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

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Project ID: PD110

WIRE TOUGH

An economical way to store energy

Overview

Timeline and Budget

- Project Start Date: 09/15/2014
- Project End Date: 06/14/2017
- Total Project Budget: $ 2,463,870
- Total Recipient Share: $ 495,000
- Total Federal Share: $ 1,968,870
  - Total DOE Funds Spent*: $ 327,256

* As of 3/31/15

Partners

- **Oak Ridge National Laboratory**
- **N & R Associates**
- **CP Industries**
- **Dr. Ashok Saxena, Consultant**

Barriers Addressed

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

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Relevance

Project Objectives

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 time of the vessel must exceed 30 years/10,000 pressure cycles
- Must have a factor of safety of 3 on burst pressure to operating pressure
- Must deliver hydrogen that meets SAE J2719 hydrogen purity requirements
- The Design to be consistent with relevant ASME Codes

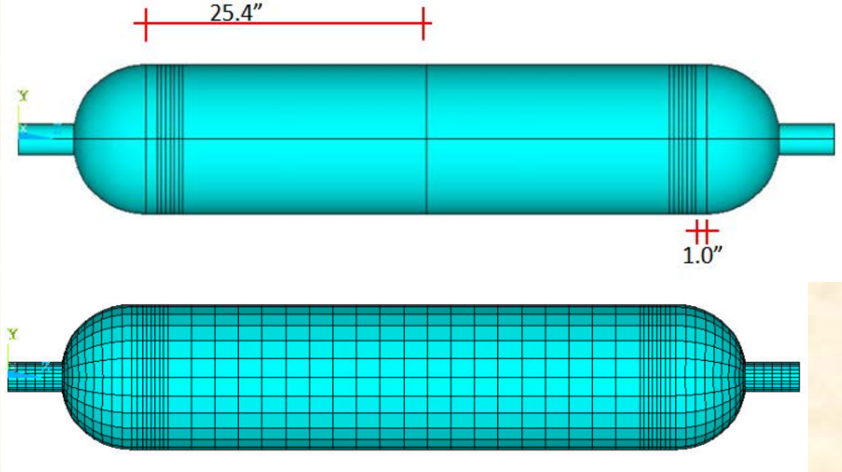
This Reporting Period (9/15/2014-3/31/2015)

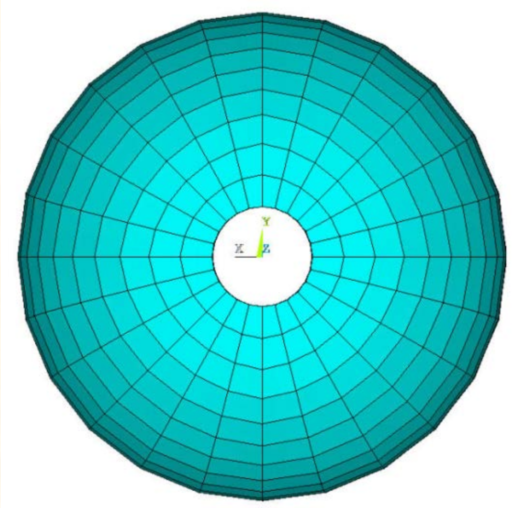
- Developed an elastic-plastic finite element model for optimizing pressure vessel designs
- Procured three short metal liners (1.9 m long) from CPI, completed wire winding one and conducted burst testing
- Initiated ASME Code approvals for wire-wrapped cylinders
- Developed a fracture mechanics model to assess integrity of the design of a high pressure (100 MPa) hydrogen storage with consideration of cyclic loading and environment assisted crack growth

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 the ability to reliably inspect
- Wiretough has a patent pending process to wrap these commercially available cylinders with ultra high strength steel wires (3 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 decreases maximum tensile hoop stresses under operating pressures, and can double 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

Accomplishments and Progress





Head

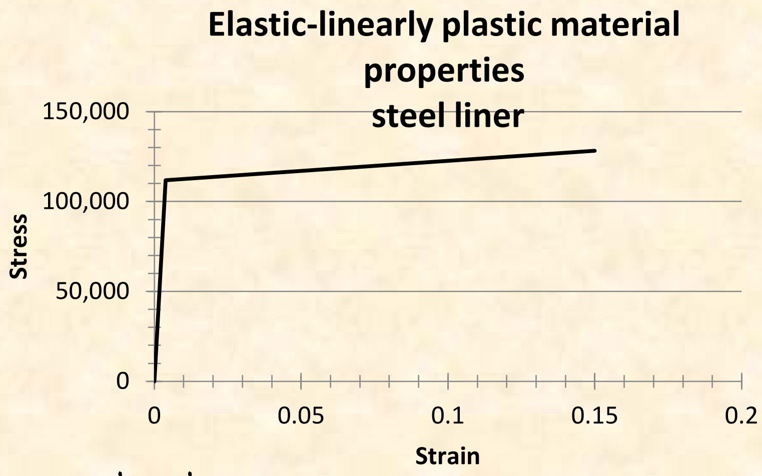
Stresses at a pressure of 38,000 psi

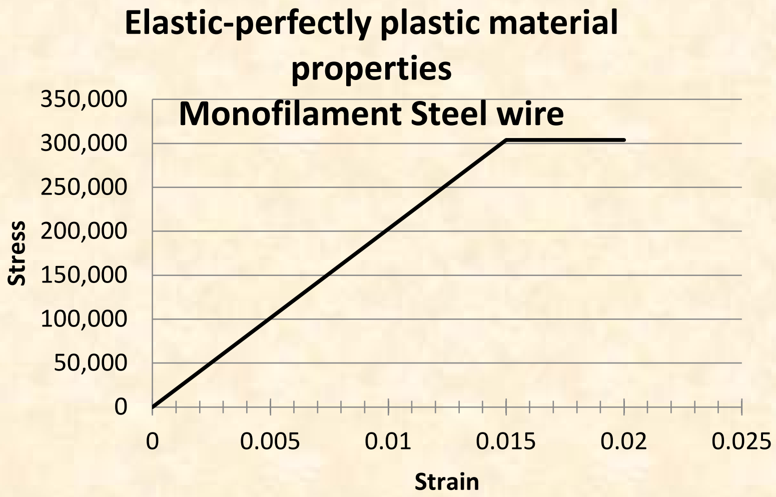
	Radial stress, (psi)	Hoop stress (psi)	Axial stress, (psi)	von Mises, (psi)
Head	28,075	111,590	87,361	113,510
Cylinder	2,214	127,760	62,050	112,600

Residual stresses after the pressure is released

Head	-899	-14,110	-2,238	13,163
Cylinder	-1,070	-61,752	-17,562	56,142

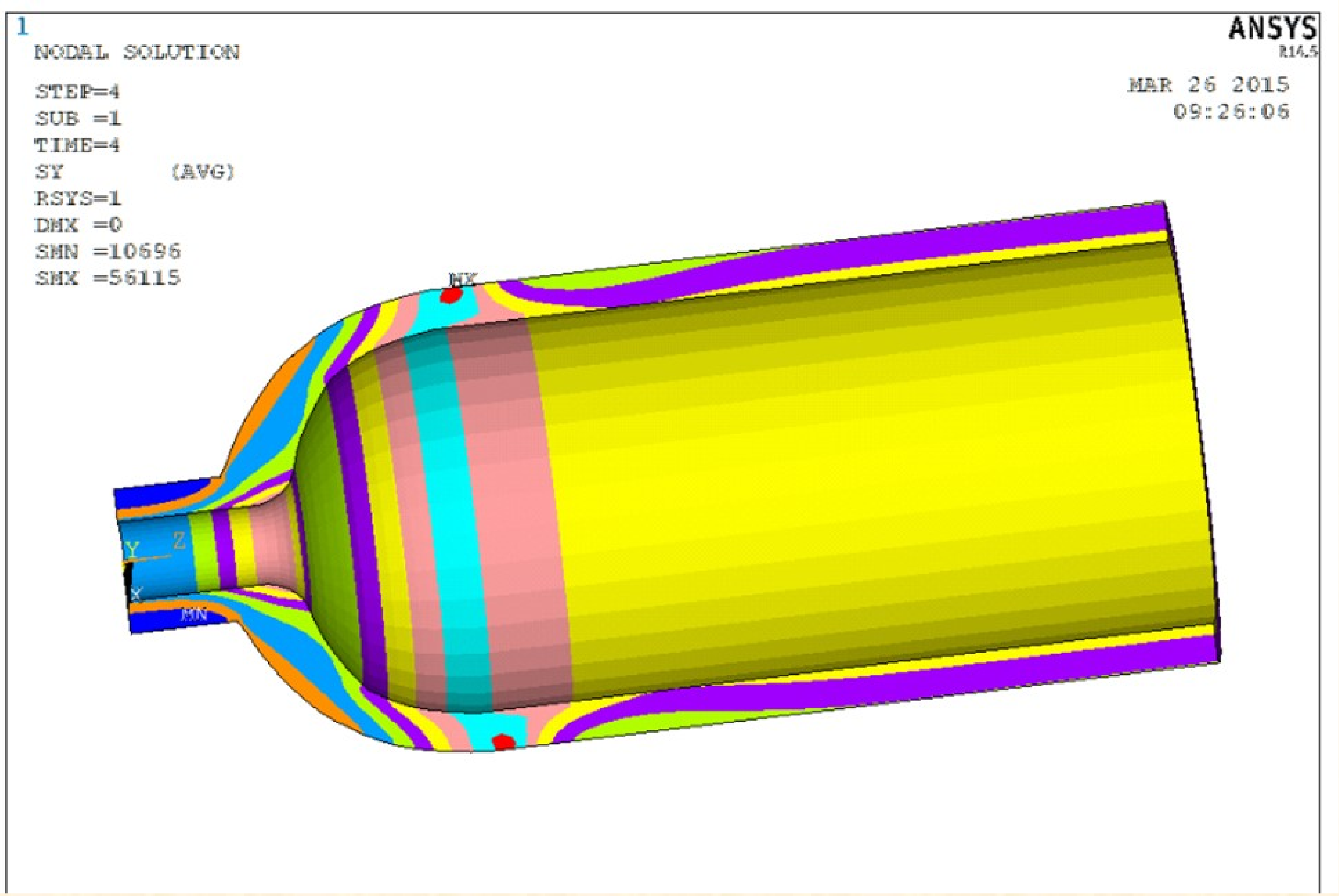
Developed a Finite Element Model





Accomplishments and Progress

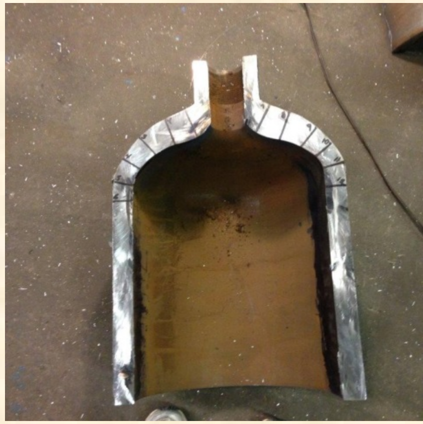
Estimated hoop stresses and identified regions of stress concentration at operating pressure of 89.6 MPa after autofrettage and accounting for wire pre-tension



Procured Liners and Tested Cylinders After Wire Wrapping

One Test on a short length cylinder successfully completed

- Three 1.9 m (72”) long , 406 mm (16 in) OD and a nominal wall thickness of 31.75 mm (1.25 in) metal liners were fabricated from ASME SA 372 Grade J, Class 70 by CP Industries and wire wrapped and tested by Wiretough
- Authorized Testing completed the test in which the internal pressure was raised to 262.7 MPa (38,100 psi). This level exceeds the target pressure of 262.5 MPa (38,072 psi) based on a safety factor of 3
- Test had to be stopped due to equipment malfunction. The tested cylinder condition was assessed:
    - No visible cracks or any other form of damage was found on the inside and outside the metal liner.
    - The wire wrap remained intact
    - High levels of compressive stresses were present in the liner
    - The residual strains were measured and compared to FE results
    - The chemical composition and mechanical properties were within the range of ASME SA 372 Class J ferritic steels



Chemical composition (wt %) of metal liner (primary elements) compared to standard ranges for ASME SA-372M-03 Grade J /Class 70 steel

Element	C	Mn	P	S	Ni	Si	Cr	Mo	Cu	Al	Fe
Heat No. 315262	0.46	0.98	0.015	0.005	0.04	0.23	1.03	0.22	0.08	0.037	Bal
Product 4145 Steel	0.48	0.96	0.014	0.005	0.03	0.23	1.08	0.22	0.08	0.033	Bal
ASME SA-372 Gr J / Class 70	0.35 - 0.50	0.75-1.05	<0.025	<0.025	-	0.15-0.35	0.80-1.15	0.15-0.25	-	-	Bal

The material properties and chemical composition were within standard specifications for SA372 Grade J Class 70 steel for the tested cylinder

Results of the tensile test performed by CP Industries on the metal liners as part of material certification.

Specimen Dimensions: 12.33 mm (0.505 in) diameter, 50.8 mm (2 in) gage length

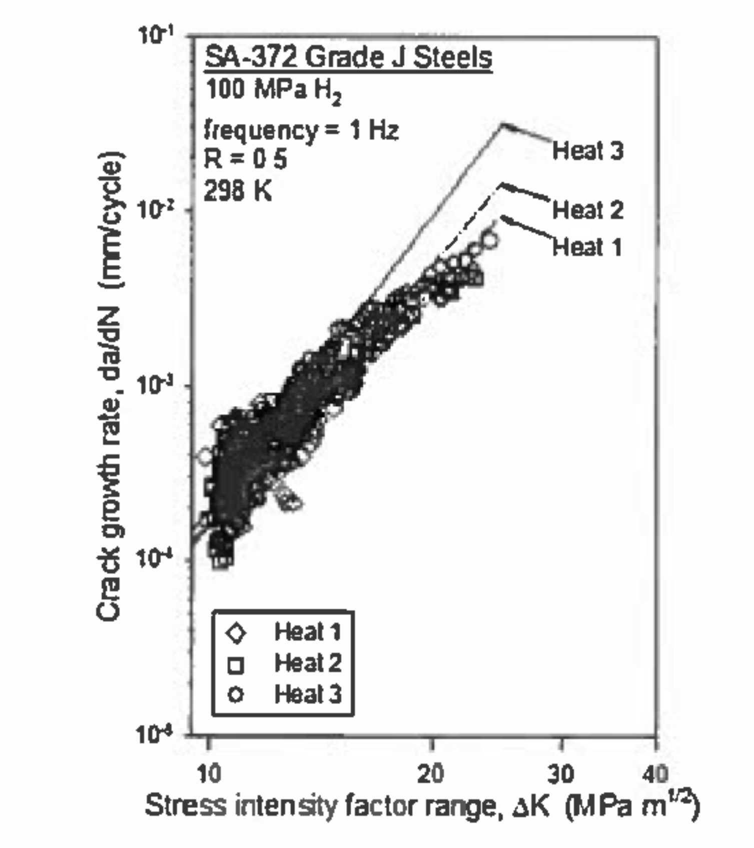
Material	0.2% Yield Strength, MPa (Ksi)	Tensile Strength, MPa (Ksi)	% Elongation	%Reduction in Area
Product 4145 Steel	770.75 (111.8)	884.5 (128.3)	21.0	60.9
SA-372 Class 70 Standard	Minimum 482.6 (70.0)	827.3-930.69 (120-135)	18 Min	-

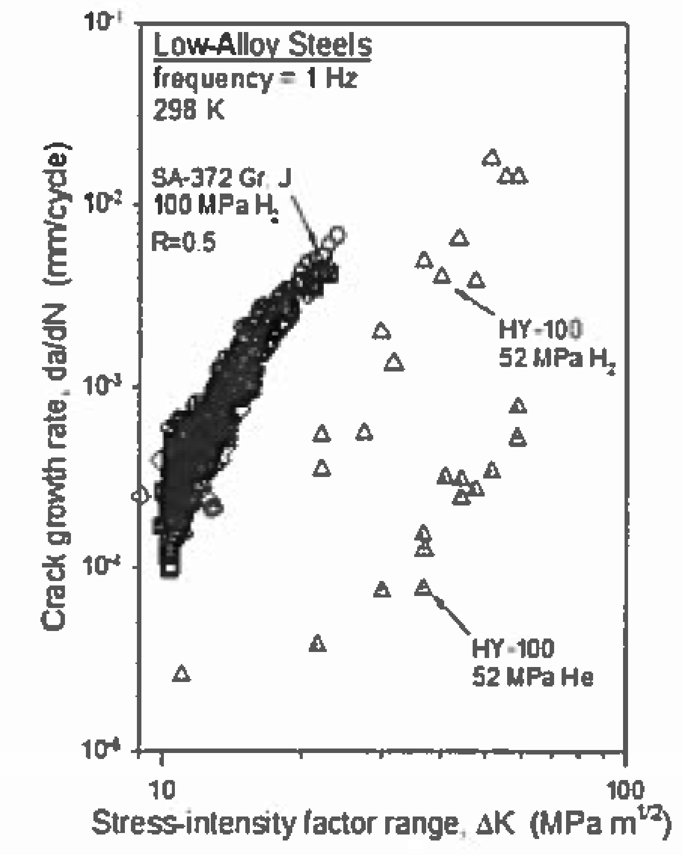
Effects of High Pressure Hydrogen on Liner Material Properties- Literature Review Completed

Literature Data on the Effects of High Pressure Hydrogen (100 MPa) on the Mechanical Properties of A372 Class J or Equivalent Steels

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

- Fatigue crack growth rate data available for load ratio of 0.5
- Fracture toughness is reported to be > 140 $MPa\sqrt{m}$





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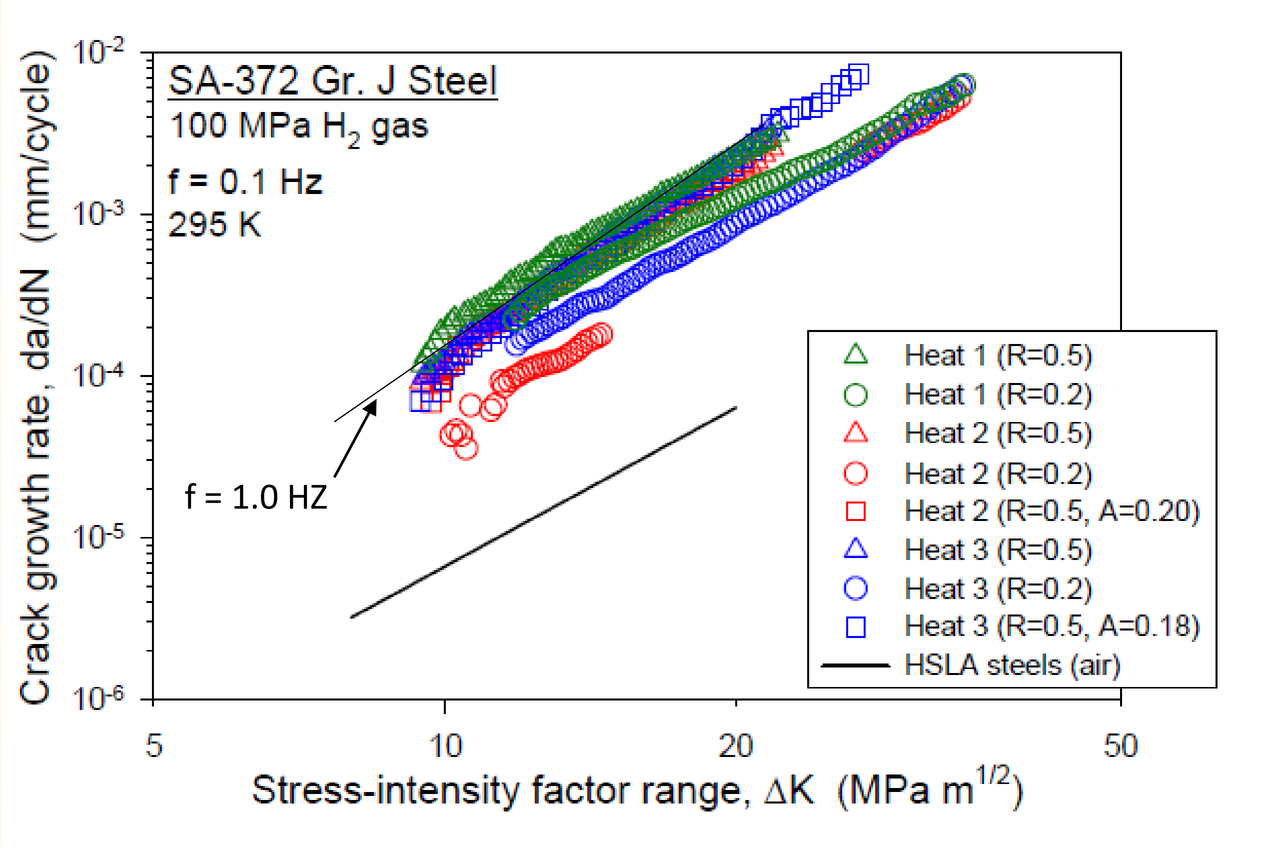
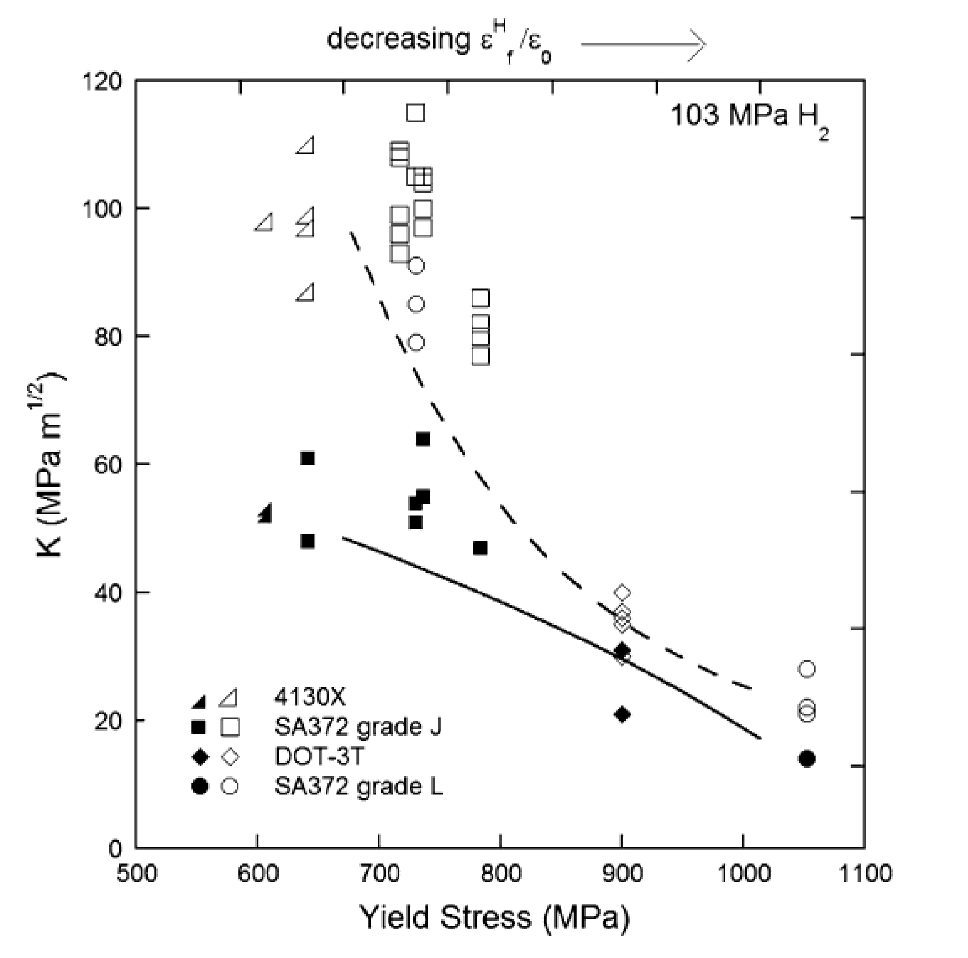
Effect of Frequency on the Fatigue Crack Growth Behavior in 100 MPa Hydrogen



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

Effect of frequency of loading between 0.1 Hz and 1 Hz seems to be minimal

Effect of Yield Strength on Threshold value of K for Environment Assisted Cracking



K.A. Nibur, B.P. Somerday, C. San Marchi, J.W. Foulk, M. Dadafarnia, P. Sofronis, Met Trans., Vol. 44A, 2013, pp248-269; reproduced with permission

Open symbols are from crack arrest tests and filled symbols are from rising load tests

Threshold stress intensity for environment assisted cracking: $K_{th,a} = 65\ MPa\sqrt{m}$ and $K_{th.i} = 45\ MPa\sqrt{m}$

Meeting requirements of ASME Boiler and Pressure Vessel Code -Section VIII (Rules for Construction of Pressure Vessels) Division 3 (Alternative Rules for Construction of High Pressure Vessels)

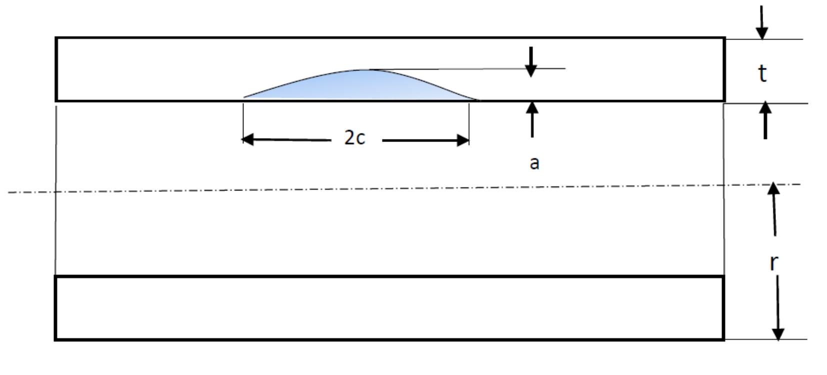
- Part KD-Design Requirements
  - KD-3 Fatigue Evaluation
  - KD-4 Fracture Mechanics Evaluation
  - KD-10 Special Requirements for Vessels in Hydrogen Service

Analyses Being Conducted to Support the Code Approval Application

- FE Analysis
- Fatigue Analysis (KD-3)
- Fracture Mechanics Analysis (KD-4)

Fatigue Crack Growth Model

r= 203 mm
t = 31.75 mm



Fatigue Crack Growth Life in Cycles, N, for a_o = 0.03t and a_f = 0.25t		
Stress range, ksi	t= 1.25 in	t= 0.35 in
50	63,300	214,760
45	89,000	302,800
40	130,900	444,510
35	202,400	686,150

Cyclic Stress, ksi	Crack depth, a in	Half crack length, c in	ΔK_a $ksi\sqrt{in}$	ΔK_c $ksi\sqrt{in}$	da/dN in/cycle	dc/dN in/cycle	N, Cycles
35	0.0375	0.05625	9.43	8.47	2.93×10^{-7}	2.06×10^{-7}	0
	0.3125	0.3572	24.37	25.58	6.48×10^{-6}	7.58×10^{-6}	202,400
	0.625	.7429	36.8	40.1	2.49×10^{-5}	3.28×10^{-5}	227,500
	1.0	1.2925	52.3	60.9	7.8×10^{-5}	1.28×10^{-4}	236,320
40	0.0375	0.05625	10.77	9.68	4.53×10^{-7}	3.2×10^{-7}	0
	0.3125	.357	27.86	29.23	1×10^{-5}	1.17×10^{-5}	130,900
	0.625	.743	42.1	45.83	3.85×10^{-5}	5.07×10^{-5}	147,250
	1.00	1.292	59.8	69.6	1.2×10^{-4}	1.98×10^{-4}	152,920
45	0.0375	0.05625	12.12	10.89	6.64×10^{-7}	4.69×10^{-7}	0
	0.3125	0.3572	31.3	32.9	1.4×10^{-5}	1.72×10^{-5}	89,000
	0.625	0.7442	47.41	51.62	5.67×10^{-5}	7.45×10^{-5}	100,030
	1.00	1.295	67.27	78.31	1.77×10^{-4}	12.9×10^{-4}	104,160
50	0.0375	0.05625	13.47	12.12	9.37×10^{-7}	6.69×10^{-7}	0
	0.3125	0.3572	34.82	36.6	2.08×10^{-5}	2.44×10^{-5}	63,300
	0.625	0.743	52.5	57.08	7.96×10^{-5}	1.05×10^{-4}	71,140
	1.00	1.2925	74.74	87.0	2.5×10^{-4}	4.1×10^{-4}	73,880

Takeaways from Fracture Mechanics Analysis

- ΔK levels during service should be less than 10 $MPa\sqrt{m}$ to avoid significant environmental effects on crack growth
- Fatigue crack growth data at negative load ratios at 100 MPa hydrogen pressure are needed to improve crack growth life estimates
- Alternate approaches to 3% of the wall thickness for specifying the initial crack sizes are needed for meaningful estimates of the fatigue crack growth life

Collaborations

(not including subcontractors)

Organization	Description of the Collaboration
Oak Ridge National Laboratory	Fatigue of wires, Effects of hydrogen on the liners
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

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Proposed Future Work

(Next 12 months 4/1/2015-3/31/2016)

ASME Boiler and Pressure Vessel Code Approvals

Wire wrapped cylinder design approvals being sought for the following cylinders:

Cylinder Model	Liner Drawing	Material SA372	OD (in)	Length (75 in)	Liner Wall Thickness (in)	Auto-frettage pressure (psi)	Use Pressure (psi)	Comp. date
WTA-167513	A-10316-2	J-70	16.0	75.0	1.25	28,000	13,000	6/2017
WTA 167508	A-10316-2	J-70	16.0	75.0	1.25	0	8,000	12/2015
WTA 167505	WTA-197505L1	E-70	16.0	75.0	0.35	0	5,000	12/2015

Wire Specifications: SA905, Class 1 0.02”x0.08”; Min UTS = 296 ksi, Min Yield 260 ksi

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Proposed Future Work

(Next 12 months 4/1/2015-3/31/2016)

- Complete following tasks by 6/30/2015 related to Go/No-Go for Budget Period 1
  - Complete wire wrapping of 1.9m short cylinder
  - Use finite element model to lower stresses in the transition region between the head and the main cylinder body and select the most appropriate autofrettage pressure
  - Demonstrate with one additional burst test that the burst pressure exceeds 2625 bar
- Work with SNL to obtain fatigue crack growth data at lower (close to 0) load ratios under 100 MPa hydrogen pressure
- Conduct fatigue crack growth testing at negative load ratios in hydrogen environment
- Design and install wire winding machines for 9.5 m long cylinders
- Develop appropriate NDE evaluation guidelines for thick wall pressure vessels as an alternative to the initial crack size equal to 3% of wall thickness
- Continue to work toward ASME code approval

Summary

- Significant progress made towards goal of designing and demonstrating viability of a low-cost, high pressure (875 bar) hydrogen storage cylinder for filling stations
- Three short cylinders have been produced and one was tested after wire wrapping to demonstrate that the burst pressure is at least 3 times of the design pressure
- A finite element model of the wire wrapped cylinder was developed and verified for use in detailed design of future cylinders
- Fatigue crack growth data at high hydrogen pressure has been obtained from the literature for use in the fracture mechanics analysis
- A fracture mechanics model to assess the fatigue crack growth life and inspection criteria/inspection interval in accordance with ASME-BVP Division III- article KD-10 has been developed