Overview of NASA White Sands Test Facility Composite Overwrapped Pressure Vessel Testing

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# Special Thanks

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Introduction

• Composite overwrapped pressure vessel (COPV)
  – Typically a metallic liner overwrapped with a fiber epoxy matrix
• Weight advantage over a traditional all-metal design
History of COPV Testing

- NASA-GRC\(^1\) Kevlar\(^\circledast\) COPV development (early 1970s)
- LLNL\(^2\) Kevlar Testing of Subscale COPVs (mid 1970s)
- NASA-JSC\(^3\) Kevlar Shuttle Transportation System (STS) Fleet Leader Program (late 1970s)
- NASA-WSTF Kevlar COPV Fluids Compatibility Testing (1990s)
- NASA-WSTF Carbon Impact Study (1990s)
- NASA-WSTF Carbon Fluids Compatibility Study (1990s)
- NASA-WSTF Subscale Carbon COPV Stress Rupture Program (1990s-current)
- NASA-WSTF STS Kevlar COPV Testing (current)
- NASA-WSTF PBO COPV Testing (1990s-current)
- NASA-WSTF Carbon COPV Shelf Life, Humidity & Vacuum Testing (buildup)
NASA-WSTF COPV Test Program

- Kevlar® COPV
  - Stress Rupture Burst
- PBO COPV
  - Stress Rupture Burst
- Subscale COPV
  - Stress Rupture Burst
- Carbon COPV
  - Stress Rupture Burst
- Fluids Compatibility Burst
- Cycle Burst Stress Rupture
- Carbon Fiber Hypergolic Fuel Compatibility Study
- Carbon Fiber COPV Impact Damage Study
- Subscale COPV Stress Rupture Study
- Vacuum, Humidity and Shelf Life Stress Rupture Vacuum Burst
**Stress Rupture Facilities**

- New Stress Rupture Test Facility (Test Cell 862)
  - Thermally controlled
  - Backup power for data acquisition and thermal control
  - Will house 15 blast enclosures for testing up to 26-in. COPVs and one blast enclosure to house up to a 40-in. COPV
Stress Rupture Facilities

• Subscale COPV testing (Test Cell 270A)
• Carbon fiber and PBO COPVs currently in test
Stress Rupture Facilities

- Fleet leaders for ISS (Test Cell 275)
- Various flight-qualified configurations
- Eight impact-damaged COPVs on test
- Test started ~ 8 years ago
Burst Test Facility

- Burst up to 26-in. COPVs (upgrading to burst up to 40-in. COPVs at 50 psi/s)
- Thermally controlled enclosure
- Remote data acquisition
Vacuum Test Facility

- Vacuum Stress Rupture Testing of COPVs
  - Thermally controlled
  - Facility in preparation for test
  - Controlled gas and humidity environment
**Fluids Compatibility**

- Fluids Compatibility Testing
  - Expose COPV to fluid and burst test
  - Cryogenic fluids
  - MMH, NTO, LN₂, hydrazine, and unsymmetrical dimethylhydrazine
Pneumatic COPV Test Facility

- Pneumatic burst after mechanical impact
- 250-ft drop tower
- COPV drop testing
**Current WSTF COPV Test and Analysis Objectives**

- Evaluate safe operating life remaining for Kevlar® COPVs on the Space Shuttle
  - Kevlar stress rupture life prediction model is being prepared using COPV stress rupture and strand data (Phoenix Model II)
  - Flight qualified COPV testing required to adjust parameters of the model
- Provide fleet leader data for ISS and evaluate remaining safe operating life on carbon COPVs
- Provide test data and design of future COPV applications (Constellation Program)
Kevlar Test and Analysis Objectives

• Provide flight qualified COPV test data to feed into life model

• Evaluate conservatism in current lifing numbers
  – Relate fiber strain condition with stress rupture life
  – Evaluate transverse COPV stiffness
  – Assess fiber creep with time (liner pre-stress)
    – Measure liner pre-stress
    – Record fiber strain with pressure and volume expansion

• Provide a data-validated FEA model for damage assessment
Kevlar COPV Testing

- Strain gauges
- Fiber Bragg gratings
- Acoustic emission
- Eddy current
- Volume measurement
- Girth measurement
- Digital image correlation
- Load cell
- X-ray
- Temperature, pressure
New Measurement Development

- Volumetric strain measurement
  - Fluid input and output measurements
- Strain measurement
  - Fiber-optic Bragg gratings
- Composite thickness measurement
  - Eddie current
- Digital image correlation
  - Full field strain measurement

\[
\text{Black} \quad \text{Stress} = \frac{PR}{2tc}
\]
Kevlar Test Data

- Volumetric expansion with pressure
- Through-the-thickness stress gradient
- Liner pre-stress
- Evaluation of fiber creep with time
- Behavior beyond yield
- Burst volume
- Burst fiber strain
**Digital Image Correlation Results**

![Graph showing strain during pressurization cycle](image1)

**Pressure Cycle Captured for DIC**

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<td>1</td>
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<tr>
<td>5</td>
<td>6450</td>
</tr>
<tr>
<td>6</td>
<td>6450 2 Minutes</td>
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<tr>
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<tr>
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Kevlar Test Data Analysis

• Comparison of data for flight rationale
  – Scale to fiber strength

• Variables that affect fiber strength include:
  – Fiber denier, volume fraction, COPV geometry, fiber strain at autofrettage (pre-strain), UV exposure, time at pressure and temperature

• Approach for comparison
  – Evaluate differences: liner load carrying effect, volume fraction, fiber differences, time at temperature and pressure, UV exposure, impact damage, etc.
Kevlar® Test Data Analysis

• Statistical approach based on comparison of distribution of test data
  – Assume data follow a Weibull distribution
  – Comparison of data sets shown on one plot

• Small sample statistics are used
  – Small data set
Sample Kevlar® Stress Rupture Life Chart

SAMPLE: Stress Rupture Chart for Kevlar
Carbon Test and Analysis Objectives

- Provide fleet leader COPVs for ISS
- Evaluate lower-than-expected burst results for carbon subscale COPVs
- Provide stress rupture data for construction of carbon stress rupture life prediction model
Carbon Results to Date

- No new failure mode found for failures at lower-than-expected burst pressures
- Shelf life is being evaluated
  - Burst testing COPVs of different unpressurized shelf lives resulted in no significant difference in the Student’s t-test
- Stress ratio calculation methods are in review
- Subscale COPVS are not flight-like
  - Minimized wrap (limit of what would be considered a COPV)
  - Less rigorous quality control than for flight COPVs
- Impact damage is a concern—was observed to reduce burst pressure
**General Observations**

- Understanding how stress ratios are calculated is important in evaluating remaining reliable stress rupture life.
- Carbon COPVs are impact-damage sensitive and can burst before leak.
- Kevlar® COPVs are more susceptible to stress rupture than carbon fiber COPVs (reflected in AIAA S-081*).

<table>
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<tr>
<th>AIAA S-081-2000 Stress Rupture Requirements</th>
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Numbers represent the lowest fiber reinforcement stress ratio at MEOP.

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