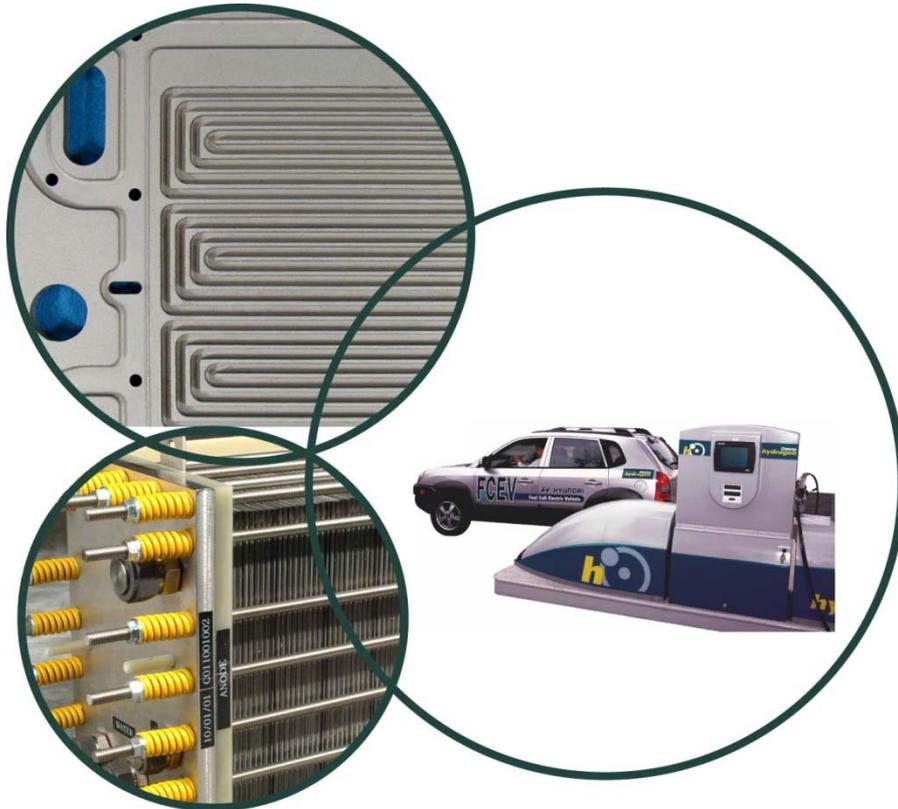


Composite Technology for Hydrogen Pipelines

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Arlington, Virginia
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Project ID #: PDP_24_Smith



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

Overview

Timeline

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

Budget

- Total project funding
 - DOE: \$1.65M
- Funding received in FY 08
 - \$600k
- Funding for FY 09
 - \$0k

Barriers

- D. High Capital Cost and Hydrogen Embrittlement of pipelines
- Technical Targets on next slide

Partners & Collaborators

- Fiberspar, PolyFlow
- Arkema, Ticona, Fluoro-Seal
- SRNL
- Pipeline Working Group

Overview

- **Technical Targets**

Category	2005 Status	2012	2017
Pipelines: Transmission			
Total Capital Investment (16-in pipeline, \$/mile)	\$720k	\$600k	\$490k
Pipelines: Distribution			
Total Capital Investment (2-inch pipeline, \$/mile)	\$320k	\$270k	\$190k
Pipelines: Transmission and Distribution			
Reliability/Integrity (including 3rd-party damage issues)	Acceptable for current service		Acceptable for H ₂ as a major energy carrier
H ₂ Leakage *	Undefined	TBD	< 0.5%

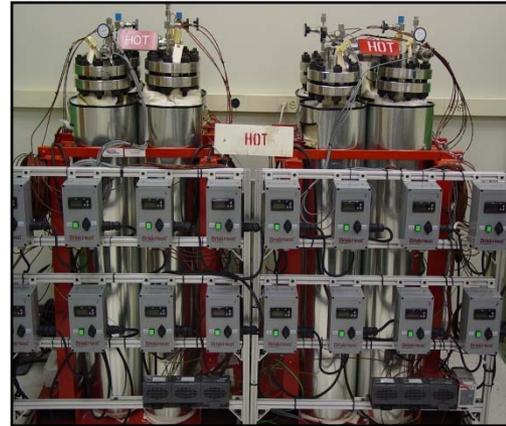
* Leakage targets are being reviewed by the Delivery Tech Team

Project Milestones

Month-Year	Milestone or Go/No-Go Decision
Sep 2008	Milestone: Survey of existing modifications and treatments available for reducing permeability in liner materials completed and reported (completed) Milestone: Recommendations for sensor integration, manufacturing and joining technologies completed and reported (50% complete)
May 2009	Milestone: Hydrogen compatibility evaluations of composite pipeline materials and construction completed (60% complete).

Technical Accomplishments-Initial Compatibility Testing Completed

- Pipeline materials compatibility testing
 - Hydrogen compatibility testing following eight-month accelerated-aging protocol showed no quantifiable materials degradation
 - Hydrogen leakage measurements in Fiberspar pipeline yielded smaller than predicted leak rates (<0.02% per day); Leakage measurements on PolyFlow FRP pipeline are in progress
 - Fiberspar FRP pipeline specimen passed blowdown testing with hydrogen



H₂ exposure station at SRNL



Pipeline test specimens



Leakage measurement at ORNL

Technical Accomplishments-Evaluation of Joining Technologies is Progressing

- **Joining and sensor technologies**
 - Hydrogen leakage through Fiberspar LinePipe™ connectors is very low, $<3 \times 10^{-6}$ mol/s
 - Collaborative effort underway with SRNL to assess joint loading, pipeline flexure, and pressure/temperature cycling on hydrogen leakage for both Fiberspar and PolyFlow connectors



FiberSpar connector with compressive o-ring seals



PolyFlow swaged connector

Completed H₂ compatibility screening of Fiberspar pipeline and materials

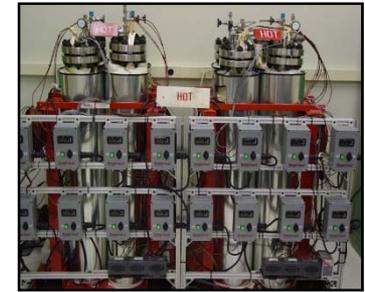
- Accelerated aging procedure used to screen for long-term effects of hydrogen exposure on composite pipeline under normal-usage conditions
- Completed post-treatment tests of Fiberspar pipeline and constituent materials
 - Immersion in 1000 psi H₂
 - Accelerated aging at 60°C for 8 months (equivalent to 5+ years at RT)
 - No deleterious effects due to H₂ noted in qualification testing of pipelines or tensile and DMA testing of polymer and composite matrix resin specimens



4-pt bending test specimen



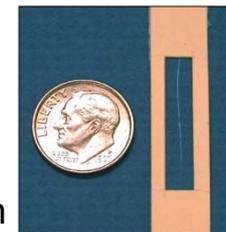
Compression test specimen



SRNL H₂ exposure station



Liner test specimen



Glass filament specimen

Hydrogen blowdown testing of composite pipeline

- **Guidance: API 15S - Qualification of Spoolable Reinforced Plastic Line Pipe, Appendix D**
 - **Specimen filled with hydrogen* to pressure rating, specimen heated to temperature rating, these conditions held until pipeline structure is saturated with gas**
 - **Following hold period, specimen depressurize at a rate greater than 1000 psi/min**
 - **Following blowdown, specimen liner was examined and no visual evidences of liner blistering or collapse**

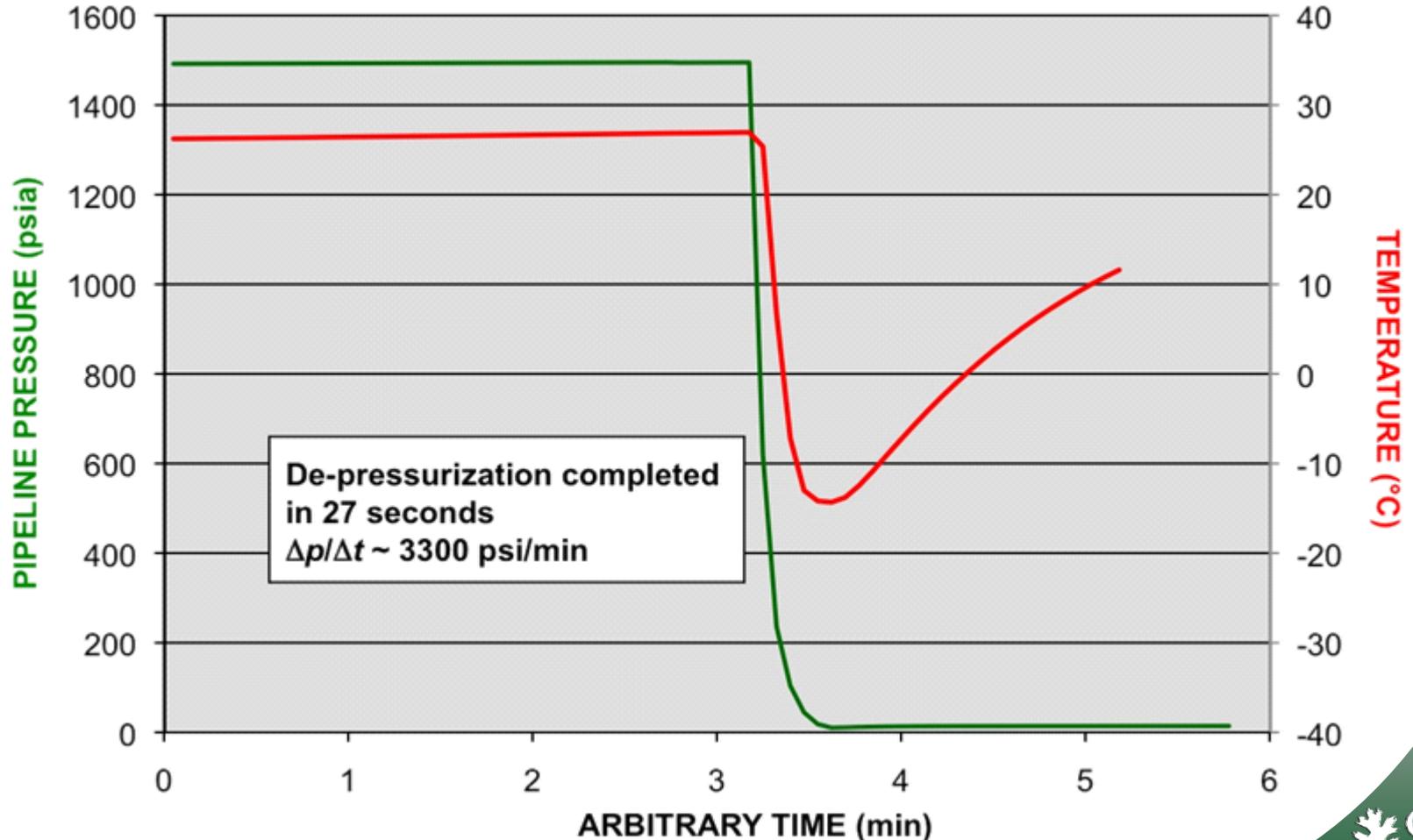


3-ft pipeline specimen being instrumented for blowdown testing

***API 15S specifies the use of supercritical CO₂ for blowdown testing**

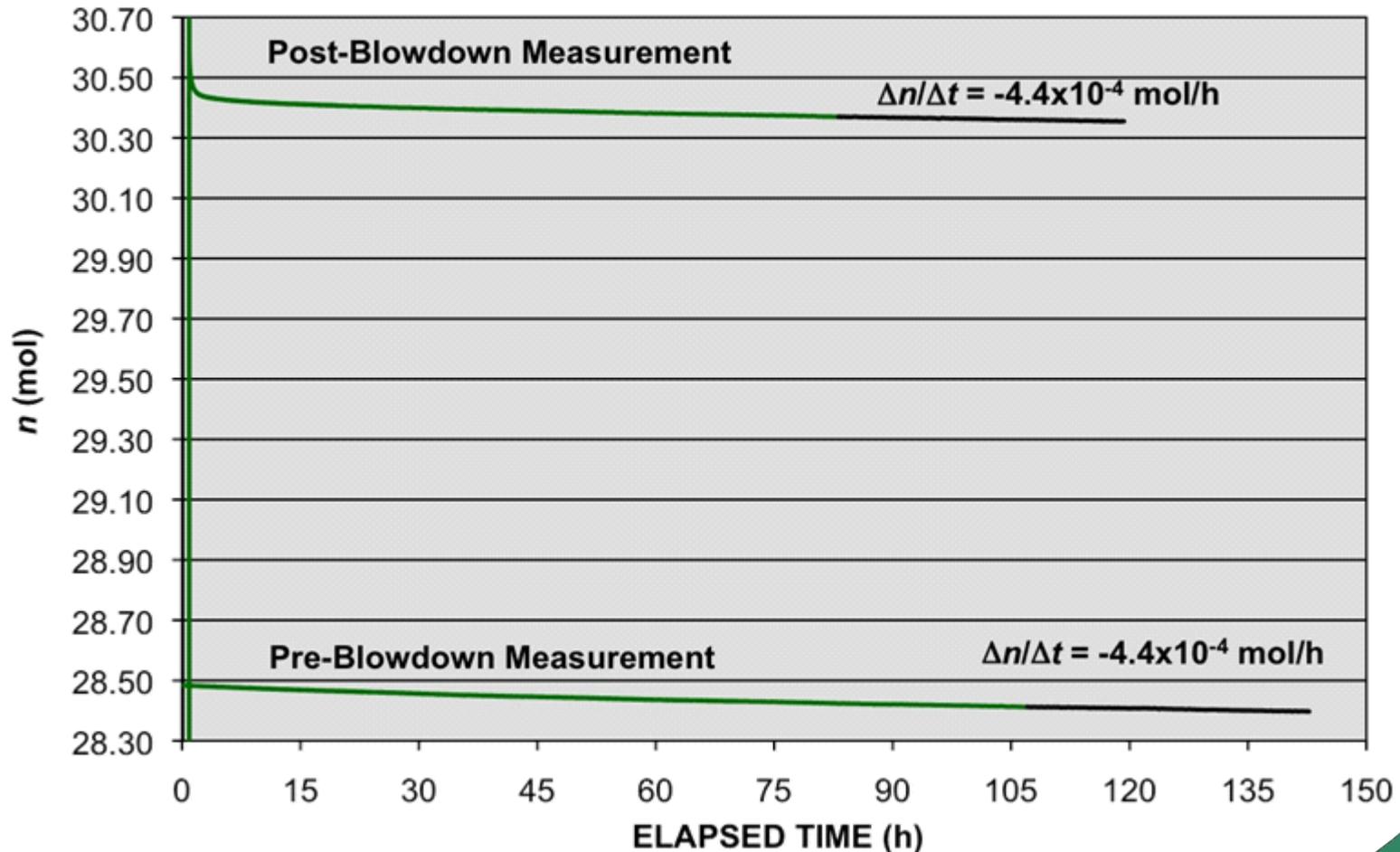
Blowdown de-pressurization rate was 3X specified minimum rate

HYDROGEN BLOWDOWN TEST IN FIBERSPAR LP 4-1/2 1,500(E)
3-FT PIPELINE SPECIMEN
DE-PRESSURIZATION PROFILE



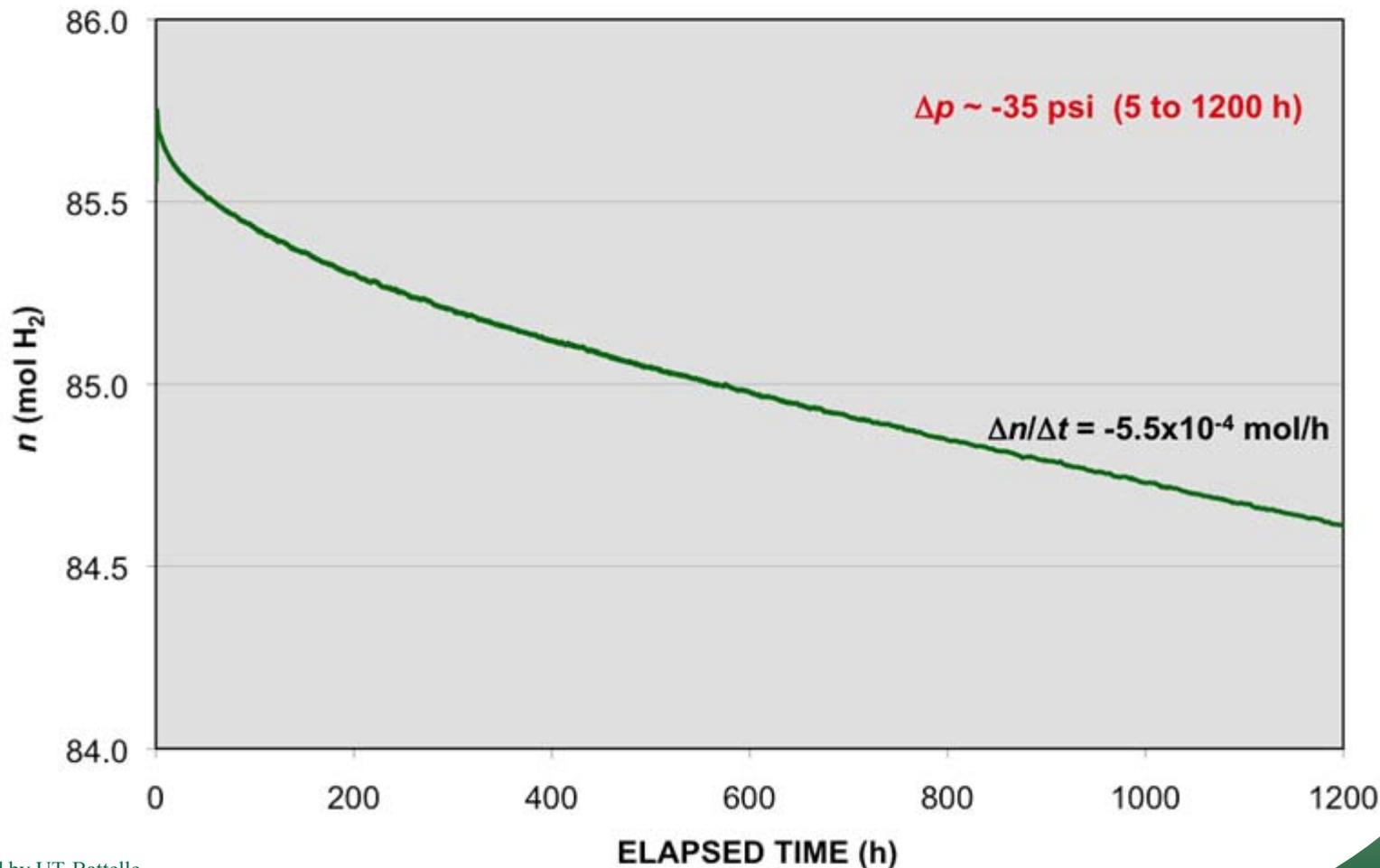
Post-blowdown leakage rate was identical to pre-blowdown rate

FIBERSPAR PIPELINE LEAKAGE MEASUREMENT
Nominal 1500 psia Pressurization
Moles of Hydrogen Gas in 3-ft Pipeline Specimen



Actual H₂ leakage rate is nearly 50X below predicted rate

FIBERSPAR PIPELINE LEAKAGE MEASUREMENT
Nominal 1500 psi Pressurization
Moles of Hydrogen Gas in 9-ft Pipeline Specimen



Summary of H₂ leakage rate measurements for Fiberspar LinePipe™

Start Date	Specimen	Nominal Pressure	Leakage Rate (mol/h)
5/15/08	3-ft pre-blowdown	1500 psi	-4.4x10 ⁻⁴
5/22/08	3-ft post-blowdown	1500	-4.4x10 ⁻⁴
6/3/08	3-ft post-blowdown	500	(+7.6x10 ⁻⁵)
3/26/08	6-ft	1500	-5.5x10 ⁻⁴
4/7/08	6-ft	500	(+3x10 ⁻⁴)
8/25/08	9-ft	1500	-5.5x10 ⁻⁴

Summary of H₂ leakage rate measurements to date

Specimen Length	Nominal Pressure (psig)	Measured Leakage Rate (mol/h)	Predicted Leakage Rate (mol/h)
3-ft	1500	-4.4×10^{-4}	-8.2×10^{-3}
6-ft	1500	-5.5×10^{-4}	-1.6×10^{-2}
9-ft	1500	-5.5×10^{-4}	-2.5×10^{-2}

In most extensive test to-date, hydrogen lost due to permeation and leakage through end cap seals was less than 0.02% per day. The rate is 45 times below the predicted value for HDPE (PE-3408) liner.

Summary of H₂ leakage rate measurements to date

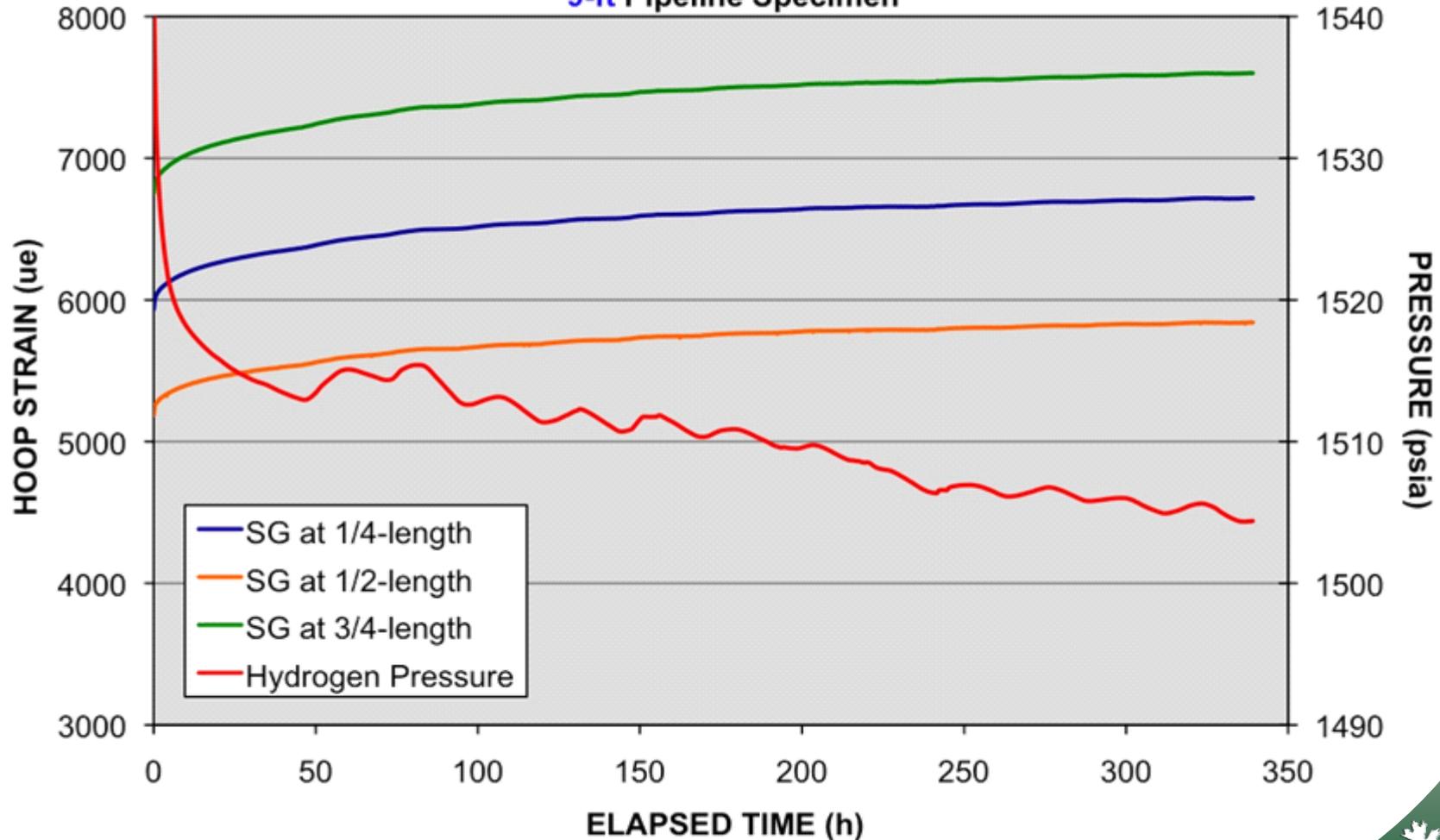
- **Loss due to leakage is much lower than expected (and might be good enough to meet leakage target)**
- **Reinforcement layer might be providing some gas barrier benefit but probably can't account for full extent of discrepancy between predicted and measured values**
- **Rapid decompression of pipeline is probably not going to be a failure mechanism for liner**
- **Joints with elastomeric seals have worked well (so far)**

Future directions for H₂ leakage rate measurements in Fiberspar FRP pipeline

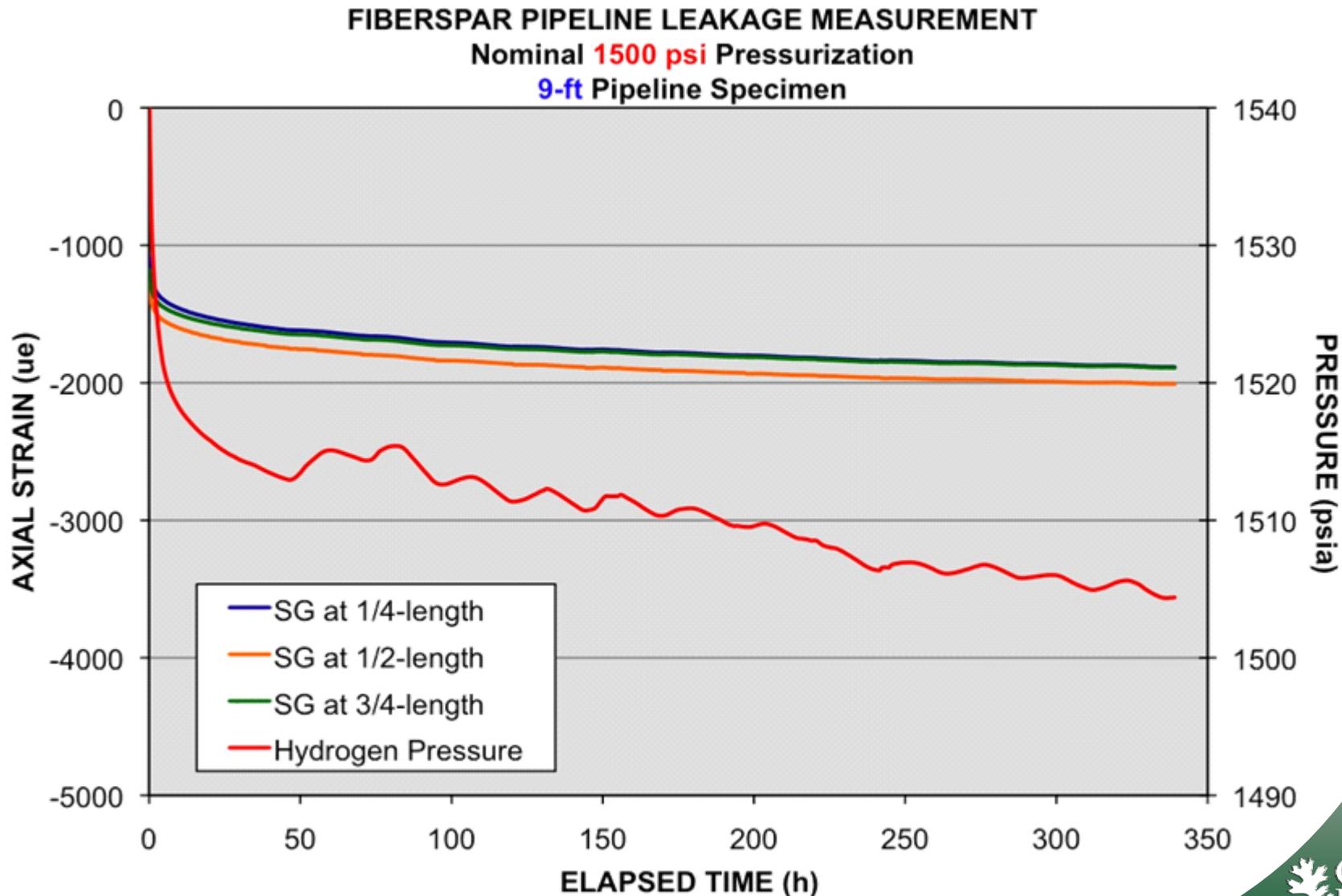
- **Subject specimens to 4-pt bend testing to reveal the extent of how microcracking increases permeation and leakage**
- **Measure pressure as a function of depth in wall or within composite layers**

Hoop strain in Fiberspar FRP pipeline during leakage measurements

FIBERSPAR PIPELINE LEAKAGE MEASUREMENT
Nominal 1500 psi Pressurization
9-ft Pipeline Specimen

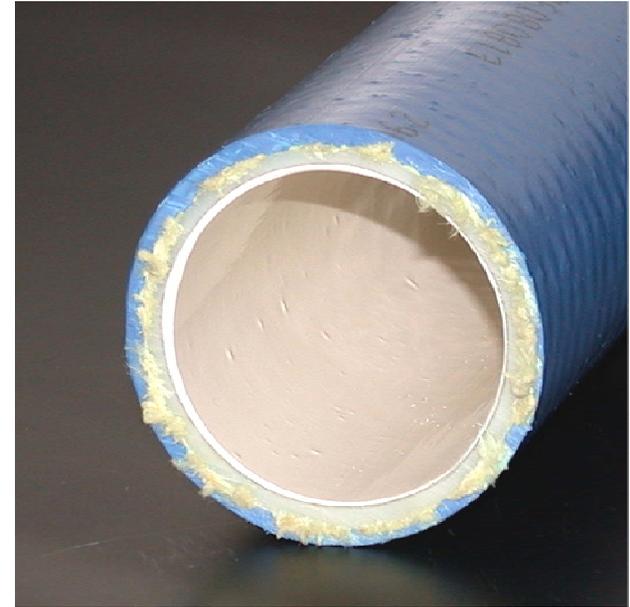


Axial strain in Fiberspar FRP pipeline during leakage measurements



H₂ leakage rate measurements in PolyFlow Thermoflex[®] Reinforced Pipe

- **Liner: Coextruded PPS and PA-6**
- **Reinforcement: aramid fiber rovings braided on liner, laid over four longitudinal rovings**
- **Burst strength determined by braid angle, not by number of plies**
- **PP jacket with damage indicating colorant**
- **Couplings with swaged metal seals**
- **Leakage rate measurements in progress**



Future Work

- **FY 2009**

- Report test results from 8-month accelerated aging and hydrogen exposure of pipeline and material specimens
- Continue measurements of liner materials, including measurements of surface fluorination samples, using new diffusion and permeation measurement apparatus for polymers with additional capabilities
- Begin assessment of possible hydrogen-induced cracking in the reinforcement layers during cyclical strain, perform long-term stress rupture tests, perform high-pressure cyclical fatigue tests, assess joint sealing under cyclic loading
- Collaborate on development of codes & standards for hydrogen-service FRP pipelines

- **FY 2010**

- Coordinate initial field test of FRP pipeline for hydrogen service, providing springboard for commercially viable demonstration project

Project Summary

- Relevance:** Need viable alternative to metallic pipelines to achieve cost and performance targets for hydrogen transmission and distribution
- Approach:** Investigate applicability of commercially available FRP polymer pipelines and develop path forward for hydrogen delivery
- Progress:** Cost scenario shows composite pipelines can meet DOE 2012 goals and are close to 2017 goals; hydrogen compatibility of pipeline materials is acceptable; pipeline leakage rates are lower than predicted
- Collaborations:** Pipeline and polymer industries, National Lab
- Future:** Codes & standards; prototype FRP pipeline system for H₂ delivery; demonstration project