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Volume: Issue: AIAA-1989-2642
Month/Year: 1989 Pages: not known

Article Author: AIAA/ASME/SAE/ASEE Joint Propulsion Conference (25th; 1989; Monterey, Calif.)

Article Title: VEYS, RONALD B.; Design and development of an aluminum lined composite overwrapped spherical pressure vessel

Imprint: New York, N.Y. ; American Institute of A

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AIAA-89-2642
Design and Development of an Aluminum Lined Composite Overwrapped Spherical Pressure Vessel
Ronald B. Veys, Alvin R. Cederberg, and Dale B. Tiller
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Lincoln, NE

AIAA/ASME/SAE/ASEE
25th Joint Propulsion Conference
Monterey, CA / July 10-12, 1989

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DESIGN AND DEVELOPMENT OF AN ALUMINUM LINED COMPOSITE OVERWRAPPED SPHERICAL PRESSURE VESSEL

Ronald B. Veys  
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Dale B. Tiller  

BRUNSWICK CORPORATION, DEFENSE DIVISION  
LINCOLN, NEBRASKA

Abstract

Various space and missile systems require lightweight pressure storage vessels with low leakage requirements. These requirements have previously been met by composite pressure vessels with metallic liners made from relatively high yield strength materials such as titanium, Inconel, and stainless steel. These high yield strength materials are typically used to allow the liners to be designed to cycle elastically during operation.

Aluminum is a desirable liner material because of its moderate cost and low density. In high performance composite pressure vessels requiring extensive cycle life, the modulus of elasticity and relatively low yield strength of aluminum alloys normally preclude their use as a liner material. This limitation is minimal, however, if the basic vessel is designed to a relatively high factor of safety for long term storage, gunfire resistance, or other reasons.

Brunswick Corporation has designed and qualified a Kevlar®/epoxy composite spherical pressure vessel with a 2219-T62 aluminum liner for a space application requiring a high factor of safety.

The liner of the vessel consisted of two hemispheres welded together at the girth. Each hemisphere was machined from a forging and included integral polar bosses. The liner was overwrapped with Kevlar®/epoxy composite using two sequences of wind patterns. Each sequence consisted of multiple layers of composite with the layers at various angles relative to the axis of the vessel. A bimetallic tube was threaded into the port boss and welded to provide a positive seal. The bimetallic tube provided the interface between the 2219-T62 liner and the 304 L stainless steel tubing which was subsequently welded to the vessel.

The vessel design was analyzed utilizing the finite element method. The analytical model focused on determination of the strain concentrations in the liner at the transitions from the polar bosses to the membrane region. The model was constructed to allow sliding of the composite relative to the liner, a phenomena which occurs near the polar bosses. The analysis included the effects of material yielding and friction at the interface of the liner and composite.

Qualification testing included cyclic fatigue, vibration, and burst strength. The vessel design has been successfully qualified and has met all performance requirements. The feasibility of using an aluminum liner in a relatively large spherical pressure vessel has been established.

Background

Various space and missile systems require lightweight pressure storage vessels with low leakage requirements. These requirements have previously been met by composite pressure vessels with metallic liners made from relatively high yield strength materials such as titanium, Inconel, and stainless steel. These high yield strength materials are typically used to allow the liners to be designed to cycle elastically during operation.

Aluminum is a desirable liner material because of its moderate cost and low density. The modulus of elasticity and relatively low yield strength of aluminum alloys normally preclude their selection as a liner material in high performance composite pressure vessels requiring extensive cycle life. This limitation is minimal, however, if the basic vessel is designed to a relatively high factor of safety for long term storage, gunfire resistance, or other reasons.

Brunswick Corporation has designed and qualified a Kevlar®/epoxy composite spherical pressure vessel with a 2219-T62 aluminum liner for a space application requiring a high factor of safety.

Pressure Vessel Design and Analysis

A lightweight spherical composite pressure vessel, depicted in Figure 1, with an aluminum liner has been designed to contain helium gas at a pressure of 3000 psig and to have a minimum burst pressure of 12,000 psig.
The vessel parameters include a weight limit of 280 pounds and a volume greater than 18,817 cubic inches when unpressurized. A summary of these and other primary design requirements is provided in Table 1.

### Table 1: Pressure Vessel Design Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (Unpressurized)</td>
<td>18,817 cl</td>
</tr>
<tr>
<td>Contained Gas</td>
<td>Helium</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>3000 psi</td>
</tr>
<tr>
<td>Proof Pressure</td>
<td>6000 psi</td>
</tr>
<tr>
<td>Burst Pressure</td>
<td>12,000 psi (min.)</td>
</tr>
<tr>
<td>Leakage Rate</td>
<td>$1 \times 10^{-6}$ sccs max.</td>
</tr>
<tr>
<td>Operating Cycles</td>
<td>50 cycles (0-3000-0 psi)</td>
</tr>
<tr>
<td>Fatigue Cycles</td>
<td>100 cycles (0-3000-0 psi)</td>
</tr>
<tr>
<td>Weight</td>
<td>280 pounds (max.)</td>
</tr>
<tr>
<td>O.D. (pressurized)</td>
<td>36.20 inches (max.)</td>
</tr>
</tbody>
</table>

The liner is designed as two hemispheres welded together at the girth. The liner halves include integral bosses with interfaces for vessel support, weld lands for the girth weld, and a precisely contoured transition region between the membrane portion of the liner and the boss regions. The transition design is critical in order to minimize the stress and strain concentrations between the relatively rigid boss and the highly stressed membrane regions. The membrane portion of the liner is nominally 0.125 inch thick.

The composite overwrap is nominally 1.16 inches thick in the membrane region, with additional thickness near the polar bosses. This composite construction, which provides a nearly isotropic (E=5.0 msi) shell in the membrane region, is obtained by using 36 different planar wrap wind patterns and circumferential wraps near the girth. The planar angle for the helical patterns varies from 4.6 to 82.7 degrees. A summary of the vessel weight is provided in Table 2.

### Table 2: Weight Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Max. Weight, lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner</td>
<td>62.23</td>
</tr>
<tr>
<td>Bimetallic Inlet tube</td>
<td>0.21</td>
</tr>
<tr>
<td>Liner Subassembly</td>
<td>62.44</td>
</tr>
<tr>
<td>Kevlar® Fiber</td>
<td>144.12</td>
</tr>
<tr>
<td>Epoxy Resin</td>
<td>71.56</td>
</tr>
<tr>
<td>Barrier Coating</td>
<td>1.12</td>
</tr>
<tr>
<td>Composite Weight</td>
<td>216.80</td>
</tr>
<tr>
<td>Total Weight</td>
<td>279.24</td>
</tr>
</tbody>
</table>
The liner of the vessel is designed to operate elastically after an initial pressure cycle which autofrettages, or "sizes," the liner. This pressure cycle, which also serves as the proof test for the vessel, develops a residual compressive stress in the liner when the vessel is unpressurized. The prestress condition extends the elastic operating range of the liner and has a favorable influence on the cyclic fatigue life of the liner material. This effect is shown in Figure 2.

![Figure 2 Typical Liner Stress-Strain Curve](image)

The vessel was designed to a maximum allowable fiber stress of 320 ksi. The predicted burst strength based on fiber failure is 13,800 psig. This prediction recognizes that the liner would carry approximately five percent of the load at burst.

The pressure vessel was analyzed by the finite element method to determine maximum stresses and strains in the metallic liner and composite overwrap. The analysis performed recognized the importance of determining the maximum liner strain in the transition regions between the boss and membrane regions of the vessel, and the dependence of this strain level on liner yielding and sliding relative to the composite overwrap. The analysis was performed with a computer code specifically developed for analyzing spherical composite vessels with yielding metallic liners. The basis for this program is provided in Reference 1.

The key elements of the analytical model were to represent the potential for sliding between the liner and the composite overwrap and yielding of the metallic liner. The stress-strain curve of the liner material was modeled as being bilinear with initial and secondary moduli of elasticity. The ability of the liner to slide relative to the composite was provided by use of a "gap" element between the liner and the overwrap elements. The properties of the thin gap element were computed from preliminary analyses to provide an effective coefficient of friction for the interface. The gap element maintains displacement compatibility between the liner and composite overwrap until the frictional force capability is exceeded. If the frictional force is exceeded, the liner is allowed to "slide" parallel to the inner surface of the composite.

The maximum equivalent liner strain in the transition regions at the minimum burst pressure of 12,000 psig was found by analysis to be 3.8 percent. This is well below the maximum stable strain of 6-7 percent typical for the 2219-T62 aluminum alloy. Therefore, the liner has sufficient ductility to achieve the burst requirements of the vessel.

**Materials of Construction**

The pressure vessel was designed using a 2219-T62 aluminum liner, Kevlar®/epoxy overwrap, and a bimetallic inlet tube. The reinforcing fiber was DuPont's aerospace grade Kevlar® 49 in a 4-end roving. The resin was Brunswick's Lincoln Resin Formulation (LRF) 0092, an anhydride type epoxy which is qualified to Mil-C-47257 and has been used in many pressure vessels for aircraft and space applications.

The bimetallic inlet tube was used to transition from the 2219-T62 aluminum material used in the liner to the 304L stainless steel material used in the tubing to which the vessel would subsequently be welded.

**Manufacturing Flow Plan**

The manufacturing processes selected for fabrication of the spherical pressure vessel were similar to those utilized in fabrication of the Space Shuttle Pressurant Tankage, which Brunswick developed in 1976. The difference in liner materials, 2219 aluminum versus 6AL4V titanium, and the addition of a bimetallic tube did require some modification in the type of processes that were utilized in the manufacture of the metallic liner/tube assembly.

**Liner Fabrication.** As in the case of the Space Shuttle Tankage, the liner was manufactured from hemispherical forgings that were machined and girth welded. The 2219 aluminum forgings were manufactured in a closed die forging and heat treated at 995 °F for a minimum of 10 hours to
obtain T4 properties. The forgings were then rough machined and subjected to ultrasonic inspection. A girth trim ring provided material for obtaining physical properties on each forging. As required by MIL-S-22771, a forging from each lot was also destructively tested for macro examination, mechanical property evaluation, and microstructure evaluation. The semi-machined forgings were chemically etched and penetrant inspected prior to finish machining.

The forgings were finish machined, with the exception of the polar bosses, by first machining the ID and then the OD contours. Additional tensile coupons were manufactured from the parted girth trim ring. These coupons were cleaned and aged with the liner assembly, and subsequently tested to verify the physical properties of the heat treated liner. The finish machined hemispheres were cleaned and etched, and subjected to liquid penetrant inspection.

The finish machined hemispheres were prepared for welding by chemically cleaning the hemispheres and mechanically cleaning the girth weld zone. The hemispheres were joined via electron beam welding at the girth. The weld schedule had been qualified by previously welding two sets of hemispheres. These weldments were dimensionally, radiographically, and penetrant inspected prior to destructive testing. Coupons were prepared from the weldments to obtain physical properties in the weld and parent material. A macrostructure examination of the weld was also performed. Welded liner assemblies were radiographically and penetrant inspected. Weld splatter, caused by the electron beam weld process, was removed from the liner ID by tumbling the part with walnut shells. The liner ID was cleaned by removing the walnut shells and performing a hot deionized water rinse.

After weld inspection and cleaning, the liner was aged to obtain T62 properties and the polar bosses were finish machined and anodized. As in the case of the finish machined hemispheres, a thorough dimensional inspection of the liner was performed.

The bimetallic tube stock was fabricated by explosively joining plate stock of 304 stainless steel and 2219 aluminum. This material stock was machined to provide the finished tube assembly. To qualify the bimetallic joint and the subsequent electron beam weld, a simulated boss/tube assembly was subjected to acceptance and burst testing. The stainless steel portion of the tube was passivated. A nut and sleeve were assembled to the tube via swaging to provide a means for pressure testing the liner and vessel assemblies. The finished tube was cleaned, assembled and electron beam welded to the port boss. After inspection of the electron beam tube weld, a chromate conversion coating was applied to the liner exterior surfaces. The completed liner assembly was then ready for acceptance testing.

The finished liner assembly was examined for workmanship, identification, dimensions, cleanliness, and material traceability. The liner was weighed, and the internal volume was measured. A proof pressure test and helium leak test were then performed. After pressure testing, the liner was 100% penetrant inspected on all exterior surfaces. Cleanup was the final operation performed on the liner assembly prior to overwrapping.

Composite Fabrication. The completed liner assembly was prepared for filament winding by first applying a thin, uniform coat of mold release to the entire exterior surface of the liner. The purpose of this release coating was to prevent the composite overwrap from bonding to the liner surface. As a precaution against liner buckling during the filament winding and cure operations, the liner assembly was pressurized.

The Kevlar® roving was vacuum dried and impregnated with an epoxy resin prior to winding. The Brunswick proprietary impregnation process controls the resin content of a spool of roving within ± 2% by weight. The impregnated roving was stored at freezer or cooler conditions until required for the wind operation.

Filament winding was accomplished in a Brunswick designed, computer controlled multi-axis winding machine. At the winder, the spools of roving were loaded on tension control devices. The strand tension was pre-set and controlled throughout the vessel wind process. Excluding transition patterns, the vessel wind consisted of 38 wind patterns, utilizing as many as 16 spools for each pattern. To provide the optimum laminate properties for the final composite thickness, the vessel wind process was interrupted after the 19th pattern so that an intermediate b-stage could be accomplished. This b-stage was performed at 135 °F until the composite was judged to be "tack free". A final b-stage at 135 °F for 24 hours minimum was accomplished at the completion of wind. An oven cure at 295 °F followed the second b-stage operation.

The filament wound vessel was then coated with a clear polyurethane coating as a means of providing a limited amount of scuff resistance to the composite surface. This coating has also been proven to provide some protection to other
environmental conditions such as moisture and ultraviolet light.

Numerous in-process inspections assured manufacturing compliance to the vessel design requirements. After a comprehensive inspection for workmanship, material traceability, and dimensions; the composite pressure vessel was released for acceptance testing.

Acceptance Testing

Each filament wound vessel assembly was subjected to acceptance testing to verify the liner and composite manufacturing processes. The vessel was weighed and the pre-proof volume was measured. A proof pressure test was accomplished at 6000 psig and a post-test volume measurement was made. A helium leak test was then performed on the vessel assembly, as well as a radiographic inspection of the liner girth weld. The radiographic evaluation was performed with the vessel internally pressurized to place the liner in slight tension.

Upon completion of acceptance testing, the bimetallic tube was cut to remove the fitting and sleeve, and trimmed to the final overall length. The tested vessel assembly was final inspected for workmanship, identification, dimensions, cleanliness, and material traceability. The liner ID was then precision cleaned, and the vessel assembly was sealed until integration with the space vehicle.

Qualification Testing

The pressure vessel design was subjected to a series of tests for qualification. These included proof pressure, reverse pressure, blowdown/life cycle, vibration, helium leakage, and burst tests.

The pressure vessel was subjected to a proof test pressure of 6000 psig. The vessel was pressurized with deionized water at a nominal rate of 100 psig per second. The pressure was maintained at 6000 psig for 30 seconds minimum. The pressure was then released at a rate of 100 psig per second. The vessel design was subjected to, and satisfactorily withstood, a reverse pressure test of 20 psid for a period of 12 hours.

The blowdown/life cycle testing performed on the vessel assembly is defined in Table 3. The blowdown cycles were performed by venting the helium stabilized at 171 °F through a 0.055 inch diameter sharp edged orifice. The vessel was leak tested at various intervals during the test and after completion of the test. The vessel satisfactorily withstood the blowdown/life cycle test. The minimum temperature observed during blowdown was approximately 50 °F. The helium leakage rate measured after the test was 1 x 10^-10 scss with the vessel pressurized to 3000 psig.

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>Fluid Medium</th>
<th>Pressure Range, psi</th>
<th>Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowdown</td>
<td>Helium</td>
<td>3000-0</td>
<td>5</td>
</tr>
<tr>
<td>Pressure</td>
<td>DI Water</td>
<td>0-3200</td>
<td>25</td>
</tr>
<tr>
<td>Pressure</td>
<td>DI Water</td>
<td>0-4500</td>
<td>1</td>
</tr>
<tr>
<td>Pressure</td>
<td>DI Water</td>
<td>0-3200</td>
<td>75</td>
</tr>
<tr>
<td>Blowdown</td>
<td>Helium</td>
<td>3000-0</td>
<td>5</td>
</tr>
</tbody>
</table>

The vessel was subjected to vibration levels parallel and perpendicular to the vessel axis of 9.3 and 7.4 grms, respectively. The vibration spectrum spanned from 20 to 2000 hertz. The maximum acceleration spectral density was approximately 0.2 g^2/Hz at a frequency of 200 Hz. The vessel was subjected to random vibration in each direction for a period of two minutes. The vessel satisfactorily withstood the random vibration test as determined by die penetrant inspection and helium leak test. No cracks were found and the helium leakage rate was within specifications.

The vessel was subjected to a burst test after completion of other qualification tests. The vessel was pressurized with water at a rate of 80 psi per second to a pressure of 6000 psig. The pressure was maintained at 6000 psig for approximately 130 seconds while the intensifiers were refilled. The vessel was then pressurized at a rate of 80 psi per second until the vessel ruptured at 12,230 psig. The rupture is perceived to have initiated in the liner and then progressed to the composite as the load from the liner transferred to the composite shell. This failure mode could be expected since the liner had been subjected to considerable fatigue during the qualification tests and may not have maintained sufficient ductility to demonstrate the full strength of the composite overwrap. The predicted fiber stresses prior to and after liner failure at the rupture pressure of 12,230 psig are 294 and 322 ksi, respectively. The latter exceeds the design allowable fiber stress of 320 ksi. Therefore, composite rupture could reasonably be expected.

Conclusions

The feasibility of using an aluminum liner for a relatively large spherical composite pressure vessel has been proven for a space application. A 36-inch diameter vessel employing a 2219-T62 liner and a
Kevlar®/epoxy overwrap has been developed and qualified. The use of aluminum provides a means for reducing the cost of metal lined composite pressure vessels while maintaining excellent structural performance. The use of aluminum liners is particularly attractive for pressure vessel applications which have relatively low cyclic fatigue requirements, such as occur in single mission space vehicles. The use of more ductile aluminum alloys, such as 6061-T6, provides the opportunity for extending the fatigue life of the metallic liner beyond that demonstrated with this vessel design.

References