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
• 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

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

Profile just above weld

~0.050 in. min. to max.

0.040 in. range
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.
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

Overwrap Thickness Vs. Pressure

Liner Thickness Vs. Pressure
NNWG Kevlar AE Data-Subscale

Events and Energy vs. Time (Accelerated)

AE indications begin to grow well before rupture occurs.

Last 6.25 hrs. (Total rupture time 91 hrs)

~2.6 Hrs to failure

~16 min. to failure

~1.5 Hrs to failure

NNWG Kevlar AE Data-Subscale

Events and Energy vs. Time (Accelerated)
AE Effective in Monitoring Orbiter 40-in. Vessel Stress Rupture Progression to Failure

AE Data Analysis by Eric Madaras

Event No. vs. Time

Energy vs. Event Time

180° view—Back view

0° view—Front view
Portable Raman System Developed to Allow Real-time Raman Spectroscopy During Testing

Portable WSTF/LaRC Raman developed and applied \textit{in situ} to Orbiter 40 in. vessel in stress rupture test

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

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

532 nm, 50 ms exposure, 10 accumulations

1610

1278 1325

1550 1570 1590 1610 1630 1650 1670 1690

Wavenumber (cm$^{-1}$)

1550 1570 1590 1610 1630 1650 1670 1690

Intensity (a.u.)

0% strain

0.75% strain

Strain-Induced Raman Shift in Kevlar 49 Fiber
Real-time Raman During COPV SN007 Stress Rupture Testing - 8/15-10/22/09

1610 cm$^{-1}$ Peak FWHM Normalized by 1325 cm$^{-1}$ Peak

Aging induced peak broadening

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
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
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

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<tr>
<th>Method</th>
<th>Measurement Results</th>
<th>Location/Responsible Group</th>
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<tbody>
<tr>
<td>Guided Wave</td>
<td>Defects in the wave path and modulus change</td>
<td>GRC/GFC (others as available)</td>
</tr>
<tr>
<td>Laser-induced UT</td>
<td>Defects in the path of wave path and modulus change</td>
<td>Materials and Sensors Technologies, Inc. (MSFC if available)</td>
</tr>
<tr>
<td>Laser Profilometry</td>
<td>Inspection of the liner for dimension changes before and after aging and inspect for buckling</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Pressure, Temperature</td>
<td>Pressure and temperature for given duration</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Cabled Girth LVDT</td>
<td>Circumferential displacement measured at the middle of the barrel section</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Strain Gauge</td>
<td>Change in length. Fiber strain</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Fiber Bragg Grating</td>
<td>Change in length. High resolution low fiber strain information.</td>
<td>WSTF/MSFC</td>
</tr>
<tr>
<td>Acoustic Emission (conventional and Acousto-Optics)</td>
<td>Acoustic noise. Fiber breakage or delamination</td>
<td>WSTF/LaRC</td>
</tr>
<tr>
<td>Visual Inspection (exterior)</td>
<td>External inspection of overwrap. Indication of gross damage to the fiber overwrap</td>
<td>WSTF/WSTF</td>
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## Carbon Aging Instrumentation NDE and DI Plan (cont’d)

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

Note: ~ 100 times faster strain creep to failure when progressive failure starts
AE on smaller C/Ep vessels not always predictive without additional work
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:

\[ FR = \frac{121.2}{120} = 1.01 \]
Regions of high AE activity correspond to events occurring early in COPV life cycle up to catastrophic failure.

Correlation coefficients for ILH method good to excellent agreement ($R^2 \geq 0.90$).
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.

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)

\[ y = -0.1605x + 1.1467 \]

\[ R^2 = 0.9021 \]
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

Overview of Nondestructive Evaluation (NDE) Needs and Developments for Composites

September 22, 2009

Regor Saulsberry 575-635-7970

Future Milestones

FY 2010

• Complete stress rupture aging of the 1\textsuperscript{st} lot of 20 IM7 vessels by June 15, 2010
• Complete stress rupture aging of the 2\textsuperscript{nd} lot of 20 IM7 vessels by August 12, 2010

FY 2011

• Complete the 2\textsuperscript{nd} stress rupture aging campaign of T1000 vessels by November 3, 2010
• Complete the 2\textsuperscript{nd} stress rupture aging campaign of IM7 Vessels by January 24, 2011

FY 2012

• 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 - CPVG, 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)

Kevlar® and PBO COPV Stress Rupture/Burst
NNWG NDE Piggyback 05-09

COPV Cryogenic Carbon Composite Testing
LH2 sustained COPV/composite exposure data
Piggyback NDE Development SAW, FBG, AE, EC, Liquid Level
Advanced COPV Feasibility Evaluations – CEV etc.

Carbon COPV Stress Rupture/ Burst (Pretest & real-time NDE)
Hypergolic Propellant Compatibility Study
NESC Stress Rupture testing NNWG Piggyback FY08-10
Subscale COPV Stress Rupture Study
Carbon Fiber COPV Impact Damage Studies, NNWG Piggyback FY06-07

NNWG COPV Projects
Stress Rupture NDE Kevlar® 06-08 and Carbon 08-12
Correlating NDE Response to Burst Reductions FY06-07 (more needs to be done)
Integrating NDE into Manufacturing & Laser Profilometry - FY07-11
Characterization of Composite Micromechanics and COPV Health Monitoring e.g., Acousto-Optics - 08-10
Composite and COPV Liner NDE Standards FY05-12

Cycle Burst Stress Rupture
Characterization Through the Wall Stress Gradient
Fluids Compatibility Burst
PBO/ZYLON® Subscale COPV Stress Rupture/ Burst/impact testing
Vacuum, Humidity and Shelf Life Stress Rupture/ Burst

COPV Cryogenic Carbon Composite Testing
LH2 sustained COPV/composite exposure data
Piggyback NDE Development SAW, FBG, AE, EC, Liquid Level
Advanced COPV Feasibility Evaluations – CEV etc.

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Composite and COPV Liner NDE Standards FY05-12
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

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

- Vessel #10 Failure
- ROV's Locked after #10 fail
- ROV's Reset

Graph showing Microstrain over Time (Hours) for different vessels.
## 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**: Being applied further by manufacturing NDE Project
- **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