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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 ~~structural~~ 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.

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

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1.10 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.*

1.13 *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),~~ 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 *composite shell*—a multilayer filament-winding that comprises a second shell that reinforces the inner shell. The composite shell consists of continuous fibers, impregnated with a matrix material, wound around the inner shell, and cured in place. The number of layers, fiber orientation, and composite shell thickness may vary from point-to-point.~~

3.3.5 *disbond*—see Terminology D3878.

~~3.3.7 *filament wound pressure vessel*—an inner shell over-wrapped with composite layers that form a composite shell. The inner shell or liner may consist of an impervious metallic or nonmetallic material. The vessel may be cylindrical or spherical and will have at least one penetration with valve attachments for introducing and holding pressurized liquids or gases.~~

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.

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

[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.

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 *~~structural~~ 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, 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.

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.

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).

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 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.

TABLE 2 General Overview of Established NDT ~~Methods~~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.

5.6 *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,

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.

criticality (length of data retention), specification change, specification revision and date, software and hardware considerations will also govern how reporting is performed.

TABLE 3 Application Examples of Established NDT ~~Methods~~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 ~~Methods~~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.

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.

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

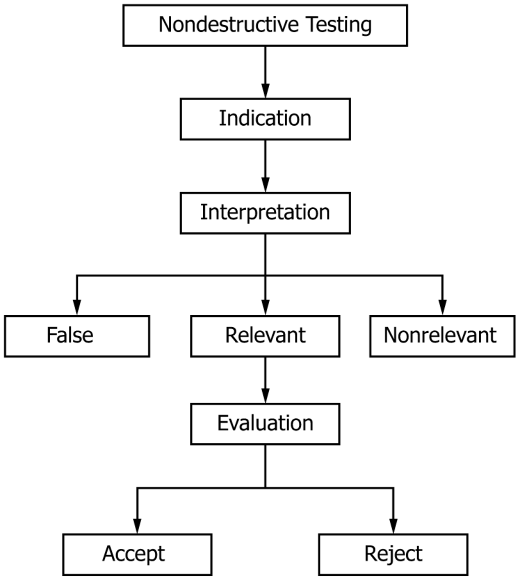

FIG. 1 Consequences of Detecting a Material Discontinuity (Indication) by NDT

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).

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 ~~external~~ 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 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.

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[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.

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 ~~iii)~~*(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 ~~generator.~~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
E1570 Practice for Computed Tomographic (CT) Examination
E1672 Guide for Computed Tomography (CT) System Selection

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.

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). ~~While obtaining~~ Obtaining sufficient contrast is ~~more difficult for flat panel based CT systems, this 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. ~~Further,~~ Furthermore, high-resolution CT reconstruction algorithms require ~~that a full~~ collection of more than 180 degrees of data ~~be collected~~ by the scanner. Object size or opacity limits