Composite Overwrapped Pressure Vessels (COPV)

Part 1 - COPV Overview and Recent Liner Buckling Anomalies

Part 2 - Mars Environmental Rover Ultralight Propellant Tank Status

August 30, 2002
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Briefing Objectives

- Provide background on ‘generic’ COPV liner buckling and need for NASA action
- Provide background on the MER Ultralight Tank situation and how close we are to flight qualification
- Solicit support of the In-Space Propulsion Program
Benefits of COPV Technology

- **Mass Reduction** Compared to Monolithic Titanium Vessels
  - Two-thirds reduction for high-pressure COPV’s
  - Fifty percent reduction for low-pressure COPV’s (propellant tanks)
  - 8 kg mass saving for two tanks on MER

- **Cost Reduction** Compared to Monolithic Titanium Vessels
  - Up to fifty percent reduction for high-pressure COPV’s
  - Comparable cost for low-pressure COPV’s

- **Schedule Reduction** Compared to Monolithic Titanium Vessels
  - Up to fifty percent for high-pressure COPV’s
  - Up to fifty percent for low-pressure COPV’s
Composite Overwrapped Pressure Vessels (COPV) consist of a metallic liner overwrapped with a high-strength fiber/polymeric matrix resin composite.

- Non-load-bearing liner provides hermetic seal, stresses are carried by high-strength, low-density composite.

- **Liner Materials**
  - Aluminum alloys
  - Titanium alloys
  - Inconel Alloys
  - Stainless Steels

- **Fiber Materials**
  - Graphite – 850,000 psi tensile strength
  - Polybenzoxazole (PBO) – 800,000 tensile strength
  - Kevlar
  - Glass

- **Matrix Resins**
  - Epoxies
  - Isocyanate-base polymers
  - Polyimides
  - Other polymers
Overview
Description of COPV, continued

• Inside the tank are various types of propellant management devices (PMD)
  – Surface tension and diaphragm are the most common

• Surface Tension:
  – Lightest weight
  – Non-recurring design costs high
  – Not usable in some environments
  • Aerocapture, landing, missile interception, and other high G loads

• Diaphragm:
  – Lightest weight with positive expulsion (all environments)
  – Never been qualified other than traditional thick Titanium liner
COPV Applications in Aerospace

Status of COPV Technology Within the Aerospace Industry

- Dedicated safety standard (AIAA S-081) released and adopted by NASA
- High-Pressure Applications
  - COPV’s have totally replaced monolithic titanium vessels for high-pressured aerospace applications
    - Pressurant tanks for chemical propulsion systems
    - Gas-supply tanks for cold-gas attitude control systems
    - Gas-supply tanks for inflation systems, science instruments, etc.
    - Xenon propellant tanks for electric propulsion systems
    - Tanks for high-pressure liquid reactants e.g., LASERS
- Low-Pressure Applications
  - Low-pressure propellant tanks are just starting to be flown
  - SSTI / Lewis Spacecraft
  - CHANDRA
- Used in launch vehicles, earth orbiting and planetary spacecraft
Near Term Applications of COPVs

Examples

- Mars Recon Orbiter - JPL/Lockheed
  - State-of-the-art 20 mil or greater Titanium liner thickness
- New Millenium ST5 - GSFC
  - Modified Ultralight Aluminum tank liner 10 mil thick
- Airborne Laser - DOD
  - State-of-the-art 30 mil thick stainless steel liner
Buckling of Liners in Composite Overwrapped Pressure Vessels

Description of Problem
- Liners are above tensile yield at MEOP
- Liners are above compression yield at zero pressure
  - Composite is elastic and causes liner to yield compressively
- Adhesive bond between liner and composite prevents bucking
- Lack of bonding or weak adhesion results in buckling
- Cyclic buckling causes liner to crack

Effect of Liner Material
- Aluminum, titanium and stainless steel liners have buckled

Effect of Liner Thickness
- All thicknesses up to practical limits buckle
  - 0.005 inch, 0.020 inch, 0.030 inch
- Making liner thick enough to avoid buckling results in unacceptable mass
- Propensity to crack during buckling increases with increasing liner thickness
<table>
<thead>
<tr>
<th>Program</th>
<th>Tank Type</th>
<th>Supplier</th>
<th>Tank Size (in)</th>
<th>Liner Mat'l and Min. Thickness (in)</th>
<th>Composite Mat'l</th>
<th>Bondline Adhesive and Thickness (in)</th>
<th>Type of Bondline NDI</th>
<th>Tank Burst Factor</th>
<th>Type of Failure</th>
<th>Failure Detected</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Exploration Rover</td>
<td>Prop</td>
<td>Pressure Technology Division of Carleton</td>
<td>16.2 dia 18.0 length</td>
<td>6061-T62 Aluminum 0.005</td>
<td>PBO / Epoxy</td>
<td>FM-73 0.005</td>
<td>C-scan Ultrasonic (passed)</td>
<td>2.0</td>
<td>Buckled Liner</td>
<td>Visually, during tank assembly after bondline NDI</td>
<td>Yet to be determined</td>
</tr>
<tr>
<td>Mars Reconnaissance Orbiter</td>
<td>GHe</td>
<td>PSI</td>
<td>16.7 dia 29.6 length</td>
<td>CP Ti 0.020</td>
<td>Graphite / Epoxy</td>
<td>FM-73 0.005</td>
<td>None</td>
<td>1.5</td>
<td>Liner crack due to buckling</td>
<td>Pressure-cycle test</td>
<td>Unknown</td>
</tr>
<tr>
<td>Airborne Laser</td>
<td>Prop</td>
<td>Lincoln Composites</td>
<td>24.0 dia 120.0 length</td>
<td>Annealed Austenitic S.S. 0.030</td>
<td>Graphite / Epoxy</td>
<td>Unknown</td>
<td>2.5</td>
<td>Liner crack due to buckling</td>
<td>Pressure-cycle test</td>
<td>Unknown</td>
<td></td>
</tr>
</tbody>
</table>
Buckling of Liners in Composite Overwrapped Pressure Vessels

- NDI Processes to Detect Buckling

  - All processes require calibration on real tanks with built-in unbonded areas
  - C-Scan Ultrasonic Inspection
    - Coupling is critical
    - Sensitivity needs to be determined
  - Thermal Scans should be assessed
  - Endoscopic Visual Inspection
    - Requires access that will permit all areas of liner to be viewed
    - Not as sensitive as ultrasonic inspection
5 suppliers
- Arde, Lincoln Composites, PSI, Carleton, TRW (?)

Need to re-establish tank integrity

JPL is qualified to lead a NASA effort to requalify materials/processes/inspection to preclude use of buckled liners in COPV applications

Preliminary Cost est ~$500k
Mars Ascent Propulsion System Technology Task
- 0.005-inch thick aluminum liners, graphite/epoxy and PBO/epoxy
- Three high-pressure and three low-pressure liner performance demonstration tanks with seamless liners
  - Passed qualification tests
- Three high-pressure and three low-pressure flight weight prototype development tanks with welded liners
  - Low-pressure tank passed qualification tests
  - One high-pressure tank survived LOx pressure-cycle testing at NASA/MSFC

Mars Micro Missions Project
- Started design and qualification of high-pressure pressurant tank, fuel tank and oxidizer tank
  - Propellant tanks were to have internal titanium prop management devices
  - 0.005-inch thick welded aluminum liners, graphite/epoxy (pressurant tank) and PBO/epoxy (Propellant tank) composites

Mars Exploration Rover Project
- Designed and fabricated two qualification tanks and one flight tank for hydrazine monopropellant system
  - Internal surface tension titanium PMD’s
  - 0.005-inch thick welded aluminum liners. PBO/epoxy composite
Design

- Tank Design completed
  - End Cap re-design completed Oct '01
  - Finite element analysis completed Nov '01
  - Released Source control drawing complete 12 '01
- Stress analysis done (Burst FS 2.0)
  - Peak stress in Titanium aft plug end cap assembly = 34 ksi, MS(yield)=1.8, MS(ULT)=1.6
  - Peak stress in Aluminum Liner is at aft boss radius = 12.6 ksi
  - Peak stress in the aft end cap inertial weld = 3.5 ksi, MS(yield)=2.2, MS(ULT)=2.4
  - Peak combined loads (21.25 G + MEOP) give MS 0.06 (Yield & ult)
- Negligible risk
MER Ultralight Tank Fabrication

As machined tank cup shown at right with Propellant Management Device (PMD) in place.

Tight tolerance machining to plus/minus 1 mil repeatable demonstrated.

Surface Tension PMD design, fab and testing complete.

Separate view of PMD
Tank Liner Chemical Milling

- Successfully Chem Milled 6 Mars Micromission liners at 14.6 inch dia. and 8 MER liners at 16.4 inch dia.
  - From .067” to .006” +/- .001” parent metal, weld .030”+/- .001”

- Development weld qual rings successfully chem milled
  - .200” to .020”+/- .001”
  - .067” to .030”+/- .001”

- Negligible risk

Liner - post chem milling
Fiber Overwrapping

PBO fiber overwrapping repeatably demonstrated

Installing End Caps

- Inertia welding at component level repeatable demonstrated
- EB and TIG welding of sub-assemblies and final assembly are standard processes
- Negligible risk
Due to late welding step tank drop outs and one liner buckling problem MER Project Management switched to standard heavy Titanium tank technology in April 2002.

NEEDED: Resolution to buckle phenomenon and a more robust weld process would be economically beneficial to increase tank yield.

View of liner
Buckle about 1 1/2 inch long and 1/2 inch wide
NASA Code S Has Made Significant Investment in Ultralight Tank Technology

<table>
<thead>
<tr>
<th>Program Sponsor</th>
<th>Dollars Invested, $M</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Technology</td>
<td>0.7</td>
<td>1998 - 2000</td>
</tr>
<tr>
<td>Mars Micromission</td>
<td>0.35</td>
<td>2000</td>
</tr>
<tr>
<td>MER Project</td>
<td>2.3</td>
<td>2000 - 2002</td>
</tr>
<tr>
<td><strong>Total Code S to date</strong></td>
<td><strong>3.35</strong></td>
<td><strong>1998 - 2000</strong></td>
</tr>
</tbody>
</table>
Relatively Small Cost to Complete Qualification of Ultralights

- MER Project has produced 3 flight “qualifiable” Ultralight tanks - now available
  - Total cost to qualify these tanks is $279K
  - One of these tanks is shown on right with black plastic UV mitigation cover. Pictured is final N2 drying of tank.
  - Final total tank system mass
    2.5 kg vs. 5.2 kg for Ti tank
    (both with service valve)
- MER Project has produced other tanks with weld cracks, one leaker, and one tank with liner buckle
  - Total cost to complete anomaly investigation is $93K
  - To reduce manufacturing fallout, investigate VPPA welding, est cost $350K
Ultralight Tanks - needed now & in the future

- Over 90% of all Team X Propulsion designs assume Ultralight Tanks
- DAWN Discovery Mission will have to drop Ultralights from baseline
- Significant issue in NSI missions e.g. large Xenon tanks
- Commercial benefits
Investigation of Leak in S/N 006 MER Ultralight Tank

<table>
<thead>
<tr>
<th>Activity</th>
<th>Weeks After Start</th>
<th>Estimated Cost $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Review radiographs of leakage area at Cedtech</td>
<td>1</td>
<td>$1,687</td>
</tr>
<tr>
<td>Have Cedtech do penetrant inspection of inside surface of weld</td>
<td></td>
<td>$2,687</td>
</tr>
<tr>
<td>Cut leakage area from tank</td>
<td></td>
<td>$844</td>
</tr>
<tr>
<td>Remove composite from liner in leakage area by soaking in NTO</td>
<td></td>
<td>$5,062</td>
</tr>
<tr>
<td>Examine leakage area under high-power optical microscope</td>
<td></td>
<td>$1,687</td>
</tr>
<tr>
<td>Have Cedtech do penetrant inspection of composite side of liner in leakage area</td>
<td></td>
<td>$1,844</td>
</tr>
<tr>
<td>If leak point is located, examine leak point under SEM</td>
<td></td>
<td>$1,687</td>
</tr>
<tr>
<td>If leak point is located, examine leak path metallographically</td>
<td></td>
<td>$5,062</td>
</tr>
<tr>
<td>Prepare Report</td>
<td></td>
<td>$5,062</td>
</tr>
<tr>
<td>Engineering Coordination</td>
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<td>$20,000</td>
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<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td><strong>$45,622</strong></td>
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### Ultralight Tank Buckle Evaluation

**Investigation of Buckled Liner in S/N 004 MER Ultralight Tank**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Weeks After Start</th>
<th>Estimated Cost $</th>
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</thead>
<tbody>
<tr>
<td>Examine original ultrasonic record of bond line inspection</td>
<td></td>
<td>$1,687</td>
</tr>
<tr>
<td>Ship tank to Carleton</td>
<td></td>
<td>$1,344</td>
</tr>
<tr>
<td>Re-inspect bondline in buckled area</td>
<td></td>
<td>$8,687</td>
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<tr>
<td>Pressure-cycle test tank</td>
<td></td>
<td>$3,687</td>
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<tr>
<td>Ship tank to PSI</td>
<td></td>
<td>$500</td>
</tr>
<tr>
<td>Cut tank apart and remove PMD</td>
<td></td>
<td>$844</td>
</tr>
<tr>
<td>Cut buckled area from tank</td>
<td></td>
<td>$844</td>
</tr>
<tr>
<td>Open up buckled area for visual inspection of bond line</td>
<td></td>
<td>$844</td>
</tr>
<tr>
<td>Inspect de-bonded surfaces with optical microscope</td>
<td></td>
<td>$1,687</td>
</tr>
<tr>
<td>Prepare Report</td>
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<td>$5,062</td>
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<td>Engineering Coordination</td>
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<td>$22,000</td>
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<tr>
<td><strong>Total Cost</strong></td>
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<td><strong>$47,186</strong></td>
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## Completion of Qualification of MER Ultralight Tanks

<table>
<thead>
<tr>
<th>Activity</th>
<th>Location</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship Tanks to Carleton</td>
<td>JPL</td>
<td>$3,800</td>
</tr>
<tr>
<td>Review records at Carleton</td>
<td>Carleton</td>
<td>$6,470</td>
</tr>
<tr>
<td>Proof and Leak Test Tanks</td>
<td>Carleton</td>
<td>$5,940</td>
</tr>
<tr>
<td>Pressure-cycle Tests</td>
<td>Carleton</td>
<td>$5,940</td>
</tr>
<tr>
<td>Leak Tests</td>
<td>Carleton</td>
<td>$3,470</td>
</tr>
<tr>
<td>Ship Tanks to JPL</td>
<td>Carleton</td>
<td>$3,000</td>
</tr>
<tr>
<td>Vibration Tests</td>
<td>JPL</td>
<td>$55,470</td>
</tr>
<tr>
<td>Ship One Tank to PSI</td>
<td>JPL</td>
<td>$1,340</td>
</tr>
<tr>
<td>Bubble Point Test PMD in One Tank</td>
<td>PSI</td>
<td>$4,470</td>
</tr>
<tr>
<td>Ship Two Tanks to NTS-LA</td>
<td>PSI / JPL</td>
<td>$1,840</td>
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<tr>
<td>Leak Test Three Tanks</td>
<td>NTS-LA</td>
<td>$9,400</td>
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<tr>
<td>Burst-pressure Test Two Tanks</td>
<td>NTS-LA</td>
<td>$3,940</td>
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<tr>
<td>Ship Two Tanks to JPL</td>
<td>NTS-LA</td>
<td>$1,800</td>
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<tr>
<td>Completion of Qualification Test Procedures</td>
<td>JPL</td>
<td>$15,000</td>
</tr>
<tr>
<td>Qualification Test Report/Engineering Oversight</td>
<td>JPL</td>
<td>$157,000</td>
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</table>

**Total Cost** $278,880
COPV Summary

- A supplier recovery effort lead by NASA seems to be in order due to liner buckling
  - Preliminary estimate is in range of $500K
- MER Ultralight Tanks were bit by liner buckling late in flight delivery schedule
  - Above effort directly applicable to Ultralights
- Ultralight Aluminum liner COPV is within $375K of being flight qualified; out of $3.35M spent to date -- will In-Space Propulsion fund directly?
  - Dozens of future missions impacted by lack of ultralight