Development of Standards for Nondestructive Evaluation of COPVs Used in Aerospace Applications

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NASA-JSC White Sands Test Facility

Session 2:

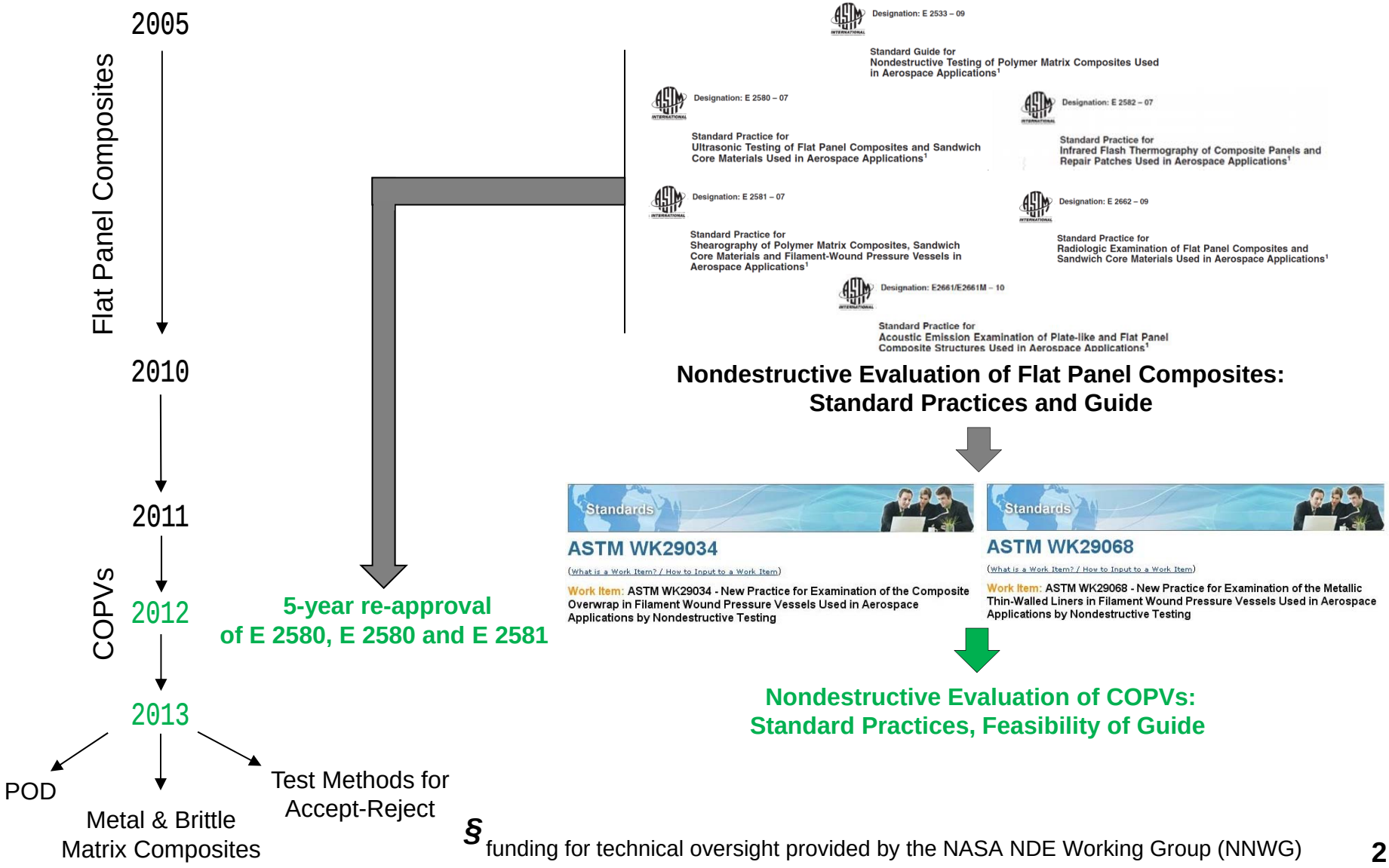
Non-Destructive Evaluation (Health Monitoring)

Composite Conference 2012

Las Cruces, NM

Tuesday, August 14, 2012

ASTM E07 Standards for NDE of Composites
2005 to present §



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

NDE of COPV Issues

- COPVs are currently accepted by NASA based on design and qualification requirements and generally not verified by NDE for the following reasons:
  - Manufactures and end users generally do not have experience and validated quantitative methods of detecting flaws and defects of concern
    - If detected, the flaws are not adequately quantified and it is unclear how they may contribute to degradation in mechanical response
    - Carbon-epoxy COPVs also extremely sensitive to impact damage and impacts may be below the visible detection threshold
      - If damage is detected, this generally results in rejection since the effect on mechanical response is generally not known
- NDE response has not generally been fully characterized, probability of detection (POD) established, and processes validated for evaluation of vessel condition as manufactured and delivered.

COPV Issues (con't)

COPVs demonstrate a large amount of variability in burst pressure and stress rupture progression rate (Weibull statistics)

- NDE processes need to be integrated into manufacturing to reduce variability (by detecting out-of-family behavior) and improve quality
- NDE can often be applied at each major step from fabrication through qualification by targeting the following areas of concern:
  - Crack and grain boundary issues during liner spinning
  - Weld flaws after welding
  - Bridging during winding
  - Liner to composite adhesive disbond from CTE mismatch during cure
  - Composite weak areas from poor wetting or outgassing during cure
  - Growth of pre-existing flaws during autofrettage
  - Creation of new flaws during autofrettage
  - Excessive fiber breakage during autofrettage
  - Stress/strain distribution between liner/overwrap after autofrettage
  - Liner deformation and buckling issues after autofrettage

NDE of COPV Standard Considerations

- The new Standards can have either a manufacturing or end-user bias; NDE prerogatives will differ for each:
  - need to inspect liner before wrapping or after autofrettage places responsibility on COPV manufacturers
  - need to periodically inspect liner during service places responsibility on end user
- In other words, the NDE procedures described can focus on any one of the following areas during the life cycle of the COPV:
  - *(a)* product and process design and optimization
  - *(b)* on-line process control
  - *(c)* after manufacture inspection
  - *(d)* in-service inspection
  - *(e)* health monitoring

Current & Future COPV Manufacturer NDE

- **Used during:**
  - (a) product and process design and optimization
  - (b) on-line process control
  - (c) after manufacture inspection
- **Penetrant Testing (PT)**
  - ATK: the manufacturer of the MSL Cruise-Stage Propellant tank, had previously developed an "*Enhanced Special Penetrant Inspection Process*" (PSI 90-000141)
  - GD: PT done before welding
- **Radiography (RT)**
  - Weld inspection (welded liners and PVs only)
  - Pre- & post-proof (autofrettage)
    - Tangential x-ray (buckling)
- **Phased Array Ultrasound (UT)**
  - ATK: used to detect delamination, FOD and bondline defects
  - Need to consider incorporating procedure into WK29034
- **Helium Leak Test (LT)**
- **Visual Inspection (VI)**
- **Acoustic Emission (AE), Eddy Current Testing (ET) and Laser Profilometry (LP) all show promise and/or are being implemented**

WK 29068 Background
Special NDE

- NASA-STD-5009 *Nondestructive Evaluation Requirements for Fracture Critical Metallic Components*
  - If Standard NDE requirements cannot be met, or smaller cracks or crack-like flaws than those shown in Table 1 or 2 have to be detected, then the inspection processes shall be considered Special NDE; and the following requirements shall apply:
    - A 90/95 percent flaw detection capability shall be demonstrated before a Special NDE inspection can be implemented
    - The Special NDE crack size can be any demonstrated size
- What are the critical flaw sizes for COPV metal liners having thicknesses from 2.3 mm (0.090 in.) down to 0.3 mm (0.010 in.), and the effective POD at that flaw size?
- For COPV composite overwraps and the overwrap/liner interface (WK29034), what are the critical flaw types?
  - delamination
  - porosity
  - bondline separation
  - bridging (welded liners only)

Current and Considered Peer Review

- NASA
  - GSFC (Parker)
  - JPL (Grimes-Ledesma, Lewis)
  - JSC (**Castner**, Koshti)
  - KSC (Hamilton, Russell)
  - LaRC (Burke, Madaras, Prosser, **Wincheski**)
  - MSFC (Russell, Suits, Walker)
  - WSTF (**Saulsberry, Spencer, Waller, Yoder**)
- Other Government
  - USAF (Voeller, Carreon)
  - NIST (McColskey, Fekete)
  - DOT (**Toughiry**)
  - FAA (Broz)
- COPV Manufacturers
  - ATK (Deemer, Papulak, Thompson)
  - General Dynamics (Heckman)
  - Lincoln Composites (**Newhouse**)
- Academia
  - University of Denver (Hamstad)
- Commercial Aerospace
  - Aerospace Corp. (Kenderian, Chang)
  - Boeing (**Engel**)
  - Honeywell (Singh)
  - Lockheed (Nightengale, Rownd)
  - Pratt & Whitney/UTC (**James**)
  - Space X (Lavoie)
- NDE Equipment Manufacturers, Test Labs and Consultants
  - A-Scan Labs (**Collingwood**)
  - Assoc. of Engineers & Architects of Israel (**Muravin**)
  - DigitalWave (Gorman)
  - Jentek Sensors (**Washabaugh**)
  - MAST, Inc. (**Djordjevic**)
  - Mistras/PAC (Carlos)
  - LTI (**Newman**)
- Standards Development Orgs.
  - AIAA (Hamilton)
  - ASME (Koehr)

NASA New Project Starts for FY12-13

- FY12-13 Funding Approved

- Submit ready-for-review drafts to ASTM E07.10 in February 2012

NNWG New Project Start

FY12-13 Schedule/Milestones

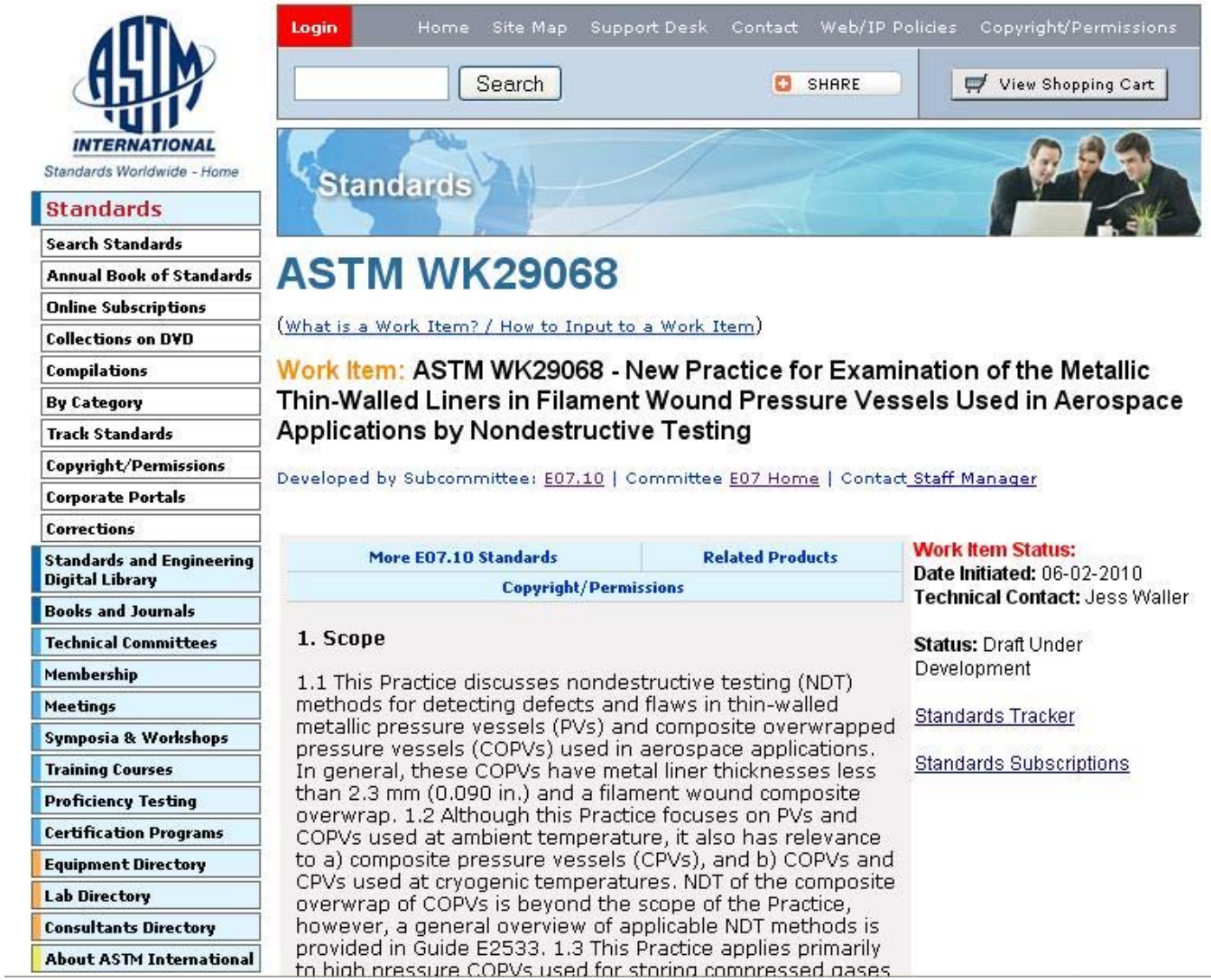
Milestone	Description	Milestone Date
1	a) Status ASTM E07 and technical writing teams on draft progress b) Initiate 5-year re-approval cycle for E2580-07, E2581-07 and E2582-07 c) Establish feasibility of new Standards for NDE of composites	1/2012
2	Submit WK29034 and WK29068 to ASTM for 1st round of balloting	2/2012 5/2012
3	Status ASTM E07 and technical writing teams on balloting progress	6/2012
4	a) Submit WK29034 and WK29068 to ASTM for 2nd round of balloting b) Re-approval *with* change: POCs begin revision or submit of E2580, E2581 and E2582 for first round of balloting	10/2012
5	a) Status ASTM E07 and technical writing teams on balloting progress b) Status NNWG on FY12/current accomplishments c) Propose NNWG FY14-on effort (if needed)	1/2013
6	Respond to Spring balloting call as needed, submit WK29034 and WK29068 to ASTM for 3rd round of balloting (S/C or main)	3/2012
7	Status ASTM E07 and technical writing teams on balloting progress, resolve any negatives	6/2013
8	Submit WK29034 and WK29068 to ASTM for 4th round of balloting (main)	7/2013
9	a) Secure formal adoption by ASTM of 2 Standards on NDE of COPVs b) Obtain re-approval of E2580-12, E2581-12 and E2582-12	9/2013
10	Disband E07.10 TG on NDE of Aerospace Composites, or define carry-on effort for FY14 onwards	12/2013

WK 29068

Standard Practices for Nondestructive Evaluation of Thin-Walled Metallic Liners in Filament Wound Pressure Vessels Used in Aerospace Applications

Item Registered

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



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Standards

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

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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

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

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

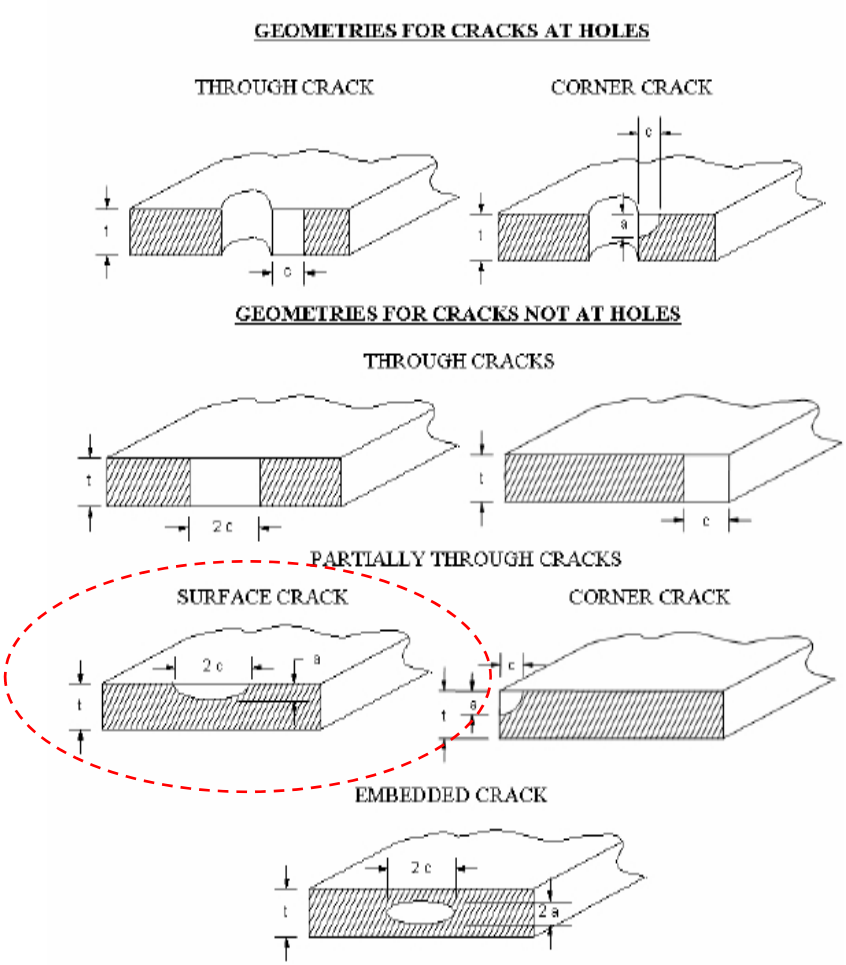
WK 29068 Background
Standard NDE and POD

The new ASTM Standard for NDE of COPV Liners operates under the backdrop of NASA NDE requirements documents

- NASA-STD-5009 *Nondestructive Evaluation Requirements for Fracture Critical Metallic Components*
  - Rely on NDE to ensure significant crack-like flaws are not present in critical areas
  - NDE shall detect the initial crack sizes used in the damage tolerance fracture analyses with a capability of 90/95 (90 % POD at a 95 % confidence level)
  - Standard NDE methods shall be limited to:
    - ET:
      SAE-ARP-4402 or SAE-AS-4787 or NASA-approved internal specs
    - PT:
      ASTM E1417 Level IV sensitivity, SAE-AMS-2647 or NASA-approved internal specs
    - RT:
      ASTM E1742 or NASA-approved internal specs
      minimum sensitivity shall be 2-1T
      film density shall be 2.5 to 4.0
      beam axis within +/-5 degrees of crack plane orientation
    - UT:
      ASTM E2375 or NASA-approved internal specs
  - No reference in NASA documentation for Laser Profilometry (LP) or Leak Testing (LT) - unique to WK29068 and supporting ASTM documents

WK 29068 Background
Standard NDE and POD

For COPV liners, interested in detection of partially through surface cracks



Also, need exists to detect/monitor liner buckling and other defects for which accept-reject exist or is prudent

WK 29068 Background
Standard NDE and POD

Per NASA-STD-5009, for standard NDE, 90/95 POD needs to be established for the following minimum detectable crack sizes:

U. S. CUSTOMARY UNITS (inches)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a*	Crack Dimension, c*
Eddy Current NDE				
Open Surface	t ≤ 0.050 t > 0.050	Through PTC[1]	t 0.020 0.050	0.050 0.100 0.050
Edge or Hole	t ≤ 0.075 t > 0.075	Through Corner	t 0.075	0.100 0.075
Penetrant NDE				
Open Surface	t ≤ 0.050 0.050<t <0.075 t > 0.075	Through Through PTC	t t 0.025 0.075	0.100 0.150 - t 0.125 0.075
Edge or Hole	t ≤ 0.100 t > 0.100	Through Corner	t 0.100	0.150 0.150
Magnetic Particle NDE				
Open Surface	t ≤ 0.075 t > 0.075	Through PTC	t 0.038 0.075	0.125 0.188 0.125
Edge or Hole	t ≤ 0.075 t > 0.075	Through Corner	t 0.075	0.250 0.250
Radiographic NDE				
Open Surface	t ≤0.107 t > 0.107	PTC PTC Embedded	0.7t 0.7t 2a=0.7t	0.075 0.7t 0.7t
Ultrasonic NDE Comparable to a Class A Quality Level (ASTM-E-2375)				
Open Surface	t ≥ 0.100	PTC Embedded**	0.030 0.065 0.017 0.039	0.150 0.065 0.087 0.039

[1] PTC - Partly through crack (Surface Crack)
* See figure 1 for definitions of "a" and "c" for different geometries.
** Equivalent area is acceptable, ASTM-E-2375 Class A.

lacks sensitivity for COPVs

Background

Need for Quantitative NDE of COPVs

- Identify current best practice that is able to detect flaw sizes lower than attainable using Standard NDE methods, i.e., focus is on 'Special' NDE methods

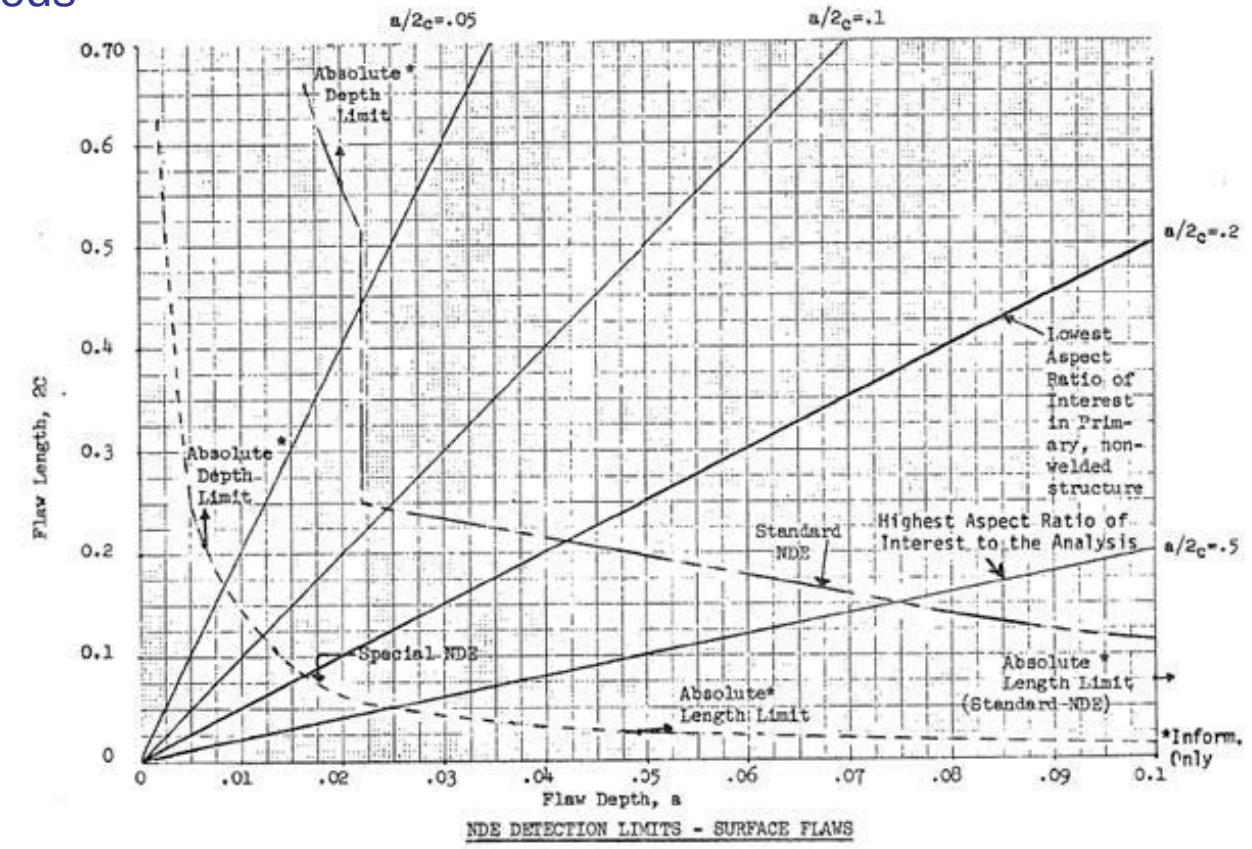
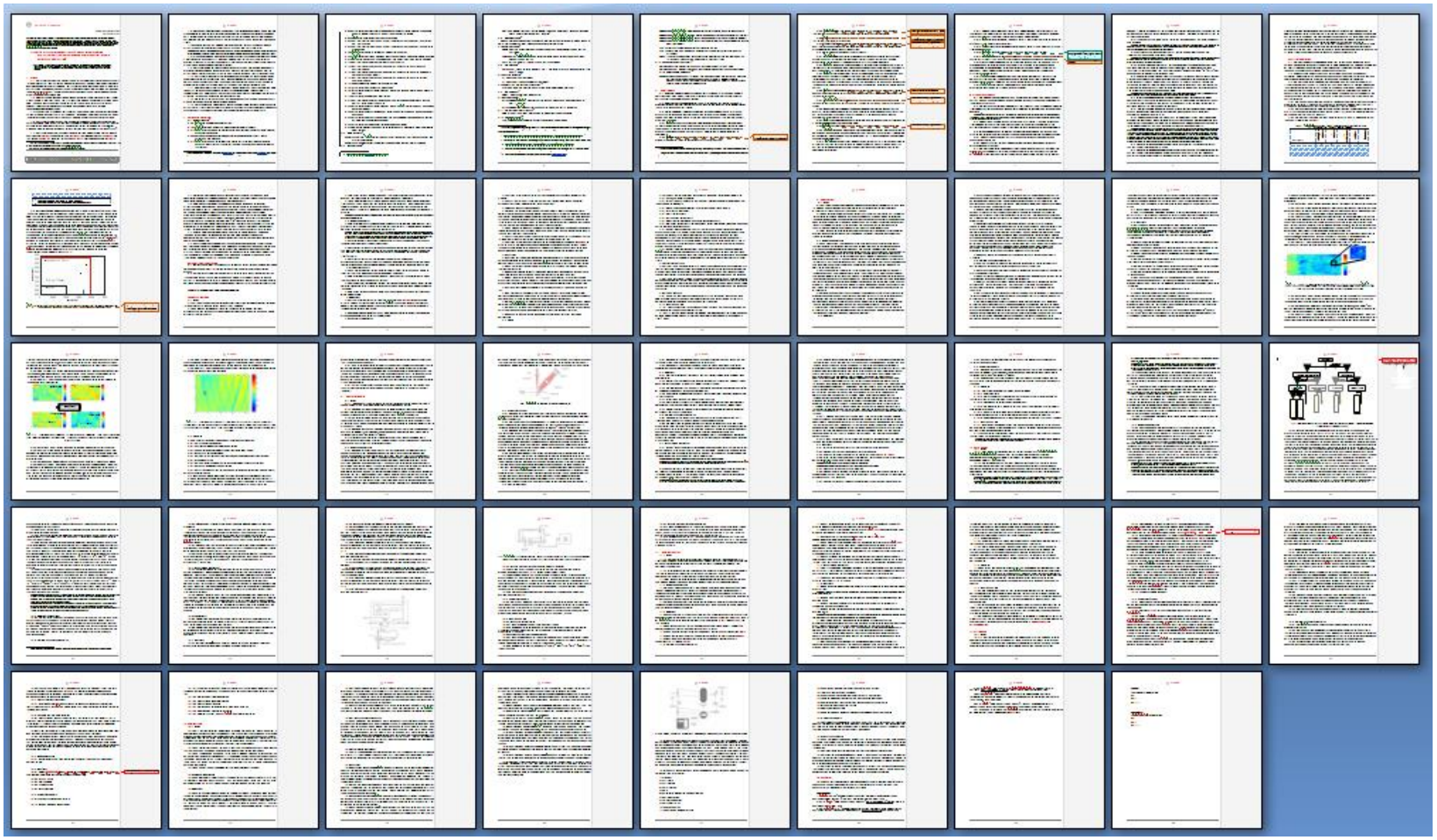


Figure 5.0-1. Orbiter Fracture Control Program NDE Detection Limits

Candidate NDE Methods for COPV Liners

- A-List: Standard NDE performed at 90% POD at 95% confidence level (90/95), but need more detail for Special NDE methods
  - eddy current (ET)
  - penetrant testing (PT)
  - radiography (RT) (e.g., weld inspection)
  - ultrasound (UT) (lamb wave, phased array, and/or pulse-echo)
- A-List, POD not applicable or not performed
  - laser profilometry (detect pitting, buckling, radius & thickness changes)
  - leak testing (LT) (detect through cracks)
- B-List: Supplemental:
  - acoustic emission (AE) (COPVs before wrapping & PVs)
  - visual inspection (VT)
    - Borescopy (superseded by laser profilometry)

WK 29068 COPV Liner Draft Exists



- Contains procedural NDE detail for AE, ET, LT, Profilometry, PT and RT
- Underwent administrative ASTM balloting in February
- In NASA review currently (NESC)

WK 20968 Liner Writing Teams

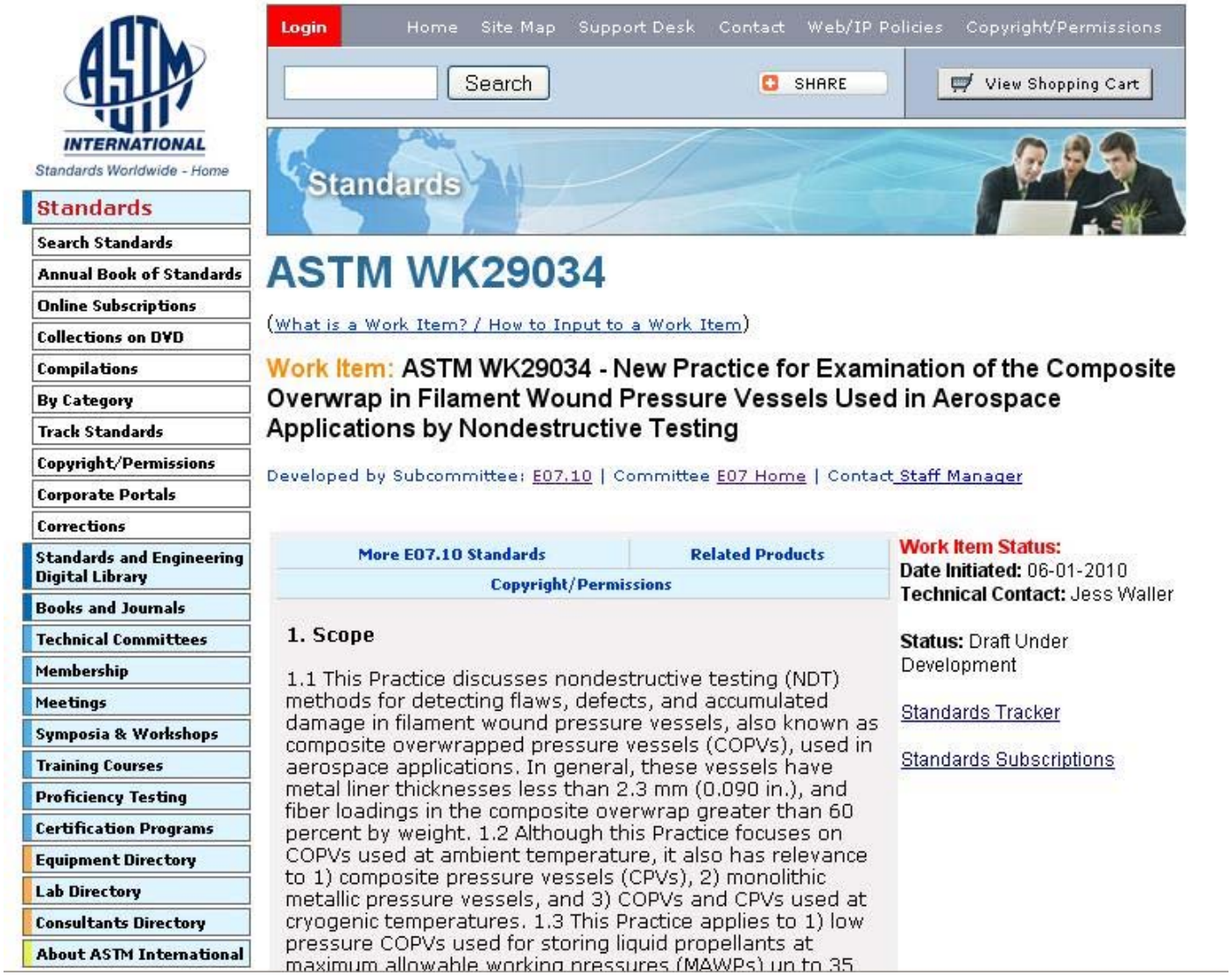
- Acoustic Emission: Muravin
  - Carlos (E07.04 liaison)
  - New section completed since June 2011 Anaheim meeting
  - Newhouse added to team
    - AE protocol currently in ASME Section X , Apppendix 8
- Eddy Current: Wincheski
  - Washabaugh (E07.07 liaison)
- Penetrant Testing: Castner
  - Collingwood (E07.03 liaison)
- Radiography: Engel (interim lead)
  - Kropas-Hughes (E07.01 liaison)
- Leak Testing: Waller (interim lead)
  - Anderson (E07.08 liaison)
- Laser Profilometry: Saulsberry
  - Clausing (E07.10 liaison)
- Ultrasound: James
  - Ruddy (E07.06 liaison)

WK 29034

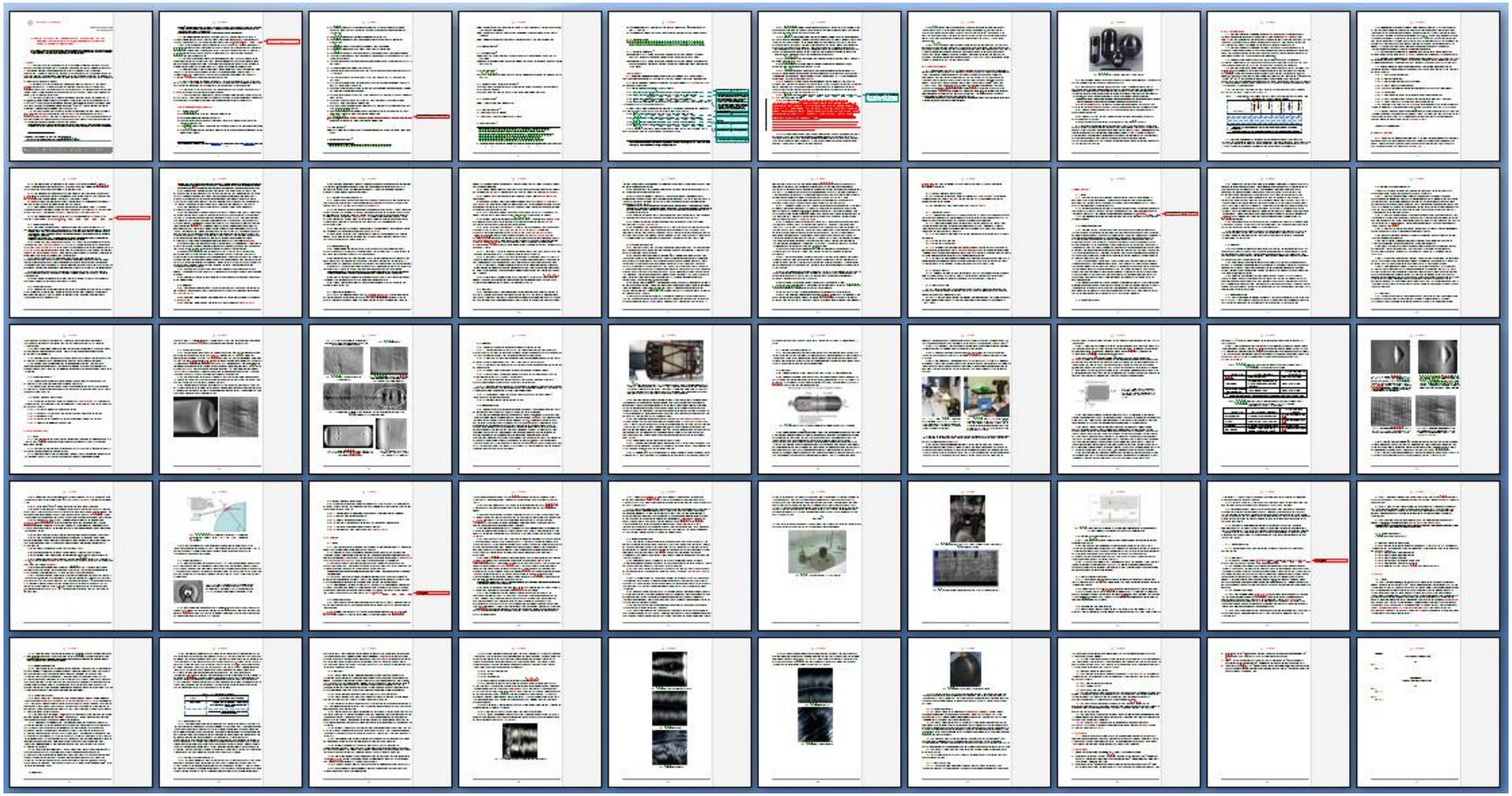
Standard Practices for Nondestructive Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications

Item Registered

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



WK 29034 COPV Overwrap Draft Exists



- Contains procedural NDE detail for AE, ET, Shearography, UT and VI
- Underwent administrative ASTM balloting in May
- In NASA review currently (NESC)

WK 29034 Overwrap Writing Teams

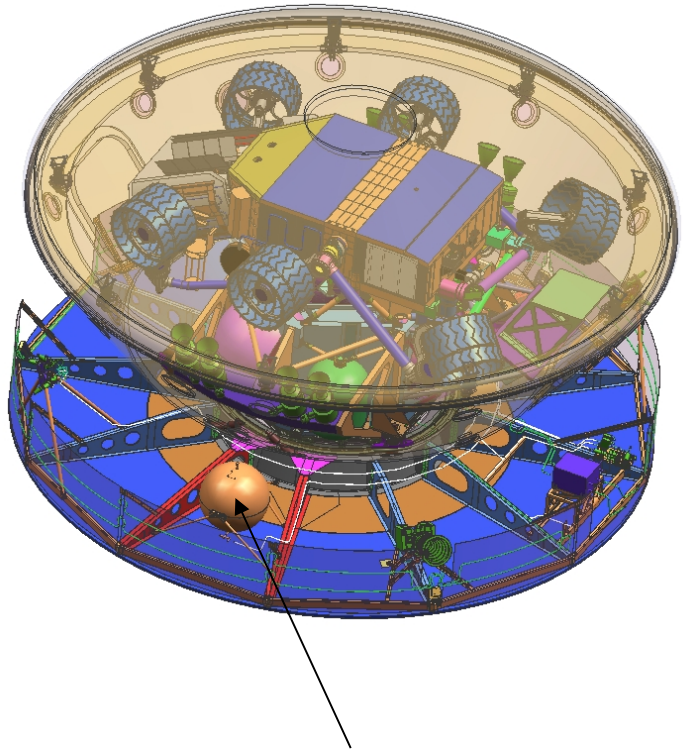
- Acoustic Emission: Muravin
  - Carlos (E07.04 liaison)
  - Gorman (Digital Wave Corp.)
  - Hamstad (University of Denver)
  - NASA: Madaras (LaRC), Nichols (WSTF), Walker (MSFC), Waller (WSTF)
  - Newhouse (Lincoln Composites, collab. with DWC and DOT)
  - Toughiry (DOT)
  - v. K. Hill (Embry-Riddle Aeronautical University (ERAU))
- Eddy Current: Washabaugh
  - Washabaugh (E07.07 liaison)
- Shearography: Newman
  - Clausing (E07.10 liaison)
- Ultrasound: James
  - Ruddy (E07.06 liaison)
  - ATK (Deemer, Papulak, Thompson) – pulse echo and phased array UT
  - Burke (NASA LaRC) – captured water column focused UT
  - Djordjevic (MAST, Inc.) – laser guided wave laser UT
  - Engel (Boeing)
  - Spencer (WSTF)
- Visual Inspection: Yoder
  - Clausing (E07.10 liaison)

WK 29034 and 29068 Plans

- Submit for July 15, 2012 E07.10 S/C balloting
  - WK 29068 (liner)
    - Retain AE section if database or prior precedent exists for AE procedure to characterize welds and is pertinent for thin-walled metal COPV liners
    - Incorporate negatives and comments from February ASTM admin ballot
    - Accomplish NASA peer review
  - WK 29034 (composite overwrap)
    - Consider adding section from phased array UT
    - Incorporate negatives and comments from May ASTM admin ballot
    - Accomplish NASA peer review
    - Accomplish peer review by M. Hamstad

Example of POD Requirement for NASA Hardware

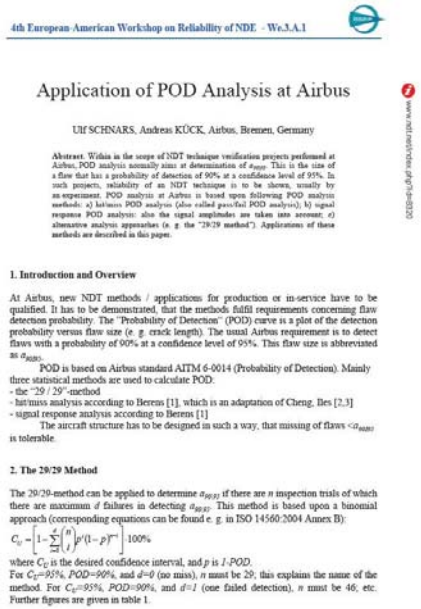
- Monolithic titanium propellant tank for MSL procured under ANSI/AIAA S-080-1998
  - NDE methods provide 90/95 POD for crack size used for fracture mechanics safe-life analysis
  - Flaw shape or crack aspect ratio (a/2c) must be considered over range of 0.1 to 0.5
- Agency Penetrant POD Requirements
  - Orbiter Fracture Control Program previously established crack length minimum limit for penetrant inspection of 0.050 in. (for 0.5 aspect ratio) and requires validation testing
  - NASA-STD-5009 does not set minimum detection limits, but requires validation testing for crack sizes less than Standard NDE sizes



Mars Science Laboratory (MSL) Propellant Tank

POD on Composite Overwraps

- Issues:
  - Effect-of-defect needs to be established for given flaw types
    - cut tow
    - tow termination errors
    - porosity
    - impact
    - delamination
    - disbond (buckling)
    - bridging, etc.



4th European-American Workshop on Reliability of NDE - We.3.A.1

Application of POD Analysis at Airbus

Ulf SCHNARS, Andreas KÜCK, Airbus, Bremen, Germany

Abstract. Within in the scope of NDT technique verification projects performed at Airbus, POD analysis normally aims at determination of $a_{90/95}$. This is the size of a flaw that has a probability of detection of 90% at a confidence level of 95%. In such projects, reliability of an NDT technique is to be shown, usually by an experiment. POD analysis at Airbus is based upon following POD analysis methods: a) hit/miss POD analysis (also called pass/fail POD analysis); b) signal response POD analysis: also the signal amplitudes are taken into account; c) alternative analysis approaches (e. g. the "29/29 method"). Applications of these methods are described in this paper.

1. Introduction and Overview

At Airbus, new NDT methods / applications for production or in-service have to be qualified. It has to be demonstrated, that the methods fulfil requirements concerning flaw detection probability. The "Probability of Detection" (POD) curve is a plot of the detection probability versus flaw size (e. g. crack length). The usual Airbus requirement is to detect flaws with a probability of 90% at a confidence level of 95%. This flaw size is abbreviated as $a_{90/95}$.

POD is based on Airbus standard AITM 6-0014 (Probability of Detection). Mainly three statistical methods are used to calculate POD:
- the "29 / 29"-method
- hit/miss analysis according to Berens [1], which is an adaptation of Cheng, Bes [2,3]
- signal response analysis according to Berens [1]

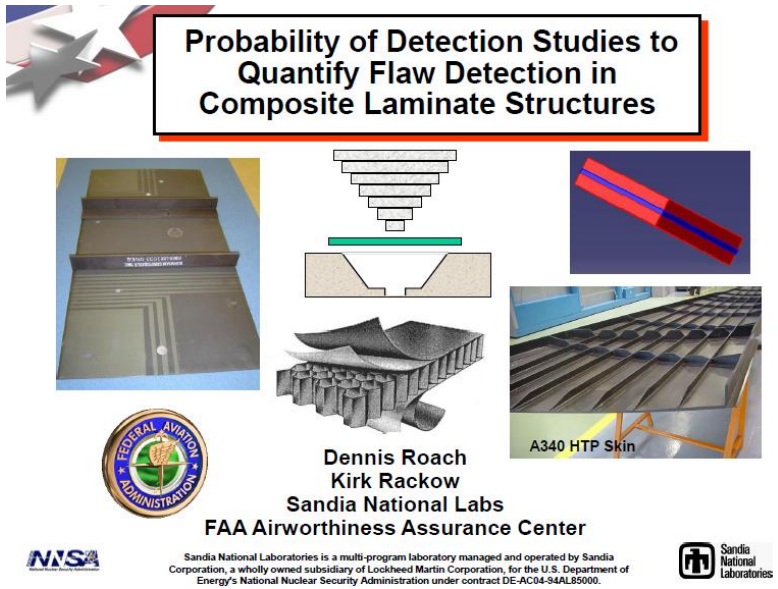
The aircraft structure has to be designed in such a way, that missing of flaws $<a_{90/95}$ is tolerable.

2. The 29/29 Method

The 29/29-method can be applied to determine $a_{90/95}$ if there are n inspection trials of which there are maximum d failures in detecting $a_{90/95}$. This method is based upon a binomial approach (corresponding equations can be found e. g. in ISO 14560:2004 Annex B):

$$C_C = \left[1 - \sum_{i=0}^{d} \binom{n}{i} p^i (1-p)^{n-i}\right] \cdot 100\%$$

where C_C is the desired confidence interval, and p is *1-POD*.
For C_C=95%, *POD*=90%, and d=0 (no miss), n must be 29; this explains the name of the method. For C_C=95%, *POD*=90%, and d=1 (one failed detection), n must be 46, etc. Further figures are given in table 1.



  - ATK 29-29 Method (Airbus)
    - Based on hit-miss analysis according to Berens[1]
  - Sandia POD Method (FAA)
    - Commonly observed flaws bracketed using POD test specimens

[1] Berens, Alan P. (1989): NDE Reliability Data Analysis. In: *Metals Handbook, Vol. 17, AMS International, Metals Park, Ohio, 689-701.*