Overview

- Pretest Nondestructive Evaluation (NDE)
  - External/Internal Visual Inspection
  - Raman Spectroscopy
  - Laser Shearography
  - Laser Profilometry

- Real-Time NDE
  - Eddy Current
  - Acoustic Emission (AE)
  - Real-time Portable Raman Spectroscopy

- AE Application to Carbon/Epoxy (C/Ep) COPVs
Pretest NDE Data Review

Pretest Health Assessment
OMS S/N 007

- Visual Inspection
  - External
    - Generally clean
    - Matrix cracking, scuffs, loose fibers
    - No significant mechanical damage observed
  - Internal
    - Ripple imprints throughout
    - Debris around bottom portion of vessel
    - Minor stains and discolorations
Pretest Internal Visual Inspection of OMS 40-in. Kevlar COPV S/N 007 (cont'd)

Rust Colored Stain
Reflective Debris
Black Stain
Weld Splatter

Strain Mapping by Raman Spectroscopy
Jeff Eldridge (GRC) & Tim Galus (WSTF)

- Tripod-mounted probe collects Raman spectra along boss-to-boss meridian at 0 psi

Raman measurement configuration using Kaiser PhAT probe
- 785 nm laser, 100 mW onto COPV, 6 mm spot size, 8 in. working distance
- 5 sec/measurement
- 3 equally spaced meridians/vessel (0°, 120°, 240°), 35-37 wraps/meridian, 3 repeats/wrap
Comparison of Strain Profiles on 3 Orbiter Vessels at 0 psi (0°, 120°, & 240° Meridians)

The Orbiter vessel SN007 strain profile was similar to previously tested vessels SN001 & SN006.

Shearography Setup

- LTI-5100HD Shearography Camera
- COPV Pressurized with GN₂
- Test Parameters:
  - COPV biased pressure: 70 psi
  - Test pressure differential: 10 psi
  - Shear vector: 0.375 in. x, y
  - Field of view: 14.25 in.

LTI5100 HD on floor for Band 4 Test
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Shearography Scan Plan

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Shearography Results – Y Shear
Indications – X Shear

Top of COPV AN-4

Band 1

Band 2

Band 3

Band 4

Band 5

Not Inspectable

Brief Analysis of Indications

Indication #1 Band 1 @ 270° 1.2 x 1.2 in. area with 0.038 μm/psi greater z axis deformation rate than adjacent Kevlar material.

AN-4 Fitting

Pressure Shearogram, 10 psi, X Shear

Integrated Shearogram showing 2 axis deformation due to pressure change of 10 psi.
**Brief Analysis of Indications**

**Indications #2, #3, #4**

Location: Band 3 @ 170° to 300°, 14 in. below AN-4 fitting, along the center of the equatorial circumferential Kevlar wrap

Size: #2 is 12 in. long, #3 is 9.5 in. long, and #4 is 9.0 in. long

Indications are variations in the Z axis displacement. The circumferential wrap should ideally provide uniformity around the equator. Shearography is detecting slight variations in the strength of this wrap.

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**Kevlar NDE Reference Standard Helped Quantify Defects**

- Manufactured “damage” built into standard
- Wound at OEM
- 18 in. diameter sphere
  - Kevlar-49 fiber thick-walled (24 layers—48 plys)
- Numerous types of damage inflicted during winding process
  - Cut fibers
  - Simulated delaminations
**Type of Defects in Kevlar NDE Standard**

- Fiber Cuts: 1 in. and 3 in. long cuts (1 and 2 layers deep = 2-4 plies)
- Individual Delaminations: Four sizes of heat-sealed 5 mil FEP Teflon® (1 x 1 in., 1 x 2 in., 1 x 3 in., and 1 x 4 in.)
- Locations kept confidential

![Typical Large Cut](image1)
![Typical Delamination](image2)

**Examples of Shearography Response to Kevlar NDE Standard**

Z axis deformation at this anomaly is greater than adjacent areas of Kevlar wrap by 0.095 µm/psi.

![Shearography Image](image3)
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Laser Profilometry

- WSTF/Laser Techniques Company developed a specialized laser profilometer to scan and map the interior of the vessel.

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Laser Profilometry Accurately Quantifies Liner Buckling and Other Surface Features

Calibration traceable to National Standard and demonstrated better than 0.001 accuracy/repeatability on 20-in. and better than 0.002 accuracy/repeatability on 40-in. CPVs.
Profilometry of S/N 007

Upper Linear Indication Height

0.040-in. range

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.
OMS Kevlar Pretest NDE Conclusion

- With exception of the large ripples around the girth well, no indications were observed that were an issue with planned stress rupture testing.
- Eddy current (EC) 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, signifying that the indications were not a concern.

Eddy Current Testing to Address Buckling Question

- Three EC sensors (#1 - 3) were placed over the peak of the largest liner ripple indications, and one sensor (#4) was placed in the liner membrane region as a reference.
  - Response of Sensors #1 - 3 was in family with the membrane reference sensor, indicating ripples were not behaving as unstable “buckles” during pressurization.
  - Stand-off change of 1 to 2 mils per 1000 psi was consistent with EC data obtained from other 40 in. Kevlar COPV testing.
Real-Time NDE

AE Data Review
Testing: 3/18/09-10/23/09: Last 400 Hours

Very high rates

Longer term slower rates

Testing: 3/18/09-10/23/09: Final Week

-6 events / hour

~2 events / hour

~4 events / hour
Comparison of AE Events to Strain During Final Week

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

Testing: 3/18/09-10/23/09
Testing: 3/18/09-10/23/09: Last 400 Hours

Energy vs. Event Time

Energetic Signal Levels vs. Time: Final Week
This is a view of all the AE events to date as seen from a top down view. Some event clusters appear near the equator. A few loose groupings near the poles.
This is a view of all the AE events to date as seen from a top down view. Some event clusters appear near the equator. A few loose groupings near the poles.
Testing: 10/13/09-10/23/09: Energetic Locations

Locations of Energetic Events

-90° view—Back side view
90° view—Front side view

Locations of Energetic Events

0° view—Front view
180° view—Back view
Testing: 10/13/09-10/23/09:
Final High Energy Burst (Final 24 h)

Locations of Energetic Events:
- Red lines mark the locations of the larger events.
- The dark red line marks 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.
  - Over 3000 recorded events during the last 10 days.
  - 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°.
Portable Raman System Developed to Allow Real-time Raman Spectroscopy During Testing

SWF/LaRC Portable Raman developed and applied in situ to Orbiter 40" vessel in stress rupture test

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

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

1610 cm⁻¹ peak FWHM normalized by 1325 cm⁻¹ peak FWHM

Aging induced peak broadening

Burst
AE Application to Carbon COPVs
Looking to the Future

IM7 C/Ep COPV AE ENERGY
EVENTS vs. TIME

- Channel 2
- Channel 3
- Channel 4
- Channel 5
- Channel 6
- Channel 7
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:

\[ FR = \frac{121.2}{120} = 1.01 \]

C/Ep Results & Discussion

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 (R² ≥ 0.90)
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**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.

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**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.