VI.6 Development of Advanced Manufacturing Technologies for Low-Cost Hydrogen Storage Vessels

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Subcontractors:

- Boeing Research and Technology, Seattle, WA
- Pacific Northwest National Laboratory (PNNL), Richland, WA

Project Start Date: September 26, 2008
Project End Date: September 30, 2013

Overall Objectives

Develop new methods for manufacturing Type IV pressure vessels for hydrogen storage with the objective of lowering the overall product cost by:

- Optimizing composite usage through combining traditional filament winding (FW) and advanced fiber placement (AFP) techniques.
- Exploring the usage of lower-strength, higher-modulus fibers on the outer layers of FW.
- Building economic and analytical models capable of evaluating FW and AFP processes including manufacturing process variables and their impact on vessel mass savings, material cost savings, processing time, manufacturing energy consumption, labor and structural benefits.
- Studying polymer material degradation under high-pressure hydrogen environment to optimize storage volume.

Fiscal Year (FY) 2013 Objectives

- Refine the mWind software using data collected from vessels designed with mWind.
- Build and test hybrid vessels designed with mWind.
- Improve the quality of dome caps.
- Allow more control over the test process of liner material.

Technical Barriers

The project addresses the following technical barriers from the Manufacturing R&D section (3.5) of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(M) Lack of Low-cost Carbon Fiber

(N) Lack of Low-cost Fabrication Techniques for Storage Tanks

Contribution to Achievement of DOE Manufacturing R&D Milestones

This project will contribute to achievement of the following DOE milestone from the Manufacturing R&D section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Milestone 7.2: Develop fabrication and assembly processes for high pressure hydrogen storage technologies that can achieve a reduction of 10% off the baseline cost of $18/kWh for Type IV, 700 bar tanks. (4Q, 2015)

FY 2013 Accomplishments

- Improved the in-house computer program, mWind, which allows more composite shell layer options using AFP methods to generate finite element analysis (FEA) models of composite shells.
- Verified and confirmed the accuracy of mWind with strain gage and optical strain measurements.
- Completed the latest vessel design with mWind to incorporate AFP dome caps and baseline fiber.
- Conceptualized a three-piece layup tool to allow an easy extraction of the composite dome cap from the mandrel tool.
- Installed a new smart-motor control system and a newly designed dancer system to allow for better control, high torque output and consistent tension on each tow.
- Upgraded in situ tester for testing liner material by adding a programmable logic controller to apply a constant strain rate.

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INTRODUCTION

The goal of this project is to develop an innovative manufacturing process for Type IV high-pressure hydrogen storage vessels, with the intent to significantly lower manufacturing costs. The development is to integrate the features of high-precision AFP and commercial FW while satisfying design requirements.

APPROACH

The hybrid vessel designs were based on FEA results to optimize strain distribution and achieve uniform displacement in the domes of the vessel. The modified in-house software for generating FEA models of the composite shells with the option of using AFP methods was further refined and improved based on computed tomography (CT) scans, strain gage, and optical strain measurements last year. AFP dome caps were manufactured by Boeing according to Quantum designs based on FEA results. A series of testing to national standards will be conducted to validate the hybrid designs.

RESULTS

Vessel Design Iterations

Vessel 12: At the time of writing the 2012 annual report, the Vessel 12 design was just completed with the latest version of mWind at that time. This design incorporated AFP with baseline and lower-cost fibers. The major difference on this design was that the AFP dome cap terminations were further into the cylinder section to improve load transfer between AFP and FW, eliminating the fiber strain spikes in the forward and aft transition areas between AFP and FW. The burst pressure reached 144.5 MPa (20,958 psi), short of meeting the minimum requirement of 157.5 MPa (22,843 psi). The burst location was in the transition area between AFP and FW. It was discovered that the vessel was not built per design—more baseline fiber layers were replaced by lower-cost fiber. Since the tensile strength of the lower-cost fiber is not significantly different from that of the baseline fiber, the proper number of lower-cost fiber layers would not have made up the 13 MPa deficit during the burst test. In addition, the calculated hoop thickness between dome caps did not match the height of the dome caps at tangent points, resulting an uneven surface for bridging to occur when applying the first helical pattern. In the last annual report, it was mentioned that the baseline fiber was the most cost-effective option in terms of performance per dollar. The remaining designs would focus on passing the burst test and other national standard tests without using lower-cost fiber.

Before the start of Vessel 13 design, the features not working correctly previously in mWind were debugged and fixed. Bugs encountered included the composite thickness in the dome and start and end points of non-continuous fiber layers.

Vessel 13: The Vessel 13 design increased the number of initial hoop layers to eliminate the bridging issue seen in Vessel 12. The additional hoop layers caused extra bending into the dome near the tangent line. The dome caps needed additional layers (from 12 to 20) to counter the additional stress. Increasing the number of dome caps layer maximizes the benefits of AFP, eliminating the unnecessary fibers that would have been in place if those were filament wound.

The dome caps were built at Boeing with a process using a solid, sealed foam tool and a freezing approach for extracting the dome caps from the tool. The layup was successfully completed with no visible wrinkles or defects. Figure 1 shows the in-process layup of the aft dome cap on the sealed, foam tool. This picture shows a ply placement that will be later covered with additional fiber-placed plies.

Upon installing the dome caps onto the liner, it was discovered that the length of the dome caps on the cylinder section was one inch longer than the design value. The difference was due to how the tangent point was defined. Boeing defined the tangent point of each dome by measurement of the liner with a coordinate measuring machine, while Quantum based their tangent point on geometry of the tooling used to manufacture the liner.

The number of hoop layers per design that was applied between the dome caps did not provide the required thickness to match the dome cap thickness at the tangent points. The winding layup was adjusted to relocate some hoop layers from the outer layers to the inner layers to avoid fiber bridging in the dome-cylinder transition areas. In addition, bridging between layers was observed in the aft end during winding. This type of buildup was a concern for Vessel 13 to have low burst strength.

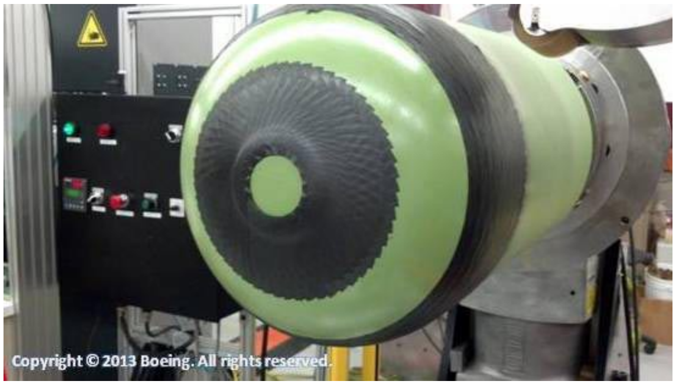

FIGURE 1. Layup of Aft Dome Cap on Foam Mandrel—the Mandrel has a Released Coating (Green) to Facilitate the Removal of the Layup

Before performing the burst test, CT scanning was completed on the domes. The CT scans of the aft end revealed bridging. When compared to the build up near the aft polar boss between CT scan images and FEA design layup, it was very similar. However, small adjustments were made to the material buildup in mWind to better correlate the predicted and measured profiles in the future.

Optical and physical strain measurements were performed on the vessel prior to burst test. Optical measurements were performed with ARAMIS, supported by the Boeing Company. The surface strains were calculated from the measured displacements at specific pressure loads. The strain gages were mounted in the transition areas between domes and cylinder section, as well as in mid cylinder. Strain gage measurements showed the value was approximately 5,000 micro strain for hoop strain at the aft dome and cylinder transition, while ARAMIS measured 4,000-5,000 micro strain at the same location. The results showed that ARAMIS was sufficiently accurate that its measurements could be used to analyze the design and help verify the strain calculations from mWind.

Figure 2 shows the hoop and axial strains measured and predicted by the FEA model of Vessel 13 with correct material buildup. There was good correlation in the upper portion of the dome section. The predicted and measured strains tend to diverge near the polar opening part of the dome due to voids in this area and effects of dome curvature. These results showed that FEA models provided a good prediction of the actual stress/strain conditions in a composite pressure vessel. The dome caps are generally farther away for the polar region and do not have the bridging and voids seen in this area. Thus, mWind and ANSYS are adequate to design the composite knuckle region which contains both FW and AFP layers.

The burst pressure reached 142.6 MPa (20,679 psi), which was below the requirement. Rupture occurred in the aft dome polar boss, as shown in Figure 3. The location was consistent with where bridging occurred.

Vessel 14: The focus of the Vessel 14 design was to reduce the voids in the aft end polar opening area. The stresses and strains in other areas of the dome increased as layers were reduced in the polar opening. A significant

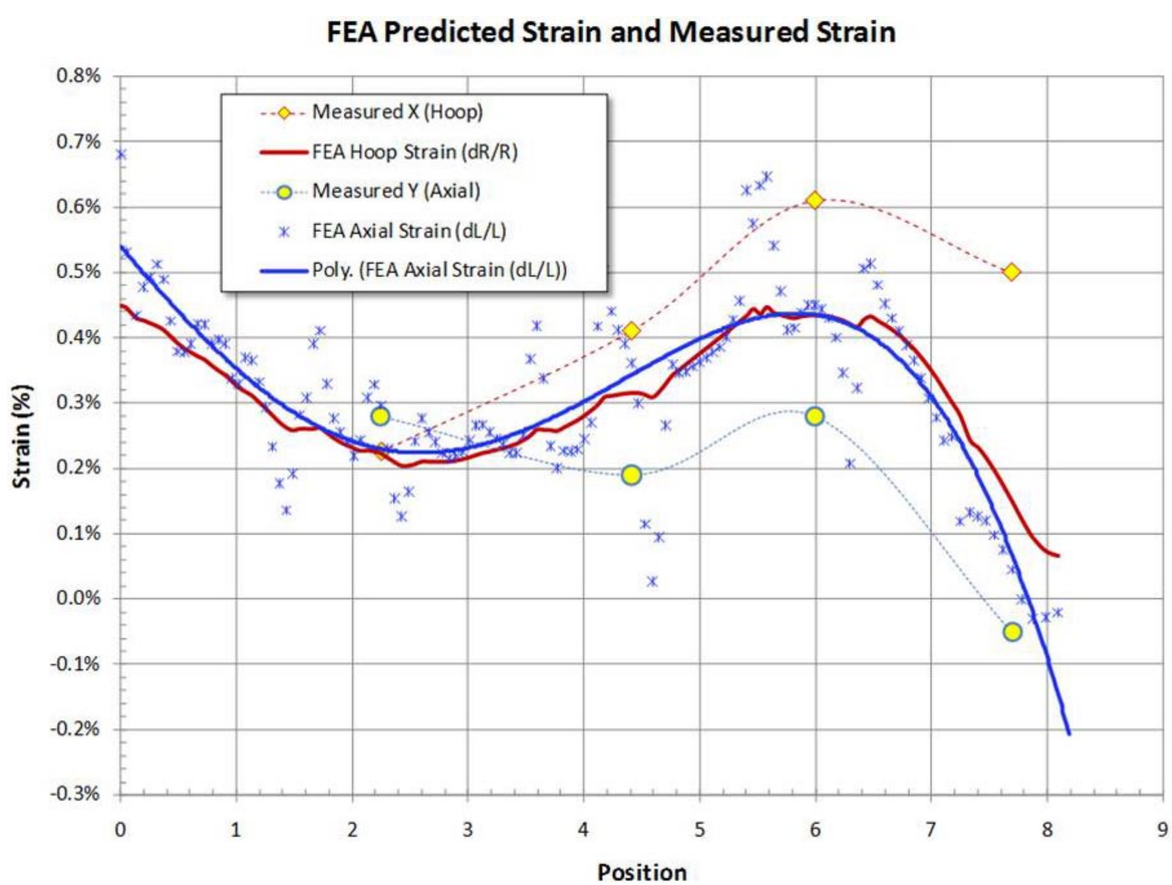

FIGURE 2. Measured and Predicted Hoop and Axial Strains of Vessel 13

FIGURE 3. Vessel 13 Burst Test High-Speed Video Frame

reduction of layers was accomplished with the latest design, which reduced 3.6 kg (7.9 lbs) of weight when compared to Vessel 13. FEA showed the maximum fiber strain was in the hoop section without any spikes in the helical layers in the dome section.

Boeing built the latest dome caps, which reduced from 20 to 14 plies with different layup sequence per design. The tangent point was also clarified to resolve an earlier issue associated with differing definitions between FW and AFP. Fabrication of these dome caps was successful and demonstrated a continual improvement over previous versions.

During the build, when a partial helical layer was applied on the liner to pull the dome caps tight onto the liner ends, fiber bridging was observed across two different layers of the aft dome cap. Upon removing the partial helical, chopped fiber mixed with resin was used to fill the air gap. As the partial helical was re-applied onto the liner, small wrinkles were observed on the aft dome cap. Instead of winding a partial helical, a complete helical layer was applied onto the vessel, with the expectation the helical pattern would be able to flatten out the wrinkles. The fiber tension eventually "collected" all the small wrinkles to form two larger wrinkles. This most likely was caused by a small difference in size of the AFP tooling and the liner geometry thus resulting in a gap between the liner and the dome cap. This full helical was removed before winding the vessel per design. After the first helical pattern per design was applied, the vessel was allowed to cure at room temperature overnight while rotating on the winding machine. The wrinkles on the aft dome were then solid which allowed the dome to be smoothed by filing of the high spots. The wrinkle size was kept to a minimal this way without affecting the next filament wound layers. For potential design improvements, strain gage and optical strain measurements and usage of high speed camera during burst test have been planned. The burst test is tentatively scheduled for early August 2013.

Continuous Process Improvement–Collapsible Tool Concept

Boeing's AFP process "lays" prepreg material onto a hard tool surface, forming the exact shape of the dome while eliminating wrinkling–a significant problem identified earlier in our project. Because the layup tool is a single, solid piece, it requires a difficult freezing step in order to release the layup from the tool. To solve this problem, a three-piece layup tool has been conceptualized. The tooling concept uses three pieces. The first piece is a wedge that slides out from the back of the tool, after which the remaining two sections will hinge together to allow for an easy extraction of the composite dome cap from the mandrel tool. By incorporating this collapsible tool into the robotic cell, the fixture will easily be removed with little downtime, increasing the overall efficiency of the cell and processes. Building the collapsible tool is pending coordination of the effort.

Fiber Creel System Upgrade

Boeing installed a new smart-motor control system from Animatics onto their existing creel system, along with a newly designed dancer system. The Animatics motors allow for better control and higher torque output as compared to previous systems. This system also allows for a dynamically controlled, closed-loop-active tow tensioning, allowing for consistent tension on each tow regardless of tow direction or speed.

Cost Model

PNNL updated the cost model during FY 2013 to use material cost assumptions that are consistent with DOE's other hydrogen storage programs. Strategic Analysis was contracted by DOE to compile consensus values of material costs for comparison of vessel costs across DOE projects. PNNL incorporated Strategic Analysis's carbon fiber cost information into the cost model used by the project. Increasing the carbon fiber cost from $11/lb to $13/lb further accentuates the cost savings of the project's optimized vessel designs that reduce the total mass of carbon fiber used.

Characterization of Polymer Liner Materials

PNNL has developed a miniature in situ test frame for characterizing the strength and modulus of vessel liner materials—high-density poly-ethylene. The tensile load frame fits into PNNL's high-pressure hydrogen autoclave for testing materials in the real-world environment of a pressurized vessel. Previous ex situ tests show a strong time dependence on material properties indicating that in situ properties could be different. PNNL built the prototype in situ tensile rig in FY 2012 and performed proof of concept testing in hydrogen. The system has been upgraded significantly in FY 2013 by adding a programmable logic controller to control the solenoid power, giving the ability to apply a constant strain rate. The tensile tester was also repackaged in a more rigid frame to reduce the system compliance that was observed on closer review of the tensile test data. Figure 4 shows the excellent repeatability of the system in performing nine in-air tests of commercial high-density poly-ethylene liner material.

CONCLUSIONS AND FUTURE DIRECTIONS

- mWind is sufficiently accurate for hybrid vessel designs.
- FEA on the latest vessel design provides high confidence on passing the burst pressure requirement, but bridging and wrinkles on the aft dome are factors that could affect the outcome.
- Boeing's manufacturing process for dome caps has improved to show insignificant amount of wrinkles on the parts before installation.
- The carbon fiber cost used in the cost model now matches with the consensus value used in other DOE hydrogen storage projects.
- PNNL's improved in situ tester shows excellent repeatability of test results.
- Perform burst test, ambient temperature cycle test, drop test, extreme temperature cycle test, and accelerated stress rupture test to validate process/material changes critical to hybrid vessel design.
- Boeing will continue to support dome cap manufacturing.
- Update cost model with the cost and amount of fiber used in the final hybrid design.
- Perform high-density poly-ethylene tensile tests in high-pressure hydrogen.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels, Annual Merit Review and Peer Evaluation Meeting, Department of Energy, May 13–17, 2013, Arlington, Virginia.

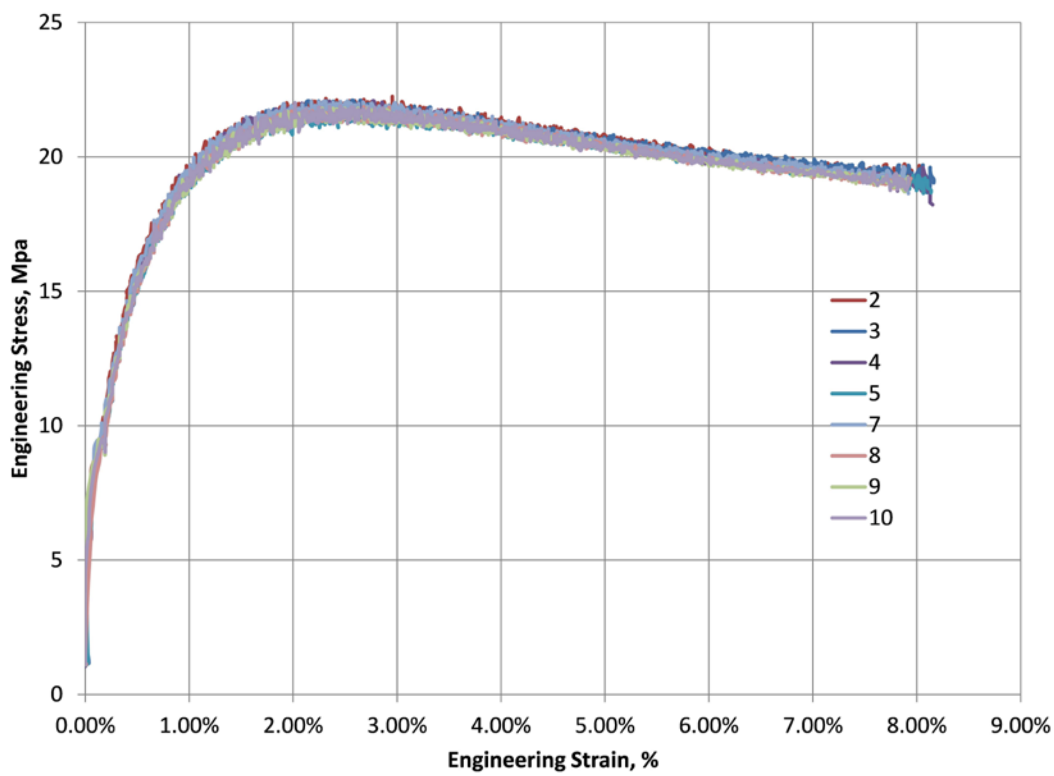

FIGURE 4. Repeatability of High-Density Poly-Ethylene Tensile Tests Performed in Air using the In Situ Test Frame