube window effects.

10.2.5.8 Consult EN 14784-1 for a discussion of: *1*) CR quality indicators (including descriptions of CR quality indicators for user and manufacturer tests, application procedures for CR quality indicators, image plate fading), *2*) procedures for quantitative measurement of image quality parameters (including descriptions of measurement of the normalized signal-to-noise ratio (SNR), measurement of minimum read out intensity, determination of unsharpness, and other tests, and *3*) CR system classification and interpretation of results (including descriptions of range of CR system classification and determination of CEN speed).

10.2.5.9 Consult EN 14784-2 for a discussion of the general rules for industrial CR using storage phosphor imaging plates (IPs), including a classification of CR techniques, general considerations (surface preparation, identification of radiographs, marking, overlap of phosphor imaging plates, image quality indicators), and recommended techniques for making computed radiographs (test arrangements, choice of voltage and radiation source, phosphor imaging plate-scanner systems and screens, system unsharpness, beam alignment, reduction of scattered radiation, source-to-object distance, maximum area for a single exposure, minimum read-out intensity, and monitor and film viewing conditions).

10.2.6 *Use of Referenced Documents: Equipment, Instrumentation, and Materials:*

10.2.6.1 Consult Guides E94 and E2007, Practices E1742, E1815, E2033, E2445, E2446 and E2104, and MIL-HDBK-728/5A for information about radiographic instrumentation and equipment, such as, area shielding equipment, cassettes, darkroom, monitors, densitometers, diaphragms and collimators, digitizing techniques, exposure areas, film systems, imaging plate systems, film processing solutions, film, film holders, identification and orientation markers, linear and angular measuring devices, non-film radiographic recording media, penetrameters (IQIs), positioning devices, identification and orientation markers, viewing areas, X-ray tube windows, X-ray sources, etc.

10.2.6.2 Consult SAE ARP1611, Revision A for information about radiopaque tracer materials used to detect and size imperfections or discontinuities in composite materials and components.

10.2.7 *Geometry and Size Considerations:*

10.2.7.1 *Test Geometry*—The relative geometric placement of source, the article under test, and film (or non-film detection device) is critically important for the following reasons: *(1)* the area of exposure is usually a function of the distance of the article under test from the source, *(2)* the intensity of the beam and exposure time required is a function of the distance between the source and the film (or non-film detection device), *(3)* the magnification factor between the image and the article under test is the ratio of the detector-source distance (d_d) to the article-source distance (d_s), and *(4)* the sharpness of the image will be a function of the difference between dd and ds times the effective diameter of the source. In CR systems, unsharpness in the image can also result from limited spatial resolution of the IP and scanner (80–260 µm unsharpness corresponds to 40–130 µm basic spatial resolution or effective pixel size).

NOTE 15—Optimum geometrical sharpness of the image is obtained when the radiation source is small, the distance from the source to the article under test is large, and the distance from the article to the detector (for example, the film) is small. The magnification factor approaches unity under these conditions, and usually radiographic magnification will be close to unity unless an extremely small focal spot was purposely designed into the X-ray system.

10.2.7.2 *Composite Article Thickness*—As the thickness of an article under test increases, the time required to obtain a radiograph also increases. Therefore, for a given X-ray energy, there exists a maximum thickness above which radiography is not feasible due economic (time) considerations, and a minimum thickness below which radiography is not feasible due to beam detector saturation and loss of contrast.

10.2.7.3 *Observable Defect Sizes*—X-ray radiography is capable of detecting three-dimensional defects that have a size in the direction of the incident radiation that is equal to or greater than 1 to 2 % of the thickness of the article under test. Two dimensional cracks are detectable only if they present an effective thickness equal to or greater than 1 to 2 % of the thickness of the article under test, *and* the crack plane is parallel or nearly parallel to the incident beam.

10.2.8 *Safety and Hazards:*

10.2.8.1 The basic principles that govern radiation safety are *(1)* allowable working time, *(2)* working distance, and *(3)* shielding. Safe radiographic procedures employ these concepts.

10.2.8.2 The safety procedures for the handling and use of ionizing radiation sources must be followed. Mandatory rules and regulations are published by governmental licensing agencies. Careful radiation surveys should be made in accordance with regulations and codes and should be conducted in the examination area as well as in adjacent areas under all possible operating conditions.

10.2.8.3 Issues associated with personnel protection against X-rays and gamma-rays are not covered by this document. For information on personnel protection, refer to documents issued by the National Committee on Radiation Protection and Measurement, Federal Register, U.S. Energy Research and Development Administration, National Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards), and to state and local regulations, if such exist. For specific radiation safety information, refer to NBS Handbook 114, 10 CRF 20, 21 CFR 1020.40, and 29 CFR 1910.1096 or state regulations for agreement states.

10.2.8.4 Radiographic examination procedures shall be conducted under protective conditions so that personnel will not receive radiation dose levels exceeding that permitted by company, city, state, or national regulations. The recommendations of the National Committee on Radiation Protection (NCRP) should be a guide to radiation safety. NRCP 49, NCRP 51, NRCP 91, and NSB Handbook 114 may be used as guides to ensure the radiographic or radioscopic procedures are performed so that personnel shall not receive a radiation dose exceeding the maximum permitted by city, state, or national codes.

10.2.8.5 *Electrical Safety*—The radiographer must comply with safe electrical practices when working with X-ray equipment. Modern X-ray equipment uses high voltage circuits. Permanently installed X-ray facilities are designed so that personnel will encounter few electrical hazards; however, use of portable X-ray equipment requires that added precaution be taken such as insuring that units are grounded appropriately, power cables are free from wear, and condensers are discharged prior to checking of circuits.

10.2.9 *Calibration and Standardization:*

10.2.9.1 *Radiographic Quality Level*—The quality level required for radiography is 2 % unless a higher or lower value is agreed upon by the purchaser and supplier. At the 2 % subject contrast level, three quality levels of inspection are available: 2-1T, 2-2T, and 2-4T (see Practice E1025). If IQIs of material radiographically similar to the article under test are not available, IQIs of the required dimensions but of a lower absorption material may be used. If film density varies by more than +30 to –15 % from the density measured through the body of the IQI, two IQIs may be used so that the required sensitivity is attained for the most and least dense portions of the radiograph.

10.2.9.2 *Total Image Unsharpness (Spatial Resolution)*—Conventional IQIs described in Practices E747 and E1025 combine the contrast sensitivity and resolution measurements into an overall figure of merit. Such figures of merit may not be adequate to detect subtle changes in the imaging system's performance. When it is determined necessary to evaluate and measure the total image unsharpness (spatial resolution) of an imaging system separately and apart from contrast sensitivity measurements, a tool or gauge as described in Practice E2002 can be used.

10.2.9.3 *Densitometers*—Calibrate prior to each use, using calibrated film strips.

10.2.10 *Physical Reference Standards:*

10.2.10.1 *Radiographic Acceptance Standards*—Whenever possible, a series of radiographs that exhibit the same types and sizes of imperfections or discontinuities and acceptance variables should be utilized. These radiographs are referred to "radiographic acceptance standards," and are used by the radiographer to determine if the radiographs being inspected meet or exceed these radiographic standards. While such standards are available for certain metallic alloys, they may not be available for composite materials and components that are representative to those being tested.

10.2.10.2 *Image Quality Indicators (IQIs)*—Penetrameters are very important for measuring radiographic quality level; however, they are not always sufficient since they do not always represent actual defects or imperfections or discontinuities being sought. In this case, reference blocks or representative quality indicators in accordance with Practice E1817 shall be used.

10.2.10.3 *Reference Blocks*—The reference block may be an actual object with known defects and imperfections or discontinuities that are representative of the range of defects and imperfections or discontinuities to be detected, or may be fabricated to simulate the article under test with a suitable range of representative defects and imperfections or discontinuities. A suitable range, for example, might include defects and imperfections or discontinuities both in the acceptable and unacceptable range. Alternatively, the reference block may be a one-of-a-kind reference object containing known imperfections that have been verified independently. Reference blocks containing known, natural defects are useful on a single-task basis, but are not universally applicable. Where standardization among two or more radiographic examination systems is required, a duplicate manufactured reference block should be used. The reference blocks should approximate the object as closely as is practical, being made of the same material with similar dimensions and features in the examination region of interest. Manufactured reference blocks should include features at least as small as those that must be reliably detected in the actual article under test. Where features are internal to the article under test, it is permissible to produce the reference block in sections. Reference block details are a matter of agreement between the user and the supplier of radiographic and radioscopic examination services.

10.2.10.4 *Use of a Reference Block*—The reference block should be placed in a radiographic or radioscopic system in the same position as the article under test and may be manipulated (in the case of radioscopy and tomography) through the same range of motion through a given exposure that the article under test is subjected to.

10.3 *Radioscopy*

10.3.1 *General Procedure*—Radioscopy consists of real-time or near real-time nonfilm detection, display, and recording of radiographic images. Like all X-ray transmission NDT procedures, radioscopy is based on the attenuation of X-rays during their passage through an article under test. Additionally, significant spatial spreading occurs due to system imperfections, nonsymmetric radiation transport, and the image formation process. Significant variations in the recorded radiation near edges and material discontinuities therefore occur and manifest themselves by intensity variations in the radioscopic image.

10.3.2 *Significance and Use*—As with conventional radiography, radioscopic examination is broadly applicable to any composite material or component through which a beam of penetrating radiation may be passed and detected. Although closely related to radiography, radioscopy has much lower operating costs in terms of time, manpower, and material. In addition to the benefits normally associated with radiography, radioscopic examination may be either a dynamic, filmless technique allowing the examined part to be manipulated and imaging parameters optimized during examination; or a static, filmless technique wherein the examined part is stationary with respect to the incident radiation. Recent technology advances in the area of projection imaging, detectors, and digital image processing provide acceptable sensitivity for a wide variety of applications.

10.3.2.1 Both manual and computer-aided automated radioscopic systems of varying complexity are used. Systems having a wide range of capabilities between these two extremes can be assembled.

10.3.2.2 Radioscopy can be a versatile nondestructive tool. It provides immediate information regarding the size, location, and distribution of imperfections, both internal and external. By manipulation of the source relative to the composite structure being examined, three-dimensional information about the sizes and relative position of items of interest within the composite material or component can be obtained. Radioscopy permits timely assessments of product integrity, and allows prompt disposition of the product based on acceptance standards.

10.3.2.3 Long-term records of the radioscopic image may be obtained through motion-picture recording (cinefluorography), video recording, or "still" photographs using conventional cameras. The radioscopic image may be electronically enhanced, digitized, or otherwise processed for improved visual image analysis or automatic, computer-aided analysis, or both.

10.3.2.4 Since there are many methods for real-time and near real-time detection of radiation, its energy, and flux density, there are a number of possible systems. Radioscopic systems are conveniently classified into two main categories: *(1)* those based on conversion of X-rays into light using phosphors, scintillators, or X-ray intensifiers (direct viewing systems) and *(2)* those based on conversion of X-rays into electrons using semiconductor junctions or microchannel plates (remote viewing systems).

10.3.3 *Advantages and Applications*—Radioscopy is preferred when information about the three-dimensional distribution of imperfections, defects, and discontinuities within a composite material or component is needed. Radioscopy provides a rapid check of dimensions and the internal configuration within composite materials and components, and may be used to assess the real-time functioning of a composite material or component. Radioscopy has advantages over radiography for characterization of nonsymmetrical articles under test because of the three-dimensional capability when using mechanical motion of the article relative to the X-ray beam.

10.3.4 *Limitations and Interferences*—As in radiography, perhaps the biggest challenge in X-ray radioscopy as applied to composite materials and components is to obtain sufficient contrast between low atomic number composite substructures (for example, matrix, fiber, laminates). Accordingly, it is often necessary to enhance contrast by using radiopaque materials or contrast agents. Despite numerous advances in radioscopic systems, sensitivity and resolution of real-time systems usually are not as good as can be obtained with film. Dynamic scenes require a higher X-ray flux level to develop a suitable image compared to static scenes. Product-handling considerations in a dynamic imaging system mandate that the image plane be separated from the surface of the product resulting in perceptible image unsharpness. Limitations imposed by a dynamic system make control of scatter and geometry more difficult than in conventional radiographic systems. Lastly, dynamic radioscopic systems require careful alignment of the source, article under test, and detector. Radiation handling requirements and positioning devices peculiar to dynamic systems usually result in greater capital equipment costs than in conventional static radiography.

10.3.5 *Use of Referenced Documents:*

10.3.5.1 Consult Guide E1000 for a tutorial outline of the general principles of radioscopic imaging. The guide describes procedures and image quality measuring systems for real-time, and near real-time, nonfilm detection, display, and recording of radioscopic images. These images, used in materials examination, are generated by penetrating radiation passing through the subject material and producing an image on the detecting medium. The image detection and display techniques are nonfilm, but the use of photographic film as a means for permanent recording of the image is not precluded. Guide E1000 also includes descriptions of different radioscopic system configurations (X-ray/light conversion systems involving fluorescent phosphors or scintillation crystal imagining devices, and X-ray/electron conversion systems involving semiconductor junctions or microchannel plate imaging devices), radiation sources (low- and high-energy radioactive isotope sources, source geometry), display and recording devices, and image quality considerations.

10.3.5.2 Consult Practice E1255 for application details for radioscopic examination using penetrating radiation. This includes dynamic radioscopy and, for the purposes of this practice, radioscopy where there is no motion of the object during exposure (referred to as static radioscopic imaging). Since the techniques involved and the applications for radioscopic examination are diverse, this practice is not intended to be limiting or restrictive, but rather to address the general applications of the technology and thereby facilitate its use. The general principles discussed in this practice apply broadly to penetrating radiation radioscopic systems. Practice E1255 also includes discussion on minimum system configuration, practice, system performance, and performance measurement.

10.3.5.3 Consult Practice E1411 for test and measurement details for measuring the performance of radioscopic systems. Since radioscopic examination applications are diverse, system configurations are also diverse and constantly changing as the technology advances. This practice is intended as a means of initially qualifying and requalifying a radioscopic system for a specified application by determining its performance level when operated in a static mode. System architecture including the means of radioscopic examination record archiving and the method for making the accept/reject decision are also unique system features and their effect upon system performance must be evaluated. The general principles, as stated in this practice, apply broadly to transmitted-beam penetrating radiation radioscopy systems.

10.3.6 *Geometry and Size Considerations:*

10.3.6.1 Radioscopy is well suited for characterization of nonsymmetrical articles because of the three-dimensional capability when using mechanical motion of the articles relative to the X-ray beam.

10.3.6.2 Considerations about test geometry (relative placement of source, article under test, and imaging devices), article thickness, and observable defect sizes are covered in 10.2.7.

10.3.7 *Calibration and Standardization:*

10.3.7.1 *Reference Standards*—Reference radiographs produced by ASTM and acceptance standards written by other organizations may be employed for radioscopic examination as well as for radiography, provided appropriate adjustments are made to accommodate for the differences in the fluoroscopic images.

10.3.7.2 *Reference Standards*—Reference radiographs produced by ASTM and acceptance standards written by other organizations may be employed for radioscopic examination as well as for radiography, provided appropriate adjustments are made to accommodate for the differences in the fluoroscopic images.

10.3.7.3 *Image Quality Considerations*—Image quality is governed by two factors, image contrast and image resolution. A number of different approaches to assessing image quality are discussed in Section 11 of Guide E1000.

10.3.7.4 *Use of Duplex Wire Gauge and Step Wedge*—A duplex wire gauge, as described in Practices E1255 and E2002, and a contrast sensitivity gauge or a step wedge as described in Practice E1647 may be used, if so desired, to determine and track radioscopic system performance in terms of spatial resolution and contrast sensitivity. The duplex wire gauge is used without an additional absorber to evaluate system spatial resolution. The contrast sensitivity gauge or step wedge is used to evaluate system contrast sensitivity.

10.3.7.5 *Equipment Qualifications*—A listing should be made of the system features that must be qualified to ensure that the system is capable of performing the desired radioscopic examination task (with Practice E1411). Additionally, radioscopic system qualification shall be in accordance with Practice E1411 and can best be evaluated with IQIs similar to the imperfection or discontinuity type being examined.

10.3.8 *Safety and Hazards:*

10.3.8.1 A general discussion about radiological safety and hazards and applicable Federal and NCRP documents are given in subsection 10.2.8 (Radiography and Computed Radiography).

10.3.8.2 Radioscopic systems wherein the radiation source and detection system are manipulated instead of, or in addition to, the article under test will entail the use of more stringent shielding requirements.

10.3.9 *Physical Reference Standards:*

10.3.9.1 *Penetrameters (IQIs)*—Radiographic sensitivity is indicated by the conventional IQI measures contrast and, to a limited degree, resolution. Since most radioscopic systems are resolution limited, however, a greater emphasis is placed on IQIs that measure resolution (such as wire mesh or a line pair test pattern).

10.3.9.2 *Use of a Reference Block*—See 10.2.10.3 for a description of the reference block. The reference block should be placed into the radioscopic system in the same position as the actual article under test and may be manipulated through the same range of motions through a given exposure for dynamic radioscopic systems as are available for the actual object so as to maximize the radioscopic examination system's response to simulated imperfections.

10.4 *Digital Radiography (DR) with Digital Detector Array (DDA) Systems*

10.4.1 *General Procedure*—A DR system consists of near real-time nonfilm radiographic images acquisition, display, and storing. Like all X-ray transmission NDT procedures, DR systems are based on the attenuation of X-rays during their passage through an article under test.

10.4.2 *Significance and Use*—As with conventional radiography, DR system examination is broadly applicable to any composite material or component through which a beam of penetrating radiation may be passed and detected. Although closely related to radiography, DR systems have much lower operating costs in terms of time, manpower, and material. In addition to the benefits normally associated with radiography, DR system examination may be either a dynamic, filmless technique allowing the examined part to be manipulated and imaging parameters optimized during examination; or a static, filmless technique wherein the examined part is stationary with respect to the incident radiation. Recent technology advances in the area of X-ray tubes, detectors, and digital image processing provide acceptable sensitivity for a wide variety of applications.

10.4.2.1 The images from a DR system provide a very large number of grey levels (up to 65 000). Therefore DR systems are always computer-aided; image processing functions are necessary to operate a DR system. Powerful image processing tools are available on the market.

10.4.2.2 DR systems can be versatile nondestructive tools. They provide immediate information regarding the size, location, and distribution of imperfections, both internal and external. By manipulation of the source relative to the composite structure being examined, three-dimensional information about the sizes and relative position of items of interest within the composite material or component can be obtained. DR systems permit timely assessments of product integrity, and allow prompt disposition of the product based on acceptance standards.

10.4.2.3 The DR system image may be electronically enhanced or otherwise processed for improved visual image analysis or automatic, computer-aided analysis, or both. Long-term records may be obtained through storing the images on a CD, DVD, or on network drives.

10.4.2.4 Since there are many methods for real-time and near real-time detection of radiation with digital detector arrays, there are a number of possible systems. DR systems are conveniently classified into two main categories: *(1)* those based on conversion of X-rays into light using scintillators, *(2)* those based on conversion of X-rays into electrons using semiconductor junctions (direct conversion).

10.4.3 *Advantages and Applications*—DR systems are preferred when information about the three-dimensional distribution of imperfections, defects, and discontinuities within a composite material or component is needed.

10.4.3.1 DR systems provide a rapid check of dimensions and the internal configuration within composite materials and components.

10.4.3.2 DR systems have advantages over radiography for characterization of nonsymmetrical articles under test because of the three-dimensional capability when using mechanical motion of the articles under test.

10.4.3.3 DR systems provide a much better contrast resolution than radioscopy systems. Using the integration functionality of the PC software, very high SNRs (>>1000) are possible and with this high SNR the contrast sensitivity can be better than 0.5 %. This obtains sufficient contrast between low atomic number composite substructures (for example, matrix, fiber, laminates). No use of radiopaque materials or contrast agents may be necessary.

10.4.3.4 DR systems can offer a high geometrical resolution with: *(1)* a small pixel size (50 µm), *(2)* a micro focus tube and larger magnification. Combinations are possible.

10.4.3.5 The screens and the front cover of a detector from a DR system can be adapted to very low energies. This leads to a high sensitivity at low energies, for example, 20 keV. The low energy reduces the scatter radiation of the composite material in the beam.

10.4.4 *Limitations and Interferences*—DR systems require careful alignment of the source, article under test, and detector. As DR systems have a larger tolerance to the dose than radioscopic systems the alignment must not be as perfect as with radioscopic systems.

10.4.4.1 Radiation handling requirements and composite article positioning devices peculiar to dynamic systems usually result in greater capital equipment costs than in conventional static radiography.

10.4.4.2 DR systems require operation of a computer system. The operator should be familiar with X-ray technology and additionally with the use of a computer system.

10.4.4.3 The very high SNR of a DR system is possible only with a carefully calibrated detector. The calibration process requires dedicated effort by the operator.

10.4.5 *Use of Referenced Documents:*

10.4.5.1 Consult Practice E2597 for comparison of Digital Detector Arrays (DDAs) so that an appropriate DDA is selected to meet NDT requirements, using a common set of technical measurements; namely, basic spatial resolution, efficiency, achievable contrast sensitivity, specific material thickness range, image lag, burn-in, bad pixels and internal scatter radiation.

10.4.6 *Geometry and Size Considerations:*

10.4.6.1 DR systems are well suited for characterization of nonsymmetrical articles under test because of the three-dimensional capability when using mechanical motion of the article relative to the X-ray beam.

10.4.6.2 Considerations about test geometry (relative placement of source, article under test, and imaging devices), thickness of the article being tested, and observable defect sizes are covered in 10.2.7 (Radiography).

10.4.7 *Safety and Hazards:*

10.4.7.1 A general discussion about radiological safety and hazards and applicable Federal and NCRP documents are given in subsection 10.2.8.

10.4.7.2 DR systems wherein the radiation source and detection system are manipulated instead of, or in addition to, the article under test will entail the use of more stringent shielding requirements.

10.4.8 *Calibration and Standardization:*

10.4.8.1 *Reference Standards*—Reference radiographs produced by ASTM and acceptance standards written by other organizations may be employed for DR examination as well as for radiography, provided appropriate adjustments are made to accommodate for the differences in the fluoroscopic images.

10.4.8.2 *Image Quality Considerations*—Image quality is governed by three factors: contrast resolution, spatial resolution, and image noise. A number of different approaches to assessing image quality are discussed in Section 11 of Guide E1000, in Guide E2736, and also in Practices E2445, E2446, E2597, and E2737.

10.4.8.3 *Use of Duplex Wire IQI and Duplex Step Wedge*—A duplex wire IQI and a step wedge with grooves on any step may be used, if so desired, to determine and track DR system performance in terms of spatial resolution, contrast sensitivity, SNR, dynamic range, and image LAG behavior. The duplex wire IQI is used without an additional absorber to evaluate detector spatial resolution. The grooved step wedge is used to evaluate system contrast sensitivity, the SNR, and the dynamic range. The image lag can be measured by capturing a sequence of images in which the source is cut off.

10.4.8.4 *Equipment Qualification*—For DDAs, Practice E2737 is followed, which includes a long-term stability test. For radioscopy systems, Practice E1411 is followed. When specific qualification instructions are not available, a listing should be made of the system features that must be qualified to ensure that the system is capable of performing the desired examination task. Additionally, DR system qualification can best be evaluated with IQIs similar to the imperfection or discontinuity type being examined.

10.4.9 *Physical Reference Standards:*

10.4.9.1 *Penetrameters (IQIs)*—Radiographic sensitivity is indicated by the conventional IQI measures contrast and, to a limited degree, resolution. With DR systems both parameters are very different with different types of detectors. Both parameters should be measured independent from each other.

10.4.9.2 *Use of a Reference Block*—See 10.2.10.3 for a description of the reference block. The reference block should be placed into the DR system in the same position as the actual article under test and may be manipulated through the same range of motions through a given exposure for dynamic DR systems as are available for the actual object so as to maximize the DR examination system's response to simulated imperfections.

11. Shearography

11.1 *Referenced Documents*

11.1.1 *ASTM Standards:*[2]

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

F1364 Practice for Use of a Calibrated Device to Demonstrate the Inspection Capability of an Interferometric Laser Imaging Nondestructive Tire Inspection System

11.1.2 *Federal Standards:*[11]

21 CFR 1040.10 Laser Products

21 CFR 1040.11 Specific Purpose Laser Products

11.1.3 *Laser Institute of America (LIA) Document:*[12]

ANSI, Z136.1-2000, Safe Use of Lasers

11.1.4 *The British Standards Institution (BSI) Document:*[13]

EN 60825-1 Safety of Laser Products—Part 1: Equipment Classification, Requirements and User's Guide

11.2 *General Procedure*

11.2.1 Shearography NDT systems use a common path Michelson-type interferometer to image the first derivative of the out-of-plane deformation of the article under test surface in response to a change in load. Loads can be thermal, pressure, or vacuum stresses, or acoustic or ultrasonic vibrations. Care is taken to ensure that the magnitude of the applied load is far below the damage threshold of a given article under test. The optimum load type and magnitude depend on the imperfection or discontinuity type and depth and is best determined before serial testing by making trial measurements. The Shearography NDT procedure consists of illuminating an article under test with fixed frequency laser light before and after a small proof load is applied. A mirror (the tilt mirror) is precisely tilted to induce an offset, or sheared image, of the article under test with respect to a second image of the part. The amount of image shear can be represented as a vector quantity with an associated angle and displacement. The shear vector, among other factors, determines the sensitivity of the interferometer to surface displacement derivatives, $\partial w / \partial x$. The two sheared images of the test image are focused onto the charge-coupled device (CCD) camera (Fig. 3). Light from pairs of points in each sheared image interfere with each other, causing interference at every paired point across the field of view. A phase shift mirror in the interferometer may be phase stepped using a piezoelectric device and the images combined to create a phase map. Further processing using any number of unwrapping algorithms may be used to generate fringe free images of local surface deformation derivatives. Each video frame, comprised of the complex addition of these two sheared images can be subtracted from a stored reference image. Loaded articles

TABLE 11 Summary of Shearography

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Whole field, noncontact, real-time detection of disbonds, delaminations, cracks, impact damage, modulus changes. High-speed, cost effective inspection technique for quality assurance, material optimization, and manufacturing process control. May be built as portable units or into gantry systems for scanning large structures. Can be used to measure the deformation response of a structure to an applied load.	Shearography is an interferometric method that requires application of a small proof load to an article under test between the initial and final image capture. By subtracting or superimposing images of the composite article taken in the unloaded and loaded states, detection of localized strain concentrations caused by subsurface imperfections or discontinuities is possible.	Sensitive to out-of-plane micron to submicron level deformations. Can perform large area inspections. Less sensitive to the image degrading effect of environmental vibration compared to other interferometric techniques. Operating equipment requires less technical understanding. No film material is consumed. Can be automated for production environments. Robust construction for industrial use. High-speed throughputs in the range of 10 to 50 m^2/h (~100 to 500 ft^2/h) are possible.	Surface condition, especially glossiness, can interfere or prevent accurate shearographic detection, thus requiring the use of surface dulling agents (exception: thermal shearography). Additional equipment is required to determine surface derivative slope changes, and thus use the method as a quantitative tool.	Imperfection or discontinuity-induced out-of-plane deformation is typically displayed as interference fringes on a monitor. System output images show qualitatively pictures of structural features and surface and subsurface anomalies as well as quantitative data such as defect size, area, depth, material deformation vs. load change and material properties. Quantitative measurements are based on point-to-point changes in the surface slope, $\partial w / \partial x$.

---

[11] Published by the Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration (FDA), available from Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401.

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

[13] Available from the British Standards Institute, 389 Chiswick High Road, London, W4 4AL, United Kingdom.

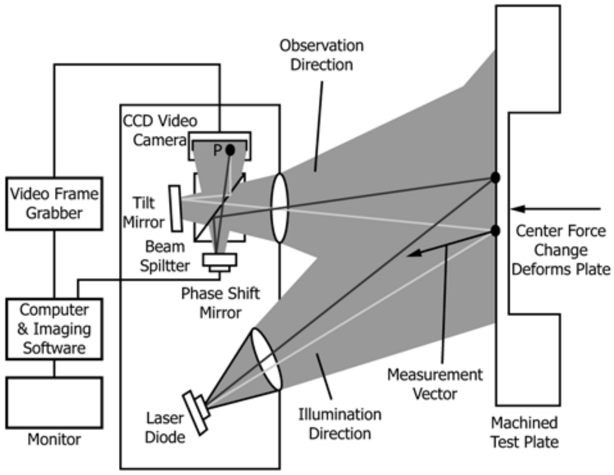

FIG. 3 Schematic Diagram of an Interferometer and Machined Test Plate (Reference Standard) Consisting of a Plate with a Flat-Bottom Hole

under test will show out-of-plane deformation (strain concentration) near imperfections or discontinuities that is significantly greater than the out-of-plane deformation produced in imperfection or discontinuity-free areas. These areas containing imperfections or discontinuities are indicated by the presence of interference fringes (Fig. 4).

11.3 *Significance and Use*

11.3.1 Shearography systems may be built as portable units or into gantry systems, similar to UT C-Scan systems, for scanning large structures.

11.3.2 Changes in the applied load required to reveal subsurface anomalies frequently induce gross deformation or rotation of the article under test.

11.3.3 Laser interferometric imaging techniques such as shearography have seen dramatic performance improvements in the last decade and wide acceptance in industry as a means for high-speed, cost effective inspection and manufacturing process control. These performance gains have been made possible by the development of the personal computer, high resolution CCD and digital video cameras, high performance solid-state lasers and the development of phase stepping algorithms. System output images show qualitatively pictures of structural features and surface and subsurface anomalies as well as quantitative data such as defect size, area, depth, and changes in deformation as a function of load and material properties.

NOTE 1—The shearogram shows the positive (white) and negative (black) slope change indicating a 7-micron out-of-plane deformation.

FIG. 4 A Phase Map Shearogram of a Reference Standard Consisting of a Plate with a Flat-Bottom Hole Using a Horizontal Shear Vector

11.3.4 Gantry mounted production shearography systems share many operational features with UT C-scan systems. These include: teach/learn part scan programming, electronic imaging of entire articles under test, image analysis and defect measurement tools, and automated operation.

11.3.5 *Advantages and Applications*—Laser shearography has shown to be an effective inspection method, for fast and accurate defect location and sizing. It is a noncontact inspection method that lends itself to in process inspection of composites. Surface deformations as small as 2–3 nanometers can be detected and quantitatively measured using laser shearography. Some specific applications include:

11.3.5.1 *Portable Systems*—Can be used to identify repair areas in composite laminates, such as those with far side, bonded stringers (diagonal linear features).

11.3.6 *Pressure Shearography*—Pressure shearography has shown to be an effective inspection method for filament-wound pressure vessels constructed from aluminum or non-corrosive steel liners housing liquid fuel or chemicals, for example. Pressurization of these vessels increases the hoop and longitudinal strain on the vessel surface. The *z*-axis component of strain concentrations are detected, allowing the liner-to-composite bond integrity to be evaluated.

11.3.7 *Thermal Shearography*—Unlike thermography, which is sensitive to changes in surface temperature (or the derivatives of the temperature change), thermal shearography is sensitive to changes in the thermal expansion of a structure. Since impact damage (in carbon and Kevlar fiber wound pressure vessels, for example), disbonds, foreign object debris, and delaminations all produce local changes in the coefficient of thermal expansion, such defects can be detected by this method.

11.3.7.1 *Vacuum Shearography*—The technique has been successfully used to detect discontinuities such as local delamination in composite helicopter blades during production. For example, production shearography systems can be placed on a gantry inside a vacuum test chamber that simulates pressure cycling between ambient pressure and 2 kPa (0.3 psi).

11.3.7.2 *Acoustic Shearography*—This technique is used to image disbonds and voids during spray-on-foam-inspection (SOFI) on rocket launch vehicles requiring extensive thermal protection systems to prevent damage from combustion flame, frictional aerodynamic heating during flight in the atmosphere, and loss of cryogenic propellants.

11.3.7.3 *Ultrasonic Holography*—This technique has been used to inspect Feltmetal and plasma-sprayed aircraft abradable seals (inspection standard since 1982). It combines time-averaged holography with a low frequency ultrasonic vibration applied to the compressor shroud. Holography provides excellent disbond detection with easily interpreted images essentially identical to UT results, but not affected by part geometry or material thickness changes. Early systems used film holography with a one step chemical process, which produced production quality holograms in approximately 10 seconds. The results were viewed on a video monitor. Electronic holography currently using mega-pixel CCD cameras has radically improved system operation speed and reliability.

11.3.8 *Limitations and Interferences*—The shine condition of a surface, like a dark glossy surface, can deflect the laser speckle pattern and a coating to dull the surface may be required. (Thermal shearography is not generally affected by variations in emissivity or paint on the test part surface.)

11.4 *Use of Referenced Documents*

11.4.1 Consult Practice F1364 for a description of the construction and use of a straining block device that can be used to calibrate the anomaly detection capability of shearography systems.

11.4.2 Consult Practice E2581 for a description of shearography procedures for polymer matrix composites and sandwich constructions, and Guide E2981 for filament-wound pressure vessels.

11.5 *Geometry and Size Considerations*

11.5.1 Depending on the object size, laser diodes, gas lasers, and solid-state lasers are used as light sources.

11.5.2 Shearography results are not affected as much by part geometry or thickness changes compared to other NDT techniques such as UT.

11.5.3 Shearography cameras can be positioned on multi-axis positioning systems to enable whole field characterization of articles under test with complex shapes (cones, cylinder) and features (edges, flanges).

11.6 *Safety and Hazards*

11.6.1 *Laser Safety*—Shearography uses laser light to illuminate the surface of the article under test. A laser is simply a convenient source of monochromatic and coherent light that makes the implementation of shearography possible. 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 in accordance with 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 BS). 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 shearography 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 shearography systems.

11.6.2 Systems classified as 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 five 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 (that is, binoculars or telescopes). This does not include normal corrective lenses.

11.6.3 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.

11.7 *Calibration and Standardization*

11.7.1 Precision calibration of the shearogram image scale (pixels/inch) and the shear vector allow further processing of shearography data to determine defect indication dimensions, area, and the deformation of the material. The digital measurement of the deformation derivative may be integrated to show the shape of the target surface deformation as well as the magnitude of the deformation at any location.

11.8 *Physical Reference Standards*

11.8.1 *Straining Blocks*—Straining blocks as described in Practice F1364 are designed to create an image of a known anomaly against which the performance of the shearography system may be evaluated. The block is constructed by securing a deformable membrane over a rigid block that contains a series of holes of various sizes and shapes. The membrane should be made of a material that retains its physical properties over time with minimal aging effects. Interior holes in the block are either vented to atmospheric pressure or sealed at nominal pressure, allowing differential pressure to exist in the membrane when the block is subjected to vacuum. It is the deflection of the membrane under this differential pressure that is measured by the shearography system. By studying the presence and clarity of fringe pattern obtained from straining blocks, adjustments such as optical alignment, laser power, stressing (vacuum) level, beam ratio modifications, etc., can be made, thus ensuring optimal system performance. Detailed instructions on how to fabricate straining blocks can be obtained from ASTM.[4]

12. Strain Measurement (Bonded Strain Gauges)

12.1 *Referenced Documents*

12.1.1 *ASTM Standards:*[2]

E251 Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gauges

E1237 Guide for Installing Bonded Resistance Strain Gauges

E2208 Guide for Evaluating Non-Contacting Optical Strain Measurement Systems

TABLE 12 Summary of Strain Measurement (Bonded Strain Gauges)

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Can be used to measure both static and dynamic strain. Strain measurement at cryogenic to very high temperatures is possible. In applications where higher unit resistance and sensitivity (higher gauge factor) are needed, semiconductor wafer sensors are preferred. In applications where less sensitivity to temperature variations and lower drift are needed, metallic bonded strain gauges are preferred. In applications where stable installation, less drift, and elimination of errors due to creep and hysteresis are needed, thin-film and diffused semiconductor strain gauges are preferred. Arrays of strain gauges can be used to completely characterize axial (tensile and compressive) strain, as well as shearing, Poisson, bending, and torsional strains.	Metallic bonded resistance strain gauges consist of a grid of wire filament or metal foil (a resistor) bonded directly to the strained surface by a thin layer of epoxy resin. When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the wire or foil which varies linearly with strain. The metal grid and adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the grid and the composite article's surface. Semiconductor strain gauges, consisting of a wafer with the resistance element diffused into a substrate, measure piezoresistive changes in the silicon or germanium as a function of stress as opposed to strain. The gauge is bonded directly to the strained surface by a thin layer of epoxy resin. Thin-film and diffused semiconductor strain gauges are permanently attached to the test surface, obviating the need for adhesive bonding.	Relatively inexpensive. Less bulky and better resolution than extensometers. Highly sensitive and can achieve overall accuracy of better than ± 0.10% strain. Have small physical size and low mass. Available in a variety of gauge lengths (0.2 to 100 mm (0.008 to 4 in.)).	Individual strain gauges cannot be calibrated. Response to strain is low. The low level of the signal makes strain gauges susceptible to unwanted noise from other electrical devices, thus necessitating shielding or guarding. Strain gauge measurement is subject to numerous potential sources of error such as: Expansion or contraction of the strain-gauge element and/or the base material. Change in the resistivity or in the temperature coefficient of resistance due to temperature or aging leading to apparent strain or drift, respectively. Hysteresis and creep caused by imperfect bonding. Nonlinear resistance-to-strain relationships for semiconductor strain gauges.	The output of a resistance measuring circuit (for example, a Wheatstone bridge) is expressed in millivolts output per volt input. Since a very low voltage output signal is generated, sensitivity of 100 microvolts or better is required.

12.2 *General Procedure*

12.2.1 Bonded strain gauges consist of a grid of very fine metallic wire, foil, or semiconductor material bonded to the strained surface or carrier matrix by a thin insulated layer of epoxy (Fig. 5). When the carrier matrix is strained, the strain is transmitted to the grid material through the adhesive. The variations in the electrical resistance of the grid are measured as an indication of strain. The grid shape is designed to provide maximum gauge resistance while keeping both the length and width of the gauge to a minimum. In bonding strain gauge elements to a strained surface, it is important that the gauge experience the same strain as the object. With an adhesive material inserted between the sensors and the strained surface, the installation is sensitive to creep due to degradation of the bond, temperature influences, and hysteresis caused by thermoelastic strain. Because many glues and epoxy resins are prone to creep, it is important to use resins designed specifically for strain gauges. The three primary considerations in gauge selection are: operating temperature, the nature of the strain to be detected, and stability requirements. In addition, selecting the right carrier material, grid alloy, adhesive, and protective coating will guarantee the success of the application. In order to measure strain with a bonded resistance strain gauge, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain. Strain gauge transducers often employ four strain gauge elements electrically connected to form a Wheatstone®[14] bridge circuit. The number of active strain gauges that should be connected to the bridge depends on the application. For example, it may be useful to connect gauges that are on opposite sides of the article under test, one in compression and the other in tension. In this arrangement, one can effectively double the bridge output for the same strain. In installations where all of the arms are connected to strain gauges, temperature compensation is automatic, as resistance change due to temperature variations will be the same for all arms of the bridge.

---

[14] Wheatstone® is a registered trademark of Gary C. Snow, Brewerton, NY 13029.

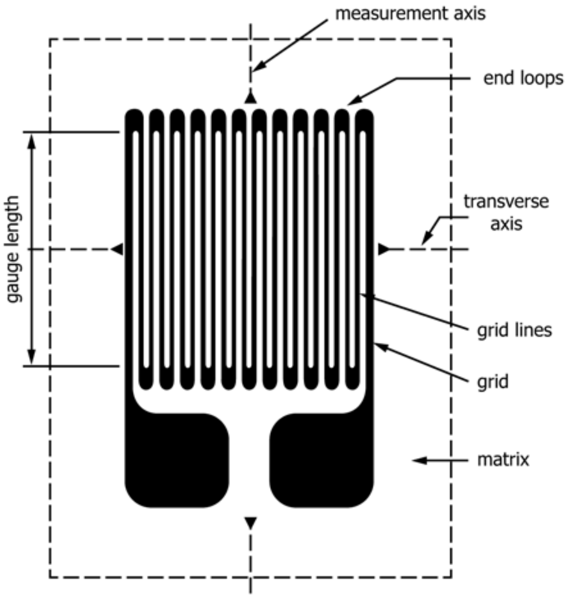

FIG. 5 Schematic of a Typical Metal-Foil Strain Gauge

12.3 *Significance and Use*

12.3.1 Strain gauges are part of a complex system that includes the article under test, adhesive, gauge, lead-wires, instrumentation, and (often) environmental protection.

12.3.2 Properly designed and manufactured strain gauges, whose properties have been accurately determined and with appropriate uncertainties applied, represent powerful measurement tools. Strain gauges are very sensitive devices with essentially infinite resolution. The performance parameters discussed in Test Methods E251 must be known to an acceptable accuracy to obtain meaningful results in field applications.

12.3.3 Bonded resistance strain gauges differ from extensometers in that they measure average unit elongation (ΔL/L) over a nominal gauge length rather than total elongation between definite gauge points.

12.3.4 Strain gauges are the most widely used devices for determining stress in structures. Since the testing is often destructive, strain gauges cannot be reused. However, strain gauge performance is affected by both the materials they are made from and their geometric design.

12.3.5 To be used, strain gauges must be bonded to a structure. Optimum and reproducible detection of surface deformation depends heavily on the materials used to clean the bonding surface, to bond the gauge, and to provide a protective coating. Skill of the installer is another major factor in success since consistent surface preparation, mounting procedures, and verification techniques are paramount. Specific factors that may affect strain gauge performance include resistive element alloy, carrier material, gauge length, gauge and resistive element pattern, solder tap type and configuration, temperature compensation characteristics, resistance of active elements, and gauge factor.

12.3.6 Finally, instrumentation systems must be carefully designed to ensure that they do not unduly degrade the performance of the gauges. In many cases, it is impossible to achieve this goal. If so, allowance must be made when considering the accuracy of the data.

12.3.7 Test conditions can be, and in some instances are, so severe that error signals from strain gauge systems far exceed those from the structural deformations being measured. Great care must be exercised in documenting magnitudes of error signals so that realistic values can be placed on associated uncertainties.

12.3.8 Although newer types of strain gauges are available (namely, semiconductor strain gauges, thin-film strain gauges, and diffused semiconductor strain gauges) this guide emphasizes the use of metallic bonded resistance strain gauges. Some of the advantages and disadvantages of these newer types of strain gauges compared to metallic bonded resistance strain gauges are summarized in Table 13.

NOTE 16—Strain can also be measured using non-contact methods using optical extensometers (video cameras). However, care has to be taken in verifying the resolution of the optical method.

12.3.9 *Advantages and Applications:*

12.3.9.1 Properly designed and manufactured strain gauges are very sensitive devices with essentially infinite resolution. They can determine small dimensional changes in structures with excellent accuracy, far beyond that of other known devices.

12.3.10 *Limitations and Interferences:*

12.3.10.1 Response to strain, however, is low and great care must be exercised in strain gauge use. Furthermore, to ensure strain gauge test data are within a defined accuracy, the gauges must be properly bonded and pretested with acceptable materials. It is normally simple to ascertain that strain gauges are not performing properly. The most common symptom is instability with time or temperature change. If strain gauges do not return to their zero reading when the original conditions are

TABLE 13 Comparison of Newer Types of Strain Gauges with Metallic Bonded Resistance Strain Gauges

Strain Gauge Type	Advantages	Disadvantages
Semiconductor	Smaller. Less expensive. Higher unit resistances.	Greater sensitivity to temperature variations. Tendency to drift. Resistance-to-strain relationship is nonlinear.
Thin-Film	Eliminates the need for adhesive bonding. Installations are much more stable (resistance values experience less drift). Stressed force detector can be a metallic diaphragm or beam with a deposited layer of ceramic insulation.	Fabrication involves vacuum deposition or sputtering techniques (installation is permanent).
Diffused Semiconductor	Eliminates the need for adhesive bonding. Smaller. Less expensive. Accurate and repeatable. Provides a wide pressure range. Generates a strong output signal. Errors due to creep and hysteresis eliminated.	Greater sensitivity to ambient temperature variations (limited to moderate-temperature applications). Measurement often requires temperature compensation. Fabrication involves a photolithographic masking technique (installation is permanent).

repeated, or there is low or changing resistance to ground, the installation is suspect.

12.4 *Use of Current Standard Documents*

12.4.1 Consult Test Methods E251 for determination of strain gauge performance characteristics. Suggested testing equipment designs are included. Methods for determining five strain gauge parameters are discussed: *(1)* Resistance at a Reference Temperature, *(2)* Gauge Factor at a Reference Temperature, *(3)* Temperature Coefficient of Gauge Factor, *(4)* Transverse Sensitivity, and *(5)* Thermal Output. These test methods do not apply to transducers, such as load cells and extensometers, that use bonded resistance strain gauges as sensing elements.

12.4.2 Consult Guide E1237 for guidance on strain gauge installation and verification. This document is *not* intended to be used for bulk or diffused semiconductor gauges, but pertains only to adhesively bonded resistance strain gauges. Detailed descriptions are provided for gauge selection, bonding technique selection, surface preparation, gauge installation (general considerations and consideration about the adhesive used), lead wire connection, verification checks, and protective coatings.

12.4.3 Consult Guide E2208 for assistance in understanding the issues related to the accuracy of non-contacting strain measurement systems (for example, moiré interferometry) and for a common framework for quantitative comparison of optical systems. The output from a non-contacting optical strain and deformation measurement system is generally divided into optical data and image analysis data. Optical data contains information related to specimen strains and the image analysis process converts the encoded optical information into strain data. Guide E2208 describes potential sources of error in the strain data and describes general methods for quantifying the error and estimating the accuracy of the measurements when applying non-contacting methods to the study of events for which the optical integration time is much smaller than the inverse of the maximum temporal frequency in the encoded data (that is, events that can be regarded as static during the integration time). A brief application of the approach, along with specific examples defining the various terms, is given in the Appendix.

12.5 *Geometric and Size Considerations*

12.5.1 Large composites structures, such as filament-wound pressure vessels which make impractical the use of conventional extensometers, are ideally suited for measurements using strain gauges.

12.6 *Safety and Hazards*

12.6.1 During specimen surface cleaning, gauge bonding, and protection steps or strain gauge installation, hazardous chemicals may be used. Users are responsible for contacting the manufacturers of these chemicals for applicable Material Safety Data Sheets and to adhere to the required precautions.

12.7 *Calibration and Standardization*

12.7.1 *Data Reduction and Statistics*—Since strain gauges used to determine values of performance characteristics are generally not reusable, the data obtained from a sample of such gauges are used to predict the performance for all other gauges in the same batch. Well established statistical methods, such as t-tests, are used to make predictions about the uncertainty in the data from an individual gauge. These methods require that tests be made upon a sample taken at random from the batch, and generally assume the test results will have a normal, that is, Gaussian, distribution. For verification of the values and tolerances furnished for a shipment of strain gauges, the reader is referred to Appendix X3 of Test Methods E251.

12.7.2 *Verification Checks*—The completed strain gauge installation shall be checked prior to use to verify its integrity and ability to provide reliable and repeatable data. Two checks are possible: *(1)* initial checks after installation, and *(2)* checks after lead-wire connections have been made.

12.8 *Physical Reference Standards*

12.8.1 It is important to realize that individual strain gauges cannot be calibrated. If calibration and traceability to a physical reference standard are required, strain gauges should not be used.

13. Infrared Thermography (Non-Contact Methods Using Infrared Camera)

13.1 *Referenced Documents*

13.1.1 *ASTM Standards:*[2]

E1213 Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems

E1311 Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems

E1543 Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems

TABLE 14 Summary of Infrared Thermography (Non-Contact Methods Using Infrared Camera)

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Can be used to detect delaminations, debonds, voids, cracks, inclusions, and occlusions, especially in thinner laminates. Thickness limit depends on the thermal diffusivity of the composite material and on the equipment and technique employed. Well-suited for rapid scanning of large surface areas. Suspect areas may be identified for more thorough evaluation. Best suited for high emissivity (low reflectivity) surfaces. A flat-black surface provides optimum results, but most dull surfaces work well. Can be configured for either single-sided or two-sided inspection.	An infrared (IR) video camera views the surface temperature distribution across the surface of the article under test either during or shortly following heating (or cooling) the area of interest. Subsurface discontinuities affect the heat flow, resulting in localized temperature variations at the surface. Thermal diffusion is the mechanism by which internal defects are located in an article under test. It is a material property defined as the ratio of its thermal conductivity and heat capacity. Changes in the rate of heat flow due to subsurface discontinuities affect the observed surface temperature distribution. Thermal diffusion can be initiated by heating (radiation, convection, or conduction), or cooling (convection or conduction), or mechanical (vibration).	Relatively fast because it is an area inspection method. In some cases, inspection details are comparable to X-ray or ultrasonic methods at a fraction (typically 20%) of the inspection time. Inspection can be completely non-contacting. Does not require access to the opposite side of the structure. Provides supplemental information to other NDT procedures. No harmful radiation is emitted, and surface heating requirements are generally small (no more than 5 to 10°C). Great versatility of applications. Can be used on a wide variety of thermally conductive materials.	The IR camera requires a direct view of the surface of the article under test, and clearance is required for focusing. Non-uniform application of heating or cooling can result in confusing thermographic images. Heating equipment may be unsafe to operate in fuel-rich environments. The surface contrast temperature due to an internal defect drops exponentially with its depth, generally limiting usage to thinner laminates (under 8.4 mm [0.33 in.] thick in most cases). Not effective on low emissivity surfaces unless a high emissivity coating is applied (such as a flat black tempera paint).	The IR camera presents a video image of the surface temperature distribution. A60 Hz frame rate is common, but other frame rates are available. Some cameras provide an analog video output for recording and/or digital input/output for interfacing to a computer. Defect areas appear as variations in the surface temperature viewed by the infrared camera. These temperature variations are mapped to color or grey-scale pallets for presentation. Images of internal defects are transitory. The appearance time, peak contrast image, and subsequent fading depends on the article under test's thermal properties and those of the defect, and also on the size and depth of the defect. In some cases, the contrast temperature is very weak and/or short lived. Image storage and/or additional data processing may be required.

E1862 Test Methods for Measuring and Compensating for Reflected Temperature Using Infrared Imaging Radiometers

E1897 Test Methods for Measuring and Compensating for Transmittance of an Attenuating Medium Using Infrared Imaging Radiometers

E1933 Test Methods for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers

E1934 Guide for Examining Electrical and Mechanical Equipment with Infrared Thermography

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

13.1.2 *Military Handbooks and Standard:*[6]

MIL-HDBK-731 Nondestructive Testing Methods of Composite Materials—Thermography

13.2 *General Procedure*

13.2.1 Thermal diffusion (heat flow) is initiated in the article under test while the evolving surface temperature is viewed with an infrared (IR) video camera. Defects, nonhomogeneities, or other undesirable conditions in the article under test will evidence themselves as local hot or cold spots in the thermographic image. The local temperature variations are transient images, meaning that they will appear, peak, and subsequently fade away over time as the temperature of the article under test re-stabilizes. The evolving surface temperature distribution is governed by thermal diffusion in the interior of the article under test, the depth of the feature of interest, and its cross-sectional area. It is important to note that you cannot obtain any information about the interior of an article under test that is in thermal equilibrium. Using an external stimulus to cause thermal diffusion in the article under test is commonly known as the *active* method. External heating is most commonly used, although cooling (removal of heat) can be equally effective. Heating may be conductive (such as a heat blanket), convective (such as a heat gun), or radiation (using flash or flood lamps). Cooling may be conductive (such as an ice pack) or convective (such as a vortex gun). For some defect types (such as tightly closed cracks), a mechanical stimulation (vibration) provides better detection. The intent of mechanical stimulation is to cause the defect area to generate heat by friction or by cyclic stress loading. Infrared cameras vary considerably in features and performance. In general, best results are achieved with higher sensitivity cameras having cooled detectors, but these are more expensive and less portable than their uncooled counterparts.

13.3 *Significance and Use*

13.3.1 Infrared Thermography inspection equipment can be very simple (a hand-held IR camera and a heat gun) to very complex (a fully integrated computer-controlled system). What is required depends on the application. Considerations include:

13.3.1.1 Defect properties (diffusivity, size, depth), 13.3.1.2 Infrared camera capabilities (sensitivity, bandwidth, frame rate, etc.),

13.3.1.3 Data capture and storage, and

13.3.1.4 Accuracy and repeatability.

13.3.2 Typical defect types generally detectable with IR thermography include voids, inclusions, cracks, delaminations, and the presence of fluids. Potential applications include monitoring/control of manufacturing processes, quality assurance of newly manufactured parts, and inspection of assemblies for various types of damage. The smallest observable defect size is limited by the distance between the camera and the part surface and by the instantaneous field of view (IFOV) of the camera. The contrast temperature appearing on the surface falls off exponentially with the depth of the defect ($1/[\text{depth}]^3$) and may also be negatively impacted by heat flowing around the defect area (small defects). As a "rule of thumb," the smallest observable defect in ideal conditions is equal or greater than its depth. Therefore, a 6.35 mm (0.25 in.) diameter void in a composite laminate will generally not be observable at a depth greater than ¼ inch.

13.3.3 In general, contrast temperatures caused by the presence of defects on composite materials are very small. Most IR cameras are designed to have a measurement range of a few hundred degrees Celsius. For materials inspection, the contrast temperature is typically no greater than a few tenths of a degree, and is often much smaller, therefore the IR cameras are often operated near their detection limits. A wide variety of IR cameras are available today. It is very important to evaluate the IR camera on a representative article under test having known defects that are similar to what needs to be found in practice. Cameras with cooled detectors are more sensitive and less noisy than their uncooled counterparts, generally resulting in easier detection of subsurface features. Newer IR cameras typically have focal plane array detectors, whereas older cameras have a single detector and a pair of mechanically rotated prisms to create a scanned IR image. Different spectral ranges are available, approximately 3–5 micron (short-wave) and approximately 7–11 micron (mid-band/long wave). Many IR cameras operate at a frame rate of 30 or 60 Hz, which is usually sufficient for inspection of composite assemblies. Some IR cameras are radiometric (meaning the IR radiation captured by the camera is translated to a temperature measurement). Radiometric cameras are often not needed, because the small contrast temperatures due to subsurface defects are often difficult to measure accurately.

13.3.4 Data storage may be either a single image showing a defect at the optimum viewing time, or may be a sequence of images showing the development and subsequent fading of the defect indication.

13.3.5 Repeatability of inspection is dependent upon both the equipment and technique used. For example, convection heating with hot or cold air is difficult to apply with repeatability. Non-uniform application of heating (or cooling) can cause localized temperature variations that may be misinterpreted as defect locations. The best repeatability is achieved using automated data acquisition and storage that is synchronized to the application of the thermal stimulus.

13.3.6 *Active Thermography*—Active thermography requires use of external stimulation to cause heat to flow (by diffusion) in an article under test. Heat may be introduced by *(1)* placing the article under test in contact with an object at a different temperature (thermal conduction), or *(2)* flowing air or fluid across the article under test surface (convection heating), or *(3)* by exposing the article under test to a flood lamp or flash lamp (radiation heating). Cooling is equally effective, but only conductive and convective transfer is available. Another form of external stimulation is by cyclic mechanical deformation of the article under test. Examples are *(1)* body resonance, or *(2)* local resonance using an ultrasonic transducer. In general, cyclic frequencies between 5 and 30 hertz are common for composite materials.

13.3.6.1 *Noncontact Methods*—Radiant energy requires no medium to transfer heat from the source to the surface of the article under test. Heat lamps (flash or flood lamps) are commonly used in non-contact heating. Additionally, forced air heating (or cooling) is usually considered non-contacting (convection heating/cooling). It is usually easier to obtain a uniform thermal emission pattern over a relatively large area using radiant heating. Radiant heating methods are also well suited for articles under test that have irregular shape or imperfect surface. Heat emission patterns acquired from radiant heating are generally more reproducible and amenable to quantitative interpretation than those acquired by convective heating.

13.3.7 *Limitations and Interferences*—Effectiveness of IR thermography inspection techniques depends on many factors, which are summarized in the following paragraphs.

13.3.7.1 Orientation of an imperfection or discontinuity relative to the principle direction of heat flow.

13.3.7.2 Depth of the imperfection or discontinuity from the viewed surface, and size of the imperfection or discontinuity relative to its depth.

13.3.7.3 The reflection of incident radiant energy at the surface of the article under test (assuming it has a reflective surface) due to heat lamp reflection or nearby hot objects can interfere with attempts to interpret the heat emission pattern, although one difference is that signals due to defects are transitory, while those due to other sources (nearby hot objects) are often constant. Therefore, looking at the evolving thermal patterns over time normally yields additional important information.

13.4 *Use of Referenced Documents*

13.4.1 For a general overview of passive and active thermographic methods using contact and noncontact methods for acquiring the heat emission patterns, refer to MIL-HDBK-731.

13.4.2 There are no ASTM standards specific to contact thermography, whether by passive or active excitation.

13.4.3 *Noncontact (Infrared) Methods:*

13.4.3.1 Consult Test Method E1213 for determination of the minimum resolvable temperature difference (MRTD) capability of the compound observer-thermal imaging system as a function of spatial frequency. MRDT values provide estimates of resolution capability and may be used to compare one system to another (lower MRDT values indicate better resolution).

13.4.3.2 Consult Test Method E1311 for determination of the minimum detectable temperature difference (MDTD) capability of a compound observer-thermal imaging system as a function of the angle subtended by the target. MDTD values provide estimates of detection capability and may be used to compare one system to another (lower MDTD values indicate better detection capability).

13.4.3.3 Consult Test Method E1543 for determination of the noise equivalent temperature difference (NETD; NEΔT) of thermal imaging systems of the conventional forward-looking IR (FLIR) or other types that utilize an optical-mechanical scanner; it does not include charge-coupled devices or pyroelectric vidicons. Parts of this test method have been formulated under the assumption of a photonic detector(s) at a standard background temperature of 295°K (22°C). Besides non-uniformity, tests made at other background temperatures may result in impairment of precision and bias. NEDT relates to the minimum resolvable temperature difference, thus, an increase in NEDT may be manifest as a loss of detail in the thermographic image.

13.4.3.4 Consult Test Methods E1862 for procedures for measuring and compensating for reflected temperature when measuring the surface temperature of a specimen with an IR imaging radiometer.

13.4.3.5 Consult Test Methods E1897 for procedures for measuring and compensating for transmittance when using an IR imaging radiometer to measure the temperature of a specimen through an attenuating medium, such as a window, filter or atmosphere.

13.4.3.6 Consult Test Methods E1933 for procedures for measuring and compensating for emissivity when measuring the surface temperature of a specimen with an IR imaging.

13.4.3.7 Consult Guide E1934 for a list of the responsibilities of the end user and the IR thermographer when examining electrical and mechanical systems. This guide outlines the specific content required to document qualitative and quantitative IR thermographic examinations.

13.4.3.8 Consult Practice E2582 for discussion of a procedure for detecting subsurface flaws in composite panels and repair patches, as applies to polymer or ceramic matrix composite structures with inspection surfaces that are sufficiently optically opaque to absorb incident light, and that have sufficient emissivity to allow monitoring of the surface temperature with an IR camera.

13.5 *Geometry and Size Considerations*

13.5.1 Since non-contact IR thermography works on the basis of optical field techniques, it can be applied to the quick observation of large surfaces.

13.5.2 For very thin materials such a composite laminates, it has been shown that the fidelity of surface thermal patterns to interior imperfections or discontinuities is good. For thicker composite materials, deeper defects will appear larger than they actually are due to lateral heat flow (image processing methods are available to compensate for this). Also, as the cross-sectional dimensions of the defect area become comparable to the defect depth, the apparent size will be larger than the actual defect size.

13.5.3 The ability of the IR camera to detect small contrast temperatures is a function of the relative angle between the surface of the article under test and the camera, with a direct viewing angle providing optimum results. Viewing angles of more than 45 degrees from normal should be avoided.

13.6 *Safety and Hazards*

13.6.1 Thermographic procedures involve the use of heated or electrically energized equipment.

13.6.2 Operation of hot air guns, flash lamps and flood lamps may not be permitted in fuel-rich environments.

13.7 *Calibration and Standardization*

13.7.1 *Infrared Cameras*—Infrared cameras require periodic re-calibration. At a minimum, the manufacturer's recommendations should be adhered to. In addition, a suitable reference standard may be used to verify that the camera is functioning properly. It is recommended that the reference standard be evaluated prior to and following an infrared thermography inspection.

13.8 *Physical Reference Standards*

13.8.1 Whenever possible, it is desirable to have a reference standard fabricated that is representative of the article under test. The reference standard should contain real or artificial imperfection or discontinuity areas that are representative of the required imperfection or discontinuity detection requirements.

14. Ultrasonic Testing

14.1 *Referenced Documents*

14.1.1 Many of the referenced documents were written before the production readiness of PMCs and so the value of these documents is the fundamental understanding of the ultrasonic technology and the different proven applications. The PMC's ultrasonic characteristics must be understood by anyone applying these standards.

14.1.2 *ASTM Standards:*[2]

E114 Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method

E214 Practice for Immersed Ultrasonic Examination by the Reflection Method Using Pulsed Longitudinal Waves

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

E664 Practice for the Measurement of the Apparent Attenuation of Longitudinal Ultrasonic Waves by Immersion Method

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

E1065 Guide for Evaluating Characteristics of Ultrasonic Search Units

E1324 Guide for Measuring Some Electronic Characteristics of Ultrasonic Examination Instruments

E1901 Guide for Detection and Evaluation of Discontinuities by Contact Pulse-Echo Straight-Beam Ultrasonic Methods

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

TABLE 15 Summary of Ultrasonic Testing

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
General Overview: Detects sub-surface imperfections or discontinuities in composites. Additional Information: Method of choice for finding delaminations and disbonds in composite products. Can be automated to screen parts during fabrication and manufacturing.	The Basics: Pulsed, high frequency sound is introduced into the part under test using a piezoelectric transducer of a specific frequency. The transducer is coupled to the part with a liquid couplant to allow the sound to pass directly into the part. The transducer may be in direct contact with the part ("contact testing") or maintained a specific distant from the part while both are submerged in a liquid medium ("immersion testing"). The transmitted sound is monitored for reflected echoes measured in amplitude and/or time of flight. Imperfections or discontinuities oriented preferably at 90 degrees to the sound path cause these properties to be altered and/or sound to be reflected, thus revealing their relative sizes and locations (see "What is Seen & Reported" column). Inspection may be performed manually or using automated systems.	General Overview: Detects sub-surface imperfections or discontinuities including porosity, cracks, inclusions, foreign materials, delaminations, and crack-like defects such as lack of fusion & lack of penetration. Additional Information: Numerous sound transmission modes available including longitudinal, shear and surface waves. Numerous techniques available including pulse-echo and through-transmission. Excellent volumetric inspection, especially for laminar imperfections or discontinuities. Imperfection or discontinuity depth can be accurately measured. Highly sensitive and accurate. Can be portable. Automated systems available for testing large parts. Equipment can vary from simple and inexpensive portable A-scan systems to massive C-scan gantry systems capable of manipulating the part and acquiring massive amounts of data.	General Overview: Requires a relatively flat and smooth surface. Material characteristics (modulus, surface condition, orientation of defects) can affect inspectability. Additional Information: Reference standards are required, and may need to be built, in order to standardize equipment and evaluate imperfections or discontinuities. A liquid couplant is required. This can lead to possible fluid entrapment in faying surfaces and internal cavities or possible fluid absorption into porous materials. Numerous ultrasonic techniques may need to be applied to ensure adequate detectability of and internal imperfections or discontinuities are varying orientation because ultrasonic inspection is not sensitive to small imperfections or discontinuities oriented parallel to the sound beam.	General Overview: Imperfections or discontinuities are not directly imaged or recorded. Imperfections or discontinuities are measured by comparing positive or negative amplitude responses from reference standard. Data can be presented in various formats, including a waveform presentation (A scan) or topographical mapping (C scan). Additional Information: Imperfections or discontinuities are "seen" on a display with a time and amplitude display and then measured by comparing amplitude of reflected signal from imperfection or discontinuity with a standard reflector. Another method of defect evaluation is loss of back reflection from areas where inadequate sound is reflected back to the transducer.

14.1.3 *Military Handbooks and Standard:*[6]

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

14.2 *General Procedure*

14.2.1 All ultrasonic tests involve introducing controlled ultrasonic energy into the article under test, and observing how the passage of sound is affected in transit. Any discontinuity can reflect, disperse, or attenuate the energy. The ultrasonic energy for testing is generated in short bursts or pulses by piezoelectric transducers driven by appropriate electronic circuitry. Test frequencies used are usually between 1 to 25 MHz. Since air will not support these higher ultrasonic frequencies, a liquid such as water or oil is used as a couplant between the transducer and the article under test. The couplant allows for the transmission of the sound into the part. It is important to have the cognizant engineering organization approve or direct the type of couplant to insure it is compatible with the material being inspected. Three techniques, contact, immersion pulse echo, and immersion through transmission, are used in ultrasonic testing. In any application, the material under test should be cleaned to remove loose particles or debris prior to test such that the sound is able to enter the material. In contact pulse-echo testing, the transducer is placed directly against the article under test with a film of liquid couplant between them. In immersion pulse-echo or through transmission testing, the article under test is placed in a reservoir of water, and the transducer(s) are placed close to, but not in contact with the article under test. Water columns between the transducers and test surface may be used when immersion is undesirable. For ease and speed of scanning, most interrogations involving imperfection or discontinuity detection in PMCs are performed in one or both of the immersion techniques and the data is recorded in a planer mode known as a C-scan.

14.2.2 A written procedure defines the ultrasonic equipment, reference standards, and parameters needed to conduct and reproduce the test. The procedure is based on recognized industry standards or company specific standards. There are different names for the procedure; work instructions, technique sheet, or inspection plan to name just a few. The procedure may be general to cover generic shapes or materials or it can be part specific. The procedure is normally approved before use by a level 3 NDT personnel.

14.2.3 *Types of Techniques:*

14.2.3.1 *Pulse Echo*—A pulse of ultrasonic energy from a single transducer is transmitted (pulse) into the article under test and a period of listening (echo) for acoustic reflections which is repeated at a selected rep rate (Fig. 6) for contact testing. A discontinuity is usually indicated by *(1)* reflection received from location where no physical discontinuities (such as back wall, end faces, grooves, or holes) are known to exist, or *(2)* reflection or loss of the signal from the known physical discontinuity. Examples of this can be the reflection from a delamination or a loss of signal caused by areas of high porosity.

14.2.3.2 *Through Transmission*—A continuous beam of ultrasonic energy is coupled into the article under test from the sending transducer. A second transducer, the receiver, is placed in a position to receive the transmitted energy. Changes in the negative amplitude of the received energy indicate discontinuities in the part (Fig. 7).

14.2.4 *Types of Procedures:*

14.2.4.1 *Contact Testing*—The transducer is placed directly against the article under test, with a film of compatible liquid couplant between them.

14.2.4.2 *Immersion Testing*—The article under test is placed in a reservoir of couplant liquid, usually water. The transducer is immersed in the reservoir and accurately positioned relative to the article under test. Water columns between the transducers and test surface may also be used if immersion is undesirable.

14.3 *Significance and Use*

14.3.1 Two of the most widely used NDT inspection techniques for composite materials and components are ultrasonic through-transmission using C-scan reporting inspection and ultrasonic pulse-echo A-scan using real time reporting inspection. Since PMC configurations are so broad, and the number of possible ultrasonic techniques and procedures so diverse, the engineering requirements and the accept/reject criteria are usually contained in a document that is referenced in the user's process specification.

14.3.2 Through transmission technique with the aid of electronic recording equipment (C-scan) are well suited for the inspection of laminate structures. This is by far the one of the most commonly applied methods for detecting delaminations, de-bonding and porosity type defects in large PMC structures.

14.3.3 Although information about a variety of possible defects or internal discontinuities can be provided by the ultrasonic techniques, the principal defects evaluated are internal voids/void content, de-bonds, delaminations, and porosity content. Determination of fiber orientation is also possible.

14.3.4 Based on the proper reference standard, the extent of discontinuities can be determined. The minimum detectable discontinuity size will depend on:

14.3.4.1 The sensitivity of the test equipment.

(1) Physical characteristic of the transducer.

(2) Gain/band width characteristics of the instrument.

14.3.4.2 The material inspected.

(1) Physical properties (modulus, crystallinity, fiber content).

(2) Surface condition (rough, smooth, wavy, scaly, coated).

14.3.4.3 The frequency used (in general, higher test frequencies allow detection of smaller discontinuities; lower frequencies allow penetration of greater thickness of material).

14.3.4.4 Orientation of a discontinuity found during through transmission scanning and its distance from the ultrasonic entrant surface can be obtained using the pulse echo technique.

14.3.5 *Pulse Echo:*

14.3.5.1 *Advantages and Applications*—Single transducer operation allows inspection with access to only one side of the article under test. The resolution and sensitivity of the pulse echo method is dependent on the ultrasonic probe characteristics.

14.3.5.2 *Limitations and Interferences*—Each technique has its limitations and should be understood by all concerned. The minimum thickness of a article under test will depend on the procedure (immersion procedures are normally preferred). For example, it may be very difficult to resolve the far ply interface when plies are very thin.

14.3.6 *Through Transmission:*

14.3.6.1 *Advantages and Applications*—The ultrasonic energy passes through the article under test only one time, allowing this test to be used on materials difficult to penetrate as well as thin materials.

NOTE 17—The use of bubblers and squirters is particularly well suited for measurements of composites with contoured surfaces.

14.3.6.2 *Limitations and Interferences*—Precision fixturing for two transducers and preparation of two test surfaces are required (transducers must be critically aligned and their motion synchronized). The through transmission technique also has poorer resolution and sensitivity compared to the pulse echo method. Discontinuity depth cannot be determined by through testing. Use of this technique is best applied with the aid of recording equipment (C-scan).

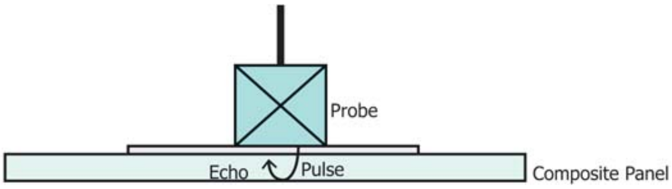

FIG. 6 Diagram of Ultrasonic Pulse Echo Contact Testing Set Up

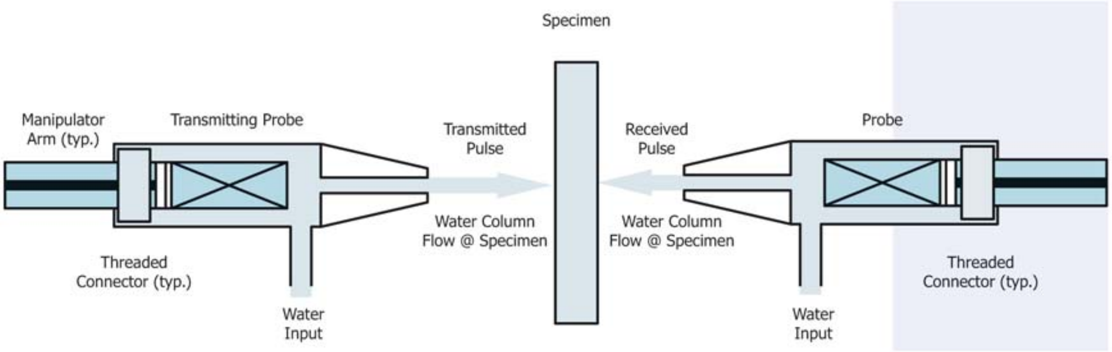

FIG. 7 Diagram of Ultrasonic Bubbler/Squirter Through Transmission Testing Set Up

14.3.7 *Contact Testing:*

14.3.7.1 *Advantages and Applications*—Contact testing involves low cost equipment. Portable, battery-operating equipment is also available. Quite often this procedure is used to verify imperfections or discontinuities found using through transmission, that is, depth information. This method is commonly used in the field for composite damage assessment.

14.3.7.2 *Limitations and Interferences*—Since rough surfaces can scatter and attenuate the sound energy, a reasonably smooth surface is required. Also, the energy cannot be readily focused to obtain better resolution and sensitivity in the given analysis area (it is difficult to control the shape and direction of the beam). The transducer is also subject to wear thus requiring replacement or wear/shoes in some applications. Last, sensitivity is variable depending on couplant efficiency.

14.3.8 *Immersion Testing:*

14.3.8.1 *Advantages and Applications*—Immersion testing allows the energy to be focused or shaped for the article under test, thus increasing resolution and sensitivity. Immersion coupling facilitates inspection of nonuniformly contoured parts and lends itself better to automatic inspection and recording of results.

14.3.8.2 *Limitations and Interferences*—Through transmission requires access to both sides of the composite. Composite materials are not normally suitable for submersion in a bath of water. Allowable article under test size is also limited by the immersion reservoir size, and equipment is more expensive than that used in contact methods.

14.4 *Use of Referenced Documents*

14.4.1 *General:*

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

14.4.2 *Pulse Echo:*

14.4.2.1 Consult Practice E114 for ultrasonic examination of articles under test by the pulse-echo method using straight-beam longitudinal waves introduced by direct contact of the search unit with the material being examined. This practice is applicable to the development of an examination procedure agreed upon by the purchaser (cognizant engineering organization) and the supplier.

14.4.2.2 Consult Practice E214 for procedures for detecting discontinuities in material using instruments that transmit and receive pulsed longitudinal ultrasonic waves introduced into the material to be examined while immersed in or impinged upon by a liquid coupling agent. This practice applies to any material that can conduct sound waves of an appropriate frequency, and can be immersed in a liquid coupling agent for inspection, or can be subject to inspection by the use of a column or stream of the couplant between the search unit and the material being examined.

NOTE 18—Practice E1001 is a complementary document that extends Practice E214 by describing more detailed procedures.

14.4.2.3 Consult Practice E664 for measuring the apparent attenuation of ultrasound in materials or components with flat, parallel surfaces using conventional pulse-echo ultrasonic imperfection or discontinuity detection equipment in which reflected indications are displayed in an A-scan presentation. The measurement procedure is readily adaptable for the determination of relative attenuation between materials. For absolute (true) attenuation measurements, indicative of the intrinsic nature of the material, it is necessary to correct for specimen geometry, sound beam divergence, instrumentation, and procedural effects. These results can be obtained with more specialized ultrasonic equipment and techniques. This practice is concerned with the attenuation of longitudinal wave introduced into an article under test by an immersion method.

14.4.2.4 Consult Practice E1001 for procedures for the ultrasonic examination of bulk materials or parts by transmitting pulsed, longitudinal waves through a liquid couplant into the material and observing the indications of reflected waves. It covers only examinations in which one search unit is used as both transmitter and receiver (pulse-echo) and in which the part or material being examined is totally submerged in the couplant (immersion testing). This practice includes general requirements and procedures that may be used for detecting discontinuities and for making a relative or approximate evaluation of the size of discontinuities. This practice complements Practice E214 by providing more detailed procedures for the selection and calibration of the inspection system and for evaluation of the indications obtained.

14.4.2.5 Consult Guide E1901 for contact ultrasonic examination of bulk materials or parts by transmitting pulsed ultrasonic waves into the material and observing the indications of reflected waves. This guide covers only examinations in which one search unit is used as both transmitter and receiver (pulse-echo). This guide includes general requirements and procedures that may be used for detecting discontinuities, locating depth and distance from a point of reference and for making a relative or approximate evaluation of the size of discontinuities as compared to a reference standard. This guide complements Practice E114 by providing more detailed procedures for the selection and calibration of the inspection system and for evaluation of the indications obtained.

14.4.2.6 Consult Practice E2580 for a description of two procedures for ultrasonic testing (UT) of flat panel composites and flat sandwich core panels (parallel surfaces) (namely, Test Procedure A, Pulse Echo, and Test Procedure B, Through Transmission procedures).

14.4.3 *Through Transmission:*

14.4.3.1 There are no known applicable ASTM standards for through transmission ultrasonic characterization of materials, composite or otherwise. Consult MIL-HDBK-787 for discussions on through transmission ultrasonic characterization of composite materials and components.

14.4.4 *Equipment and Instrumentation:*

14.4.4.1 *Equipment*—Consult Guide E1324 for procedures for measuring the following performance-related characteristics of ultrasonic instruments.

14.4.4.2 *Transducers*—Consult Guide E1065 for evaluating certain characteristics of ultrasonic search units that are used with ultrasonic examination instrumentation. This guide describes means for obtaining performance data that may be used to define the acoustic and electric responses of ultrasonic search units.

14.5 *Geometry and Size Considerations*

14.5.1 Ultrasonic transducers, often called search units, are typically less than 25 mm (1 in.) in diameter. These transducers may have different exit sound characteristics. Thus, when inspecting large objects, it is necessary to scan the object with consideration to the effective sound beam dimension associated with the transducer and the flaw size of interest.

14.5.2 If the article under test is sufficiently thick to resolve successive back reflections, then one can resort to a pulse echo scanning technique utilizing a single transducer. The selection of transducer and pulse receiver can demonstrate significant resolve for thinner structures. If, on the other hand, the article under test is too thin or very attenuating, then one must resort to a through transmission scanning technique utilizing two transducers.

14.5.3 For rounded surfaces, geometry must be considered when using contact pulse-echo methods. For example, reference blocks with flat surfaces may be used for establishing gain settings for examinations on test surfaces with radii of curvature of the order of 10 to 13 cm (4 to 5 in.) or greater. For test surfaces with radii of curvature less than 10 to 13 cm (4 to 5 in.), reference blocks with the same nominal curvature should be used, unless otherwise agreed upon by the purchaser and supplier.

14.5.4 *Examination Surface*—Surfaces should be uniform and free of foreign material which can inhibit the ability to induce adequate acoustic coupling.

14.5.5 *Geometric Similarity*—When comparing the apparent attenuations in different composite materials or components, the articles under test must be geometrically similar, and similar transducers and techniques must be applied. For example: a focused transducer used on a thin laminate with a small diameter sound beam may tolerate curvature differences. On the other hand use of a large sound beam will have greater beam modification with the smaller radii part shapes.

14.6 *Safety and Hazards*

14.6.1 Precautions must be taken to preclude the possibility of electrical shock when performing ultrasonic testing.

14.7 *Calibration and Standardization*

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

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

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

14.8 *Physical Reference Standards*

14.8.1 *Pulse Echo Reference Standards and Blocks*—The article under test itself may be an adequate standard using the back wall echo for reference or through signal amplitude. For more quantitative information, machined artificial reflectors (discontinuities), or charts representing distance-amplitude relationships of known reflectors sizes for a particular search unit and material may be used for standardization. The artificial reflectors may be in the form of foreign materials inserted during lay-up, induced porosity, flat-bottom holes, side drilled holes, or slots. The surface finish of the reference standard should be similar to that of the production item. The reference standard material and production material should be acoustically similar (in velocity and attenuation). The reference standard selected shall be used by the examiner as the basis for signal comparisons.

14.9 *Application of Ultrasonic Techniques*

14.9.1 *Contact Testing:*

14.9.1.1 *Advantages and Applications*—Contact testing is the application of the ultrasonic probe directly on the surface of the material being tested. Often, contact testing involves portable battery-operated, low cost equipment. Quite often this procedure is used to evaluate or verify indications found using through transmission. It can determine depth (ply location) and area or size of the indication. This method is commonly used in the field for damage assessment.

14.9.1.2 *Limitations and Interferences*—Since rough surfaces can scatter and attenuate the sound energy, a reasonably smooth surface is required. Sensitivity is variable depending on surface couplant efficiency. Contact application of just the ultrasonic probe cannot be readily focused to obtain better resolution and sensitivity in the given analysis area (it is

TABLE 16 Summary of Visual Testing

Applications	How It Works	Advantages	Limitations	What Is Seen and Reported?
Used to inspect surfaces for cracks due to fatigue or impact damage, pitting, voids, pores, inclusions, and to evaluate surface finish. Used during the fabrication and manufacturing cycle to ensure product quality. When used in conjunction with mechanically aided measurements, can be used to verify dimensions and tolerances. kjnnUsed during failure analysis, for example, to assess color changes caused by overheating, oxidation, etc. Used during in-service inspection to detect imperfections or discontinuities and monitor growth.	Light patterns reaching the human eye are processed as lines, spots, edges, shadows, colors, orientations and reference locations within the field of view. The visual observation is then compared with long-term memory of previously made observations, and differences due to variations in shape, pattern and color made.	Can yield quantitative data more readily than other NDT procedures. Can be performed without any intervening apparatus. When equipment is required, it is usually inexpensive (for example, mirrors, borescopes and magnifiers).	Insensitive to bulk features and characteristics. Complex structures with recessed or interior surfaces may not be inspectable. Observations are user dependent (due to differences in visual acuity). To standardize results, periodic visual acuity examinations are recommended. Similarly shaped or colored objects or patterns may be hard to differentiate. Color differentiation tends to be more difficult than geometric pattern differentiation. Scanning for multiple defects takes longer than for single defects. The presence of a defect will be easier to ascertain than its absence.	Since a transient visible light image is seen, permanent documentation using film-based or video photography is used extensively. Low magnification film photography is useful for documenting surface discontinuities, while video photography is useful for documenting inaccessible areas, particularly when moving an imaging device into inaccessible areas with the video recorder turned on.

difficult to control the shape and direction of the beam). For such applications a fixed immersion probe would be an improvement. The transducer's wear face or standoff is also subject to wear, thus requiring replacement or wear/shoes in some applications.

14.9.2 *Immersion Testing:*

14.9.2.1 *Advantages and Applications*—Immersion testing which is normally automated allows the energy to be focused or shaped for the article under test, thus increasing resolution and sensitivity. Immersion coupling facilitates inspection of non-uniformly contoured parts and lend itself better to automatic inspection and recording of results. Inspection results are normally saved via the computer and provide images of the inspection.

14.9.2.2 *Limitations and Interferences*—Through transmission requires access to both sides of the composite. Composite materials are not normally suitable for submersion in a bath. Allowable article under test size is also limited by the immersion reservoir size, and equipment is more expensive than that used in contact methods.

15. Visual Testing

15.1 *Referenced Documents*

15.1.1 *ASNT Handbook:*[3]

Nondestructive Testing Handbook, Visual and Optical Testing, Vol. 8

15.2 *General Procedure*

15.2.1 Light patterns reaching the human eye are processed as lines, spots, edges, shadows, colors, orientations and/or reference locations within the field of view. The visual observation is then compared with long-term memory of previously made observations, and differences due to variations in shape, pattern and color made. Visual testing (VT) is often used in conjunction with other NDT procedures (for example, inspecting a composite's surface for the presence of cracks, pits, or voids, before performing more elaborate and costly NDT procedures such as radiography). In many cases, V can be enhanced and extended by the use of mirrors, chemicals, magnifiers, borescopes, illuminating devices, and image processing equipment.

15.3 *Significance and Use*

15.3.1 VT by an experienced inspector is one of the most important yet simple NDT techniques to use. It provides inexpensive, wide field assurance that components meet the manufacturer's criteria and are free from mechanical damage.

15.3.2 VT involves qualitative physical inspection of a composite material or component to detect gross imperfections or discontinuities, but may require confirmation by other destructive or nondestructive means to definitively ensure that the material or component meets engineering drawing requirements and no mechanical damage has occurred.

15.3.3 VT includes but is not limited to examination for cracks, surface breaking delaminations, blisters, depressions, foreign material inclusions, ply distortions, surface finish, broken fibers or wrinkles.

15.3.4 Complete VT may involve review of a material or component's data package to verify proper materials and dimensions are maintained. It may also involve inspection of quality records (impact control plan, certificates of material conformance, etc.) to verify inspection points, required documentation, and to ensure engineering design is maintained. In some instances these data review and dimensional check portions of the inspection are conducted by an inspector assigned to the fabrication work area while the defect screening inspection is performed by a qualified NDT specialist more familiar with defect detection and the other NDT inspection processes, which may be needed to confirm VT inspection results. A qualitative description of any defects (cracks, delaminations, blisters, depressions, foreign material inclusions, ply distortions, surface features, or wrinkles) shall be provided, along with corresponding quantitative details (location, number, size, size distribution). For archival and reference purposes, inspection sheets with photo and or video documentation is recommended. Good documentation procedures should be practiced.

15.3.5 *Advantages and Applications:*

15.3.5.1 This method provides a rapid, wide field survey of a composite structure to ensure design and material compliance. It also ensures that no mechanical damage has occurred to the component. This NDT method shall be complemented with additional NDT to better understand the nature of an indication. For example, visual NDT 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, more precise NDT procedures can be used such as ultrasound for detection of delamination, and radiography for detection of voids and porosity.

15.3.5.2 VT of is performed immediately after manufacturing, usually without the aid of magnification, to ascertain the presence of excessive wrinkles, holes, gaps between adjacent plies, surface voids, cracks, bucking, fiber alignment problems, etc.

15.3.5.3 More elaborate VT may be required that entails looking for resin-rich and resin-starved regions, blisters, or delaminations in exterior plies, surface voids and edge separations. If the matrix is semitransparent, internal voids can be detected by shining a high intensity light through the structure and viewing from a darkened area.

15.3.5.4 VT is often required during in-service inspection, especially for composite materials and components exposed to weather, thermal fluctuations, and impact or handling-induced damage. Delamination, cracking and buckling may occur. Indications may necessitate follow-up NDT using other methods.

15.3.6 *Limitations and Interferences:*

15.3.6.1 Insensitive to bulk features and characteristics. VT method cannot yield information on the depth and extent of the indication. This NDT method should be complemented with additional NDT to better understand the nature of indications. Familiarity with the manufacturing process and damage tolerance must be understood to provide adequate visual test screening.

15.3.6.2 Due to user dependent variations in near and far vision acuity, color vision, depth perception, peripheral vision, and stereoscopic vision, repeatability and reproducibility errors can be significant.

15.4 *Use of Referenced Documents*

15.4.1 For details on personnel qualification, training and certification, consult SNT-TC-1A.

15.4.2 For detailed descriptions of the physiology of sight, visual acuity testing, measurement of light, testing environment, aids and accessories, codes and standards, interfacing of visual NDT with other NDT procedures, consult ASNT Nondestructive Testing Handbook, Vol. 8.

15.5 *Geometry and Size Considerations*

15.5.1 When examining large areas, peripheral vision effects, which can alter contrast and color differentiation as well as depth perception, become more important.

15.6 *Safety and Hazards*

15.6.1 Given the variety of visual tasks and types of illumination used, it is important to consider the possible long-term effects on visual acuity from excessive exposure to light, for example, when high luminance visible light sources are used, or that can also result from using insufficient light sources.

15.7 *Calibration and Standardization*

15.7.1 Since evaluations involving the human eye can be highly variable and subjective, visual inspectors should be certified periodically to ensure a necessary level of natural or corrected visual acuity, especially when visual NDT is performed on composite materials and components used in critical applications. Formal procedures for qualifying visual inspectors can be found in SNT-TC-1A. In general, eye charts are used to measure near and far vision acuity. For example, a Jaeger eye chart placed 40 cm (12 in.) from the eye or eyeglass plane is used in the United States for near vision acuity examinations. Eye charts placed 6 m (20 ft) from the eye or eyeglass plane are used in far vision acuity examinations. More clinically precise visual acuity examinations are also available (for example, color cap charts for assessing color vision acuity0. Both eyes are tested independently.

15.7.2 Personnel performing visual inspections shall be trained and qualified in the field of composite inspection. However, specialized visual inspection training and certification opportunities specific to the inspection of composite materials are not as commonly available as for other applications (for example, visual weld inspection). The employer may need to develop and administer adequate training, applicable to the applications and product being inspected.

15.7.3 Proper posture, control of viewing angle, adequate lighting (the human eye operates optimally under normal daylight illumination) are important considerations that need to be taken into account when performing VT.

15.7.3.1 When inspecting reflective surfaces, the viewing angle should be off normal but not to exceed 45 degrees. When inspecting nonreflective surfaces, the preferred viewing angle should be normal to the inspected surface.

15.7.3.2 Since VT methods involving physical inspection may be highly subjective, repeatability and reproducibility errors must be known and controlled. These errors shall be minimized and controlled through proper training and associated certification programs. To minimize these errors standardized inspection procedures should be implemented. Conveying detailed specific criteria and instructions as well as maintaining a set of sketches, photographs, or actual defective parts containing the size and types of imperfections or discontinuities expected can greatly reduce the subjective variations between inspectors.

15.7.3.3 VT should be performed at 25 to 60 cm (10 to 24 in.).

15.7.3.4 Both human vision acuity and the resolution of electronic imaging equipment systems are greatly reduced as the viewing distance is increased. Lenses or imaging systems that can reduce the viewing focal distance below 25 cm (10 in.) provide the benefit of relative magnification. For example, a borescope lens able to focus at a 6.35 mm (0.25 in.) focal distance provides the equivalent magnification of 20×.

15.7.3.5 As a general rule, it is recommended to match the relative resolution of digital viewing system components.

15.7.3.6 A source of natural or artificial light of adequate intensity and spectral distribution is necessary. For most visual tests, incandescent lighting is recommended. A minimum intensity of 160 lx (15 ftc) should be used for general VT. A minimum of 500 lx (50 ftc) should be used for critical or fine detail testing.

NOTE 19—Incandescent light sources are generally preferred when differentiating lines, spots, edges, shadows, and orientations. Fluorescent lamps, especially those listed at full spectrum, are good for color examinations.

NOTE 20—Oblique lighting should be used to distinguish between protruding or concave surface features.

15.8 *Physical Reference Standards*

15.8.1 Vision acuity charts consisting of black characters or letters on a white matte background, and illuminated by room lighting sufficient to bring the chart background luminance up to 85 ± 5cd m^{-2}, are recommended.

16. Keywords

16.1 acoustic emission (AE); aerospace composites; bubble leak testing; composite shell; computed radiography (CR); computed tomography (CT); digital detector arrays (DDA); digital radiography (DR); fiber reinforced composites; helium leak testing; high modulus fibers; high performance composites; hydrostatic leak testing; image quality indicator (IQI); infrared thermography; leak testing (LT); nondestructive evaluation (NDE); nondestructive inspection (NDI); nondestructive testing (NDT); penetrating radiation; polymeric matrix composites (PMC); pulse-echo; radiographic testing (RT); radioscopy or realtime radiography (RTR); shearography; strain gauges; strain measurement; thermal conductivity leak test; thermal imaging systems; thermography; tomography; ultrasonic testing (UT); visual testing (VT)