NanoSonic, Inc.

2019 DOE Hydrogen and Fuel Cells Program
Annual Merit Review and Peer Evaluation Meeting (AMR)
PI: Dr. Jennifer Lalli
5/1/2019

Cryogenically Flexible, Low Permeability H_2 Delivery Hose

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project ID # in010

Overview

Timeline:

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

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

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

Partners:

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

Relevance:

Develop a H_2 Hose for Fuel Cell Vehicles

Objectives:

- Flexible: H_2 hose to enable affordable delivery
- 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 > 36,000 psi for H35 Service
- Goal: Metal Free Hose Design and Custom Fitting to Enable Long-term H70 Service

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

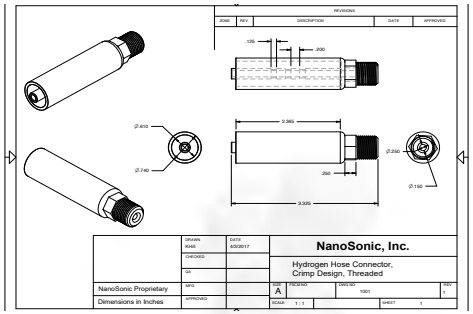
- **Surpass 3500 Bar hydrostatic burst strength (> 50,763 psi) held for 1 min**
- **Survive 875 Bar pressure cycle at (50,000x at -50F and 50,000x at 85F)**
- **No contaminant leaching, Competitive cost, mechanical durability, and environmental lifetime**

Phase IIB Commercialization Challenge

Lack of Commercial Fittings for New Hoses

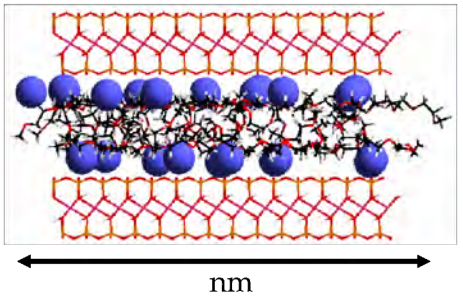
1. Design New Fittings

- For current cores
- Address leakage
- Custom OD and ID



2. Design New Cores

- For new fittings
- Advanced materials
- Custom ID



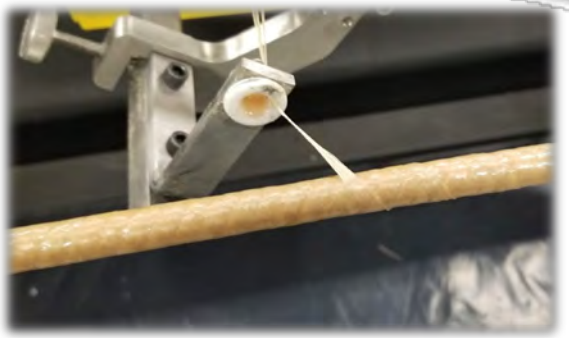
PRESSURE RATING
Hose Assembly
(hose + fitting)

4:1 safety factor

Working Pressure (1)
Burst Pressure (4x)

Technical Approach to Flexible Metal-Free H_2 Hose

Filament Winding



2 (3m) hoses per run
16 hoses per day

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.

Demonstrated Hoses with Varied Fibers with Hydrostatic Burst Strengths > 36,000 psi

Major Accomplishment in Filament Wound Hose

Pressure Cycling: Leak before Burst ~52,000x

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 (-40°F) and
- 50,000 cycles at 12,000 psi (827 Bar) at 85°C (185 °F)

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

NanoSonic Hose Survived 51,988 cycles at 12,000 psi over -40 °C to 85 °C prior to leak rather than burst

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 (max is 20,000 psi)

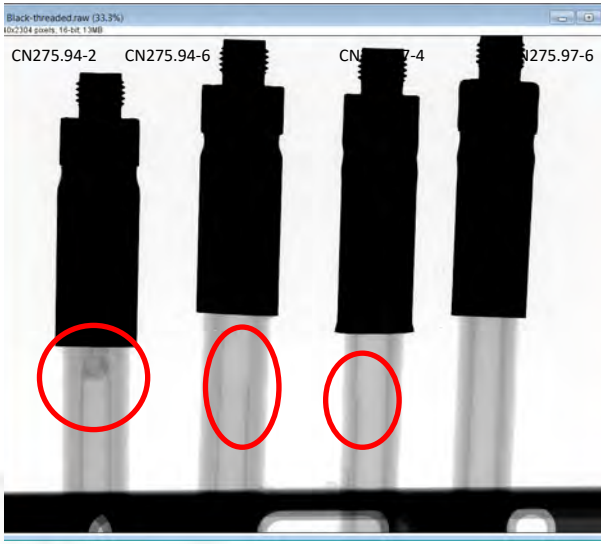
Accomplishments in New Fittings

X-ray analysis – core defect characterization

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

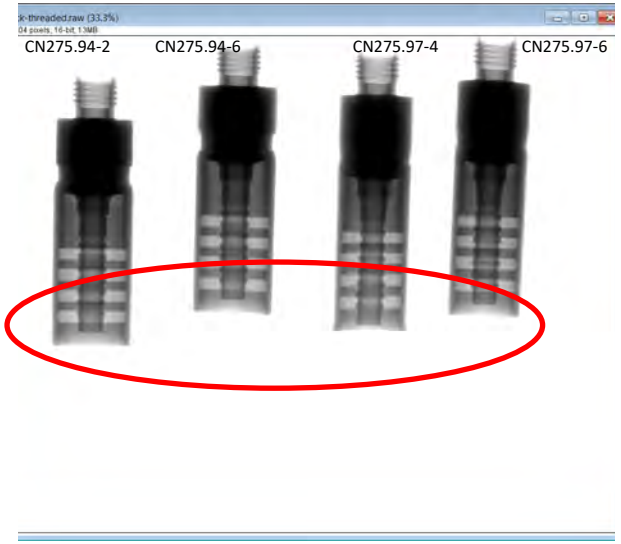
H2@Scale
U.S. Department of Energy

X-ray analysis at PNNL for defect characterization



Core defects

Socket symmetry



Stem depth

Method of Fitting Installation (physical drill, physical pressure, and thermal viscoelastic) Clearly Identifies Extent of Core Damage Prior to Burst Testing

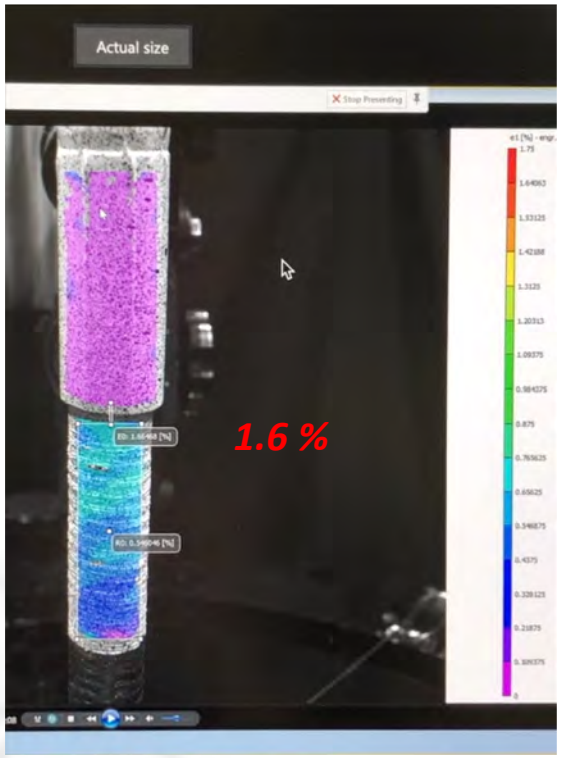
Accomplishments in New Fittings

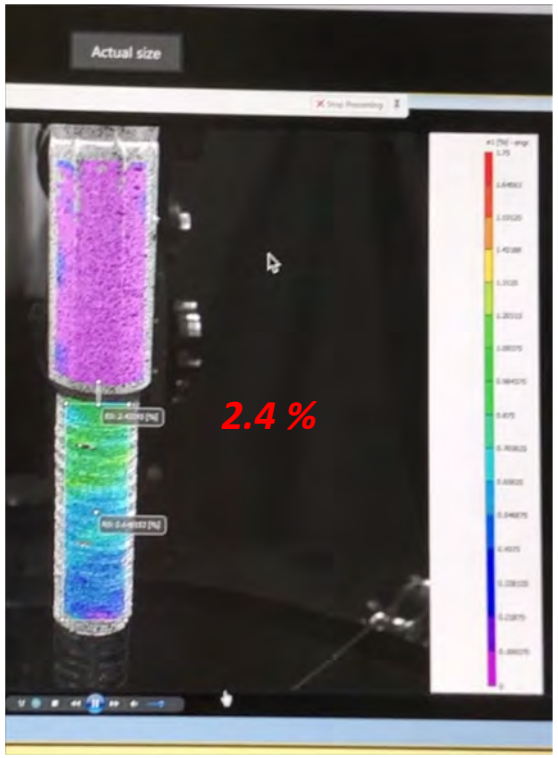
In-situ pressurization – leak and strain characterization

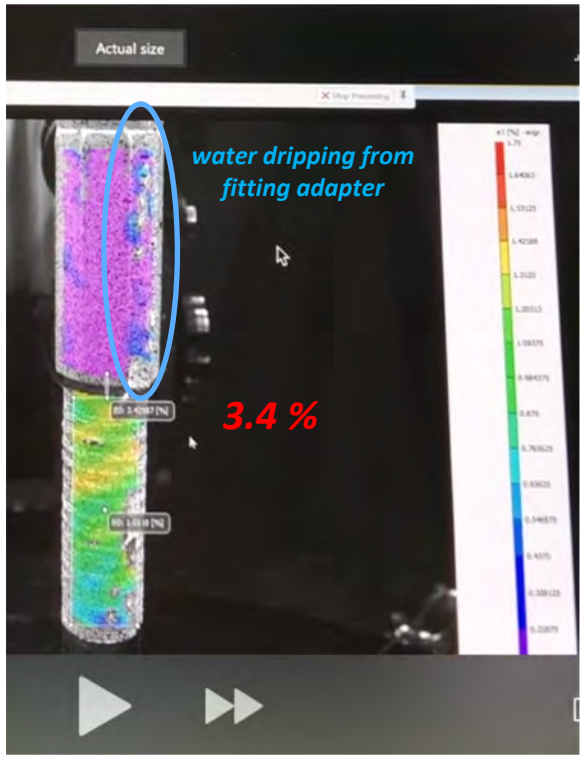
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

H2@Scale
U.S. Department of Energy

Digital Image Correlation with in-situ 25,000 psi Strain Characterization at PNNL







DIC Verified Leakage in Fitting Coupling and 3% strain at Hose/Fitting Interface at 25k psi

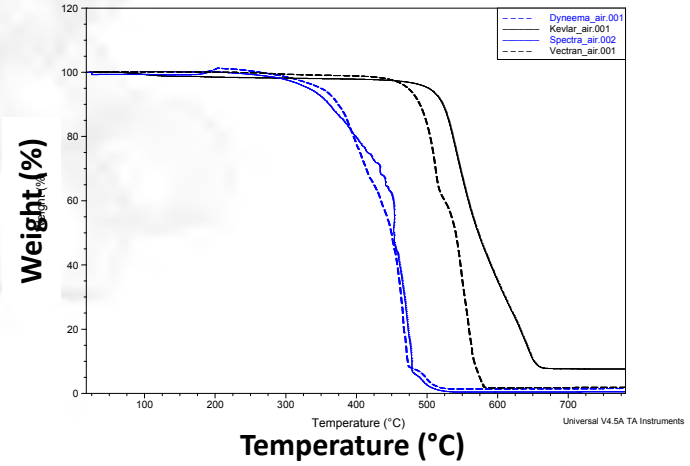
Accomplishments in Burst Strength

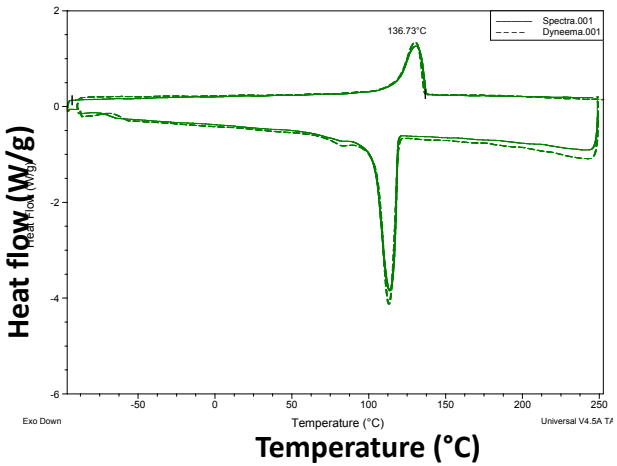
Sample ID	Sample Length (in)	Hose ID (mm)	Fitting Type	Burst	Leaked	Before	After
11 - 2/8/18	14"	1/4"	Swagelok	21,681			
12 - 2/8/18	14"	1/4"	Swagelok	17,995			
13 - 2/8/18	14"	1/4"	Swagelok	20,485			
14 - 2/8/18	14"	1/4"	Swagelok	18,236			
15 - 2/8/18	14"	1/4"	Swagelok	33,134			
16 - 2/8/18	14"	1/4"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

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

Accomplishments in New Fibers

Thermal Properties

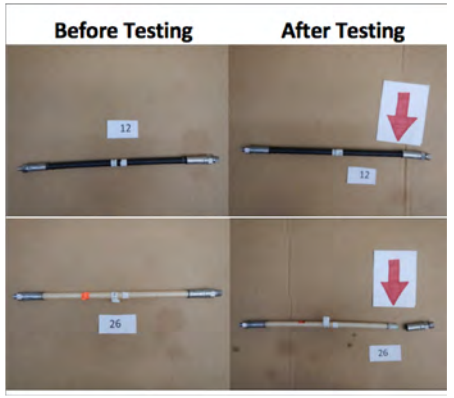




New Liquid Crystalline Polymer Fiber Reinforced Hoses with Enhanced Flexibility meet both High (T_m 137 °C) and Low Temperature Resilience Requirements (-196 °C)

Accomplishments in New Fibers

Burst Strength

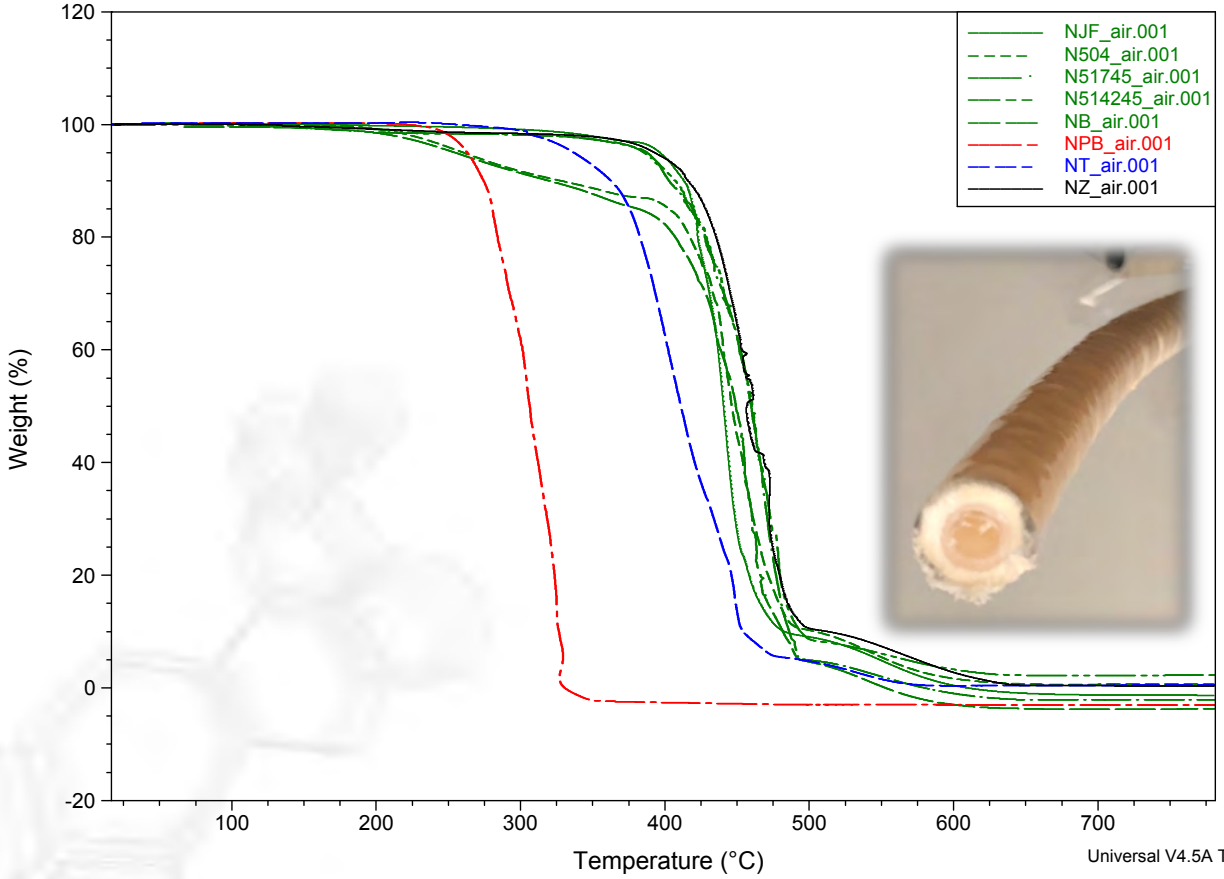


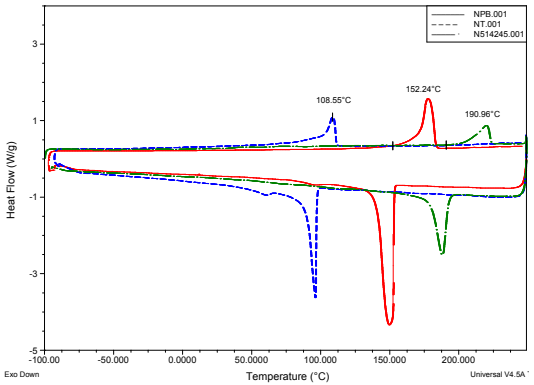
Hose Core	Average Filament Wound Burst Strengths		
	Carbon Burst (psi)	New Fiber 1 Burst (psi)	New Fiber 2 Burst (psi)
A	32,000	16,000	15,000
B	36,000	32,000	26,000
C	36,000	32,000	15,000

New Fiber Reinforced Hoses and More Flexible Cores Offer Burst Strength > 32,000 psi and Failure Remains Due to Fitting Slippage

Accomplishments in Cores

Thermal Properties and H_2 Permeation Underway





NanoSonic Shall Modify Cores With Exfoliated Clays, Tailor ID, and Evaluate H_2 Permeation

Accomplishments in New Modified Cores

Thermal Properties

5% wt loss

Benchmark: 368 °C

Clay 1: 358 °C

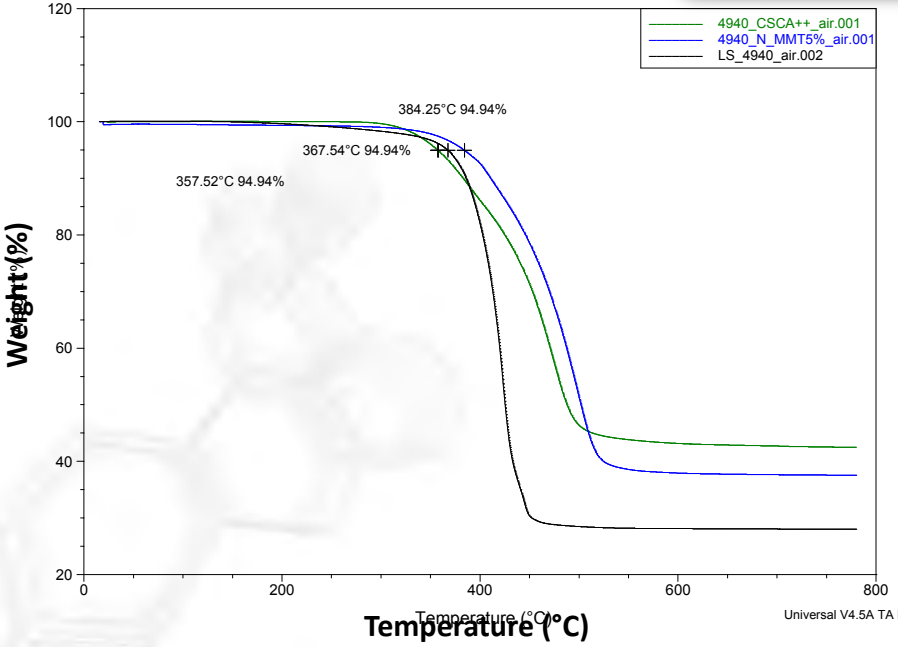
Clay 2: 385 °C

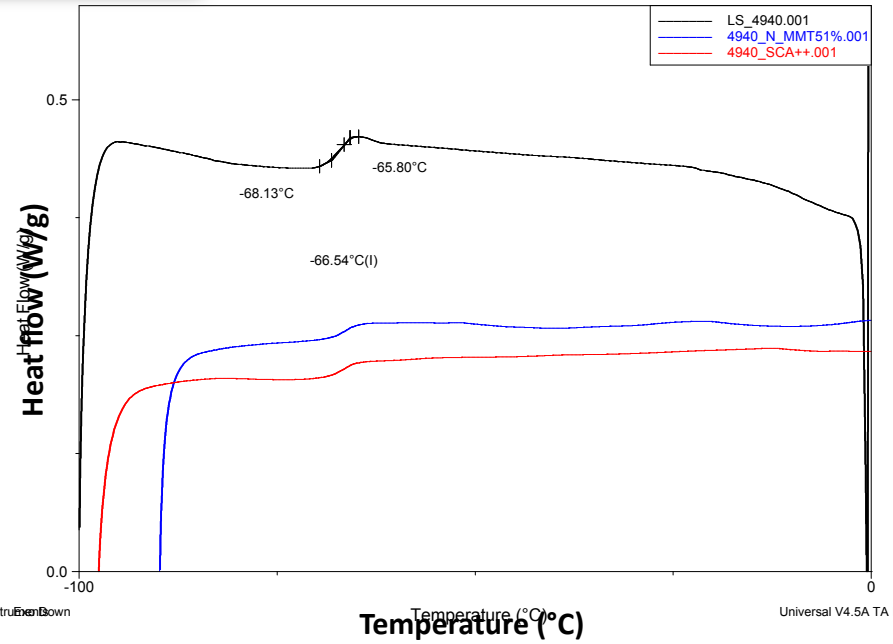
T_g

Benchmark: -67 °C

Clay 1: -67 °C

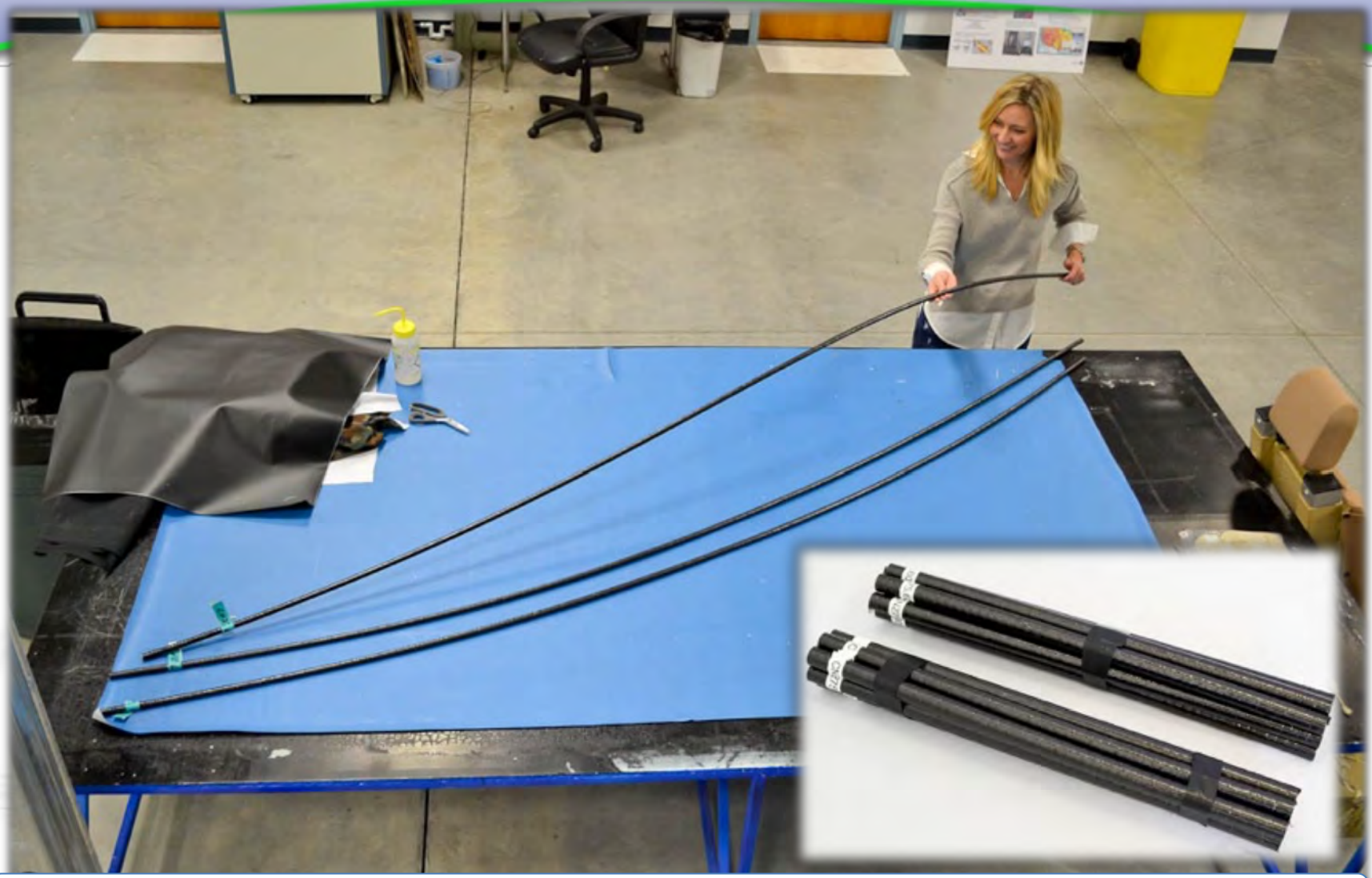
Clay 2: -67 °C





Exfoliated clays offer potential for significantly less H_2 effusion, enhanced high temperature stability and with no change in low temperature flexibility

Accomplishments in Scaling



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

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

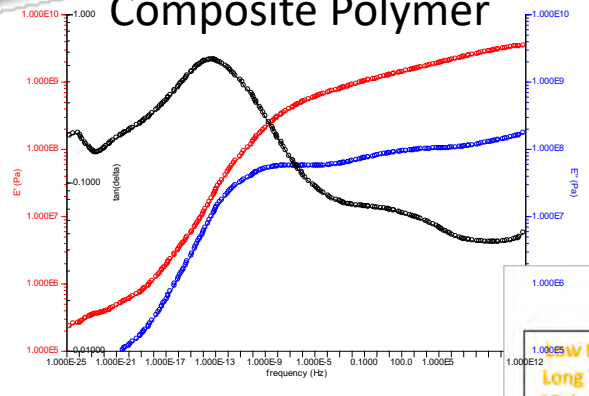
TECHSBURG
Engineering or Manufacturing, Techsburg is Your Partner in Creation

WEH®

Ongoing Work

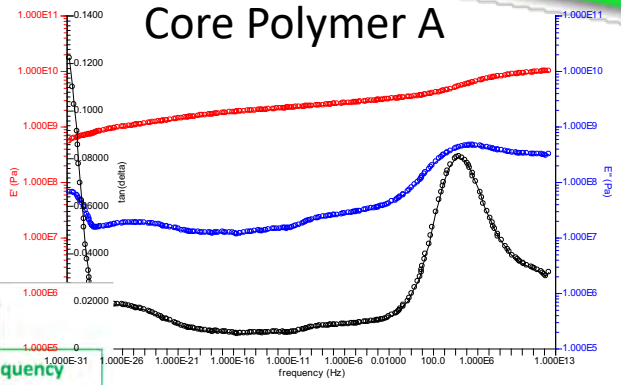
Compare DMA TTS in air vs. H_2 (at PNNL) to assess performance over 2 years

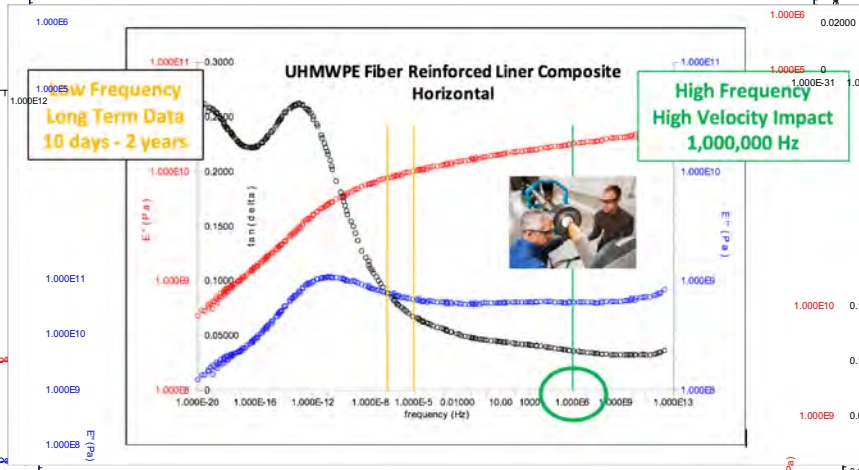
Composite Polymer



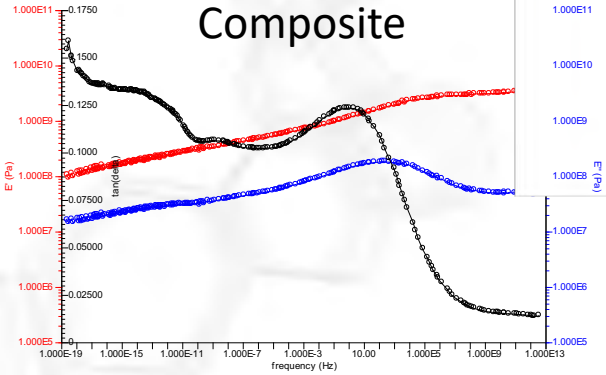
LIFETIME PREDICTION in HYDROGEN

Core Polymer A

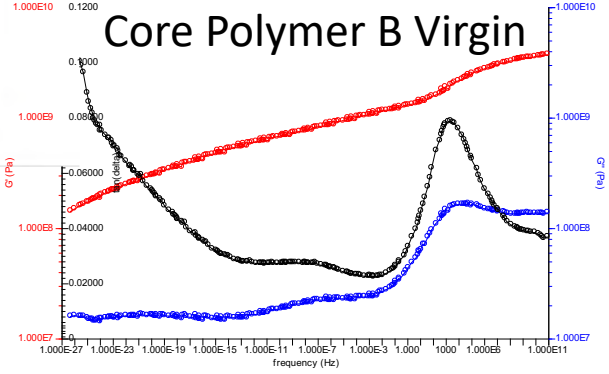




Composite



Core Polymer B Virgin



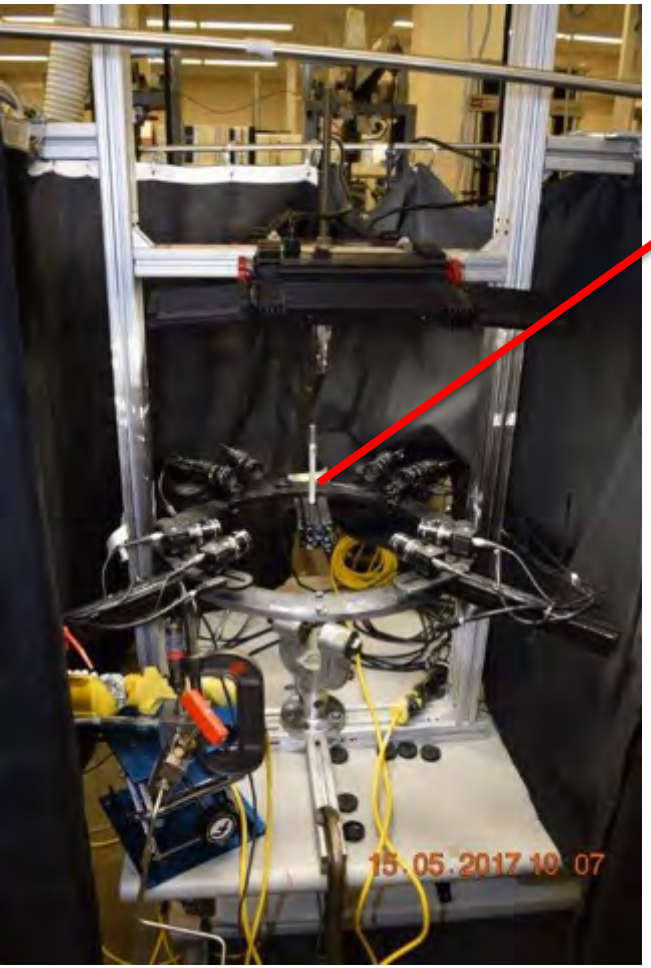
- NanoSonic DMA TTS data for polymer core, polymer composite, composite in air
- Core Polymers analyzed before and after hydrostatic burst testing

Future Work

H_2 Service and Durability Testing at PNNL and NREL

DIC System for multi-strain imaging during tube burst test

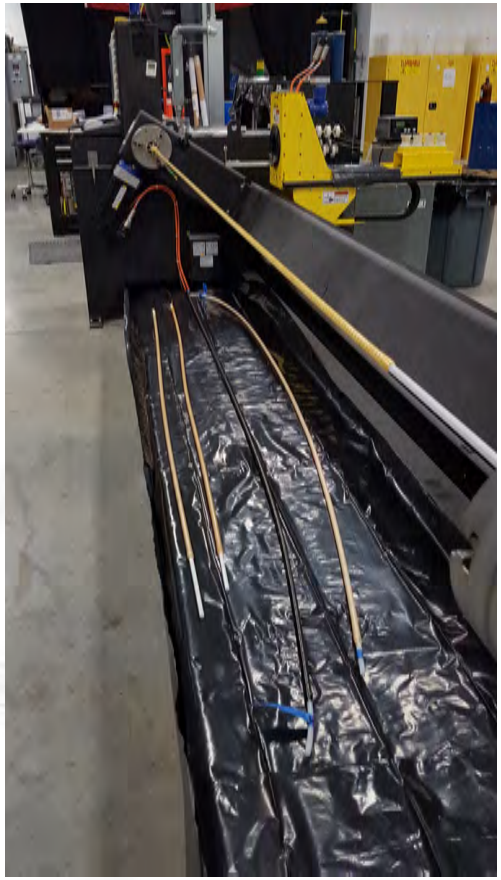
Pacific Northwest NATIONAL LABORATORY

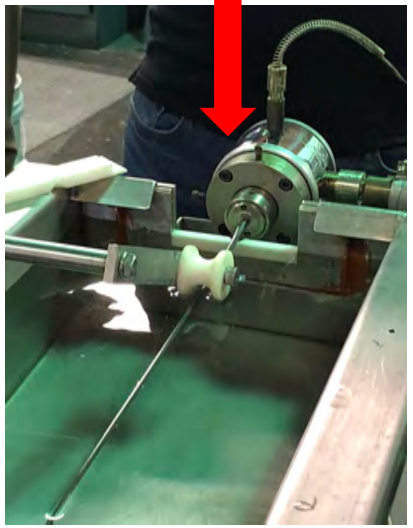


Remaining Challenges and Barriers:

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 > 36,000 psi
  - Demonstrated 50,000 cycles at -40C / 12,000 psi, and ~ 2,000 cycles at +85C / 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.

Questions & Acknowledgements

This material is based upon work supported by the Department of Energy under Award No. DE-SC0010162

Contact: Jennifer Lalli (540) 626-6266
jhlalli@nanosonic.com

DOE-EERE DOE Fuel Cell Technologies Office:
Neha Rustagi, James Vickers, Sunita Satyapal, Charles James, Grace Ordaz, Laura Hill, and Erika Gupta

Phase II Integrators and Testing Facilities