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

PI: Dr. Amit Prakash, President
Co-PI: Dr. Ashok Saxena, Consultant

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



DOE Annual Merit Review
June 6, 2017

Project ID: PD110



An economical way to store energy

Overview

Timeline and Budget

- Project Start Date: 09/15/2014
- Project End Date: 02/28/2018
- 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	Targets
E. Gaseous Hydrogen Storage and Tube Trailer Delivery Costs	<ul style="list-style-type: none">• Cost of tank must be < \$1000/Kg of hydrogen• Tank capacity must be 765 liters at 875 bars of hydrogen pressure• Life time of storage tanks > 30 years• Deliver high purity hydrogen as per SAE standard J 2719



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Statement of Project Objectives and Work Plans

Goal: 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 (H₂).

Accomplishments: Developed a vessel that meets goal, and has:

- an estimated **life of 24 years** based ASME Section VIII-Division 3, KD-10 (Requirements for fitness for service in hydrogen)
- The **cost target has also been** met with a decent margin

Approach

Challenge:

- Type I metal cylinders (406 mm OD) are limited to pressures of 55 MPa
- Wall thickness restricted by considerations of microstructural consistency and the ability to reliably inspect

Wiretough Approach

- Wrap commercially available Type I cylinders with ultra high strength steel wires (>2 GPa in strength) to double their pressure capability
- Autofrettage wrapped cylinders to lock high compressive stresses on the inside surface of the liner
- Decrease maximum tensile hoop stresses under operating pressures, and improve pressure capability of the vessel
- Established viability of concept by wrapping short, 1.9 m long cylinders



Accomplishments This Reporting Period (4/1/16- 3/31/17)

ASME approval for Wiretough design obtained

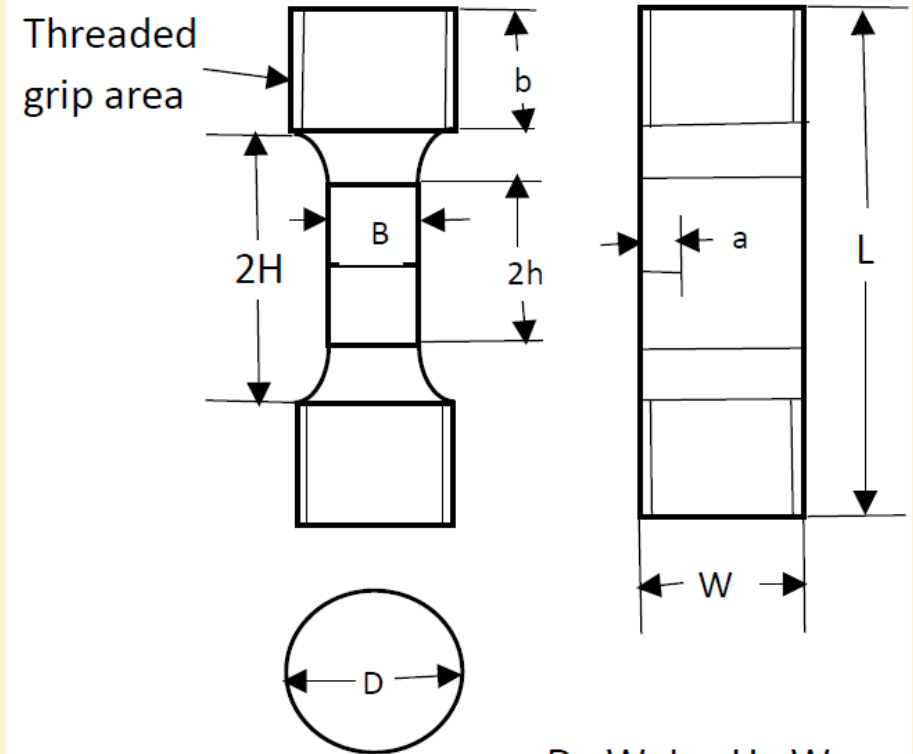
- Fatigue crack growth testing in hydrogen (10 MPa) at negative load ratios (compression) completed
- Self-certification process for the 765 liter capacity cylinder for ASME Section VIII Division 3 approval for service in hydrogen (KD-10) completed
- ORNL completed several tests to assess the integrity of wires in hydrogen environment
- Several design improvement options explored and implemented
- Two papers accepted for publication one in press and the other published

FCGR at negative R values characterized using specially designed SEC(T) specimens



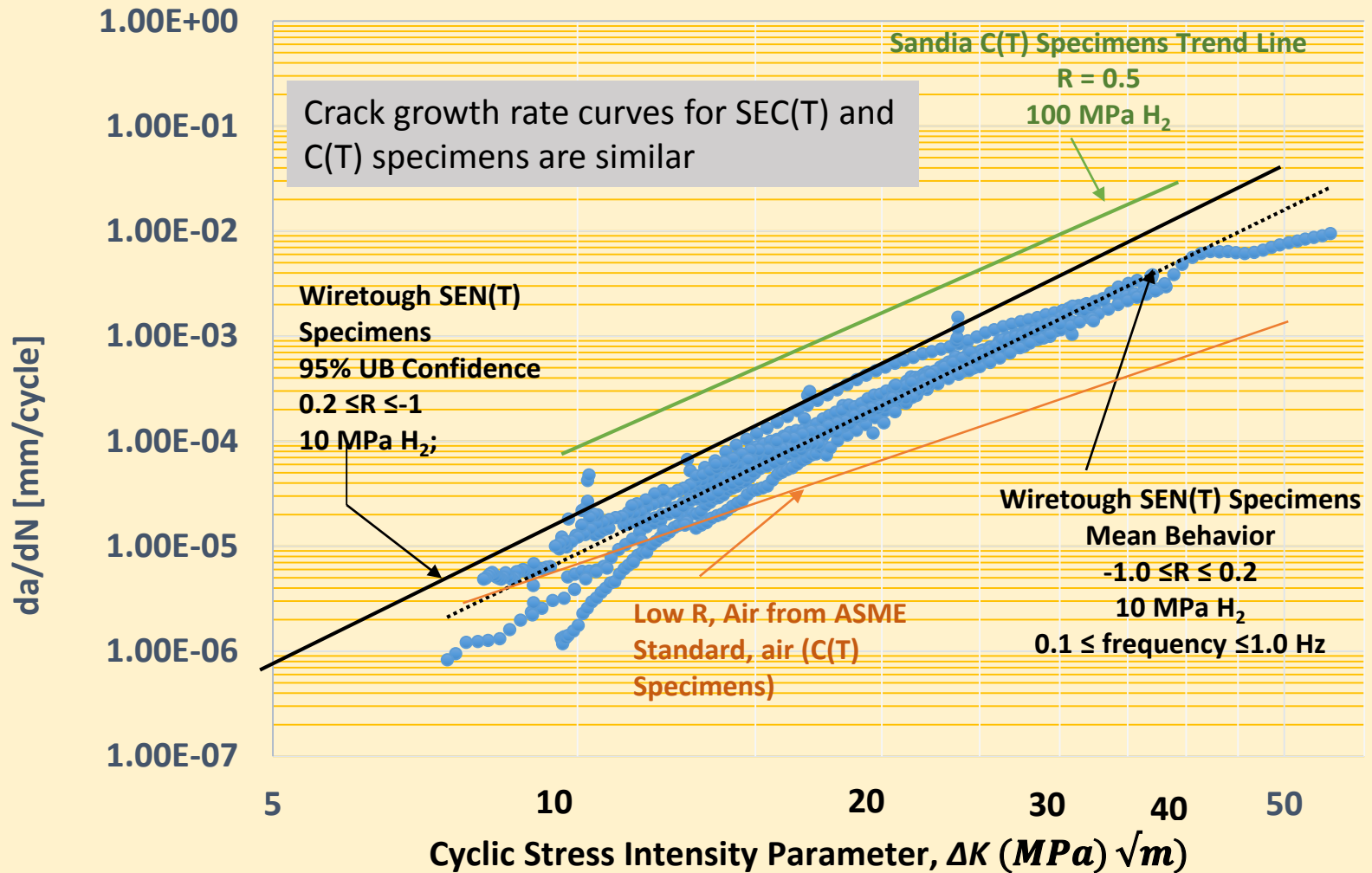
“On Single-Edge-Crack Tension Specimens for Tension-Compression Fatigue Crack Growth Testing”

Ashok Saxena, Federico Bassi, Kevin Nibur and James C. Newman,
Engineering Fracture Mechanics, 2017



$$D = W; L = H + W;$$
$$b = W; h = H - W/2$$

Validity of Wiretough's SEN(T) approach to characterize fatigue was verified through comparison with Sandia's results from C(T) specimens



Derived fatigue crack growth relationships for Wiretough pressure vessels (based on experimentation)

Fatigue Crack Growth Rate Law

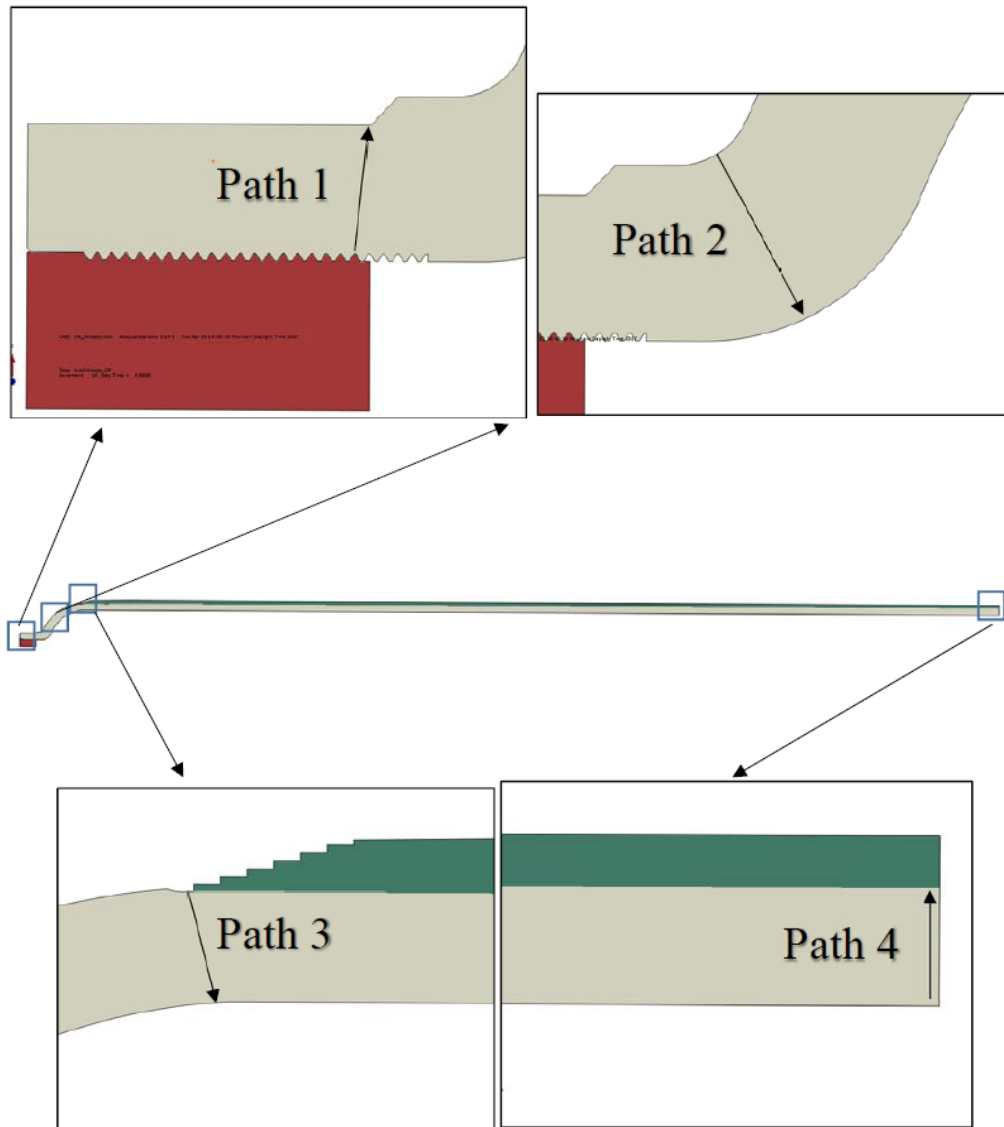
$$\frac{da}{dN} = C(\Delta K)^n$$

Test Environment / R	$c \left(\text{ksi}\sqrt{\text{in}} \right)^{-n}$	$c \left(\text{Mpa}\sqrt{\text{m}} \right)^{-n}$	n
Air / 0.1	1.95×10^{-10}	3.63×10^{-9}	3.26
10 MPa H ₂ / 0.2 ≤ R ≤ -1.0, upper bound of 95% confidence band	2.58×10^{-11}	4.2×10^{-10}	4.69
10 MPa H ₂ / 0.2 ≤ R ≤ -1.0, mean behavior	1.06×10^{-11}	1.723×10^{-10}	4.69
100 MPa H ₂ / R = 0.5 [Sandia Data]	1.907×10^{-10}	3.185×10^{-9}	4.4

User Defined Specifications for Design Life Calculations

- **Maximum Design Pressure during service:**
103.4 MPa (1000 Bar; 15,000 psi)
- **Max Operating Pressures during service:**
90 MPa (875 Bar; 13,000 psi)
- **Duty cycles:**
 - Ambient to autofrettage pressure of 190 MPa (27.5 Ksi) -1x at the beginning and unload
 - Ambient to hydrotest pressure of 131 MPa (19.0 Ksi) -1 x at the beginning and unload
 - Operating pressure of 90 MPa (13.0 Ksi) to ambient – 2x/year
 - Operating pressure of 90 MPa (13.0 Ksi) to 69 MPa (10 Ksi)- 10x/day
- **Liner Dimensions:**
 - 31.75mm (1.25”) wall thickness
 - OD of 406.4mm (16”), , 9.2 m (30’) long

Accomplishment: Crack Paths for calculating expected vessel life



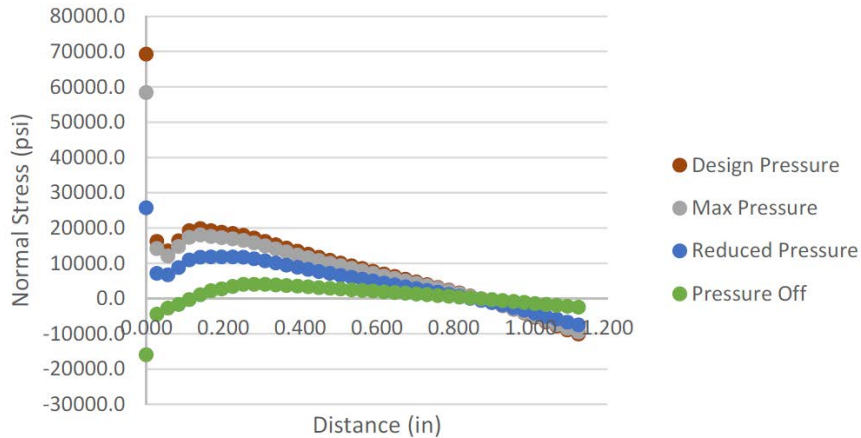
Design Life Reported

- Total life from initial flaw size to reach critical size
- $\frac{1}{2}$ cycles to reach critical crack size

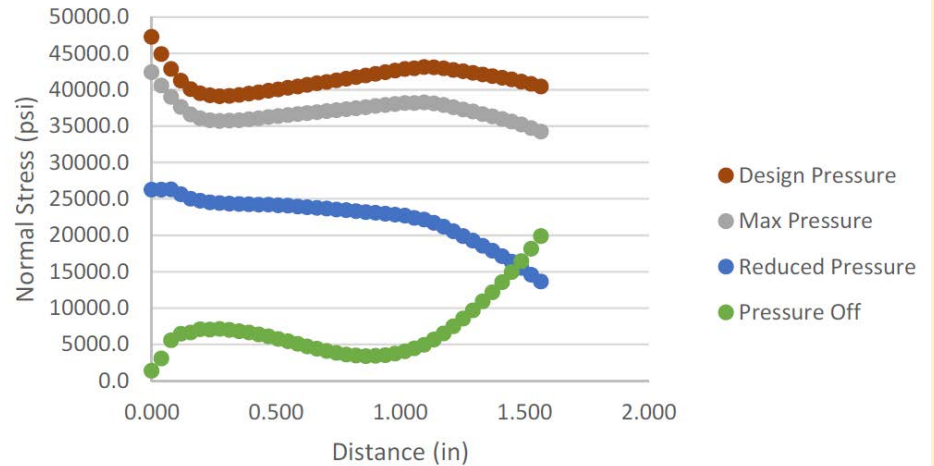
Path	Initial Flaw Size (depth x length), mm
1	1.52 x 4.57
2	0.635 x 1.9
3	0.635 x 1.9
4	0.635 x 1.9

Accomplishment: Stress Analysis Results

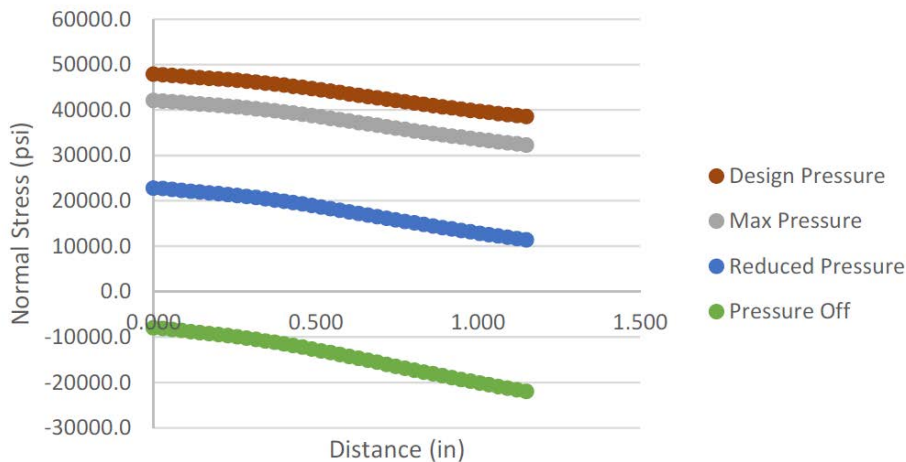
Fracture Mechanics Stresses - Path 1



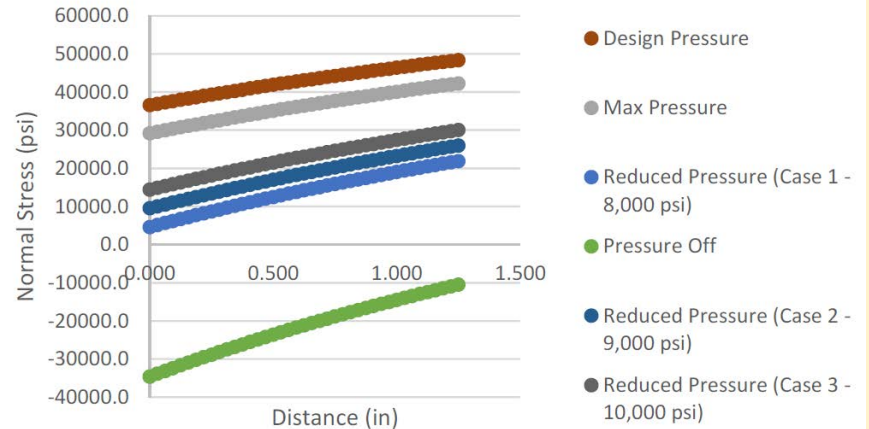
Fracture Mechanics Stresses - Path 2



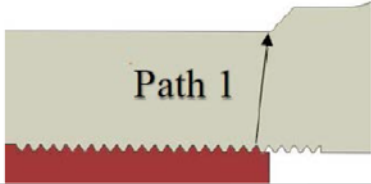
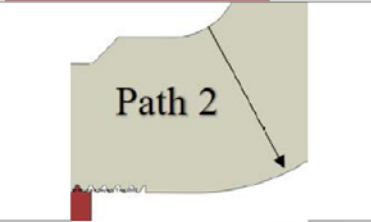
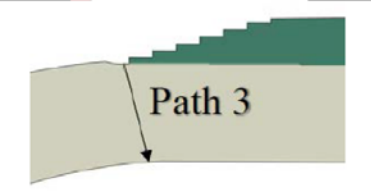
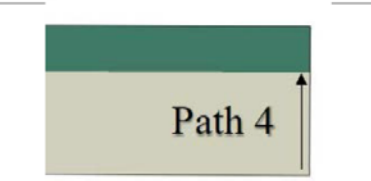
Fracture Mechanics Stresses - Path 3



Fracture Mechanics Stresses - Path 4



Projected life assuming 10 cycles/day from 90 MPa to 89 MPa (13,000 to 10,000 psi)

Crack Path	Projected Life, Years	
	Initial crack size to critical	50% of life
 Path 1	49 ¹	24.5 ¹
 Path 2	728 ¹	364 ¹
 Path 3	281 ¹	140.5 ¹
 Path 4	48 ²	24 ²

Conservatism in ASME KD-10 Procedure

- Data for $R = 0.5$ used throughout the life calculations because no extrapolations in effects of pressure were allowed
- The life is further reduced by a factor of 2

¹Based on reduced pressure of 55 MPa (8.0 Ksi)

²Based on reduced pressure of 69 MPa (10 Ksi)

Remainder of BP-3 to focus on producing 750 liter wire-wrapped vessel and design optimization

- Produce at least two 30' long prototypes of cylinders
- Develop a formal protocol to ensure that adequate compressive stresses are developed during the autofrettage process
- Explore methods/protocol for inspection/hydrotesting at the end of originally estimated life
- Complete wire testing in H₂
- Apply for new ASME code cases that are more suitable for Wiretough design
- Complete a Project Final Report



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Key Collaborations

Organization	Description of the Collaboration
Oak Ridge National Laboratory	Experimentation to determine effects of fatigue and hydrogen on wires
Sandia National Laboratory	Assessment of effects of high pressure hydrogen on fatigue crack growth behavior of A372 steels
State of Virginia	Infrastructure support, Financial support via grants, publicity
Strategic Analysis, Inc.	Review of costs of manufacturing process

Produced an ASME Code compliant 875 Bar -765 liter capacity, hydrogen cylinder using Wiretough's patented approach.

Expected cost unchanged from previous projections (< \$1000/Kg)



Thank you to the remarkable team in Bristol for their dedication to the success of the program!



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Thank you!
Questions?