III.E.3 Fiber-Reinforced Polymer Pipelines for Hydrogen Delivery

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

Objectives

- Investigate the use of fiber-reinforced polymer (FRP) pipeline technology for transmission and distribution of hydrogen, to achieve reduced installation costs, improved reliability and safer operation of hydrogen pipelines.
- Evaluate current FRP 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 FRP 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 (HFCIT) 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%

Accomplishments

Work on this project restarted in November 2006 after being inactive in FY 2006 due to budgetary constraints in the Hydrogen Program. In the six months that the project has been restarted, we have made the following progress toward meeting the project milestones:

- Used the recently released H2A Hydrogen Delivery Scenario Analysis Model and industry estimates to predict the cost for a hypothetical hydrogen transmission pipeline and showed that total capital investment for FRP pipeline could achieve the 2012 cost target and is only 20% above the 2017 cost target.
- Designed procedures to screen hydrogen compatibility of FRP pipelines and constituent materials and began fabricating test facilities for the screening.
- Continued hydrogen permeability measurements of pipeline liner materials to assess ability of liners to meet technical target for pipeline leakage.

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Introduction

Pipelines are at present the most feasible option for delivering large quantities of gaseous hydrogen over long distances and distributing it in urban scenarios. However, the existing steel and un-reinforced plastic pipeline technologies cannot be extrapolated to provide pipelines that achieve the cost and performance goals required for hydrogen delivery.

FRP pipeline technology is a promising alternative to low-alloy, high-strength steel pipelines from both performance and cost considerations. FRP pipeline is typically constructed as an inner non-permeable barrier tube, or liner, that transports the fluid (pressurized gas or liquid), a protective layer over the liner, an interface layer over the protective layer, multiple glass or carbon fiber composite layers, an outer pressure barrier layer, and an outer protective layer. The pipeline has improved burst and collapse pressure ratings, increased tensile strength, compression strength, and load carrying capacity, compared to non-reinforced plastic pipelines. FRP pipelines can tolerate large longitudinal strains, allowing it to be spooled onto large-diameter reels for transportation from factory to installation site. 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 using simple connection techniques. The requirements to emplace FRP pipelines are dramatically less than those for metal pipe; installation can be done in a narrower trench using light-duty, earth-moving equipment. This enables the pipe to be installed in areas where right-of-way (ROW) 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, measuring permeabilities in pipeline liner materials, 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

Materials costs for FRP pipelines are sometimes cited as an obstacle to their use for gas pipeline transmission. Therefore, it is instructive to estimate the capital investment required to install a hypothetical FRP hydrogen pipeline to transmit hydrogen from a central production facility to an urban population. This estimate allows us to compare today's FRP pipeline capitalization cost with the capital cost target for transmission pipelines. We used the Hydrogen Delivery Scenario Analysis Model (HDSAM) [1] to calculate pipeline delivery parameters (peak demand, pipeline diameter, number of pipelines) based on service to urban populations of 200,000 and 1,000,000 people. For the demand calculations, we specified a 50% market penetration of light-duty hydrogen fuel cell vehicles in these urban areas. The pipeline length was specified as the default distance from centralized production to distribution terminal, 62 mi (100 km). The inlet and outlet pressures were the default values of 1,000 and 700 psi (6.9 and 4.8 MPa), respectively. At present, the largest diameter available in a commercial FRP pipeline is a 4.5-inch inside diameter (ID) in a 1,500 psi rated, high density polyethylene (HDPE)-lined product, so we modified the *Panhandle B* equation in the H2 Pipeline worksheet to force it to specify the number of 4.5-inch ID pipelines needed to service the two populations. Table 1 shows the delivery parameters calculated using HDSAM.

TABLE 1. Calculation of Pipeline Quantity and Size for Hypothetical Transmission Pipeline

Urban population	200,000	1,000,000
Peak H_2 demand (kg/d)	58,600	293,000
Daily H_2 demand (kg/d)	41,000	205,000
4.5-inch ID pipelines required	4	17
ID required for a single pipeline (inches)	7.25	13.75

Materials and installation costs for a 4.5-inch ID, 1,500 psi-rated FRP pipeline (pipeline, connectors, transportation, and installation) are approximately $80K per mile. The installation of four 4.5-inch ID pipelines would thus require an investment of $331K to $346K per mile, excluding ROW and permitting costs and assuming the trenching costs are in the range $10.6K to $26.4K per mile. Table 2 shows our estimation of the capital investment that would be required to install four 4.5-inch ID FRP pipelines to service an urban population of 200,000 people.

TABLE 2. Capital Investment Required for Various Components of a Hypothetical Hydrogen Pipeline Serving an Urban Population of 200,000

	$K/mi
FRP Pipeline, Materials & Installation	331–346
Estimated ROW & Permitting	250
Total Capital Investment	**581–596**
2012 Capital Cost Target	**600**
2017 Capital Cost Target	**490**
Total Capital Investment for 16-in Steel Pipeline (2005)	636

The total capital investment for the FRP hydrogen pipeline, using today's cost figures, would be just under $600k per mile. This is below the 2012 technical target and approximately 20% above the 2017 technical target. In comparison, the HFCIT Technical Plan [2] estimates the capital investment for a 16-inch steel pipeline at approximately $636K per mile. FRP pipelines show promise toward meeting the cost targets.

Several polymeric materials such as polyethylene (PE), polyamide (PA) and polyvinylidene difluoride (PVDF) have been approved for use as liners in FRP pipelines. The permeability of the polymers to hydrogen will determine the leak rate of hydrogen from the pipeline. Most published measurements of hydrogen permeabilities in these polymers are for cast film samples [3] and the values might not be applicable for extruded/blown liners or for containment of high-pressure hydrogen. As part of our test matrix we measured the permeability of extruded HDPE at temperatures in the range 10 to 60°C and compared the permeability coefficients to published values for HDPE films. Figure 1 shows the results of the measurements. PE 100 was a sample of pipeline-grade HDPE and original equipment manufacturer (OEM) HDPE was a sample of the liner from a high-pressure hydrogen storage tank. Hostalen HDPE values are from the Plastics Design Handbook [4]. The permeability of cast film samples of HDPE appears to be slightly greater than that of extruded HDPE samples at all temperatures. These permeation measurements allow us to predict very low loss (less than 0.1% of the delivery quantity) from FRP pipelines lined with HDPE.

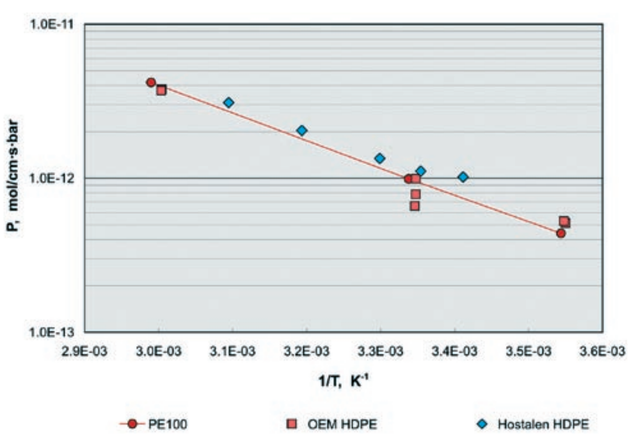

FIGURE 1. Permeability *P* of HDPE polymers, measured in a diffusion/permeation test facility at ORNL and obtained from the Plastics Design Library. The temperature dependence of the permeability is evident in this Arrhenius-type plot.

FRP pipelines intended for oilfield flowline applications, including transport of hydrocarbon gases, are qualified by numerous American Petroleum Institute and American Society for Testing and Materials standards and recommended practices. The qualification of the pipeline for hydrogen service will require similar guidelines for their design, manufacture and application. ORNL, Fiberspar LinePipe and Savannah River National Laboratory have devised an initial screening procedure to assess the effects of hydrogen exposure on samples of FRP pipeline manufactured by Fiberspar. The procedure consists of immersing the samples in high-pressure hydrogen and subjecting them to elevated temperatures to provide accelerated aging conditions. These tests are underway at the time of this report. Following exposure, the samples will be evaluated using standard FRP pipeline qualification procedures such as hydrostatic burst pressure tests, compression tests, bend tests and blowdown tests to detect gross structural degradation.

Conclusions and Future Directions

- Estimated capital investment for installing a hypothetical FRP pipeline is comparable to the 2012 cost target. Materials and installation costs show promise of meeting 2017 cost target.
- Some approved polymeric liner materials have low hydrogen permeabilities and the calculated leak rates are low (below 0.1% loss of delivered hydrogen).
- Screening procedure to uncover possible hydrogen-damage mechanisms in FRP pipeline specimens is underway.
- Permeation measurements in FRP pipeline specimens will be performed next year.
- Bench-scale tests of integrated sensor performance in short sections of FRP pipeline will be performed next year.
- Hydrogen blowdown tests to evaluate reinforcing layer blistering or delamination and liner collapse or delamination will be performed next year.
- 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 2007 Publications/Presentations

1. Barton Smith, Barbara Frame, Cliff Eberle, Larry Anovitz, Tim Armstrong, Chris Makselon (Fiberspar LinePipe, LLC) and Thad Adams (SRNL), "Fiber-Reinforced Polymer Pipelines for Hydrogen Delivery," presented at the National Hydrogen Association Annual Conference, March 21, 2007, San Antonio, Texas.

References

1. HDSAM, version 1.0, available at www.hydrogen.energy.gov/h2a_analysis.html. In HDSAM, the user defines a scenario by selecting an urban or rural interstate market type, specifying the population size, estimating the market penetration of light-duty hydrogen-fueled vehicles in the market, and then selecting a delivery mode.

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

3. See "Standard Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting," ASTM D 1434 – 82 (2003), ASTM International, West Conshohocken, PA.

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