



NDE Methods for Certification and Production/Performance Monitoring of Composite Tanks

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Use of Modal Acoustic Emission to Monitor Damage Progression in Carbon Fiber/Epoxy Tows and Implications for Composite Structures

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Applications of Acoustic Emission to Composite Pressure Vessels – Manufacturing Certification and Correlations with the Residual Strength Loss Due to Impact Damage

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Nondestructive Evaluation and Monitoring Results from COPV Accelerated Stress Rupture Testing

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NASA LaRC: Eric Madaras

NASA JSC: Scott Forth

NASA MSFC: Curtis Banks

NASA/KSC: Richard Russell

Cornell University: Leigh Phoenix

Background

Problems:

- COPVs can be at risk for catastrophic failure
 - Risk of insidious burst-before-leak (BBL) stress rupture¹ (SR) failure of carbon-epoxy (C/Ep) COPVs during mid to late life
 - Risk of lower burst strength of C/Ep COPVs subjected to impact damage
 - Failure at lower pressure than previous proof cycle was pressurized
- Issues with manufacturing defects and inspectability of COPVs on NASA spacecraft (ISS, deep space)
- Lack of quantitative NDE is causing problems in current and future spacecraft applications
 - Must increase safety factor or accept more risk
 - Thinner liners are driving need for better flaw detection in liner and overwrap

¹ SR defined by AIAA Aerospace Pressure Vessels Standards Working Group as “the minimum time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environment”

Background and Issues

- Safe applications of Composite Pressure Vessels (COPVs) 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

Background and Issues (con't)

- 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

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

Technical Methodology/Approach

- The recent carbon stress rupture testing builds on previous Kevlar[®] composite projects
 - NNWG carbon stress rupture project 2008-2012
 - NNWG Kevlar Stress Rupture 2006-2008
 - Orbiter Kevlar testing 2006-2009
 - 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

Expanded Composite Stress Rupture NDE Team

WSTF:

- Regor Saulsberry – PM/project oversight, piggyback campaigns
- Jess Waller – acoustic emission, scheduling and project tracking assistance
- Mark Leifeste – laboratory analysis
- Tony Carden, Eddie Andrade, Charles Nichols – acoustic emission
- 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

UM-Columbia:

- Glenn Washer – Raman spectroscopy, technical recommendations

Cornell University:

- Leigh Phoenix – Stress rupture consulting and laboratory testing

Technical Methodology/Approach (con't)

- 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

WSTF Orbiter COPV Instrumentation and NDE During Rupture and Stress Testing

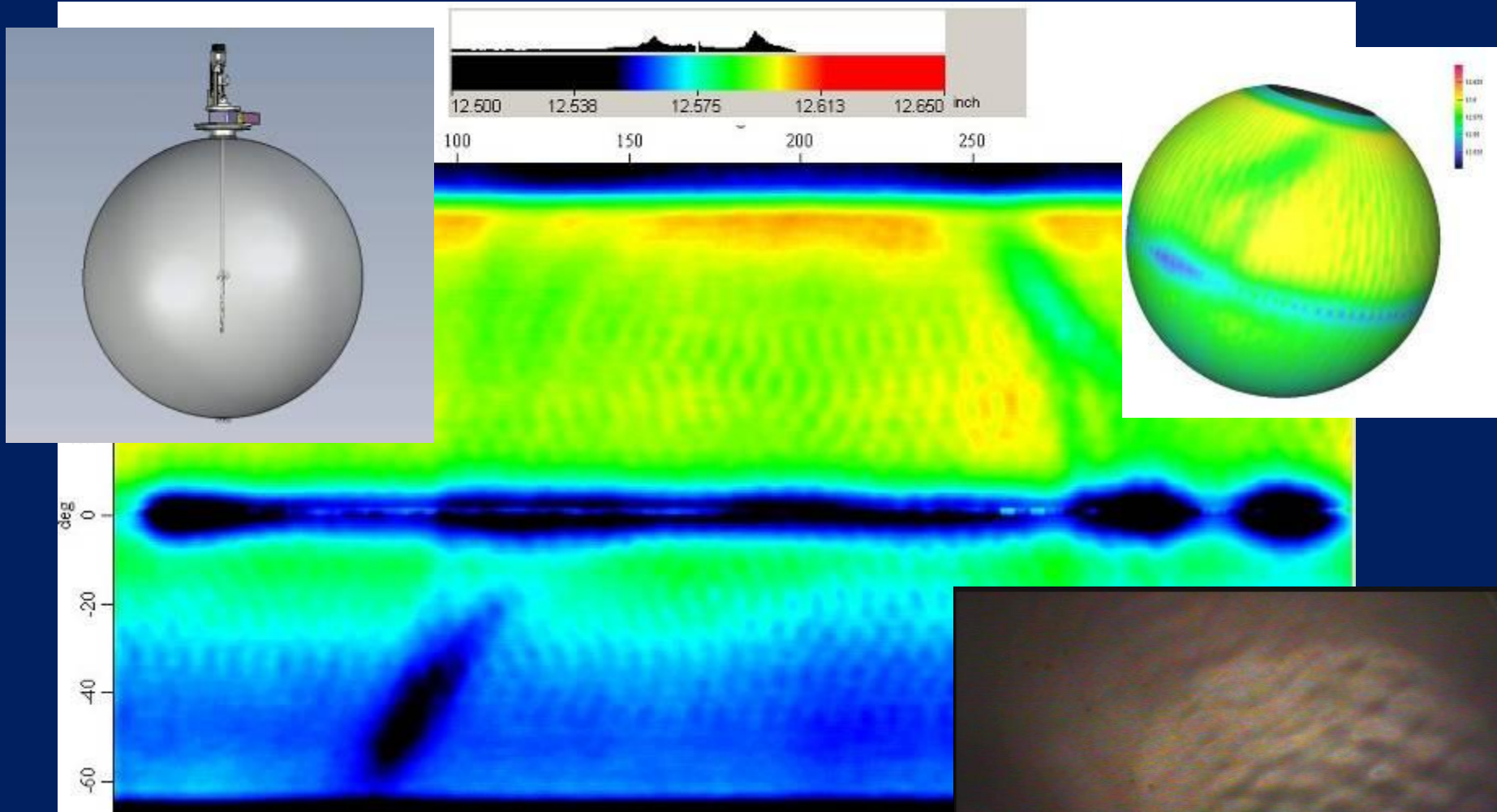
Method	Measurement
Visual Inspection (Pretest)	External inspection of overwrap. Indication of gross damage
Both Flash and Heat Soak Thermography (Pretest)	Heat Signature Decay Sub-surface Ply Delamination. Heat soak or thru transmission works better with thicker composites.
Videoscope Inspection (Pretest)	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)

Pretest NDE

Orbiter Real-Time NDE

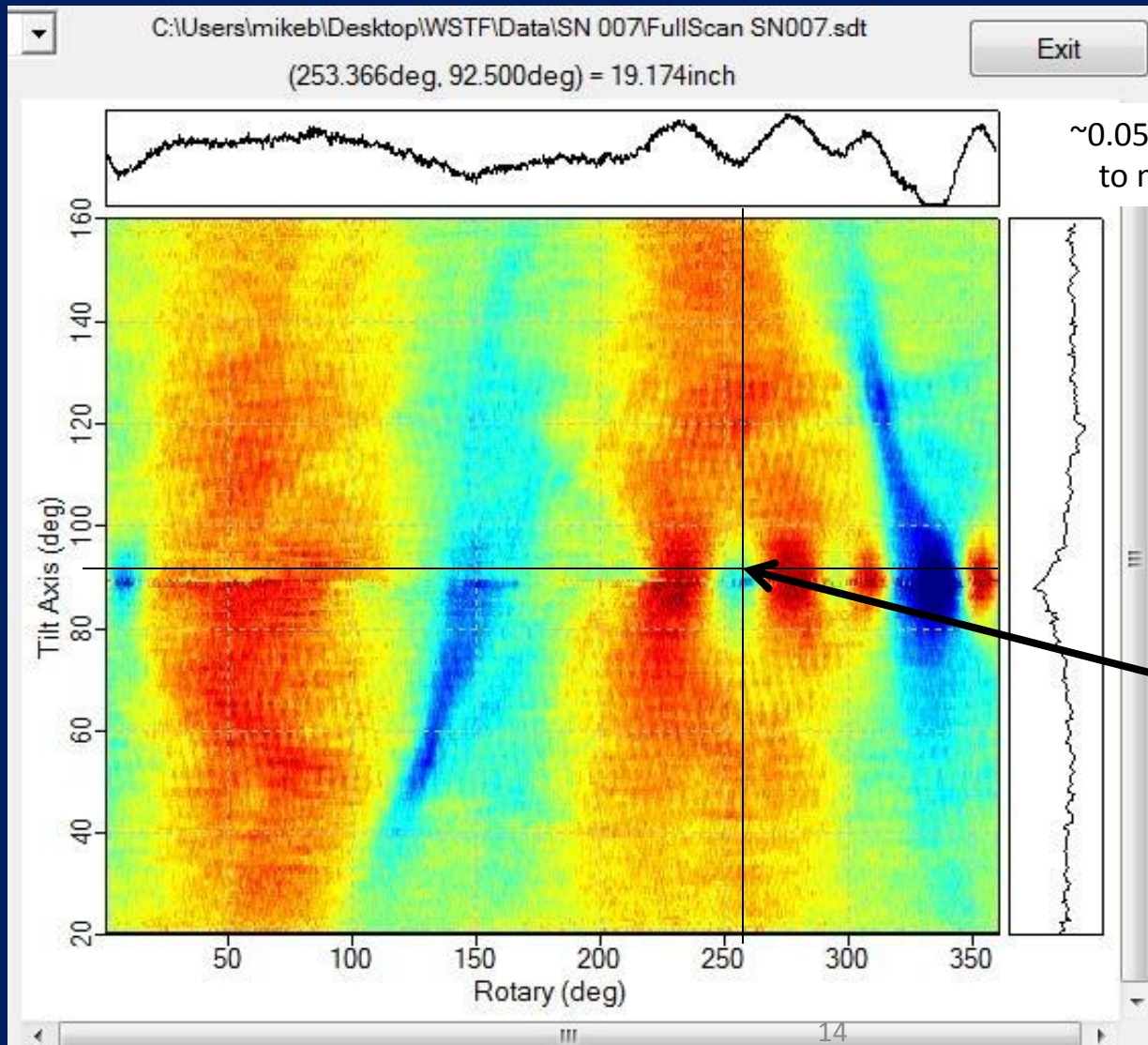


Laser Profilometry Accurately Quantifies Liner Buckling and Other Surface Features



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.



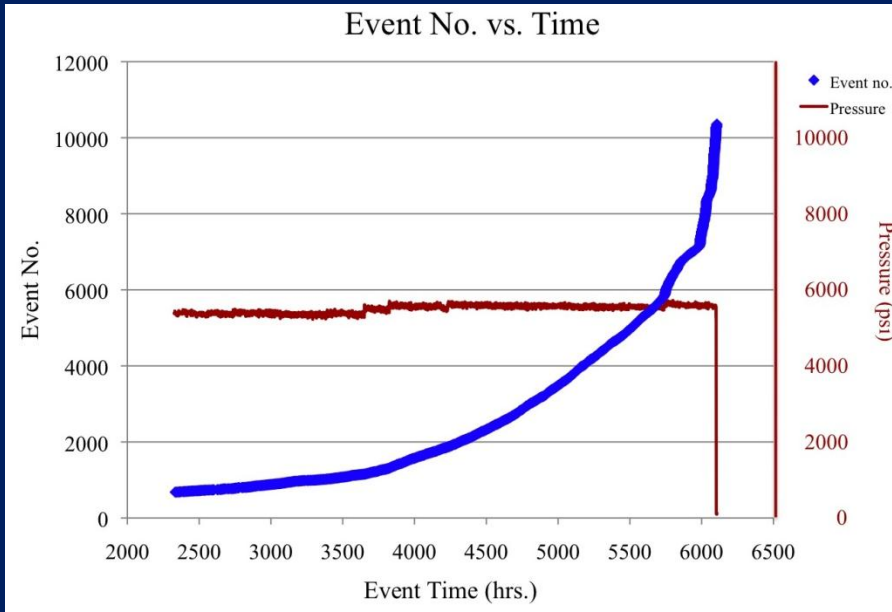
0.040 in. range

Profile just above weld

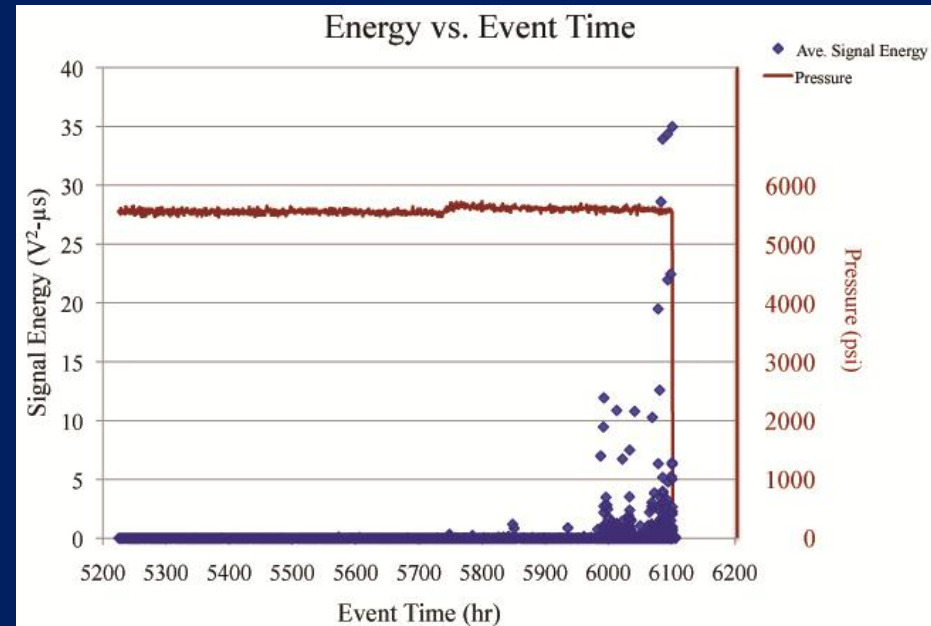
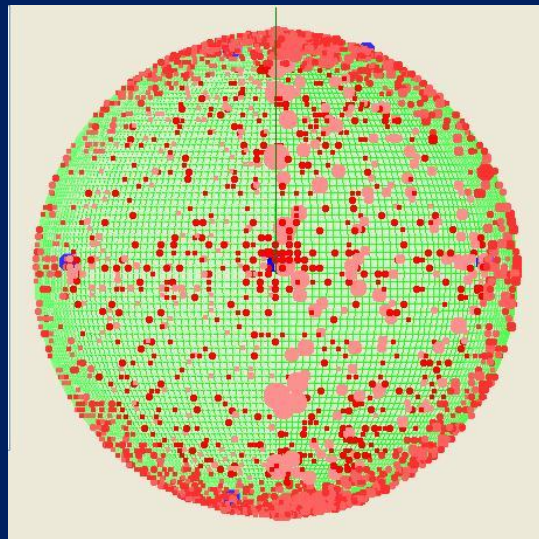
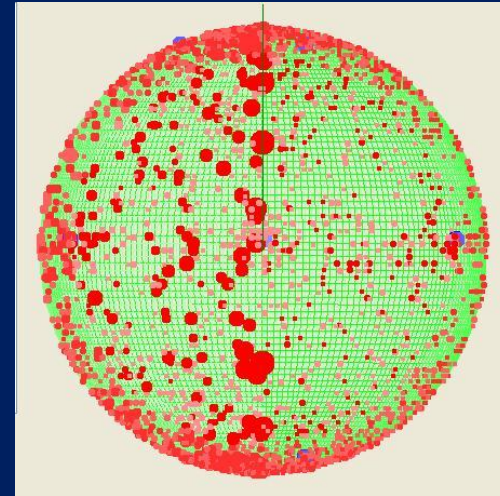
OMS Kevlar Pretest NDE Conclusion

- The large ripples around the girth weld raised a question, but no other 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

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

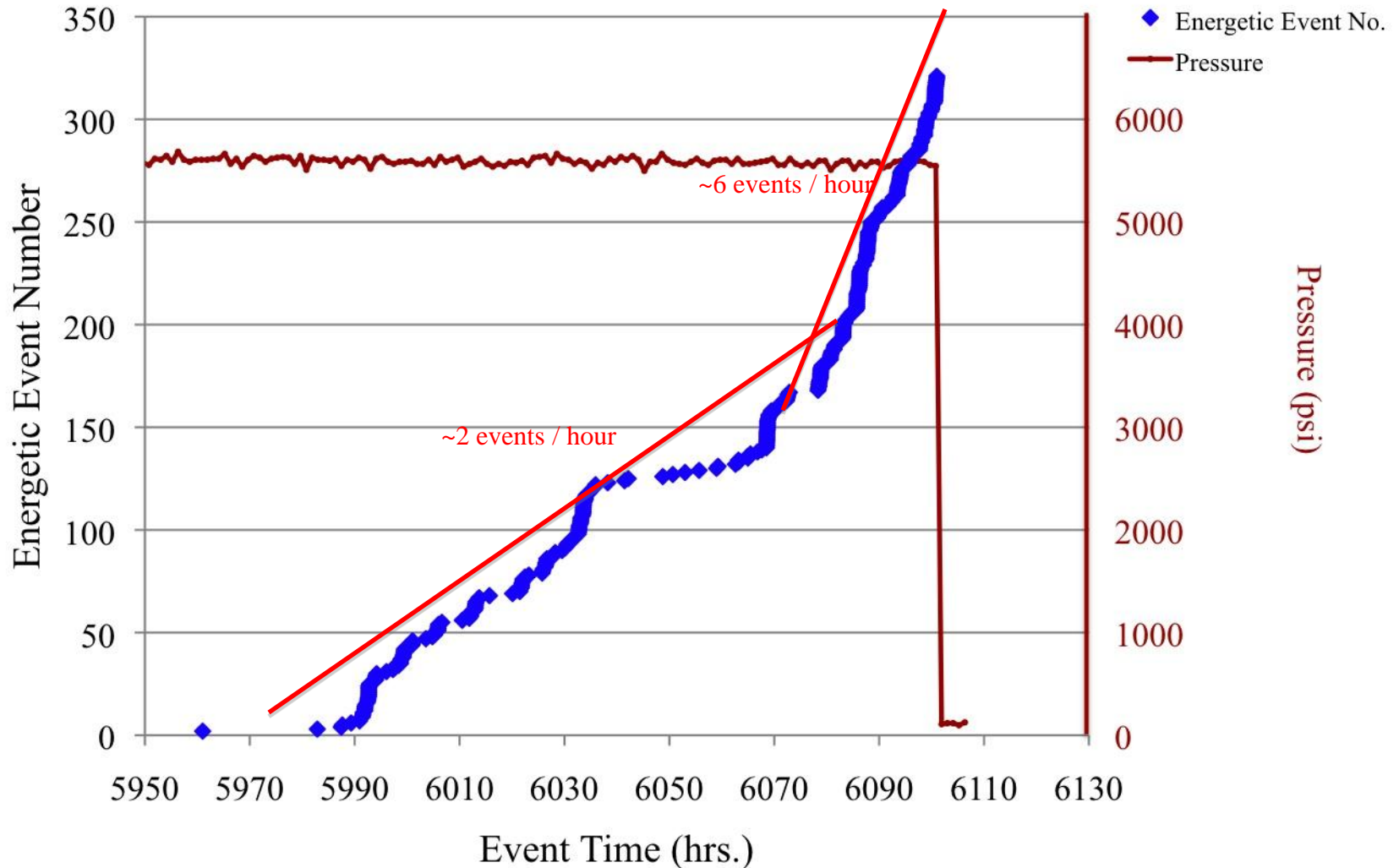


AE Data Analysis by Eric Madaras

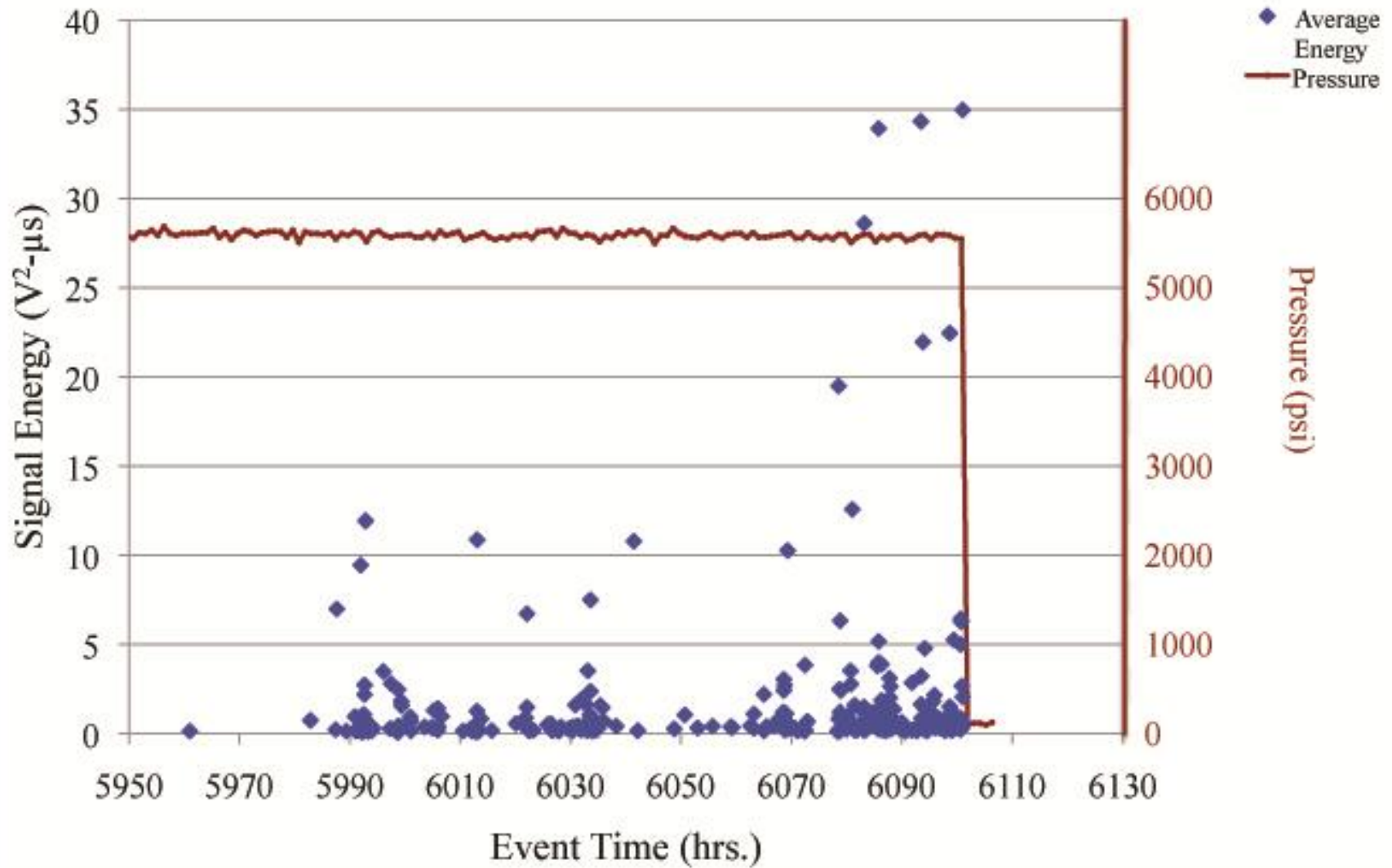


Final week of testing

Energetic Event No. vs. Time: Final Week

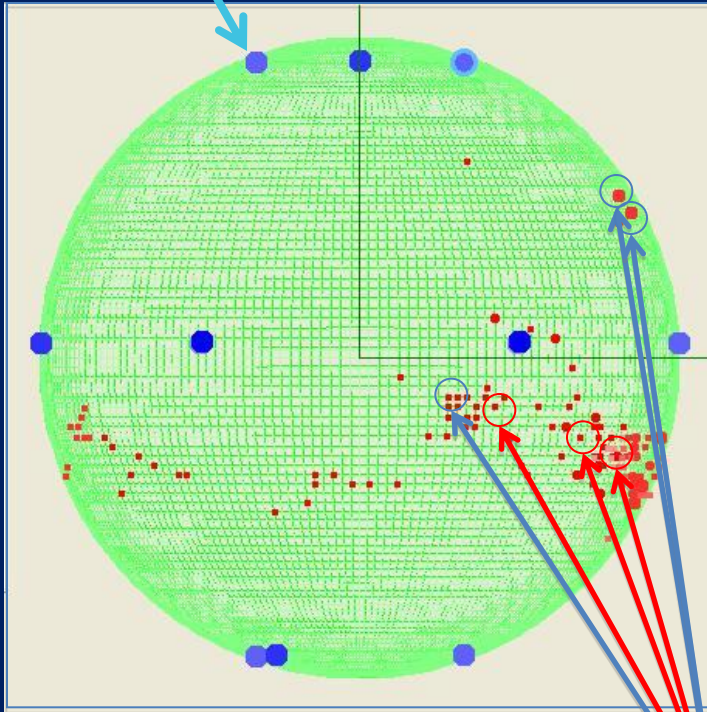


Energetic Signal Levels vs. Time: Final Week

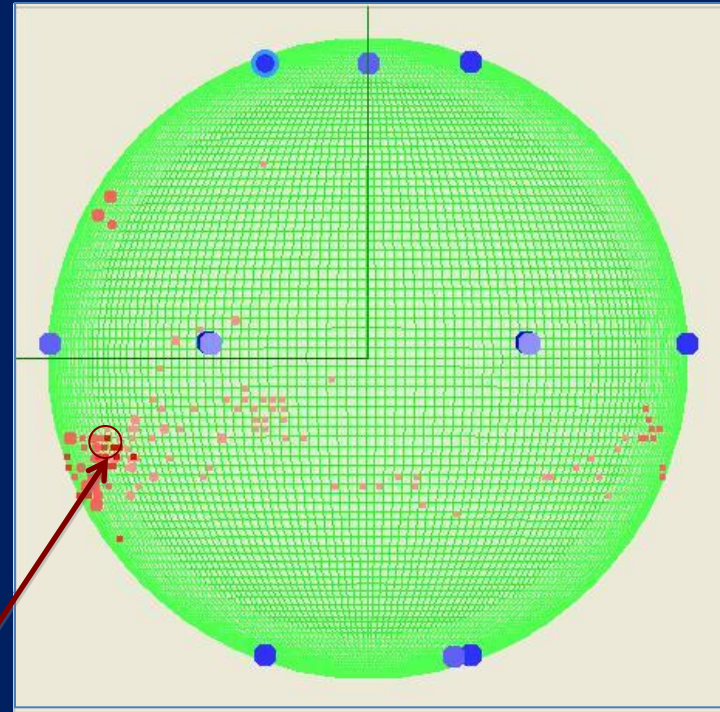


Final High Energy Burst (Final 24 h)

Sensors



-90° view—Back side view



90° view—Front side view

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)

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 $\sim 45^\circ$ below the equator and near the azimuth angle of 45° .

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
- NASA Engineering Safety Center (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)

- 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 hold pressure at approximately ± 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 – 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 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

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
Ultrasonic 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

Progress – Carbon Stress Rupture Project

- 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 waveform of 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

Progress – Carbon Stress Rupture Project (cont'd)

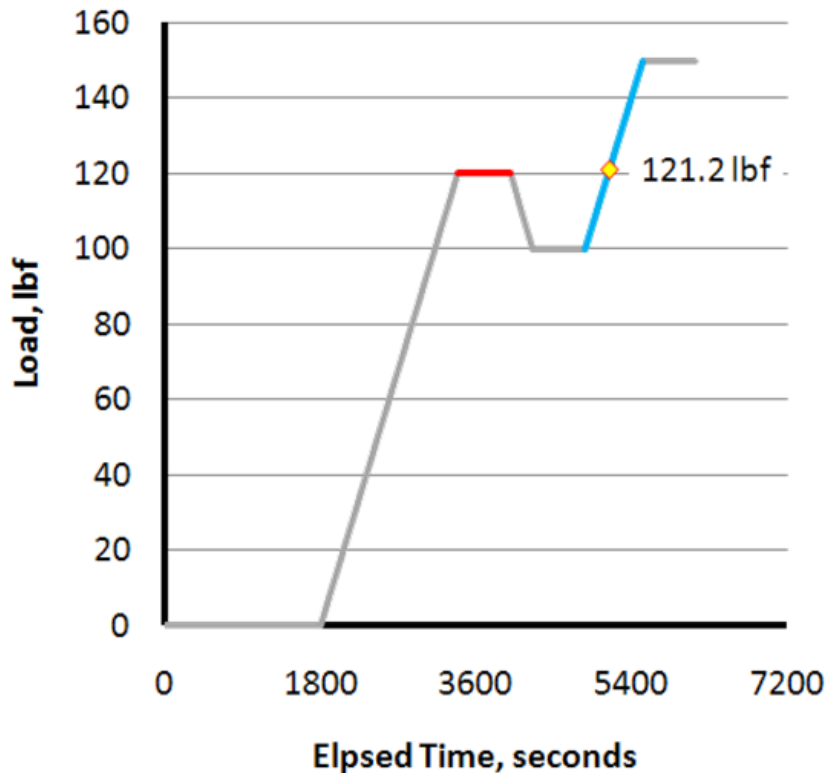
- NESC correlating stress rupture progression rate data with existing community database
 - Carefully controlled data should improve database
 - Profilometry also being done to directly evaluate residual deformation and growth (strain measurement) over the stress rupture period

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:

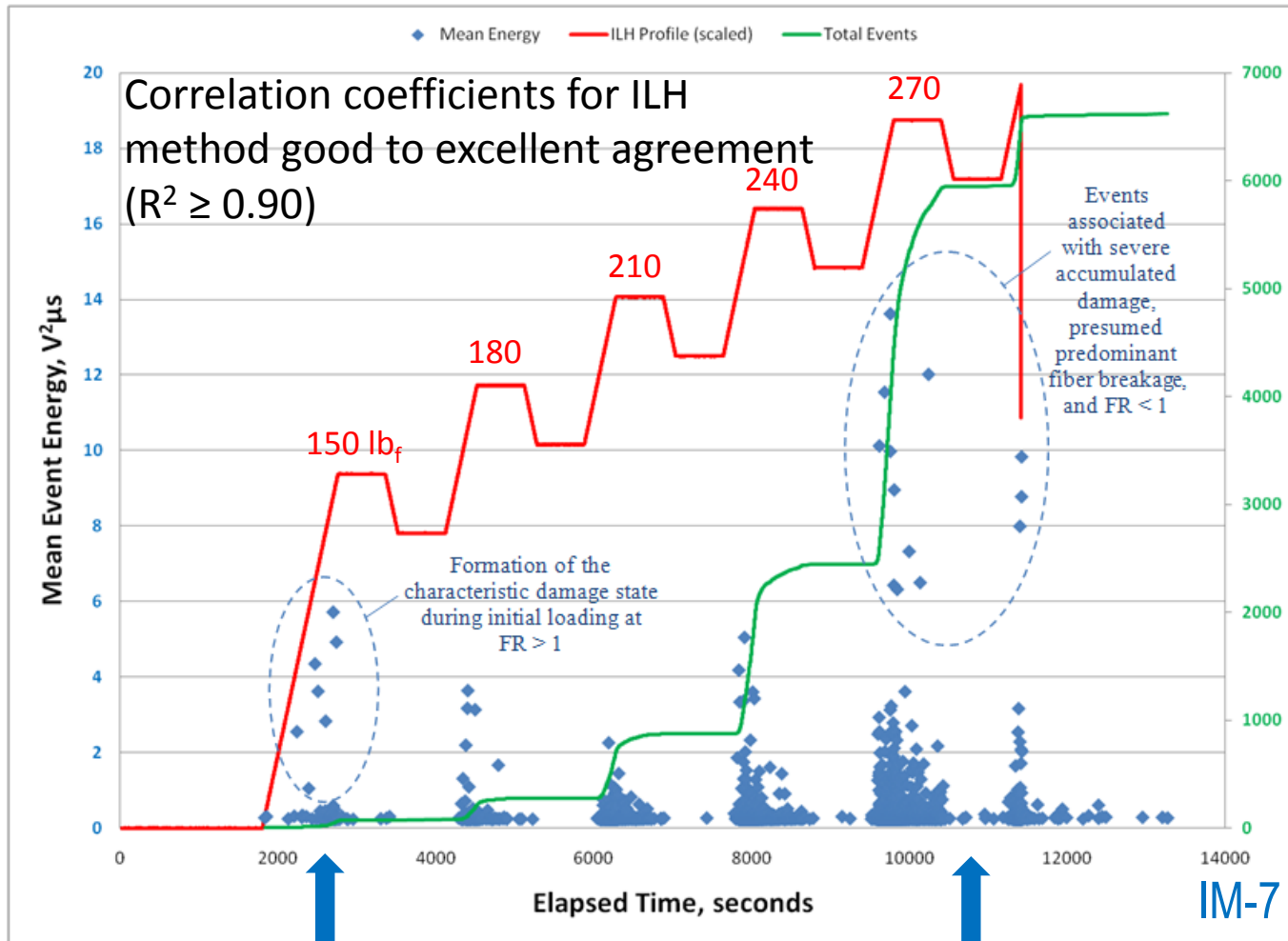


- Load Profile
- Previous Max Load Plateau
- Loading Phase
- ◆ First Significant AE (loading)

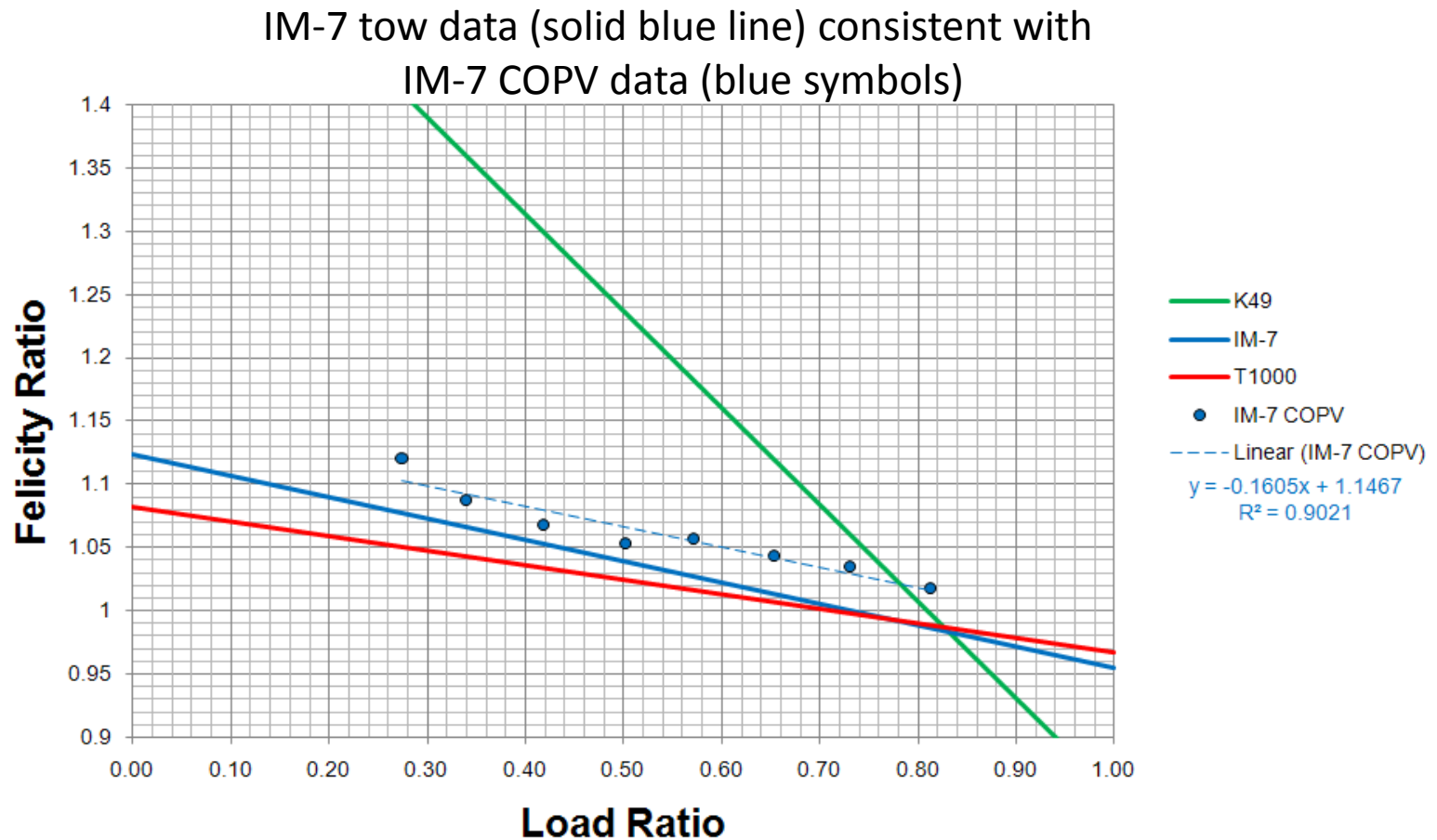
$$FR = \frac{121.2}{120} = 1.01$$

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

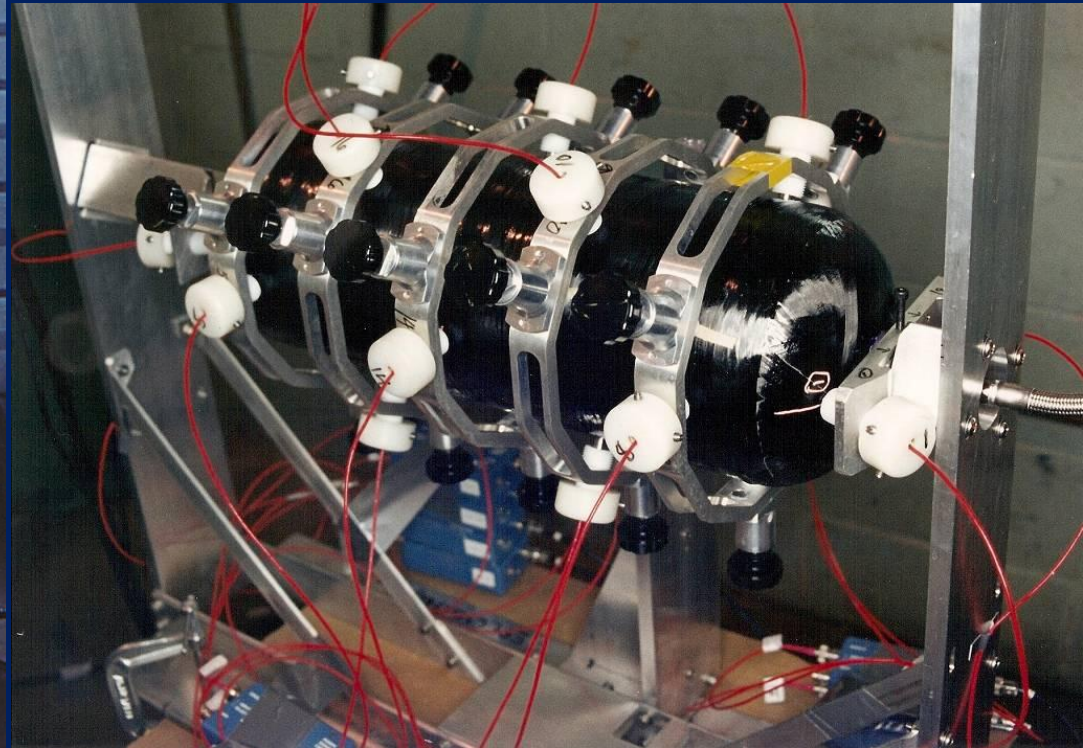
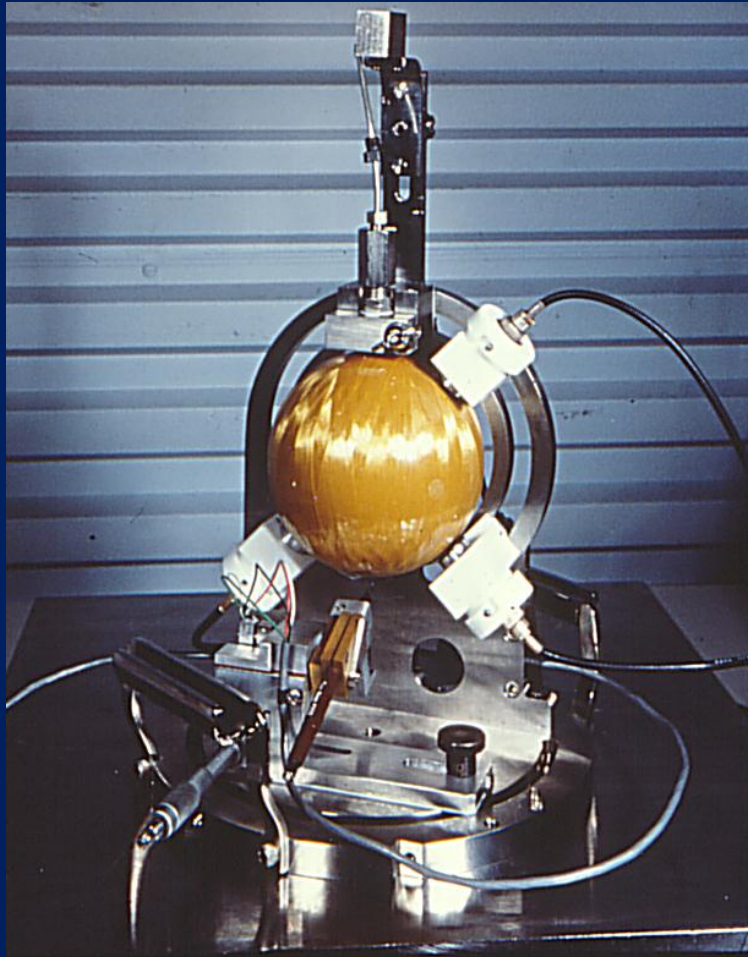


Proof-of-concept Felicity ratio analysis of an IM-7 reinforced C/Ep COPV (blue dots) superimposed on Kevlar[®] 49 (green line), T1000 (red line), and IM7 (blue line) single tow data

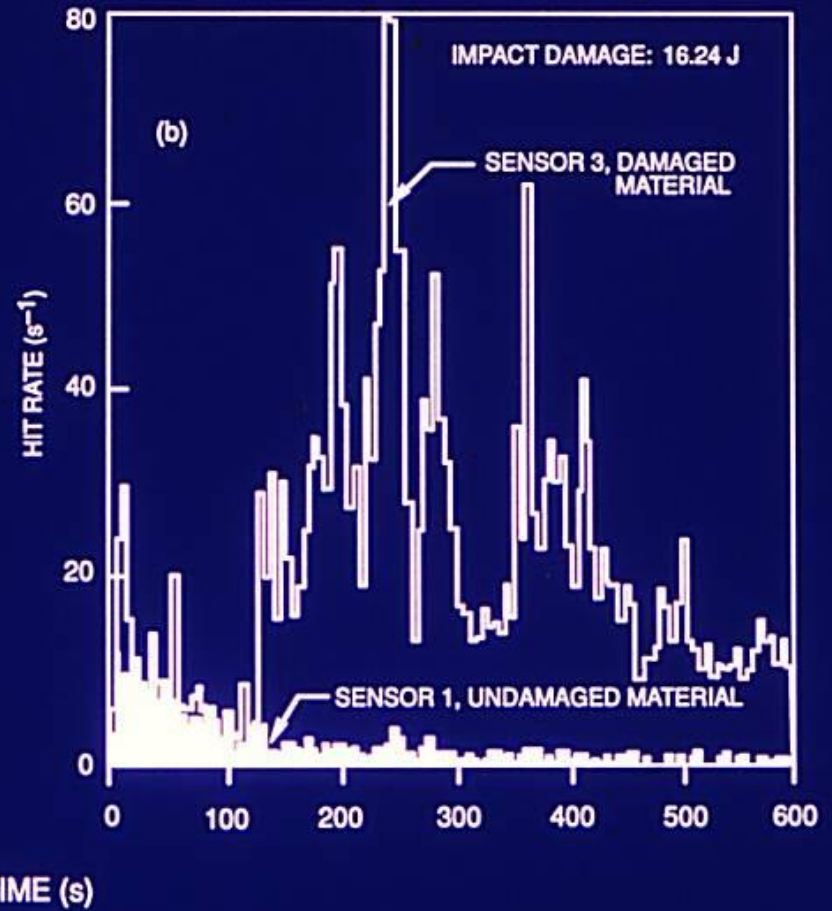
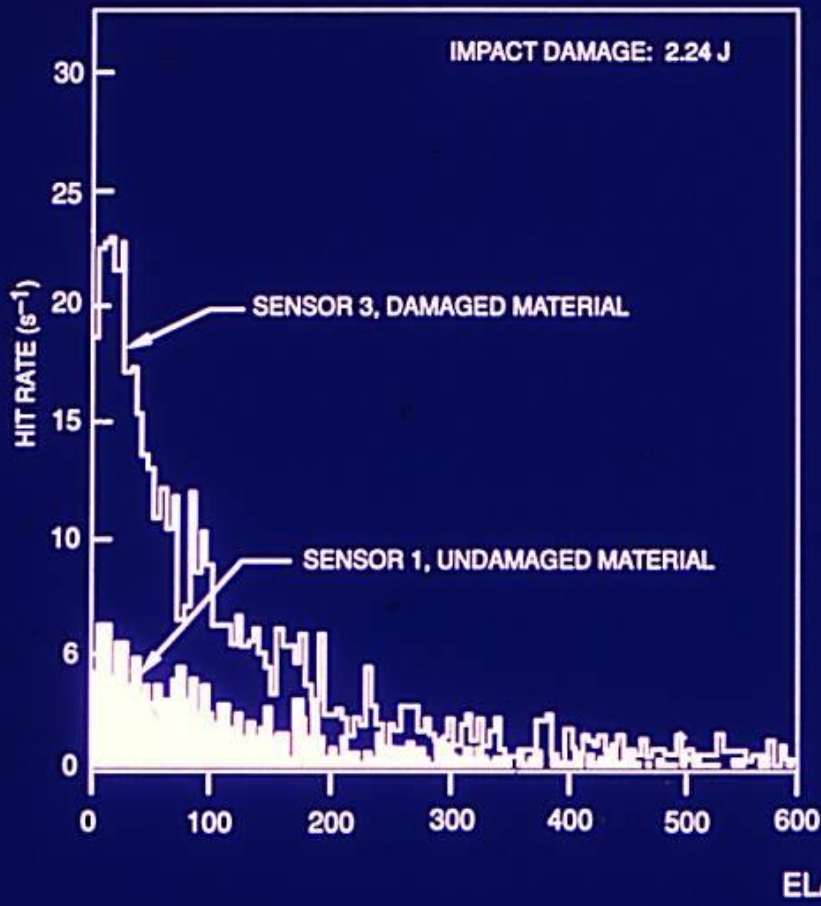
FR and Shelby Ratio (SR) show some promise of predictability of stress-rupture “when related to damage-site monitoring”

Virgin pressurization AE can provide a measure of repeatability of COPV manufacturing process

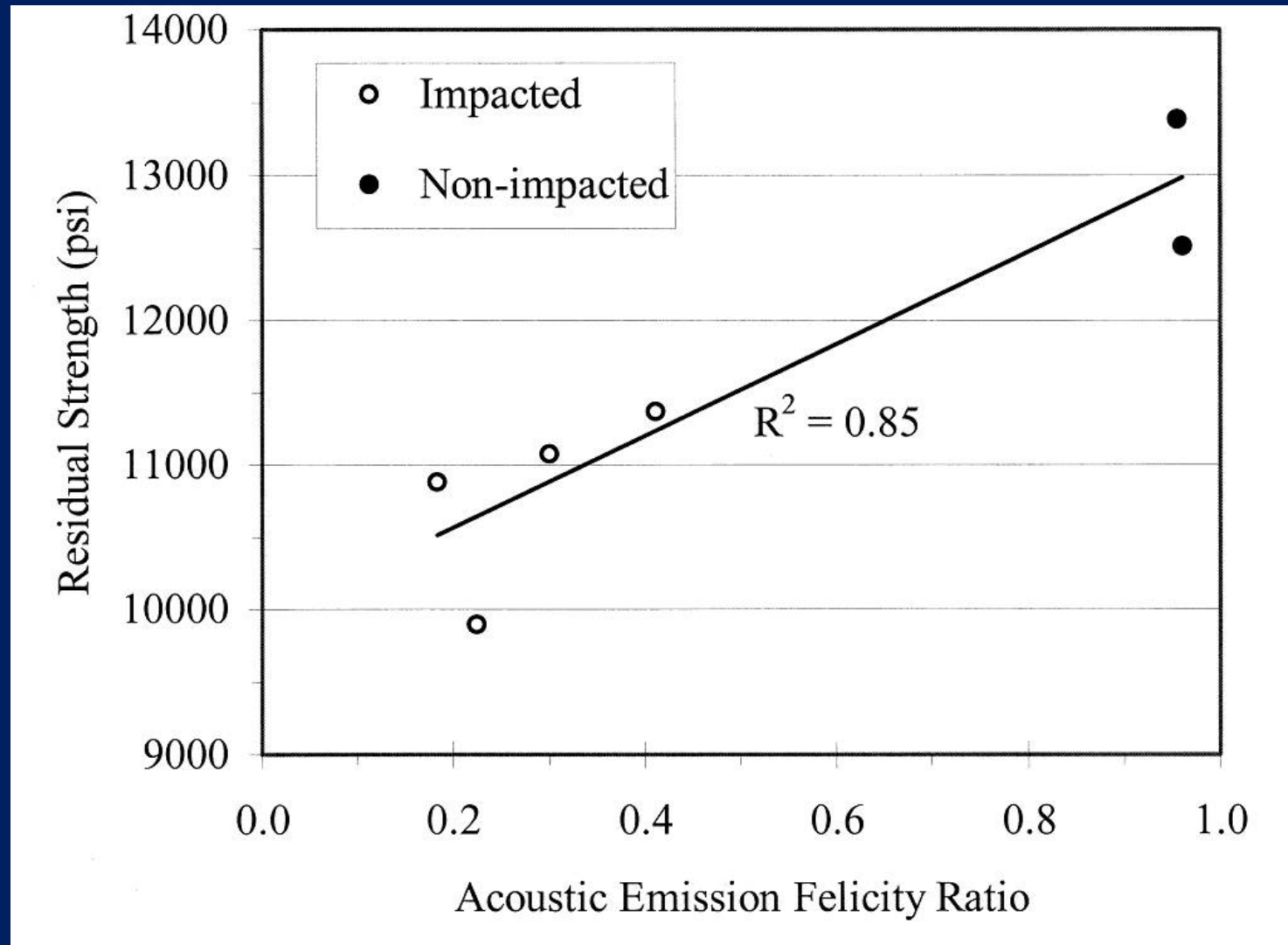
Test fixture for Kevlar/epoxy COPV proof testing with AE and for Carbon/epoxy proof testing



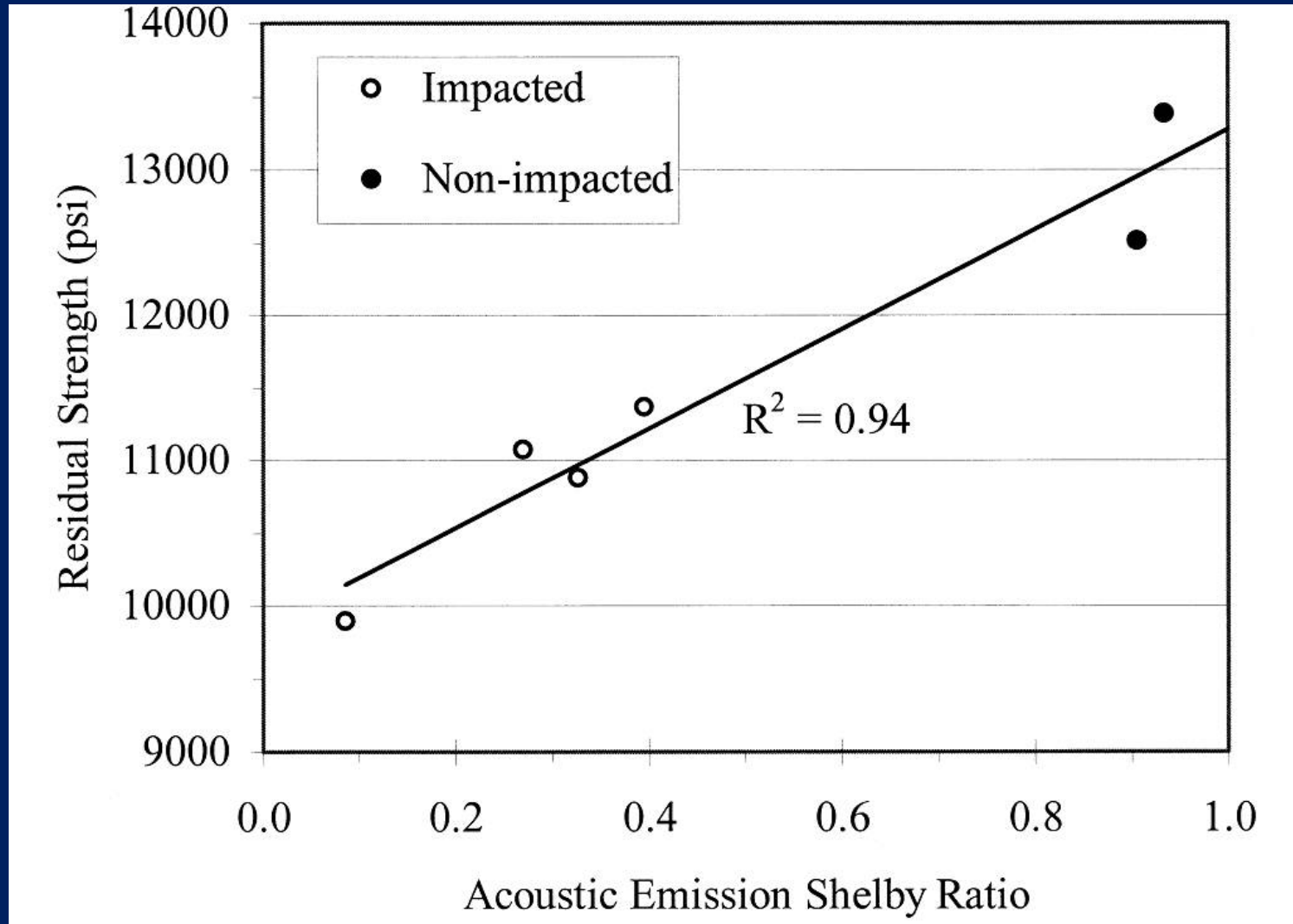
AE during a static hold pressure varied with the time, location and degree of impact damage of Kevlar/epoxy pressure vessels



AE from the second pressurization (to the proof level) of a cylindrical carbon/epoxy pressure vessel correlates with the residual strength, if AE from the region of the impact (eventual failure location) is considered

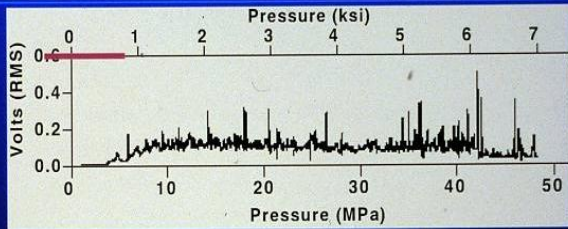


AE from the second de-pressurization (from proof level) of a cylindrical carbon/epoxy pressure vessel correlates with the residual strength, if AE from the region of the impact (eventual failure location) is considered

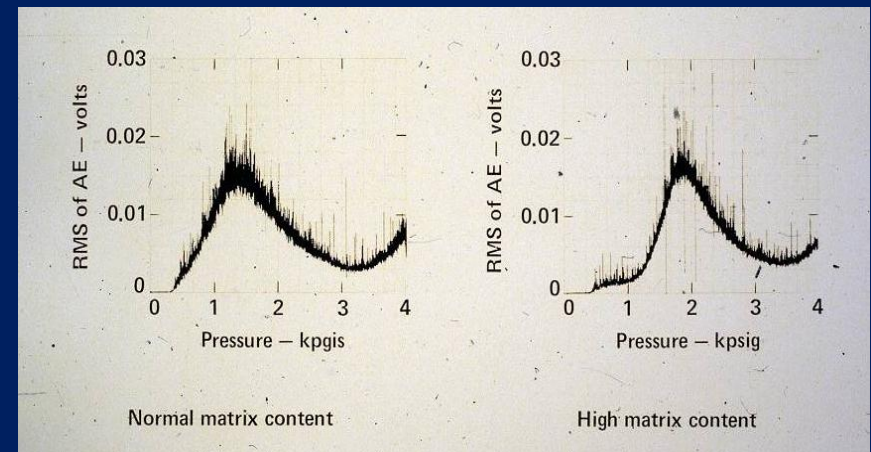
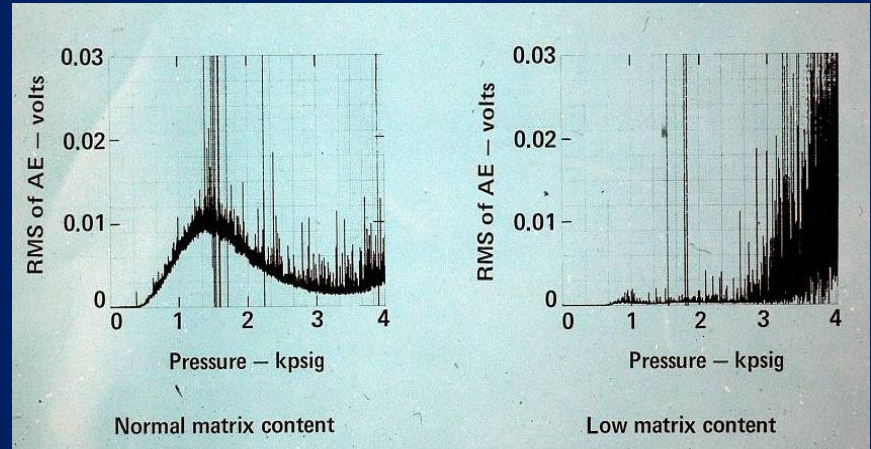
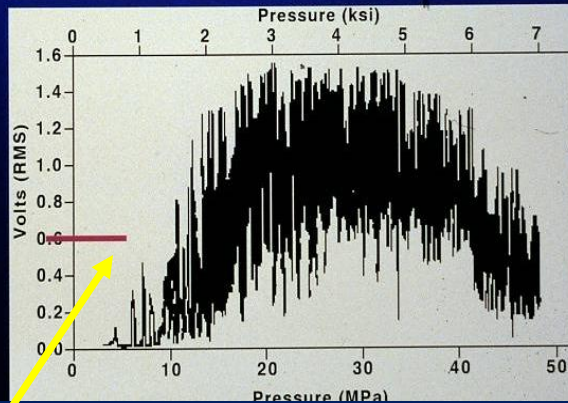


AE signatures versus pressure during the virgin pressurization (autofrettage or proof test) of COPVs can indicate whether composite has been filament wound correctly

Low Resin Content



High Resin Content



Same level as full scale in top figure

Cases of low and high matrix content

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

**The NASA Engineering and Safety Center
Technical Assessment Report (Par 4.5.1) has
established a requirement that, for the NORS
vessels (S-081-2000)....**

“An inspection master plan shall be established prior to start of fabrication. The plan shall specify appropriate inspection points and inspection techniques for use throughout the program, beginning with material procurement and continuing through fabrication, assembly, acceptance-proof test, and operation, as appropriate. In establishing inspection points and inspection techniques, consideration shall be given to the material characteristics, fabrication processes, design concepts, structural configuration, corrosion control, and accessibility for inspection of flaws. Acceptance and rejection standards shall be established for each phase of inspection, and for each type of inspection technique.”

Need for consensus standards

According to the CSA:

“A standard is a document that specifies minimum requirements for design, construction, performance and quality control during production of the product”

Doug Horne, Clean Vehicle Education Foundation:

Incidents in North America

- Since 1984 CVEF has recorded 97 incidents of which 67 involved CNG vehicles
 - 37 incidents involve either a CNG leak (15) or a release of CNG by the PRD activation (22)
 - There were 18 cylinder failures:
 - 4 **Type 1** (all steel) -1 in fire where PRD failed, 1 by external corrosion and 2 by over pressurization by faulty fueling system
 - 4 **Type 2** (hoop wrapped) -1 by fire where PRD was isolated from cylinder body, 3 from a combination of SCC and over pressurization
 - 8 **Type 3** (full wrap and metal liner) –SCC from acid/chemical degradation of e glass wrap
 - 2 **Type 4** (full composite with plastic liner) –1 in localized fire and 1 by physical damage

December 10, 2009 DOE –DOT-CNG –H2 Workshop
www.cleanvehicle.org

In the U.S.....

It will take only one catastrophic, well-publicized COPV explosion to send CNG or hydrogen fueled vehicles (or NASA) back to the drawing board. We need to be proactive, not reactive with regards to harmonized standards and improved COPV manufacturing, testing and utilization. An extensive database on COPV performance (pressurized-cyclic, pressurized-static, chemical and environmental effects, manufacturing variability, etc.) should be developed, along with a comprehensive study of proposed and existing NDE techniques that can monitor COPV integrity and reliability from the start of the manufacturing process through the life of the vessel.

Thank You

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