Overview of ASTM Standardization Efforts Related to COPVs

Jess M. Waller
NASA-JSC White Sands Test Facility

Session I:

Standards, Codes and Regulations (Common Protocols)

Composite Conference 2012

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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

D30 Composite Materials
   - 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
   - D2990Test 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

D20 Plastics
   - 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

D35 Geotextiles
   - 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.)

E07 Nondestuctive Testing

- 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[1]

Designation: E 2581 – 07

Standard Practice for
Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for
Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

Accomplishments Since 2007

Designation: E 2662 – 09

Standard Practice for
Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2533 – 09

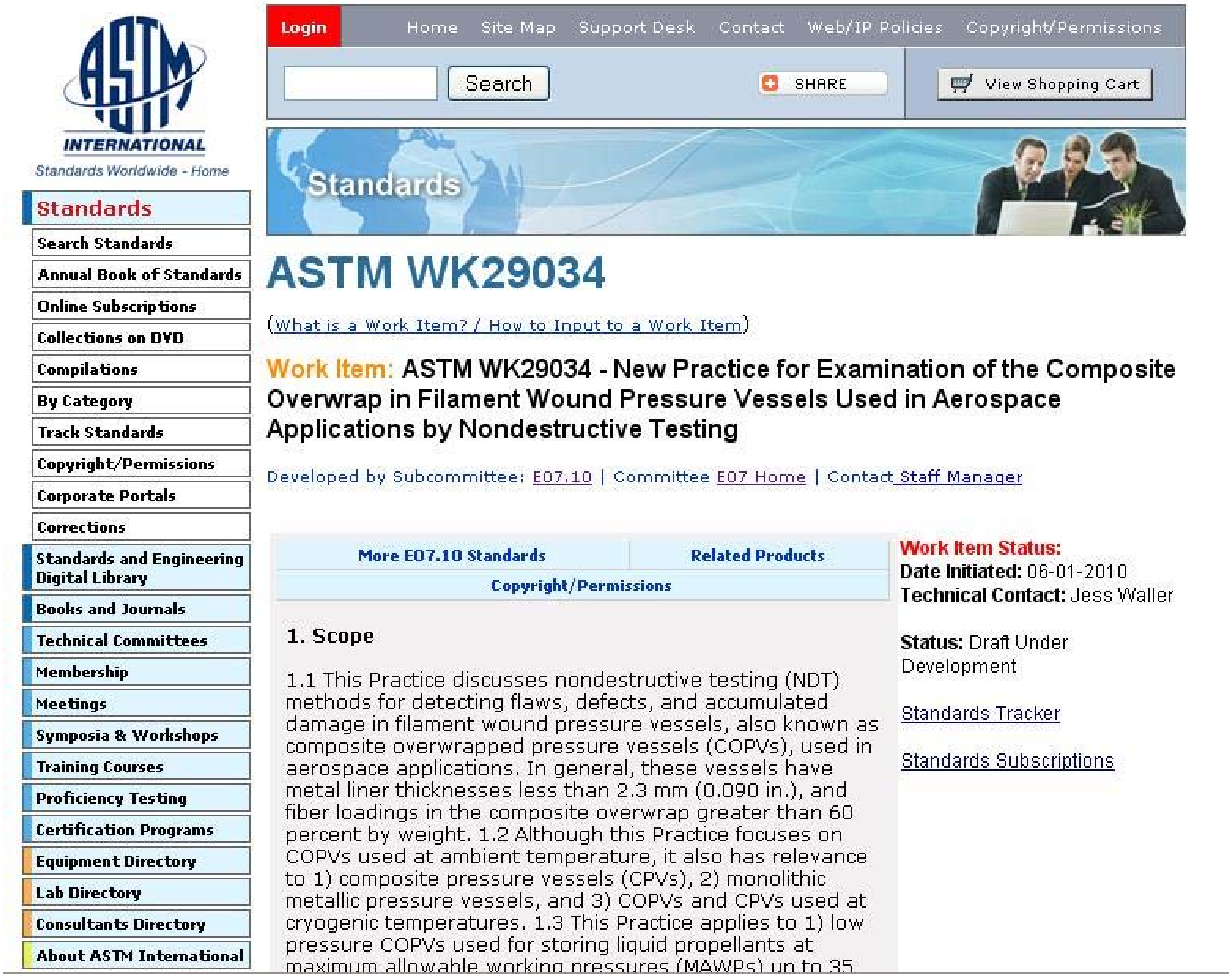
Standard Guide for
Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for
Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

Item Registered for COPV Overwrap Standard in 2010

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



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ASTM WK29034

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

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

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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 (MAWPs) up to 35

Work Item Status:
Date Initiated: 06-01-2010
Technical Contact: Jess Waller

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

Item Registered for COPV Liner Standard in 2010

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

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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

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Work Item Status:
Date Initiated: 06-02-2010
Technical Contact: Jess Waller

Status: Draft Under Development

Standards Tracker

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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 overwrap. 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 overwrap of COPVs is beyond the scope of the 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 §

2005

Flat Panel Composites

2010

2011

COPVs

2012

2013

POD

Metal & Brittle Matrix Composites

Test Methods for Accept-Reject

Designation: E 2533 – 09

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

Designation: E 2580 – 07

Standard Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

Designation: E 2581 – 07

Standard Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2662 – 09

Standard Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

Nondestructive Evaluation of Flat Panel Composites: Standard Practices and Guide

5-year re-approval of E 2580, E 2580 and E 2581

ASTM WK29034

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

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

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

Nondestructive Evaluation of COPVs: Standard Practices, Feasibility of Guide

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

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Flat Panel Composites

NASA White Sands Test Facility technicians perform radiographic inspection on a filament wound pressure vessel.

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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Ellegood, who also serves on the Leadership Committee of the Federal Working Group on Industrial Digital Radiography, says that NASA, the U.S. Department of Defense and manufacturers of aerospace and aircraft structures using lightweight composite panels will be the primary users of ASTM E2662.

Three additional practices developed under the guidance of the task group and published earlier are:

- E2580, Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications;
- E2581, Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications; and
- E2582, Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications.

The task group is now moving forward with the development of proposed guides and practices for the inspection/examination of more complex composite components, such as composite overwrapped pressure vessels. All interested parties, including engineers working in nondestructive testing, materials and aerospace, are welcome to contribute to the ongoing development of these proposed standards.

CONTACT

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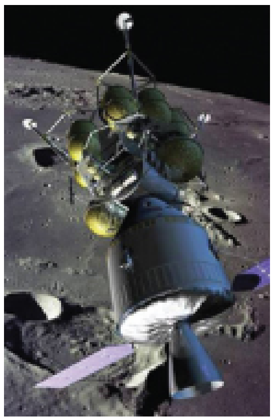

Phased Arrays, Aerospace Applications, Digital Imaging

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ASTM International Committee E07 on Nondestructive Testing has recently approved three new standards on phased arrays, polymer matrix composites for aerospace applications and digital imaging. The committee will be meeting in Plantation, Fla., Jan. 24-28, and welcomes participation in its standards developing activities.

Ultrasonic Methods

Thousands of portable phased array units, used for weld inspections, have now been sold worldwide. There are many benefits to these devices, including speed, cost, imaging, flexibility and setups, along with no radiation, licensing or contamination. Despite these advantages, there was not a universal inspection procedure for phased array inspection of welds. A new standard, E2700, Practice for Contact Ultrasonic Testing of Welds Using Phased Arrays, provides such an inspection test.

E2700 was developed by Subcommittee E07.06 on Ultrasonic Method. According to Michael Moles, senior technology manager, Olympus NDT, and an E07 member, E2700 will be most useful to inspection companies that need to write and follow procedures and to end users and regulators who need to establish practices for the inspection companies.

"E2700 will be very helpful as it covers the relevant aspects for most weld inspections, so details will not be ignored or forgotten," says Moles.

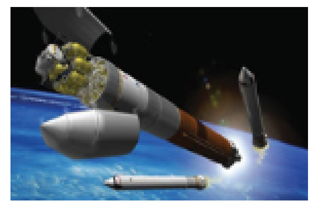
Specialized NDT Methods

A new guide gives an introductory overview that describes how mature and established nondestructive testing methods that are routinely used by industry are applied specifically to the characterization of polymer matrix aerospace composites. E2533, Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications, is under the jurisdiction of Subcommittee E07.10 on Specialized NDT Methods.

"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.



The aerospace industry will use new standards approved by Committee E07 on Nondestructive Testing in the development of future spacecraft.

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;
- WK17436, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Digital Radiographic (DR) 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)

http://www.nnwg.org/Recent Publications/Directed Design.pdf

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 (DOEPOD)

E. R. Generazio[1]

[1]National Aeronautics and Space Administration, Hampton, VA 23681

ABSTRACT. The capability of an inspection system is established by applications of various methodologies to determine the probability of detection (POD). One accepted metric of an adequate inspection system is that there is a 95% chance that the POD is greater than 90% (90/95 POD). Directed DOEPOD has been developed to provide an efficient and accurate methodology that yields observed POD and confidence bounds for both Hit-Miss or signal amplitude testing. Specifically, DOEPOD demands utilization of observance of occurrences. Directed DOEPOD does not assume prescribed POD logarithmic or similar functions, so that multi-parameter curve fitting or model optimization approaches are not required.

Keywords: Probability of Detection, POD, NDE, NDI, NDT, Nondestructive
PACS: 02.50.Cw, 81.70.–q

INTRODUCTION

Directed DOEPOD utilizes the concept of probability of a Hit (POH) at any flaw size. That is, the number of Hits observed per set of samples exhibiting flaws of similar characteristics (e.g., flaw lengths). The determination of POH at any selected flaw size is a measured or observed quantitative value between zero and one, and knowledge of POH also yields a quantitative measure of the lower confidence bound (value). This process is statistically referred to as "observation of occurrences" and is distinct from use of functional forms that estimate or predict POD. The driving parameters of DOEPOD are the observed POH and the lower confidence bounds (values) of the observed POH. The binomial distribution has been used previously for determining POD by observation of occurrences. Prior work[1,2] used a selection of arrangements for grouping flaws of similar characteristics. Yee (1976) used smoothing optimized probability and overlapping sixty point methods grouping by number of flaws into a class and by cumulative sums of fixed flaw size class intervals, while Rummell (1982) used fixed class widths. These binomial approaches have lead to the acceptance of using the 29 out of 29 (29/29) point estimate[1,2,3] method, in combination with validation that the POD is increasing with flaw size, in order to meet the requirements of MSFC-STD-1249[3] and NASA-STD-(I)-5009[4]. DOEPOD extends work in binomial applications for POD by adding the concept of lower confidence bound maximization as the driver for establishing 90/95 POD. DOEPOD satisfies the requirement for critical applications where validation of inspection systems, individual procedures, and operators are required even when a full POD curve[5] is estimated or predicted.

DOEPOD CONCEPTS

DOEPOD 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

ASTM WK29631

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

Work Item: ASTM WK29631 - New Practice for Probability of Detection Analysis for Manual Inspection Hit/Miss Data

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1. Scope

This practice defines the accepted procedure for performing a statistical analysis on manual inspection hit/miss data to determine the demonstrated probability of detection (POD) for a specific set of test parameters. Topics covered include the standard hit/miss POD curve formulation, validation techniques, and correct interpretation of results. Currently there is no specification that addresses this subject. The Air Force has released a Handbook with guidelines on how to fabricate POD specimens and conduct/analyze POD studies using hm1823 POD software. The Handbook is not a requirements document and does not describe the general procedure for analyzing manual inspection hit/miss data and verifying the results for correctness regardless of the software being used to perform the analysis.

Keywords

Penetrant inspection, binary response, logistic regression

Work Item Status:
Date Initiated:07-13-2010
Technical Contact: Steve James

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

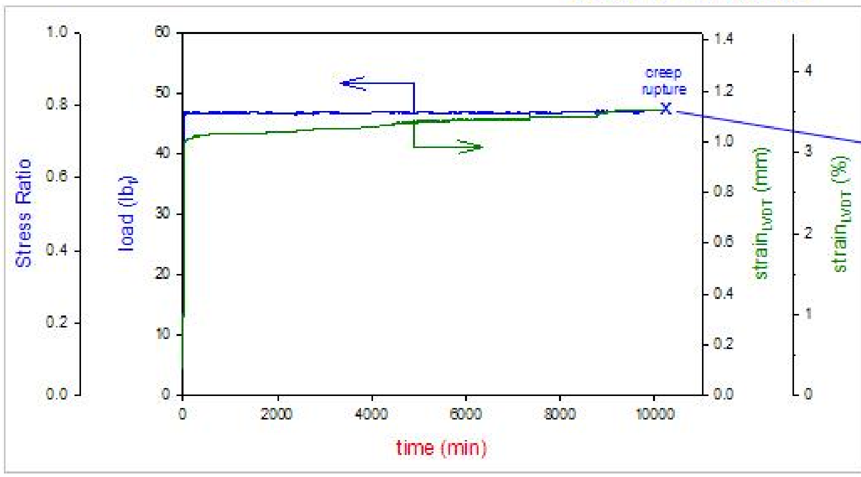
Quick Look at ASTM Standards Used at WSTF for Composite Tow and COPV Testing

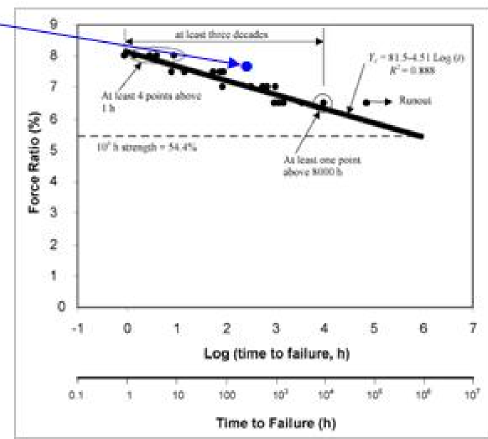
Long-Term Creep Testing

- 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

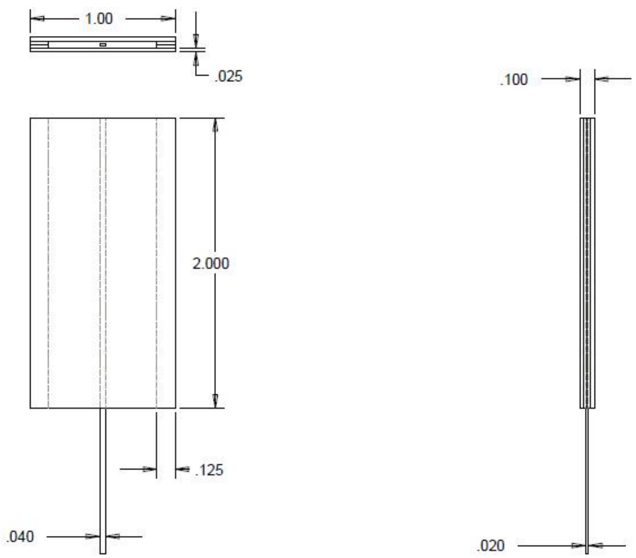
Plot stress ratio vs. log time to failure to predict when SR will occur at a given operational stress ratio

§ ASTM D 3039, Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials, American Society for Testing and Materials, West Conshohocken, PA (2007)

Composite Tow Tests

COPV Materials-of-Construction

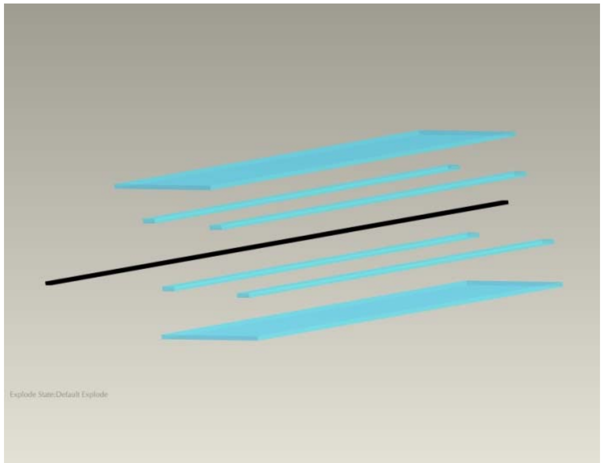
Tabbing: shear strength of epoxy and bonded grip length important variables[§]

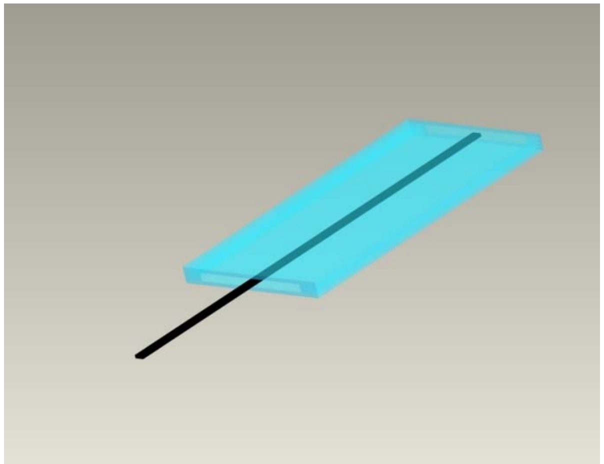


$$L_{min} = F^{tu}h/2F^{su}$$

where:

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



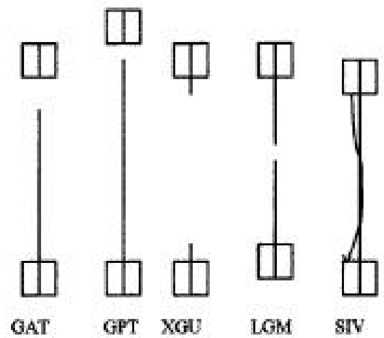


§ ASTM D 2343, *Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics*, American Society for Testing and Materials, West Conshohocken, PA (2009)
ASTM D 3039, *Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials*, American Society for Testing and Materials, West Conshohocken, PA (2008)

Fiber Composite Tow Tensile Tests
COPV Materials-of-Construction

Establish typical fiber and composite tow and laminate failure modes§

ASTM D 4018

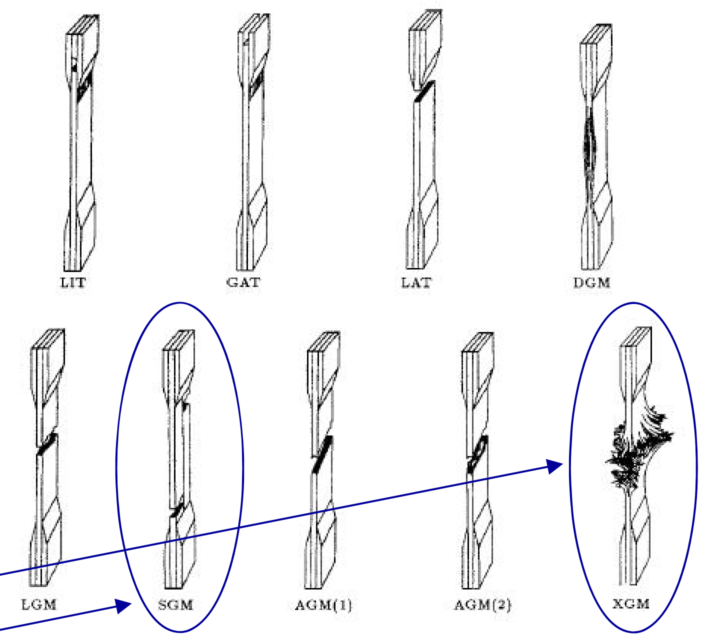


First Character		Second Character		Third Character	
Failure Type	Code	Failure Area	Code	Failure Location	Code
Grip/tab	G	Inside Grip/Tab	I	Bottom	B
Lateral	L	At grip/tab	A	Top	T
Long Splitting (fiber pullout)	S	<1W from grip/tab	W	Middle	M
EXplosive	X	Tab Pullout	P	Various	V
Other	O	Various	V	Unknown	U
		Unknown	U		

FIG. 1 Three-Part Failure Mode Code

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

ASTM D 3039



First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xyz)
long. Splitting	S
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

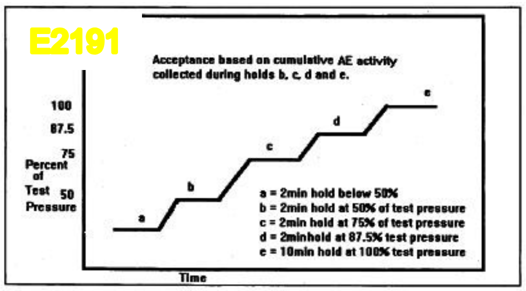
§ ASTM D 4018: *Properties of Continuous Filament Carbon and Graphite Fiber Tows*, American Society for Testing and Materials, West Conshohocken, PA (2009)

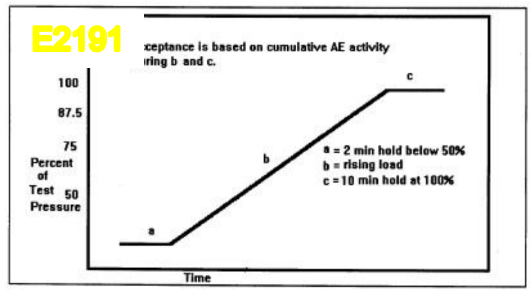
ASTM D 3039, *Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials*, American Society for Testing and Materials, West Conshohocken, PA (2008)

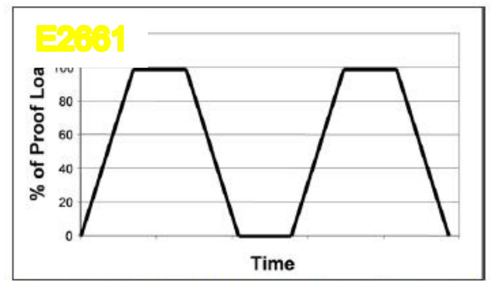
Pressure Schedules

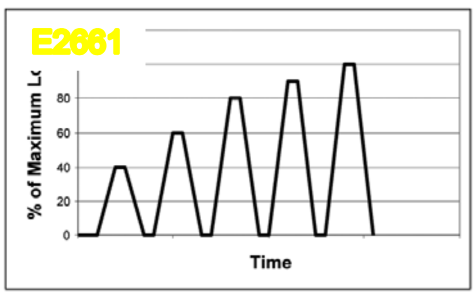
Depends on COPV Application

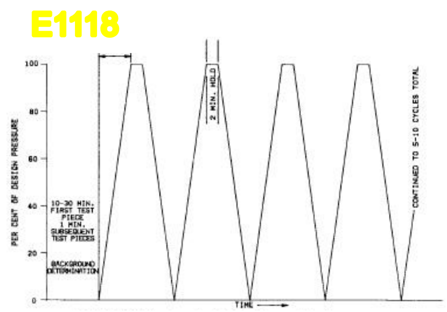
Possible pressure schedules for analytical testing of COPVs:

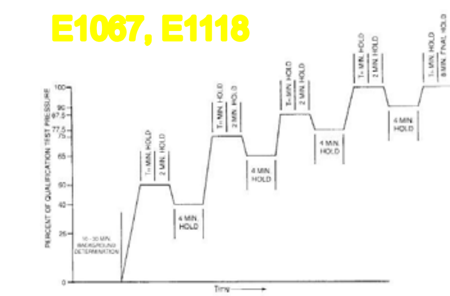


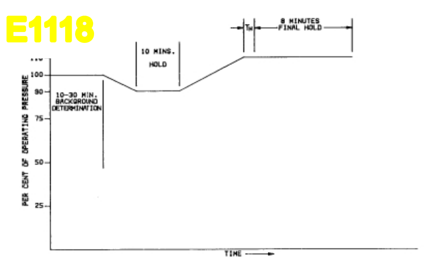












NOTE 1—Diameter to thickness ratio (d/t) ≥ 16, T_H = 2 min. Diameter to thickness ratio (d/t) < 16, T_H = 4 min.

FIG. 7 RTRP System In-Service Test, Option I, Pressurizing Sequence

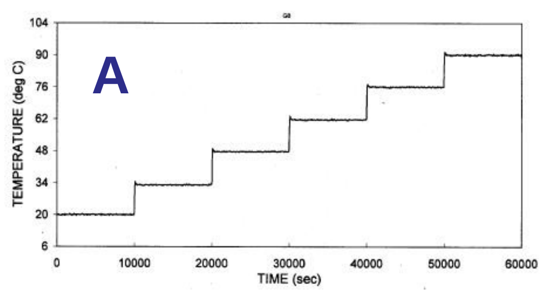
Commons goals:

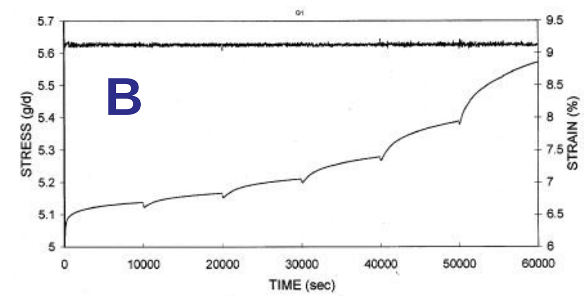
1. manufacturer's test
2. Periodic removal and inspect requalification
3. simulate in-service pressure schedule

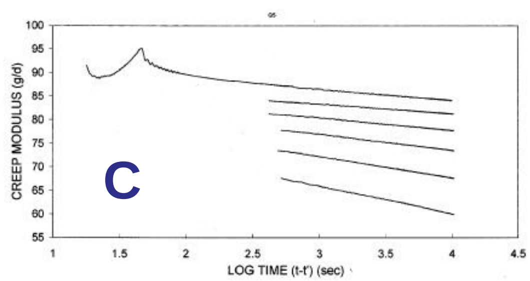
Accelerated Aging Using Temperature
COPVs and Strand

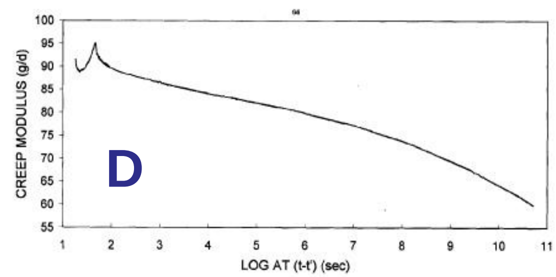
ASTM D 6992 Stress Rupture Method

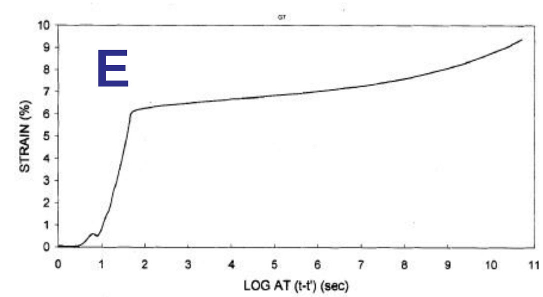
Used during NNWG-sponsored NDE of COPV SR project conducted on 6.3-in-diameter Kevlar-epoxy and carbon-epoxy COPVs §











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

§ ASTM D 6992, *Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method*, American Society for Testing and Materials, West Conshohocken, PA (2008)

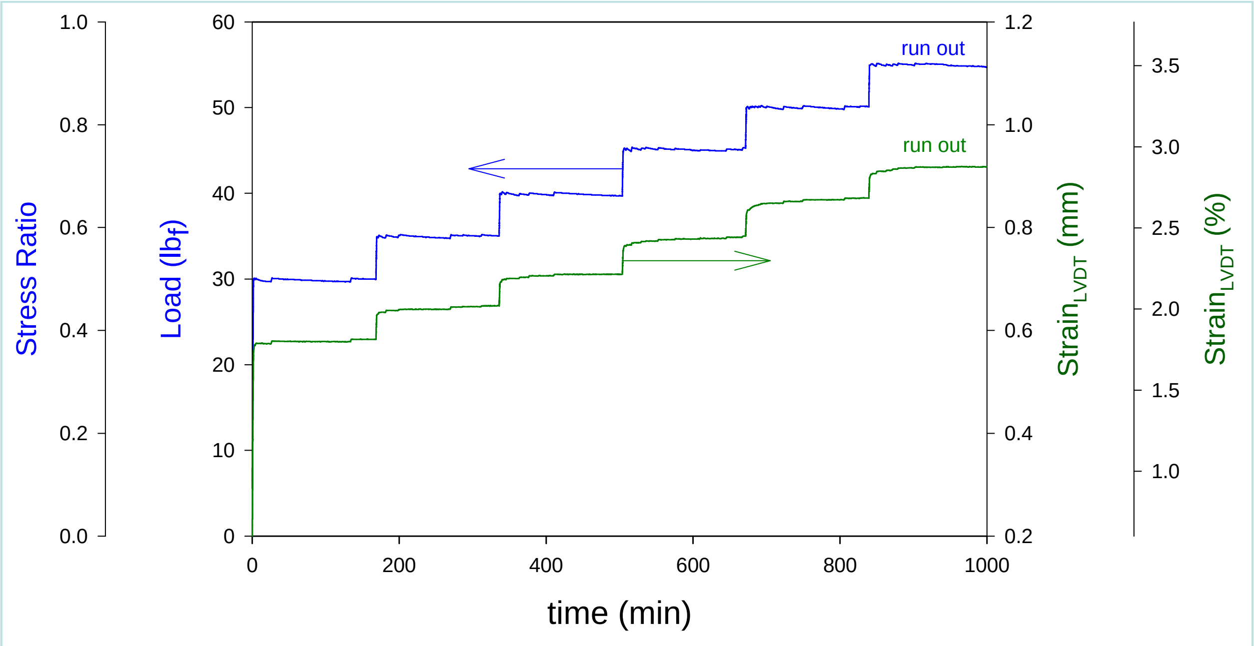
Accelerated Aging Using Stress

COPVs and Strand

Stepped Stress Method (SSM):

1140 denier ATK Kevlar 49/epoxy strand

32-mm gage length, poured Epon 828 tabs



Objective:

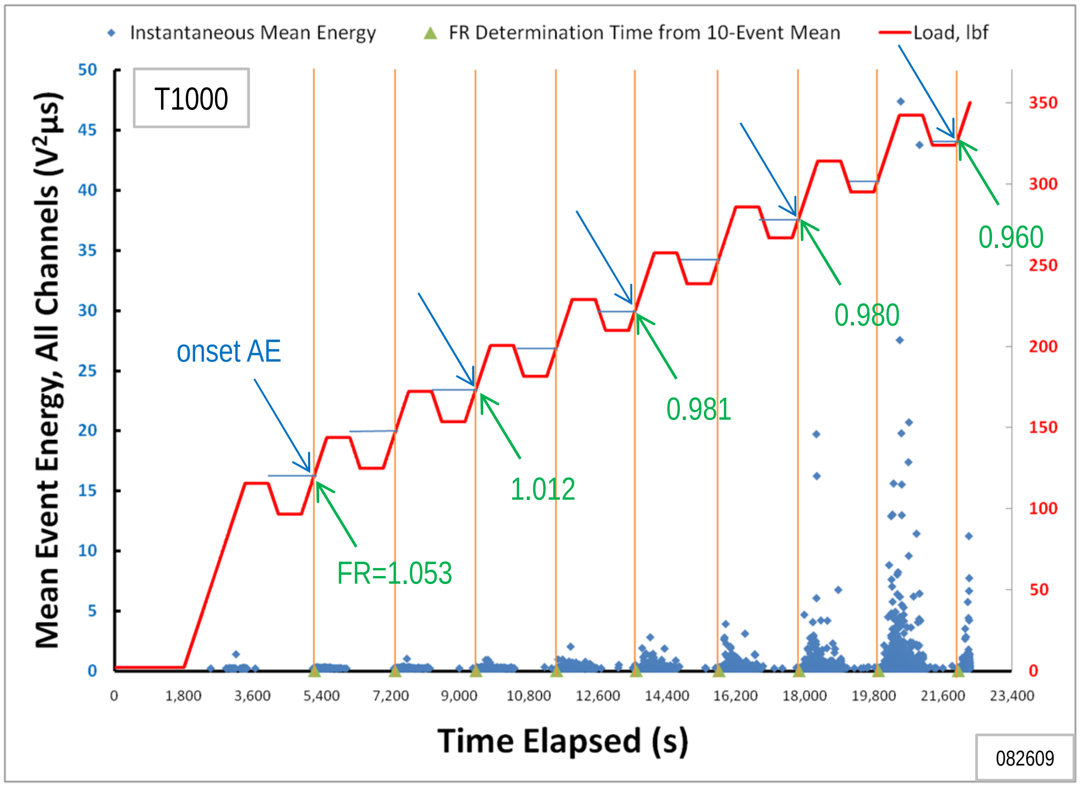
Generate strain vs. log time master curve to predict when SR will occur at a given stress level

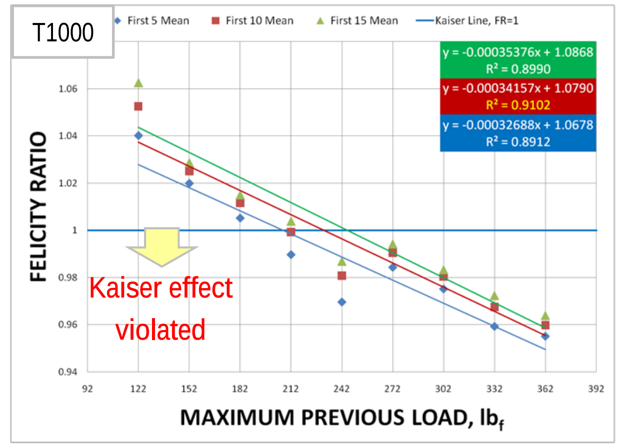
No ASTM or equivalent standard adopted at the point

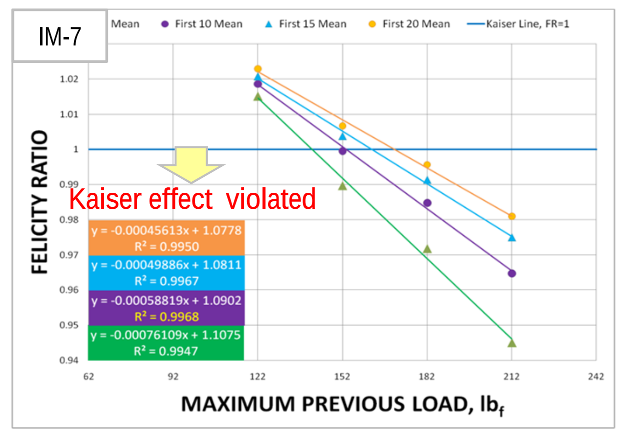
Intermittent Load Hold Testing

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§

§ ASTM, *Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels*, E 1067, American Society for Testing and Materials, West Conshohocken, PA, 19428-2959, 2001.

Proof Cycling

COPVs (ASME Test)

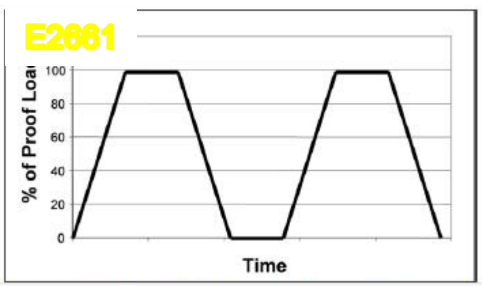
AE event decay rate analysis on load holds using ASME Section X, Appendix 8[1]

$$y = Ae^{Bt} + C$$

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

Acceptable Event Stability:

$-0.1 < B < -0.0001$ & $R^2 \geq 0.80$

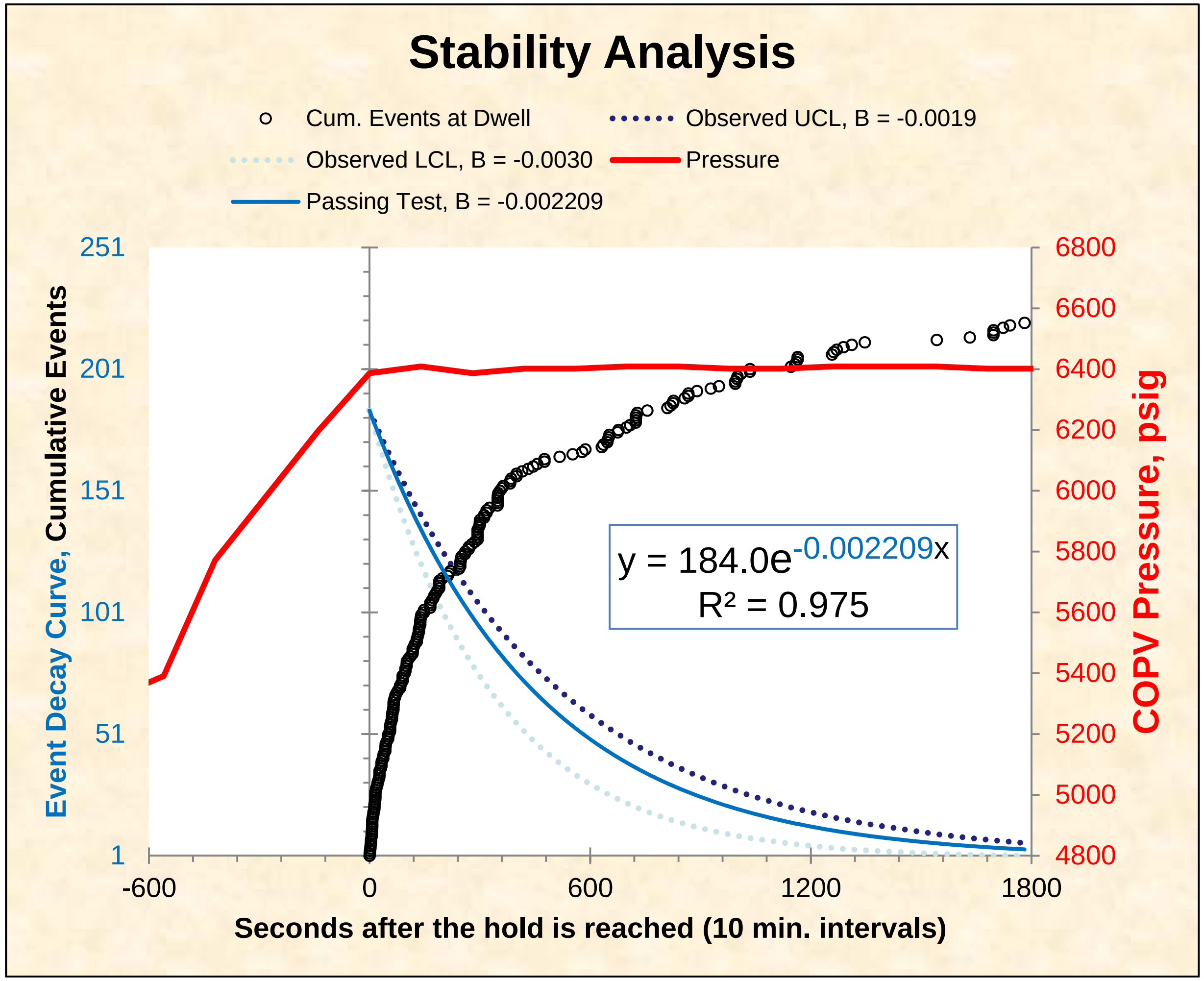


Shape factor B can also be expressed as the time required for the structure to emit 99% of events on a dwell.

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

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.*