III.9 Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap

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- N & R Engineering, Parma Heights, OH
- C P Industries, McKeesport, PA
- Ashok Saxena, Consultant, Fayetteville, AR
- Pressure Science Inc., Dallas, TX

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Project End Date: June 14, 2017

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 liters rated at a pressure of 460 bar to boost its pressure capacity to 875 bar while maintaining a safety factor of 3 on the burst pressure.
- 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 years, and deliver hydrogen that meets the SAE J2719 hydrogen purity requirements.

Fiscal Year (FY) 2015 Objectives

- Develop an elastic-plastic finite element analysis model for analyzing stresses in wire wrapped high pressure storage tanks and evaluate/optimize design alternatives
- Procure 1,900-mm long and 408-mm diameter steel liners, wire wrap them, and demonstrate that the burst pressure exceeds three times the operating pressure of 875 bar
- Develop a fracture mechanics model to analyze the effects of high pressure H_2 on vessel properties to support ASME code analyses
- Initiate work on obtaining ASME code approval
- Develop specifications for a machine capable of wire wrapping full length (9.14-m long) steel liners

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office (FCTO) 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 FCTO'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 H2 Ground Storage Systems

Characteristics	2020 Target	Wiretough
High Pressure (860 bar) Purchased Capital Cost ($/kg of H_2 stored)	1,000	On target to meet in 2017

FY 2015 Accomplishments

- Developed and validated an elastic-plastic finite element model for optimizing wire-wrapped pressure vessel design and evaluating design alternatives
- Modified the wire winding machines to accommodate 408-mm diameter liners with nominal wall thickness of 31.5 mm
- Procured four 1.9-m long metal liners and completed wire winding on two cylinders and burst testing on one cylinder
  - Second cylinder is currently being prepped for burst testing
  - Third liner is being used for material testing, and another is being used to optimize reinforcements in the transition regions between the cylinder body and the domes on the two ends

- Initiated ASME code approvals for wire-wrapped cylinders
- Completed literature review to assess susceptibility of SA 372 Class J steel liner to hydrogen assisted fatigue crack growth
- Developed a fracture mechanics model to assess integrity of high pressure (90 MPa) hydrogen storage vessel under cyclic loading

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INTRODUCTION

The DOE Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy is supporting research and development (R&D) 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 liters of gaseous 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 H_2.

APPROACH

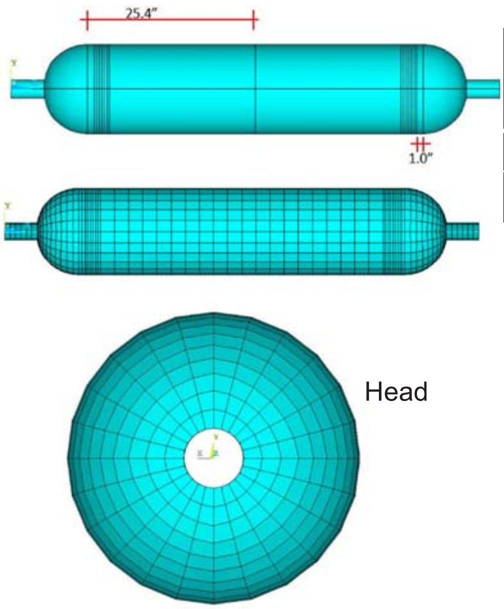
Type I metal cylinders (406-mm outer diameter) have been used for compressed natural gas (CNG) and hydrogen storage for several decades but are limited to pressures of 55 MPa for various technical reasons. Wiretough has a patent pending process to wrap these commercially available cylinders with ultra-high-strength steel wires (3 GPa in strength) to 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 inner liner is left with high residual compressive hoop stresses. This process decreases the maximum tensile hoop stress in the liner under the operating pressure and can thus enhance the fatigue life of the vessel very significantly. In this project, this concept will first be demonstrated using short, 1.9-m long cylinders and then extended to 9.14-m long cylinders.

RESULTS

Four 1.9-m long (short) metal liners with outside diameter of 406 mm (16 in) and a nominal wall thickness of 31.75 mm (1.25 in) made from ASTM SA 372 Grade J Class 70 steel were produced by CP Industries and shipped to Wiretough's Bristol, VA, facility for wire wrapping, burst testing, and for characterizing material properties such as fatigue crack growth behavior in an H_2 environment. One of the metal liners was wrapped successfully and sent to Authorized Testing Inc., an independent test facility in Riverside, CA, for hydrostatic burst testing. Authorized Testing completed the test in which the internal pressure was raised to 262.7 MPa (38,100 psi) without any signs of failure; thus, the design met the factor of safety of 3 requirement on the burst pressure. Subsequent to pressure testing, a detailed destructive examination of the tested vessel was conducted, and no evidence of cracking was found (see Figure 1).

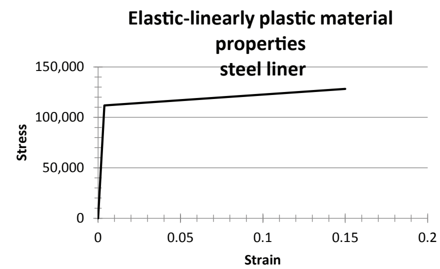
Finite element studies to support cylinder design, including establishing parameters such as autofrettage pressure, pre-tension in the wire during wrapping, and the optimum number of layers of wrapping, were successfully conducted to finalize those design details. Figure 2 shows the finite element model used in the analysis, the material properties used for the liner, and the wires. The figure also shows a table with the radial and hoop stresses predicted in the wall and the head regions of the liner at a pressure of 262 MPa (38,000 psi) and after release of the pressure. These results clearly show the high compressive hoop stresses locked in the liner wall after the pressure is released. The corresponding values of strains were compared with measured strains during the destructive testing of the tested cylinder, and very good agreement was found between the predicted and measured values of strains, validating the finite element model.

FIGURE 1. The condition of the liner after an attempted burst test during which the pressure was raised to 262.7 MPa (38,100 psi). Subsequently, the wires were cut to expose the surface of the cylinder. No visible sign of damage/cracking is seen anywhere on the liner walls.



Stresses at a pressure of 38,000 psi

	Radial stress, (psi)	Hoop stress (psi)	Axial stress, (psi)	von Mises, (psi)
Head	28,075	111,590	87,361	113,510
Cylinder	2,214	127,760	62,050	112,600
Residual stresses after the pressure is released				
Head	-899	-14,110	-2,238	13,163
Cylinder	-1,070	-61,752	-17,562	56,142



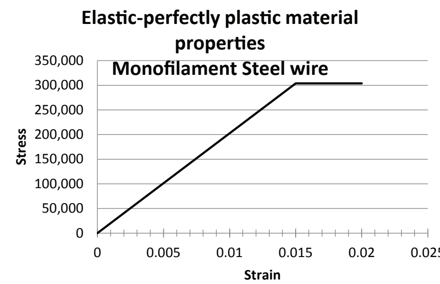


FIGURE 2. Finite element model for the cylinder body and the end caps also showing the material deformation model for the liner and the wires. The table in the figure presents values of hoop and radial stresses in the main liner body and dome in the hoop and radial directions at pressure and after the pressure has been removed.

A detailed literature survey was conducted to document the FCGR behavior and environment assisted crack growth behavior of SA 372 Grade J Class 70 steels in high pressure (100 MPa) hydrogen environment. This work has been conducted primarily at Sandia National Laboratories in the research group of Dr. Brian Somerday [1]. Figure 3a shows the fatigue crack growth behavior of SA 372 Grade J class 70 steel at a frequency of 1 Hz and a load ratio of 0.5 in 100 MPa hydrogen as compared to the behavior of similar steels in less demanding and innocuous environments. These results clearly demonstrate that high pressure hydrogen considerably accelerates the FCGRs (up to factor of 100) in these steels, so this degradation mechanism must be considered in the design of cylinders for H_2 storage. At stress intensity parameter values of less than 10 $MPa(m)^{1/2}$, it is observed that the effects of environment are not as significant. This provides guidance for the allowable design stress and inspection crack sizes.

The effects of high pressure hydrogen and load ratios on the FCGR behavior of SA 372 Grade J Class 70 steels at a frequency of 0.1 Hz were investigated [2] and are reported in Figure 3b. The average trend observed for a frequency of 1 Hz at R = 0.5 from Figure 3a was compared to the data at a frequency of 0.1 Hz in Figure 3b and was not found to differ significantly. The effect of frequency is thus minimal, as seen in the figure. Since ASME article KD-10 requires data to be generated at 0.1 Hz, the above result is significant for choosing conditions for generating additional data.

The load ratio, R, is an important variable in determining FCGR behavior, as demonstrated in Figure 3b. FCGRs are higher for R = 0.5 than for R = 0.2. For pressure vessels such as Wiretough's design that are subjected to autofrettage, the minimum stress will be compressive during a loading cycle. Thus, FCGR data are needed for R = -1.0 to -0.5 for estimating crack growth rates. Wiretough has placed a subcontract with a test laboratory very experienced in testing under hydrogen environment to characterize the effects of negative load ratios on the fatigue crack growth behavior in H_2 environment.

Figure 4 shows the environment-assisted crack growth rate data under high pressure hydrogen for SA 372 Grade J Class 70 steels [3]. The open symbols are from crack arrest tests in which the cracks are exposed to values of stress intensity parameter (K) that are higher than the threshold K under fixed displacement conditions, and then the K values corresponding to arrest are measured. These values are designated as $K_{th.a}$ and are about 65 $MPa(m)^{1/2}$ for these materials. The rising load tests yield lower threshold values of about 45 $MPa(m)^{1/2}$ for the same materials. The latter is more conservative and should be used as the maximum allowable K for this application. A fracture mechanics model has been developed to account for all these considerations in predicting the design life of the vessel.

Other progress includes preparing the specifications for a wire winding machine capable of wrapping 9.14-m long liners. This is now complete, and vendors are being identified

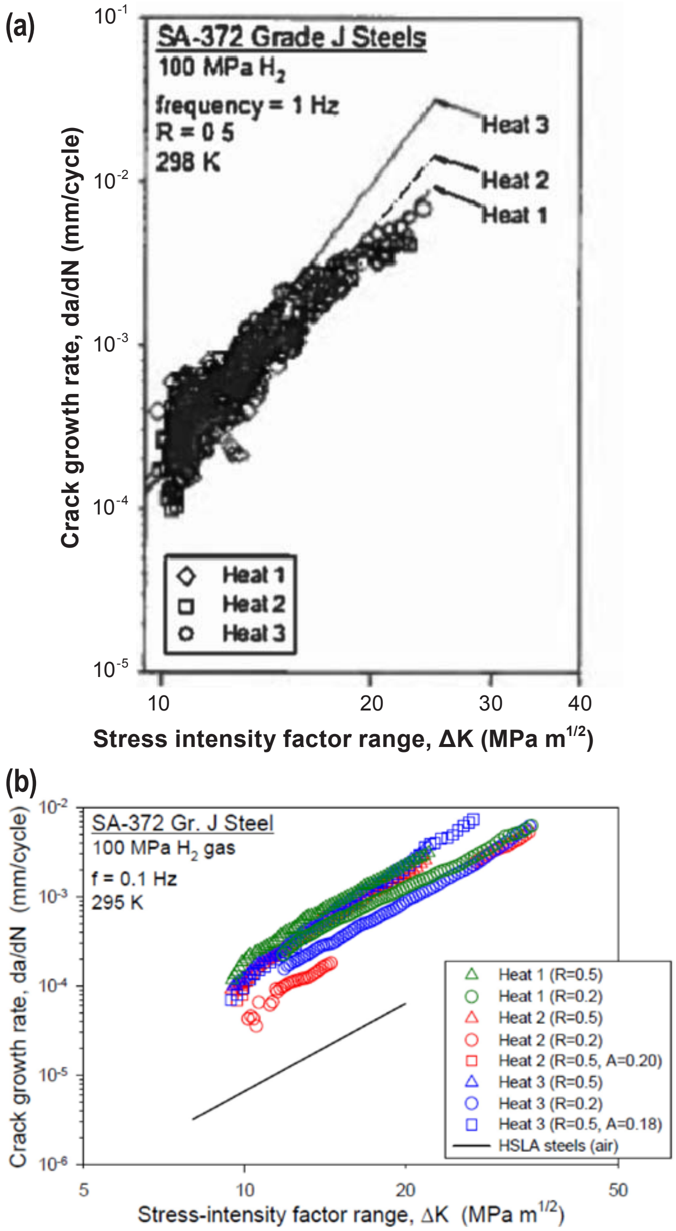


FIGURE 3. (a) FCGR behavior of SA 372 Grade J Class 70 steel under high pressure hydrogen (100 MPa) compared to the FCGR behavior of comparable steels under innocuous environments or lower hydrogen pressure (52 MPa) [1]. (b) FCGR behavior of A 372 Grade J Class 70 steels at a frequency of 0.1 Hz [2].

to produce and deliver the machine. The application for ASME code approval was also initiated.

CONCLUSIONS AND FUTURE DIRECTIONS

- The results produced during FY 2015 on this project appear promising for meeting the targets set by DOE as scheduled. All major milestones for Budget Period 1 are on target.

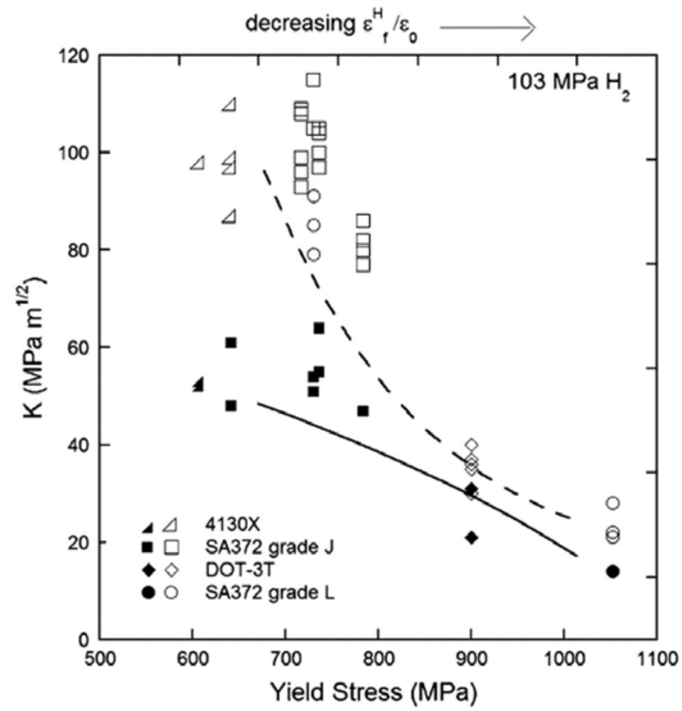


FIGURE 4. Effect of yield strength on the threshold value of K for environment assisted cracking in SA 372 Grade J Class 70 steels. Open symbols are from crack arrest tests, and the filled symbols are from rising load tests [3]. Since the rising load tests give lower values of threshold, those results are used in fracture mechanics calculations of fatigue crack growth life.

- There is a need to investigate the effects of hydrogen on FCGRs at negative load ratios to meet ASME requirements. This work, which will require six months for completion, was initiated in July of 2015.
- From the fracture mechanics model calculations it was determined that the nondestructive evaluations (NDEs) of the liners currently conducted by the suppliers are insufficient for high pressure H_2 storage tanks using thick wall liners. New NDE standards for this application are needed for ASME certifications of the design.
- The ASME code case application for non-hydrogen use of wire-wrapped cylinders of up to 750 liter capacity for pressure range up to 875 bar has been filed. The plan is to add storage of hydrogen to the application once the remaining crack growth data and inspection techniques are available.

SPECIAL RECOGNITIONS & AWARDS/PATENTS ISSUED

1. Wiretough Cylinders, LLC was awarded a $2M grant over a two-year period beginning in mid-May of 2015 by the Tobacco Commission of the Commonwealth of Virginia to further develop technology for commercializing wire-wrapped ground storage tanks for CNG and H_2 storage applications.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. A. Prakash and A. Saxena, "Light-weight Type II CNG Tank," DOE Project Kick-off Meeting, Oak Ridge National Laboratory, Oak Ridge, TN, August 13, 2014.

2. A. Prakash and W.H. Thomson, "Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap," Hydrogen Delivery Tech Team Meeting, Southfield, Michigan, March 18, 2015.

3. 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 8–12, 2015.

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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.