III.10 Composite Technology for Hydrogen Pipelines

Barton Smith (Primary Contact), Barbara J. Frame and Lawrence M. Anovitz
Oak Ridge National Laboratory (ORNL)
P. O. Box 2008
Oak Ridge, TN 37831
Phone: (865) 574-2196
Email: smithdb@ornl.gov

DOE Manager
HQ: Sara Dillich
Phone: (202) 586-7925
Email: Sara.Dillich@ee.doe.gov

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Fiscal Year (FY) 2012 Objectives

- Complete high-pressure cyclic fatigue tests to verify that a combination of H_2 environment and stress does not adversely affect composite pipeline integrity and service life.
- Identify the requisite data, provide data, and contribute to the codification of hydrogen composite pipelines, in collaboration with Savannah River National Laboratory (SRNL), American Society of Mechanical Engineers (ASME), et al.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies (FCT)Program Multi-Year Research, Development and Demonstration Plan [1]:

(D) High Capital Cost and Hydrogen Embrittlement of Pipelines

Technical Targets

The long-term project objective is to achieve commercialization and regulatory acceptance of fiber-reinforced polymer (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 [2]:

- Transmission pipeline total capital cost: $735k per mile (2015), $710k per mile (2020)
- Hydrogen delivery cost: <$2.00/gge by 2020
- Transmission and delivery reliability: Acceptable for H_2 as a major energy carrier
- Hydrogen pipeline leakage: < 80 kg/mi/y (2020)

FY 2012 Accomplishments

- Completed cyclic fatigue testing on FRP pipeline specimen using H_2 pressurizations to maximum allowable working pressure (MAWP) – Test results 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) and 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.

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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

We performed a cyclic fatigue test on an FRP pipeline specimen using high-pressure H_2 to assess the effect of the combination of H_2 environment and pressure-induced fatigue on pipeline integrity and service life. Fatigue testing via gas pressurization-depressurization cycling will provide information valuable for codification of composite reinforced polymer pipelines for hydrogen service. The pipeline specimen was a 4-ft-long Fiberspar LPJ 2.5-inch inside diameter (ID) 1,500(E) LinePipe™, with the open ends capped with Fiberspar steel joint connectors. A series of three viton o-rings in each connector served to pressure-seal the connector end cap to the high-density polyethylene (HDPE) liner (gas barrier) in the pipeline. We affixed strain gages at multiple locations along the pipeline length to record hoop-direction strains during the pressurization-depressurization cycles. Before beginning the pressure cycling we performed three temperature cycles between room temperature and 60°C, at 1,500 psig H_2 pressurization, which is the specified MAWP for the pipeline. Immediately following the temperature cycling, which conditioned the pipeline and saturated the liner and reinforcement layers with H_2, we performed 50-plus pressurization cycles (500-1,500 psig) at room temperature. When the pressure cycling was completed we raised the pipeline temperature to 60°C and subjected the pipeline to a pressure blowdown test from 1,500 psig to atmospheric pressure ($\Delta p/\Delta t$ >6,000 psi/min). We then performed a pressure-decay leak measurement and inspected the liner for blistering or delamination. The pressure-decay leak measurement was supplemented with a leak measurement using a thermal conductivity-type gas leak detector with H_2 sensitivity ~1×10^{-5} cc/s. No increase in leak rate attributable to the cyclic fatigue test was detected and there was no visible damage to the liner. Following leak testing, the pipeline specimen was shipped to Fiberspar for standard quality assurance testing to verify performance of the product against new, unused product. These quality assurance tests revealed that the pipe retained performance that was indistinguishable from that of newly manufactured pipe.

At the recommendation of the FCT Program Delivery Tech Team, we updated our capital cost estimate for installation of an FRP hydrogen pipeline. We used the H2A Delivery Scenario Analysis Model, version 2.3.1, to guide us in the determination of pipeline parameters. We assumed a pipeline transmission distance of 300 miles and hydrogen inlet and outlet pressures of 1,000 psia (69 bar) and 700 psia (48 bar), respectively (no compressor substations). The peak hydrogen flow rate was specified as 135,000 kg/day, and a calculation using the Panhandle B pipeline equation predicted that four 4.5-inch ID FRP pipelines with HDPE liners would provide a flow rate equivalent to one 8-inch ID steel pipeline. The pipeline flow efficiencies used in Panhandle B were 0.92 for steel and 0.98 for HDPE. To calculate costs we used the current pricing sheet for Fiberspar's 4.52-inch ID, 1,500 psi rated, HDPE-lined FRP linepipe, with 316 stainless steel connectors at 2,100-foot intervals, and factored in a mean labor cost of $5 per foot for trenching and installation. The material cost for four 300-mile-long pipelines with connectors was estimated at $138M, and the trenching and installation cost was estimated at $32M. We did not include an estimate for inspection and testing–requirements which are undefined at present. The total material and labor cost is then $170M, for a total capital investment of approximately $570,000 per mile, excluding permitting and right-of-way costs.

Table 1 compares this estimate with those of our earlier (2007) cost estimate for FRP hydrogen pipelines, the cost estimate for an 8-inch-diameter natural gas pipeline, and the 2020 cost target for a hydrogen transmission pipeline. Our earlier cost estimation was about 40% lower than the present estimate because in it we did not allow for the cost of stainless steel connectors and because the present estimate reflects a slight increase in the cost of raw materials used in the pipelines. The present cost estimate is about 25% lower than that for the equivalent steel pipeline and is about 20%

TABLE 1. Estimates for total capital investment for hydrogen pipelines compared with 2020 cost target technical and an estimate for hydrogen loss from FRP pipelines compared with 2020 technical 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 [3]	765,000 [4]	570,000	710,000 [2]
H_2 leakage, in kg H_2/mile/y			<60 [5] (<0.1%) [6]	<780 [2] (<0.5%) [6]

ROW - right of way

[2] Fuel Cells Technology Program Multi-Year Research, Development and Demonstration Plan–Hydrogen Delivery, Table 3.2.3, Technical Targets for Hydrogen Delivery Components (2012, draft).

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

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

[5] 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.

[6] Leakage expressed as a percentage of total hydrogen transmitted; 2020 target from Table 3.2.2 Technical Targets for Hydrogen Delivery, in Fuel Cells Technology Program Multi-Year Research, Development and Demonstration Plan–Hydrogen Delivery, October 2007.

below the 2020 cost target. In addition, our calculation of the anticipated loss due to permeation through the pipeline wall and leakage through the o-rings at the connectors is 13 times smaller than the technical target.

Conclusions and Future Directions

Conclusions from this year's work:

- Initial cyclic fatigue testing on FRP pipeline specimens using H_2 pressurizations showed that a combination of H_2 environment and pressure-induced stress does not measurably affect pipeline integrity and service life.
- Our estimate for total capital investment for pipeline emplacement–based on current pricing for commercially available FRP pipelines and realistic pipeline operational parameters–indicates that FRP polymer pipelines could meet the FCT Program's 2020 cost and leakage targets for a transmission pipeline.

Respecting the very limited amount of funding that might be available in the next project year, we intend to focus our efforts on outlining a concrete research plan for providing the data required to close the knowledge gap between the work done and work that needs to be done to qualify composite pipelines for H_2 service. These knowledge gaps, which are in effect the barriers to technology adoption through codification, are:

- Processes by which testing procedures can be directed and coordinated to provide the requisite performance data for H_2 pipeline codes and standards.
- Test data on fatigue due to cyclic pressurization during H_2 service.
- Test data from studies done to assess environmental effects on FRP pipeline systems in hydrogen service (all H_2 evaluations to date have been done in lab settings):
  - Tests conducted with and without water exposure
  - Tests conducted on potential impacts of geotechnical phenomena
  - Tests conducted with real third-party damage
  - Microanalysis and chemical analysis to determine effects of environment on pipeline structure
  - Hydrogen delivery "test loop" that includes all the delivery infrastructure relevant to full pipeline emplacement and operation (i.e., a few miles of pipeline with fittings, compressors, etc., in varying terrains and environments)
  - Harmonization of results obtained in the lab and in field installation
- Identification of gas purity requirements and pipeline gas purity data.
- Expanded knowledge of H_2 performance in commercial products—testing to date focused mainly on FRP pipeline products offered by two domestic manufacturers.

FY 2012 Publications/Presentations

1. 2012 DOE Hydrogen Program Annual Merit Review, Arlington, Virginia, May 17, 2012, presentation PD024.

2. Keynote address on "Commercial Deployment of FRP Hydrogen Pipelines," presented at Composite Conference 2012, August 13–17, 2012, Las Cruces, NM.

References

1. Fuel Cells Technology Program Multi-Year Research, Development and Demonstration Plan–Hydrogen Delivery, page 3.2-19 (2007).