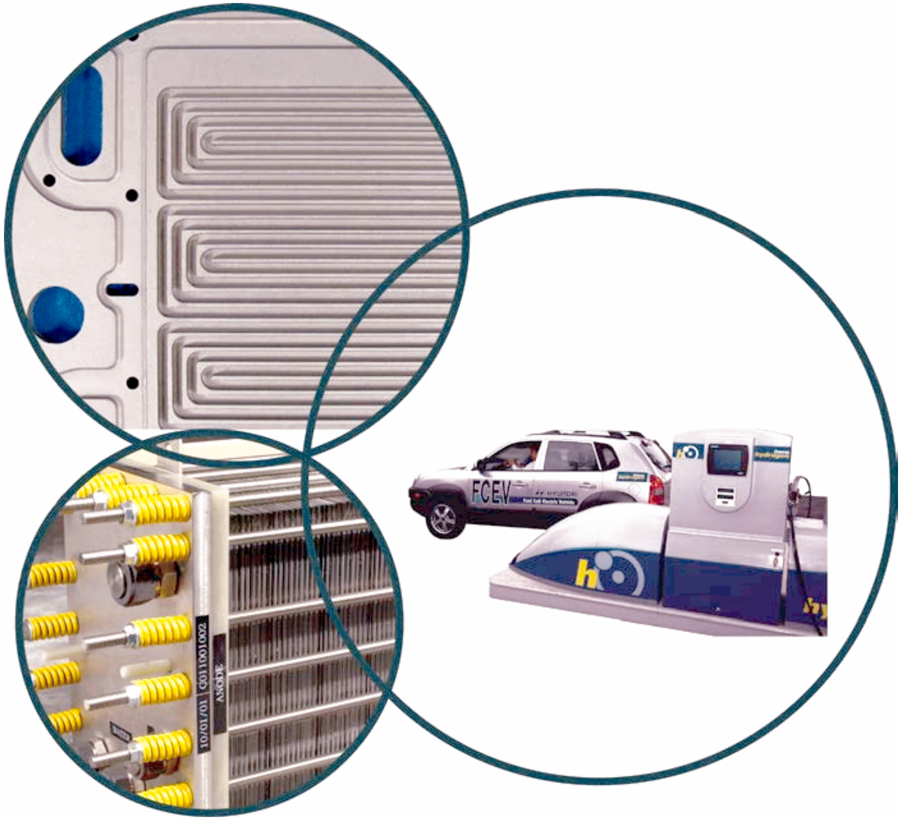
Composite Pipeline Technology for Hydrogen Delivery



Barton Smith, Barbara Frame, Lawrence Anovitz

Oak Ridge National Laboratory

Annual Merit Review
Washington, DC
May 17, 2012

Project ID #: PD024

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

Oak Ridge National Laboratory

Overview

Timeline

- Start: Jan 2005
- Finish: Project continuation & direction determined annually by DOE

Barriers

- Barriers and Technical Targets on following slide

Budget

- Total project funding
  - DOE: $2M
- Funding for FY 2012
  - $80k

Partners & Collaborators

- Fiberspar, PolyFlow, Flexpipe
- Arkema, Ticona, Fluoro-Seal, Dow Chemical/Polypipe
- SRNL, Pipeline Working Group, ASME

Relevance – Barriers and Technical Targets

Barriers Addressed:

Pipeline Capital Cost, Reliability, Leakage;
Hydrogen Compatibility of Pipeline Materials;
Technology Acceptance

Technical Targets:

Transmission pipeline total capital cost:
$735k per mile (2015), $715k per mile (2020)

H_2 delivery cost: < $0.90/gge

Transmission pipeline reliability: Acceptable for H_2 as a major energy carrier

H_2 pipeline leakage: < 780 kg/mi/y (2020)

Barriers and technical targets are from the Technical Plan-Delivery, in the DOE *Hydrogen MYRDD Plan*, October 2007, and Table 3.2.3, Technical Targets for Hydrogen Delivery Components, in the draft *2011 MYRDD Plan for Hydrogen Delivery*

Collaborations

- **Fiberspar, Polyflow, Flexpipe**
  - Manufacturers of fiber-reinforced polymer pipelines
  - Provided pipeline specimens, testing, advisement
- **Akema, Ticona, Dow Chemical/Polypipe, (Lincoln Composites)**
  - Polymer manufacturers, polymer end-users
  - Provided specimens of polymeric barriers for testing as potential pipeline liner materials
- **Fluoro-Seal**
  - Advisement on surface treatments to decrease permeation rates
  - Pending: fluorination of polymer specimens
- **SRNL**
  - Collaboration on hydrogen compatibility studies of FRP pipelines and constituent materials
  - Collaboration with ASME on codification of composite hydrogen pipelines
- **Pipeline Working Group and Delivery Tech Team**
  - Provide project review and guidance
  - Information clearinghouse

Approach – FY 2012 Tasks and Milestone

- **Complete high-pressure cyclic fatigue and stress-rupture tests**
  - Verify that combinations of hydrogen environment and stress do not adversely affect composite pipeline integrity and service life
- **Collaborate on ASME Codes and Standards Acceptance**
  - Identify the requisite data, provide data, and contribute to the codification of hydrogen composite pipelines, in collaboration with SRNL, ASME, *et al*.

Date	Milestone or Go/No-Go Decision
Sep 2012	**SMART Milestone:** Complete fatigue testing of fiber-reinforced polymer pipeline to demonstrate durability of FRP pipeline capable of achieving the 2012 DOE H_2 transmission target of <$0.90/gge H_2 (75% complete)

Approach – Technical Highlights

- **Cyclic fatigue testing on FRP pipeline specimen using H_2 pressurizations to MAWP is nearly complete**
  - Test results to date show that the pipeline retains performance similar to that of newly manufactured pipe following thermal cycling, pressurization-depressurization cycling and blowdown testing
- **Codes and standards acceptance**
  - Participated in codification kickoff meeting with ASME at SRNL (August 2011)
  - Contributed summary of ORNL testing and analysis on FRP pipelines for joint preparation of proposal to ASME for inclusion of composite hydrogen pipeline in B31.12, Part PL
- **New diffusion and permeation system is providing faster, more accurate measurements of diffusion and permeability of polymer liners**

Technical Progress – Cyclic fatigue tests in H_2 environment

- Next step in evaluating H_2 compatibility of FRP polymer pipelines: Assess performance deterioration during H_2 pressurization-depressurization cycles
- High-pressure cyclic fatigue tests are the basis for verifying that the combination of H_2 environment and pressure-induced stress does not affect pipeline integrity and service life
- Fatigue testing via H_2 gas pressurization-depressurization cycling provides information valuable for codification of composite reinforced polymer pipelines for hydrogen service (ASME B31.12, Part PL - Pipelines and Distribution Piping), including
  - Resistance to liner damage (similar to blowdown testing)
  - Integrity of joint attachment/joint sealing under cyclic loading
  - Resistance to micro-cracking, crazing, crack propagation, fiber-resin interface failure, *etc*. of composite reinforcement layer
  - Resistance to environmental stress-corrosion phenomena
  - Identification of hydrogen-affected mechanical properties

Technical Progress – Cyclic fatigue tests in H_2 environment

- **ASTM D2143 (2005) – Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe**
  - Determine failure characteristics of reinforced plastic pipe when subjected to cyclic hydraulic pressure
  - Ratio of pipe diameter to wall thickness > 10:1
  - *Expose pipe specimens to cyclic internal pressures at several different pressure levels and determine the number of cycles to failure at each of these pressures*
  - Neglect creep and non-recoverable deformation properties
  - Test fluid: 2% aqueous sodium chloride
  - Test fluid temperature determines test temperature
  - Cycling rate: 25 ± 2 cycles per minute
  - Report number of cycles to failure

Number of cycles to failure is likely to be millions of cycles if H_2 pressure is limited to the rated pressure!

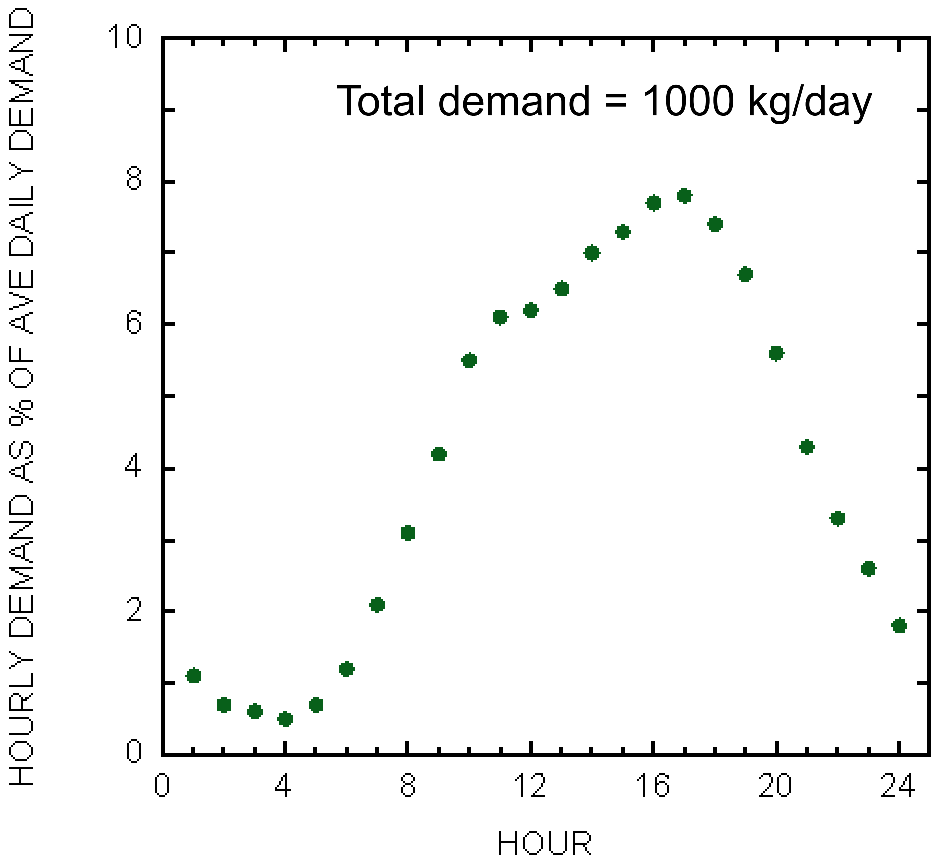
Technical Progress – Cyclic fatigue tests in H_2 environment

- **What are typical operational parameters of existing hydrogen pipelines?**
  - Pipe diameters range from 4 to 12 inches
  - Operating pressures range from 350 to 1900 psi (24 to 131 bar)
  - All current hydrogen pipeline systems use steel pipe
  - Majority of pipelines have operating stresses limited to 30% of Specified Minimum Yield Strength
  - Extensive use of automated Excess Flow Valves that limit release of hydrogen in event of third-party damage to pipeline

Parameters taken from presentation by LeRoy H. Remp, Lead Project Manager, Air Products Pipeline Projects, at the DOE Hydrogen Pipeline Working Group Workshop, August 31, 2005, in Augusta, Georgia

Technical Progress – Cyclic fatigue tests in H_2 environment

- Filling station demand profile could be indicative of pipeline pressure cycle rate
  - Demand profile for Chevron hydrogen filling station (Friday workday) has peak at 5 pm and valley at 4 am



Perhaps one pressure cycle per day in pipeline, but what would be the *amplitude* of the pressure cycle?

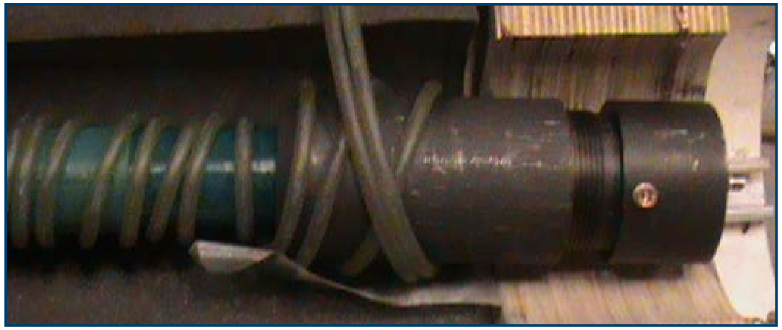
Station demand data provided by Amgad Elgowainy, ANL

Technical Progress – Cyclic fatigue tests in H_2 environment

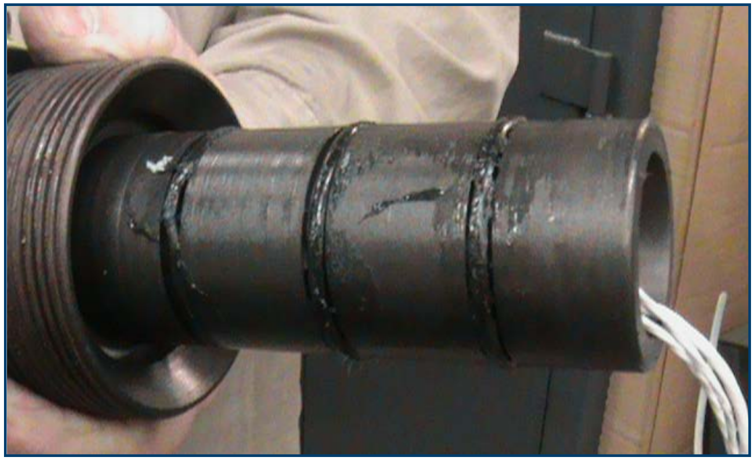
- **Two pipeline test articles**
  - Fiberspar LPJ 2.5-inch ID 1,500(E) LinePipe™
  - Each test article is 4 feet in length
  - Open pipeline ends capped with Fiberspar steel joint connectors
    - Viton o-rings seal connector to HDPE liner
  - Strain gages at multiple locations along length (in hoop orientation)
- **Test article #1**
  - Temperature cycling between room temperature and 60°C
    - 3 temperature cycles at 1500 psig H_2 pressurization (MAWP)
  - H_2 pressurization-depressurization cycling between 500-1500 psig
    - 50-plus pressurization cycles at room temperature
  - 1 final temperature cycle between RT and 60°C at 1500 psig H_2
  - H_2 blow-down test at 60°C
  - Pressure-decay H_2 leak rate measurement
  - Inspection of liner for blistering, delamination

Technical Progress – Cyclic fatigue tests in H_2 environment

Pipeline test article assembled with end caps, strain gages in place, wrapped with water-filled tubing for temperature control



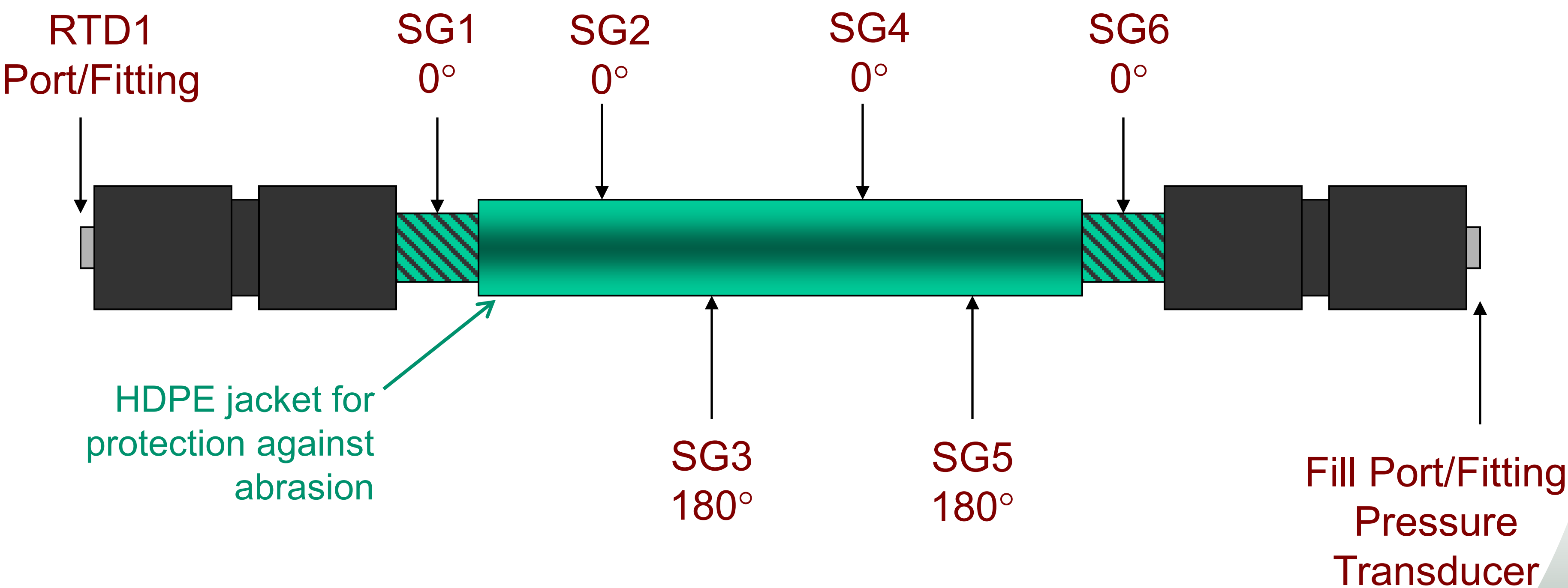
Pipeline joint connector with end cap



O-ring seals on joint connector

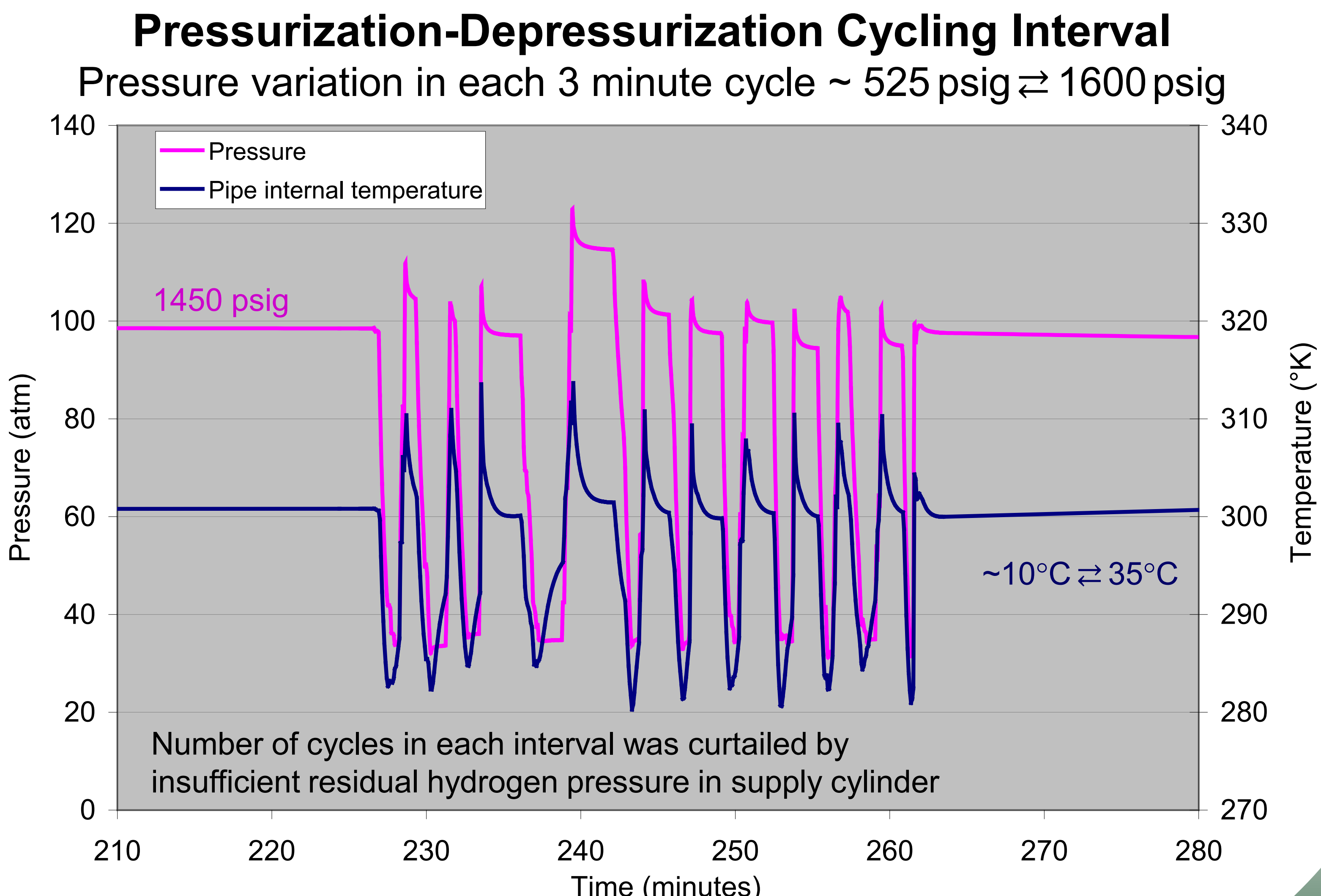
Technical Progress – Cyclic fatigue tests in H_2 environment

Location of strain gages on pipeline (all oriented in hoop direction)

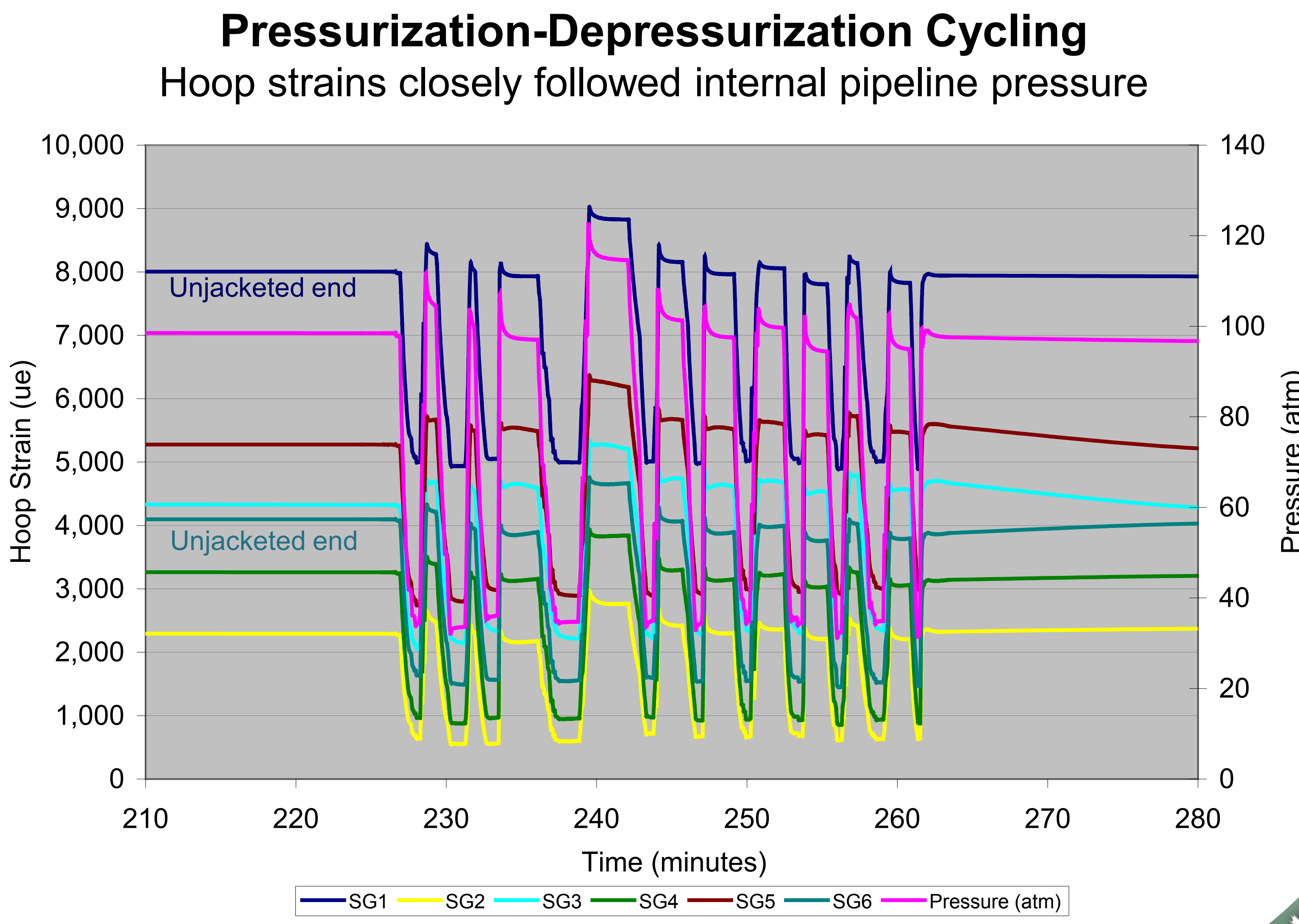


Slight residual curvature in pipeline (due to its storage on spool prior to testing) prevented useful longitudinal strain measurements

Technical Progress – Cyclic fatigue tests in H_2 environment



Technical Progress – Cyclic fatigue tests in H_2 environment



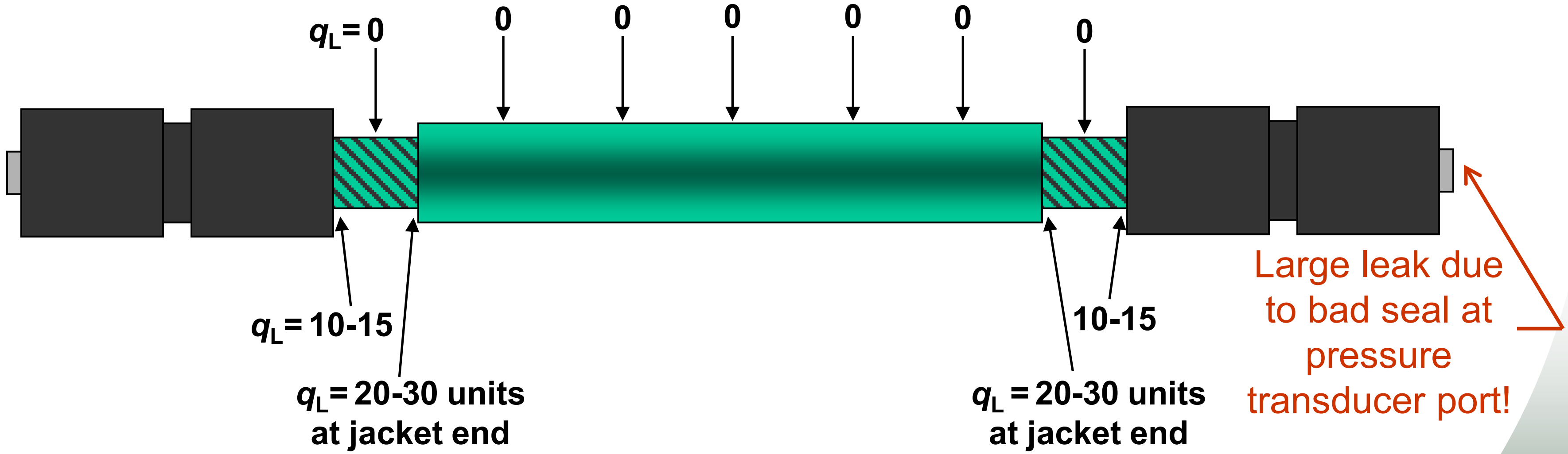
Technical Progress – Cyclic fatigue tests in H_2 environment

Customary pressure-decay leak rate measurement done post-cycling was invalid due to bad seal at pressure port

We therefore used a thermal conductivity-type gas leak detector with H_2 sensitivity ~1×10^{-5} cc/sec to screen for damage to liner. Leak rates were near lower detection limit and are shown in relative units.

No H_2 detected at points along jacketed and unjacketed pipeline surfaces

→ No cracks in liner, glass fiber epoxy matrix or HDPE jacket

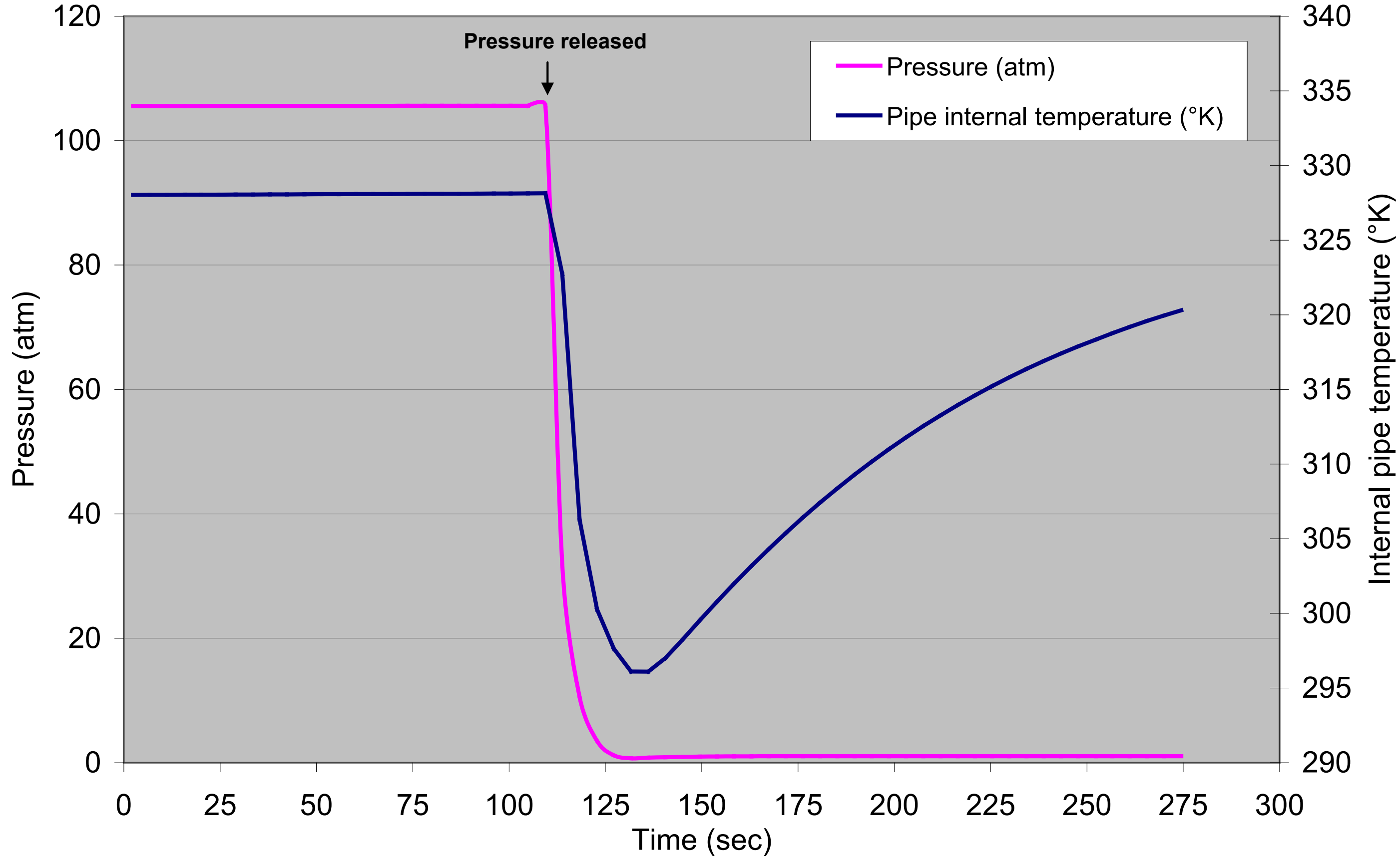


H_2 detected at jacket ends and end joint connectors

→ Permeated gas is *captured* in microscopic separation between reinforcement and jacket, then migrates to jacket ends

Technical Progress – Cyclic fatigue tests in H_2 environment

No blistering or delamination of liner evident during visual inspection of liner following pressure blowdown (│d*p*/d*t*│ > 6000 psi/min at 55°C)



Technical Progress – Cyclic fatigue tests in H_2 environment

Following blowdown test, pipeline specimen was shipped to Fiberspar for standard quality assurance testing to verify performance of the product against new, unused product.

Property Testing	Method	Result	Factory Acceptance Minimum	Pass/Fail	Specimen ID
Liner Melting Point (C)	WI10.004-5	131.45	130	Pass	FS 14188L
Liner Visual Examination	40X Optical	Excellent	n/a	Pass	FS 14188
Laminate Glass Trans Temp (C)	WI10.004-5	127.99	115	Pass	FS 14188
Laminate Visual Examination	40X Optical	No Defects	n/a	Pass	FS 14188
Pressure Burst (psi)	WI10.007	5,446	4,838	Pass	FS 14188
Overall Condition	Visual	Good	n/a	Pass	FS 14188

QA test results showed that the pipe retained performance similar to newly manufactured pipe following thermal cycling, pressurization-depressurization cycling, and blowdown testing.

Technical Progress – Cyclic fatigue tests in H_2 environment

- **Complete 2nd cyclic fatigue test (in progress)**
  - Test article #2
    - Temperature cycling between room temperature and 60°C
    - Pressurization-depressurization cycling between 500 and 1500 psig
    - Blow-down test
    - Measure leak rate
  - Repeat above steps until test article exhibits physical damage, leak rate increases, or seals begin to fail
    - Funding is (at present) insufficient to test through a simulated service life (1,500 cycles)
- **Evaluate seals in joint fittings (connectors)**
  - Pressure decay leak rate measurement with minimum pipe length between fittings (just enough to assemble fittings at ends) will yield definitive seal leak rate (we hope)
  - Assess effects of thermal cycling, pressure-depressurization cycling on o-ring elastomers

Technical Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

Previous capital cost estimate by ORNL for FRP hydrogen transmission pipeline was presented in 2007

- Smith, Frame, Eberle, Anovitz and Armstrong, 2007 AMR presentation PD14
- Employed HDSAM version 1.0 to determine number of pipelines required to provide flow for peak demand
  - Assumed city population of 200,000 with market penetration of 50% light-duty HFC vehicles → peak demand = 58,600 kg/day
  - Distance from centralized production to distribution: 62 miles
  - Pipeline inlet/outlet pressures = 1000 psig/700 psig
  - Peak demand would necessitate installation of four 4.5-inch ID FRP pipelines (parallel emplacement in single trench)
- **Estimated costs using price list data for commercial FRP pipeline manufactured for upstream oil and gas operations**
  - Total cost for material and labor (excluding ROW and permitting costs) ranged from **$331,00 to $346,000 per mile** (cost varies with ruggedness of terrain)

Technical Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

Recent estimation and comparison of cost advantage of FRP compared to steel, based on industry survey

- From Daryl Brown (PNNL), private communication; and Elgowainy (ANL), Mintz (ANL) and Brown, 2011 AMR presentation PD14
- Relative labor costs, FRP/steel ≈ 0.54 (range 0.45-0.75, depending on FRP manufacturer)
  - Cost savings are in construction, inspection, deployment
    - Present-day costs for emplacement are ~25% less
    - Future costs could be 40% less
  - Costs of FRP and steel are about equal for field labor, project engineering and construction management
- Relative material costs, FRP/steel ≈ 1.18
  - Materials: pipelines, connections, fittings
  - Future FRP costs could be reduced as much as 10%
- About 15% overall cost reduction provided by FRP, compared to steel
- Future: Field learning and competition could provide additional cost advantage relative to steel

Technical Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

- **H2A Delivery Scenario Analysis Model - Version 2.3.1**
  - Pipeline length: 300 miles
  - Inlet, outlet pressures: 1000 psia, 700 psia (69 bar, 48 bar)
  - Peak hydrogen flow rate: 135,000 kg/day
  - Panhandle B equation → Four 4.5-inch ID FRP pipelines with HDPE liners provide flow rate equivalent to one 8-inch ID steel pipeline
    - Flow efficiency assumptions: 0.92 for steel, 0.98 for HDPE
- **Fiberspar Linepipe™ FRP (GRP), 4.52-inch ID, 1500 psi rating, HDPE liner**
  - Material costs from pricing sheet: pipeline, $20/ft (2100 ft spooled length); 316 SS connectors, $3825 ea
  - Labor costs for trenching and installation: $2/ft for soft soil up to $12/ft for rocky terrain; mean cost ~$5/ft

Technical Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

- **Estimate of capital cost for installation of 300 miles of FRP pipelines for hydrogen transmission**
  - Four pipelines with connectors: $138M
  - Trenching and installation: $32M
  - Inspection and testing: *TBD*
  - Total material and labor: $170M
  - Total capital investment: **$570,000/mile**

Technical Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

Estimate for total capital investment indicates FRP polymer pipeline could meet 2012 cost target

Gaseous Hydrogen Delivery				
Transmission Pipeline				
	2007 Estimate for FRP Pipeline	**2009 Estimate for Natural Gas Pipeline**	**2012 Estimate for FRP Pipeline**	**2020 Target**
Total capital investment, in $/mile (excluding costs for ROW and permitting)	**346,000** [1]	**765,000** [2]	**570,000**	**710,000** [4]
H_2 leakage, in kg H_2/mile/y			**<60** [3] **(<0.1%)** [5]	**<780** [4] **(<0.5%)** [5]

[1] From Smith, Frame, Eberle, Anovitz and Armstrong, 2007 AMR, presentation PD14, May 16, 2007.

[2] From Elgowainy, Mintz and Brown, 2011 AMR, presentation PD14, May 10, 2011 (for 8-inch steel pipeline).

[3] Estimate based on FRP pipeline leak rate from Smith, Frame and Anovitz, 2009 AMR, presentation PDP24, May 19, 2009, and connector leak rate from Adams, 2008 AMR, presentation PD20, June 11, 2008.

[4] From Table 3.2.3, Technical Targets for Hydrogen Delivery Components, Draft 2011 MYRDD Plan-Hydrogen Delivery.

[5] Leakage expressed as a percentage of total hydrogen transmitted; 2020 target from Table 3.2.2 Technical Targets for Hydrogen Delivery, in 2007 MYRDD Plan-Hydrogen Delivery, October 2007.

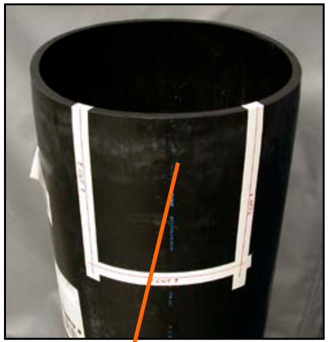
FY 2012 work beyond AOP tasks – Complete permeation measurements in pipeline liners

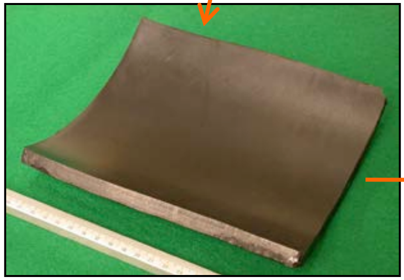
Pipeline Polymer Specimens	Measurement Status
PE3408 (extruded pipe)	Extensively studied in early project years (completed)
PE3608 (extruded pipe)	Recently completed
HDPE (injection molded)	In progress
PA-6 (extruded pipe, with carbon black)	In progress
PA-6 (extruded pipe, without carbon black)	In progress
HDPE with nano clay (injection molded)	To be done
HDPE with nano TiO2 (injection molded)	To be done
EVOH ("low permeation")	Low priority
MDPE (extruded pipe)	Low priority

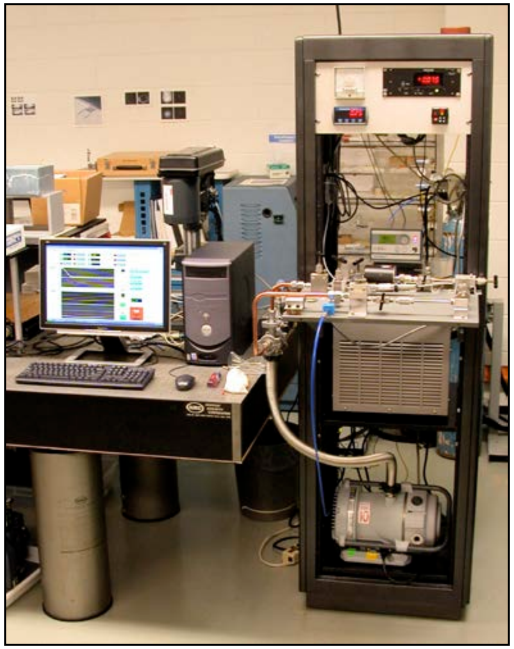
New polymer diffusion and permeation measurements apparatus

New automated system provides faster, more reliable diffusion and permeation measurements in polymer specimens

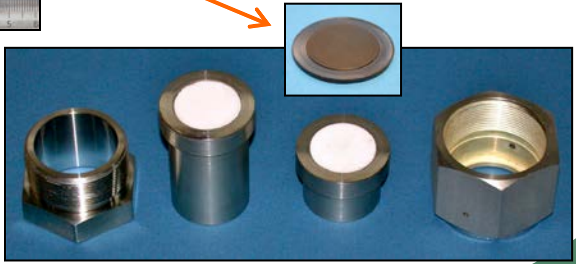
Liner specimens are sectioned from commercial pipelines and storage tanks, then carefully machined to 35-mm diameter by 1-mm thick discs to enable accurate and reproducible measurements







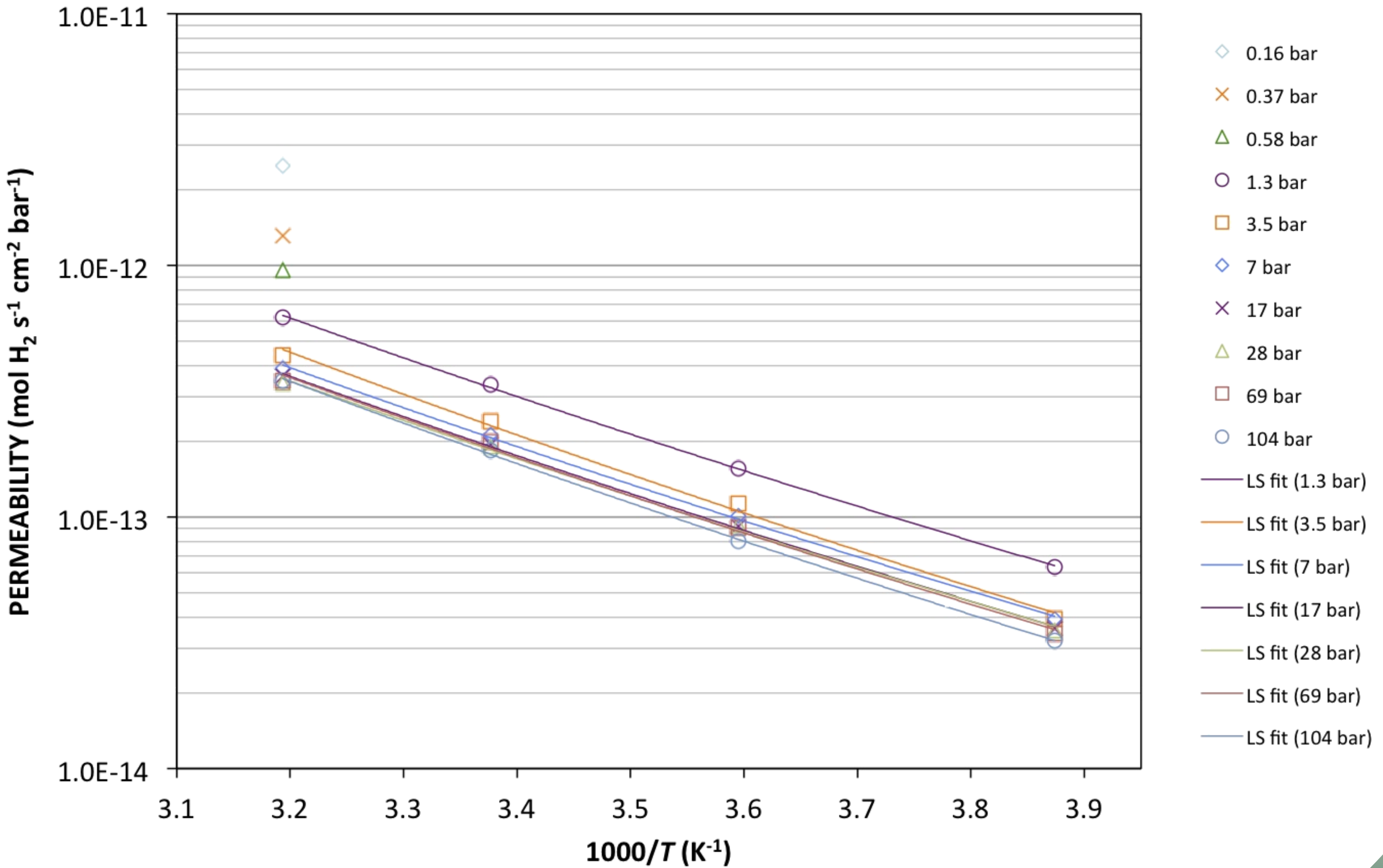
Measurements of D and P at T = –40 to 85°C, $p \leq$ 480 bar (7000 psi)



Simplified polymer specimen holder (gasket-less high-pressure seal)

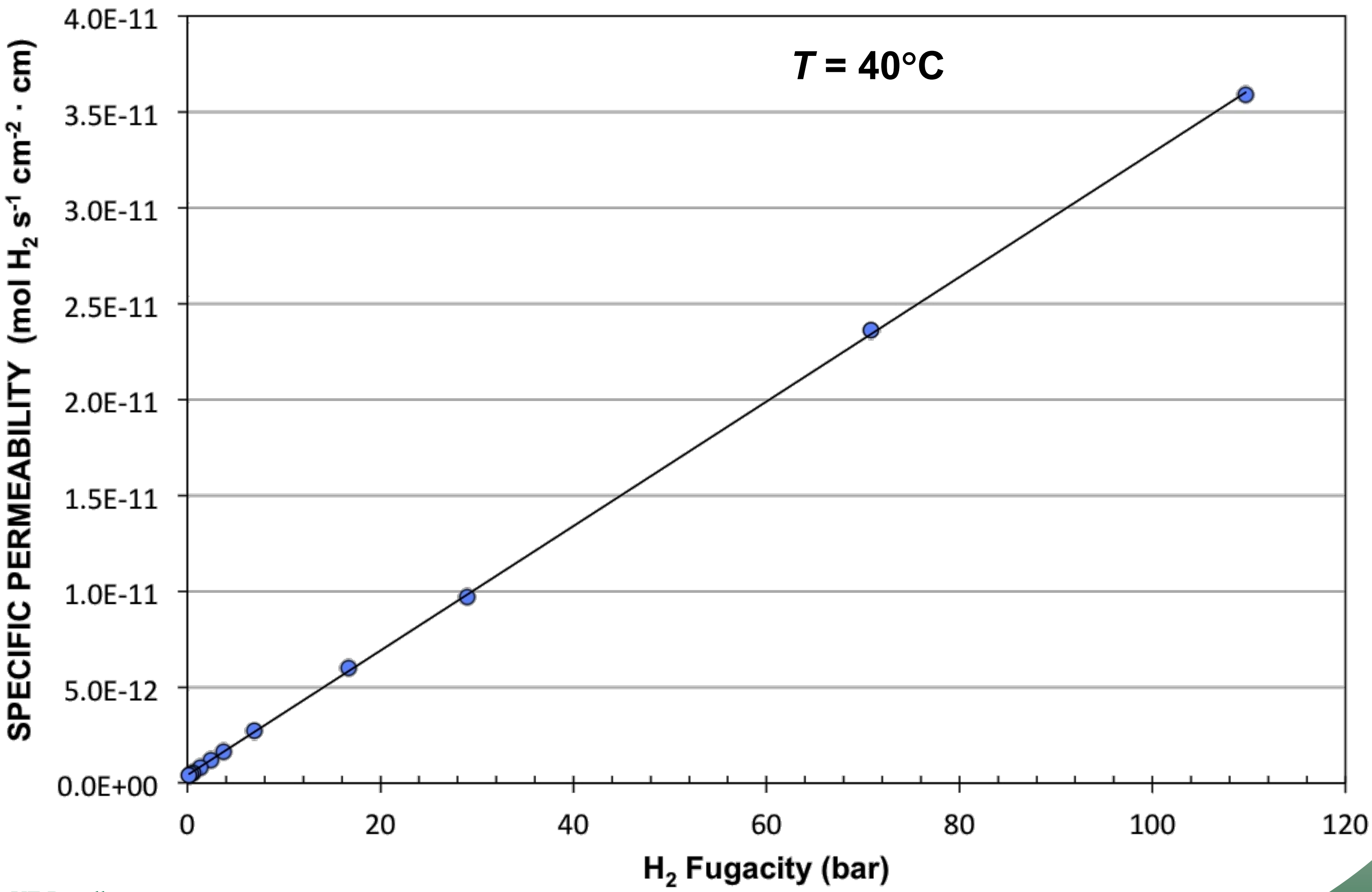
Technical Progress – H_2 permeability in PE3608

Ten-fold increase in H_2 permeability in PE3608 between -15 and 40°C



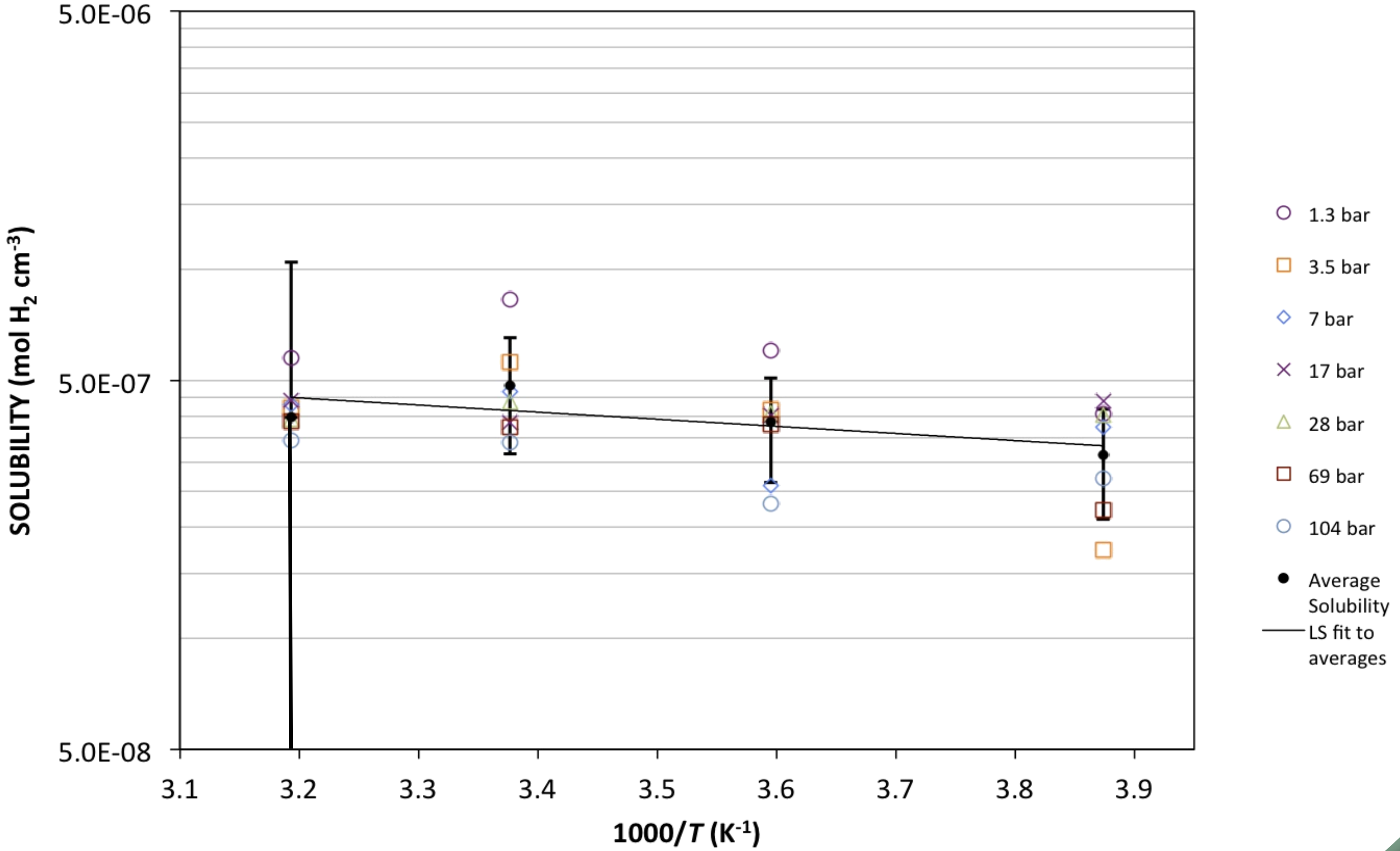
Technical Progress – Specific Permeability in PE3608

Specific permeability in PE3608 is *linearly dependent* on H_2 fugacity in range 0.2 to 104 bar



Technical Progress –Temperature Dependence of H_2 Solubility in PE3608

No significant temperature dependence for H_2 solubility between -15 and 40°C



Future Work

- **Collaborate with FRP pipeline manufacturers, SRNL, the Pipeline Working Group, ASME, pipeline operators and other stakeholders on acceptance of FRP pipelines for hydrogen delivery through a codification and standardization process**
  - Complete a rigorous review of the work done to date with ASME, FRP manufacturers and the companies that would build and operate FRP hydrogen pipelines
  - Put together a comprehensive list of all of the testing and performance requirements with ASME and other stakeholders.
  - Identify research that needs to be completed to close knowledge gaps, and establish plans to conduct the research

    Example: If 3rd party damage to an FRP hydrogen pipeline produced a widespread depressurization event in the pipeline, how could the pipeline operator assess damage to the affected length of pipeline, and if the pipeline is damaged, how should the operator repair the damage? What measures are effective for avoiding damage due to rapid depressurization?

Project Summary

Relevance: Composite FRP pipelines are an economically and technically viable alternative to metallic pipelines

Approach: Assess pipeline capital cost, test pipeline reliability, leakage, hydrogen compatibility, develop path forward for technology acceptance

Progress: Cost scenario shows composite pipelines can meet DOE 2012 goals; hydrogen compatibility of pipeline materials is acceptable; pipeline leakage rates are acceptable from economic and safety standpoints

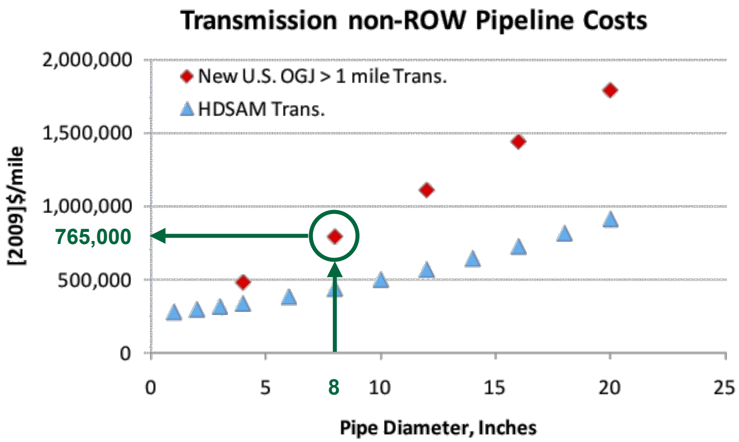
Collaborations: Pipeline and polymer manufacturers, National Lab, HFC program advisement organizations

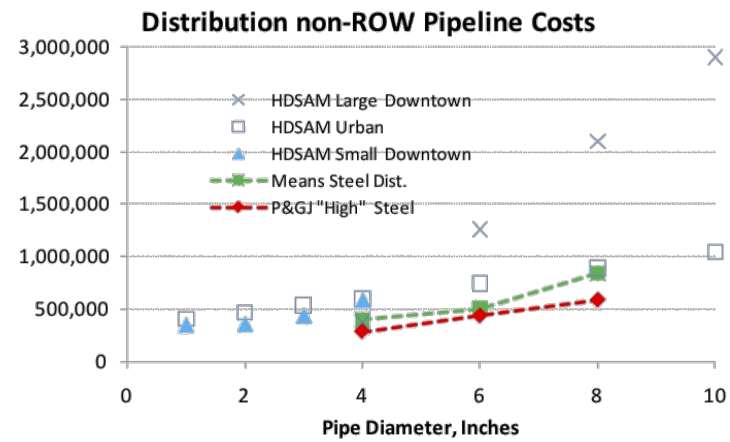
Future: Codification, standards development, technology demonstration project, durability and lifecycle testing

Technical Backup Slides

Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

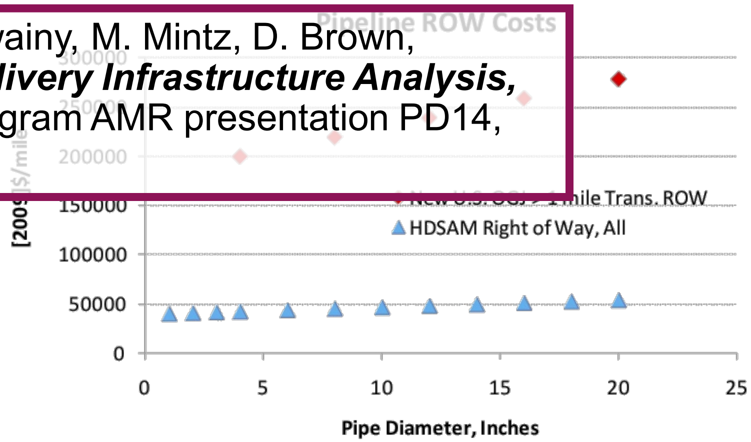
Pipeline Cost Function Updates





Non-ROW costs have increased by up to a factor of two

From A. Elgowainy, M. Mintz, D. Brown, ***Hydrogen Delivery Infrastructure Analysis,*** 2011 HFC Program AMR presentation PD14, May 10, 2011.



ROW costs have increased the most on a percentage basis

8

OAK RIDGE National Laboratory

Progress – Updated Capital Cost Estimate for FRP Hydrogen Pipeline

Estimation of hydrogen leak rate in FRP pipeline

- Hydrogen flux through the cylindrical polymer liner in the pipeline is given by

$$\frac{dn}{dt} = \frac{2\pi \cdot P}{\ln(b/a)}(p_1 - p_0)$$

  where $P = 2\times10^{-13}$ mol/cm·s·bar is the permeation coefficient at 103 bar and 23C, a=5.74 cm and b=6.24 cm are the inner and outer radii of the liner, and p_1 and p_0 are the hydrogen pressures inside (103 bar) and outside (0 bar) the liner.

  Solving this equation and converting to appropriate units yields a leak rate of $dm/dt \approx 10$ kg/year per mile of pipeline. The four pipelines together would then lose approximately 40 kg H_2/year/mile.

- Leakage loss at the connectors can be projected from the 30 sccm leak rate provided in 2008 by SRNL following measurements on Fiberspar connectors. Their leak rate implies a loss of ~1.5 kg H_2/year/connector and, assuming there are approximately 2.5 connectors per mile of pipeline, the annual loss of hydrogen due to leaking at the connectors would be 3.8 kg H_2/year/mile. Multiplying this loss by 4 to get the total contribution from four pipelines yields an estimated loss of 15 kg H_2/year/mile.

- Therefore, the total leakage for the pipelines would be <60 kg H_2/year/mile. If the pipelines deliver a daily average of 50,000 kg H_2, the annual loss due to leakage over a distance of 300 miles of pipelines would be less than 0.1% of the total transmitted H_2.