III.A.2 FRP Hydrogen Pipelines

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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, considering the hydrogen permeabilities of the liner materials to determine the degree of improvement (if any) that is necessary, and proposing a path forward that is based on the available liner materials and modifications or treatments.

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

This purpose of this project is to develop fiber-reinforced polymer technology and engineered plastics for constructing high-pressure pipelines for hydrogen transmission and distribution. These materials will provide major performance improvements and cost reductions in pipeline construction, compared to high-strength, low-alloy steels. The long-term objective is commercialization of non-metallic pipeline technology that attains the DOE hydrogen delivery performance and cost targets for 2015:

- Transmission pipeline total capital cost: \$800K per mile
- Distribution pipeline total capital cost: \$200K per mile
- Hydrogen delivery cost: $<$ \$1.00/gge
- Transmission and delivery reliability: high, with metrics to be determined
- Hydrogen pipeline leakage: $<$ 0.5%

Accomplishments

- This project was not funded in FY 2006 due to budgetary constraints in the Hydrogen Program, hence there is no significant technical progress to report for this year. In the initial project year, we had the following significant accomplishments.
- We completed an assessment of the capital cost for FRP pipeline delivery of hydrogen from production centers to population centers, using existing commercially available pipeline technology, and reported a cost estimate that is below DOE 2015 target.
- We synthesized a sample of modified PET (polymeric nanocomposite) with an organo-modified clay additive and demonstrated a 60% decrease in hydrogen permeability, compared to pure PET.

Introduction

Gas pipelines are at present the most feasible option for transmitting large quantities of hydrogen over long distances, and pipeline transmission is expected to be the means by which hydrogen is delivered from future large-scale, centralized production plants and distributed to fueling stations. However, the existing hydrogen pipeline technology cannot be applied to achieve the cost and performance goals required for successful implementation of this distribution network.

Fiber-reinforced polymer (FRP) pipelines are emerging as a feasible alternative to steel pipelines with regard to performance and cost. An FRP pipeline is typically constructed as an inner non-permeable barrier tube that transports the fluid (pressurized gas or liquid), a protective layer over the barrier tube, an interface layer over the protective layer, multiple glass or carbon fiber composite layers, an outer pressure barrier layer, and an outer protective layer. An FRP pipeline is a composite structure in the purest engineering sense of the term, as each of the several components provides a distinct function and the interaction between the components produces a structure with exceptional performance characteristics. The pipeline has improved burst and collapse pressure ratings, increased tensile strength, compression strength, and load carrying capacity, compared to non-reinforced, non-metallic pipelines. The ability of FRP piping to withstand large strains allows it to be coiled so long lengths can be spooled onto a reel in an open bore configuration. Spoolable FRP piping is gaining acceptance as the technology of choice for flowline installation from oil and gas wells, remediating existing (steel) flowlines, and functioning as a flexible drill pipe. Approximately one mile of continuous pipe can be spooled and later emplaced as a seamless monolith, and connection techniques for pipe segments are simple enough that they can be done in the field at the time of installation. The requirements for emplacement of FRP pipe are dramatically less than that for metal pipe; installation can be done in a narrow trench 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, copper signal wires, power cables or capillary tubes installed directly into the structural wall of the piping. This offers the option of manufacturing the pipe with embedded sensors and operating it as a so-called smart structure. Sensors embedded in the pipe can be powered via copper wire from remote locations and real-time data from the sensors can be returned through fiber optics. This provides the unique advantage of lifetime performance monitoring of the pipe.

Approach

The challenge for adapting FRP pipeline technology to hydrogen service consists of evaluating the pipeline materials for hydrogen compatibility, developing methods for manufacturing large-diameter pipelines, developing a plastic liner with acceptably low hydrogen permeability, determining the necessary modifications to existing codes and standards to validate the safe and reliable implementation of the pipeline, and assessing the availability of sensor technology that ensures the safe and reliable use of the pipeline during its service lifetime.

The issues currently being considered are: identifying the advantages and challenges of the various manufacturing methods, evaluating methods and sensors for monitoring the structural health of the pipeline during its lifetime, and critiquing options for pipeline joining technologies. The requirements for structural health monitoring and embedded real-time measurements of gas temperature, pressure, flow rate, and pipeline leakage are being assessed. Requirements for bench-scale tests of FRP pipelines to determine their long-time compatibility with hydrogen are also being investigated.

Work after year one will focus on advancing materials performance beyond the proof of principle stage, evaluating of life-cycle costs and failure modes, qualifying of the materials and construction methods, integrating of sensors, complying with manufacturing codes and standards, and implementing a commercialization strategy.

FRP hydrogen pipelines will require liners (low-permeability barrier tubes) that contain the hydrogen flows. We are evaluating the plastic liners that are in current used in commercial FRP pipelines, as well as plastics that are available for use as liner materials, to get baseline figures to determine the degree of improvement, if any, that is necessary. This will provide a tabulation of published diffusivities/permeabilities for liner materials and will necessitate some new measurements of diffusivities/permeabilities in samples of OEM liners (unpublished data). We will add to this tabulation an evaluation of all the current modifications and treatments for reducing permeability in the liner materials. Furthermore, we will use the Multi-Year RD&D Plan and the H2A model to better quantify an acceptable leak specification (e.g., leak rate per unit pipeline length). These activities will enable an intelligent assessment of the improvement required, and we will use this information to propose a path forward that is based on currently available liner materials and modifications or treatments.

Hydrogen permeability testing will be carried out in an ORNL facility for sample testing at high hydrogen pressures over broad temperature ranges. The system incorporates a sample holder designed for small (~1 cm) diameter coupons of metal or ceramic, and can straightforwardly be modified for tests of polymer composite material by using an appropriate support (e.g., metal frit). In addition to the tests on hydrogen permeability, sample coupons will be mechanically tested (e.g., modulus of elasticity) before and after hydrogen exposure to assess the effects of exposure on mechanical properties.

Results

In the initial project year we developed an initial cost estimate for hydrogen delivery via FRP pipeline technology, and assessed hydrogen demand for transportation use as a first step in assessing the feasibility of the technology. Hydrogen demand was obtained from technical targets and existing transportation data. The estimated demand is approximately 0.5 kg H_2 per day per capita. Natural gas pipelines deliver large quantities of energy from a limited number of sources or terminals, moving the gas cross-country in large pipelines serving tens of millions of people. To replicate this energy delivery with hydrogen would require pipelines with a diameter of several feet. Fortunately, a hydrogen economy with distributed hydrogen production lends itself to a regional infrastructure, where hydrogen can be delivered using smaller diameter pipes. For this analysis, we considered the case where a hydrogen generation plant is located 200 miles from the population it serves, and then estimated the pipeline sizes required to serve populations of 100,000, 1 million, and 10 million people. Using spoolable composite piping greatly simplifies the manufacturing and installation of the pipeline. Today, spoolable composite piping is readily available in sizes up to four-inch ID, with pressure ratings to 3,000 psi for the four-inch pipe. Larger composite pipes are contemplated and are therefore considered in this analysis. It is assumed that hydrogen enters a 200-mile long pipeline at 1,000 psi pressure and the allowable pressure drop is 300 psi. The implications of these assumptions are discussed later. As estimated above, time-averaged demand is assumed to be 0.5 kg H_2 per day per capita. However, as with electricity, demand varies diurnally and seasonally, so an assumption that peak demand is 1.5 times average demand was made.

Case 1: For a city population of 100,000, peak demand would be approximately 3,000 kg H_2/h. Five parallel spoolable, 4-inch diameter pipes or a single 8-inch diameter pipe will serve this city's demand.

Case 2: For a city population of 1,000,000, peak demand will be approximately 30,000 kg H_2/h. In this case, 50 parallel 4-inch diameter pipes, nine parallel 8-inch diameter pipes, three parallel 12-inch diameter pipes, or a single 18-inch diameter pipe would be required.

Case 3: For a metropolitan area with a population of 10,000,000, peak demand will be about 300,000 kg H_2/h. In all probability, such a large population would be served by multiple hydrogen generating stations, so it is likely that several pipelines similar to those in Case 2 would be needed. If the city is served by a single pipeline, that line would consist of 500 parallel 4-inch diameter pipes, or 90 parallel 8-inch diameter pipes, 30 parallel 12-inch diameter pipes, or a single 44-inch diameter pipe.

The above estimates are summarized in Table 1.

TABLE 1. Hydrogen Pipeline Size Estimates for a 1,000 psi Source Pressure and a 300 psi Pressure Drop

Population	100,000	1,000,000	10,000,000
Peak Demand, kg/h	3,000	30,000	300,000
No. 4-inch pipes	5	50	500
No. 8-inch pipes	1	9	90
No. 12-inch pipes	N/A	3	30
Single pipe ID, inches	8	18	44

The data in Table 1 shows that either a single large pipe or many small pipes would be required to serve populations exceeding one million. This requirement can be reduced if source pressure is increased, as higher pressure increases density and therefore decreases fluid velocity for a given mass flow rate. The data in Table 2 shows the pipeline estimates if source pressure is increased to 3,600 psi (a typical compressed natural gas fuel tank rating) with demand and allowable pressure drop unchanged. The specific energy loss is about the same for both cases.

TABLE 2. Hydrogen Pipeline Size Estimates for a 3,600 psi Source Pressure and a 300 psi Pressure Drop

Population	100,000	1,000,000	10,000,000
Peak Demand, kg/h	3,000	30,000	300,000
No. 4-inch pipes	3	30	300
No. 6-inch pipes	1	10	100
No. 8-inch pipes	N/A	5	46
No. 12-inch pipes	N/A	2	16
Single pipe ID, inches	6	15	36

Increasing the allowable pressure drop also reduces the required pipe size or number of pipes, but introduces the penalty of greater energy loss in transmission. Installing surge capacity in the population center could also have a very significant effect, as it reduces the peak flow rate in the transmission pipeline. Pipeline pressure, allowable pressure drop, and surge capacity need to be studied in the context of total system economics that includes the cost of pumping, storage infrastructure, and so on. The intent of the presentation of Table 2 is to demonstrate that these very simple parametric choices can significantly affect transmission cost and thus should not be made arbitrarily.

With the above analysis in mind, FRP pipe economics is very attractive, especially in regional or distributed service. FRP 4-inch, 1,000 psi rated spoolable pipe costs about $10 per foot installed; for 3,000 psi pressure rating, the installation cost increases to about $14 per foot. In both cases, installation costs are about $2 per foot and terrain is assumed to be rural, level ground with deep soil. With allowances for installation complexity in mountainous or urban terrain, the total installed cost will range from $10 to $20 per foot for 4-inch diameter spoolable composite pipe. Today, spoolable piping manufacturers could install a composite pipeline to serve a 100,000 person population for a cost of $250,000 to $500,000 per mile (not including the cost for right-of-way), which is well below DOE's capital cost target. When one considers the opportunities for operational cost savings due to integrated health monitoring, the composite pipe is extremely attractive economically.

There also appear to be some compelling advantages associated with using a few small FRP pipes instead of one large diameter pipe. First, it allows the pipeline to continue operating at reduced capacity in case of damage to one pipe. Second, it offers the opportunity to stage capital investment by installing only one pipe to satisfy demand during the early transition period, then adding capacity as demand increases. This option is made attractive by the very low installation cost associated with spoolable FRP pipe.

A limitation on pipe diameter could be imposed by the feasibility of transporting it from the manufacturing factory. Four-inch pipe can be spooled for highway transport. Larger diameter pipe requires larger diameter spools to avoid exceeding material strain limits. In offshore applications, where the spool can be transported by barge, spoolable pipe can exceed one foot in diameter. Therefore, larger diameter spoolable FRP pipe may be an option for hydrogen pipeline infrastructure methods for transporting it from the factory to the pipeline emplacement can be determined. At this time we have no data on costs or pressure ratings associated with spoolable pipe exceeding four inches in diameter.

Conclusions and Future Directions

- Using multiple, small-diameter FRP pipelines for hydrogen transmission is practically and economically feasible.
- Tabulate the diffusivities in existing liner materials and summarize the existing modifications and treatments available for reducing permeability in liner materials.
- Perform bench-scale tests of integrated sensor performance in short sections of FRP pipeline.
- Make recommendations for sensor integration, manufacturing and joining technologies.
- Evaluate the 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.
- Provide support to the Hydrogen Delivery Technical Team.

References

1. B. J. Chisholm, R. B. Moore, *et al*., Macromolecules, 35 5508 (2002).

FY 2006 Publications/Presentations

1. An invited talk on FRP Hydrogen Pipeline technology was given at the FuelCellSouth Winter Partners Forum, February 23, 2006, Oak Ridge, Tennessee.