III.4 Fiber Reinforced Composite Pipeline

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Project Objectives

Successfully adapt spoolable fiber reinforced polymer composite pipeline (FRP) currently used in the oil and natural gas industry for use in high-pressure hydrogen delivery systems and development of the data needed for codification of fiber reinforced composite piping into the American Society of Mechanical Engineers (ASME) B31.12 Hydrogen Piping Code.

Fiscal Year (FY) 2014 Objectives

- Perform fatigue testing of FRP at the product rated design pressure of 1,500 psig to determine the effect of R ratio on the cyclic life of fiber reinforced piping. Testing will be performed between a range of R values of 0.7 maximum and 0.3 minimum.
- Present the technical basis for FRP and a technical proposal for inclusion of FRP into the B31.12 Code to the Code Committee.
- Provide a technical evaluation for the extension of the design life of fiber reinforced piping from 20 years to 50 years.
- Provide a technical report evaluating concepts for improved FRP joints, with emphasis providing a more robust hydrogen seal and maintaining the structural integrity requirement for pressure retention.

Technical Barriers

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

(D) High As-Installed Cost of Pipelines

(J) 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 $715k, per mile (2020)
- H2 delivery cost <$0.90/gasoline gallon equivalent
- H2 pipeline leakage: <780 kg/mi/y (2020)

FY 2014 Accomplishments

In FY 2014, the main activity at SRNL was to complete the required fatigue testing for the FRP project. During FY 2014 two additional samples were tested. The maximum pressure for each test was the 1,500 psi, rated FRP sample pressure. These tests were performed at a stress ratio or R-ratio values of 0.3 and 0.5. The fatigue test data directly support both FRP codification and the evaluation of a 50-year FRP design life.

A report providing the basis for extension for the design life for FRP was completed. The technical basis for codification of FRP material into the B31.12 Hydrogen Piping Code was expanded to include the results of the additional fatigue tests and the life extension evaluation. A separate effort in FY 2014 was the completion of a report to evaluate new concepts for improved FRP joints.

- FRP Fatigue Testing
  The fatigue tests were completed at a maximum pressure of 1,500 psi, the rated FRP sample pressure. These tests were performed at R-ratio values of 0.3 and 0.5.
- FRP Codification into ASME B31.12
  The initial proposal (Code Language) for codification into ASME B31.12 was presented to the Code Committee at a March 2014 meeting.
- Extension of Design Life of FRP
  A technical report providing a basis for the extension of the design life of FRP from 20 years to 50 years was completed.

- Improved Joint Concepts for FRP
  A technical report providing an evaluation of new FRP joint concepts with an improved hydrogen seal for the inner polyethylene liner was finalized.

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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 pipelines.

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 testing performed by SRNL has:

- Critically evaluated the current application of available FRP product standards through independent testing.
- Defined changes to the current FRP product standards to meet the ASME Code Methodology.
- Provided a body of data to support inclusion of FRP in the ASME B31.12 Hydrogen Piping Code.

RESULTS

Fatigue Testing

Fatigue testing of FRP was initiated at SRNL in FY 2012 and continued through 2014. During FY 2013 six fatigue tests were completed at pressure levels ranging from 750 psi to 3,000 psi. The pressure levels ranged from half to twice the rated pressure of the FRP product test samples. The range of test pressure was selected to provide sufficient data to understand the general shape of the FRP fatigue curve. All these tests were performed at a R- ratio of 0.1. The stress-ratio is defined as $R = \sigma_{min}/\sigma_{max}$. There σ_{min} is the minimum pipe stress and σ_{max} is the maximum pipe stress.

During FY 2014 two additional samples were tested. The maximum pressure for each test was 1,500 psi, the rated FRP sample pressure. These tests were performed at a stress ratio or R-ratio values of 0.3 and 0.5. The FY 2014 fatigue tests show that the FRP product is sensitive to R-ratio. The test data is shown in Figure 1. The fatigue test data directly support both FRP codification and a 50-year FRP design life.

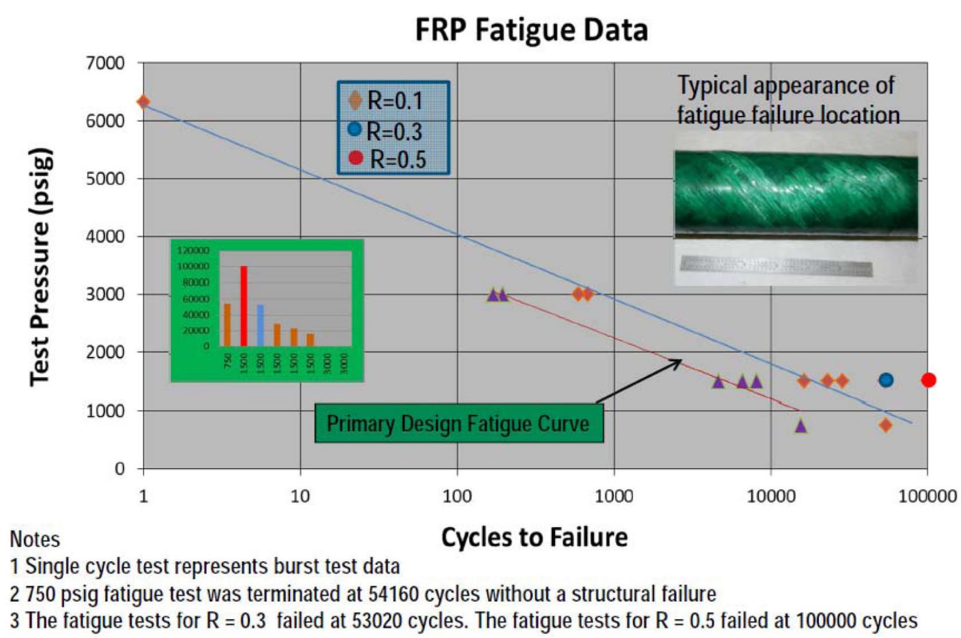

FIGURE 1. FRP Preliminary Fatigue Curve

FRP Codification into ASME B31.12

A report summarizing the FRP testing by SRNL and Oak Ridge National Laboratory has been completed. The report will become the basis for ASME Codification of FRP into the B31.12 Hydrogen Piping Code. In FY 2014 the report was expanded to include both the additional fatigue testing and the technical basis for a FRP 50-year design life. The initial proposal (code language) for codification into ASME B31.12 was presented to the Code Committee in March 2014.

Extension of Design Life of FRP

The evaluation project for FRP has reviewed the structural integrity of FRP for both the hydrostatic design basis that affects the long-term stress rupture of the glass fiber and the fatigue strength of the FRP product. Both of these modes of failure require review when increasing the design life.

Defining the effect on the stress rupture life or the hydrostatic design basis for the FRP is straight forward. The increase in design life is an increase in the total time the pipe is under maximum pressure. To evaluate the required change on hydrostatic design stress to increase the stress rupture life from 20 years to 50 years, stress rupture data for the FRP material was obtained. The design data and calculation procedure are expressed in hours of service. A plot of the D2992 stress rupture data is provided in Figure 2. A review of the graph shows that the stress rupture data can be reasonably modeled by a log-log least squares regression analysis as recommended by ASTM standard D2992.

Table 1 provides the calculation results showing the reduction in stress level in the glass fiber forming the structural layer of the FRP product required to increase design life from 20 to 50 years. The data shows that a decrease in the fiber stress level by 4.3% will provide the required increase in design life.

The data from the FRP fatigue tests completed by SRNL for the DOE Hydrogen Production and Delivery Program shown in Figure 1. This set of data is for tests of FRP samples. The rated pressure of the FRP test specimens is 1,500 psi. The data for the failure curve is for testing that was performed for an R ratio of approximately 0.1.

TABLE 1. Rupture Stress vs. Time for FRP

Years	Time (hours)	Rupture Stress (psi)
1	8,760	42,113
20	175,200	36,465
50	438,000	34,894

The increase in fatigue life is more difficult to define because the number of operational cycles per time will depend on how the industrial gas suppliers operate the pipeline. The fatigue life is affected by both the total number of cycles and the magnitude of the cycles, and both of these parameters can be controlled.

The initial SRNL fatigue evaluation assumed one stress cycle per day for fatigue life. Based on the peak demand for the fueling stations occurring twice a day, corresponding to high demand occurring in both the morning, when the public is traveling to work and in the evening at the end of the work schedule, two cycles a day were assumed in this review. Current hydrogen pipelines are operated at much lower cyclic rates. If conservative equipment maintenance demands are considered the fatigue demand for FRP can be greatly reduced. The values provided in Table 2 below show these effects on required fatigue design life. The low R ratio tests at 1,500 psi pressure show that the fatigue life for FRP does not support the 50-year fatigue life based on refueling demand. The FY 2014 testing at higher R ratio values of 0.3 to 0.5 show much higher fatigue life for FRP. The current data for the 0.3 and 0.5 R ratio tests indicate that a small change in the stress level of the fiber may be needed for the fatigue life to reach the 50-year goal to reach the refueling demand level. The current FRP design will support a 50-year design life if

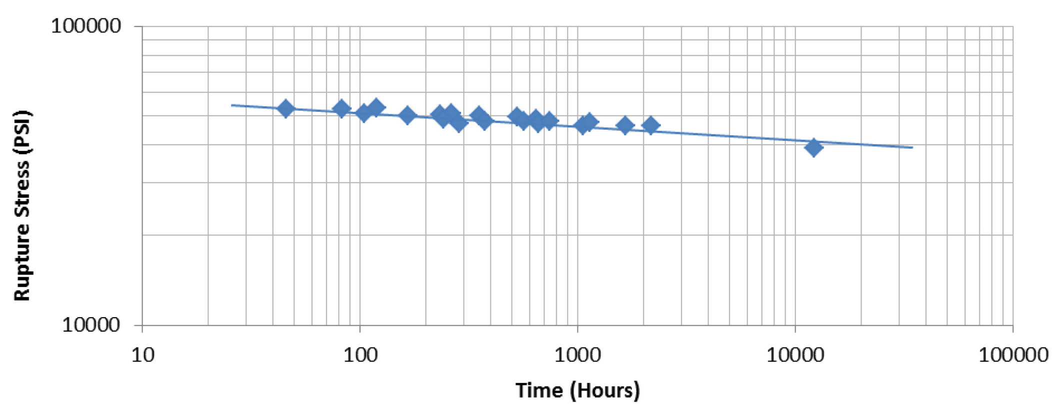

FIGURE 2. ASTM D2992 Data Set for FRP

the pressure rating is reduced from 1,500 psi to 1,400 psi and the pressure cycles are limited to 28,500 at an R ratio of 0.5.

TABLE 2. Design Life Values for Increase from 20 Years to 50 Years

Years	Equipment Maintenance Demand		Refueling Station Demand	
	Fatigue Life (@ 1 Cycle per Month)	Fatigue Life (@ 2 Cycles per Month)	Fatigue Life (@ 1 Cycle per Day)	Fatigue Life (@ 2 Cycles per Day)
1	12	24	365	730
20	240	480	7,300	14,600
50	600	1,200	18,250	36,500

Improved Joint Concepts for FRP

Three concepts have been developed for improving the existing FRP joint design. The emphasis for the new design is on a more robust seal for the polyethylene inner layer. The structural elements for the joint are fundamentally the same as for the existing design. The evaluation addressed elements of the joint that form the leakage connection to the polyethylene liner and the structural connection to the fiberglass structural layer. The specific requirements for FRP joints are as follows:

- Seal the inner layer so that leakage at the joint is $\leq 5\ x10^{-4}$ STD CC H_2/Sec.
- The joint shall be rated to the full strength of the attached piping:
  - The burst strength of the joint shall exceed the burst strength of the FRP
  - The joint shall exceed the axial strength (tensile strength) of the FRP
- Metallic joint components shall be designed to the requirements of the ASME B31.12 Hydrogen Piping Code.

Fusion Bonded Joints

Polyethylene piping is commonly joined today using two types of fusion processes. These processes are heat fusion bonding and the electrofusion bonding. There is extensive successful experience joining polyethylene material with these fusion processes. The current polyethylene natural gas distribution system utilizes the heat fusion process for the majority of the systems installed today. Both these methods have specific requirements for installation procedures. Both methods are addressed by ASTM standards that provide the requirements for joining procedure qualification. A review of these techniques showed that these bonding processes are candidates for joining the inner polyethylene layer of FRP. Two concepts have been developed for improving the joint by fusion bonding the inner liner. The fusion bonding techniques are applied to bond the liner in these designs. Where the heat fusion joint is more like a butt weld connection the electrofusion joint is more like a brazed connection.

Heat Fusion FRP Joint

In the heat fusion concept, the fiberglass structural layer would be cut away exposing the polyethylene inner layer. The concept for the heat fusion design is shown in Figure 3.

The heat fusion joint will only require a very small section of the fiberglass structural layer to be removed. When whole spools of piping are used, the ends of the liner would be left unwrapped during manufacturing. The heat fusion process described above would be used to form a permanent leak tight joint in the inner polyethylene layer. The heat fusion bead is indicated by the yellow line shown in Figure 3. The internal diameter of the pressure fitting will be sized to have a small clearance above the outside diameter of the structural fiberglass layer. The pressure fitting will be centered on the joint. The gap at the weld bead will be filled with epoxy or other suitable material to provide radial transfer of the pressure load from the exposed section of polyethylene at the fusion bead to the pressure fitting. The pressure fitting will have threaded ends to accept a connector nut that would tighten onto the compression slip ring. The

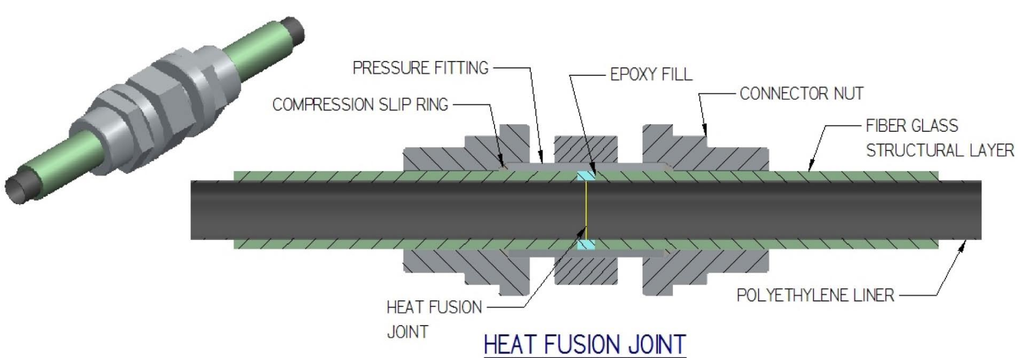

FIGURE 3. Heat Fusion Joint Concept

compression slip ring provides the axial load path across the joint. The compression slip ring is wedged into the pressure fitting, forcing it downward, generating a normal force between the ring and the pipe surface. The resulting frictional force transmits the load from the FRP to the metallic fitting.

Electrofusion FPR Joint

The electrofusion joint is similar in design to the heat fusion joint. The concept for the electrofusion joint is an integral fitting including the polyethylene electofusion fitting and the metallic pressure fitting. In the electrofusion design, a longer section of the fiberglass layer is required to be removed to allow the polyethylene liner to slip into the electrofusion fitting. The concept design is shown in Figure 4.

The development of this joint would entail combining the electrofusion fitting (purple section in Figure 4) with the metallic pressure fitting. The combining of the fusion fitting and the pressure fitting is a requirement for this joint type because ports have to be provided in the pressure fitting for the electrical connection to the electrofusion fitting (yellow section in Figure 4). Where there is an obvious gap requiring reinforcement at the fusion bead in the heat fusion design, additional development work is needed to determine the clearances and gaps in the electrofusion design. The required thickness of the polyethylene to accommodate the heating element will drive the dimensional requirements for this fitting concept. The thickness of the pressure fitting for the electrofusion concept will be fundamentally the same as for the heat fusion fitting, with some possible small increase in thickness required to reinforce the opening for the electrical ports. The ends of the pressure fitting will be threaded with the connector nut and compression slip ring providing for the same load transfer concept as in the heat fusion joint described above.

Welded FRP Joint

The FRP welded joint concept relies on the technology developed by Hexagon Lincoln Inc. The concept was developed for Lincoln's Tuffshell™ Tank product line. The concept is shown in Figure 5.

The aluminum boss is the specific part that will be modified to form the welded FRP joint. The metallic boss is injection molded into the polyethylene material. The keyways lock the metallic part into the polyethylene. To fabricate the joint for FRP the metallic part is reshaped to function in a tubular product form that would be integrally molded into a polyethylene tube, as shown in Figure 6. The concept is the same at the Hexagon Lincoln tank boss, in that keyways

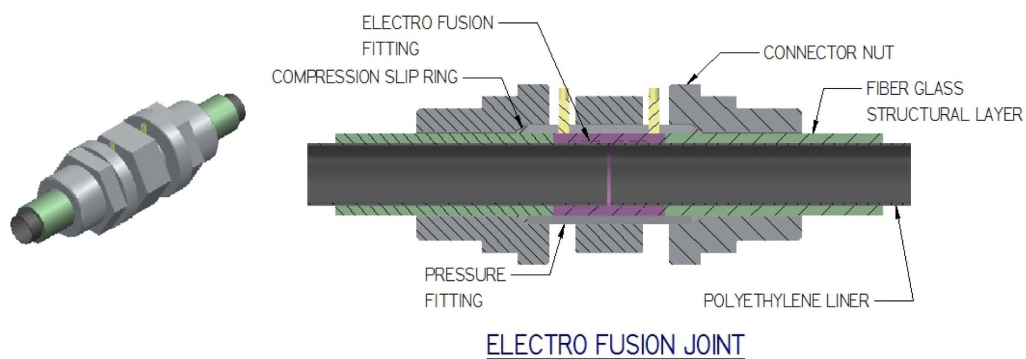

FIGURE 4. Electrofusion Joint Concept

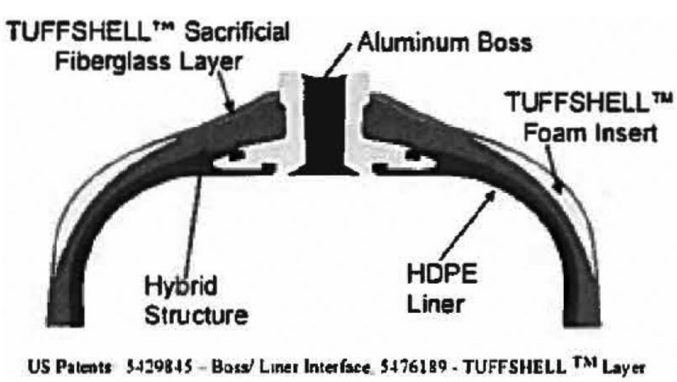

FIGURE 5. Hexagon Lincoln Aluminum Boss Design

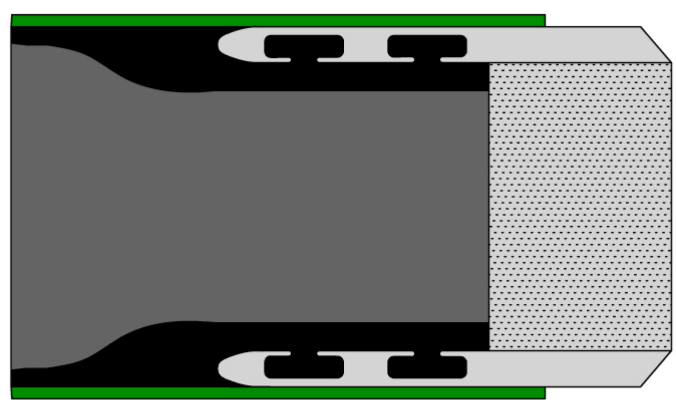

FIGURE 6. FRP Tubular Connector Design

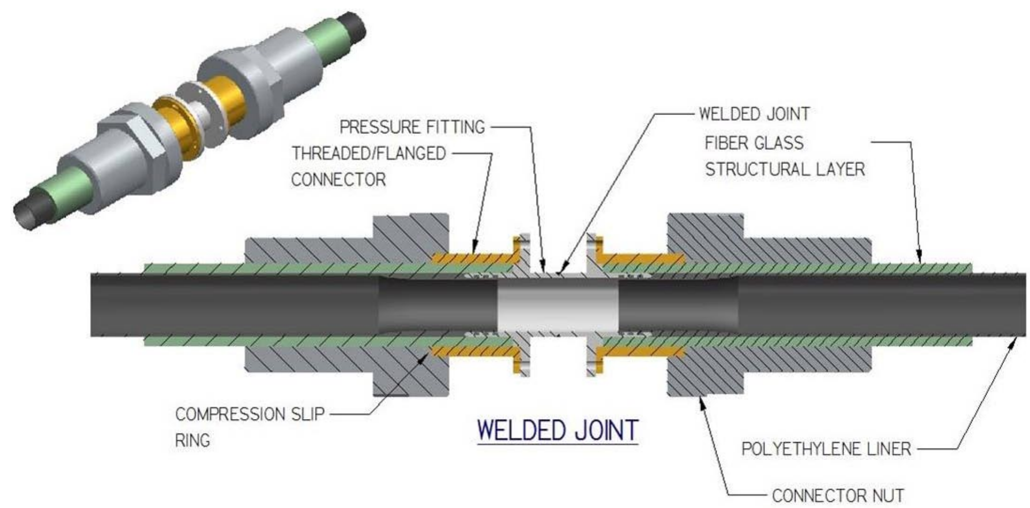

FIGURE 7. Welded Joint Concept

are used to form an integral metallic-polyethylene part that would be injection molded. These parts would be fusion welded to the polyethylene coil and wound into spoolable pipe with welded end connections.

The complete design concept for the welded FRP joint is shown in Figure 7. The pipe to pipe joint for this concept would be made with a standard butt weld. The butt weld would be made using accepted ASME welding practices. The pressure fitting is integral with the FRP section for the welded joint concept. The axial load path for this joint design functions in the same manner as the models shown for the fusion joints. The connector nut is tightened onto the compression slip ring to generate a frictional force to transfer the load across the discontinuity in the fiberglass structural layer. In the welded joint concept an additional part, identified as the thread/flanged connector in Figure 7, is used to link the connector nut to the pressure fitting and complete the axial load path. The length of the metal extending past the fiberglass layer will have to be sufficiently long to ensure that the polymer materials are not damaged by high temperature generated during welding.

The axial load path could also be developed for the welded joint design by placing a metallic sleeve over the metallic-polyethylene part. This sleeve design would be the same concept as the pressure fitting connector nut detail used for the heat fusion concept as shown in Figure 5. One disadvantage to the welded detail is that it is more applicable to FRP manufactured in standard lengths. As shown, the fiber reinforced layer is wrapped over the connection between the metallic-polyethylene part and the remaining FRP section. Achieving the continuity in the structural layer could be difficult to achieve in field fabrication. A technical report providing an evaluation of an improved hydrogen seal for the FPR inner polyethylene liner was finalized.

CONCLUSIONS AND FUTURE DIRECTIONS

Conclusions

- The design life evaluation supports that an increase in design life from 20 years to 50 years is feasible for FRP.
- The codification of FRP will proceed with a recommendation for a 50-year design life. The proposed fatigue testing provided in the B31.12 Code proposal is well suited to address the required fatigue life.
- Fatigue testing over the range of 750 psig to 3,000 psig was completed in FY 2013. The data provides an indication on the fatigue life of FRP. The FY 2013 tests were performed at an R- ratio of 0.1.
- Fatigue testing continued in FY 2014. The first fatigue test at an R ratio of approximately 0.5 has been tested to 100,000 cycles without failure. The second test with an R ratio of approximately 0.3 has been tested to 53,000 cycles. The testing shows that the FRP has a significant sensitivity to R-ratio.

Future Work

- Complete the FRP Codification into ASME B31.12
- Complete collaboration with Fiberspar to determine the variability in the fatigue data and effect of cycle frequency.
- Collect and document available service history data for FRP from literature and FRP manufacturers.
- Continue the evaluation of non-mechanical joints for FRP application.
- Development an in-service inspection criteria for FRP.
- Continue to support the development of an FRP demonstration project.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. B31.12 Hydrogen Piping Committee Meeting, Portland, ME October 2013.

2. Hydrogen Delivery Workshop, Denver, CO, March 2014.

3. B31.12 Hydrogen Piping Committee Meeting, Washington, DC, March 2014.