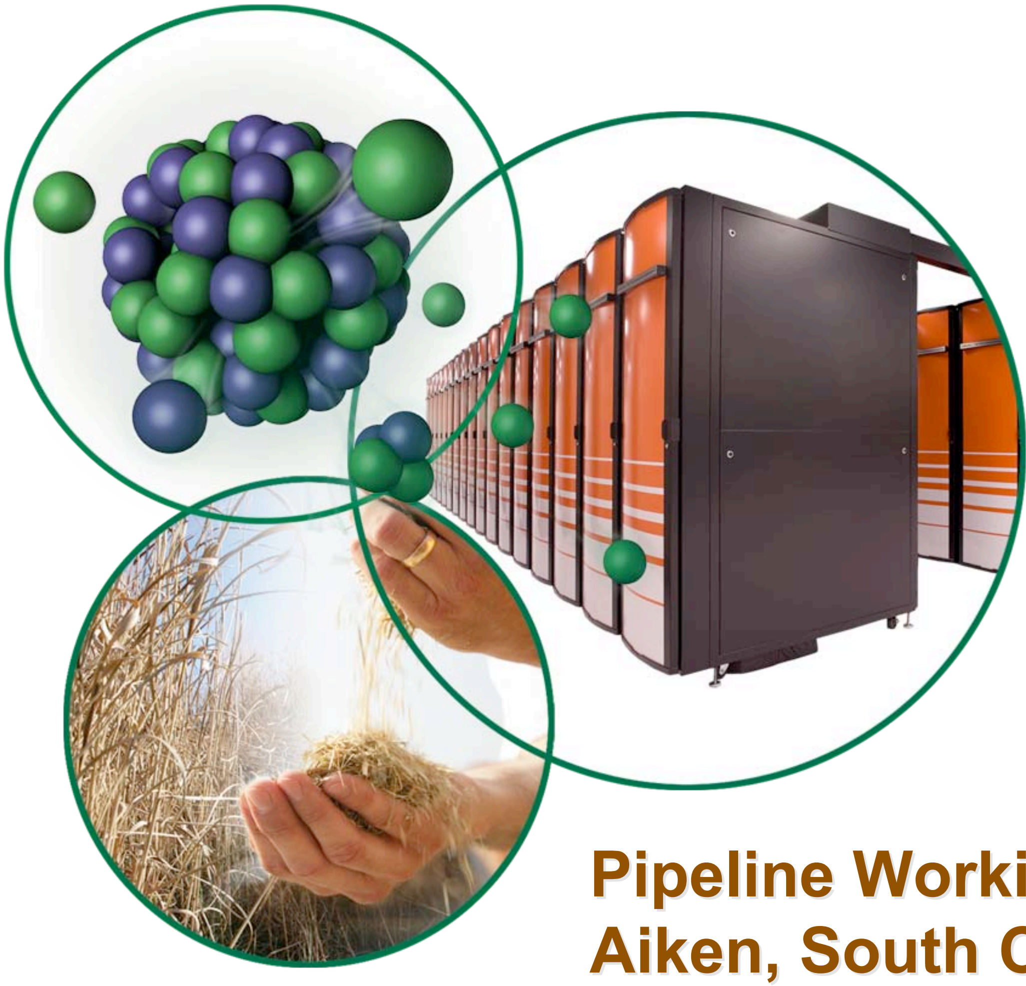
Composites Technology for Hydrogen Pipelines



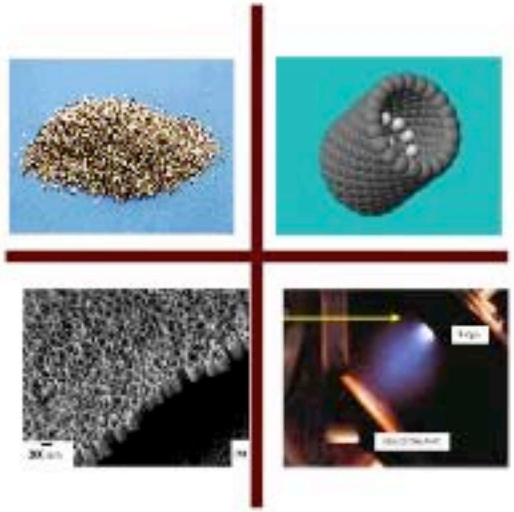
Barton Smith, Barbara Frame, Larry Anovitz and Cliff Eberle

Oak Ridge National Laboratory

Pipeline Working Group Meeting
Aiken, South Carolina
September 25-26, 2007

WSRC-STI-2007-00481

SRNL Support for FRP Piping Project



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SAVANNAH RIVER NATIONAL LABORATORY

We Put Science To Work

George Rawls
Thad Adams
SRNL Materials Science and Technology

Pipeline Working Group—FRP Piping Project

September 25, 2007

Composites Technology for Hydrogen Pipelines

Fiber-reinforced polymer pipe has excellent burst and collapse pressure ratings, large tensile and compression strengths, and superior chemical and corrosion resistance. Long lengths can be spooled for delivery, and a few workers can install thousands of feet of pipeline per day.

Fiber optic sensors, copper wires and power cables can be embedded a composite pipeline, enabling it to function as a *smart structure*.

Project Overview: Investigate application of composite, fiber-reinforced polymer pipeline technology for hydrogen transmission and distribution.

Technical Targets (2017):

- $490k/mile capital cost for transmission pipelines
- $190k/mile capital cost for distribution pipelines
- Hydrogen delivery cost below $1.00/gge
- High reliability
- Low hydrogen permeation

Technical Approach:

- Evaluate H_2 compatibility of pipeline materials
- Identify advantages and challenges of various manufacturing methods
- Identify polymeric liners with acceptably low hydrogen permeability
- Evaluate options for pipeline joining technologies
- Implement composite pipeline codes & standards
- Determine requirements for structural health monitoring and real-time measurements of H_2 parameters

Impact:

- Composite pipeline technology has the potential to reduce installation costs, improve reliability and provide safer operation of hydrogen pipelines.

Points of contact:

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Partners & Collaborators

- Fiberspar LinePipe, LLC - Houston, TX
- PolyFlow, Inc. - Oaks, PA
- SRNL
- University of Tennessee - Knoxville, TN
- Pipeline Working Group

Pipeline liner materials provided by

- Fiberspar - PE100
- Lincoln Composites - PE
- Ticona (Celanese) - PPS
- Arkema - PA11, PVDF

Composite Pipeline Installations (Oil and gas gathering lines)

Photos provided courtesy of PolyFlow, Inc.

Plan & Approach - FY 2008

- Task 1: Evaluation of composite pipelines and materials with respect to hydrogen delivery

- Task 2: Evaluation of liner materials

- Task 3: Evaluation of composite pipeline joining and integrated sensor technologies

Plan & Approach - FY 2008

- **Task 1: Evaluation of composite pipelines and materials with respect to hydrogen delivery**
  - Hydrogen compatibility testing
  - Hydrogen pipeline leakage measurements
  - Blowdown testing
  - Potential stress-corrosion cracking in composite construction
  - Long-term stress rupture tests
  - High-pressure cyclic fatigue tests
  - Joint attachment/joint sealing under cyclic loading
  - Third-party damage issues!

Plan & Approach - FY 2008

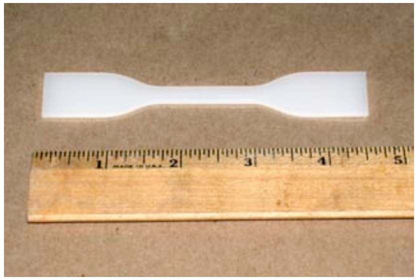
- Task 2: Evaluation of liner materials
  - Continue diffusion and permeation measurements of pipeline liner materials at 5 to 60 °C and at pressures from just above 1 atmosphere to the anticipated operating pressure in the pipelines
  - Build additional diffusion and permeation facility *just for polymers* with additional capabilities
    - Temperatures -40 to 150 °C
    - Pressure differentials up to 15,000 psi (345 bar)
    - Ability to assess effect of contaminants on diffusion/permeation values
    - Downstream purity measurements via mass spectroscopy

Plan & Approach - FY 2008

- **Task 3: Evaluation of pipeline joining and integrated sensor technologies**
  - Assess methods for joining FRP pipelines during emplacement, joining FRP pipelines to pipelines of other materials, and repairing FRP pipelines
  - Assess needs for structural health monitoring, leakage and gas property sensing
  - Coordinate pipeline sensor needs with sensors R&D in Safety, Codes and Standards program

Hydrogen Compatibility Testing

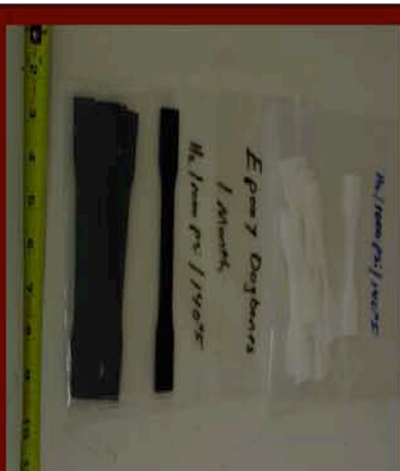
- **ORNL, Fiberspar, SRNL devised a screening procedure to assess effects of H_2 exposure on samples of commercially available FRP pipeline and constituent materials**
  - **Immersion in 1000 psi H_2**
  - **Accelerated aging (60°C)**
  - **1 mo, (1 wk,) 1 yr exposure times**



SRNL Support for FRP Piping Project
Progress


4-Ft FRP Sections


Compression Samples

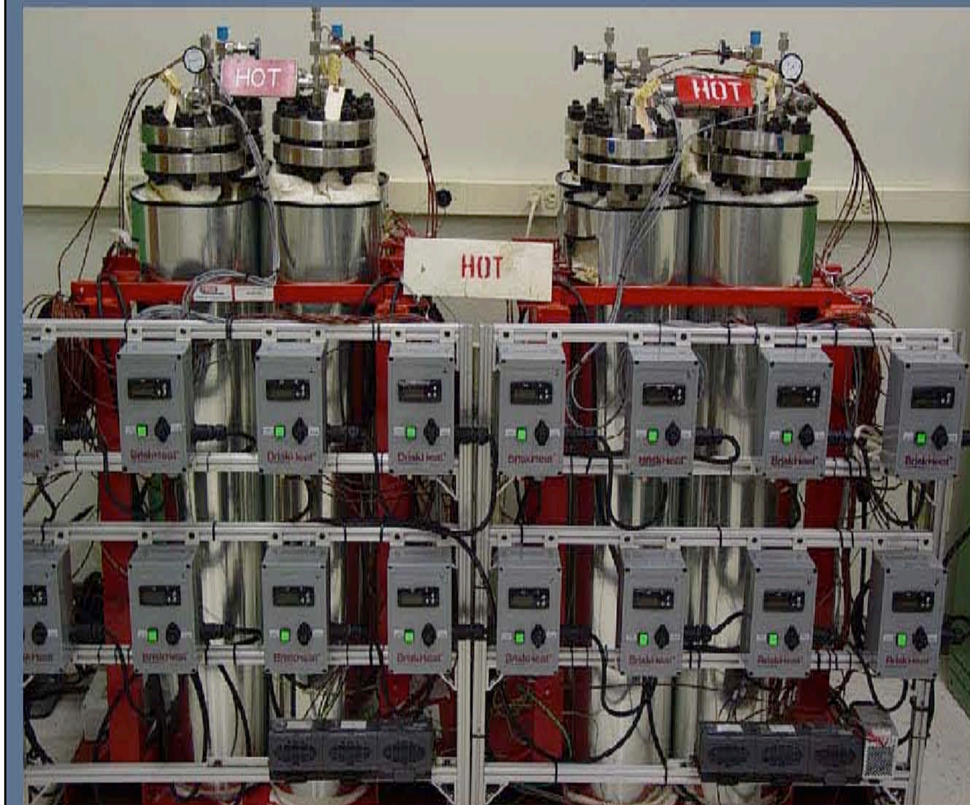

Tensile Samples

DMA Samples

- **Hydrogen Exposure Test Matrix**
  - Initial 1-month Exposures
    - 2-FRP Pipe Section for Hydrostatic Burst
    - 2-FRP Pipe Sections for Radius Bend Test
    - Glass Fiber, Resin, HDPE Liner Samples
  - 1-year Exposures
    - 2-FRP Pipe Section for Hydrostatic Burst
    - 2-FRP Pipe Sections for Radius Bend Test
    - Glass Fiber, Resin, HDPE Liner Samples
- **Control Sample Thermal Exposures**
  - 1-month and 1-year exposures

SRNL Support for FRP Piping Projec

Progres



SRNL Hydrogen Exposure Station

- No Existing Large Chamber Hydrogen Exposure Systems
- Developed a Design and Procure Large Section Hydrogen Exposu Vessels
  - Swagelok Manufactured
  - Rated for 1,400psig @
  - Accommodates up to 4-ft FRP Sections
- Installed in New SRNL Hydrogen Technology Research Laborator
- 1-month Exposure Testing Bein Initiated

SRNL

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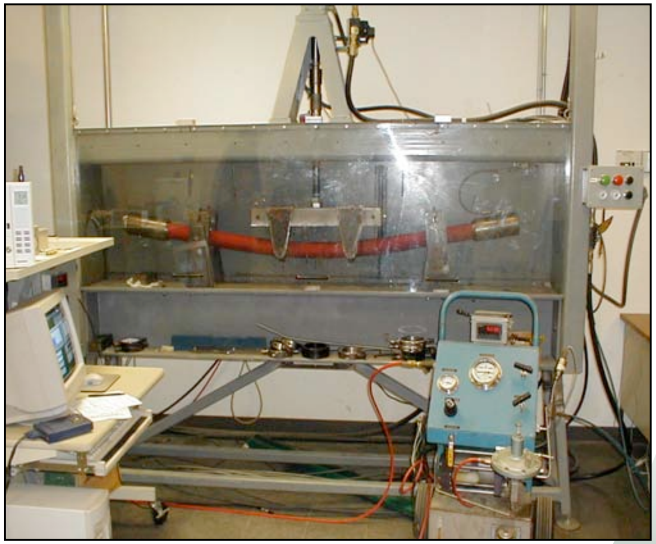
Hydrogen Compatibility Testing

- **Post-exposure, perform standard test procedures to detect gross structural degradation**
  - ***Hydrostatic burst pressure tests* to assess overall integrity of the specimens**
  - ***Compression tests* to determine ultimate compressive strength of the laminates and determine adverse effects on the polymer matrix**
  - ***Bend testing* to assess integrity of the laminate**
  - **Test for conformance with API 15HR, ASTM D2996, ASTM D2517 specifications**



Hydrogen Compatibility Testing

- Post-exposure: test constituent materials
  - Tensile tests and dynamic mechanical analysis of pipeline liner material & composite matrix resin specimens to measure changes in polymer properties
  - Tensile tests of glass filaments to measure changes in fiber reinforcement properties

Capital cost estimate for FRP hydrogen transmission pipelines

- Compare present-day FRP pipeline costs with capital cost target
- Use Hydrogen Delivery Scenario Model (HDSAM version 1.0, 4/1/06) to calculate delivery criteria
  - Model inputs and assumptions:
    - City populations: 200,000 and 1,000,000 people
    - Market penetration: 50% light-duty HFC vehicles
    - Distance from centralized production to city: 62 mi
    - P_1 = 1000 psi, P_2 = 700 psi
- FRP pipeline
  - Commercial, off-the-shelf linepipe for oil & gas market
  - 4.5-inch ID, 1500 PSI rating, PE liner

Capital cost estimate for FRP hydrogen transmission pipelines

- **Calculation of pipeline quantity and size** (via manipulation of Panhandle B equation)

City Size	Peak H_2 Demand (kg/d)	Daily H_2 Demand (kg/d)	4.5-inch ID Pipelines Required	ID Required for Single Pipeline (inches)
200,000	58,600	41,000	4	7.25
1,000,000	293,000	205,000	17	13.75

Photo provided courtesy of Fiberspar LinePipe, LLC

Capital cost estimate for FRP hydrogen transmission pipelines

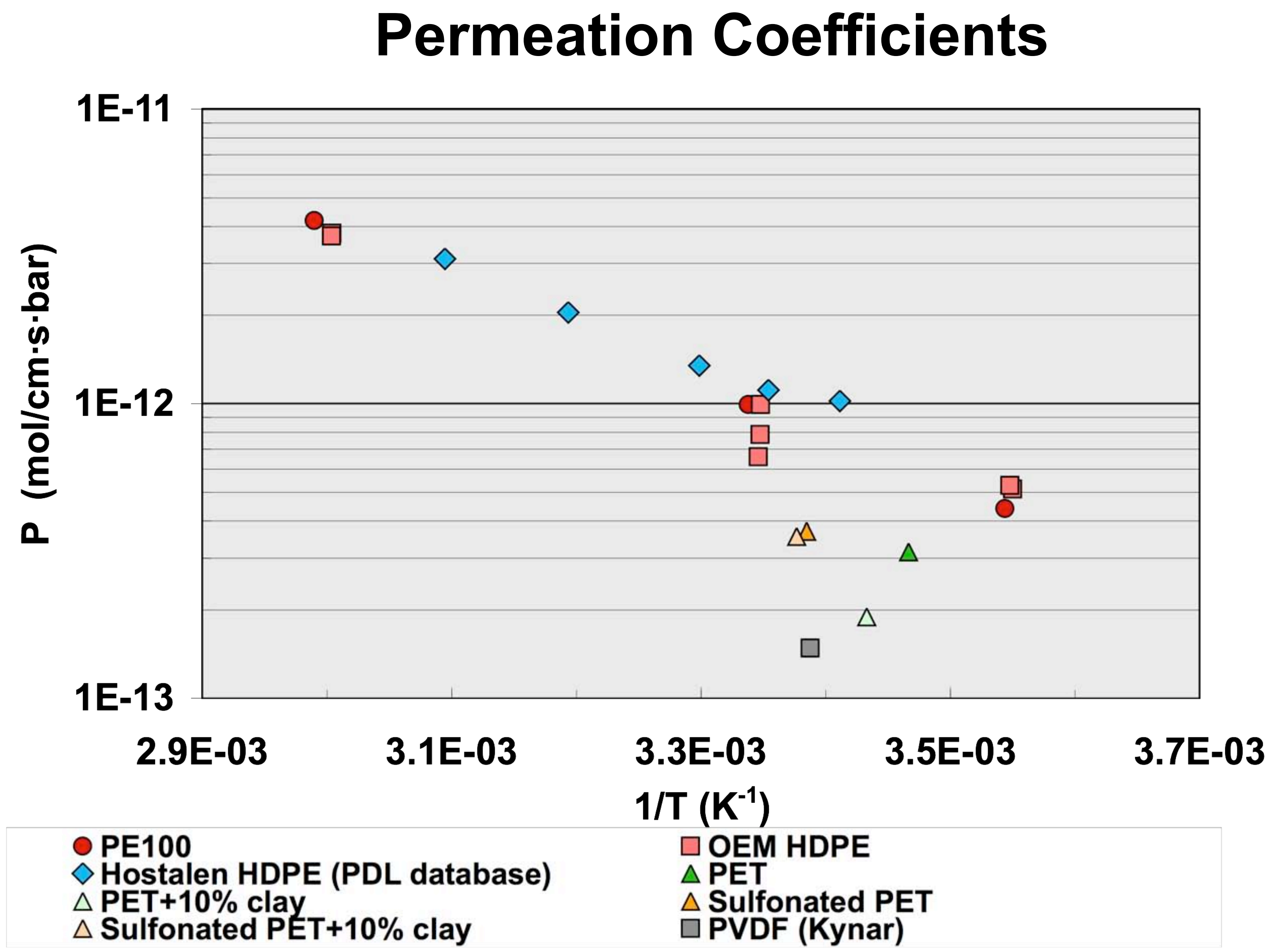
- Present-day cost for 4.5-in ID, 1500-psi FRP pipeline (pipeline, connectors, transportation, installation) is approximately **$80k per mile**
- Installation of four 4.5-in ID pipelines would require an investment of **$331k to $346k per mile**, excluding ROW and permitting costs

City Size	FRP Pipelines Installed ($k/mi)	Estimated ROW & Permitting ($k/mi)	Total Capital Investment ($k/mi)	2017 Cost Target ($k/mi)	16-inch ID Steel Pipeline ($k/mi)
200,000	331 – 346	250	581 – 596	490	636

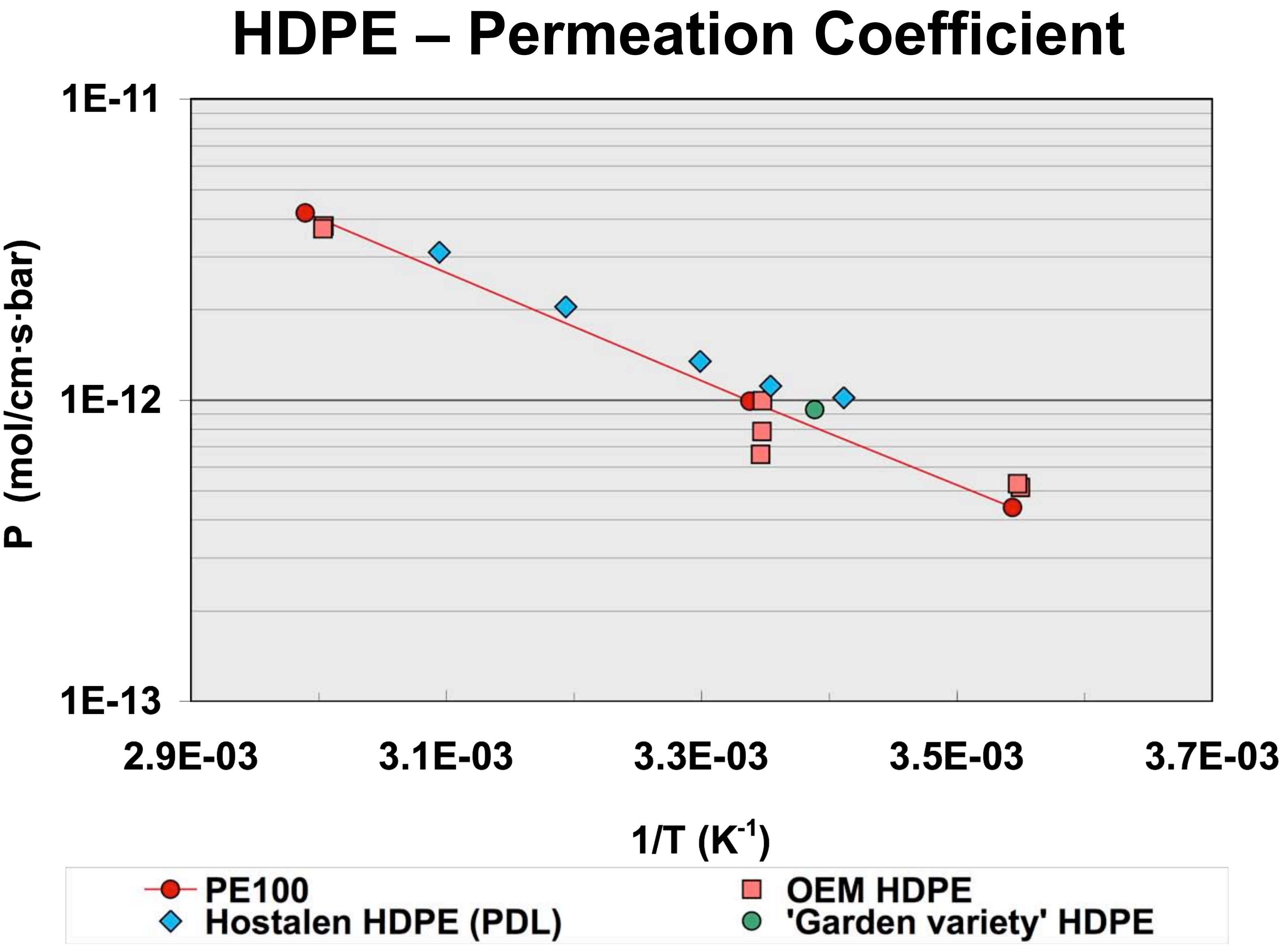
Diffusion and Permeation Measurements

- **Tabulate hydrogen diffusivities and permeabilities of liner materials**
  - **Measure diffusivities and permeabilities in samples of extruded liner materials (*e.g.* PE, HDPE, PEX, PA, PPS, PVDF)**
- **Use this information to propose path forward for liner development**
  - **Evaluate applicability of existing modifications and treatments for reducing permeability in liner materials**
  - **Use the RD&D Plan, H2A model and other resources to quantify acceptable leak specifications**

Diffusion and Permeation Measurements

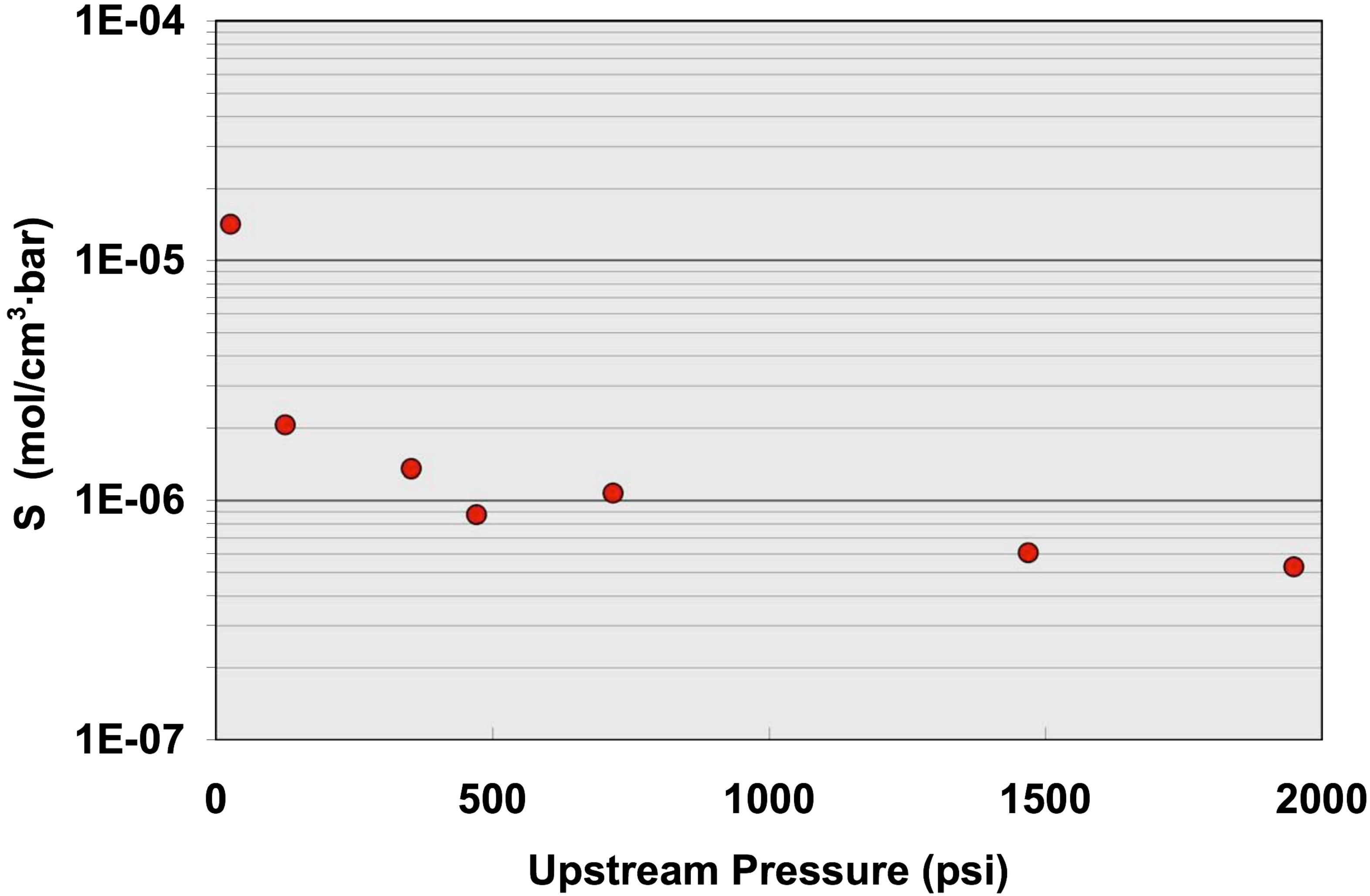


Diffusion and Permeation Measurements

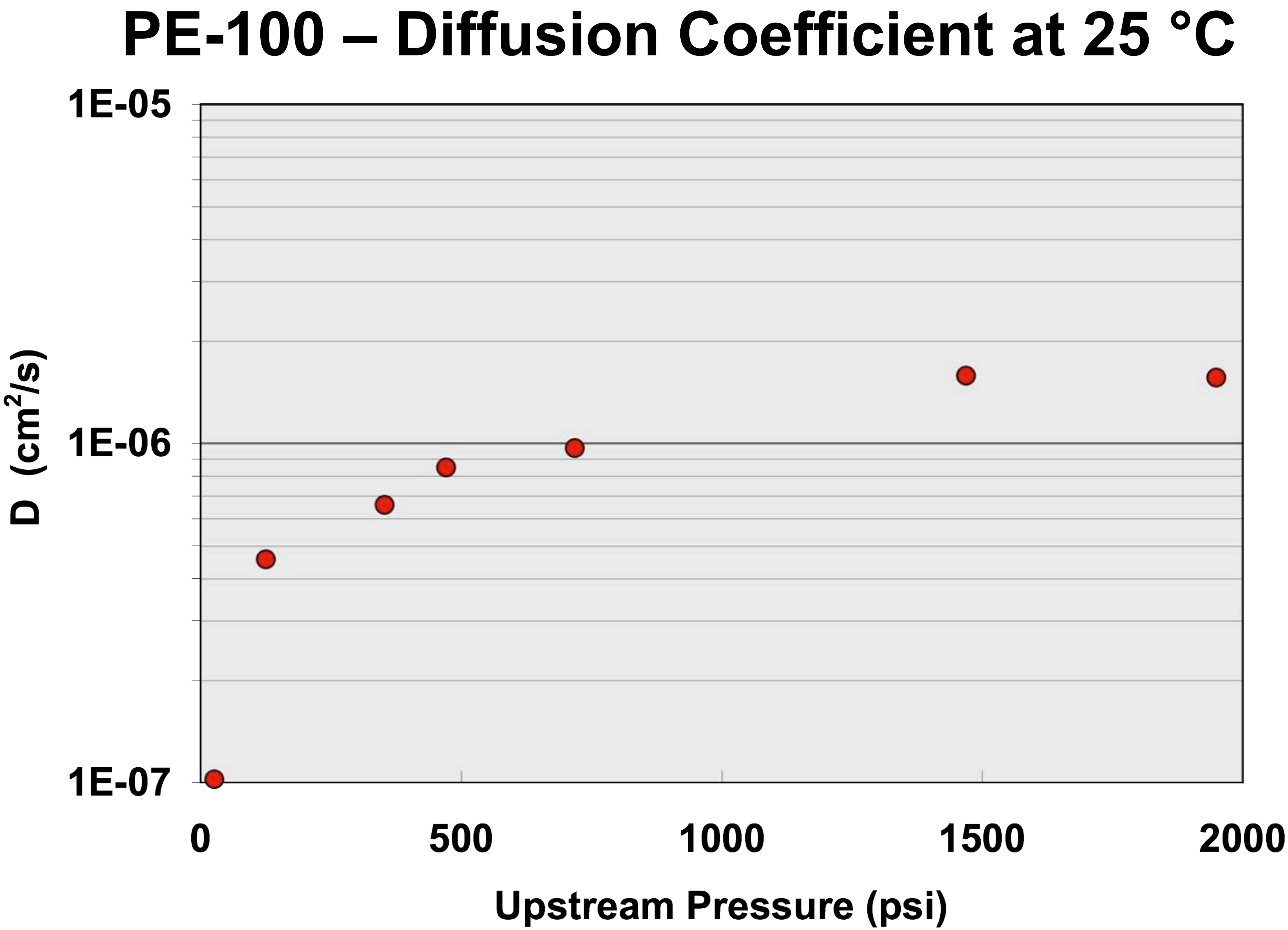


Diffusion and Permeation Measurements

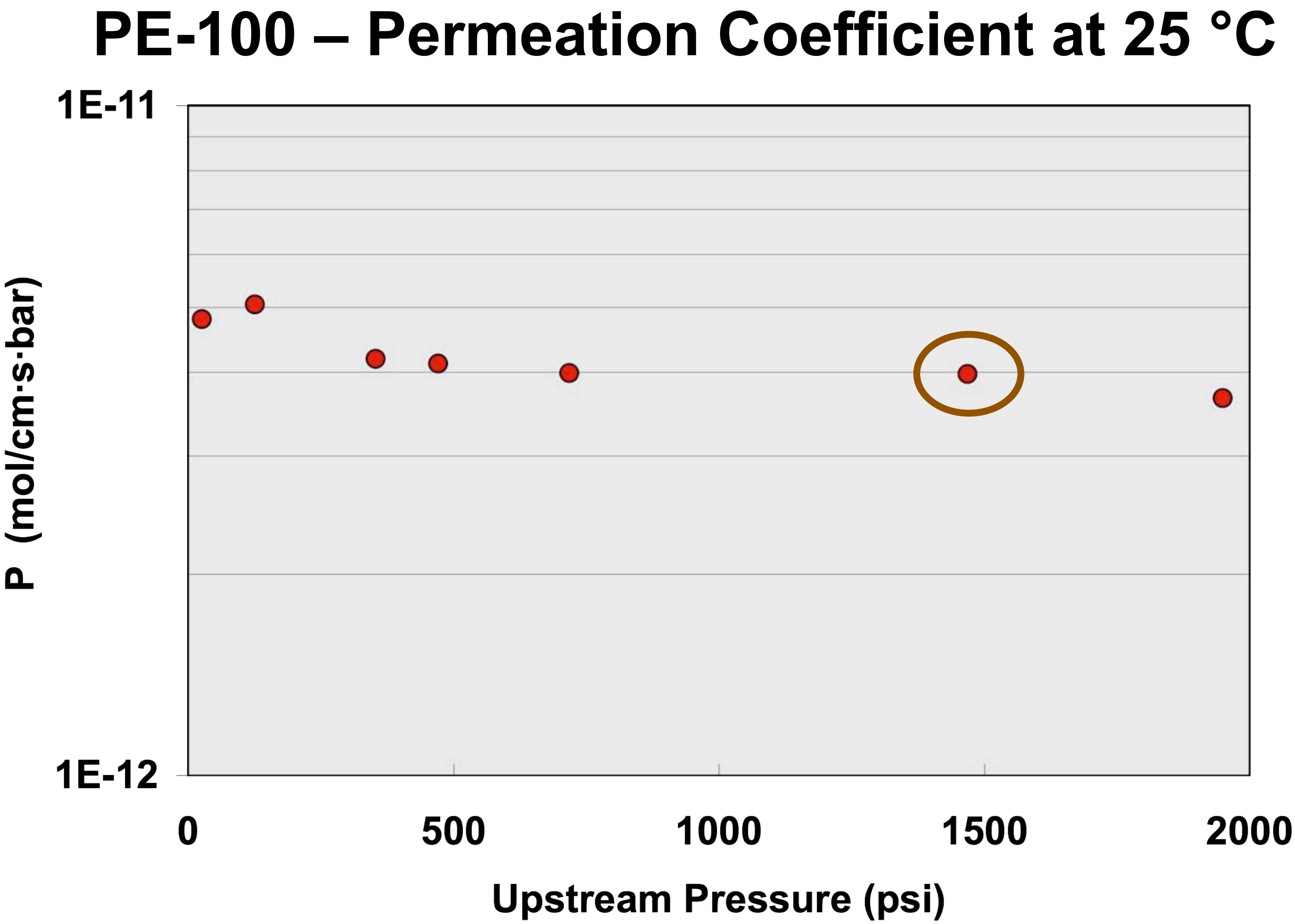
PE-100 – Solubility Coefficient at 25 °C



Diffusion and Permeation Measurements



Diffusion and Permeation Measurements



Predicted H_2 Leak Rate in FRP Pipeline

- **Fiberspar *FS LP 4-1/2 1500* linepipe**
  - PE-3408/PE-100 barrier tube
  - 0.526-cm tube wall thickness
  - 10.1 cm tube ID
- **Hydrogen leak rate through tube wall**

$$\frac{dQ}{dt} = \frac{PA}{l}\left(p_0 - p_1\right)$$

P = permeability coefficient for hydrogen in HDPE,
A = tube's surface area per unit pipeline length,
t = tube wall thickness,
p_0, p_1 = hydrogen pressures inside, outside tube

Predicted H_2 Leak Rate in FRP Pipeline

- **Parameter values**

  P = 4×10^{-12} mol/cm·s·bar at 25 °C and 1500 psi

  A = 3173 cm^2 per meter of pipeline

  l = 0.526 cm

  p_0 = 103 bar

  p_1 = 1 bar

- **Hydrogen leak rate**

  dQ/dt = 2.5×10^{-6} mol/s per meter of pipeline

  = 5.0×10^{-9} kg/s per meter of pipeline

Leak rate through a 36-in diameter, 0.5-in thick steel pipeline at 25 °C and 5000 psi is ~4×10^{-7} mol/s per meter (about 20 times better than HDPE)

Predicted H_2 Leakage in FRP Pipeline

- **From HDSAM – Daily H_2 delivery per pipeline**

  41,000 kg/d ÷ 4 = 10,250 kg/d = 0.12 kg/s

- **Leakage (loss) due to permeation through pipeline liner**

  5.0×10^{-9} kg/s per meter × 100 km = 5×10^{-4} kg/s

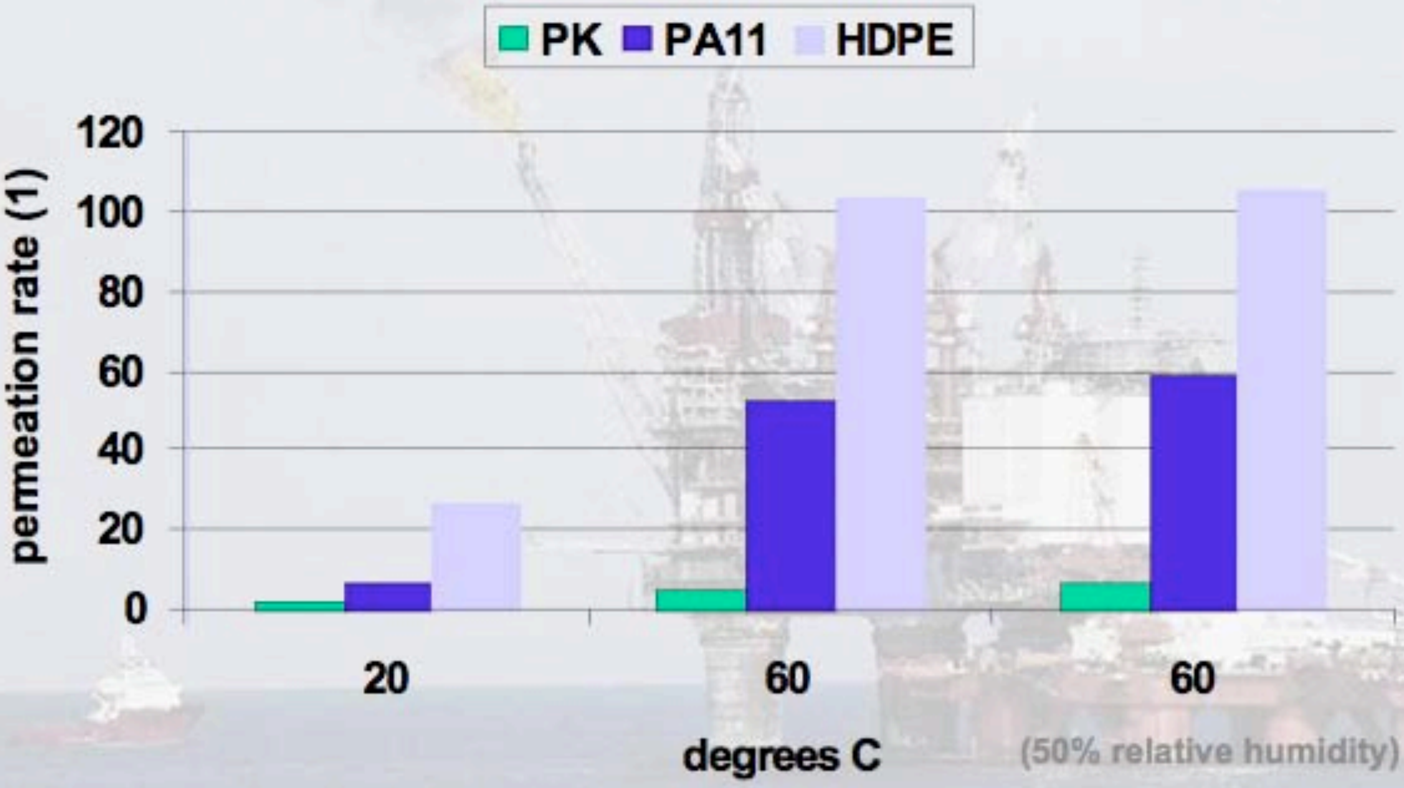
- **Leakage as a percentage of delivery**

  5×10^{-4} / 0.12 × 100% = 0.4%

- **When delivery is high (at or near pipeline capacity) the loss due to pipeline leakage will be low**

CO_2 Permeation

(0%, 50% relative humidity)



(1) units = (10^9 * cm^3 * cm) / (cm^2 * s * bar)

all data measured at independent laboratory

SRNL Support for FRP Piping Project

Progress

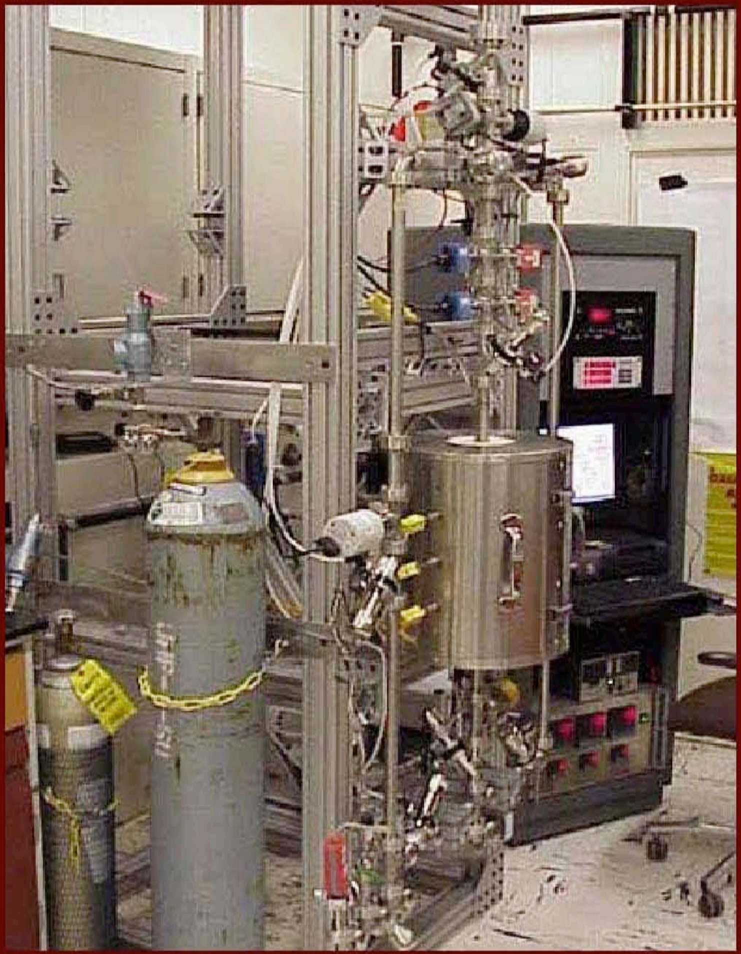
- **FRP Test Protocol Evaluations**
  - **FRP Pipe Fabricated to API 15HR and ASTM D2996 Code**
- **ASTM D2996 Requires:**
  - **D638--**Test Method for Tensile Properties of Plastics
  - **D1598--**Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure
  - **D1599--**Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings
  - **D2105--**Test Method for Longitudinal Tensile Properties of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube
  - **D2143--**Test Method for Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe
  - **D2412--**Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading
- **Fiberspar Tests for Product Quality**
  - **Radius Bend, Compression, Burst**

- **Parallels to Metallic Pipe Test**
  - **Tensile—ASTM E8**
  - **Fracture—K_{IH}, K_{IC}/J_{IC}--ASTM 1821/399/1681**
  - **Fatigue—ASTM E647**
- **Parallels to Composite Vessels**
  - **Burst**
  - **Pressure Cycling**
  - **Drop**
  - **Penetration (gunfire)**

- **Issue is How to Evaluate in Hydrogen and also how to use data for Engineering Design Purposes??**

- **New Tests/Codified Tests for Composite Fiber Reinforced Pipe in Hydrogen??**

SRNL Support for FRP Piping Project
Path Forward FY08



SRNL Hydrogen Permeation Rig

- FY08 Planned Tasks
  - DOT Gap Analysis Report Identifies 4 Major Needs for Composite FRP Piping
    - Lack of Design Specifications
    - Qualified Joints/Joining
    - Permeation
    - Robustness to External Damage
  - SRNL Focus on 2 of these Issues
    - Permeation of Materials of Construction
    - Leak Test of Existing Joint Design
- Permeation of Liner and Resin/Materials
  - Low Pressure < 760Torr
  - Temperature to ≅150°C
- Joint Leak Test
  - Fiberspar—Metal Coupling Design
  - FuturePipe—Flange Joint
  - Bell jar Leak Rate Detection System 10^{-9} cc/sec

Blowdown Testing of Polymer Lined FRP Pipelines

- Guidance: API 15S - Qualification of Spoolable Reinforced Plastic Line Pipe
- Fill specimen with hydrogen to pressure rating, heat specimen to temperature rating, and hold these conditions until pipeline structure is saturated with gas
- Following hold period, de-pressurize specimen at a rate not less than 1000 psi/min
- Examine specimen liner for evidence of blistering or collapse
- FRP pipelines are qualified using CO_2

Questions