# III.5 Composite Technology for Hydrogen Pipelines


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Projected End Date: Project continuation and direction determined annually by DOE

## Objectives

- Investigate the use of composite pipeline technology (i.e., fiber-reinforced polymer [FRP] pipelines) for transmission and distribution of hydrogen, to achieve reduced installation costs, improved reliability and safer operation of hydrogen pipelines.
- Evaluate current composite pipeline liner materials with respect to their performance as a hydrogen barrier; consider the hydrogen permeabilities of the materials to determine the degree of improvement (if any) that is necessary, and propose a path forward based on the available liner materials and modifications or treatments.
- Assess joining methods for composite pipelines.
- Determine integrated sensing and data transmission needs for pipelines to provide health monitoring and operational parameters; report on state-of-the-art in structurally integrated sensing and data transmission.

## Technical Barriers

The project addresses the following technical barriers from the Hydrogen Delivery Section (3.2.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(D) High Capital Cost and Hydrogen Embrittlement of Pipelines

## Technical Targets

The long-term project objective is to achieve commercialization and regulatory acceptance of FRP pipeline technology for hydrogen transmission and distribution. Accordingly, the project tasks address the challenges associated with meeting the DOE hydrogen delivery performance and cost targets for 2017:

- Transmission pipeline total capital cost: \$490K per mile
- Distribution pipeline total capital cost: \$190K per mile
- Hydrogen delivery cost: <\$1.00/gge
- Transmission and delivery reliability: Acceptable for $H_2$ as a major energy carrier
- Hydrogen pipeline leakage: <0.5% (leakage target is currently under review by Delivery Tech Team)

## Accomplishments

- Pipeline materials compatibility testing:
  - Completed short-term hydrogen immersion exposure of FRP pipelines and performed post-immersion qualification testing. Evaluations showed no evidence of hydrogen-induced degradation of the materials or pipeline performance.
  - Completed initial series of pipeline leakage measurements in Fiberspar FRP pipelines. The measured hydrogen leak rate of 0.03% per day is significantly smaller than that predicted using permeation coefficient measurements in liner materials.
  - Completed hydrogen blowdown testing of Fiberspar FRP pipeline specimen. No blistering or delamination visible following rapid depressurization. Pipeline leakage rate was unaffected by the depressurization.
- New contributions to polymer permeation literature:
  - Observed pressure dependence in permeation coefficients for $H_2$ in high-density polyethylene (HDPE).
  - Permeation coefficients for $H_2$ in polyamide and polyphenylene sulfide are smaller than those for HDPE, indicating they might be candidate pipeline liner materials.
- Joining and sensor technologies:
  - Indirect quantification of hydrogen leakage through Fiberspar LinePipe™ connectors showed very low leakage rate ($<3\times10^{-6}$ mol/s per connector).

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## Introduction

Pipelines could be a feasible long-term solution for delivering large quantities of gaseous hydrogen over long distances and distributing it in urban and rural settings. However, there are hydrogen compatibility issues in steel pipelines and the capital costs for pipeline installation must be dramatically reduced. Composite pipeline technology is a promising alternative to low-alloy high-strength steel pipelines from both performance and cost considerations. For instance, FRP pipelines are engineered composite pipelines that are widely used in upstream oil and gas operations and in well interventions. FRP pipelines typically consist of an inner non-permeable liner that transports the fluid (pressurized gas or liquid), a protective layer applied to the liner, an interface layer between the protective layer and the reinforcement layers, multiple glass or carbon fiber reinforcement layers, an outer pressure barrier layer, and an outer protective layer. The pipeline has large burst and collapse pressure ratings, high tensile and compression strengths, and tolerates large longitudinal and hoop strains. Thousands of feet of continuous pipe can be unspooled and trenched as a seamless entity, and adjoining segments of pipeline can be joined in the trench without welding using simple connection techniques. The emplacement requirements for FRP pipelines are dramatically less than those for metal pipe; installation can be done in narrower trenches using light-duty, earth-moving equipment. This enables the pipe to be installed in areas where right-of-way restrictions are severe. In addition, FRP pipe can be manufactured with fiber optics, electrical signal wires, power cables or capillary tubes integrated within its layered construction. Sensors embedded in the pipeline can be powered from remote locations and real-time data from the sensors can be returned through fiber optics or wires. This allows the pipeline to be operated as a smart structure, providing the unique advantage of lifetime performance and health monitoring.

## Approach

The challenges for adapting FRP pipeline technology to hydrogen service consist of evaluating the constituent materials and composite construction for hydrogen compatibility, identifying the advantages and challenges of the various manufacturing methods, identifying polymeric liners with acceptably low hydrogen permeability, critiquing options for pipeline joining technologies, ascertaining the necessary modifications to existing codes and standards to validate the safe and reliable implementation of the pipeline, and determining requirements for structural health monitoring and embedded real-time measurements of gas temperature, pressure, flow rate, and pipeline permeation.

These challenges are being addressed by performing bench-scale tests of FRP pipelines and constituent materials to determine their long-time compatibility with hydrogen, identifying pipeline liner materials that exhibit good performance in hydrogen environments, evaluating current methods for pipeline joining with consideration of the unique requirements for hydrogen service, and assessing the state-of-the-art in integrated sensing technologies for composite structures.

## Results

During the previous year we devised a rudimentary method to screen for hydrogen-induced damage in FRP pipelines and their constituent materials. The method involved immersion of FRP pipeline specimens in high-pressure (1,000 psi) hydrogen at elevated temperatures (140°F) to achieve accelerated aging conditions. Specimens of fiberglass rovings, resin matrix and liner materials were immersed simultaneously with the linepipe specimens, and all specimens were subjected to either a short- or a medium-length exposure in this environment. Following exposure, the pipeline specimens were evaluated for degradation using hydrostatic burst pressure tests to assess the overall integrity of the structure, compression tests to assess the integrity of the polymer matrix, and bend testing to assess the integrity of the laminate. Tensile tests and dynamic mechanical analysis were performed on the constituent materials.

Our results from the one-month (short) exposure showed that there were no statistically significant differences between the test results of off-the-shelf and hydrogen-aged pipeline specimens and materials. The evaluation of the medium-duration exposure was not complete at the time this progress report was submitted.

We measured the hydrogen leak rate in two short sections of Fiberspar FRP pipeline to assess how well the pipeline contains high-pressure hydrogen gas. The measurements were done on off-the-shelf 10-cm internal diameter pipelines. The liner was 0.526-cm-thick pipeline grade HDPE (PE-3408). The hydrogen pressurization in the pipelines was 1,500 psi (99 bar) (the pipeline pressure rating) and all measurements were done at ambient lab temperature. The pipeline was capped on each end using modified Fiberspar LinePipe™ connectors with elastomer seals. The leak rate was calculated from the pressure decay curve. We corrected the pressure for temperature-induced changes using the Abel-Noble equation of state. We ignored the changes in volume that occurred due to pressure-induced dimensional changes in the pipeline length and circumference because it was expected to be <0.01% per psi near 1,500 psia.

The predicted hydrogen leak rate per meter of liner is given by

$$\frac{dn}{dt} = \frac{2\pi P}{\ln(b/a)}\left(p_0 - p_1\right) \qquad \text{mol/s}\cdot\text{m}$$

where $P$ is the permeation coefficient for hydrogen in PE-3408, $a$=5.05 cm and $b$=5.576 cm are the inner and outer radii of the liner tube, and $p_0$=99 bar and $p_1$=1 bar are the hydrogen pressures inside and outside the liner. In an earlier measurement we found that $P \approx 4\times10^{-12}$ mol/cm·s·bar.

The predicted leak rate for a 1.8-meter long pipeline is $-1.7\times10^{-2}$ mol $H_2$/h, assuming the leak rate from the steel end caps seals is negligible compared to the leakage through the polymer liner.

The results of our measurement on a 1.8-meter-long pipeline are shown in Figure 1. After allowing a couple of days for the pipeline to stabilize and adjust to the pressurization, we observed that the pressure decay curve was nearly linear. From the decay curve we determined that the pipeline was leaking approximately $-7\times10^{-4}$ mol $H_2$/h during the 10 day-long test. The loss of stored hydrogen was 0.03% $H_2$ per day. Thus the measured leak rate was 1/24$^{th}$ the predicted leak rate, indicating that the HDPE liner is very good at containing hydrogen under these conditions. The result of our leak rate measurement on a 1-meter length of pipeline was consistent with this result.

We performed a hydrogen blowdown test on the 1-meter FRP pipeline specimen. We used the procedure in Appendix D of American Petroleum Institute (API) Standard 15S to perform the test. We pressurized the specimen with hydrogen to its 1,500-psi maximum pressure rating, heated the specimen to its 140°F temperature rating, and held it at these conditions until the pipeline liner was saturated with hydrogen gas. Following this hold period, we depressurized the specimen at the prescribed rate of 1,000 psi/min. Following the depressurization, we disassembled the end caps from the specimen and examined the liner for evidence of blistering, collapse or delamination. There was no visually apparent damage to the liner. We then reinstalled the end caps and performed a leak rate measurement on the specimen. The result of the leak rate measurement was identical to the result obtained before blowdown testing, indicating that the blowdown procedure had no harmful effect on the ability of the liner to contain hydrogen.

We are producing a compendium of hydrogen permeability coefficients for the polymers being used as liners in composites-based hydrogen-storage structures (i.e., pipelines and high-pressure tanks) and are using this information to determine suitable liner materials for composite hydrogen pipelines. The hydrogen permeability of the polymer liners is a primary indicator of the potential leakage of hydrogen from composite pipelines. Figure 2 shows the results of some of our permeation coefficient measurements on pipeline and tank liner HDPE and pipeline polyphenylene sulfide (PPS). The variation among coefficients for pipeline, tank and generic HDPE is very small. The PPS sample tested had $P$ values that were about 2.5 times lower than those for HDPE. Also included on the graph for comparison are some $P$ values for the polyamide used in the Air Liquide high-pressure hydrogen storage tank. We observed a slight pressure dependence in the permeation coefficients for HDPE (Figure 3).

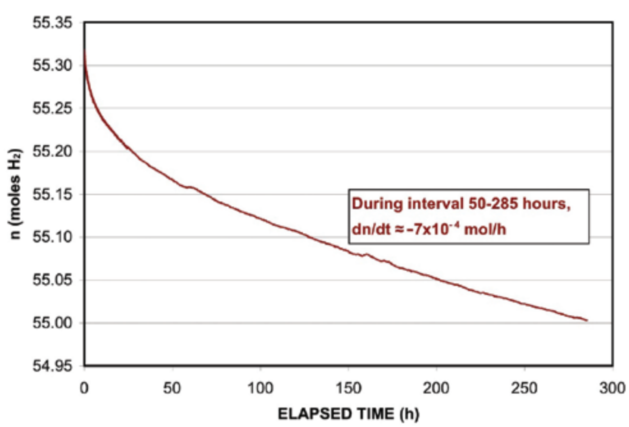


**FIGURE 1.** Pressure decay curve obtained during a hydrogen leak rate measurement on a 1.8-meter long, 10-cm diameter FRP pipeline. The measured leak rate of $-7 \times 10^{-4}$ mol/h was about 24 times less than that predicted using the permeation coefficient for the pipeline liner material.

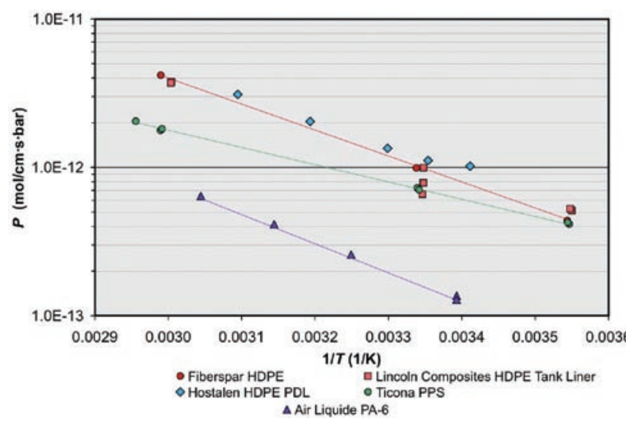


**FIGURE 2.** Hydrogen permeation coefficients $P$ from measurements in several polymers, plotted to show the Arrhenius relationship between $P$ and the temperature. The permeation coefficients for pipeline grade HDPE (Fiberspar), tank liner HDPE (Lincoln Composites), and Hostalen-process HDPE (Plastics Design Library) are similar. PPS (Ticona Fortron) is a better hydrogen barrier. Also shown for comparison are coefficients for tank liner PA-6 (from Weber *et al.*).

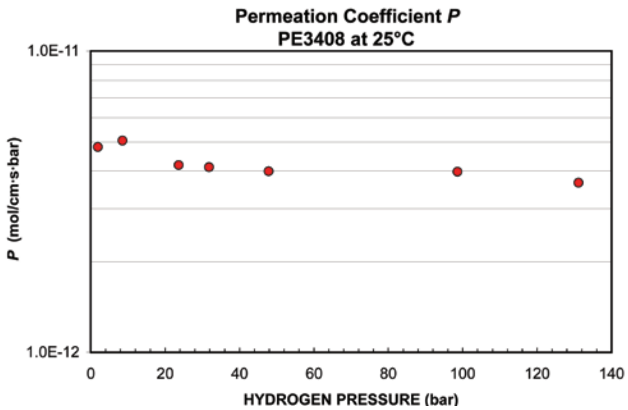


**FIGURE 3.** Hydrogen permeation coefficients in pipeline grade HDPE, plotted as a function of applied hydrogen pressure.

## Conclusions and Future Directions

- No observed hydrogen incompatibility in composite pipeline materials after accelerated aging testing.
- Hydrogen leakage rates in off-the-shelf FRP pipelines are much better than expected.
- Hydrogen blowdown testing in Fiberspar pipelines showed no deleterious effects on liner integrity or adhesion to reinforcement layers.
- We expect to begin the next phase of hydrogen compatibility testing by evaluating composite pipelines for environment- and strain-induced hydrogen deterioration.
  - Objective: Verify that the combinations of hydrogen environment-and-stress do not adversely affect composite pipeline integrity and service life.
- Perform long-term stress rupture tests and high-pressure cyclic fatigue tests:
  - Stress rupture testing is the API prescription for qualifying the pressure rating of the pipeline.
  - High-pressure cyclic fatigue tests provide information on pipeline integrity after repeated hydrogen gas pressurization-depressurization cycles.
  - Fatigue tests provide information that can't be derived from constant pressure testing, including liner collapse resistance (similar to blowdown testing), resistance to micro-cracking, crazing, crack propagation, fiber-resin interface failure of composite reinforcement layer, resistance to environmental stress-corrosion phenomena.
- Assess the integrity of joint attachment/joint sealing under cyclic loading.
- Out-year plans: Evaluate feasibility of large-scale manufacturing operations, plan prototype manufacturing for a demonstration project, manufacture prototype FRP pipeline for hydrogen service, coordinate commercial demonstration of pipeline technology.

## FY 2008 Publications/Presentations

**1.** 2008 DOE Hydrogen Program Annual Merit Review – Arlington, Virginia – June 11, 2008. Presentation PD19.

## References

**1.** HFCIT MYRDD Plan, Table 3.2.2, page 3.2-13, and footnote *b*, page 3.2-16.

**2.** API Recommended Practice 15S, "Qualification of Spoolable Reinforced Plastic Line Pipe-Appendix D-Blowdown Test Procedure," March 2006.

**3.** Permeability & Other Film Properties of Plastics and Elastomers, Plastics Design Library Staff, (William Andrew Publishing, Morris, NY) 1995.

**4.** M Weber, S Colom, R Reneault, and T Vinard, "Assessment of hydrogen permeation through polymer materials used in composite hydrogen storage tank," presented at the World Hydrogen Energy Conference, Brisbane, Australia, June 16, 2008.