LOW COST HYDROGEN STORAGE AT 875 BAR USING STEEL LINER AND STEEL WIRE WRAP

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Co-PI: Dr. Ashok Saxena, Consultant

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Virginia 24202, USA

DOE Project Review, June 7, 2016
Overview

Timeline and Budget

- Project Start Date: 09/15/2014
- Project End Date: 06/14/2017
- Total Project Budget: $2,463,868
- Total Recipient Share: $495,000
- Total Federal Share: $1,968,868

Barriers Addressed

<table>
<thead>
<tr>
<th>Barriers Addressed</th>
<th>Targets</th>
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<tbody>
<tr>
<td>B: The cost of hydrogen storage systems is too high</td>
<td>• Cost of tank must be &lt; $1000/Kg of hydrogen</td>
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<tr>
<td></td>
<td>• Tank capacity must be 765 liters at 875 bars of hydrogen pressure</td>
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<tr>
<td>D: Durability of hydrogen storage systems is inadequate</td>
<td>• Life time of storage tanks &gt; 30 years</td>
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<td></td>
<td>• Deliver high purity hydrogen as per SAE standard J 2719</td>
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</table>

Partners

- Oak Ridge National Laboratory
- N & R Associates
- CP Industries
- Dr. Ashok Saxena, Consultant
- Structural Integrity Associates
- Hy Performance Materials Testing, LLC

An economical way to store energy
Approach

- **Type I metal cylinders** (406 mm OD) have been used for CNG and hydrogen storage for several decades but are limited to pressures of 55 MPa
  - Wall thickness is restricted by considerations of microstructural consistency and the ability to reliably inspect
- Wiretough has a patented design approach involving wrapping commercially available cylinders with ultra high strength steel wires (2 GPa in strength) to double their pressure capability
- Following wire wrapping, cylinders are subjected to autofrettage pressures which when released, lock high compressive stresses on the inside surface of the liner
  - This process further decreases maximum tensile hoop stresses under operating pressures, and can significantly improve the pressure capability of the vessel
- Demonstrate the concept using short, 1.9 m long cylinders and then extend it to 9.5 m long cylinders
Develop a pressure vessel with a capacity of 765 liters to safely store hydrogen at 875 bar that also meets the DOE storage tank cost target of <$1000/kg hydrogen ($H_2$).

- Life > 30 years/10,000 pressure cycles
- 3X safety factor on burst pressure
- Hydrogen purity meets SAE J2719 requirements
- Design consistent with ASME codes
Accomplishments and Progress

Accomplishments This Reporting Period (4/1/15- 3/31/16)

ASME Code case for Wiretough design approved

Demonstrated proof of concept on 1.9 m long cylinders
- Four 406 mm diameter, 1.9 m long cylinders manufactured and successfully wire wrapped
- Two cylinders subjected to burst testing; and elastic-plastic finite element analyses were conducted to successfully demonstrate burst pressures in excess of 2,625 bars
- Elastic-plastic finite element analyses conducted to simulate the autofrettage process and subsequent service pressure cycle conditions to estimate maximum, minimum and cyclic stresses in the critical regions of the cylinder.

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Accomplishments and Progress

Accomplishments This Reporting Period (4/1/15-3/31/16)

Materials compatibility testing, and scale-up addressed

- Fatigue crack growth tests in hydrogen at negative load ratios performed
- Fatigue testing in hydrogen performed on high strength wire at ORNL
- Finite element model used to identify approaches to reduce stress in transition region between the wire wrap and the dome of liner
- Alternate methods of NDE explored to reliably detect flaw sizes less than 3% of the wall thickness (industry standard)
- Specifications developed for wire wrapping machine for 9.1 to 12 m long cylinders, and order placed. Installation scheduled to begin in July of 2016 with a completion date of end of August of 2016.

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WIRE TOUGH
Wiretough Receives ASME U3 Certification for Producing Type 2 Cylinders for Ground Storage of CNG and Hydrogen

• After a review of the stress analysis, manufacturing process, and inspection standards conducted by an ASME Team: **ASME U3 Stamp was granted on March 9, 2016**
• Approval gained under ASME’s Boiler and Pressure Vessel Code (BPVC) Section VIII- Division 3
• Liner outer diameter of 16”
• Liner length ranging to 25’ to 30’ with a capacity of 700+ liters
• Round and flat wires using SA905, Class 1  min UTS = 296 ksi, min Yield = 260 ksi wires with specified pre-tension
• Allowable maximum pressures in the range of 10,000 to 15,000 psi
• Applies to pressure vessels for ground storage of gases such as CNG, Hydrogen, air etc.

An economical way to store energy
Fracture Mechanics Evaluation of Vessel for Hydrogen Storage Underway

**SELF CERTIFICATON** FOR HYDROGEN STORAGE FOLLOWING KD-10 RULES

Self-certification expected to be complete by 8/20/2016. Basis includes:

- Fatigue crack growth rate studies under +ve load ratio, R, values (Sandia)
- Fatigue crack growth rate studies under –ve R values (Wiretough)
- Finite element stress analysis (Wiretough)

An economical way to store energy
FCGR measurements from Wiretough’s SEN(T) specimens compare well with Sandia’s results from C(T) specimens

- FCGR measurements at R=0.2 are comparable at hydrogen pressures of 10 and 103 MPa at high crack growth rates

**Note:** The SEN(T) data are preliminary and may require minor adjustments after completion of an ongoing study to verify the K-calibration expressions used.
Accomplishments and Progress

FCGR at $-ve \, R$ values comparable to low $+ve \, R$ values in hydrogen environment

- FCGR at load ratios of -1.0 and -0.5 in hydrogen are comparable to the rates at low load ratios such as 0.1
- The differences in FCGR in hydrogen and in air diminish considerably at low values of $\Delta K$
- When $\Delta K$ approaches 8 MPa$\sqrt{m}$, the FCGR in air and in hydrogen for $-1.0 \leq R \leq 0.2$ appear to be converging
- More data are being gathered to confirm this trend

An economical way to store energy
Preliminary fracture mechanics model calculations show that there is adequate fatigue life in wire-wrapped and autofrettaged liners in high pressure hydrogen.

<table>
<thead>
<tr>
<th>Stress, ksi</th>
<th>Cycles to Failure in air</th>
<th>Cycles to Failure in Hydrogen (assuming 4x reduction due to higher crack growth rates in hydrogen)</th>
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<tbody>
<tr>
<td>45</td>
<td>89,000</td>
<td>22,250</td>
</tr>
<tr>
<td>40</td>
<td>130,000</td>
<td>32,500</td>
</tr>
<tr>
<td>35</td>
<td>212,000</td>
<td>53,000</td>
</tr>
</tbody>
</table>
Design improvements being considered for further reducing peak stresses in the transition region of the liner

1. Extend the wrap further into the dome region by another 0.5 to 0.75 in

2. Spray metal on the outer surface in the transition region to extend the region for wire winding

3. Build a carbon fiber composite jacket over the dome region and extend it to the end of the wire wrap

4. Shrink fit a ring to extend the region for wire winding

An economical way to store energy
Lower yield strength material may be used to lower peak stress in the liner

- Lower yield strength of the liner material to 550 MPa (80 ksi) and limit maximum stress to 310 MPa (45 ksi) and UTS to less than 758 MPa (120 ksi).

- This will considerably reduce the autofrettage pressure required to lock-in high compressive stresses and reduce the peak stresses significantly.

- There **may be** added potential benefits of reduced susceptibility to hydrogen assisted cracking.
Remainder of BP-2 and BP-3 to focus on producing 750 liter wire-wrapped vessel and on self-certification of the design

- FEM analysis to optimize transition region design
- Complete FCGR Testing in H₂ environment
- ASME KD-3 and KD-10 analysis of the 30’ long cylinder
- Explore YS/UTS reduction of liner material for reducing autofrettage pressures and peak stresses
- Develop NDE criteria for liners
- Testing of wires in hydrogen environment
- Production of 30’ long (750L) cylinders
  - Machine Installation
  - Winding of 30’ long cylinders
- Manufacturing cost analysis
- Analysis to demonstrate ASME Section VIII Division 3 Requirements

An economical way to store energy
<table>
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<tr>
<th>Remaining Tasks /Milestones</th>
<th>Months after 4/1/2016</th>
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<tr>
<td>• FEM analysis to optimize transition region design</td>
<td>0 - 3: X 4 - 6: X 7 - 9: X 10 -12: X 13-15: X</td>
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<td>• ASME KD-3 and KD-10 analysis of the 30' long cylinder</td>
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<tr>
<td>• 7th Quarterly report</td>
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<td>• 8th Quarterly report</td>
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<td>• 9th Quarterly report</td>
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<td>• 10th Quarterly report</td>
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<td>• 2nd Annual report</td>
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## Collaborations

(not including subcontractors)

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<thead>
<tr>
<th>Organization</th>
<th>Description of the Collaboration</th>
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<tbody>
<tr>
<td>Oak Ridge National Laboratory</td>
<td>Fatigue of wires, Effects of hydrogen on the wires</td>
</tr>
<tr>
<td>Sandia National Laboratory</td>
<td>Effects of high pressure hydrogen on fatigue crack growth behavior of A372 steels</td>
</tr>
<tr>
<td>State of Virginia</td>
<td>Infrastructure support, Financial support via grants, publicity</td>
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Concluding Remarks

- Had very successful first and second years
- On track to produce a successful ASME certified design of 875 Bar -765 liter capacity, hydrogen cylinder using Wiretough’s patented design
- Expected cost unchanged from previous projections (< $1000/Kg)