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

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**WIRETOUGH CYLINDERS LLC**  
14570 Industrial Park Road, Bristol  
Virginia 24202, USA



**DOE Project Review, June 7, 2016**

Project ID: PD110



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# 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

## Partners

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

## Barriers Addressed

Barriers Addressed	Targets
B: The cost of hydrogen storage systems is too high	<ul style="list-style-type: none"><li>• Cost of tank must be &lt; \$1000/Kg of hydrogen</li><li>• Tank capacity must be 765 liters at 875 bars of hydrogen pressure</li></ul>
D: Durability of hydrogen storage systems is inadequate	<ul style="list-style-type: none"><li>• Life time of storage tanks &gt; 30 years</li><li>• Deliver high purity hydrogen as per SAE standard J 2719</li></ul>



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# 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**



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# Statement of Project Objectives (SOP) and Work Plans

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<sub>2</sub>).

- 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 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 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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# 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.



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# Fracture Mechanics Evaluation of Vessel for Hydrogen Storage Underway

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

ASME BPVC.VIII.3-2015

### ARTICLE KD-10

### SPECIAL REQUIREMENTS FOR VESSELS IN HYDROGEN SERVICE

**KD-1010 FRACTURE MECHANICS EVALUATION**

**KD-1022 QUALIFICATION TESTS FOR THRESHOLD STRESS INTENSITY FACTOR FOR HYDROGEN-ASSISTED CRACKING,  $K_{IH}$**



### CERTIFICATE OF AUTHORIZATION

The named company is authorized by the American Society of Mechanical Engineers (ASME) for the scope of activity shown below in accordance with the applicable rules of the ASME Boiler and Pressure Vessel Code. The use of the certification mark and the authority granted by this Certificate of Authorization are subject to the provisions of the agreement set forth in the application. Any construction stamped with this certification mark shall have been built strictly in accordance with the provisions of the ASME Boiler and Pressure Vessel Code.

COMPANY:

Wiretough Cylinders LLC  
14570 Industrial Park Rd  
Bristol, Virginia 24202

SCOPE:

Manufacture of pressure vessels at the above location only (This authorization does not cover welding or brazing)

AUTHORIZED: March 9, 2016

EXPIRES: March 9, 2019

CERTIFICATE NUMBER: 48,899

American Society of Mechanical Engineers

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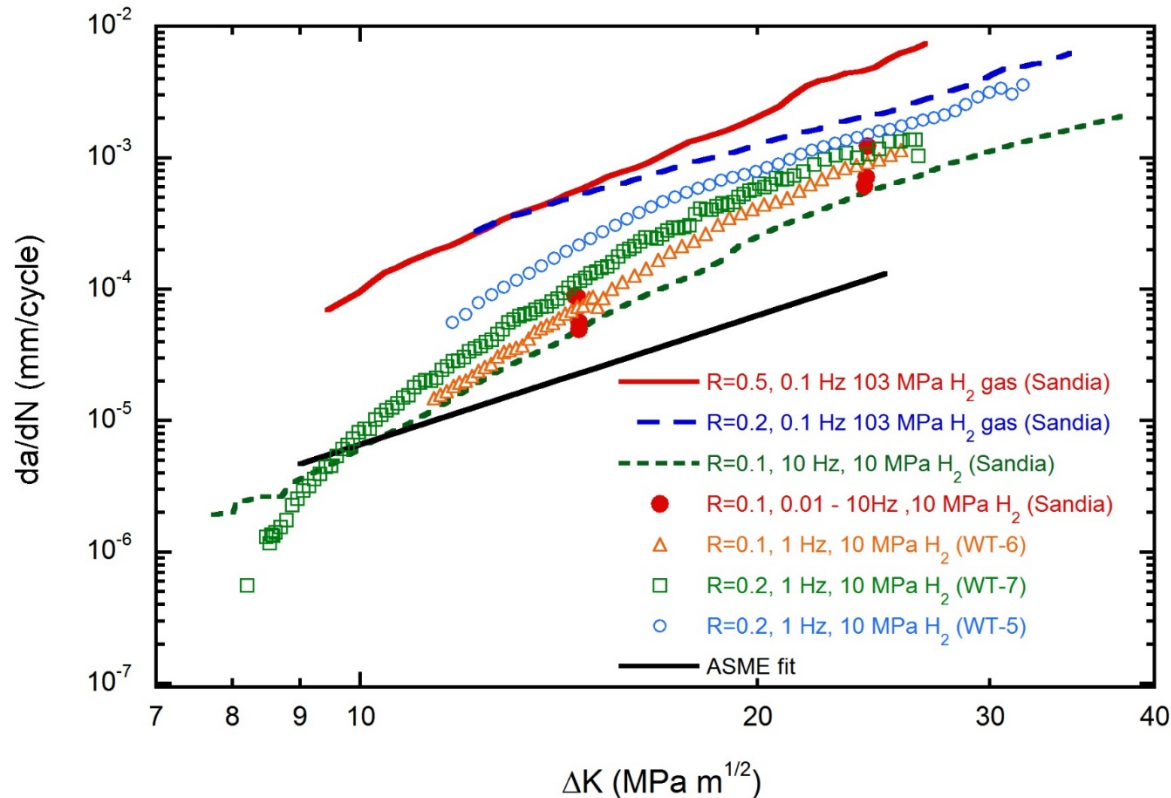
**Self-certification expected to be complete by 8/20/2016. Basis includes:**

- 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)





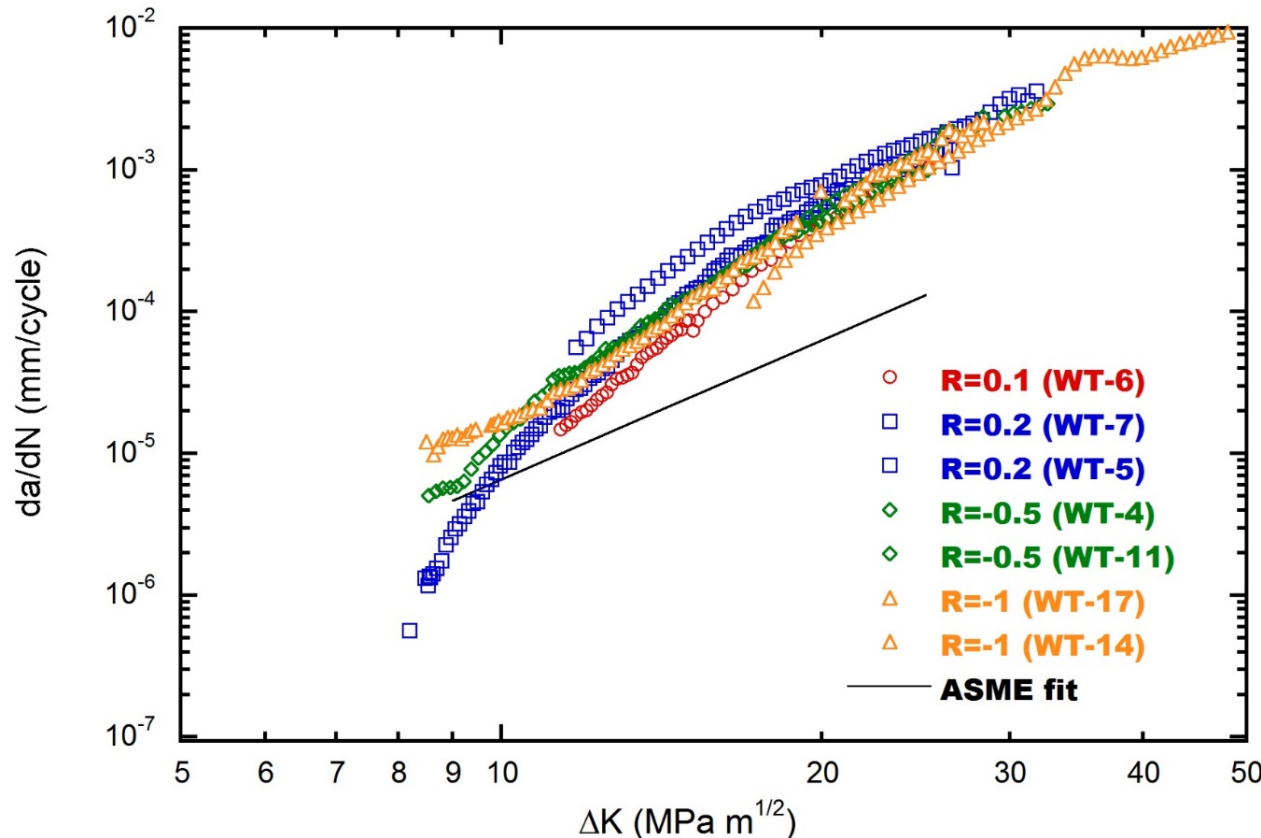
# FCGR measurements from Wiretough's SEN(T) specimens compare well with Sandia's results from C(T) specimens



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

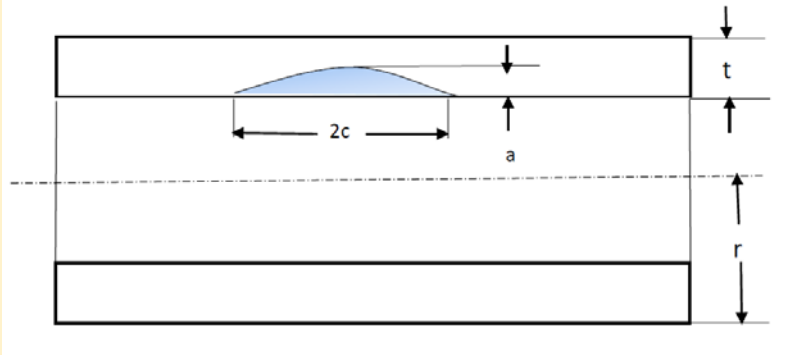
**Note:** The SEN(T) data are preliminary and may require minor adjustments after completion of an ongoing study to verify the K-calibration expressions used

# 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

# Preliminary fracture mechanics model calculations show that there is adequate fatigue life in wire-wrapped and autofrettaged liners in high pressure hydrogen

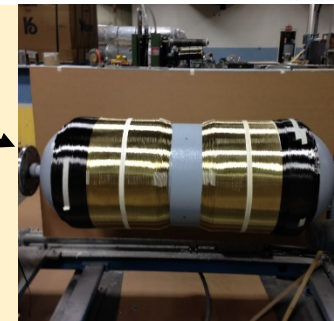
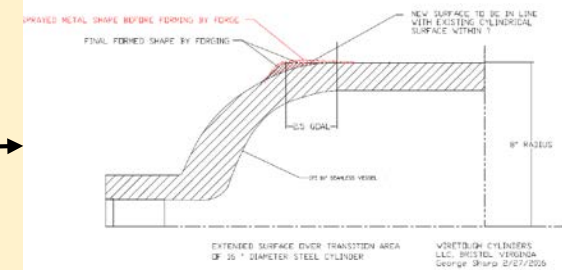
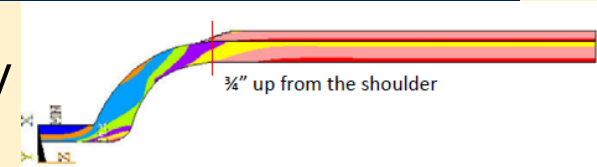


**Fatigue Crack Growth Life in Cycles, N, for Initial Crack Size = 3% of Thickness,  $t = 1.25$  in, and a Final Crack Size =  $0.25t$**

Stress, ksi	Cycles to Failure in air	Cycles to Failure in Hydrogen (assuming 4x reduction due to higher crack growth rates in hydrogen)
45	89,000	22,250
40	130,000	32,500
35	212,000	53,000

# 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



## 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 H<sub>2</sub> 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

# Major Milestones and Deliverables

Remaining Tasks /Milestones	Months after 4/1/2016				
	0 - 3	4 - 6	7 - 9	10 -12	13-15
<ul style="list-style-type: none"> <li>FEM analysis to optimize transition region design</li> </ul>	X—X				
<ul style="list-style-type: none"> <li>Complete FCGR Testing in H<sub>2</sub> environment</li> </ul>	X—	—X			
<ul style="list-style-type: none"> <li>ASME KD-3 and KD-10 analysis of the 30' long cylinder</li> </ul>		X—X			
<ul style="list-style-type: none"> <li>Explore YS/UTS reduction of liner material for reducing autofrettage pressures and peak stresses</li> </ul>	X—	—X			
<ul style="list-style-type: none"> <li>Develop NDE criteria for liners</li> </ul>		X—X			
<ul style="list-style-type: none"> <li>Testing of wires in hydrogen environment</li> </ul>	X—		—X		
Production of 30' long (750L) cylinders					
<ul style="list-style-type: none"> <li>Machine Installation</li> </ul>		X—X			
<ul style="list-style-type: none"> <li>Winding of 30' long cylinders</li> </ul>			X—X		
<ul style="list-style-type: none"> <li>Analysis to demonstrate ASME Section VIII Division 3 Requirements</li> </ul>			X—X		
<ul style="list-style-type: none"> <li>Manufacturing cost analysis</li> </ul>				X—X	
Reporting					
<ul style="list-style-type: none"> <li>7<sup>th</sup> Quarterly report</li> </ul>	X				
<ul style="list-style-type: none"> <li>8<sup>th</sup> Quarterly report</li> </ul>		X			
<ul style="list-style-type: none"> <li>9<sup>th</sup> Quarterly report</li> </ul>			X		
<ul style="list-style-type: none"> <li>10<sup>th</sup> Quarterly report</li> </ul>				X	
<ul style="list-style-type: none"> <li>2<sup>nd</sup> Annual report</li> </ul>					X
<ul style="list-style-type: none"> <li>Final contract report</li> </ul>					X—X

# Collaborations

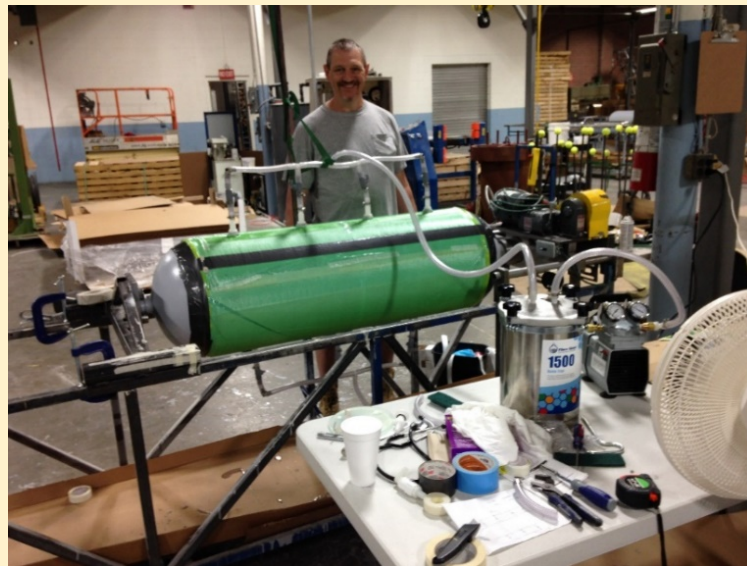
(not including subcontractors)

Organization	Description of the Collaboration
Oak Ridge National Laboratory	Fatigue of wires, Effects of hydrogen on the wires
Sandia National Laboratory	Effects of high pressure hydrogen on fatigue crack growth behavior of A372 steels
State of Virginia	Infrastructure support, Financial support via grants, publicity



# 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)



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