Overview of ASTM Standardization Efforts Related to COPVs

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Session I:
Standards, Codes and Regulations (Common Protocols)
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COPV Standards

• No less than half a dozen voluntary consensus organizations (VCOs) are actively involved in promulgation of standards directly and indirectly related to COPVs

• ASTM standards consist of Practices, Test Methods, Guides, Terminology, and Specifications:
  – Practice: tells how to perform a test
  – Test Method: tells how to produce a numerical result, often used as an accept-reject criterion
  – Guide: general instruction and overview
  – Terminology: establishes consistent naming conventions and definitions
  – Specification: establishes uniform material and component properties

• ASTM standards usually focus on a technique, but can focus on material or component type, e.g., a COPV, subject to testing using a variety of techniques
Voluntary Consensus Organization Standards Relevant to COPVs
(non-inclusive list)

1. **AIAA/ANSI**
   - S-080 Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
   - S-081 Space Systems - Composite Overwrapped Pressure Vessels (COPVs)
   - NGV2-2007 American National Standard for Natural Gas Vehicle Containers

2. **ASME**
   - Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels, Appendix 8-620 Supplementary Examination Requirements
   - STP-PT-021 Non Destructive Testing and Evaluation Methods for Composite Hydrogen Tanks
   - STP-PT-023 Guidelines for In-service Inspection of Composite Pressure Vessels

3. **ASTM**
   - D1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases
   - D2585 Test Method for Preparation and Tension Testing of Filament-Wound Pressure Vessels
   - D2990 Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics
   - D3039 Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials
   - D3878 Standard Terminology for Composite Materials
   - D4018 Properties of Continuous Filament Carbon and Graphite Fiber Tows
   - D4762 Guide for Testing Polymer Matrix Composite Materials
   - D5687 Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation
   - D7337 Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars
   - D2343 Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics
   - D3299 Specification for Filament-Wound Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks
   - D5262 Test Method for Evaluating the Unconfined Tension Creep and Creep Rupture Behavior of Geosynthetics
   - D6992 Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method
Voluntary Consensus Organization Standards Relevant to COPVs
(non-inclusive list)

5. ASTM (cont.)
   - 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)
   - E1419 Test Method for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission
   - E1736 Practice for Acousto-Ultrasonic Assessment of Filament-Wound Pressure Vessels
   - E1930 Practice for Examination of Liquid-Filled Atmospheric and Low-Pressure Metal Storage Tanks Using Acoustic Emission
   - E2191 Test Method for Examination of Gas-Filled Filament-Wound Composite Pressure Vessels Using Acoustic Emission
   - E2478 Practice for Determining Damage-Based Design Stress for Glass Fiber Reinforced Plastic (GFRP) Materials Using Acoustic Emission
   - E2533 Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications
   - E2581 Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications
   - E2661 Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications

6. CGA
   - Pamphlet C-6.2, Standard for Visual Inspection and Requalification of Fiber Reinforced High Pressure Cylinders
   - Pamphlet C-6.4, Methods for Visual Inspection of AGA NGV2 Containers

7. ISO
   - 6046 Gas cylinders - Seamless steel gas cylinders - Periodic inspection and testing
   - 10461 Gas cylinders - Seamless aluminium-alloy gas cylinders - Periodic inspection and testing
   - 11119-1 Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 l
   - 11119-2 Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Part 2: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners
   - 14623 Space Systems - Pressure Vessels and Pressurized Structures - Design and Operation
ASTM Committee E07
Flat Panel and COPV Standards
Accomplishments Since 2007

Designation: E 2580 – 07

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

Designation: E 2581 – 07

Standard Practice for
Shearography of Polymer Matrix Composites, Sandwich
Core Materials and Filament-Wound Pressure Vessels in
Aerospace Applications

Designation: E 2582 – 07

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

1 These standards are available from ASTM International.
Accomplishments Since 2007

Designation: E 2662 – 09

Standard Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications

Designation: E 2533 – 09

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

Designation: E2661/E2661M – 10

Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications
Item Registered for COPV Overwrap Standard in 2010

http://www.astm.org/DATABASE.CART/WORKITEMS/WK29034.htm

ASTM WK29034

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

Developed by Subcommittee: E07.10 | Committee E07 Home | Contact Staff Manager

1. Scope

1.1 This Practice discusses nondestructive testing (NDT) methods for detecting flaws, defects, and accumulated damage in filament wound pressure vessels, also known as composite overwrapped pressure vessels (COPVs), used in aerospace applications. In general, these vessels have metal liner thicknesses less than 2.3 mm (0.090 in.), and fiber loadings in the composite overwrap greater than 60 percent by weight. 1.2 Although this Practice focuses on COPVs used at ambient temperature, it also has relevance to 1) composite pressure vessels (CPVs), 2) monolithic metallic pressure vessels, and 3) COPVs and CPVs used at cryogenic temperatures. 1.3 This Practice applies to 1) low pressure COPVs used for storing liquid propellants at maximum allowable working pressures (MAWP) up to 35.
Item Registered for COPV Liner Standard in 2010

http://www.astm.org/DATABASE.CART/WORKITEMS/WK29068.htm

ASTM WK29068
(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

Developed by Subcommittee: E07.10 | Committee E07 Home | Contact Staff Manager

1. Scope

1.1 This Practice discusses nondestructive testing (NDT) methods for detecting defects and flaws in thin-walled metallic pressure vessels (PVs) and composite overwrapped pressure vessels (COPVs) used in aerospace applications. In general, these COPVs have metal liner thicknesses less than 2.3 mm (0.090 in.) and a filament wound composite overlap. 1.2 Although this Practice focuses on PVs and COPVs used at ambient temperature, it also has relevance to a) composite pressure vessels (CPVs), and b) COPVs and CPVs used at cryogenic temperatures. NDT of the composite overlap of COPVs is beyond the scope of this Practice, however, a general overview of applicable NDT methods is provided in Guide E2533. 1.3 This Practice applies primarily to high pressure COPVs used for storing compressed gases.
ASTM E07 Standards for NDE of Composites
2005 to present

Nondestructive Evaluation of Flat Panel Composites:
Standard Practices and Guide

Nondestructive Evaluation of COPVs:

funding for technical oversight provided by the NASA NDE Working Group (NNWG) and ASA Technical Standards Program (NTSP)
Flat Panel Composites

A series of standards on nondestructive inspection and examination of aerospace composites has been developed under the jurisdiction of ASTM International Committee E07 on Nondestructive Testing. Several years ago, with impetus and input from representatives of the U.S. National Aeronautics and Space Administration, a task group on NDE for aerospace composites was formed under Subcommittee E07.10 on Specialized NDT Methods.

The task group, chaired by George Matzkanin from the Texas Research Institute, Austin, was established to foster the development of standards for NDE of aerospace composites. A recently published standard, ASTM E2533, Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications, was developed under the guidance of task group and E07.10 subcommittee member Jess Waller, NASA White Sands Test Facility. This guide helps engineers select appropriate nondestructive testing methods to examine and characterize aerospace composites.

In addition to the guide, several standard practices have been developed and published to document and establish control requirements of current established industry practices so that these standards can be specified in contracts. One such practice is the new standard ASTM E2662, Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications, developed under the guidance of task group member John Ellegood, Lockheed Martin Space Systems Co. This standard was developed under the jurisdiction of Subcommittee E07.01 on Radiology (X and Gamma) Method.

ASTM E2662 provides process control requirements for film and digital radiography of aerospace composite panels. "Using ASTM E2662 will improve accuracy and reliability of radiographic examinations for these low density structures," says Ellegood, a staff quality engineer and Level 3 radiographer. "Often, examinations are not performed at optimal levels due to inadequate experience and lack of requirements."

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ASTM Publicity

"The practical value of E2533 is that the major, accepted nondestructive testing methods are covered in a single document," says Jess Waller, a materials scientist at GeoControl Systems Inc. and a member of E07.10. "Primary users of the standard will be the aerospace industry and its primary contractors in building spacecraft and launch vehicles for present and future NASA programs." This includes all government and industrial entities involved in:

- Product and process design and optimization;
- Online process control;
- After manufacture inspection;
- In-service inspection; and
- Health monitoring of polymer matrix aerospace composites.

Waller notes that E2533 can be used to select an appropriate nondestructive test depending on the type of flaw a user is trying to detect and to provide instruction on where in the life cycle of a composite material or component a particular test can be used. In addition, the advantages and limitations of each of the major nondestructive tests are discussed, with reference to relevant standards.

Digital Imaging and Communication in Nondestructive Evaluation

A new standard developed by Subcommittee E07.11 on Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) will fill a need in the nondestructive testing industry for a transparent and industry standard data format with which to store digital inspection data.

E2663, Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Ultrasonic Test Methods, will be used by manufacturers to develop ultrasonic test equipment that communicates and stores inspection data in a nonproprietary format that will be used for decades.

"Critical national and commercial infrastructure requires long-term data management solutions for inspection data," says Patrick Howard, GE Aviation, who notes that, in the United States, nuclear power plants are typically licensed for 40 years but can obtain an operating extension for an additional 20 years.

"Over such long time periods, inspection equipment is replaced with new models, and equipment vendors may go out of business while the need to access the data acquired with the equipment remains," says Howard. "There is a need to promote interoperability as inspection equipment is modernized to provide long-term data access."

E2663 will serve as a companion standard to E2339, Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE). While E2339 addresses digital data transmission and storage for all nondestructive evaluation modalities, E2663 addresses digital data transmission and storage specific to ultrasonic testing.

Howard also notes that E07.11 is now at work on the following related proposed practices:

- WK17435, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for X-Ray Computed Tomography (CT) Test Methods;
- WK20537, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Eddy Current Test Methods; and
Current POD Activities/Resources

NASA NDE Working group (NNWG, Dr. Edward Generazio)

NASA Engineering and Safety Center (NESC, Dr. William Prosser)
ASTM E07.10 (various)
http://www.astm.org/DATABASE.CART/WORKITEMS/WK29631.htm

**Directed Design of Experiments for Validating Probability of Detection Capability of NDE Systems (DOE POD)**

E. R. Osesma

**Abstract**
The capability of an inspection system is established by applications of various methodologies to determine the probability of detection (POD). One accepted method of attaining inspection system is to find there is a 95% chance that the POD is greater than 95% (POD 95% POD). Directed DOE POD has been developed to provide an efficient and accurate methodology that yields observed POIs and confidence bounds for both hit Hit/Hit or signal amplitude testing. Specifically, DOE POD examines variations of occurrence. Directed DOE POD tests are conducted using existing POD, inspection or similar functions, or fast multi-parameter curve fitting or neural optimization approaches are required.

**Keywords**
Probability of Detection, POD, EPI, EPI, Nondestructive Evaluation

**Introduction**
Directed DOE POD utilizes the concept of probability of a hit (POD) at any flaw size. That is, the number of Hit observed per set of samples exhibiting flaws of similar characteristics (e.g., flaw length). The determination of POD at any selected flaw size is a measured or observed quantitative value between zero and one, and knowledge of POD also yields a quantitative measure of the lower confidence bound (LCB). This process is statistically refereed to as “observation of occurrence” and is distinct from use of functional form that estimate or predict POD. The driving parameters of DOE POD are the observed POD and the lower confidence bounds (LCB) of the observed POD. The binomial distribution has been used previously for determining POD by observation of occurrences. Pagi et al. used a selection of arrangements for grouping flaws of similar characteristics. Yes (1976) used smoothing techniques and grouping data into a class. In and by cumulative sums of fixed flaw size class intervals, while Fannin (1983) used fixed class widths. These binomial approaches have led to the acceptance of using the 79 of 39 (97.92) point estimates method, in combination with validation that the POD is increasing with flaw size, in order to meet the requirements of MESC-STD-1245 and 6990-95. DOE POD extends work in binomial applications for POD by adding the concept of lower confidence bound maximization as the driver for establishing 95% POD. DOE POD satisfies the requirement for critical applications where validation of inspection systems, individual procedures, and operators are required even when a full POD curve is estimated or predicted.

**DOE POD Concepts**
DOE POD is based on the application of the binomial distribution to a set of flaws that have been grouped into classes, where each class has a width. The classes are allowed to vary...
Quick Look at ASTM Standards
Used at WSTF
for Composite Tow and COPV Testing
Long-Term Creep Testing

• AE can be applied using a variety of different pressure profiles, for example, a ramp and hold to evaluate stress rupture§

ASTM D 7337 Stress Rupture (SR) Method
WSTF data on 1140 denier Kevlar-epoxy, 32-mm-gage length, poured Epon 828/DETA tabs

Objective
Plot stress ratio vs. log time to failure to predict when SR will occur at a given operational stress ratio

Composite Tow Tests
COPV Materials-of-Construction

Tabbing: shear strength of epoxy and bonded grip length important variables

\[ L_{\text{min}} = \frac{F_{\text{tu}} h}{2 F_{\text{su}}} \]

where:
- \( L_{\text{min}} \) = minimum required bonded tab length, mm [in.];
- \( F_{\text{tu}} \) = ultimate tensile strength of coupon material, MPa [psi];
- \( h \) = coupon thickness, mm [in.]; and
- \( F_{\text{su}} \) = ultimate shear strength of adhesive, coupon material, or tab material (whichever is lowest), MPa [psi].

Establish typical fiber and composite tow and laminate failure modes

1. explosive failure (XGM)
2. long splitting (SGM)
3. strand pull-out (not pictured)

Possible pressure schedules for analytical testing of COPVs:

Commons goals:

1. manufacturer’s test
2. Periodic removal and inspect requalification
3. simulate in-service pressure schedule
**Accelerated Aging Using Temperature COPVs and Strand**

**ASTM D 6992 Stress Rupture Method**
Used during NNWG-sponsored NDE of COPV SR project conducted on 6.3-in-diameter Kevlar-epoxy and carbon-epoxy COPVs §

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**Procedure**

A. Subject strand specimen to stepped isotherms
B. Monitor creep strain at constant stress
C. Convert creep strain to creep modulus and rescale temperature segments to achieve slope matching versus log time
D & E. Correct for thermal expansion and shift data to yield D) creep modulus, and E) creep strain master curves

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Objective:
Generate strain vs. log time master curve to predict when SR will occur at a given stress level

No ASTM or equivalent standard adopted at the point
**Intermittent Load Hold Testing**  
**COPVs and Strand**

- Intermittent load hold (ILH) stress schedule (red data) is a quick test used to identify severe accumulated composite damage using the Felicity ratio

- ILH profile is based on the pressure tank examination procedure

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**AE event decay rate analysis on load holds using ASME Section X, Appendix 8**

\[ y = Ae^{Bt} + C \]

**Acceptance criteria from ASME Section X Mandatory Appendix 8 and NB10-0601 Supplement 9:**

- Acceptable Event Stability: 
  \[-0.1 < B < -0.0001 \text{ & } R^2 \geq 0.80\]

**Proof Cycling**

COPVs (ASME Test)

\[ y = 184.0e^{-0.002209x} \]

\[ R^2 = 0.975 \]

**Stability Analysis**

- Observed UCL, \(B = -0.0019\)
- Observed LCL, \(B = -0.0030\)
- Passing Test, \(B = -0.002209\)

**Shape factor B can also be expressed as the time required for the structure to emit 99% of events on a dwell.**

\[ t_{99\%} = \frac{\ln(0.01)}{B} \]

25 to 40 minutes (1535 to 2424 sec)

1. ASME Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels, Section X, Appendix 8-620 Supplementary Examination Requirements.