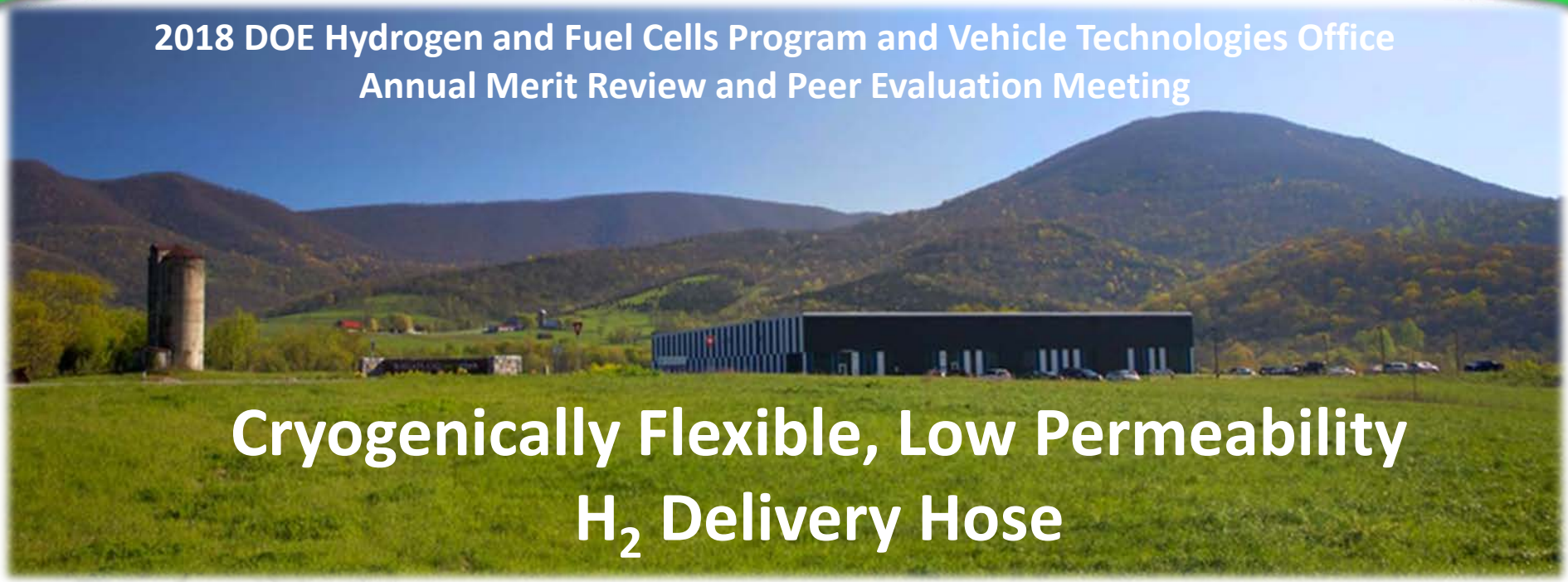
NanoSonic, Inc.

2018 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office
Annual Merit Review and Peer Evaluation Meeting



Cryogenically Flexible, Low Permeability H_2 Delivery Hose

P. I.: Dr. Jennifer Lalli, Chief Development Officer
NanoSonic, Inc.
6/14/2018

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NanoSonic

Project ID #
PD149

Overview

Timeline

- Project Start Date: 7/31/2017
- Project End Date: 7/30/2019

Barriers

- Reliability and Cost of Gaseous H_2 Compression
- Reliability and Cost of Liquid H_2 Pumping
- Eliminate H_2 Embrittlement, Increase Durability
- Lack of Fittings for New High Pressure Hoses

Budget

- FY13 DOE Ph I Funding: $150,000
- FY14 DOE Ph II Funding: $1,000,000
- FY17 DOE Ph IIB Funding:
- Total DOE Project Value: $2,150,000

Partners

- CSA Group
- NREL
- PNNL
- Cardinal Rubber & Seal
- LifeGuard Technologies
- Shell, Tatsuno, and WEH
- Giles County Government

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Relevance:

Develop a H_2 Hose for Fuel Cell Vehicles

Objectives:

- **Flexible: H_2 hose to enable delivery < $2/gge**
- **Rugged: -50 °C and 875 bar for H70 service**
- **Reliable and safe: 70 fills/day, > 2 years**

Impact in April 2017 – April 2018:

- **Produced: Low T_g, Low H_2 Permeability, Fiber Reinforced Hose with High Pressure Fittings**
- **Demonstrated: Hydrostatic Burst Strength > 33,000 psi for H35 Service**
- **Goal: Metal Free Hose Design and Custom Fitting to Enable Long-term H70 Service**

Current Approach to Hoses up to 20’ Long:
Filament Wound Metal-free H_2 Hose

NanoSonic Flexible Composite Hoses Exhibit Hydrostatic Burst Strength > 33,000 psi

Tested at RTP at CSA Group per Hydrostatic Strength (section 2.4) of ANSI/CSA HGV 4.2-2013 *Standard for hoses for compressed hydrogen fuel stations, dispensers and vehicle fuel systems*. Requires a 1 min hold without burst or visible loss of fluid at a hydrostatic pressure of four (4) times the manufacturers specified maximum allowable working pressure (MAWP). Up to a 10,000 PSI MAWP hose assembly.

Approach:

Project Phases and Selected Milestones

Evaluate FY17 Q4
critical performance metrics, fittings, partners for deployable design

Qualify FY18 Q3-Q4
H70 hose with OEM's dispenser / nozzle to assess service life (~2 years)

Test FY18 Q1-Q2
hose/fittings with H_2 via TTS (NS), robotic fill (NREL), and DMA / tribology (PNNL)

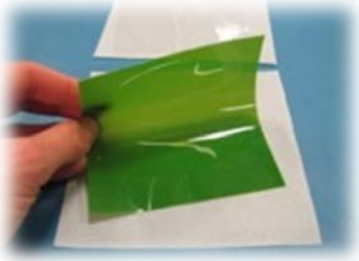
Deploy FY19 Q2
H70/H35 hoses at H_2 stations

Critical Criteria

- Surpass 3500 Bar hydrostatic burst strength (> 50,763 psi) held for 1 min
- Survive 875 Bar pressure cycle at (50,000x at -50F and 50,000x at 85F)
- No contaminant leaching, Competitive cost, mechanical durability, and environmental lifetime

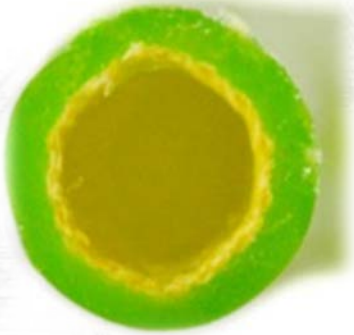
Accomplishments in Design

Evolution of the High Pressure Hose



Hydrogen Permeance by ASTM D 1434

Sample No.	
Set 4 - Lot # LB199-119	0.29 0.22 0.20
Hydrogen - 10A, 10B, 10C	AV = 0.24 ± 0.04
Hydrogen Cold - 10A, 10B, 10C	0.36 0.35 0.20
	AV = 0.31 ± 0.09

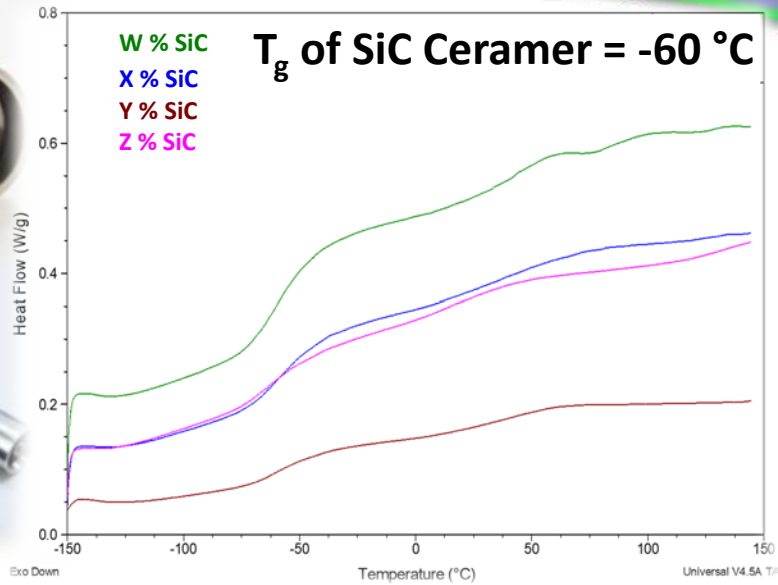


The ideal burst pressure was estimated for the single braid reinforced hoses to be ~ 2560 bar using Barlow's Formula: $P = 2\ s\ t\ /\ (d_o\ SF)$

Where, P = max. working pressure (psig), s = material strength (psi) = 10.2 x 10^6 (Aramid fiber); yield strength = 522,000 psi. t = wall thickness (in) = 0.02" (Braid thickness), d_o = outside diameter (in) = 0.563" (9/16"), SF = safety factor (in general 1.5 to 10) = 1; Calculated maximum working Pressure 37,129 psi (2560 Bar or 256 MPa)

Accomplishments in Manufacturing

Fittings Crimped In-House with Polymer Derived Ceramer Coupling Agent



Test ID	Hose	Length (inch)	Fitting Manufacturer	Fitting OD	Ceramer in Hose	Ceramer at Fitting	Burst Pressure (psi)
WH208-8C	A	17	1	proprietary	x		6446
WH208-8D	A	17	1	proprietary	x	x	8334
WH208-8E	A	17	2	proprietary	x		4304
WH208-8F	A	17	2	proprietary	x	x	7016
WH208-9A	B	17	1	proprietary			52959
WH208-9B	B	17	1	proprietary		x	58440
WH208-9C	B	17	2	proprietary			9635
WH208-9D	B	17	2	proprietary		x	26136

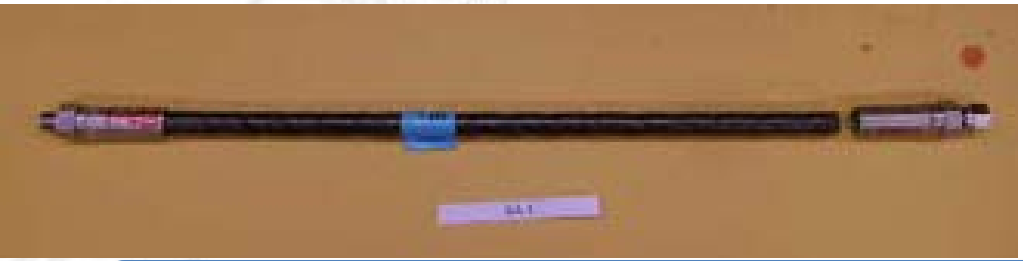
Ceramer increases burst strength by ~ 25% as a coupling agent

Accomplishments in Burst Strength

NanoSonic Carbon Fiber Hose = 31,421 psi

HOSE MFG	HOSE ID	Fitting Mfg	ACTUAL NIPPLE OD (mm)	NIPPLE	Hose O.D (mm)	Ceramer	Wrap Thickness (mm)	Number of Wraps	Wrap Angle	Burst Strength (psi)	average weight (g
NanoSonic	7-1	Swagelok	14.9	2.4	12.5	yes	3.0	3	54	19,237	200
	7-2	Swagelok	15.3	3.2	12.1	yes	2.6	3	54	26,614	
	7-3	Swagelok	15.8	3.8	12.0	yes	2.5	3	54	25380	
	8A-1	Swagelok	16.1	2.5	13.6	yes	4.1	4	54	31,421	
	8A-2	Swagelok	16.5	3.4	13.1	yes	3.6	4	54	30,475	
	8A-3	Swagelok	17.0	4.1	12.9	yes	3.4	4	54	16357	
	8B-1	Swagelok	15.2	2.0	13.2	yes	3.7	4	54	22,591	
	8B-2	Swagelok	15.2	2.3	12.9	yes	3.4	4	54	30,576	
	8B-3	Swagelok	16.1	3.4	12.7	yes	3.2	4	54	28063	
	13-1	Swagelok	15.6	2.4	13.2	yes	3.7	4 total	3 at 54 - 1 at hoop	24,916	
	13-2	Swagelok	16.0	3.3	12.7	yes	3.2	4 total	3 at 54 - 1 at hoop	24,273	
	13-3	Swagelok	16.4	3.5	12.9	yes	3.4	4 total		23522	
	41A	Swagelok	16.1	3.2	12.9	yes	NA	NA	NA	21,191	250
	41B	Swagelok	16.1	3.2	12.9	yes	NA	NA	NA	10,096	
SpirStar	WH208-9A2089	Swagelok	15.9	3.0	12.9	yes	NA	NA	NA	52,959	
	WH208-9B2089	DHH	15.9	3.0	12.9	no	NA	NA	NA	9,635	
	WH208-9C2089	Swagelok	15.9	3.0	12.9	yes	NA	NA	NA	58,449	
	WH208-9D2089	DHH	15.9	3.0	12.9	no	NA	NA	NA	26136	

Composite: ~ 10,000 psi
Core Alone: ~ 3,000 psi
CryoHose: > 30,000 psi



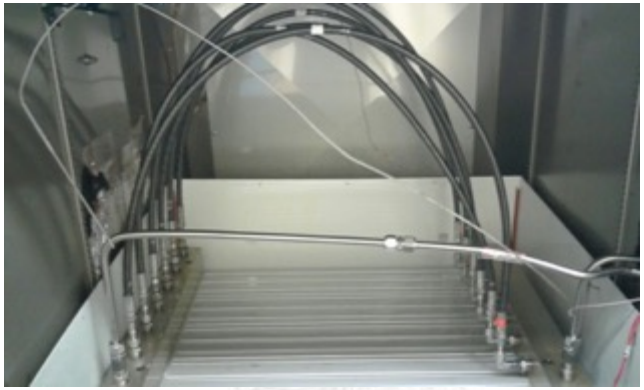
Failure Mode for NanoSonic Hose is at the Fitting – Slippage
Failure Mode for Metal Wrapped Hose is – Hose Burst

Accomplishments in Pressure Cycle Testing:

52,000x at 12,000 psi (-40 °C to 85 °C)

Pressure Cycle Test (section 2.17) of ANSI/CSA HGV 4.2-2013:

- 50,000 cycles at 12,000 psi (827 Bar) at -40°C and
- 50,000 cycles at 12,000 psi (827 Bar) at 85°C



Down-selected filament wound composite survived:

- 50,000 cycles at 12,000 psi (827 Bar) at -40°C and
- 1,988 cycles at 12,000 psi (827 Bar) at 85°C

Failure Mode for NanoSonic Hose is at the Fitting – Slippage

Accomplishments with Partners

Cardinal Rubber & Seal Swaged Fittings

Test Results

High Pressure Test Results

Customer:	NanoSonic Inc	Mfg. Part #:	
Part Number:	Test Hose	Description:	
Order Quantity:	1	Measured Intervals:	1
Date:	4/11/2017	Time:	10:48:17 AM
Operator:	SF	Test Pressure:	18000
Test Time:	1	Minimum Pressure:	14000

	1	2	3	4	5	6	7	8
1	19463	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0

Fittings Swaged at Cardinal Passed High Pressure Testing

Accomplishments with Techsburg Manufacturing

TECHSBURG

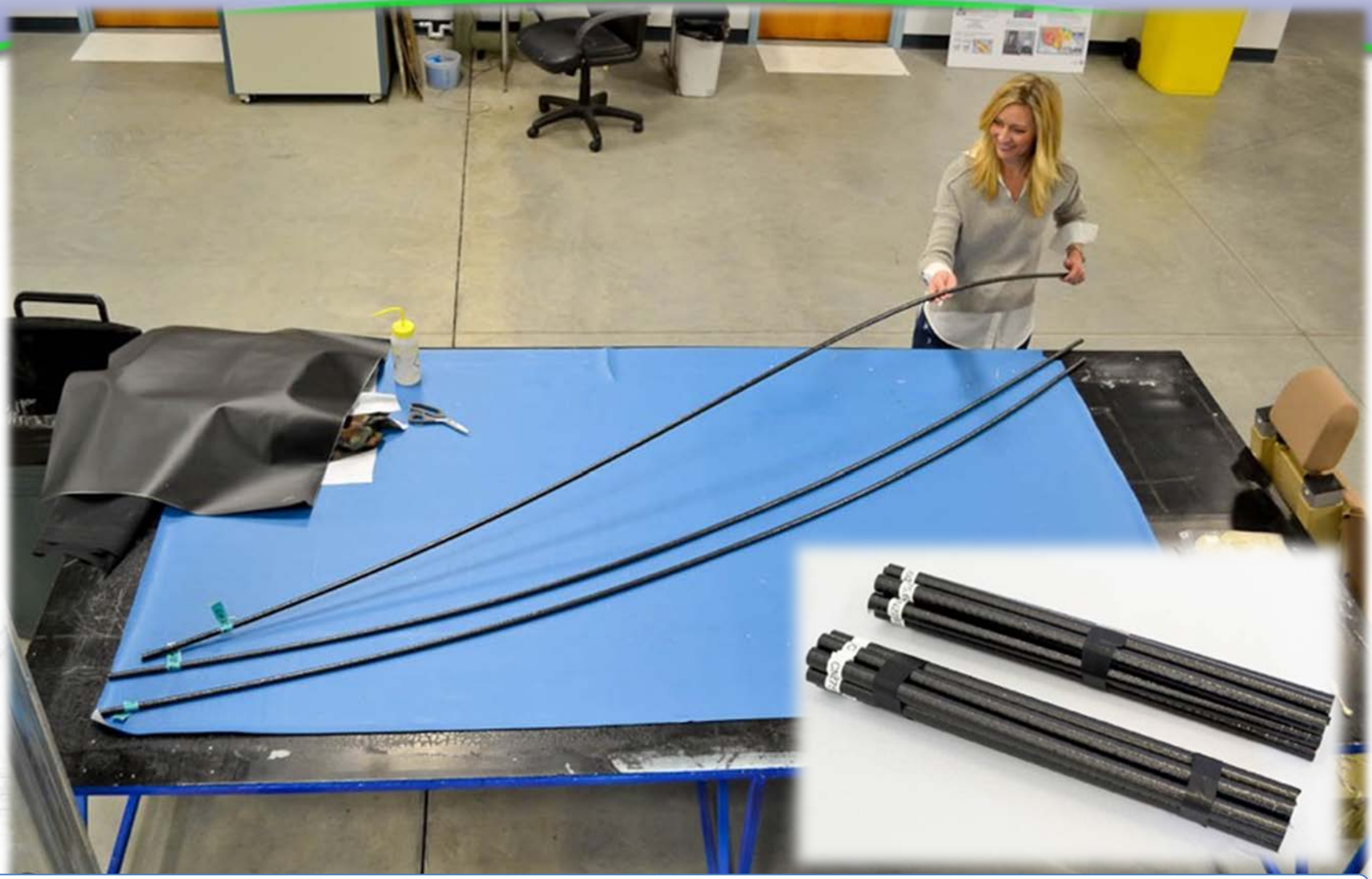
Engineering or Manufacturing,
Techsburg is Your Partner in Creation

Engineering Services Division

Manufacturing Division

2-piece fitting any metal, starting at $4/part

Accomplishments in Scaling



Scaled Hoses to 3m lengths using filament winding process in-house

Accomplishments in Burst Strength

Sample ID	Sample Length (in)	Hose ID (mm)	Fitting Type	Burst	Leaked	Before	After
1 - 2/8/18	~14"	1/2"	Swaged	18,462			
2 - 2/8/18	~14"	1/2"	Swaged	20,971			
3 - 2/8/18	~14"	1/2"	Swaged		11,526		
4 - 2/8/18	~14"	1/4"	Swaged	28,192			
5 - 2/8/18	~14"	1/4"	Swaged	28,809			
6 - 2/8/18	~14"	1/4"	Swaged	28,989			
7 - 2/8/18	14"	1/4"	Swaged		12,365		
8 - 2/8/18	14"	1/4"	Swaged	23,853			
9 - 2/8/18	14"	1/4"	Swaged	26,236			
10 - 2/8/18	14"	1/4"	Swaged		12,739		

Burst Strength Values > 28,000 psi, and failure through fitting failure or at edge

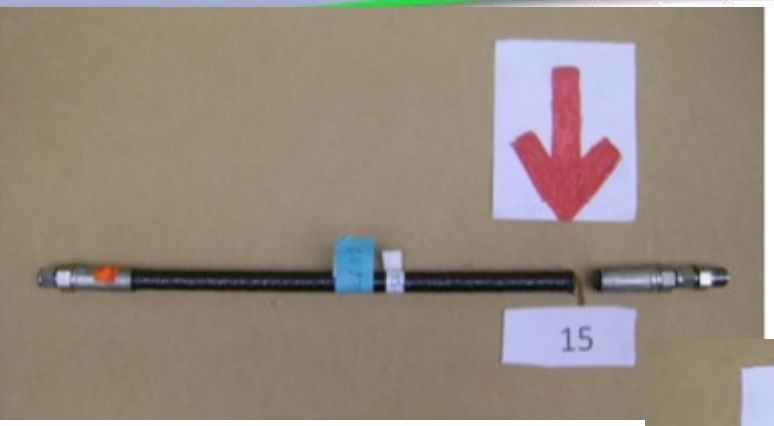
Accomplishments in Burst Strength

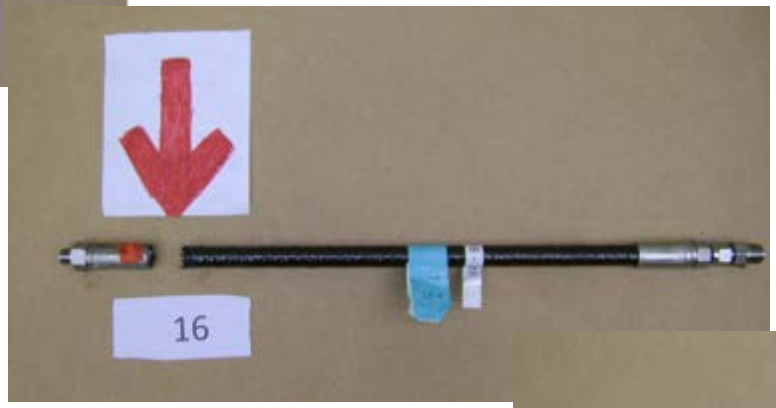
Sample ID	Sample Length (in)	Hose ID (mm)	Fitting Type	Burst	Leaked	Before	After
11 - 2/8/18	14"	1/4"	Swagelok	21,681			
12 - 2/8/18	14"	1/4"	Swagelok	17,995			
13 - 2/8/18	14"	1/4"	Swagelok	20,485			
14 - 2/8/18	14"	1/4"	Swagelok	18,236			
15 - 2/8/18	14"	1/4"	Swagelok	33,134			
16 - 2/8/18	14"	1/4"	Swagelok	33,055			
17 - 2/8/18	14"	1/4"	Swagelok	31,535			

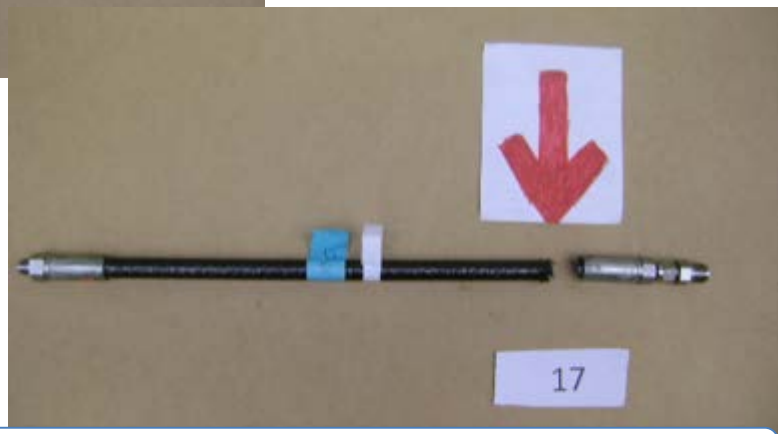
Burst Strength Values > 33,000 psi, and failure consistently at edge

Challenges with Fittings

All Fittings Fail at Crimped Edge



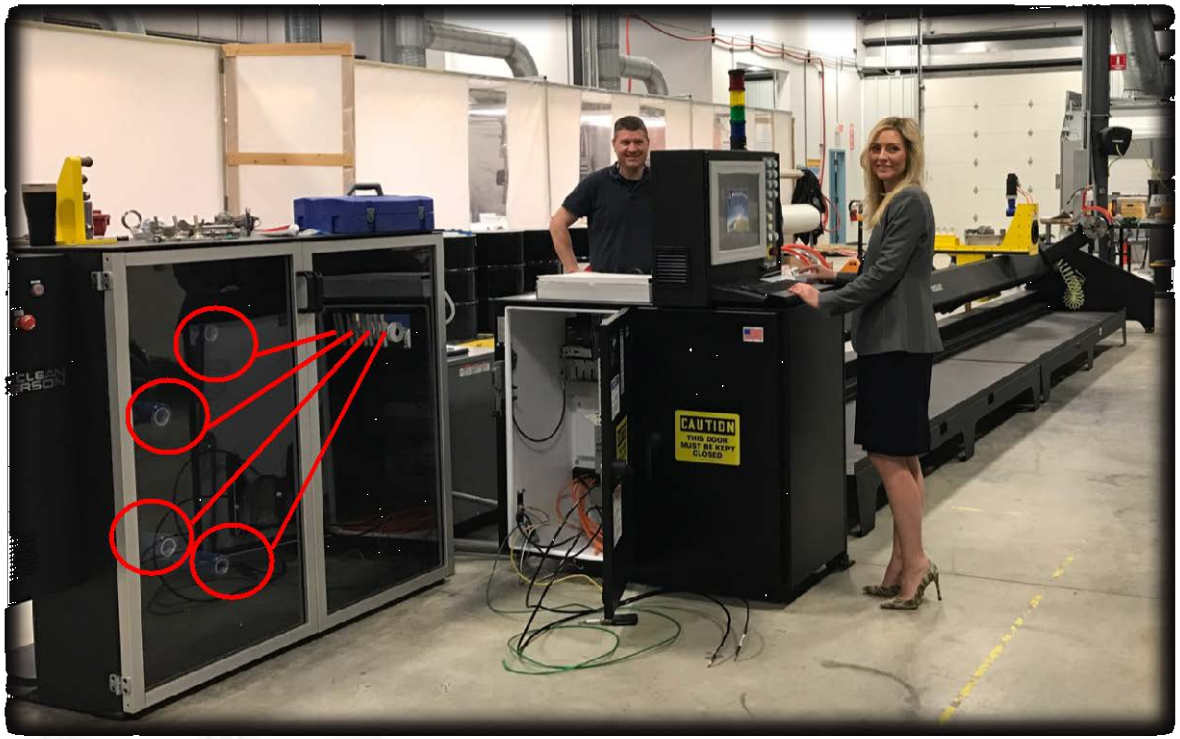




Fittings Fail due to Under-Crimping (Slippage) or Over-Crimping (Core Defect) at Edges

Econo-Technical Accomplishments

Cost



- NanoSonic can Produce 16 H_2 hoses / day, 3-m in length, at ~$600 / Hose with Fittings
- ~40% reduction over current hose
- The 4 Spool Filament Winder Enables Multiple Fiber Functionality and Reinforcement within High Performance Custom Polymer Matrix Resins

Phase II B

Commercialization and Collaborations

Shell Global

Cardinal RUBBER & SEAL, INC.

LIFEGUARD TECHNOLOGIES
The next generation in safety hoses

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

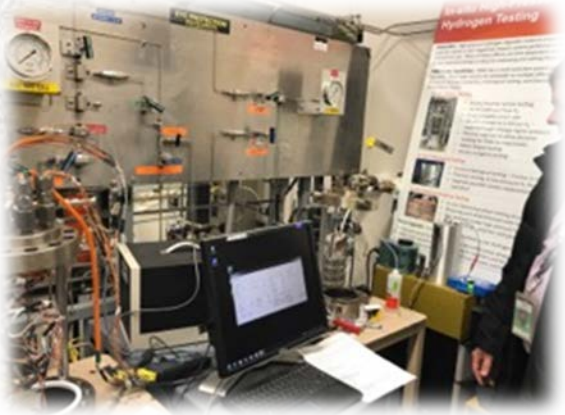
Pacific Northwest
NATIONAL LABORATORY

TATSUNO

CSA Group

TECHSBURG
Engineering or Manufacturing, Techsburg is Your Partner in Creation

WEH®



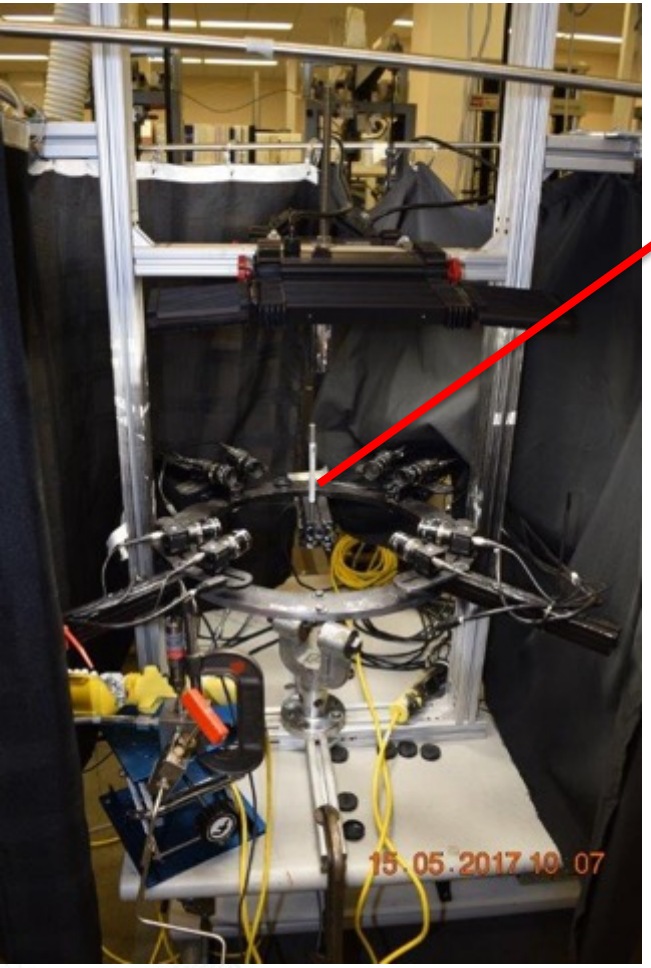
Future Work

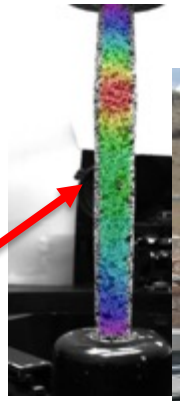
H_2 Service and Durability Testing at PNNL and NREL

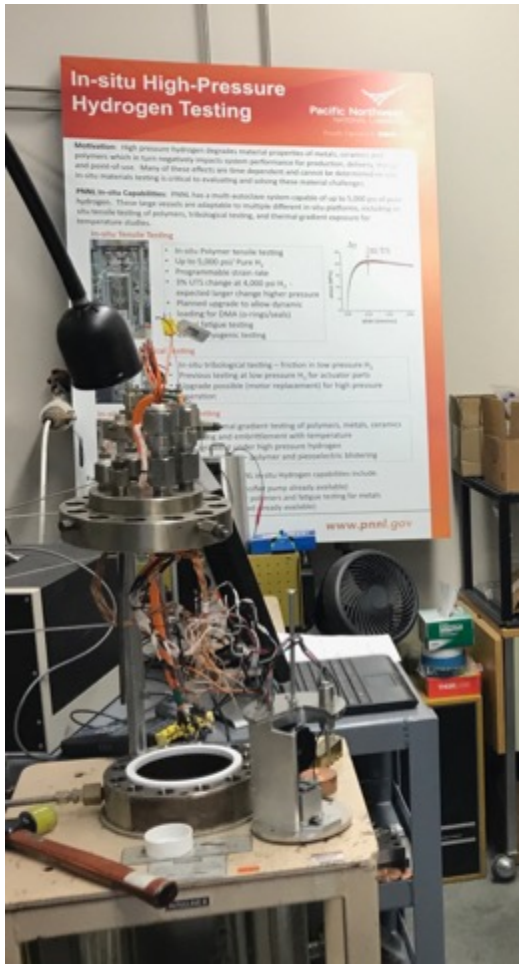
Any proposed future work is subject to change based on funding levels

DIC System for multi-strain imaging during tube burst test

Pacific Northwest NATIONAL LABORATORY

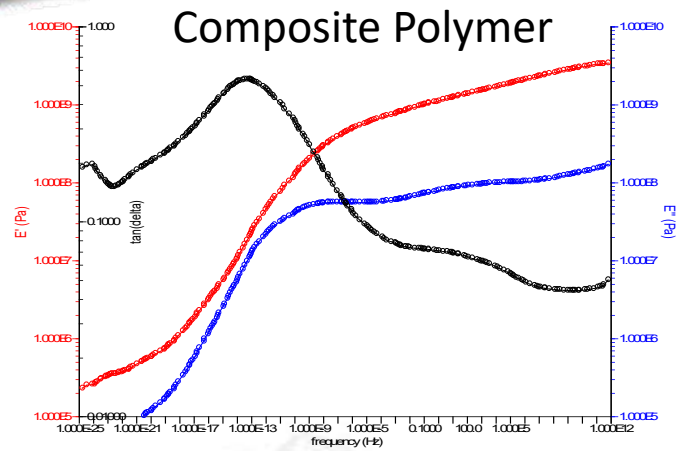


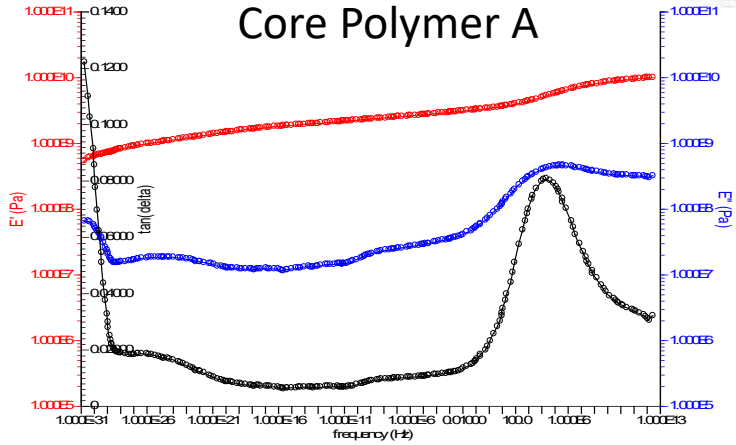


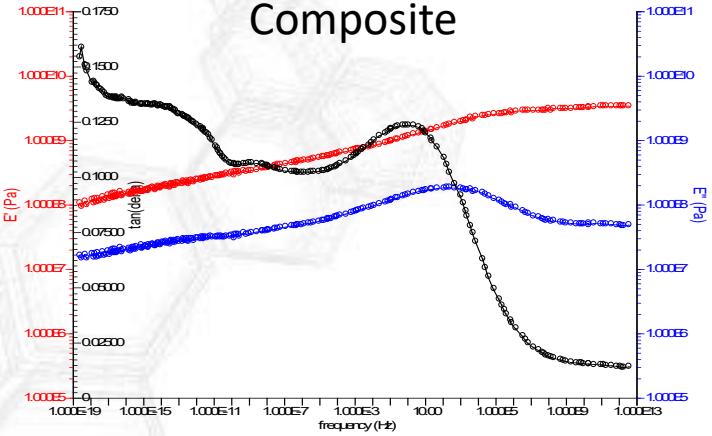


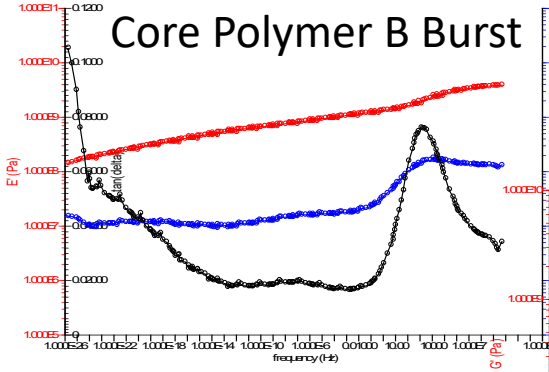
Future Work

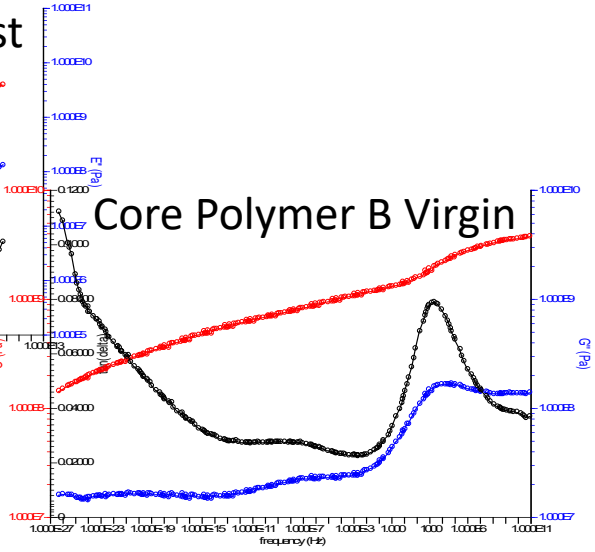
Compare DMA TTS in air vs. H_2 (at PNNL) to assess performance over 2 years











- NanoSonic DMA TTS data for polymer core, polymer composite, composite in air
- Hose Core Polymers analyzed before and after hydrostatic burst testing

Remaining Challenges and Barriers:

Fitted Hose with Commercial H_2 Hose Safety Adapters Qualification and Deployment

- Challenge: Deployment date of FY19 Q1 because of fitting construction
- Resolution: Partnered with machinist to produce durable tailored high pressure fittings
- Benefit: Sell hose and fitting as a complete qualified set
- Benefit: Investigating new fitting materials and designs for the broader hose market

Project Summary

- **Relevance**: Durable and cost effective H_2 delivery hose that resists H_2 embrittlement, survives 25,550 fills/year for H70 service, cycled at pressures > than 875 bar over a range of -50 °C to 90 °C. A single qualified hose exists.

- **Approach**: NanoSonic's all polymer new class D hydrogen dispensing hose, for use on H70 station side applications, is chemically engineered to survive 51,240 fills, resist H_2 embrittlement, survive Joule-Thompson effect, and endure mechanical fatigue at the pump. Innovative SiC ceramer adhesive is under development to enhance fitting durability

- **Technical Accomplishments**:
  - Demonstrated hydrostatic burst strength > 33,000 psi
  - Demonstrated 50,000 cycles at -40F / 12,000 psi, and ~ 2,000 cycles at +85F / 12,000 psi
  - Failure for hydrostatic burst and pressure impulse each hose is at crimped fitting edge
  - Developing fitting with manufacturer and partnered with H_2 safety fitting expert

- **Proposed Future Research**: Evaluate hose under H_2 service conditions at NREL, PNNL, and at partner/distributor test facilities. Present H_2 hose partners (dispensing stations and fittings/breakaway/fueling nozzle OEMs) with integration and cost.

NanoSonic

Questions & Acknowledgements

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Phase II Integrators and Testing Facilities