DOE Vehicular Tank Workshop
Sandia National Laboratories
Livermore, CA

Nondestructive Evaluation and Monitoring Projects NASA White Sands Test Facility (WSTF)

POCs:

NASA WSTF: Regor Saulsberry (575) 524-5518

Overview

- Background and Projects Overview
- Survey of Test Projects of Interest
- NASA Nondestructive Evaluation (NDE) Working Group (NNWG) Testing
- Orbiter Testing – NNWG Piggyback Efforts

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 was 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:

      1. Physical and chemical changes to target appropriate NDE
      2. Any NDE response that correlates to progression toward stress rupture

WSTF 2009 Composite Pressure Vessel and Structures Summit - NDE Needs from

- Quantitative inspection techniques (documented by application standards) with associated rationale and understanding of how to make necessary physical defect standards specific to composite inspections
  - Often, inspection capability is not the issue; but what do inspection results mean?
    - Relationship between defect indications and structural/damage tolerance parameter of interest (i.e., consideration of strength, residual strength, bond strength, remaining life, etc.)
    - Need for physical standards with well characterized realistic defects, especially large specimens representative of large structures to be inspected
- NDE implemented into manufacturing to ensure quality and consistency of Composites (and liners where applicable)
- If not qualified as “Safe Life,” ongoing inspection and/or health monitoring of operational vessels
  - Recertification
  - To prevent a bad day

http://www.nasa.gov/centers/wstf/news/safetysummit2009.html

Projects to Help NDE Address Needs

NNWG Projects (WSTF)

- Stress Rupture NDE Development Test Program (monitoring and predictive)
- Correlating NDE Response to Burst Reductions
- Integrating NDE into Manufacturing
- Composite PV Interior Scanning Laser Profilometry
- Characterization of Composite Micromechanics and COPV Health Monitoring
- Acousto-Optics AE Development
- Embedded Optical Fiber Research - COPVs

see http://nnwg.org/current/index.html

Projects to Help NDE Address Needs (Con't)

NASA Engineering Standards Panel (ASTM is the team Consensus Organization)

- Team completed an ASTM Standard Guide and Five Standards of Practices
  - E2533-09 Std Guide for NDT of Polymer Matrix Composites Used in Aerospace Applications
  - E2580-07 Std Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications
  - E2581-07 Std Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials, and Filament-Wound Pressure Vessels in Aerospace Applications
  - E2582-07 Std Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications
  - E2662-09 Std Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications
  - Also, 2 AE work items have been initiated and are at various stages of completion: WK12759 Acoustic Emission Examination of Plate-Like and Flat Panel Composite Structures Used in Aerospace Applications, WK19889 Standard Guide for Preparing an Acoustic Emission Examination Plan for Plate-like and Flat Panel Aerospace Composite Structures
- NASA/ASTM teams organized and developing Quantitative NDE for CPV and Liners (help to address "Safe life" per ANSI/AIAA S-O81A)
    - 1) Composite, 2) Composite to liner interface, and 3) Liner

Projects to Help Address Needs (Con't)

NESC

- Autofrettage study with comparison of in-depth T1000 and IM7 test data to models
  - Goal model refinement
- Profilometry also used for Plastically Responding Metal Liners project

Orbiter

- Real-time NDE techniques developed, monitored, and correlated with strain and volume changes during ongoing stress rupture test: Eddy Current for composite and liner thickness monitoring, extensive AE, and Raman for strain and Stress Rupture progression database collection.

Orion/new NASA vehicles

- NDE planned to be integrated with CPV manufacturing

NDE Objective

- Develop and demonstrate NDE techniques for real-time characterization of CPVs and identification of NDE capable of assessing stress rupture related strength degradation and/or making vessel life predictions
  - 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

Stress Rupture NDE Technical Methodology/Approach

- Put the right team of NDE experts together
  - Selected from the NNWG membership, the NASA Engineering and Safety Center (NESC), academia, and industry
- Current carbon stress rupture testing (2008-2012) builds on previous Kevlar® composite projects
  - NNWG Kevlar Stress Rupture 2006-2008
  - Orbiter Kevlar testing 2006-2009 (just completed)
  - On-going NESC Composite Pressure Vessel Working Group testing and analysis
- Build a state-of-the-art 20 station stress rupture NDE and monitoring test bed
  - Allow inspection and monitoring at pressure

Technical Methodology/Approach (cont'd)

- Correlate real-time NDE and instrumentation with stress Carbon rupture progression:
  - Include conventional and fiber-based acoustic emission (AE), and distributive impact detection systems (DIDS) sensors
  - Include GRC capacitance sensors, Métis system AE arrays, Agilent system, 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

Progress - Kevlar

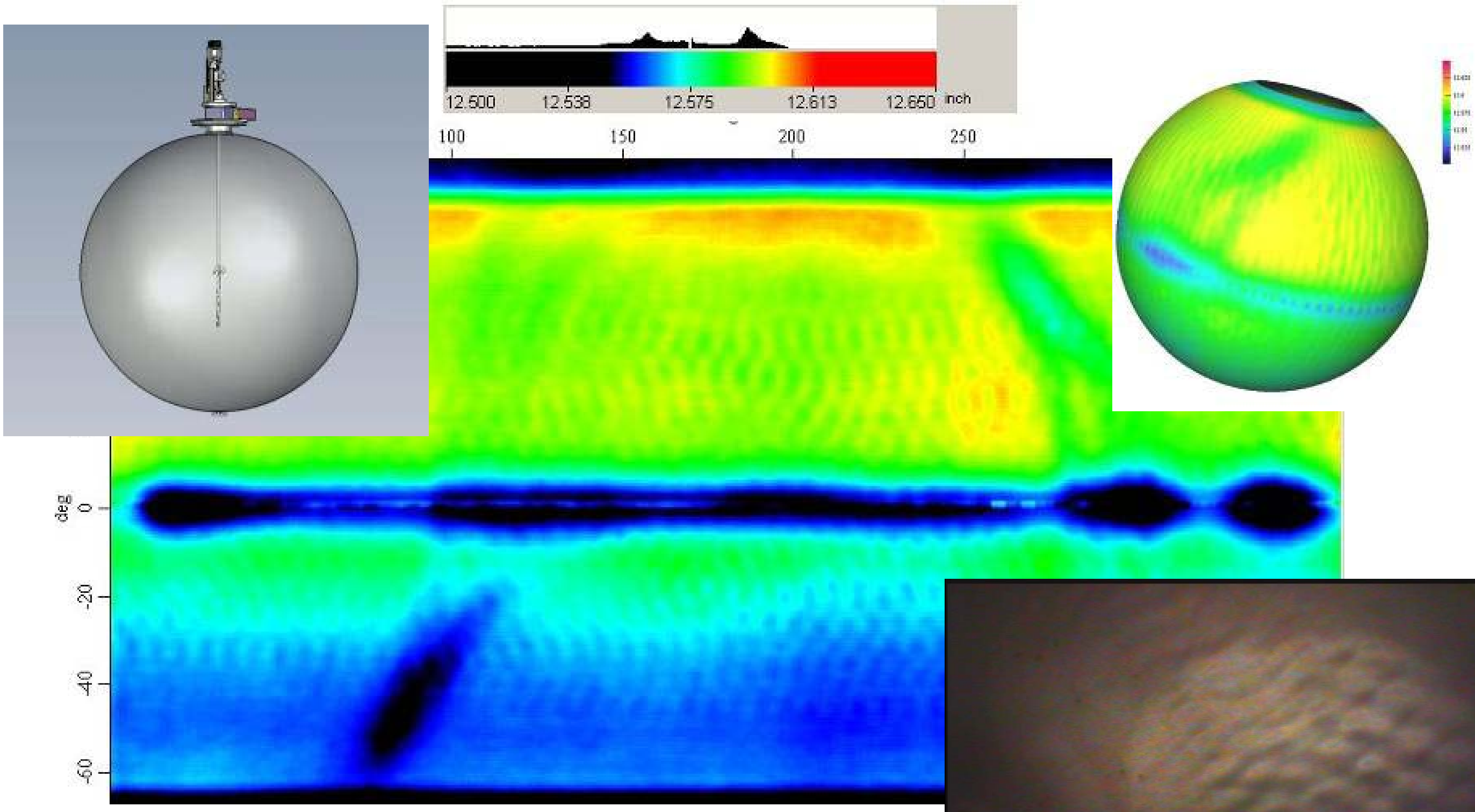
- ~18-month Orbiter Kevlar life extension test taken to stress rupture failure
  - Excellent AE data from start to vessel failure
  - Eddy current used to monitor liner and composite thickness variations
  - Portable WSTF/LaRC Raman developed and applied *in situ* to the Orbiter 40-in. vessel
    - Also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

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)

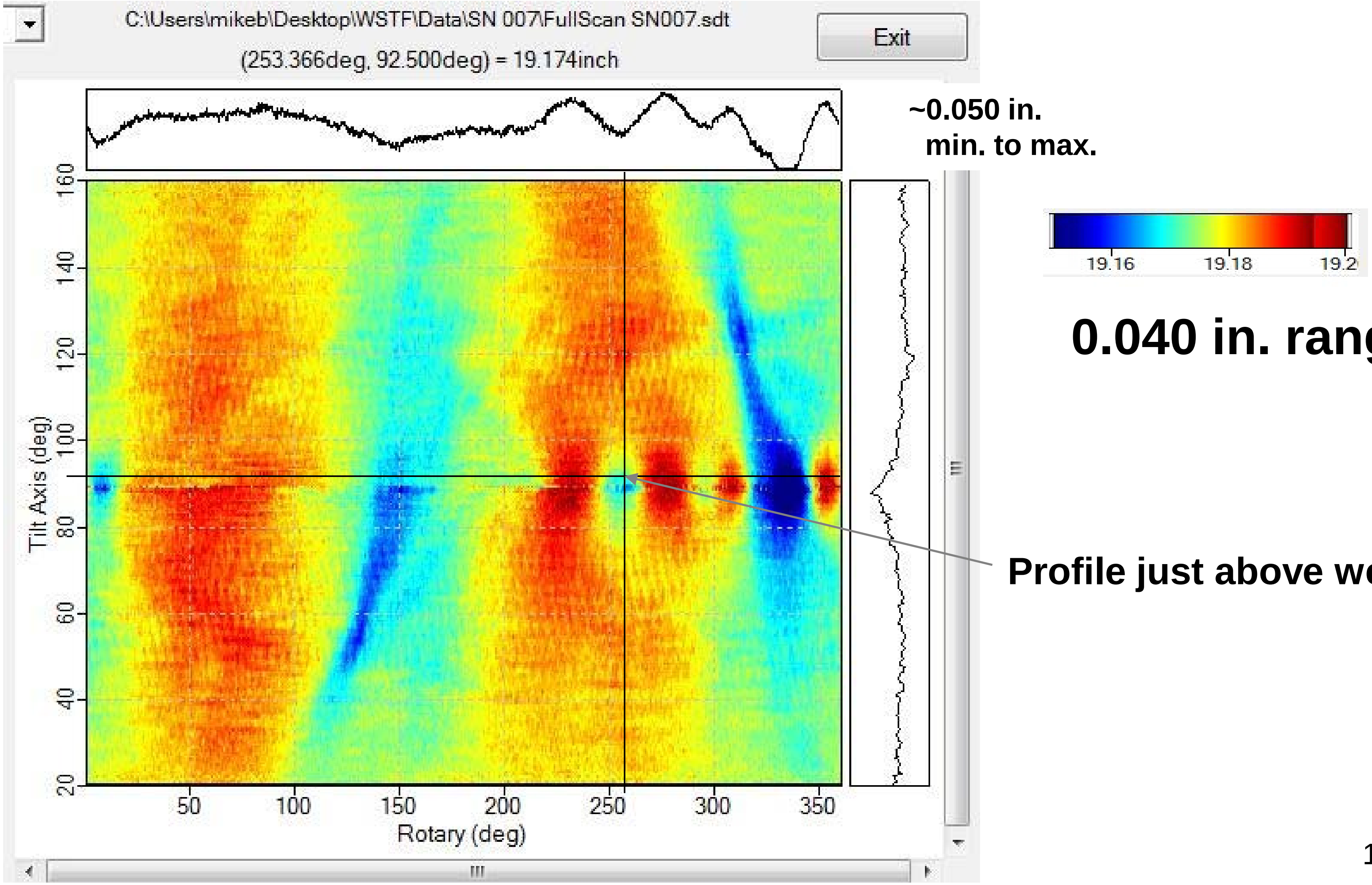
Orbiter Pretest NDE

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.

Profilometry of S/N 007 (cont'd)



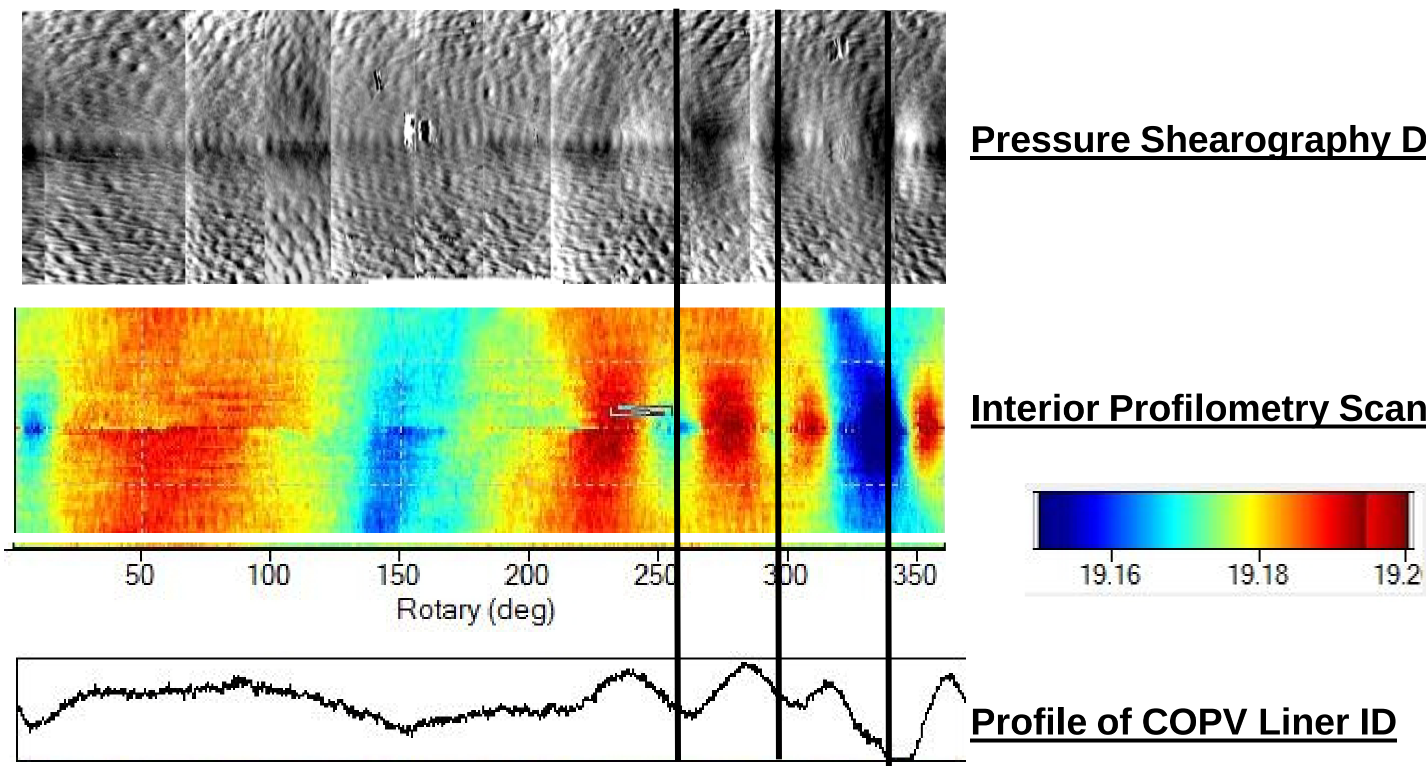
~0.050 in. min. to max.

0.040 in. range

Profile just above weld

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

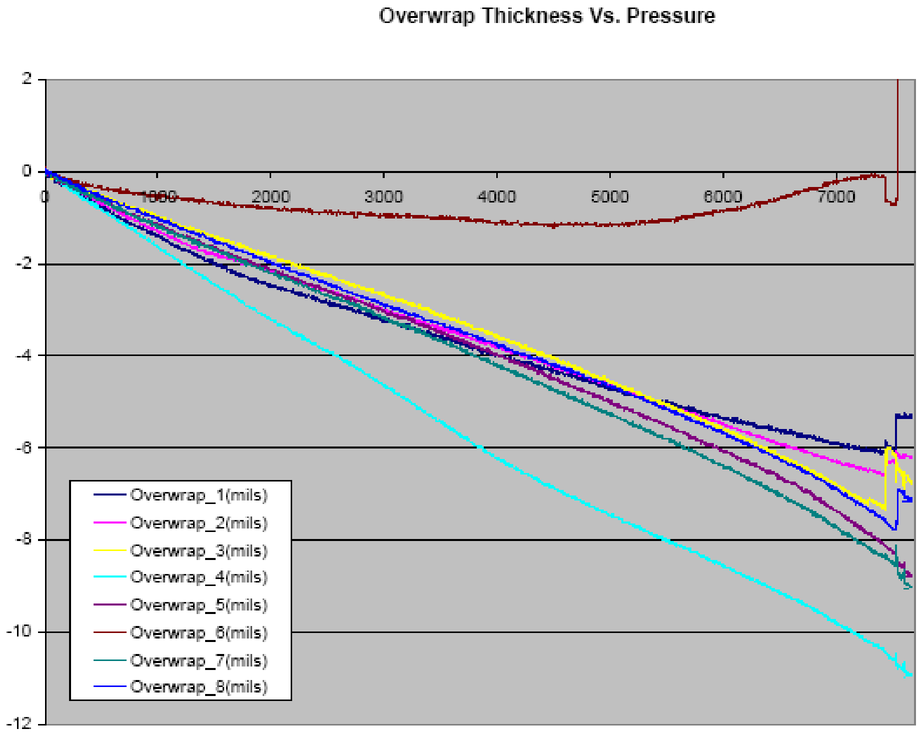
- Profilometer scan of the inside surface of the liner at the equator shows 0.020 to 0.040 in. liner deformations (large ripples) at these same locations.

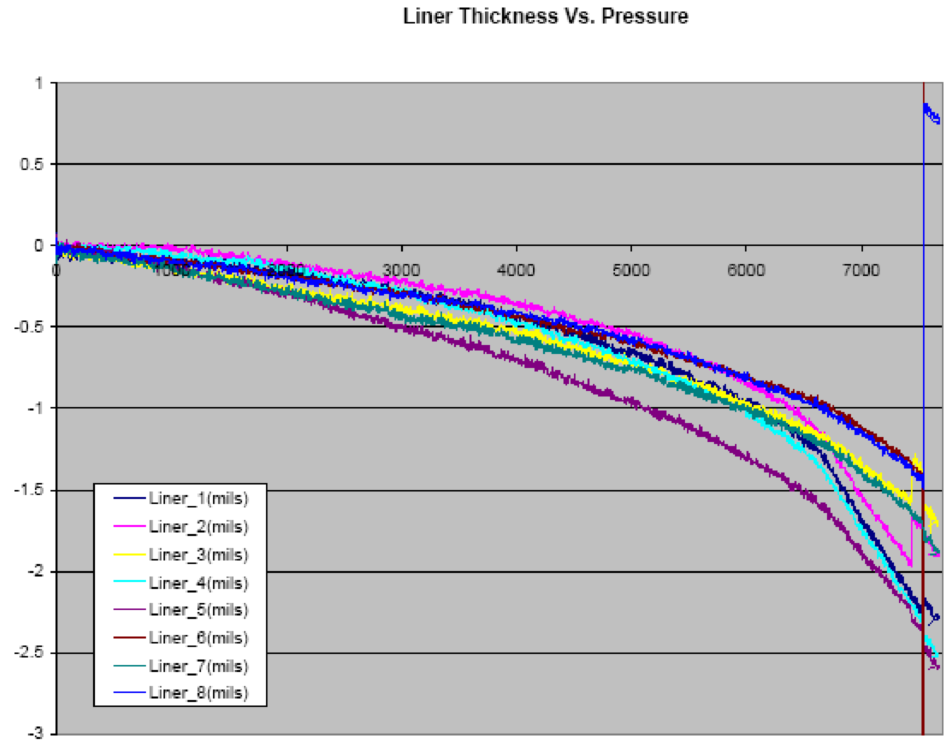


OMS Kevlar Pretest NDE Conclusion

- Large ripples around the girth weld raised a question
  - 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
    - Stand-off remained fixed during pressure cycles, indicating that the indications were not a concern

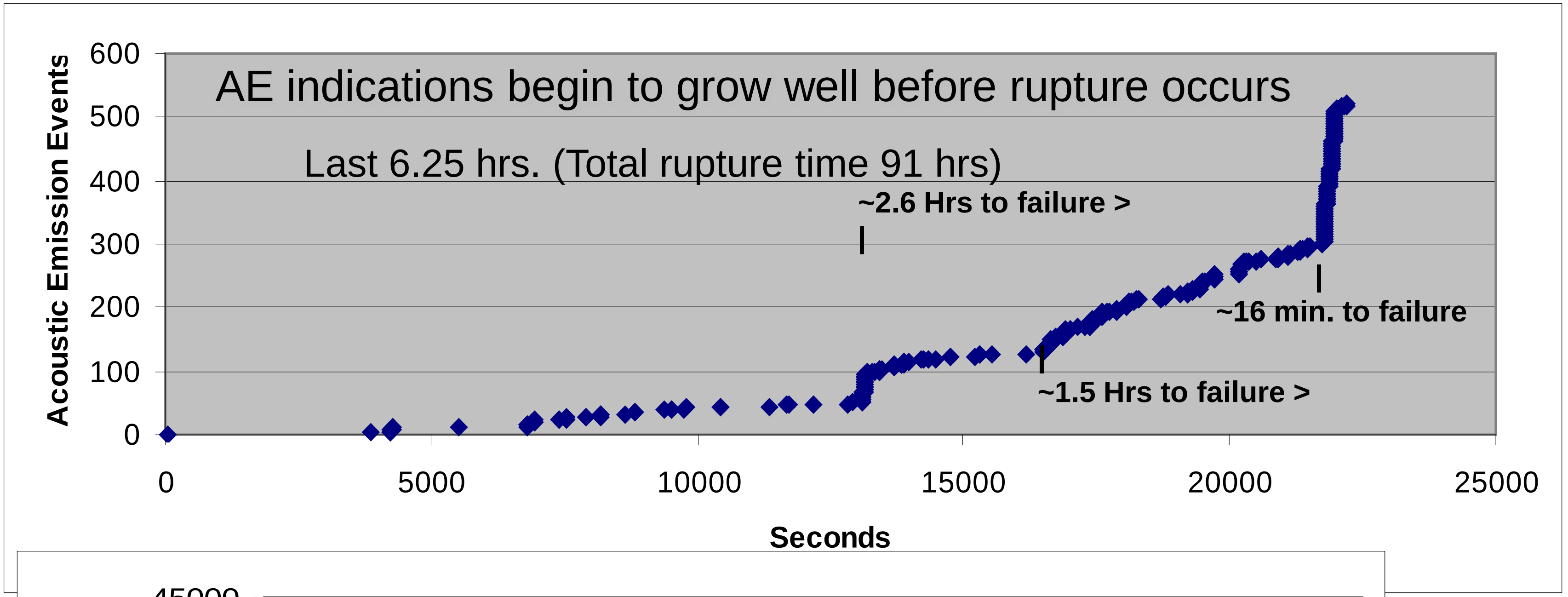
Example of Overwrap and Liner Thickness Evaluation by Eddy Current

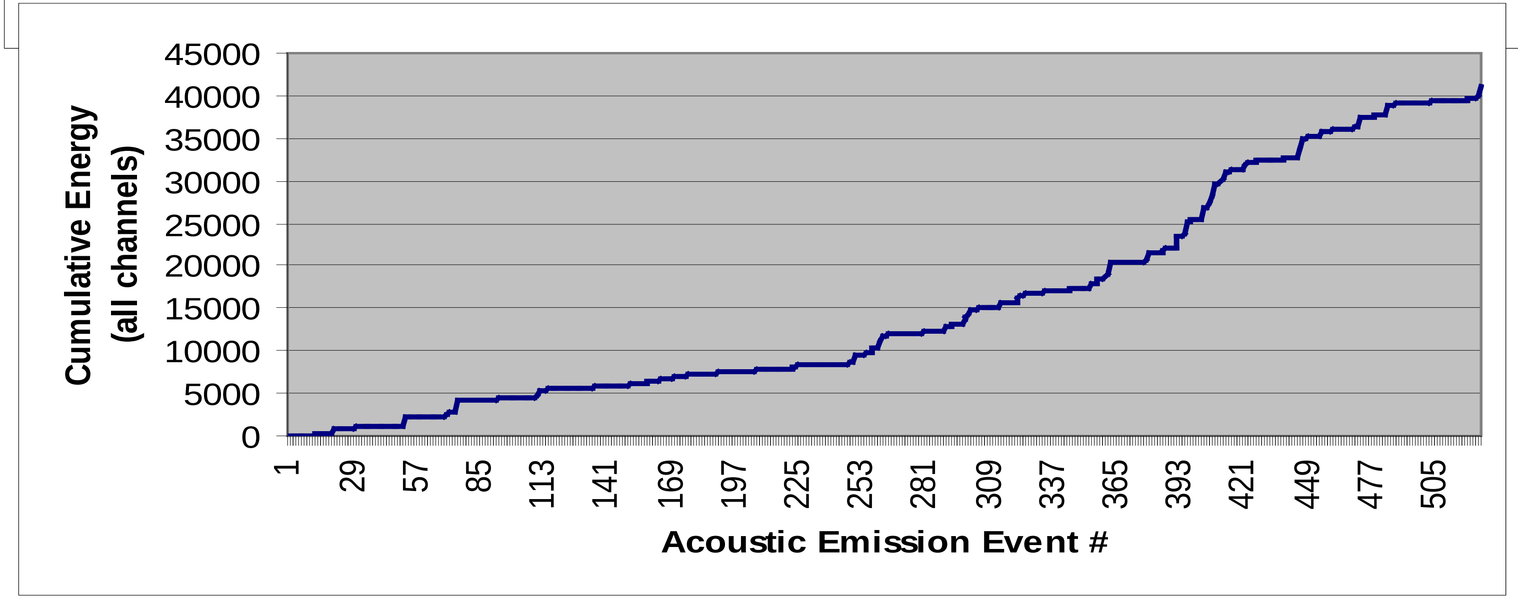




NNWG Kevlar AE Data-Subscale

Events and Energy vs. Time (Accelerated)

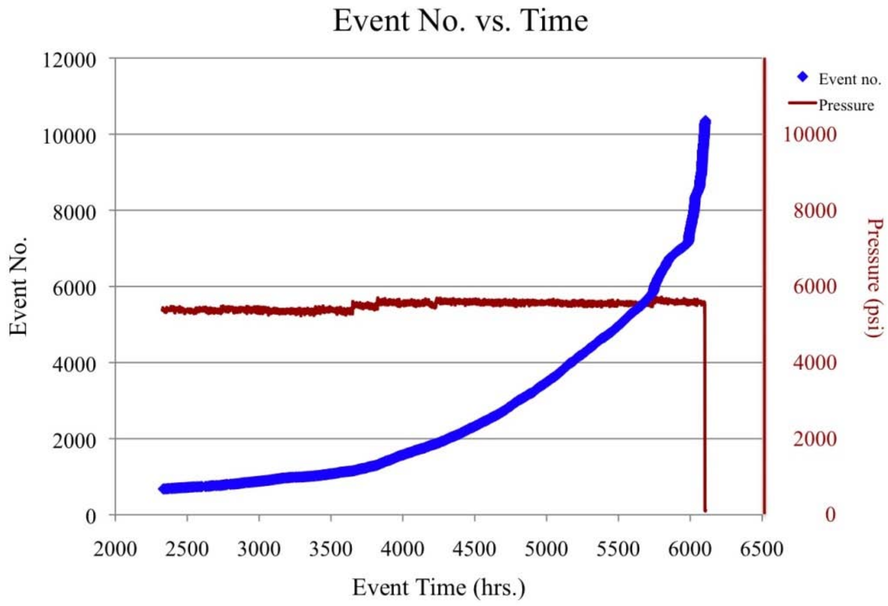


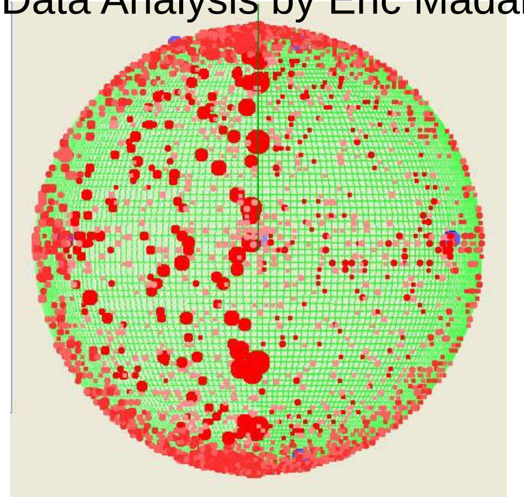


19

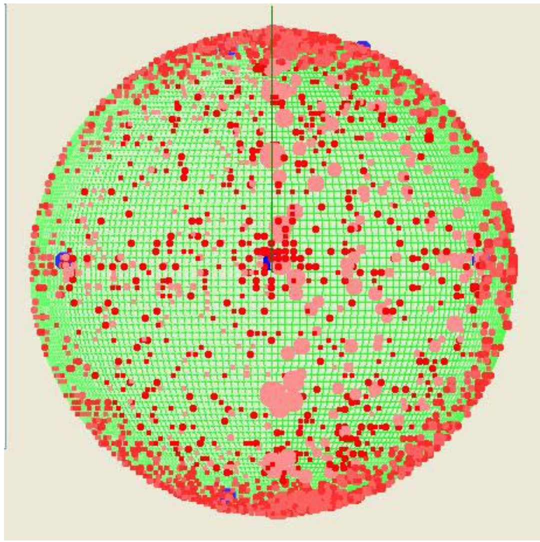
AE Effective in Monitoring Orbiter 40-in. Vessel Stress Rupture Progression to Failure

AE Data Analysis by Eric Madaras

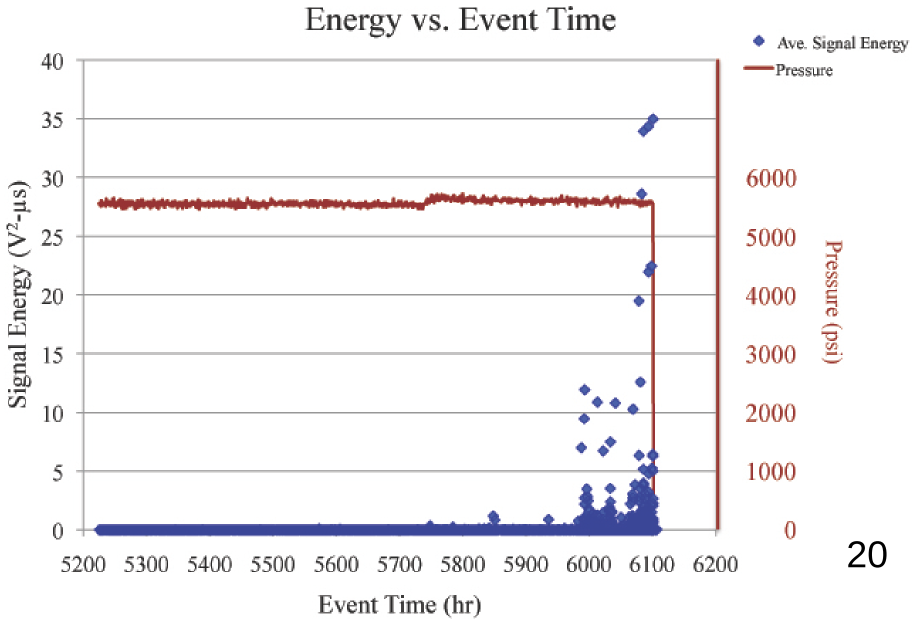




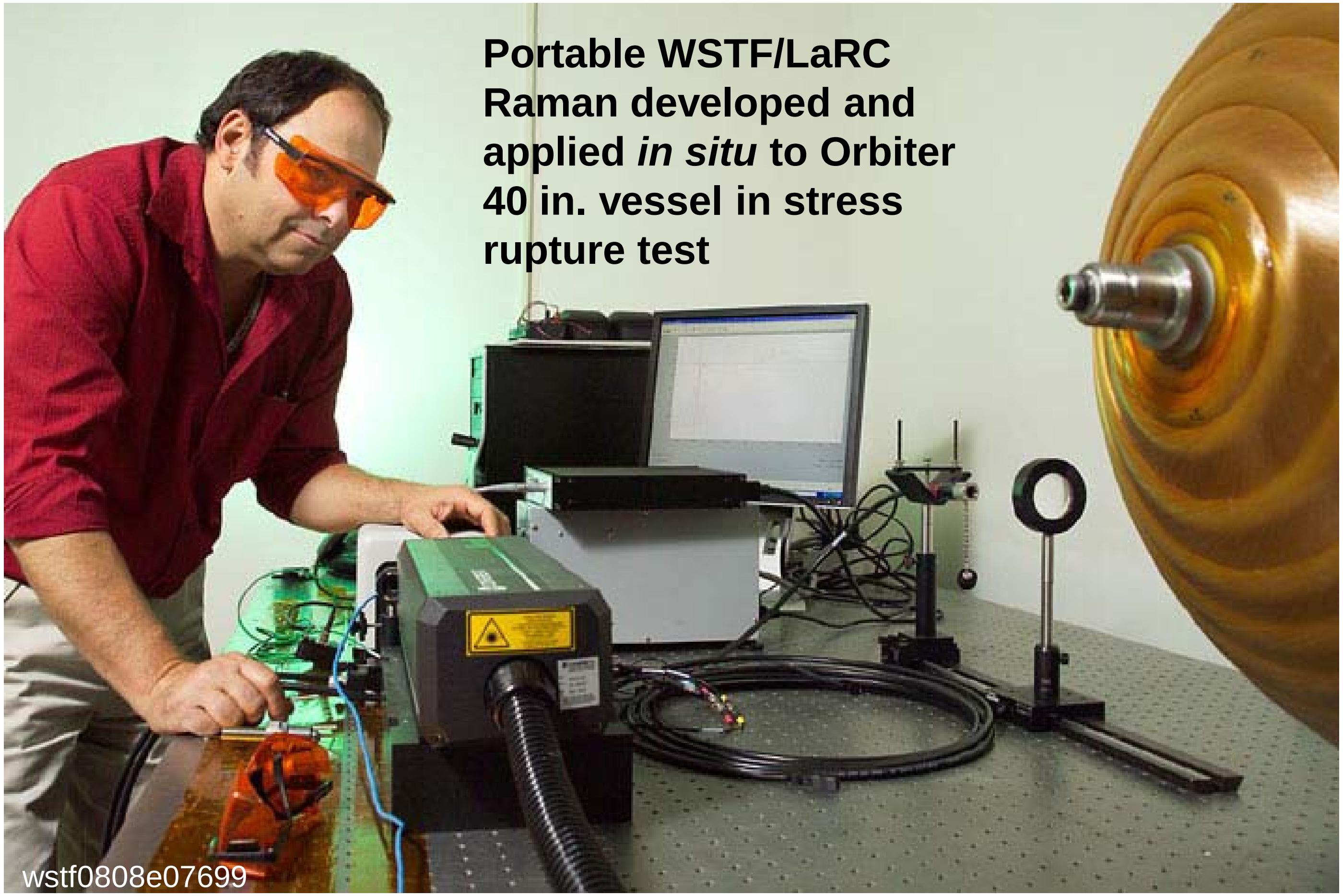
0º view—Front view



180º view—Back view

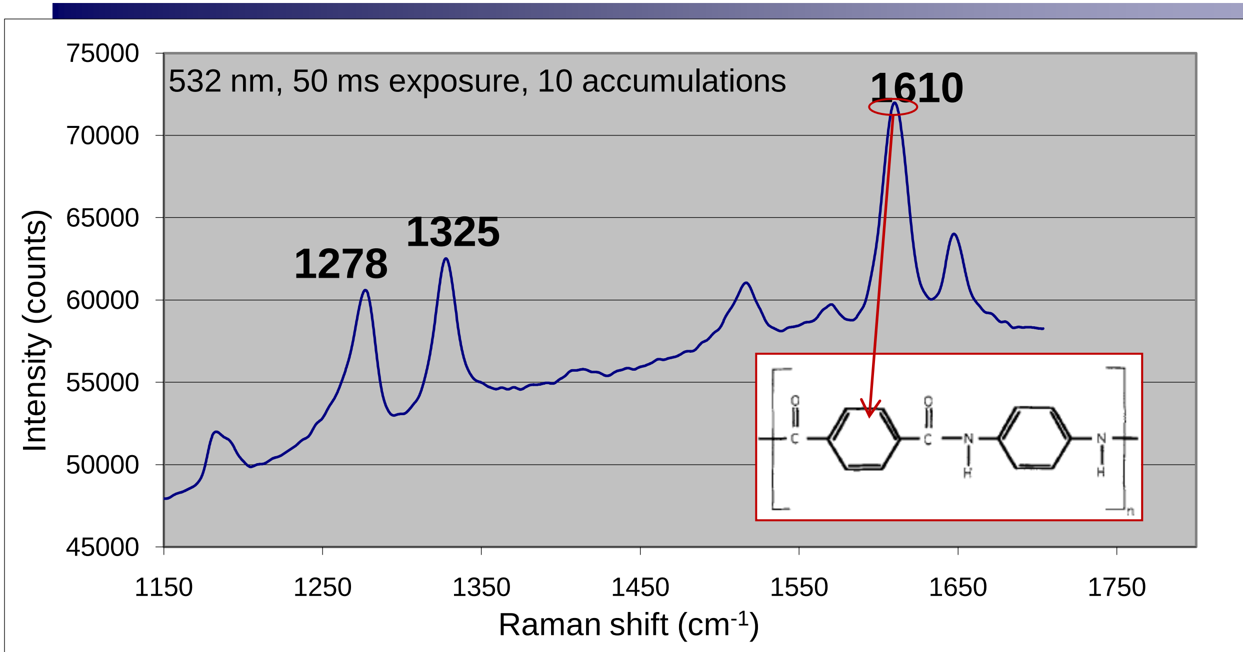


Portable Raman System Developed to Allow Real-time Raman Spectroscopy During Testing



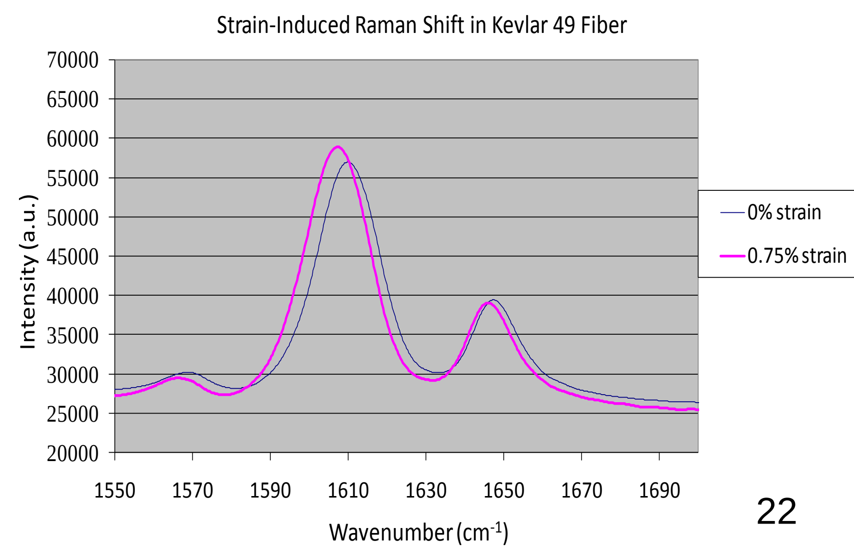
Tim Gallus performing bench top testing of a Raman spectography system prior to installation in the test cell

Typical Raman Spectrum of Kevlar

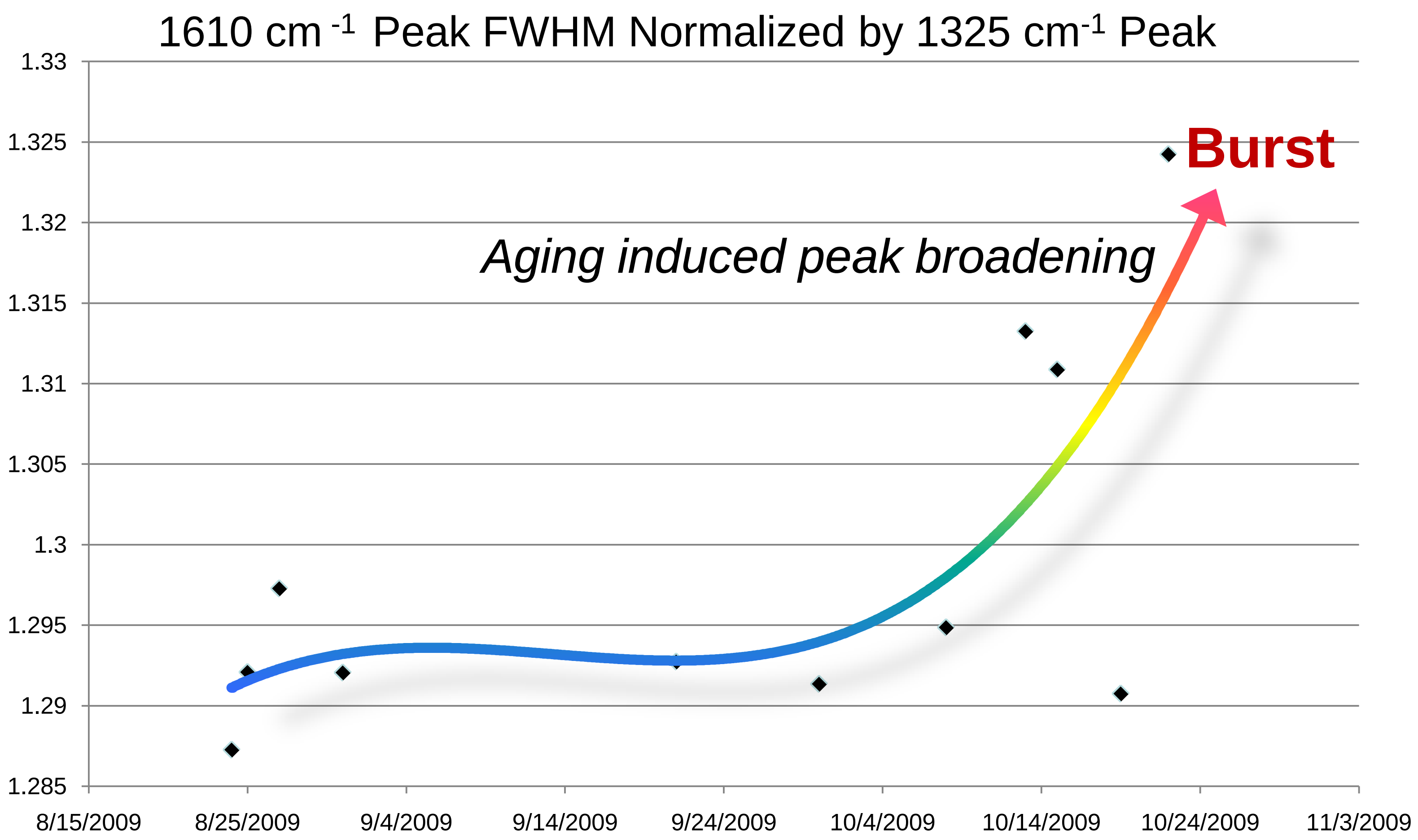


Raman Data by LaRC-Buzz Wincheski and Philip Williams

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)

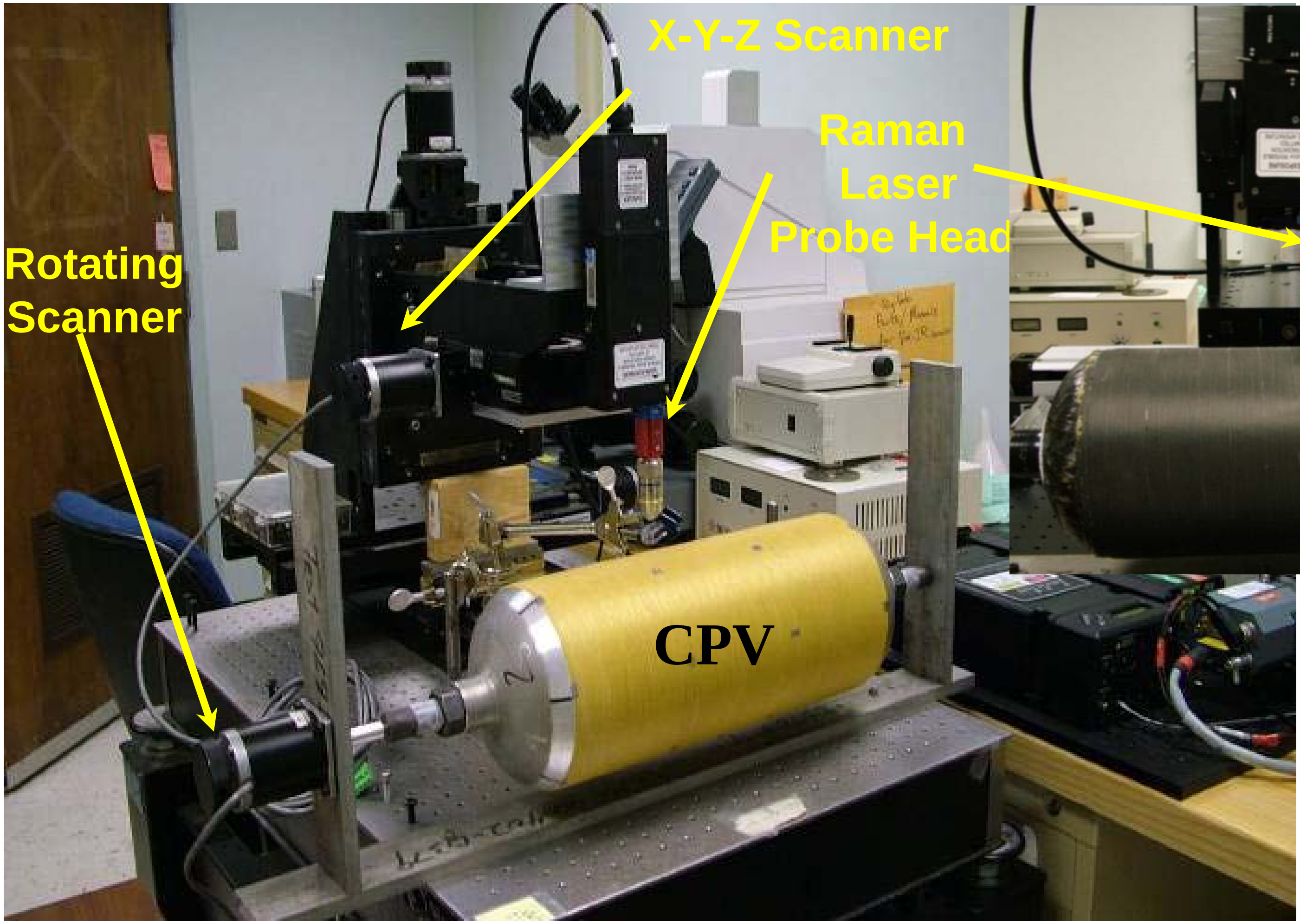


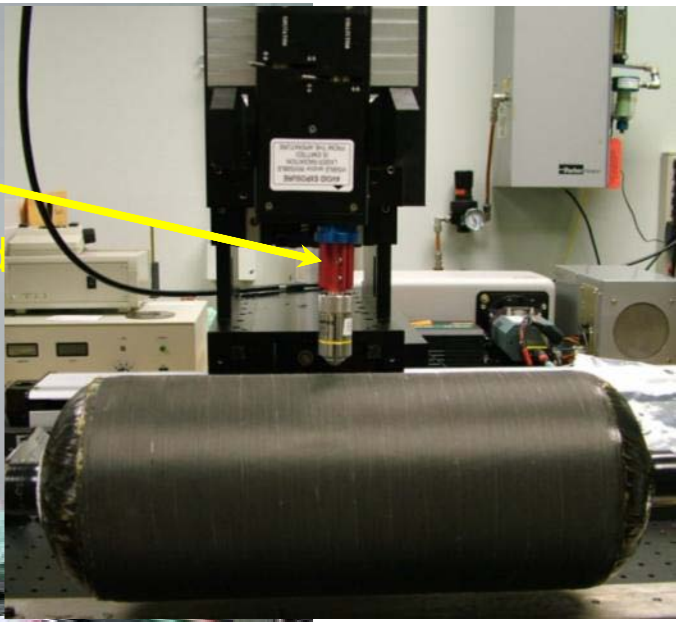
Real-time Raman During COPV SN007 Stress Rupture Testing - 8/15-10/22/09



Note: FWHM = Full Width at Half Maximum

Remote Scanning Raman Configuration

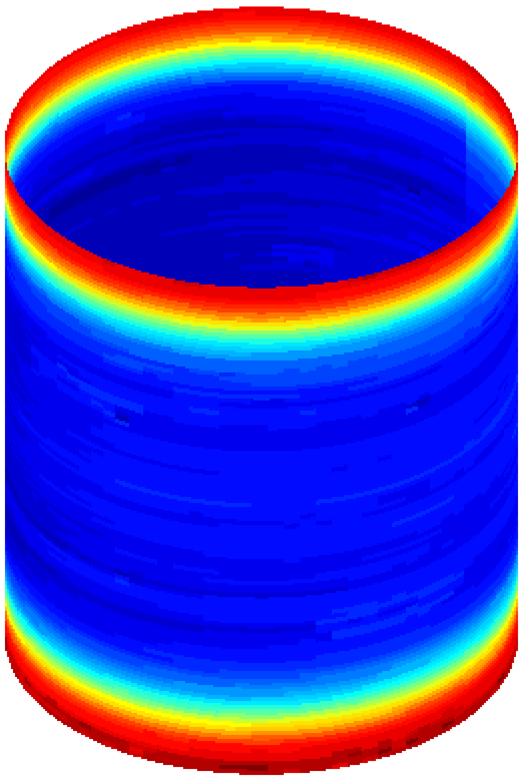




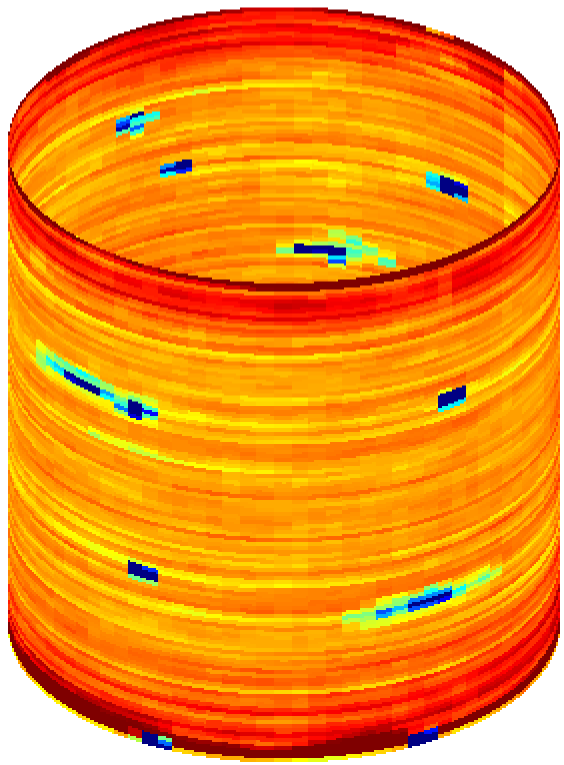
LaRC Experimental Setup for Measurements on 6.25 in. NNWG Kevlar® and Carbon CPVs

360 Degree Raman Scan of COPV S/N 009

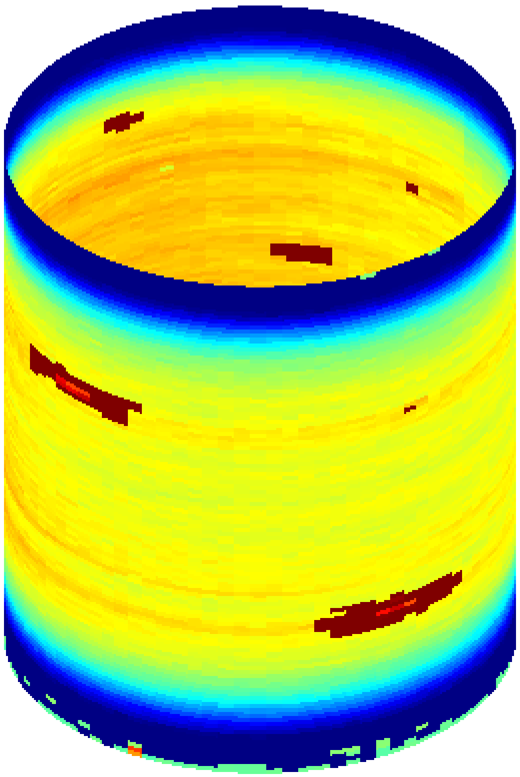
Position of 1610 cm^{-1} peak



Amplitude of 1610 cm^{-1} peak



FWHM of 1610 cm^{-1} peak



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
  - 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

Progress – Carbon Stress Rupture Project (cont'd)

- State-of-the-art 20 station test system brought on-line
  - Maintains pressure at approximately 27 ± 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

Progress – WSTF Carbon Stress Rupture Project (cont'd)

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

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 before and after aging and inspect for buckling	WSTF/WSTF
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 (conventional and Acousto-Optics)	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

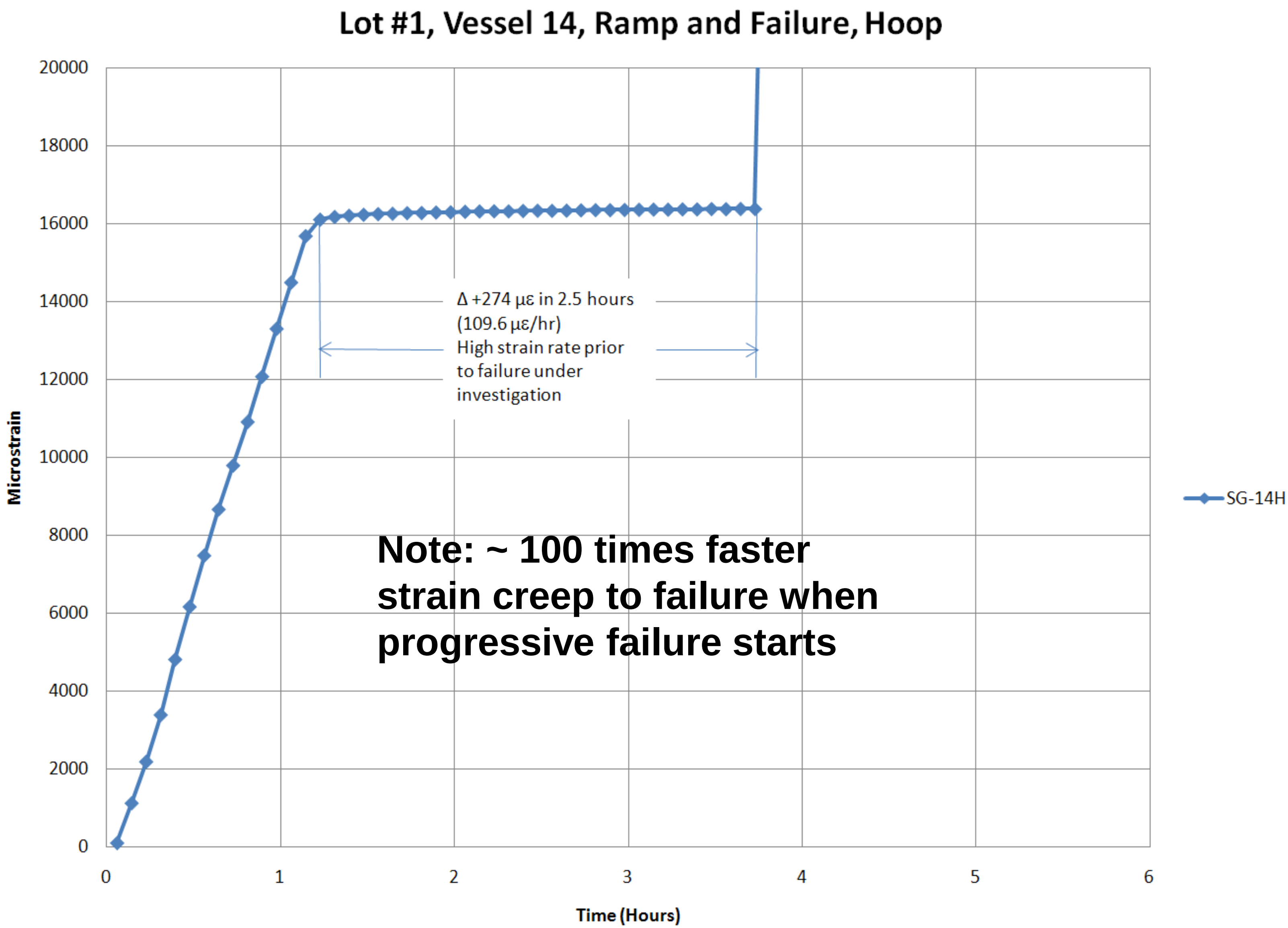
Carbon Aging Instrumentation NDE and DI Plan (cont'd)

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 applied as made available from SBIR/STTR Phase I/II and by participating Centers	WSTF/JSC, MSFC, & GRC

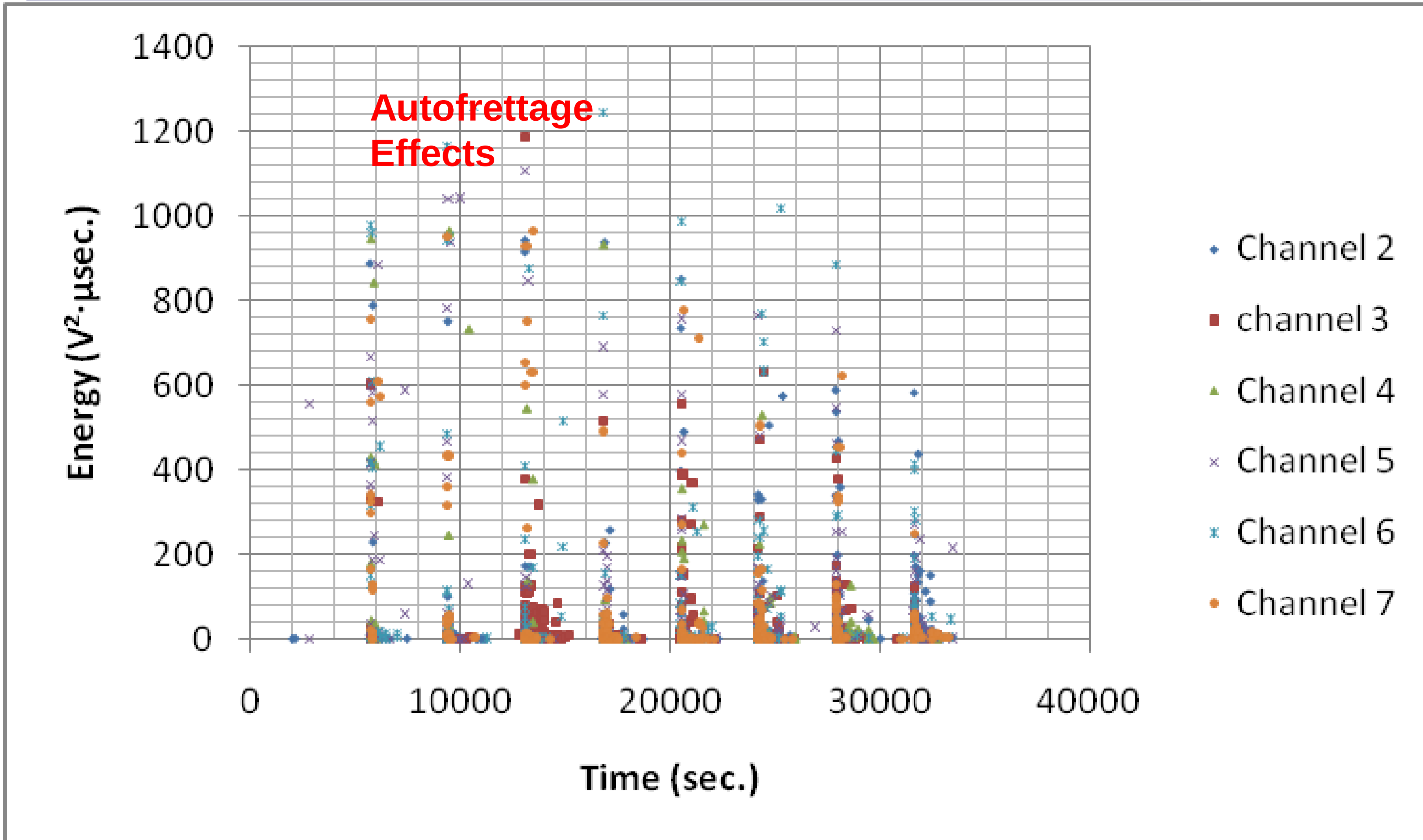
Progress – Carbon Stress Rupture Project (cont'd)

- 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
- NESC correlating stress rupture progression rate data with existing community database

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



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



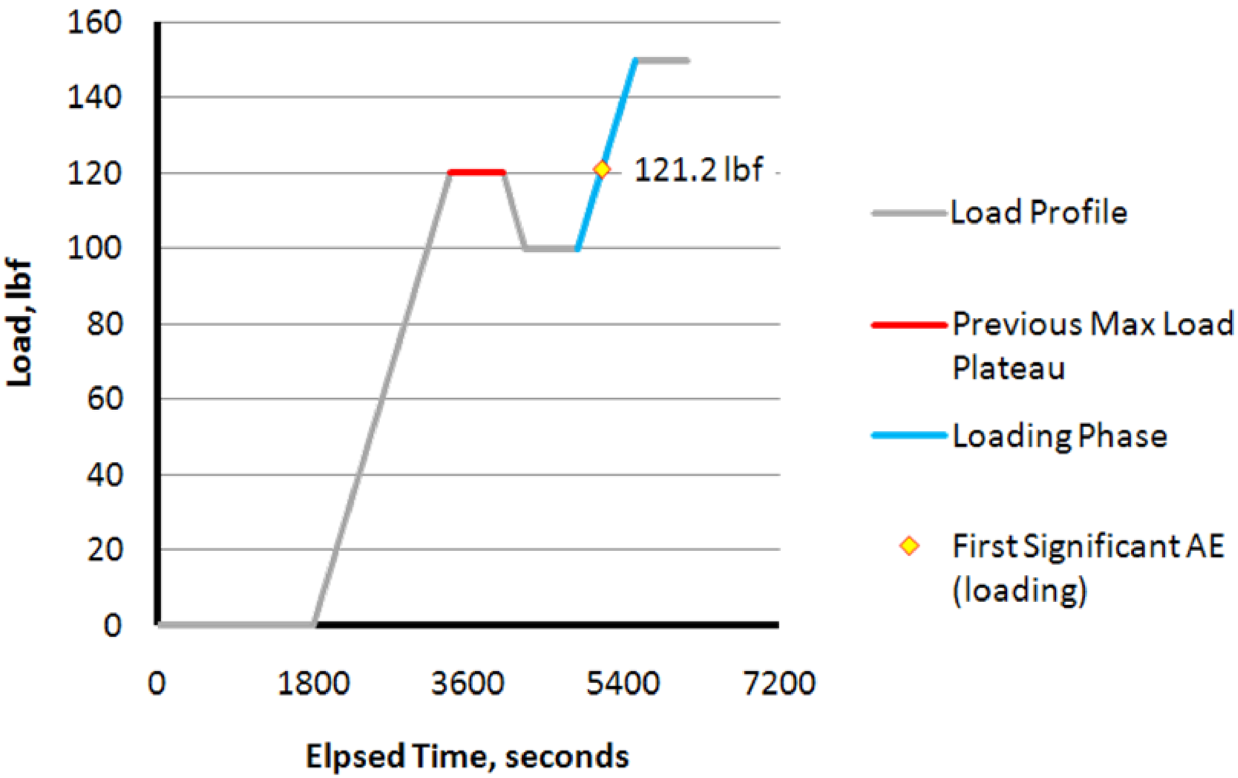
AE on smaller C/Ep vessels not always predictive without additional work

Felicity Ratio

Felicity ratio (FR) given by:

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

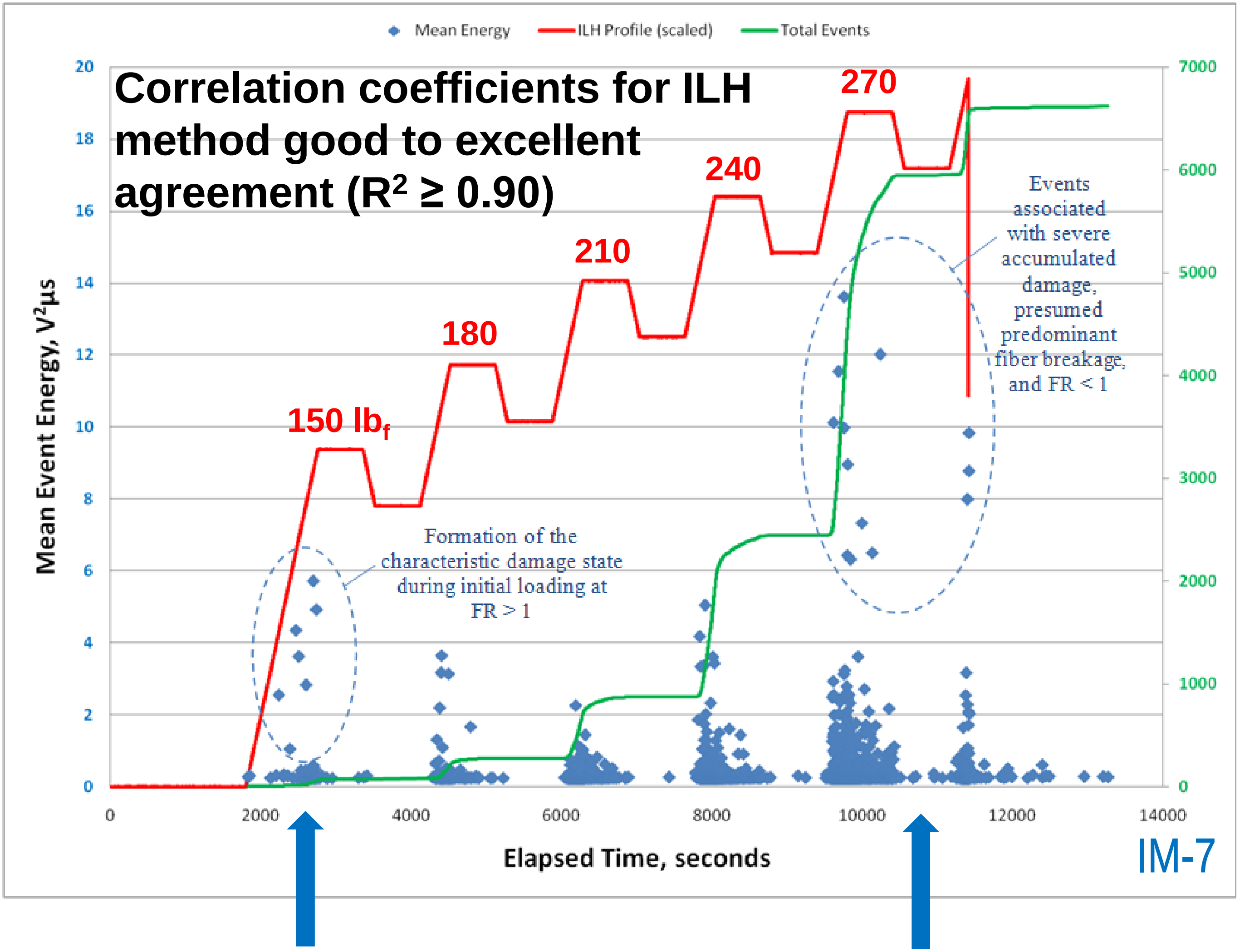
Example using an intermittent load hold (ILH) profile:



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

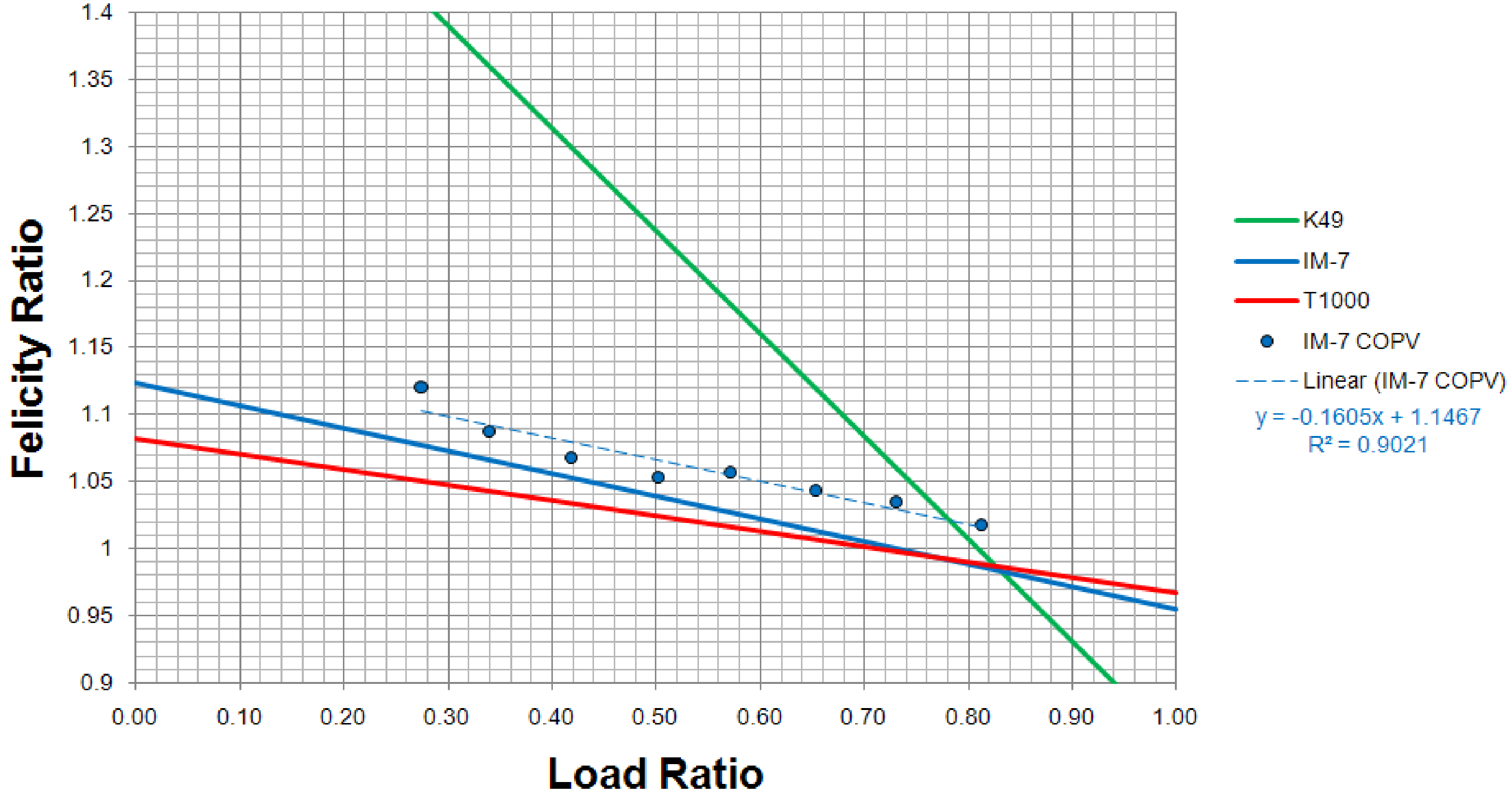
C/Ep Results & Discussion

Regions of high AE activity correspond to events occurring early in COPV life cycle up to catastrophic failure



Correlation of IM7 C/Ep COPV AE Felicity Ratio to Strand Data

IM-7 tow data (solid blue line) consistent with IM-7 COPV data (blue symbols)



Proof-of-concept Felicity ratio analysis of an IM-7 reinforced C/Ep COPV (blue dots) superimposed on Kevlar® 49 (green line), T1000 (red line), and IM7 (blue line) single tow data

Conclusion

- NDE has proven highly effective in real-time characterization of COPVs during testing
  - Accelerated stress rupture projects are being successfully performed
- NDE is reasonably effective in evaluating the initial and on-going health of COPVs, but more work is needed to make it more quantitative and predictive
- The WSTF NNWG Carbon COPV Stress Rupture test is well controlled and informative
  - Collaboration on SHM/NDE sensor evaluation is invited
- NASA WSTF is very interested in safe utilization of composite vehicle/storage vessels
  - Facilities and expertise are available to support vessel testing including hydraulic, hydrostatic (high energy blast facility), and cryo with comprehensive characterization capability

Backup

Many collaborations and partnerships formed out of the 2009 Composite Pressure Vessel Summit

http://www.nasa.gov/centers/wstf/news/safetysummit2009.html

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

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

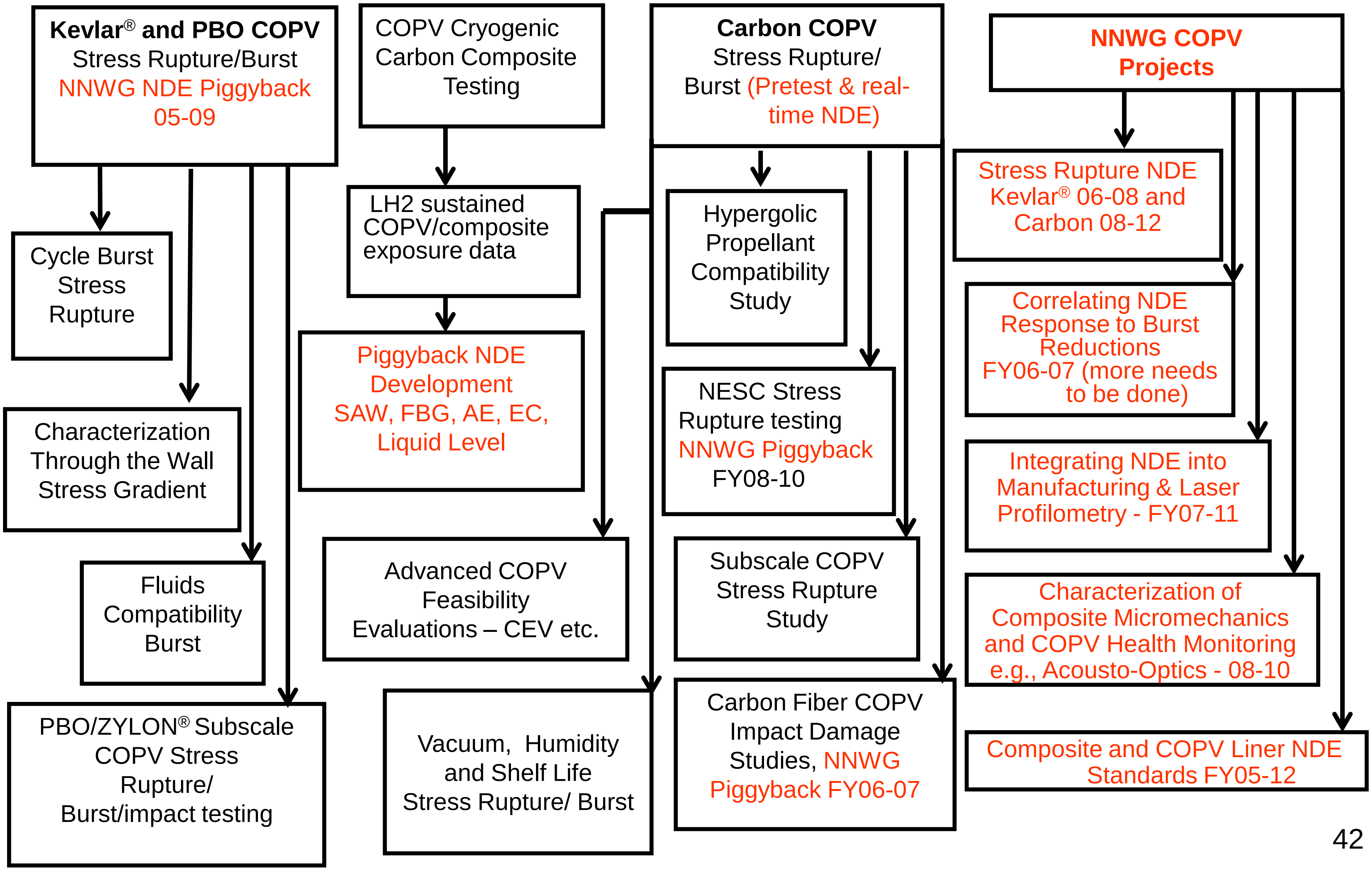
Stennis: Joseph Grant - FBG
DFRC: Lance Richards – FOBG consulting
GRC:
- Don Roth – NDE (e.g., guided waves)
- Fran Hurwitz – extensive destructive analysis (Jeffrey I. Eldridge – Raman)

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

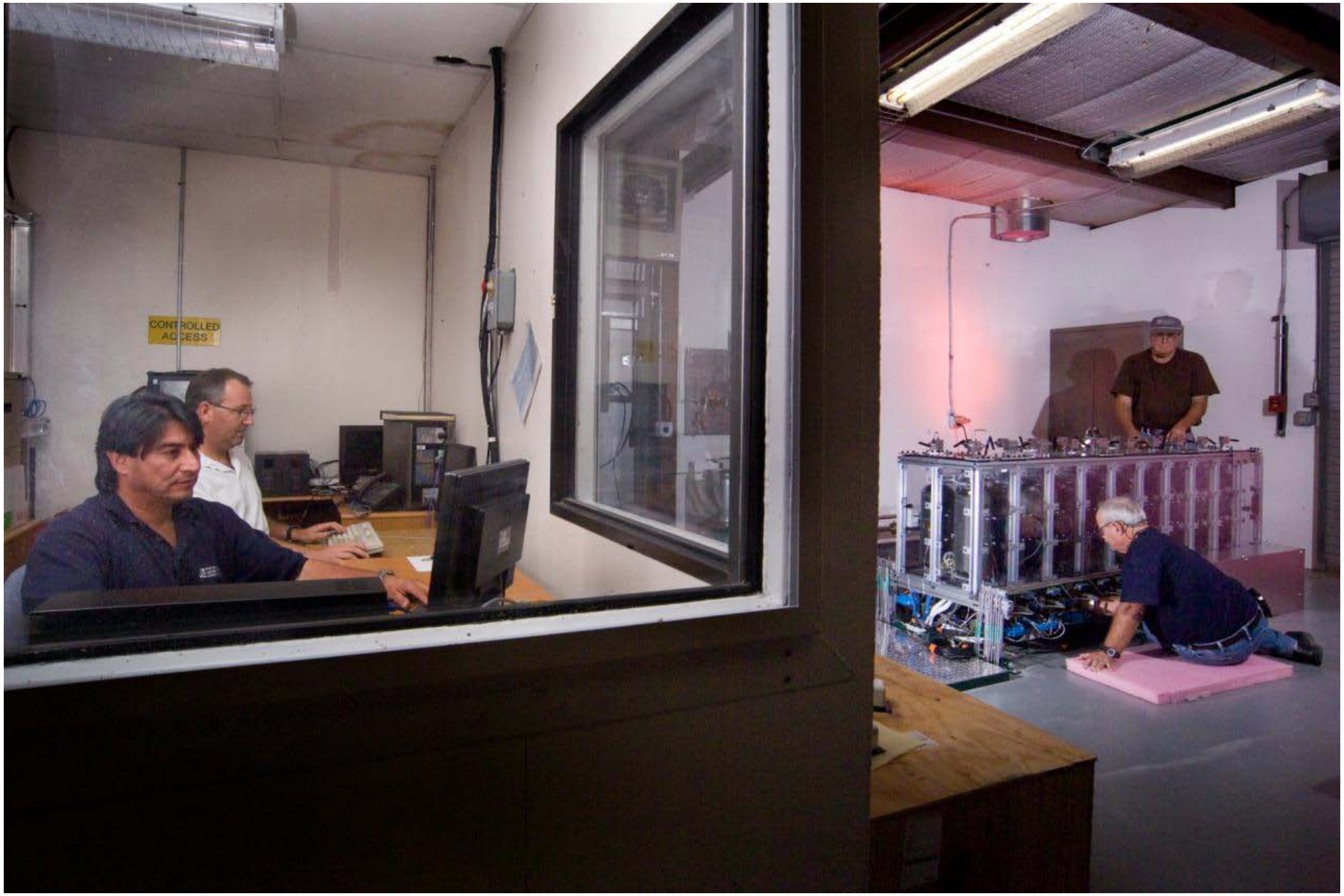
Cornell University:
- Leigh Phoenix – Stress rupture consulting and laboratory testing

Composite Vessel Test Programs – Multi-Center

(NDE in red)

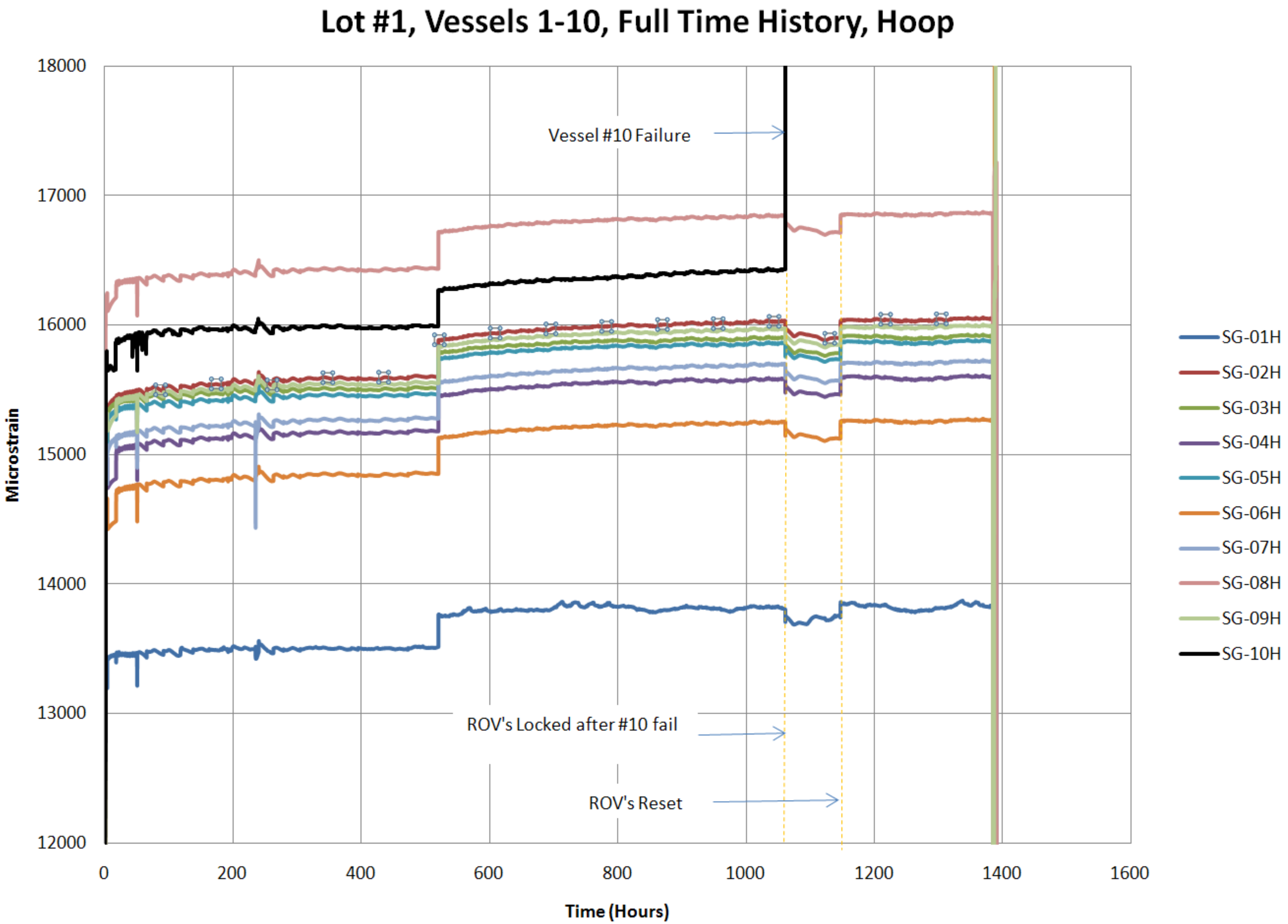


Preparing the Stress Rupture Test System



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

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



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?

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

Materials Properties Measurements