Slide 1

4th IAASS Conference - Making Safety Matter

Nondestructive Evaluation and Monitoring Results from COPV Accelerated Stress Rupture Testing, NASA White Sands Test Facility (WSTF)

(No. 1878627)

POCs:

NASA WSTF: Regor Saulsberry (575) 524-5518

NASA WSTF: Nathanael Greene

NASA LaRC: Eric Madaras

NASA JSC: Scott Forth

NASA MSFC: Curtis Banks

NASA/KSC: Richard Russell

Cornell University: Leigh Phoenix

Slide 2

Overview

- Background
- Test Programs of Focus
- NASA Nondestructive Evaluation (NDE) Working Group (NNWG) Testing
- Orbiter Testing – NNWG Piggyback Efforts

Slide 3

Background and Issues

- Safe applications of Composite Pressure Vessels (CPVs) is major concern
  - The NASA Engineering and Safety Center (NESC) conducted two major Composite Overwrapped Pressure Vessel (COPV) Technical Assessments (concerns were passed on to associated programs)
    - NDE was not adequately implemented during Shuttle and ISS COPV manufacturing, and provisions were not made for on-going COPV structural integrity or health checks
    - "Stress rupture" of Orbiter (Kevlar®) and ISS (carbon) COPVs is a major concern
      - Stress rupture failure of gas pressurized COPVs on the ground or in flight presents a catastrophic hazard
    - Findings and recommendations issued in the carbon and Kevlar reports:
      - F: No NDE technique is currently known to be directly applicable to prediction of stress-rupture and other life-limiting damage mechanisms in COPVs
      - R: The NDE, Materials, and Structures technical communities should join forces to plan and undertake a feasibility study of various potential NDE techniques that may be capable of detecting degradation leading to stress rupture in carbon COPVs. This includes:
      - Identification of physical and chemical changes to target appropriate NDE
      - Identification of any NDE response that correlates to progression toward stress rupture

Slide 4

Objective

- Develop and demonstrate NDE techniques for real-time characterization of CPVs and, where possible, identification of NDE capable of assessing stress rupture related strength degradation and/or making vessel life predictions (structural health monitoring or periodic inspection modes)
  - Secondary: Provide the COPV user and materials community with quality carbon/epoxy (C/Ep) COPV stress rupture progression rate data
  - Aid in modeling, manufacturing, and application of COPVs for NASA spacecraft

Slide 5

Technical Methodology/Approach

- The recent carbon stress rupture testing builds on previous Kevlar® composite projects
  - NNWG Kevlar Stress Rupture 2006-2008
  - Orbiter Kevlar testing 2006-2009
  - Carbon stress rupture project 2008-2012
  - On-going NESC Composite Pressure Vessel Working Group testing and analysis
- To support the effort, a team of NDE experts was selected from the NNWG membership, the NASA Engineering and Safety Center (NESC), academia, and industry, with the goal of accomplishing this project in a highly collaborative manner

Slide 6

Expanded Composite Stress Rupture NDE Team

WSTF:
- Regor Saulsberry – PM/project oversight, piggyback campaigns
- Jess Waller - scheduling and project tracking assistance
- Mark Leifeste - laboratory analysis
- Tony Carden, eddy Andrade/Charles Nichols
- Daren Cone – eddy current

JSC: Ajay Koshti – NDE liaison to CEV, Bud Castner Standards, Scott Forth – M&P/Analysis
JPL: David Mih – NDE consulting and NDE round robin
TRI
- Tom Yolken (MD) - technical oversight and project administration
- Scott Thornton (TX) – COPV aging and real-time NDE and stress testing
- George Matzkanin – ASTM Aerospace Composites Chair

LaRC
- Eric Madaras – NDE technical oversight, AE, extensive other NDE
- Buzz Wincheski – Raman/eddy current
- Phillip Williams
- Elliot Cramer – thermography

MSFC
- Curtis Banks – overall FBG, Ares Composite Structure liaison
- Thomas Delay – COPV wrapping/test article generation

Stennis: Joseph Grant - FBG
DFRC: Lance Richards – FOBG consulting
GRC:
- Don Roth – NDE (e.g., guided waves)
- Fran Hurwitz – extensive destructive analysis (Jeffrey I. Eldridge – Raman)

KSC: Rick Russell - liaison to Shuttle Orbiter Project Office, NDE/materials
NESC: Bill Prosser liaison to NESC NDE, Lorie Grimes Ledesma - CPVWG, John Thesken - analysis
UoM-C:
- Glenn Washer – Raman spectroscopy, technical recommendations

Cornell University:
- Leigh Phoenix – Stress rupture consulting and laboratory testing

Slide 7

Technical Methodology/Approach

- First, complete the NNWG Kevlar efforts and Orbiter Kevlar Stress rupture testing
- Build a state-of-the-art 20 station stress rupture NDE and monitoring test bed
  - Allow inspection and monitoring at pressure
- Evaluate numerous (80-100) carbon bottles during stress rupture progression in lots of 20
  - Fiber types are to represent ISS, current, and potential future vessels

Slide 8

Technical Methodology/Approach (cont'd)

- Correlate real-time NDE and instrumentation with stress rupture progression:
  - Include conventional and fiber-based acoustic emission (AE), and distributive impact detection systems (DIDS) sensors
  - Include GRC capacitance sensors, Métis sensors, AE arrays, Agilent passive wireless sensors (strain and temperature), and others developed by Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) to be added as available
    - Other structural health monitoring (SHM) collaborations are openly invited
  - Add *in situ* portable Raman if feasible
  - Evaluate feasibility of ISS vessel monitoring with AE sensors on interface lines

Slide 9

Progress - Kevlar

- Completed the second Kevlar® campaign
- ~18-month Orbiter Kevlar stress rupture test concluded with vessel failure
  - Excellent AE data from start to vessel failure
  - Eddy current used to monitor liner and composite thickness variations
  - Portable WSTF/LaRC Raman developed and applied *in situ* to the Orbiter 40-in. vessel
  - Also good progress made with Raman scanning of NNWG Kevlar vessels at LaRC

Slide 10

WSTF Orbiter COPV Instrumentation and NDE During Rupture and Stress Testing

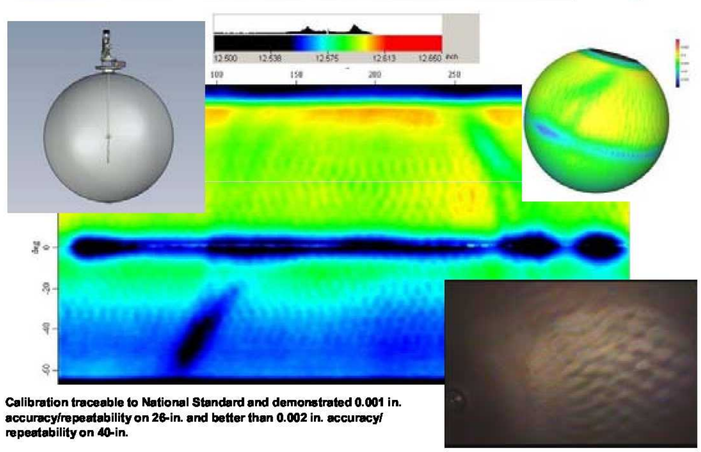
Method	Measurement
Visual Inspection (Pretest)	External inspection of overwrap. Indication of gross damage
Both Flash and Heat Soak Thermography (Pretest)	Heat Signature Decay Sub-surface Ply Delamination. Heat soak or thru transmission works better with thicker composites.
Videoscope Inspection (Pretest)	Internal inspection of liner. Indication of damage or buckling
Laser Profilometry	Internal surface mapping and measurement . Evaluate ripples, potential buckling, and crossover imprinting on spherical tanks
Laser Shearography	Differential strain resulting from any cause (e.g., impacts, delaminations, broken fiber, etc.)
Cabled Girth and Boss LVDT	Circumferential and axial displacement
Strain Gauge (Test)	Change in length. Average fiber strain under the sensor.
Fiber Bragg Grating (Test)	Change in length. More localized strain
Acoustic Emission (Test)	Acoustic noise. Fiber breakage or delamination.
Full Field Digital Image Correlation	Global or localized strain
Eddy Current Probes	Composite thickness change
Portable Raman Spectroscopy	Residual stress/identification of stress gradients. May have potential to indicate stress rupture progression (S/N 007)

Slide 11

Pretest NDE

Slide 12

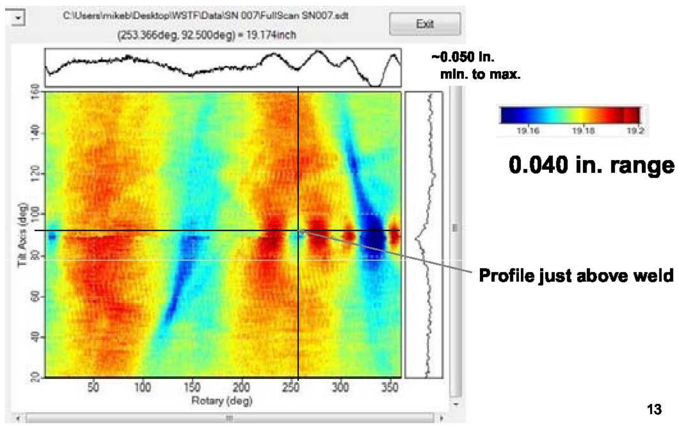
Laser Profilometry Accurately Quantifies Liner Buckling and Other Surface Features



Calibration traceable to National Standard and demonstrated 0.001 in. accuracy/repeatability on 26-in. and better than 0.002 in. accuracy/ repeatability on 40-in.

Slide 13

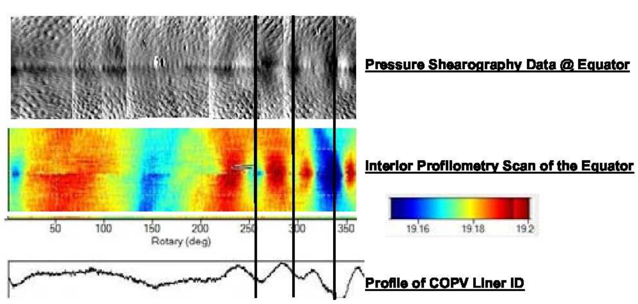
Profilometry of S/N 007 (cont'd)



Slide 14

Shearography Data at the Equator Correlated Well with COPV Liner Profilometry Scan

- Profilometer scan of the inside surface of the liner at the equator shows 0.020 to 0.040 in. liner deformations (large ripples) at these same locations.



Slide 15

Orbiter Real-Time NDE

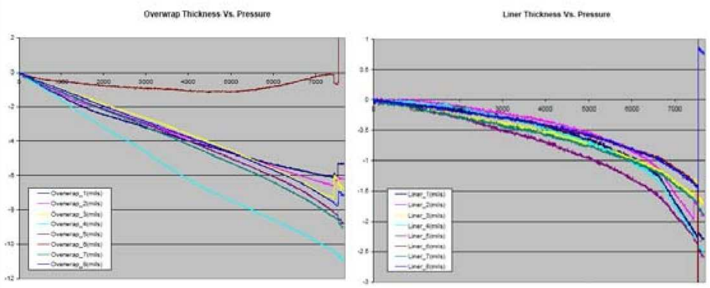
Slide 16

OMS Kevlar Pretest NDE Conclusion

- The large ripples around the girth weld raised a question, but other no observed indications were an issue with planned stress rupture testing
  - Eddy current sensors were placed over the peak of each girth ripple and monitored during pressurization to verify the liner did not flex causing a metallic fatigue concern
    - Decrease of stand-off between the fixed composite surface and liner ripple would indicate a liner buckle and associated air pocket
  - Stand-off remained fixed during pressure cycles, indicating that the indications were not a concern

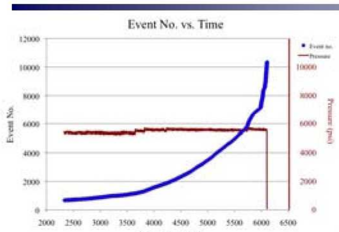
Slide 17

Example of Overwrap and Liner Thickness Evaluation by Eddy Current

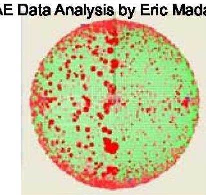


Slide 18

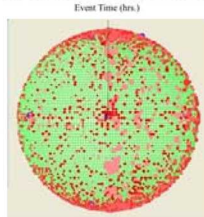
AE Effective in Monitoring Orbiter 40-in. Vessel Stress Rupture Progression to Failure



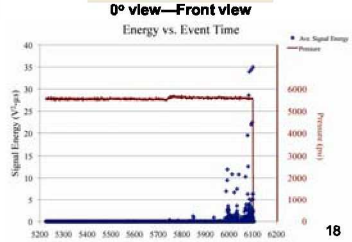
AE Data Analysis by Eric Madaras



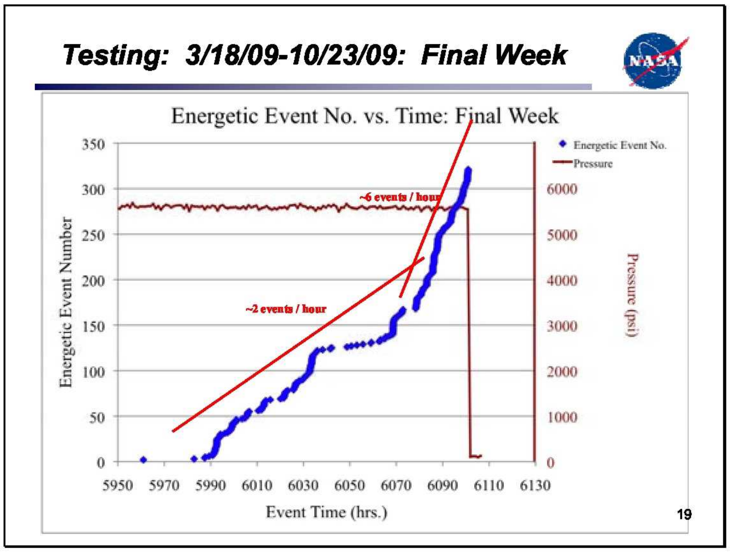
0° view—Front view



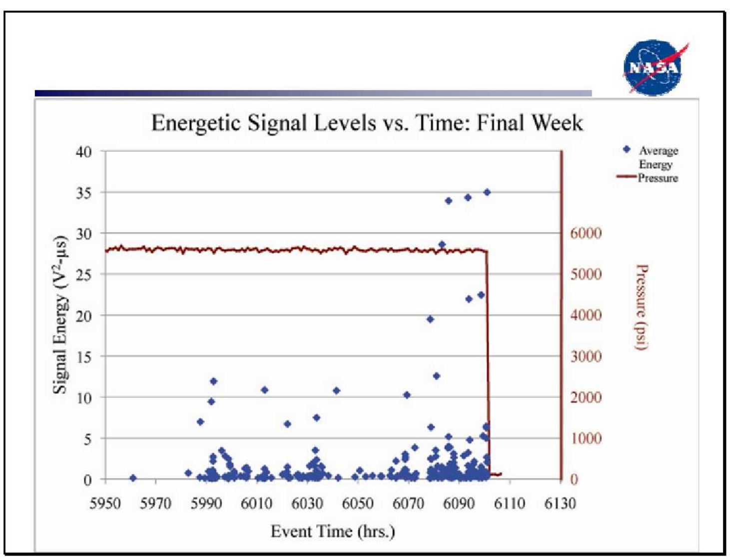
180° view—Back view



Slide 19

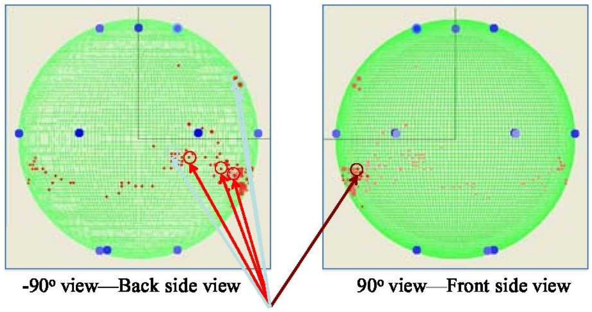


Slide 20



Slide 21

Testing: 10/13/09-10/23/09: Final High Energy Burst (Final 24 h)



Locations of Energetic Events

Red lines are the location of the larger events

The dark red line is the location at depressurization (which was the largest)

Slide 22

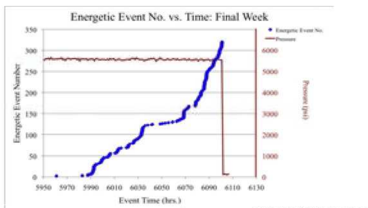
AE Summary

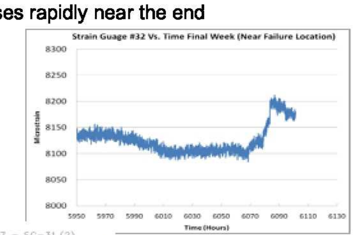
- There were two AE event rate increase periods that occurred during the last 7 days. The last rate increase ended in failure.
  - There were over 3000 recorded events during the last 10 days.
  - There were more than 300 very energetic events recorded during the last week.
  - The rate increases were coincidental with trains of very large energy signal events.
  - The first rate increase for large energy, signal events (24 to 96 hours before the end) was approximately 2/hour.
  - The second and final rate increase for large energy signal events (last 24 hours) was approximately 6/hour.
- Event energies rose to very elevated levels during the last 96 hours.
  - High energy events were > 25 times greater than energetic events in the past.
  - The loudest events occurred at the end (last 24 hours).
  - The final event, which was the loudest, was located ~ 45° below the equator and near the azimuth angle of 45°.

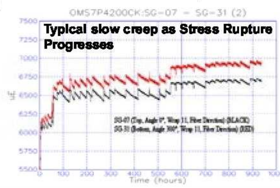
Slide 23

Comparison of AE Events to Strain During Final Week

- AE event numbers show increasing at ~6070 hours
- Strain near failure location increases rapidly near the end

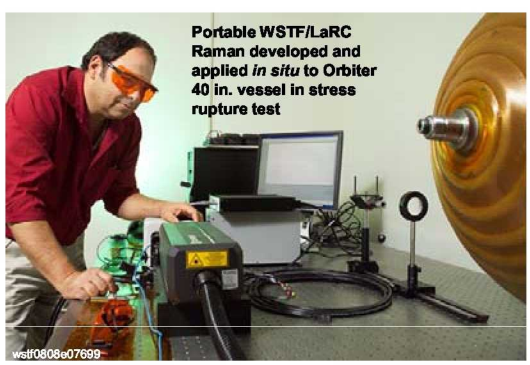






Slide 24

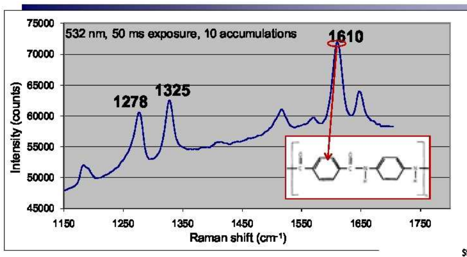
Portable Raman System Developed to Allow Real-time Raman Spectroscopy During Testing



Tim Gallus performing bench top testing of a Raman spectography system prior to installation in the test cell

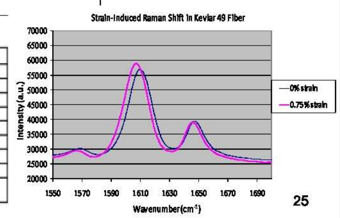
Slide 25

Typical Raman Spectrum of Kevlar



Raman Data by LaRC-Buzz Wincheski and Philip Williams

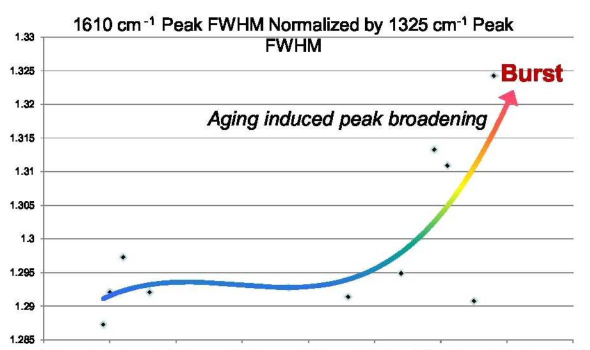
Wavenumber (cm^{-1})	Assignment
630, 732, 786	Ring vibrations
845	C-H out-of-plane bending
863	Ring vibrations
1103	C-H in-plane bending
1181, 1277, 1327, 1514	C-C ring stretching
1318	C-H in-plane bending
1569	Amide II (60% N-H bending; 40% C-N stretching
1610	C-C ring stretching
1648	Amide I (80% C=O stretching; 10% C-N stretching 10% N-H bending)



25

Slide 26

Real-time Raman During COPV SN007 Stress Rupture Testing - 8/15-10/22/09

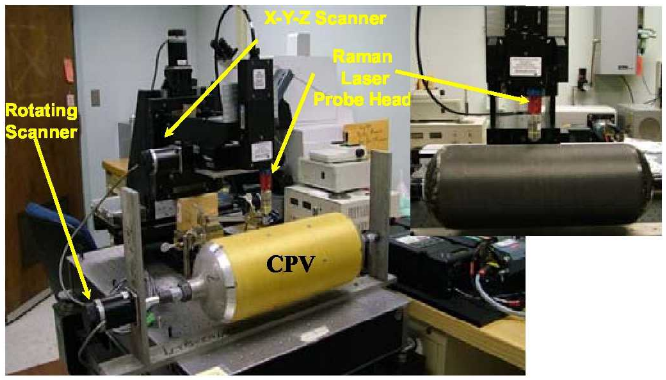


Note: FWHM = Full Width at Half Maximum

26

Slide 27

Remote Scanning Raman Configuration

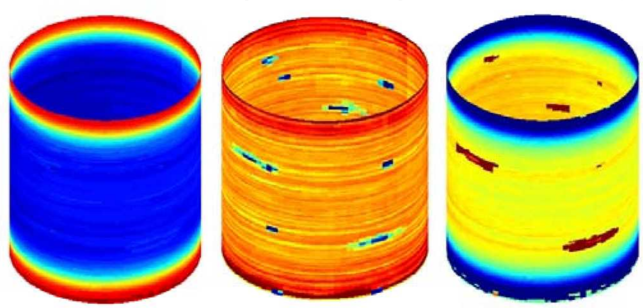


LaRC Experimental Setup for Measurements on 6.25 in. NNWG Kevlar® and Carbon CPVs

Slide 28

360 Degree Raman Scan of COPV S/N 009

Position of 1610 cm^{-1} peak **Amplitude of 1610 cm^{-1} peak** **FWHM of 1610 cm^{-1} peak**



Slide 29

Progress – Carbon Stress Rupture Project

- 100 carbon COPVs designed and fabricated
  - 50 ea IM7 carbon vessels to represent ISS
  - 50 ea from T1000 to represent Orion and potential future NASA spacecraft
  - 6.3 in. dia., 6061 T6 aluminum liners, nominal 7500 psi burst to provide adequate carbon thickness
  - Same lots of fiber used and many strand tests made to ensure quality
  - Plant trips to observe winding process and witness burst tests
- NESC assisted with comprehensive modeling of vessels in Abacus® to identify the mechanical response
  - WSTF modeled in Genoa™ and got similar results
  - Separate autofrettage tests done on identical bottles on NESC funding to evaluate response as compared to the model

Slide 30

Progress – Carbon Stress Rupture Project (cont'd)

- T1000 and IM7 strand tensile tests and stress rupture completed at Cornell University and WSTF to ensure lot consistency and help set test pressures
- State-of-the-art 20 station test system brought on-line
  - Maintains pressure at approximately 30 ± 2 psi regardless of temperature swings (appears to be a first for the Stress Rupture test industry)
  - Rapidly auto-isolates bottles as they rupture
  - Protective enclosures allow inspection of vessels up to rupture pressure
  - Extensive data acquisition and real-time NDE capability to validate sensors and NDE

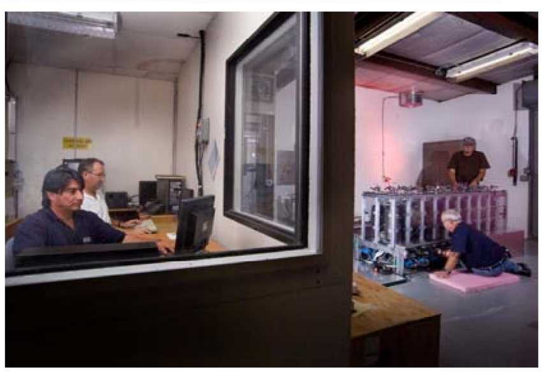
Slide 31

Progress – Carbon Stress Rupture Project (cont'd)

20 carbon vessels and real-time NDE in WSTF Lexan protective enclosure allows inspection while at test pressure

Slide 32

Preparing the Stress Rupture Test System



Team of WSTF (using Digital Wave 32 channel) and Physical Acoustics AE experts evaluate response of different AE systems during system checkout

Slide 33

Carbon Aging Instrumentation NDE and DI Plan

Method	Measurement Results	Location/Responsible Group
Guided Wave	Defects in the wave path and modulus change	GRC/GFC (others as available)
Laser-induced UT	Defects in the path of wave path and modulus change	Materials and Sensors Technologies, Inc. (MSFC if available)
Laser Profilometry	Inspection of the liner for dimension changes and for buckling	WSTF/LTC
Pressure, Temperature	Pressure and temperature for given duration	WSTF/WSTF
Cabled Girth LVDT	Circumferential displacement measured at the middle of the barrel section	WSTF/WSTF
Strain Gauge	Change in length. Fiber strain	WSTF/WSTF
Fiber Bragg Grating	Change in length. High resolution low fiber strain information	WSTF/MSFC
Acoustic Emission	Acoustic noise. Fiber breakage or delamination	WSTF/LaRC
Visual Inspection (exterior)	External inspection of overwrap. Indication of gross damage to the fiber overwrap	WSTF/WSTF

Slide 34

Carbon Aging Instrumentation NDE and DI Plan (cont'd)

Method	Measurement Results	Location/Responsible Group
Visual Inspection (interior)	Internal inspection of liner Indication of damage or buckling of the liner	WSTF/WSTF
Shearography (Barrel)	Forced out-of-plane deflection Sub-surface mechanical damage or ply delamination	WSTF/WSTF MSFC/MSFC
Flash Thermography (Domes)	Heat signature decay Sub-surface ply delamination	WSTF/WSTF
Ultra-sonic Inspection	Acoustic time of flight measurement to determine composite ply delamination and modulus	MSFC/MSFC
Specialized Thermography	Fine distributed damage from fiber breakage/matrix cracking	LaRC/LaRC
Raman Spectroscopy	Strain mapping and FWHM wave form changes	LaRC/LaRC
Real-time Raman Spectroscopy	Real-time strain mapping and FWHM wave form changes	WSTF/LaRC
Structural Health Monitoring Sensors	Multiple structural health monitoring (SHM) sensors are planned to be applied as made available from SBIR/STTR Phase I/II and by participating Centers	WSTF/JSC, MSFC, & GRC

Slide 35

Progress – Carbon Stress Rupture Project (cont'd)

- Completed stress rupture testing on the 1st and 2nd lot of 20 (each) T1000 vessels
  - Failed 6 vessels on first lot and 4 on the second lot
  - First 20 IM7 lot installed
  - NDE of aged and virgin vessels in progress at NASA Centers and at Materials and Sensors Technology (MAST Inc.)
  - Lessons learned from first round being implemented
    - e.g., autofrettage first to enhance AE, DIDS improvements
- Laser UT and low noise water jet UT looks promising at MAST Inc.
  - Laser UT especially effective in evaluation of modulus changes

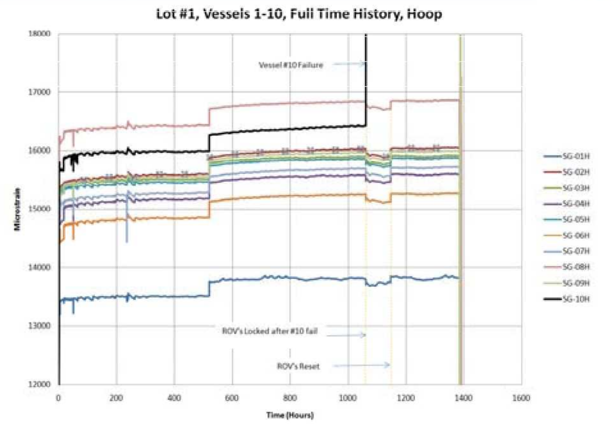
Slide 36

Progress – Carbon Stress Rupture Project (cont'd)

- NESC correlating stress rupture progression rate data with existing community database
  - Carefully controlled data should improve database
  - Profilometry also being done to directly evaluate residual deformation and growth (strain measurement) over the stress rupture period

Slide 37

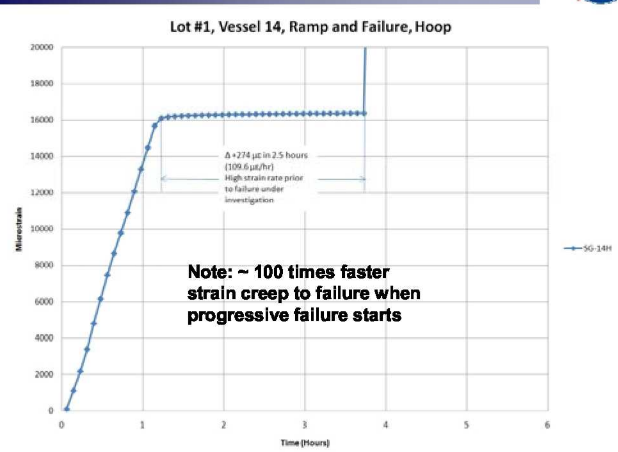
Lot #1, Vessels 1-10, Full Time History, Hoop



37

Slide 38

Lot #1, Vessel 14, Ramp and Failure, Hoop

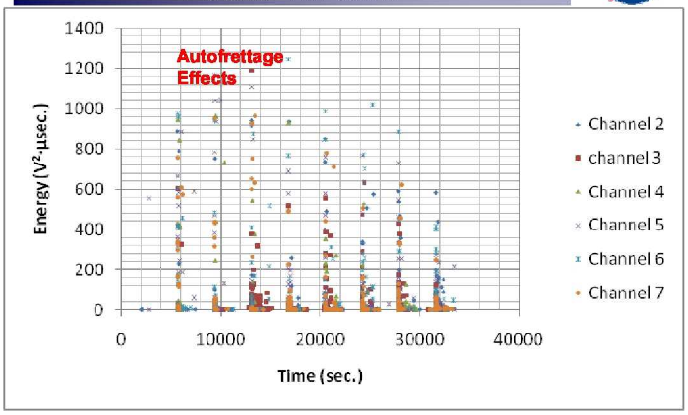


Note: ~ 100 times faster strain creep to failure when progressive failure starts

38

Slide 39

NNWG IM7 C/Ep COPV AE Energy Events vs. Time



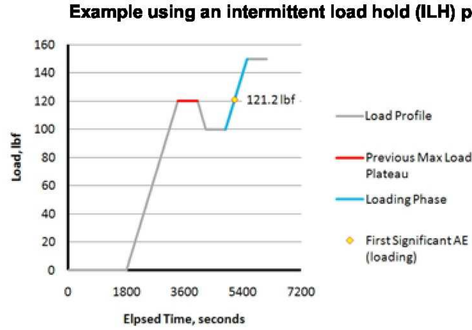
Slide 40

Felicity Ratio

Felicity ratio (FR) given by:

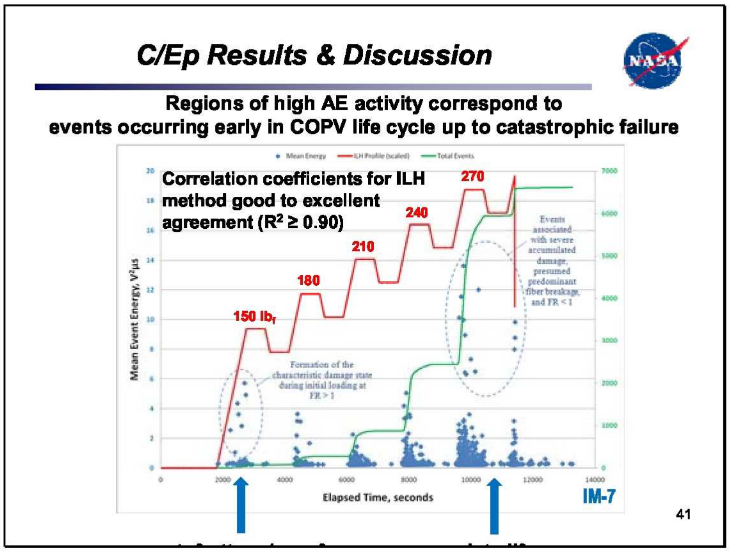
$$FR = \frac{\text{stress at onset of significant acoustic emission during loading}}{\text{maximum previous stress plateau}}$$

Example using an intermittent load hold (ILH) profile:

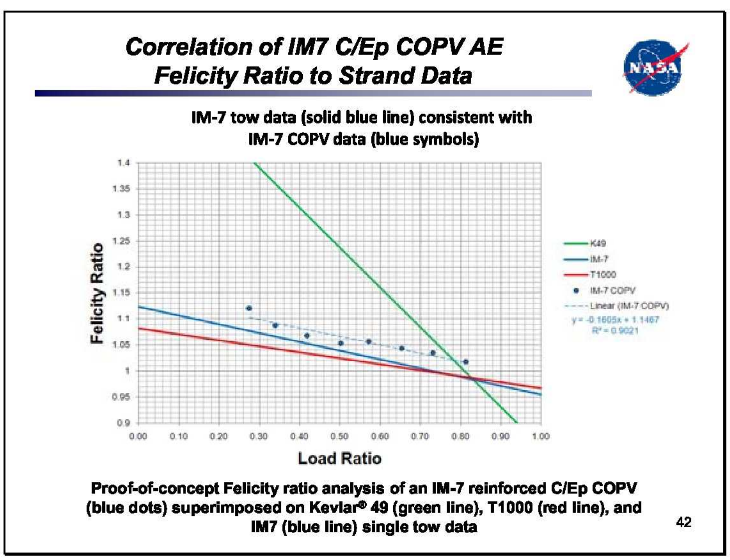


$$FR = \frac{121.2}{120} = 1.01$$

Slide 41



Slide 42



Slide 43

Schedules/Milestones

Future Milestones

FY 2010

- Complete stress rupture aging of the 1st lot of 20 IM7 vessels by June 15, 2010
- Complete stress rupture aging of the 2nd lot of 20 IM7 vessels by August 12, 2010

FY 2011

- Complete the 2nd stress rupture aging campaign of T1000 vessels by November 3, 2010
- Complete the 2nd stress rupture aging campaign of IM7 Vessels by January 24, 2011

FY2012

- Complete post-test NDE at NASA Centers by April 8, 2012
- Complete final report by August 30, 2012

Slide 44

Conclusion

- NDE has proven highly effective in real-time characterization of COPVs during testing
- NDE is reasonably effective in evaluating the health of COPVs, but still more work is needed to make it more quantitative and predictive
- Overall, a well controlled and informative Carbon COPV Stress Rupture test is being accomplished
  - Collaboration on SHM sensor evaluation is invited

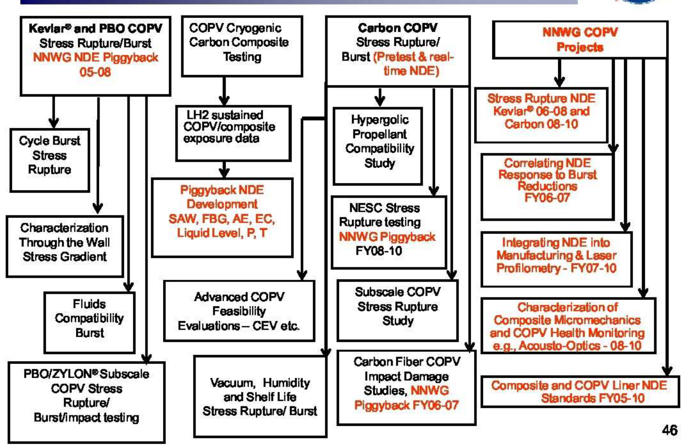
Slide 45

Backup

Slide 46

Composite Vessel Test Programs – Multi-Center

(NDE in red)



46

Slide 47

Summary/Status of NDE Methods (Full table in the Final Report)

Acoustic	
• Acoustic Emission	Promising recommend for Phase II (indirect/monitoring)
• Conventional Pulse Echo Ultrasonics	Delayed
• Acousto-ultrasonics	Exploring Lamb Waves/Plate Waves instead
• Lamb Waves/Plate Waves	GRC found delams, but further work currently in progress to evaluate stress rupture
• Laser induced Acoustic Waves	Promising recommend for Phase II, modulus (Boro Djordjevic)
Electromagnetic	
• Eddy Current	Provides indirect data for characterization
• Microwave/millimeter Wave	Promising recommend for Phase II
• Terahertz	Under further evaluation
• One-sided NMR	Delayed recommend under Phase II
• Raman Spectroscopy	Promising recommend for Phase II
• IR Thermography	Finds conventional damage, but no SR correlation
Strain Measurement	
• Distributed Strain Sensing (FBG)	Promising recommend for Phase II
• Bonded Mechanical Strain Gauges	Promising recommend for Phase II
• Belly Band LVDT	
• Image Correlation	Being applied further by manufacturing NDE Project
• Shearography	Being applied further by manufacturing NDE Project
Penetrating Radiation	
• X-ray Radiography & CT	Deemed Low chance of success, delay/delete?

47

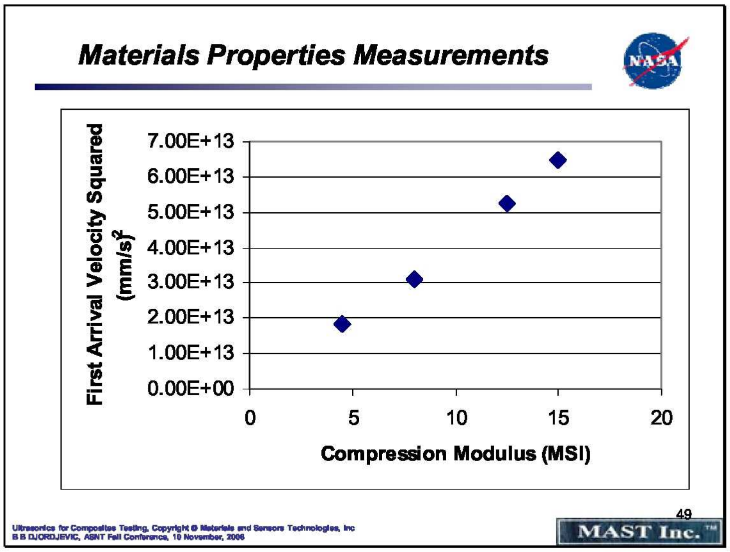
Slide 48

Summary/Status of DE Methods (Full table in the Final Report) (cont'd)

• Optical Microscopy	Successful for supporting data (fiber splitting, kink bands, ply lay-up, fiber/resin volume ratios)
• Scanning Electron Microscopy	Successful for supporting data (fiber splitting, kink sheath peeling in fracture, fiber ends taper on fracture)
• Scanning Electron Microscopy/ Micro-load frame/AE	Promising for visualization of stress rupture failure propagation events and associated AE
• X-ray Diffraction	Initial work appears promising. Indicates difference in intensities of major Bragg peaks between intact fibers, frayed fibers, fast fracture fibers, and stress-ruptured fibers. Also showed possible difference between bottles aged at elevated temperature and elevated stress.
• Energy dispersive x-ray spectroscopy	Carbon only element identified; not useful in differentiating among test bottles and rupture conditions

48

Slide 49


Materials Properties Measurements
First Arrival Velocity Squared (mm/s)²
7.00E+13
6.00E+13
5.00E+13
4.00E+13
3.00E+13
2.00E+13
1.00E+13
0.00E+00
0
5
10
15
20
Compression Modulus (MSI)
49
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