III.5 Fiber Reinforced Composite Pipeline

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Fiscal Year (FY) 2012 Objectives

Fiber Reinforced Composite Pipeline (FRP)

- Successfully adapt spoolable FRP currently used in the oil and natural gas industry to use high-pressure hydrogen delivery systems.
- Development of data needed for life management and codification FRP.

Technical Barriers

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

(D) High Capital Cost and Hydrogen Embrittlement of Pipelines
(IV) Hydrogen Leakage and Sensors
(K) Safety, Codes and Standards, Permitting

Technical Targets

This project is focused on the evaluation of FRP for hydrogen service applications. Assessment of the structural integrity of the FRP piping and the individual manufacturing components in hydrogen will be performed. Insights gained will support qualifications of these materials for hydrogen service including:

- Transmission pipeline reliability: Acceptable for hydrogen as a major energy carrier
- Transmission pipeline total capital cost $735k per mile (2015)
- Transmission pipeline total capital cost $715k, per mile (2020)
- H2 Delivery Cost <$0.90/gasoline gallon equivalent
- H2 pipeline leakage: <780 kg/mi/y (2020)

FY 2012 Accomplishments

In FY 2012, the SRNL project has focused on supporting the development of a life management methodology for FRP materials and the American Society of Mechanical Engineers (ASME) B31.12 Codification of FRP. The materials testing effort has centered on the fatigue damage of FRP for both flawed and unflawed conditions. Initial meetings were held with the ASME B31.12 Piping Committee to initiate the codification process. A functions and requirements document was also developed for a proposed integrated hydrogen demonstration project.

- FRP Materials Testing
  - Fatigue testing has been completed for both flawed and unflawed samples
  - Proposal developed for extending the service life of FRP
- FRP Codification into ASME B31.12
  - Codification workshop with all stakeholders
  - Presented technical data on FRP to B31.12 Committee
- Proposal to DOE for FRP Demonstration Project
  - Developed a concept plan for an integrated hydrogen delivery project

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Introduction

The goal of the overall project is to successfully adapt spoolable FRP currently used in the oil industry for use in high-pressure hydrogen pipelines. The use of FRP materials for hydrogen service will rely on the demonstrated compatibility of these materials for pipeline service environments and operating conditions. The ability of the polymer piping to withstand degradation while in service, and development of the tools and data required for life management are imperative for successful implementation of these materials for hydrogen pipeline.

Approach

To achieve the objective an FRP life management plan was developed. The plan was a joint document developed by SRNL and the ASME to guide generation of a technical basis for safe use of FRP in delivery applications. The plan addresses the needed material evaluations and also focuses on the needed information for codification of FRP into the ASME B31 Code of Pressure Piping. The B31.12 Hydrogen Piping Code is the existing code that provides a consensus standard for the safe and reliable implementation of the piping in hydrogen service. This plan is designed to provide the needed information to support the codification of FRP. The B31.12 Code addresses the initial construction of piping systems. The plan also identifies the tasks needed for the post construction management of FRP to insure structural integrity through end of life. The plan calls for detailed investigation of the following areas:

- System Design and Applicable Codes and Standards
- Service Degradation of FRP
- Flaw Tolerance and Flaw Detection
- Integrity Management Plan
- Leak Detection and Operational Controls Evaluation
- Repair Evaluation

Results

Burst Testing

SRNL has completed the first areas of the Life Management Plan. Codes and standards for the high-pressure piping, process, and transport pressure vessels were reviewed and design margins and qualification techniques evaluated.

SRNL and Oak Ridge National Laboratory (ORNL) have collaborated on evaluating the service degradation of FRP in high-pressure hydrogen. Initial laboratory testing indicated that there is not a degradation mechanism connected with the use of hydrogen in FRP. The codes and standard development organizations would like additional long-term data on this question to ensure the long-term life management of FRP.

SRNL has begun an investigation to determine the flaw tolerance of FRP products. Creep data on glass fiber was also reviewed to evaluate the effect of creep life on the glass fiber. The results indicate that a design margin of at least 3.5 is required to address long-term creep effects for a 20+ year design life. The use of the fiberglass creep data has been effective in evaluating the effect of flaw tolerance using a short-term burst test. Multiple tests have been completed to evaluate the effect of flaw tolerance on FRP samples. FRP designed to a recognized national consensus standard were used in the evaluation. Flaws for various depths were machined into the samples and burst tests have been performed.

To address third-party damage the sensitivity of FRP to flaws must be established. The flaw testing was performed over a range of flaw sizes to determine the flaw tolerance of the FRP. The results of the multi-layer FRP tests are provided in Figure 1. Tests were conducted for increasing flaw depths up to 40% through wall. A 28% reduction in burst pressure from the unflawed condition to a 40% through wall flaw was observed. With the 40% through-wall flaw there is still a margin of approximately 3 above the rated pressure of the FRP multi-layered product. The margin on burst of 3 provides an acceptable remaining product life to detect and repair flaws in FRP systems. Additional burst tests were conducted in on FRP samples with 40% through wall flaws to determine the variability between different samples. The results of the additional tests show that the variability between the tests is low and that all tests provide an acceptable design margin. The results for increasing the flaw length and width are also shown in Figure 1. The flaw with increased length showed no additional loss in design margin above the base flaw length. The flaw with increased width showed a small additional loss in design margin above the base flaw width. Two FRP samples were exposed to the high- and low-PH solutions and burst tested. The results are shown in Figure 2. The failure pressure for the chemically exposed samples fell within the variability of the unexposed data.

From the flawed samples, it was observed that as the flaw depth increased the failure mode changed from a local failure to a more global failure mode. The series of photos shown in Figure 2 illustrates these failure modes. The first photo from the left shows the failure of the unflawed sample indicating a global failure of the pipe. The next three photos illustrate how the failure mode changed as the flaw depth increased. The last photo on the right shows the 40% through-wall flaw. In the 40% through-wall photo, the failure encompasses most of the pipe circumference. Based on this data it was determined that the 40% through flaw was a reasonable upper limit to set for flaw detection.

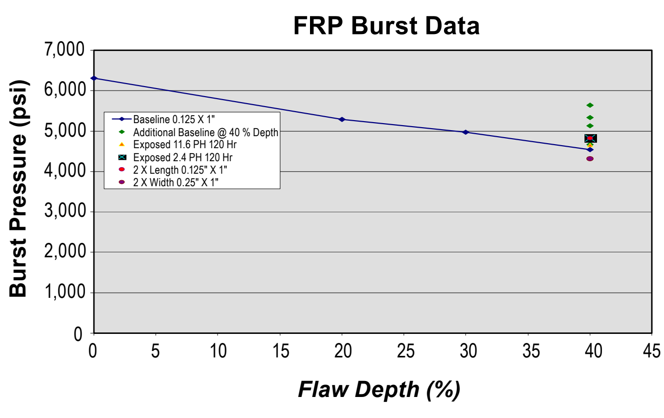

FIGURE 1. Multi-Layer FRP Flaw Tests

FIGURE 2. Photo Illustrating Failure Mode of FRP

Fatigue Testing

Fatigue testing of FRP was started at SRNL during FY 2012 and it is planned to continue this effort during FY 2013. The fatigue testing is directly tied to the FRP life management plan. During FY 2012 fatigue tests were performed on flawed and unflawed specimens.

Two fatigue tests have been performed on flawed FRP samples. The FRP samples were cycled with compressed nitrogen at 1,500 psi which is the rated pressure of the FRP product. The flaw size used for fatigue testing was 1 inch long, 0.125 inch wide, and at a 40% depth into the structural layer. This was the same flaw size as used for the previous flawed burst test. The pressure cycle interval was a minimum of 1 minute with a 30 second hold time at 1,500 psi. The hold time was specified at rated pressure to ensure that the test specimen had a portion of load at levels affecting the creep rupture strength of the fiber. The two flawed samples failed after 2,830 and 4,862 full design pressure cycles.

The failure of the flawed specimen occurred when the existing flaw propagated through the structural glass layer. The specimen started to delaminate at the bottom of the engineered flaw, as shown in Figure 3. When the flaw depth reached the polyethylene liner, loss of the pressure boundary occurred. The thin polymer liner is not intended to be pressure retaining. The pressure load in supported entirely by the glass composite.

An additional fatigue test was performed on an unflawed FRP sample. The unflawed sample was cycled for 8,077 full design pressure cycles. An 8,000 cycle limit was chosen because it represents a bounding value above the design current fatigue cycle limit for FRP of 20 years at 1 cycle per day. The unflawed sample was then burst tested and failed at 4,935 psi which shows a 22% reduction as compared to previously burst tested unflawed sample without fatigue damage. A photo of the failure location is shown in Figure 4.

The results of these tests show that FRP is susceptible to some level of fatigue damage. At the levels initially measured FRP still offers a viable alternative to metallic piping. The additional tests proposed for FY 2013 will focus on data needs for FRP piping design and codification.

B31.12 Codification

The workshop to discuss ASME B31.12 Codification of Fiber Reinforced Piping was held on August 16, 2011. The workshop was attended by DOE, ASME, SRNL, ORNL, FRP manufacturers, and Aiken County.

The technical background for Codification of FRP based on the work performed by SRNL and ORNL for the hydrogen delivery project was presented to the B31.12 Committee on March 15, 2012. An outline of the proposed B31.12 Code

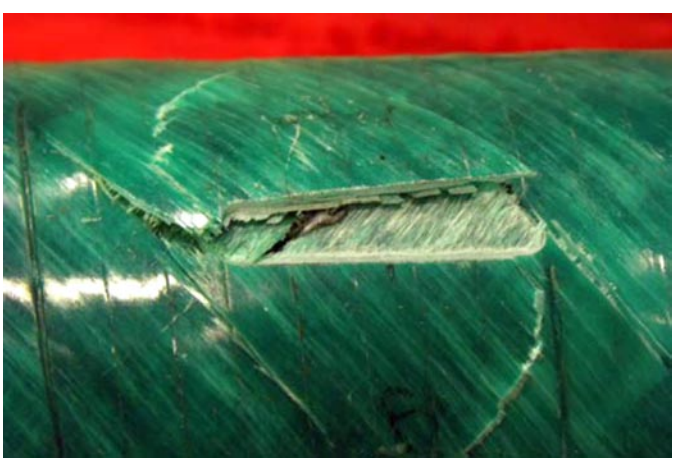

FIGURE 3. Fatigue Failure of Flawed FRP Specimen

FIGURE 4. Burst Failure Following 8077 Rated Pressure Fatigue Cycles

section has been submitted to the B31.12 Code Committee and included the following elements:

- Scope – Establish the design limits for the product
  - Product form
  - Design pressure limits
  - Design temperature limits
  - Design life
- Material – Additional controls on resigns and fibers will be required
  - Fibers
  - Resign system
  - Liner material
- Design – Design to ASTM D2992 for the pressure design basis
  - Design pressure basis
  - Maximum and minimum design temperature
  - Protective layer
- Fabrication
  - Manufacturing specification to control resin and fiber
  - Supplementary code fabrication requirements – (mechanical joint vs. wrapped joint)
- Examination
  - Qualification of nondestructive testing personnel
  - Manufacturing examination requirements
  - Supplementary code examination requirements – acceptable flaw size
- Testing
  - Qualification tests – burst, fatigue, stress rupture, flaw environmental, and permeability
  - Production tests – quality control burst tests on random production samples
- Inspection
  - Supplementary code inspection requirements

Extended Design Life for FRP

Current FRP standards are limited to a 20-year design life. Because pipelines are a large capital investment a 20-year design life could be a limiting factor in the FRP application. SRNL has started to investigate extending the current accepted 20-year service life for FRP. Based on the results of the data from the burst test and review of the available creep rupture data for glass fiber there appears to be sufficient design margin to extend the design life for some FRP product from 20 to approximately 50 years. A comparison of the difference in the required design margin between 20 and 50 years is shown in Figure 5. The required decrease in fiber stress is from 0.32 to 0.3, a change of

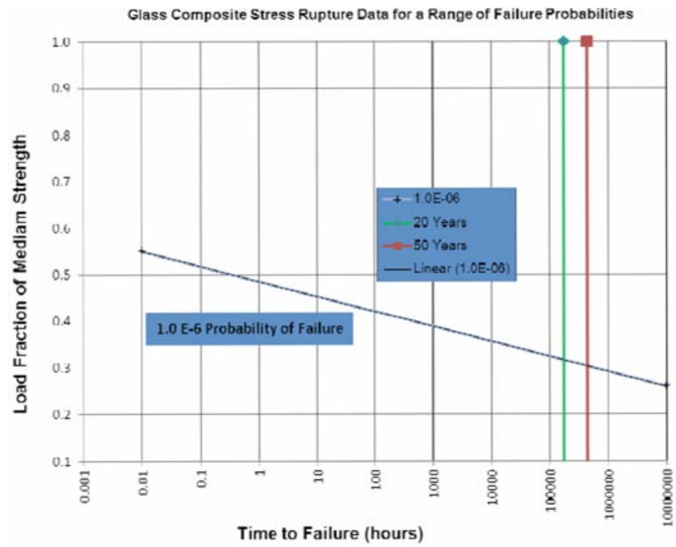

FIGURE 5. Extended Design Life for FRP

approximately 6%. Other standards are also starting to address increased design life for glass composite. The current draft International Organization for Standardization Standard 15399 is proposing a design life of up to 50 years for composite components.

Integrated Hydrogen Demonstration Project

SRNL in partnership with Aiken County Economic Development Partnership, Center for Hydrogen Research, ORNL and ASME has developed a project proposal to partner with industry and government to provide an integrated hydrogen delivery demonstration project. The objective of the project is to install at least 1,000 feet of FRP operating in hydrogen service at a design pressure of 1,500 psi. The pipeline would serve as a test and surveillance facility as a final proof of concept for FRP in hydrogen service. The proposed location of the project is SRNL with demonstration portions at the Sage Mill Central Hydrogen Facility located at Aiken County's Sage Mill Industrial Park. The facility will have an integrated educational component for the public. An artist conception on the project is provided in Figure 6.

Conclusions and Future Directions

Conclusions

- FRP is an attractive technology with potential to support the DOE goal to reduce overall pipeline installation cost.
- FRP fabricated to American Petroleum Institute (API) 15HR is the most relevant standard reviewed to date for the fabrication of FRP for hydrogen service. This standard can be tailored to address the need for hydrogen pipelines.

FIGURE 6. Integrated Hydrogen Demonstration Project

- Burst tests show that for piping with flaws up 40% through the wall and up to 2-inch length and 0.25 inch width maintain a factor of 3X on rated pressure.
- Fatigue testing of both flawed and unflawed piping sections has been conducted. These tests have shown that fatigue cycles will affect the life of FRP. Additional fatigue testing is needed.
- The current SRNL recommendation is to develop a performance-based design specification to be included in ASME B31.12.
- SRNL has started working directly with the ASME B31.12 Committee to draft code requirements for FRP.
- A proposal for an FRP demonstration project has been presented to DOE. SRNL will partner with ASME, ORNL and Aiken County to provide a demonstration project to support codification and life management of FRP.

Future Work

- Perform long-term stress rupture tests for flawed FRP samples.
- Perform additional burst testing of flawed FRP samples on aged samples.
- Recommend performance qualification tests for FRP in hydrogen service to the ASME B31.12 Committee.
- Evaluate B31.8S (Managing System Integrity of Gas Pipelines) for changes needed to address FRP in hydrogen service.
- Perform additional fatigue testing for FRP piping up to the full cyclic design life for pipelines.
- Perform long-term stress rupture tests for flawed FRP samples.
- Evaluate non-mechanical joints for pipeline application.
- Develop draft sections for ASME B31.12 Code for Hydrogen Piping and Pipeline and submit to Code Committee for review.

FY 2012 Publications/Presentations

1. Gaseous Hydrogen Embrittlement of Materials in Energy Technologies, Chapter 1, Hydrogen Production and Containment, Woodhead Publishing, 2012.

2. ASME Codification of Fiber Reinforced Composite Pipelines, Workshop with Stakeholders, Aiken, SC, August 2011.

3. SRNL FRP Piping Project, Presentation to Hydrogen Delivery Technology Team, Detroit, MI, March 2012.

4. Fiber Reinforced Composite Pipelines, Presentation to ASME B31.12 Committee, Orlando, FL, March 2012.