III.3 Low Cost Hydrogen Storage at 875 bar Using Steel Liner and Steel Wire Wrap

Amit Prakash (Primary Contact) and Ashok Saxena
WireTough Cylinders, LLC
14570 Industrial Park Rd., Suite C
Bristol, VA 24202
Phone: (276) 644-9120
Email: aprakash@wiretough.com; asaxena@uark.edu

DOE Manager: Neha Rustagi
Phone: (202) 586-8424
Email: Neha.Rustagi@ee.doe.gov

Contract Number: DE-EE0006668

Subcontractors:

- Oak Ridge National Laboratory, Oak Ridge, TN
- N & R Engineering, Parma Heights, OH
- C P Industries, McKeesport, PA
- Ashok Saxena, Consultant, Fayetteville, AR
- Structural Integrity Associates, Inc., San Jose, CA
- Hy-Performance Materials Testing, LLC, Bend, OR
- MVP Co, Seattle, WA

Project Start Date: September 15, 2014
Project End Date: February 28, 2018

Overall Objectives

The goal of this project is to develop a pressure vessel to safely store hydrogen at 875 bar with a safety factor of 3 or higher that also meets the DOE storage tank cost target of <$1,000/kg hydrogen ($H_2$). The objectives are:

- To wire wrap a standard American Society of Mechanical Engineers (ASME) approved, 406 mm diameter and 9.14 m long cylinder with a capacity of 765 L rated at a pressure of 460 bar to boost its operating pressure capability to 875 bar. The cylinder must meet the ASME PVP Section VIII-Division 3, KD-10 requirements for storing hydrogen.
- To keep the cost of producing the storage tanks to less than $1,000/kg of stored H_2, maintain a design life of 30 yr, and deliver hydrogen that meets the SAE J2719 hydrogen purity requirements.

Fiscal Year (FY) 2017 Objectives

- Design, build, and install the wire winding machine to wind 9.2 m long liners.
- Complete fatigue crack growth rate testing at negative load ratios in high pressure hydrogen and complete testing of steel wires in low concentrations of hydrogen.
- Conduct elastic-plastic finite element analysis for optimizing autofrettage pressures for use in manufacturing vessels.
- Seek ASME Code approval for the WireTough design of the full-size cylinder.

Technical Barriers

This project addresses the following technical barrier from the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Technical Targets

This project's goals are to meet the 2020 targets for high-pressure hydrogen storage in the 2012 version of Fuel Cell Technoloies Office's Multi-Year Research, Development, and Demonstration Plan, as shown in Table 1.

TABLE 1. WireTough's Progress towards Meeting Technical Targets for High Pressure H_2 Ground Storage Systems

Characteristics	2020 Target	WireTough
High Pressure (860 bar) Purchased Capital Cost ($/kg of H_2 stored)	$1,000	2017 costs lower than 2020 target cost by 20%

FY 2017 Accomplishments

- The machine for winding 9.1 m long cylinders was designed, built, tested and installed.
- Analysis of fatigue crack growth data at negative load ratios was completed and the effects of hydrogen pressure and loading frequencies on the fatigue crack growth rates were quantified.
- Oak Ridge National Laboratory completed testing of wires used in WireTough's design to explore potential effects of hydrogen.
- A process for ensuring that sufficient plastic deformation occurs during autofrettage was developed.
- The ASME self-certification process for the large cylinder design, including analysis, and preparation of the necessary manufacturer's design report (MDR), was completed.

- The cyclic life of the pressure vessel was estimated to be approximately 85,000 cycles for duty cycles involving pressure fluctuations during service to range from 13,000 psi to 10,000 psi.
- The cost of producing the vessel was shown to exceed the DOE target cost.

INTRODUCTION

The DOE Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy is supporting research and development activities leading to the development of low cost, high pressure hydrogen storage systems for use in hydrogen refueling stations (forecourt). The goal of this project is to develop a pressure vessel to safely store 750 L of gaseous hydrogen at 875 bar that meets the ASME PVP Section VIII- Division 3, Article KD-10 design requirements and also the DOE storage tank cost target of <$1,000/kg H_2.

APPROACH

Type I metal cylinders (406 mm outer diameter) have been used for compressed natural gas and hydrogen storage for several decades but are limited to pressures of 55 MPa for various technical reasons. WireTough has a patented process to wrap these commercially available cylinders with ultra-high-strength steel wires (2 GPa or greater in strength) to approximately double the pressure capability of the cylinders, with a proven record of safely storing H_2. These wire-wrapped cylinders are further subjected to an autofrettage process in which they are subjected to pressures high enough to plastically deform the inner liner, but the wire jacket remains elastic. Upon release of the autofrettage pressure, the liner is left with high residual compressive hoop stresses. This decreases the maximum tensile hoop stress in the liner under the operating pressure and can significantly enhance the fatigue life of the vessel. In this project, this concept was first demonstrated using short, 1.9 m long cylinders and is now being extended to the full size, 9.14 m long cylinders.

RESULTS

Design and Procurement of Wire Winding Machine for 9.14 m Long Cylinders: MVP, Seattle, built a custom, wire winding machine capable of wrapping 9.2 m long liners. The machine, Figure 1, was tested in MVP facilities first and then shipped and installed in WireTough's Bristol, Virginia plant. WireTough technicians were trained in the operation of the machine and have used it to wind mock liners to assure its functionality. Two 9.14 m long liners are on order from CPI and the production of the prototype cylinders is scheduled to begin shortly.

Design Analysis and Optimization: Finite element analysis model developed in previous years was used to calculate the correct autofrettage pressure that accounts for variations in liner thickness and the yield strength that is within admissible limits of the liner specification. The purpose of autofrettage in wire-wrapped pressure vessel manufacturing is to subject the vessel during assembly to a high enough pressure resulting in the liner deforming plastically while the wire jacket remains elastic. Upon release of the autofrettage pressure, the wire jacket collapses back

FIGURE 1. Photograph of an 8-axis wire winding machine procured from MVP, Inc., capable of wire winding 9.2 m long liners now installed in WireTough's Bristol, Virginia, manufacturing facility

on the liner and places the inner diameter (ID) region of the liner in severe compression (>220 MPa). These compressive residual stresses reduce the maximum stresses in the liner walls during subsequent pressurization as part of service duty cycles resulting in enhanced fatigue life.

An analytical model was first formulated that established the relationship between applied pressure and the change in volume of the liner. The plastic deformation required in the ID region of the vessel to ensure desired levels of residual compressive stresses upon removal of the autofrettage pressure was estimated using elastic-plastic finite element analyses and was further related to the change in volumetric expansion of the vessel. A procedure based on the volumetric expansion of the vessel as measured by water volume needed to accommodate the expansion was established. This procedure ensures that desired levels of residual compressive stresses are always locked on the ID region of the pressure vessel upon completion the autofrettage process. Figure 2 shows the variations in residual stresses following the application of autofrettage pressure of various levels for a liner with a yield strength level of 724 MPa (105 ksi) and a wall thickness of 31.75 mm (1.25 in). An autofrettage pressure of 27.5 ksi was specified for this case based on these results.

Effect of Hydrogen on the Fatigue Crack Growth Rate Behavior in the Liner Material: Sandia National Laboratories data on the effect of hydrogen on the fatigue crack growth rate (FCGR) behavior of ASME SA372 Grade J Class 70 steels used as liner material show a significant acceleration of the crack growth rates relative to the rates in benign environment [1–3]. However, this data is only available for load ratios, R, between 0.1 and 0.5. WireTough's wire-wrapped and autofrettaged cylinder design places the liner wall into compression when there is no pressure. Thus, service loading conditions consist of negative R and FCGR data are needed for negative load ratios. WireTough, in collaboration with Hy-Performance Materials Testing, LLC designed and verified a single-edge-notch-tension geometry specimen to obtain this data. The hydrogen pressure during these tests was approximately 10 MPa and the tests were performed at room temperature in accordance with the latest version of *ASTM Standard E647: Standard Method for Fatigue Crack Growth Testing*. This testing was completed during the past year and the FCGR behavior for $-1.0 \leq R \leq 0.2$ along with the available data from Sandia National Laboratories is shown in Figure 3.

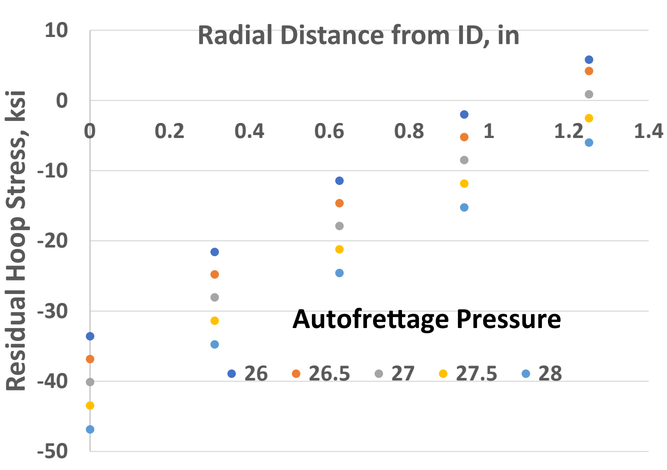

FIGURE 2. The distribution of residual compressive stresses in the liner wall as a function of autofrettage pressure estimated from the finite element analysis

Effect of Hydrogen Environment on the Wires: The preponderance of tensile strength results in specimens exposed to hydrogen fall between 3,150 MPa and 3,350 MPa. The results show little effect of the hydrogen containing environment on the tensile properties of this wire. Extended pre-exposure of the wire under stress shows little deleterious effect on the strength of the wires.

Design Life Estimation: The FCGR data were used in a crack growth calculation to estimate design lives of wire wrapped hydrogen storage cylinders containing SA 372 Grade J steel liners that were 406 mm (16 in) outer diameter (OD) with a wall thickness of 31.75 mm (1.25 in). The initial flaw size assumed for the calculations was based on a flaw depth of 2% of the wall thickness. The initial flaw length on the surface (2c) is taken as three times the depth, a.

The cyclic life based on the following duty cycles was calculated for the pressure vessel:

- Ambient to autofrettage pressure of 190 MPa (27.5 ksi) and back to ambient pressure, one cycle during manufacturing.
- Ambient to hydrotest pressure of 131 MPa (19.5 ksi) and back to ambient pressure, one cycle during manufacturing.
- Operating pressure of 90 MPa (13.0 ksi) to ambient, 2x/yr.
- Operating pressure of 90 MPa (13.0 ksi) to 69 MPa (10 ksi), 10x/d.

Four crack paths in the liner were analyzed for estimating the design life, (a) crack starting from the thread roots on the inner surface growing toward the outer surface, (b) crack starting from the outer surface at the neck and growing toward the inner surface, (c) crack starting from the outer surface at the end of the wire wrap growing toward the inner surface, and (d) radial-axial crack on the inner surface of the vessel growing toward the outer surface. The life-limiting condition is case (d), the radial-axial crack located on the inner surface of the liner. The life was estimated as 24.0 yr that exceeded the required design life of 20 yr. Thus, the proposed design meets all the requirements of ASME Section VIII, Division 3, KD-10 requirements.

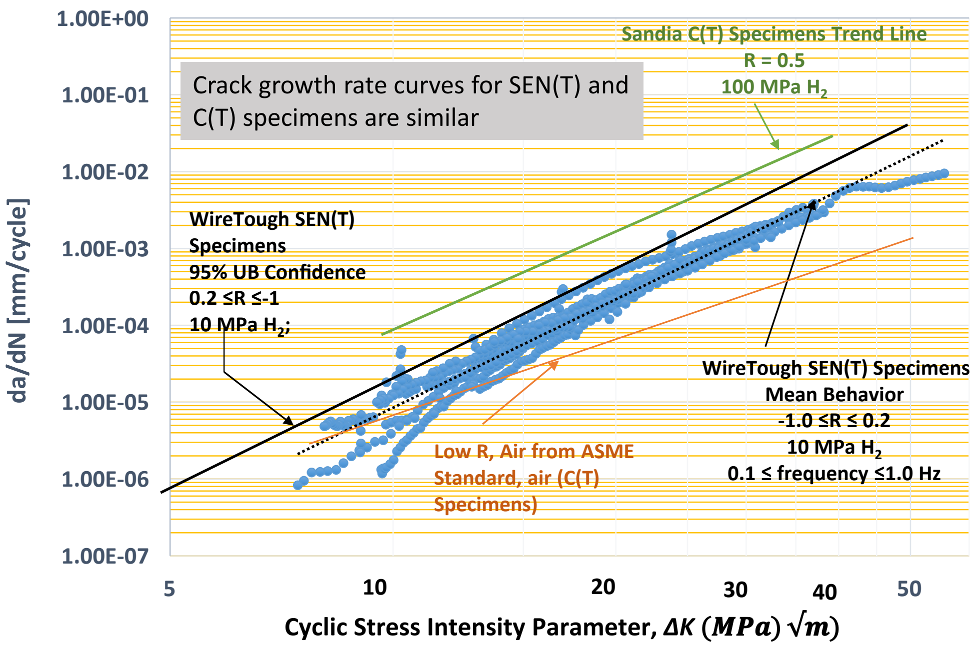

FIGURE 3. A consolidated plot of fatigue crack growth rate data in high pressure hydrogen from tests conducted by WireTough compared with literature data from Sandia National Laboratories [1–3]

ASME Certification of the WireTough Pressure Vessel Design: Structural Integrity Associates independently conducted the analysis and produced an MDR certifying WireTough's design as meeting the ASME Code.

CONCLUSIONS AND UPCOMING ACTIVITIES

- The results produced during FY 2017 on this project resulted in a successful ASME certified design of a wire wound pressure vessel for economically storing hydrogen at 875 bar.
- FCGR testing in high pressure H_2 environment at negative load ratios was completed.
- ASME KD-3 and KD-10 analysis of the 9.5 m long cylinder was completed in support of the self-certification of WireTough's design and the design is now certified.
- Testing of wires in hydrogen environment was completed by Oak Ridge National Laboratory.
- WireTough collaborated with Strategic Analysis Inc. to demonstrate that WireTough's manufacturing costs are lower than the DOE cost target for 2020.
- A machine for winding 9.5 m long (750 L) cylinders was designed, procured installed and tested. Currently the machine is undergoing preparation for producing two prototypes of our design.
- After the liners are wound, they will be shipped back to CPI for conducting the autofrettage step and the final hydrotesting as per the MDR prepared by WireTough in collaboration with Structural Integrity Associates. The interior of the vessels will be cleaned and prepared for hydrogen storage.
- WireTough expects to wrap up the project in February of 2018, meeting or exceeding all its original goals.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. A. Prakash, G.R. Sharp, B.T. Deeken, W.J. Head, W.H. Thomson, "Steel Wrapped Pressure Vessel," US Patent 9,266,642B2, Issue date February 23, 2016.

FY 2017 PUBLICATIONS/PRESENTATIONS

1. A. Prakash and A. Saxena, "Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap," DOE Annual Merit Review, Washington, DC, June 5–8, 2017.

2. A. Saxena, A. Prakash, K.A. Nibur, and I. Miller, "Considerations of the Effects of H_2 in Design of Type II Storage Vessels Built for Fatigue Resistance," Paper presented at the 2016 International Hydrogen Conference, Jackson Hole, WY, September 11–14, 2016. Paper to appear in the conference proceedings.

3. Ashok Saxena, Federico Bassi, Kevin Nibur, and James C. Newman, "On Single-Edge-Crack Tension Specimens for Tension-Compression Fatigue Crack Growth Testing," http:/dx.doi.org/10.1016/j.engfracmech.2017.03.030.

REFERENCES

1. B.P. Somerday, K.A. Nibur, C. San Marchi, "Measurement of Fatigue Crack Growth Rates for Steels in Hydrogen Containment Components," Unpublished data reproduced with permission.

2. B.P. Somerday, C. San Marchi, Kevin Nibur, "Measurement of Fatigue Crack Growth Rates for SA372-Gr J Steel in 100 MPa Hydrogen Gas Following Article KD-10," Proceedings of the ASME 2013 Pressure Vessels and Piping Conference, PVP 2013, July 14–18, 2013, Paris, France. Reproduced with permission.

3. K.A. Nibur, B.P. Somerday, C. San Marchi, J.W. Foulk, M. Dadafarnia, P. Sofronis, Met Trans., Vol. 44A, 2013, pp. 248–269; reproduced with permission.