Final Report

Evaluation of Structural Liners for the Rehabilitation of Liquid and Natural Gas Piping Systems

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Evaluation of Structural Liners for the Rehabilitation of Liquid and Natural Gas Piping Systems

The objective of the project is to perform an engineering assessment of structural composites and liners and their interaction with the host pipe to determine the characteristics required to carry the internal and external loads of a degraded host pipe. The focus will be on high-pressure (up to 350 psig) composites and liners installed using trenchless technology which can provide remediation to the pipe and its appurtenances.

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Table of Contents

Page

List of Figures

Page

List of Tables

Page

Executive Summary

The project performed an engineering assessment of structural composites and liners to determine their interaction with the host pipe and the characteristics required to carry the internal and external loads of a degraded host pipe. The focus of this work was on high-pressure composites and liners (up to 350 psig) installed using trenchless technology which can provide remediation to the pipe and its appurtenances.

The results of the testing program and analysis are presented for the composite pipes and for the high-pressure liners as follows:

<u>Composite Pipes:</u>

The composite pipes available in the market for the rehabilitation of natural gas and liquid lines were reviewed. The rehabilitation of these lines is particularly problematic in urban congested pipeline systems with very limited right of way space. Although most of the composite pipes were suitable for these rehabilitations, various characteristics govern their selection and use; including:

- Most of the composite pipes have standard diameters from 2 to 8 inches. Few of the composites manufacturers produce pipes up to 16 inches.
- The pressure capacity of the composite pipe depends on its size. All the composites in the review were designed to carry operating pressures higher than 350 psig (with some composites up to 1,500 psig).
- Pipe bends and minimum radius are the major factors which govern the selection of the composite pipe. Most of the composite pipes require large bend radius, with limited insertion capabilities in multiple bends.
- Most of composite pipes do not have hot tap connections and they accommodate laterals, valves and other fittings by transitioning back to steel pipes with the necessary fittings.

The review of composite pipes covered the current requirements by the state regulators and PHMSA for granting special permits for use of these pipes where it is difficult to replace the existing pipes.

The long-term pressure rating of composite pipes with standard end fittings was evaluated in cyclic-pressure tests at room and elevated temperatures. Cyclic pressure tests are commonly used in evaluating the strength of non-compressible liquid transmission pipes which are subjected to cyclic pressure loading during their operation.

Elevated temperature tests were used to extrapolate the long-term hydrostatic pressure by utilizing extrapolation time factors (based on ISO Standard for the determination of the long-

term hydrostatic strength of thermoplastics by extrapolation) to shift the results on a logarithmic time-scale.

Two composite pipes were evaluated in the long-term performance tests: 'Primus Liner' and 'Flexpipe'. The two composites sustained line pressures of about 750 psig for extended durations of about 350,000 pressure cycles.

The long-term life expectancy of these composites was estimated by dividing the number of experimental cycles to failure by the appropriate fatigue design factor. This factor typically ranges between 10 and 20 (the ASME Boiler & Pressure Vessel Code employs a safety factor of 20 on experimental fatigue data) to establish a design life cycles.

The design life cycles are then divided by the actual number of cycles in the field at an equivalent pressure range to obtain the expected number of years of service.

Cured-in-Place (CIP) Liners

The principal characteristic of the liners used in the rehabilitation of liquid and gas pipelines is their low permeability to a broad range of gases, vapors, and liquids. A permeability test was performed with the Starline HPL-450 High-Pressure liner in a 12-inch diameter pipe sample. The test evaluated the time for the natural gas to permeate through the liner to the pipe wall. Methane concentration was measured for a duration of 6 weeks to reach a steady-state condition through the 2-mm thick liner at 350 psig pressure at room temperature.

The interface between the CIP liner and the pipe was evaluated in a Finite Element Analysis (FEA). The analysis was performed to evaluate the bonding strength between the liner and the pipe when a rapid depressurization of high-pressure occurs, which in turn can cause a delamination of the liner from the host pipe. Various liner and adhesive parameters were evaluated when the pipe was depressurized. The gas pressure levels where disbondment occurred were determined and plotted in graphs for various void sizes, liner tensile properties, and adhesive strengths.

Laboratory tests were performed on the liner in order to evaluate gas formation in the disbonded areas (voids) during the rapid pressure depressurization. These tests evaluated the theoretical FEA development for the disbondment between the liner and pipe. No disbondment was observed when the pressure was dropped from 350 psig to atmospheric pressure in 15 minutes except in two areas near an initial void in the liner.

Tests were also performed to evaluate the effect of rapid depressurization on liners installed in pipes with various degrees of bends and elbows. The liners were installed in 12-inch diameter pipe samples with bends of 22.5, 45, and 90-degrees. No delamination was observed after the rapid depressurization of the samples from 100 and 200 psig to atmospheric pressure. A small disbonded circular area was observed in a bend after depressurization from 350 psig to atmospheric pressure.

The results confirm the applicability of using liners in bends without significant disbondment; providing that tests are performed to identify the limiting pressure before disbondment occurs. Liners in bends should also be inspected to ensure the wrinkles are fully bonded with the adhesive without any visible initial voids.

Implementation of Composite Pipes and Liners

The use of composite pipes and liners in the rehabilitation of natural gas and liquid transmission lines provides various advantages over the open-trench excavation and replacement of the deteriorating host steel pipes. These advantages include:

- The various components of the composites allow for a wide range of applications and pipe sizes with various pressure ratings,
- Composite material provide high corrosion resistance, high strength-to-weight ratio, and high resistance to chemicals and aggressive environment,
- Small diameter composites are commonly spoolable to a long length, thus facilitating the procedure of trenchless insertion with a minimum number of excavation pits and with a small footprint at the installation site.

The material cost of the composite components can be somewhat higher than steel. However, the installation cost of these pipes is much less than for the steel. Although the use of these composites in the rehabilitation of gas transmission lines can provide a safe, practical, and economical alternative, the main requirements for their approval pertain to the acceptable of the material specifications, design, installation qualification, and quality control. Some of the barriers that limit their implementation include:

- The need for establishing quality control and inspection processes during manufacturing,
- Development of Non-Destructive Evaluation (NDE), quality control, and inspection procedures during the installation of the composite pipe and in-service,
- Determine the composites susceptibility to external damage during field installation and third party excavation, and establish their Fitness-for-Service evaluation procedure.
- The need to evaluate the joints and valves used with the composite pipes in high pressure operations.

Introduction

The rehabilitation of the natural gas distribution and transmission infrastructure is particularly problematic in urban areas with congested pipeline system, very limited right of way space, and high excavation and restoration costs. The use of composite pipes and structural liners with trenchless technology in the rehabilitation of these systems is an alternative to open trench replacement option.

New composite materials are continuously being introduced and considered for the rehabilitation of ageing transmission and distribution pipelines. The qualification of these systems requires an integrated approach to determine the material characteristics and their interaction mechanism with the host pipe. Further qualification requirements of the composite systems include the following:

- Establishing the installation procedures and joining and fittings,
- Identifying the inspection procedures and the system fitness-for-service, and
- Determining long-term performance parameters and identifying the primary and secondary failure mechanisms.

Chapter 1 of the report presents a review of the composite pipes and structural liners in the market which are used in the rehabilitation of high-pressure natural gas and liquid pipelines. The chapter builds on the information provided by the manufacturers of composite pipes and reviews the currently available systems. These composites contribute to the load carrying capacity of the system and, ultimately, carry the internal and external loads of a deteriorated pipe. Most of these composites are used in offshore and onshore piping, gathering, and injection lines in oil and gas production.

Some pipeline operators have recently received special permits to use composite pipes, such as Smart Pipe, Fiberspar, and FlexSteel to rehabilitate aging pipes. Most of these systems were used in the rehabilitation of distribution, transmission, and gathering lines which operate in Class 1 and 2 locations. Chapter 2 reviews these permits and investigates the requirements for their acceptance.

A cyclic-pressure testing procedure was used to evaluate the long-term strength of the composite pipes. The procedure involved subjecting full-scale composite pipes, with standard field end-fittings, to cyclic pressures at room temperature and at elevated temperatures in excess of the field operating temperature. The long-term testing procedure is presented in Chapter 3. The results of these tests allow for estimating the long-term hydrostatic pressure of the composite pipe when the operating pressure and the annual number of cycles in the field are known. Chapter 4 presents the results and analysis of the cyclic pressure tests.

Several high pressure Cured-in-Place (CIP) liners in the market today can be used in the rehabilitation of transmission lines at operating pressures up to 350 psig. Most of these liners are designed to partially support deteriorated pipes with holes and gaps up to 2 inches in size. However, these liners still rely on the structural strength of the host pipe to carry the internal and external loads. When the CIP liners are not fully bonded with the host pipe, gas formation in the voids between the liner and the host pipes may result in disbondment when the pipe is depressurized. Chapter 5 presents a finite element analysis to investigate the liner-pipe interface mechanism and evaluates their bonding strength in high pressure applications.

The analysis is complemented by laboratory tests in Chapter 6 to evaluate the bonding strength in full-scale lined pipes. These tests were performed on high-pressure liners installed in 12-inch steel pipes to evaluate the possible disbondment of the pipes after the rapid depressurization of the system from 350 psig to atmospheric pressure. These tests were evaluated in pipe sections with various bends and gaps.

The use of the composite pipes and liners in the rehabilitation of natural gas and liquid transmission lines provides various advantages over open-trench replacement of deteriorating host pipes. These advantages include their high corrosion resistance, high strength-to-weight ratio, and their applicability for use in trenchless insertion into the host pipe with a minimum number of excavation pits. However, several barriers still limit their implementation for long-term applications, including: The need to establish installation quality control and damage inspection technologies, quantification of their susceptibility to external damage and their fitness-for-service procedures, and evaluation of the joints and valves used in field installations. A review of the performance requirements of these systems is presented in Chapter 7.

Chapter 1. Structural Composites and Liners for the Rehabilitation of High-Pressure Liquid and Natural Gas Pipelines

Various types of composite pipes and liners exist in the market and are candidates for the rehabilitation of the high-pressure oil and natural gas pipelines. These systems mainly consist of two or more dissimilar layers of materials, with one or more of the layers being the load-carrying component while the other inner and outer layers mainly provide low permeability and protection. The load-carrying component consists of various material types, including steel, fiberglass, carbon, or other reinforcement fibers.

The characteristics of composites that make them preferred candidates for pipeline rehabilitation include their resistance to chemicals and corrosion, high strength, light weight, and flexibility. There are a number of different resins and fiber reinforcement materials used in the composite pipes manufactured today. Some of the composites have layers which are only tight fitted, without a bond, in a non-matrix formation. Other composites have the load-carrying fibers bonded in a thermoset polymer resin matrix which transfers the loads between fibers. Epoxy resins are the most common resin used in these systems. These resins have high strength properties, good chemical resistance, and they generally require heat-curing.

Several types of reinforcement fibers are used, including (1):

- E-Glass: This material is a low cost fiber characterized by good strength, low modulus, and availability in many forms. It is commonly used in commercial and industrial products, mostly in filament winding.
- S-Glass: This fiber provides better strength than E-Glass, with higher modulus and cost. It is commonly used in aerospace and high performance pressure vessel applications.
- Aramid: These fibers have good strength and higher modulus with lower density (one-half of the glass fiber density). It has excellent impact and damage tolerance properties and relatively poor compression and shear strength (DuPont KEVLAR falls in this category).
- Carbon/Graphite: These materials have a wide strength range, higher tensile strength and stiffness modulus, intermediate density (two-thirds of glass fiber), and low impact or damage tolerance. They also have the highest cost of all the other fibers.

The most common type of fiberglass pipes is reinforced-thermosetting-resin-pipe (RTRP). In the oil industry, fiberglass pipe is also commonly referred to as Fiberglass Reinforced Plastic (FRP), or Glass Reinforced Epoxy (GRE). The glass-reinforced epoxy laminate pipes are commonly spoolable (such as the Fiberspar LinePipe) and are widely used in flow line applications.

The other pipe type is the Composite Reinforced Line Pipe (CRLP) and it consists of steel pipe coated or wrapped in a continuous composite shell material that adds strength and protection to the steel (such as FlexSteel pipes). The following sections present most of the composite pipes and liners which have been used in the oil and gas production and transportation.

1. Primus Line

The Primus Line is a composite structure for the trenchless rehabilitation of liquid and gas pipelines. The composite liner consists of a 3-layer high-pressure flexible tube which provides both flexibility and high material strength. The inner layer of the tube is selected for the gas media. The outer layer is made of wear-resistant polyethylene (PE) and the middle layer is a seamless aramid fabric, functioning as the load-bearing layer (Figure 1).

The liner is produced in nominal diameters from 5.2 inches (DN 150) to 18 inches (DN 500); which are suitable for installations in pipe diameters from 6 to 20 inches. The dimensions and corresponding pressure rates for the liners are shown in Table 1.

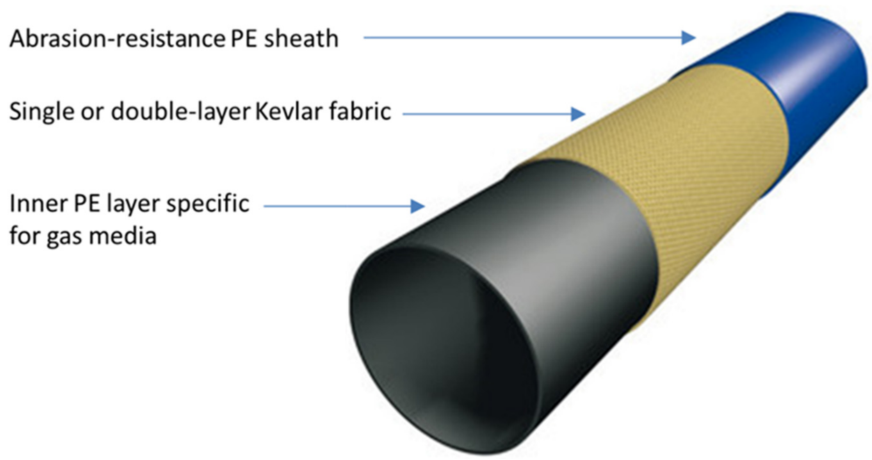


Figure 1 - The Primus Line components

In field installations, the liner is folded and inserted into the host pipe from small construction pits. The liner is not attached to the host pipe and an annulus space remains between the liner and the host pipe. A high-pressure welded or flanged connector is used at each end of the pipe to connect to the host pipe (Figure 2). The high-pressure connector consists of a contoured internal core and external sleeve. The external sleeve has a malleable steel jacket on the inside. A resin, which is injected through a valve on the external sleeve, forces the steel sleeve and the liner into the contours of the internal core.

Table 1 shows that the liner is suitable for rehabilitating high pressure gas lines up to 450 psig working pressure in 12-inch diameter pipes. It can run through several bends with minimum bend radius of 5 times the diameter.

Like most of the other composite pipes, it is made for the rehabilitation of pipe segments without service connections, drips, or valves. At the locations where joints are required, open excavations need to be performed. These locations are used as entry and exit points for the composites and end connections are installed before and after the valves and services.

Table 1 - Pressure Rates for the Primus Line (2)

Pressure range	Primus Line® flexible pressure pipe	Maximum working pressure *			Short time burst pressure	
		Gas	Oil	Water		
low pressure	Primus Line® **DN 150 / 5,2 inch** Suitable for installation into a DN 150 / 6 inch – pipe	---	---	406 psi (28 bar)	> 85 bar	> 1233 psi
medium pressure	Primus Line® **DN 150 / 5,2 inch** Suitable for installation into a DN 150 / 6 inch – pipe	493 psi (34 bar)	493 psi (34 bar)	798 psi (55 bar)	> 138 bar	> 2001 psi
low pressure	Primus Line® **DN 200 / 7,2 inch** Suitable for installation into a DN 200 / 8 inch – pipe	---	---	290 psi (20 bar)	> 60 bar	> 870 psi
medium pressure	Primus Line® **DN 200 / 7,2 inch** Suitable for installation into a DN 200 / 8 inch – pipe	363 psi (25 bar)	363 psi (25 bar)	566 psi (39 bar)	> 98 bar	> 1421 psi
high pressure	Primus Line® **DN 200 / 7,2 inch** Suitable for installation into a DN 200 / 8 inch – pipe	566 psi (39 bar)	566 psi (39 bar)	899 psi (62 bar)	> 156 bar	> 2248 psi
low pressure	Primus Line® **DN 250 / 9,3 inch** Suitable for installation into a DN 250 / 10 inch – pipe	---	---	218 psi (15 bar)	> 45 bar	> 653 psi
medium pressure	Primus Line® **DN 250 / 9,3 inch** Suitable for installation into a DN 250 / 10 inch – pipe	276 psi (19 bar)	276 psi (19 bar)	435 psi (30 bar)	> 76 bar	> 1102 psi
high pressure	Primus Line® **DN 250 / 9,3 inch** Suitable for installation into a DN 250 / 10 inch – pipe	551 psi (38 bar)	551 psi (38 bar)	870 psi (60 bar)	> 150 bar	> 2175 psi
low pressure	Primus Line® **DN 300 / 11,1 inch** Suitable for installation into a DN 300 / 12 inch – pipe	---	---	174 psi (12 bar)	> 38 bar	> 551 psi
medium pressure	Primus Line® **DN 300 / 11,1 inch** Suitable for installation into a DN 300 / 12 inch – pipe	232 psi (16 bar)	232 psi (16 bar)	377 psi (26 bar)	> 64 bar	> 928 psi
high pressure	Primus Line® **DN 300 / 11,1 inch** Suitable for installation into a DN 300 / 12 inch – pipe	450 psi (31 bar)	450 psi (31 bar)	725 psi (50 bar)	> 124 bar	> 1798 psi
medium pressure	Primus Line® **DN 400 / 13,9 inch** Suitable for installation into a DN 400 / 16 inch – pipe	174 psi (12 bar)	174 psi (12 bar)	290 psi (20 bar)	> 50 bar	> 725 psi
high pressure	Primus Line® **DN 400 / 13,9 inch** Suitable for installation into a DN 400 / 16 inch – pipe	363 psi (25 bar)	363 psi (25 bar)	580 psi (40 bar)	> 100 bar	> 1450 psi
medium pressure	Primus Line® **DN 500 / 18,1 inch** Suitable for installation into a DN 500 / 20 inch – pipe	145 psi (10 bar)	145 psi (10 bar)	218 psi (15 bar)	> 38 bar	> 551 psi

Figure 2 - Welded and flange end connections for the Primus Line

2. Smart Pipe

The Smart Pipe consists of a high-density polyethylene (HDPE) core pipe, a combination of longitudinal and helically-wrapped high-strength fabrics, carbon fiber pulling tapes, fiber optic sensors, and a thin outer HDPE protective layer (Figure 3). The liner material is deformed into a "C" shape for insertion into the host pipe. After being pulled into the host pipe, it is reformed into a tight fitting liner for sustaining the internal pressures, external loads, and bending stresses. The fiber optic provides the operators with continual condition monitoring of the pipe deformations.

The Smart Pipe is simultaneously manufactured using a portable installation unit and installed using trenchless technology in the pipeline segment. The liner is designed and manufactured in accordance with ASTM D2896 (3).

The components of the Smart Pipe are not bonded together with adhesives. Due to the absence of such matrix, the helical fibers will tend to seek out their natural wrap angle unless prevented. FEA was performed and validated with lab tests to evaluate the burst pressure of the system (4).

The number and angle of bends in the line are limited and depend on the size of the pipe. Earlier work by Smart Pipe showed the minimum radius bend that can be successfully negotiated is about 20 time the diameter (5). Special permits were filed for the installation of the composite in 6 and 12-inch gas lines. Further details of these permits are in Chapter 2.

Similar to other composites, it is used in the rehabilitation of pipe segments without services, drips, or valves in the line. These locations may be assigned as entry and exit points with valves and joints connected to the composite with steel end connections. Since the composite is simultaneously manufactured and installed, it may require a large installation area for the factory setup at the entry point as shown in Figure 4.

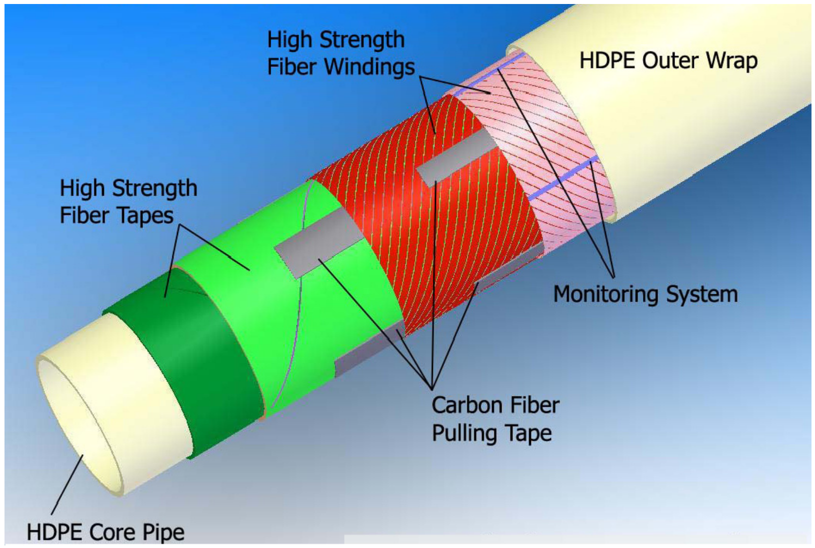


Figure 3 - The Smart Pipe Components

Figure 4 - Portable setup for the pipe fabrication

3. FlexSteel Pipe

The FlexSteel pipe consists of steel reinforced core between inner and outer PE liners for protection and corrosion resistance (Figure 5). The FlexSteel is a spoolable pipe typically installed in open trench installations in gathering and production lines. The manufacturer data estimates that it provides 50 percent average saving versus steel pipe installations. The steel core provides electrical continuity, which eliminates the need for tracer wires for stand-alone pipes, but have limited benefit if it is inserted inside a steel host pipe. The main features of the FlexSteel are:

- Diameters from 2 inches to 8 inches,
- Pressure ratings from 750 psi and up to 3,000 psi,
- Spooled on reels up to 8,858 feet (2,700 meters),
- Average bending radius of 3 to 5 feet.

The end fittings consist of a swaging unit, which use hydraulic compression to form a steel sleeve of an end fitting permanently onto the pipe wall. A hydraulic unit applies a uniform tight compression seal between the FlexSteel and the other components. The flanged end fitting (Figure 6) is the most commonly used to connect with other standard pipeline components, such as valves and other upstream/downstream connections.

The FlexSteel pipe is designed according to American Pipeline Institute (API) 17J specifications (6) for the design, manufacturing and installation of flexible pipes. The pipe is also used in the trenchless rehabilitations with long lengths. Special permits were filed for the installation of 6-inch FlexSteel pipe with a single pull of 9,500 feet through a 12-inch steel pipeline.

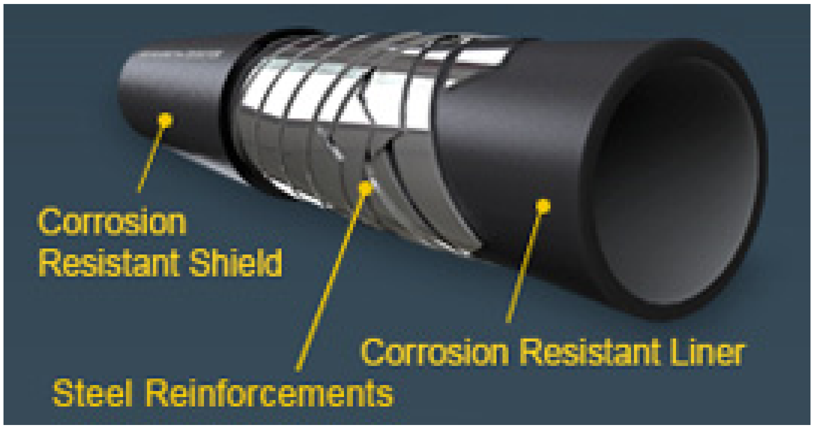


Figure 5 - The FlexSteel composite pipe

Figure 6 - Flanged end connection of the FlexSteel Pipe

Table 2 - Dimensions of the 750-psi FlexSteel Pipe

	3-inch pipes	4-inch pipe	6-inch pipe
Pipe inside diameter (inch)	2.82	3.67	5.6
Pipe Outside Diameter (inch)	3.65	4.58	6.93
Operating bend radius (ft)	2.7	3.4	5.2

4. Fiberspar LinePipe

The Fiberspar LinePipe consists of a thermoplastic pressure barrier, a helically wound glass fiber with an epoxy bonding layer, and an external wear layer (Figure 7). The pipes are produced in 2 inches to 8 inches ID, and in continuous spoolable lengths up to 36,000 ft (depending on the pipe size). The Fiberspar LinePipe is designed and manufactured in accordance with API 15HR (7), API 15S (8), and ASTM D2996 (9). The pipe end connection is shown in Figure 8.

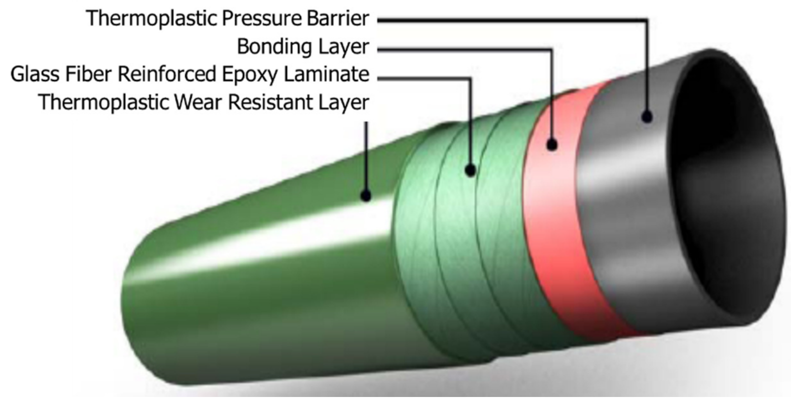


Figure 7 - The Fiberspar LinePipe

The Fiberspar Spoolable pipes were used with special permits in the following applications:

- Columbia Gas Waiver, approved March 2005, for the installation of 4,200 ft 4-inch pipe as a gas transmission line operation at 750 psig. Samples at 1, 2.5, and 5 years were removed and tested, and showed no signs of degradation.
- Anchor Point Special Permit, approved in October 2010, for the installation of 33,200 ft of 4-½ inch gas pipe operating at 1,328 psig.

The Fiberspar LinePipe is available with HDPE or high-temperature polyethylene (HTP) pressure barriers. The temperature ratings are 140ºF and 180ºF, respectively. The pipe properties are shown in Table 3.

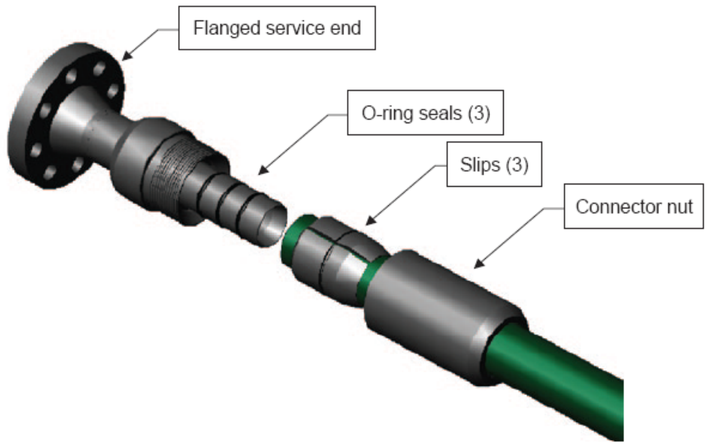


Figure 8 - Fiberspar flanged end connection to host pipe

Table 3 - Fiberspar LinePipe Specifications (10)

Product Name	ID (in.)	OD (in.)	Nominal Reinforced Wall Thickness (nom.)	Minimum Reinforced Wall Thickness (min.)	Weight (lbs/ft)	Recommended Maximum Operating Pressure* (psi)	Minimum Burst Room Temperature (psi)	Minimum Burst Operating Temperature (psi)	Maximum Recommended Install Tensile Load (lbf)	Minimum Bend Radius (in.)
300 Series										
FS LP 3" 300 (E)	2.51	3.04	0.055	0.047	1.18	300	2,219	1,886	3,000	71
FS LP 3" 300 (X)	2.51	3.04	0.055	0.047	1.18	300	2,219	1,664	3,000	71
FS LP 4" 300 (E)	3.33	4.01	0.072	0.061	1.99	300	2,165	1,840	5,480	95
FS LP 4" 300 (X)	3.33	4.01	0.072	0.061	1.99	300	2,165	1,624	5,480	95
FS LP 6" 300 (E)	4.75	5.48	0.079	0.067	2.98	300	1,698	1,443	7,960	132
FS LP 6" 300 (X)	4.75	5.48	0.079	0.067	2.98	300	1,698	1,274	7,960	132
750 Series										
FS LP 2 ½" 750 (E)	2.00	2.55	0.080	0.068	1.05	750	3,940	3,349	3,480	59
FS LP 2 ½" 750 (X)	2.00	2.55	0.080	0.068	1.05	750	3,940	2,955	3,480	59
FS LP 3" 750 (E)	2.51	3.10	0.082	0.070	1.40	750	3,266	2,776	4,480	72
FS LP 3 ½" 750 (E)	2.96	3.59	0.090	0.076	1.75	750	3,046	2,589	5,720	85
FS LP 3 ½" 750 (X)	2.96	3.59	0.090	0.076	1.75	750	3,046	2,285	5,720	85
FS LP 4" 750 (E)	3.48	4.16	0.106	0.090	2.26	750	3,101	2,636	7,960	99
FS LP 4 ½" 750 (E)	3.99	4.73	0.122	0.103	2.87	750	3,095	2,631	10,440	113
FS LP 4 ½" 750 (X)	3.99	4.73	0.122	0.103	2.87	750	3,095	2,321	10,440	113
FS LP 6" 750 (E)	4.75	5.62	0.150	0.128	4.04	750	3,200	2,720	15,360	136
FS LP 6" 750 (X)	4.75	5.62	0.150	0.128	4.04	750	3,200	2,400	15,360	136
FS LP 6 ½" 750 (E)	5.60	6.55	0.161	0.136	5.14	750	2,912	2,475	19,320	159
FS LP 6 ½" 750 (X)	5.60	6.55	0.161	0.136	5.14	750	2,912	2,184	19,320	159
1,500 Series										
FS LPJ 2 ½" 1,500 (E)	1.89	2.48	0.095	0.080	1.12	1,500	4,838	4,112	4,000	57
FS LPJ 2 ½" 1,500 (X)	1.89	2.48	0.095	0.080	1.12	1,500	4,838	3,629	4,000	57
FS LPJ 3" 1,500 (E)	2.37	3.04	0.113	0.096	1.60	1,500	4,660	3,961	5,960	71
FS LPJ 3" 1,500 (X)	2.37	3.04	0.113	0.096	1.60	1,500	4,660	3,495	5,960	71
FS LPJ 3 ½" 1,500 (E)	2.82	3.57	0.134	0.114	2.18	1,500	4,656	3,958	8,440	84
FS LPJ 3 ½" 1,500 (X)	2.82	3.57	0.134	0.114	2.18	1,500	4,656	3,492	8,440	84
FS LPJ 4" 1,500 (E)	3.33	4.18	0.161	0.136	2.95	1,500	4,722	4,014	11,920	100
FS LPJ 4" 1,500 (X)	3.33	4.18	0.161	0.136	2.95	1,500	4,722	3,542	11,920	100
FS LPJ 4 ½" 1,500 (E)	3.75	4.68	0.179	0.152	3.61	1,500	4,661	3,962	14,880	112
FS LPJ 4 ½" 1,500 (X)	3.75	4.68	0.179	0.152	3.61	1,500	4,661	3,496	14,880	112
FS LPJ 6" 1,500 (E)	4.52	5.62	0.218	0.185	5.20	1,500	4,715	4,008	22,040	135

5. Polyflow Thermoflex Tubing

The Polyflow Thermoflex tubing consists of an inner and outer protection layers and a middle fiber reinforced layer with Kevlar for strength (Figure 9). The pipe size is typically 1 to 6 inches in diameter with the properties shown in Table 4. The tubing comes in spools with the length dependent on the pipe OD as shown in the table.

The tubing is commonly used in offshore and onshore surface piping, low pressure wells, gathering and injection lines, and solid transport in CBM (coal-bed methane) applications. The couplings are stainless steel or plated carbon steel, with threaded, flanges of welded termination connections.

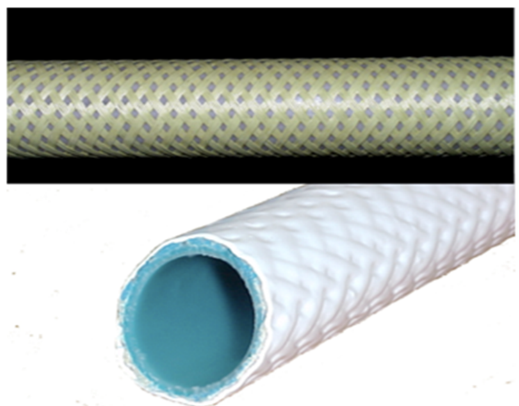


Figure 9 - The Polyflow Thermoflex Tubing

Table 4 - The Polyflow Themoflex Pipe Properties

Thermoflex® Pipe Sizes and Pressures

Size	275 PSI	500 PSI	750 PSI	1000 PSI	1500 PSI
1.00	•	•	•	•	•
1.25	•	•	•	•	•
1.50	•	•	•	•	•
1.75	•	•	•	•	•
2.375	•	•	•	•	•
3.00	•	•	•	•	•*
3.50	•	•	•	•	•**
4.00	•	•	•	•	
4.50	•	•	•		
6.00	125°F Max	125°F Max	90°F Max		

*1450 PSI @ 150°F
**1450 PSI @ 90°F and 1250 PSI @ 150°F
Call for other pipe configurations.

6. Flexpipe Systems

The Flexpipe Systems currently have 4 product lines as follows:

- Flexpipe Linepipe: It consists of helically wound fiber glass reinforcement, internal HDPE liner, and an external thermoplastic jacket for protection (Figure 10). It is available in 2, 3, and 4 inches internal diameter sizes with 300, 750, and 1500 psi pressure ratings. Table 5 shows the specifications of these lines.
- Flexpipe Linepipe High Temperature: Capable of operating up to 180°F continuously and up to 200°F for excursions. It consists of wound fiberglass with HDPE-RT internal liner and external jacket. It is available in 2, 3 and 4 inches internal diameter sizes with a maximum operating pressure of 1,500 psi.
- FlexCord Linepipe: Designed for severe pressure cycles and pulsations such as those generated by piston pumps. It consists of layers of galvanized steel cords and thermoplastic internal liner and external jacket. It is available in 3 and 4 inches internal diameter sizes and has a pressure rating of 2,000 psi.
- FlexFlow Linepipe: This line is currently under development. It has 6 and 8 inches internal diameter sizes and consists of reinforcement layers between a thermoplastic liner and a jacket. As reported by Flexpipe, the production of these pipes is expected by the end of 2015.

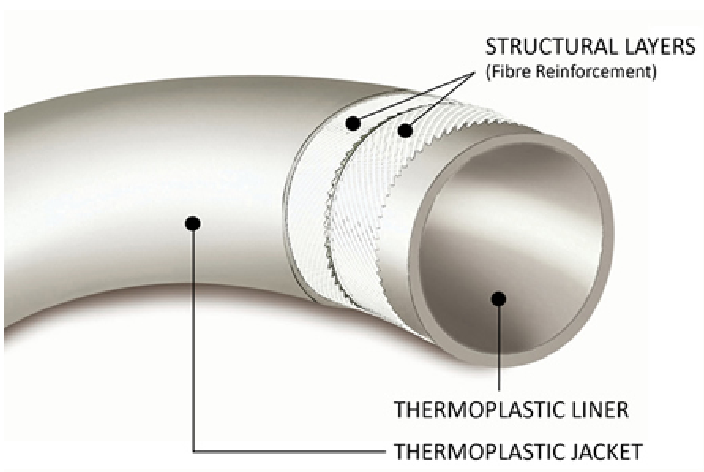


Figure 10 - The Flexpipe Linepipe

Flexpipe is used for continuous high pressure transmission feeder lines, gathering, water disposal, and injection in oil and gas production. The system is suitable for both trenching and pulling through an existing steel pipe. The high-temperature Linepipe may be applied in the rehabilitation of small diameter gas mains which are running in close proximity to high temperature steam lines.

For pipe joints and connections, a pipe-to-pipe coupling is used to join reels of pipe. An end fitting with a standard ASME B16.5 lap-joint flange is used to terminate the pipeline materials. Both the coupling and end fitting are mechanical metal fittings that are installed using specialized installation equipment. The mechanical force applied creates a clamping pressure that holds the pipe in place and provides a seal between the thermoplastic liner and the fitting. For additional seal reliability, the fitting is equipped with two O-rings made of neoprene rubber.

The Flexpipe products are designed and manufactured in accordance with API RP 15S (8), and ASTM D2992 (11).

Table 5 - Specifications of the Flexpipe Linepipe

		FP601			FP301			FP150	
Maximum Operating Pressure @ 60°C or 140°F		10,342 kPa/1500 psi			5,171 kPa/750 psi			2,068 kPa/300 psi	
Nominal Size		2″	3″	4″	2″	3″	4″	3″	4″
Outside Diameter	Metric (mm) Imperial (inches)	73 2.86	101 3.96	130 5.11	69 2.73	97 3.80	124 4.89	95 3.74	122 4.80
Inside Diameter	Metric (mm) Imperial (inches)	54 2.12	77 3.02	99 3.90	54 2.12	77 3.02	99 3.90	77 3.02	99 3.90
Weight	Metric (kg/m) Imperial (lbs/ft)	2.5 1.7	4.3 2.9	6.9 4.6	1.7 1.1	3.0 2.0	4.9 3.3	2.6 1.7	4.0 2.7
Min. Bend Radius (operational)	Metric (m) Imperial (ft)	1.2 4	1.8 6	2.1 7	1.2 4	1.8 6	2.1 7	1.8 6	2.1 7
Length / Reel	Metric (m) Imperial (ft)	1150 3773	730 2395	600 1970	1150 3773	800 2625	785 2575	800 2625	785 2575
Reel Diameter	Metric (m) Imperial (ft)	3.7 12	3.7 12	3.7 12	3.7 12	3.7 12	3.7 12	3.7 12	3.7 12
Reel Weight – Full	Metric (kg) Imperial (lobs)	3450 7600	3820 8400	5723 11600	2635 5800	3100 6800	5000 11000	2760 6100	4270 9400
Fitting Outside diameter*	Metric (mm) Imperial (inches)	80.5 3.17	108.5 4.27	139.2 5.8	75.9 2.99	103.1 4.06	131.8 5.19	101.6 4.00	129.3 5.09

7. Starline-Structural Liner

The Starline Cured-In-Place Pipe (CIPP) liners are currently used in rehabilitating pipelines with defects such as localized corrosion, welds that are weaker than required for service, and leaking joints in cast-iron pipes. The liner consists of a seamless hose made of polyester fabric with a plastic coating and it is inserted into the host pipe by the inversion process (Figure 11). The liner is uniformly glued to the interior wall of the host pipe with a solvent-free two-component adhesive (12).

The two main Starline CIPP products used in the rehabilitation of gas lines are:

- Starline 2000: Which is used in the rehabilitation of distribution natural gas pipelines. The system is installed in sections up to 1,500 ft in length and diameters from 3 to 24 inches, with minimum allowable operating pressure (MAOP) up to 100 psi.

- Starline HPL-G: This system is used in the rehabilitation of medium to high pressure pipelines from 8 inch to 24 inch. Two types of the HPL-G are used in the rehabilitation of steel pipes as shown in Table 6.

Figure 12 shows the installation equipment for the liner. Higher pressure Starline-Structural Liner is currently under development to provide stand-alone liners that can support gas pipes from 6 inches to 24 inches in diameter at operating pressures up to 350 psi.

Figure 11 - Inverted-liner in the host pipe

Table 6 - Properties of the HPL-Gas liners

Diameter	HPL-450 (Type 1 liner): 10 – 24 inches HPL-180 (Type 2 liner): 6 – 24 inches
Length	up to 2,000 ft. per line depending on installation equipment and pipe diameter
Operating Pressure	HPL-450: High pressure up to 250 psi for type 1 liner. HPL-180: High pressure up to 180 psi for type 2 liner.
Installation	- Launch and target pits are required per section. An additional small cleaning pit is needed for section lengths exceeding 1000 ft. - Pipe cleaned and dried. - Voids are filled for operating pressures above 100 psig
Pipe Condition	Partially deteriorated, e. g., with holes up to 2 inch or gaps up to 1 inch.
Joints and Tees	Tees are opened trenchless with a robotic cutter equipped and a CCTV camera.
Curing	Ambient - no additional equipment required.

Figure 12 - Installation truck for the HPL-G Liner

8. Other Composite Pipes in the Market

Several other composite pipes are used as risers and in injection, gathering, and flow lines in the oil and gas production systems (13). Most of these systems are limited by their small pipe diameters and have not been used in the gas distribution or transmission liners through special permits. Table 7 presents a summary of these systems.

Table 7 - Summary of Other Composites Pipes in the Market

Name	material	Sizes	Pressures (psig)	Notes
Airborne	PE,PP,PA	2 to 5 inches	1,500 - 2,500	
IT3 Multiwall	PE, PVC, PB, FRP	2 inches +	Up to 4,000	
Tite Liner®	HDPE, PE100	2 to 12 inches	Host pipe pressure	Loads also carried by host pipe
SRC	HDPE, PEX, PA-11	1 to 4 inches	2,250	

Chapter 2. Regulatory Requirements and Special Permits for Composite Pipes and Liners

The current pipeline design and regulation requirements in 49 CFR 192 (14) are based on using steel pipes in high-pressure gas transmission lines and they set certain design limitations in article §192.123 for using plastic pipes in the natural gas distribution system. The federal requirements for the transportation of hazardous liquids in the 49 CFR 195 (15) also limit the use of pipelines constructed with material other than steel. Article §195.8 states that:

> *"No person may transport any hazardous liquid or carbon dioxide through a pipe that is constructed … of material other than steel unless the person has notified the Administrator in writing."*

The design requirements in these codes are based primarily on Barlow's formula for hoop stress and the use of homogeneous materials. These requirements do not accommodate the more complex composition and characteristics of the composite material currently used in unregulated pipe systems (e.g., feeder, gathering and injection lines in oil and gas production). Accordingly, multiple aspects of the design, construction, testing, and operation of these composites are not covered in these regulations.

Accordingly, current use of composite material in gas and liquid transmission lines is granted by the state regulators and PHMSA through special permits based on limited allowances in situations where it is difficult to replace the existing pipe.

Special Permits Requirements

The special permit (previously called a waiver) is set by the OPS for waiving or modifying the regulatory requirements if the pipeline operator requesting it demonstrates such need. Federal and state regulators evaluate these requests to determine that granting a special permit would be consistent with pipeline safety.

The application process of the special permits is set forth in 49 CFR §190.341 and PHMSA performs extensive technical analysis on the applications and typically grants a special permit with certain conditions, providing that the performance of the proposed alternative measure will provide an equal or greater level of safety.

The state waiver is similar to the special permit, except that it waives or modifies compliance with a regulation adopted by the state pursuant to its participation in the pipeline safety program. Prior to issuing a state waiver, the state is required to provide PHMSA with a 60 day review period.

In the 49 CFR §190.341 article, the information required for the application of a special permit contains items; summarized as follows:

1. The contact information of the applicant/operator,

2. A detailed description of the pipeline facilities, including:
   - The beginning and ending points of the pipeline mileage to be covered and the counties and states in which it is located;
   - Whether the pipeline is interstate or intrastate and a general description of the right-of-way including proximity of the affected segments to populated areas;
   - Relevant pipeline design and construction information including the year of installation, the material, grade, diameter, wall thickness, and coating type;
   - Relevant operating information including operating pressure, leak history, and most recent testing or assessment results;
3. A list of the specific regulation(s) from which the applicant seeks a waiver or modification;
4. An explanation of the unique circumstances the applicant believes that the regulation or standard is unnecessary or inappropriate;
5. A description of any measures or activities the applicant proposes to undertake as an alternative, including an explanation of how such measures will mitigate any safety or environmental risks;
6. A description of any positive or negative impact on affected stakeholders and a statement indicating how operating the pipeline pursuant to a special permit would be in the public interest;
7. A certification that operation of the applicant's pipeline under the requested special permit would not be inconsistent with pipeline safety;
8. If the application is for a renewal of a previously granted waiver or special permit, a copy of the original grant of the waiver or permit;
9. Any other information PHMSA may need to process the application including environmental analysis where necessary.

Examples of Special Permit Applications for Use of Composites

PHMSA publishes the requests for special permits from pipeline operators in the Federal Docket Management System. A summary of the requests pertaining to the use of composite pipes in the oil and gas pipelines is shown in Table 8.

Table 8 - List of Special Permits for Structural Composite Pipes

Date	Requester	Regulations Affected	Nature of Permit
March 3, 2005, RSPA-04-18757	Columbia Gas		Use of Fiberspar composite to install 4,200 ft of 4-inch diameter in Dundee Storage Field (five storage wells and six lines), Class 1. Granting the special permit included a number of conditions on the qualification of the material and personnel, and follow-up inspections involving non-destructive and destructive testing.
April 17, 2009	Cinco Natural Resources		Use of FlexSteel in gas gathering in Redfish Bay, offshore Nueces and San Patricio Counties in Texas through Texas Railroad Commission (TxRRC). The permit included the installation of 25,000 feet of 6-inch FlexSteel pipe through existing 12-inch steel pipe to rehabilitate. The operating pressure of the pipe was 250 psig and the permit included 12 conditions in addition to the state waiver conditions.
October 30, 2009	THUMS, Long Beach, CA	Articles: §§195.406(a), 195.452(c) (i) (B), and 195.452(f) (2).	Use of Smart Pipe in crude oil application through CA State Fire Marshall. The permit included the replacement of 315 foot steel pipe running between processing facility and tank farm, under access roads, multiple railroad tracks and ancillary structures. The composite pipe is inserted and encased within 20-inch steel line, sleeved in 30-inch steel at pressure of 40 psi and normal operating temperature 120-125 F. The permit included 14 conditions in addition to state waiver conditions. The requester for the special permit addressed the requirements.
October 8, 2010	Anchor Point Energy, Alaska		Use of Fiberspar in 6.3 mile segment of intrastate natural gas transmission. The permit is to install two parallel 4.5-inch diameter lines, in a Class 1 zone. The special permit allowed the calculation of the pipe allowable pressure using the hydrostatic design basis (HDB) in ASTM D-2517 (16). This calculation resulted in MAOP of 1,328 psig. The special permit included 16 requirements (with many sub items) in the areas of design, construction, testing, construction quality control, corrosion control, pressure and temperature control, monitoring, O&M (including repair), and annual reporting.

Table -8 [Continued]

Date	Requester	Regulations Affected	Nature of Permit
April 21, 2010	Cinco Natural Resources Corp.	§§ 192.53, 192.55, 192.105, 192.107, 192.109, 192.111, 192.113, 192.221, 192.455, 192.503(b) and 192.619.	Use of FlexSteel for gathering system in Corpus Christi Bay, Nueces County, TX through TxRRC. The permit was for using 3-inch FlexSteel pipe in approximately 7,062 feet of an existing (but previously abandoned) 6-inch pipeline. The special permit required the inclusion of 8 PHMSA conditions in addition to TX waiver conditions.
January 20, 2011	Monument Pipeline	§§ 192.53, 192.121, 192.123 and 192.619(a)	Installation of Smart Pipe for test project at facility in Missouri City Texas through TxRRC. It includes the installation of one segment as tight fit liner inside 12" nominal steel pipe. One additional segment was to be installed independent of steel pipe and exposed to environmental and atmospheric events. The pipe was operating at pressures 600 to 800 psig.
Sept 29, 2011	Nicor Gas Company	§§192.53, 192.121, 192.123, and 192.619(a)	Use of Smart Pipe inside four 6-inch diameter steel lines underneath Illinois River through Illinois Commerce Commission. The lines are operating at 230 psig in Class 1 area. The special permit included 12 conditions (with many sub-items) in addition to Illinois conditions.
June 11, 2012	BreitBurn Energy Co. LP	§§192.121, 192.123, and 192.619(a).	Replacement of a segment of steel pipeline located in the city of Los Angeles, CA. Insert a 6-inch OD Smart Pipe system into a current 12-inch OD existing steel gas gathering line. The pipe is in need of replacement due to its age and a leak developed in August 2011 from a threaded connection. Further examination of a cut out section revealed internal corrosion. The normal operating pressure is 220 psig and MAOP is 245 psig. The line is type B as per §192.8 in a densely populated Class 4 area.

Review of the Special Permit Requirements

The review of the above permits for natural gas distribution, transmission, and gathering lines shows that they were mostly in Class 1 and 2 locations. The main requirements for their approval pertain to the acceptable of the material specifications, design, installation qualification, and quality control. The main challenges for completing these requirements can be summarized as follows:

- Most of the material specifications are based on the product/vendor-specific data. This area is vastly improving with the development of standards and practices for the material characterization (e.g., ASTM standards and API RP-15S (8)),
- The need for the design specifications to address the variable construction issues in the field such as cathodic protection and permeability,
- Long-term performance of the material, potential failure modes, cyclic fatigue effects, and repair methodologies,
- Quality control, inspection, and long term testing to confirm integrity and risk assessment,
- Fittings and interconnecting with existing standard facilities and appurtenances.

Chapter 3. Testing of Long-Term Performance of Composite Pipes

The long-term pressure rating of a composite pipe is determined from a series of stress rupture tests under various pressures at the qualification test temperature as per API Recommended Practice 15S (8). Pressure tests for obtaining the creep rupture strength of plastic pipes are commonly based on the ASTM D2992 testing procedure. In this test, creep failure points are determined from pipe samples failing at durations ranging from 100 hours to 10,000 hours when subjected to various hydrostatic pressures.

The above procedure may be adopted for evaluating the long-term pressure rating from cyclic pressure tests. Cyclic pressure tests are commonly used in evaluating the strength of transmission pipes carrying non-compressible liquid and subjected to cyclic pressure loading during their operation. The ASME PCC2 procedure for the design of composite repair systems (17) requires considering cyclic loading in the risk assessment if the predicted number of pressure cycles is more than 7,000 over the design life of the pipe.

The procedure used in this testing program involves subjecting full-scale test pipes, with standard end fittings, to various cyclic pressures at room temperature and at temperatures in excess of the standard operating temperature in the field. Elevated temperature tests also allow for extrapolation of the long-term hydrostatic pressure by utilizing the time-temperature equivalence of the material to shift the results on the time-scale.

Composite Samples

Two composite pipes were evaluated in the long-term performance tests; namely ‘Primus Liner’ and ‘Flexpipe’. The properties of the test samples of these composites are as follows:

<u>a) Primus Line:</u> The composite liner consists of a 3-layer high-pressure flexible tube. The inner layer of the liner is selected for the gas media. The outer layer is made of wear-resistant PE and the middle layer is a seamless aramid fabric, functioning as the load-bearing layer (Figure 1). The test samples were 6 ft long and 7.2-inch nominal diameter, which is used in the rehabilitation of 8-inch steel pipes. The minimum burst pressure of this size is 1,420 psig for the medium pressure composite and its pressure rating is 363 psig for gas and liquid lines as shown in Table 1.

In field installations, the composite liner is inserted but not attached to the host pipe with an annulus space between the liner and the host pipe. The test samples had high-pressure end caps at both ends to connect to the steel host pipe. The end caps were typical connectors used in the field to connect the end section of the liner to the steel pipe. Figure 13 shows the test sample inside the concrete test chamber.

Figure 13 - The Primus Line test sample with the end-caps in the test chamber

<u>b) Flexpipe Composite Pipe:</u> The composite pipe consists of helically-wound fiber glass reinforcement, internal HDPE liner, and an external thermoplastic jacket for protection. The test samples were 4.5-ft long, 4 inches internal diameter, and with 750 psi pressure rating. Table 5 shows the characteristics of the test samples.

The end-fittings in the samples were the fittings used in the field couplings. They were mechanical metal fittings installed by the manufacturer by applying mechanical force to provide a seal between the liner and the fitting. The fittings were equipped with two O-rings made of neoprene rubber for additional seal reliability. Figure 14 shows the test samples.

Figure 14 - Flexpipe composite test samples

Cycle Pressure Tests at Room Temperature

The short-term burst pressure of the composite products is commonly determined following the ASTM 1598 testing procedure (18) . For the long-term pressure rating, the API Recommended Practice 15S for the qualification of spoolable reinforced plastic pipes determines the pressure rating of the composite product from a series of stress rupture tests under constant pressures at the qualification test temperature.

The API recommendation is based on the ASTM D2992 testing procedure for obtaining the creep rupture strength of plastic pipes (11). In this testing procedure, creep failure points are determined from pipe samples failing at durations ranging from 100 hours to 10,000 hours when subjected to various constant hydrostatic pressures.

The API procedure includes a de-rating factor which accounts for the effect of cyclic service conditions on the pipe. Alternatively, cyclic pressure tests may be used to determine the pressure ratings under long-term cyclic pressures.

The cyclic pressure tests were performed with the composite samples in a concrete test chamber to evaluate their pressure rating in room temperature. Figure 15 shows the concrete chamber and test setup.

Figure 15 - The concrete chamber for room-temperature tests

The testing procedure of the long-term cyclic pressure tests was as follows:

- The test samples with the end fittings were prepared by the composites manufacturers. The samples were connected to the hydraulic system, filled with water, and pressurized to the initial test pressure. The samples were initially pressurized to 150-200 psig.
- The test samples were placed inside the concrete chamber and supported to prevent bending or deflection during the test.
- Cyclic pressures were applied to the samples to the targeted high pressure load. The loading levels varied to produce various numbers of cycles to failure. Cyclic pressure was applied using the hydraulic cyclic machine shown in Figure 16.
- The pressure cycles were applied every 5 seconds. Data monitoring was performed using a data logger. Figure 17 shows the data logger monitoring screen and Figure 18 shows the data output from a typical test.
- The results of the tests are shown in Table 9 and Table 10 for the Primus and Flexpipe samples at room temperatures, respectively. The tables show the pressures and numbers of cycles to failure.

Figure 19 to Figure 22 show the pipe samples after the long-term cyclic tests for the Primus composite at various pressure levels and Figure 23 to Figure 25 show the pipe samples after the long-term cyclic tests for the Flexpipe composite.

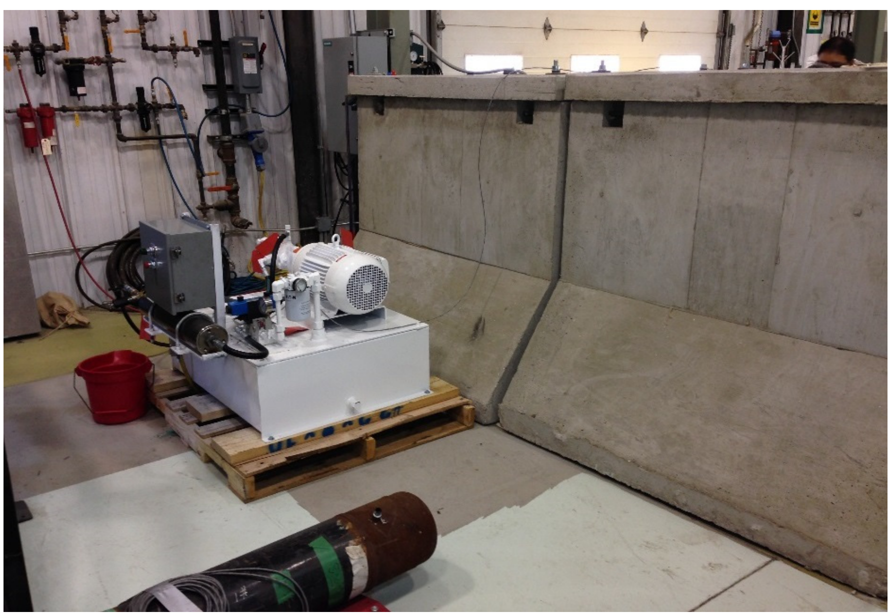


Figure 16 - The hydraulic cyclic machine and test chamber

Figure 17 - View of the data control and monitoring setup

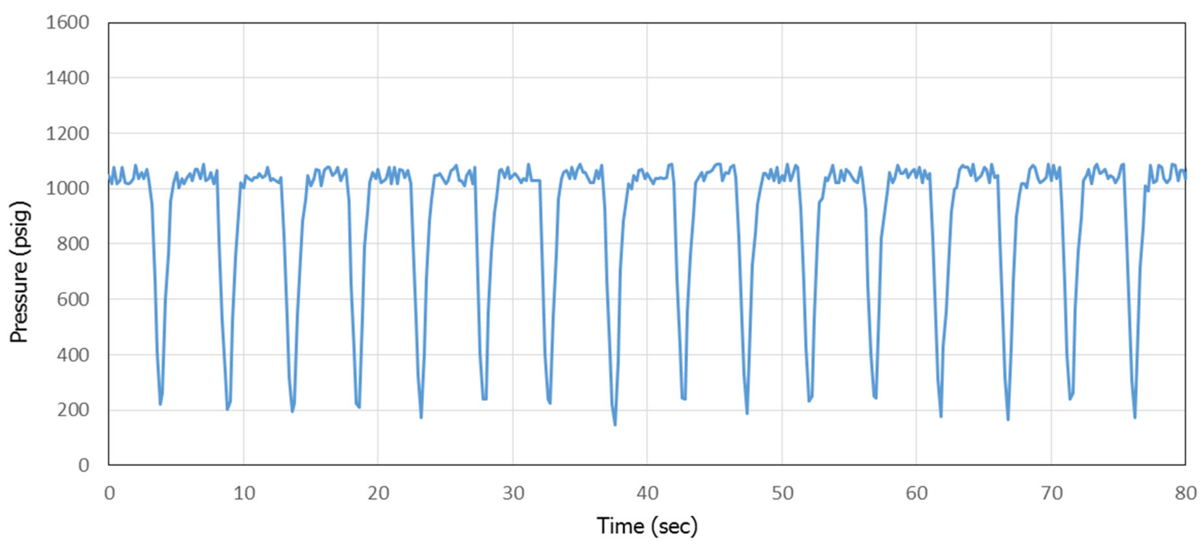


Figure 18 - Output of pressure cycles

Table 9 - Cyclic Pressure Tests of the Primus Liner at Room Temperature

Test Sample	High Pressure (psi)	No. of Cycles to Failure	Failure mode
1	1,550	1	Rupture
3	1,000	112,875	Leak
4	800	315,760	Leak
6	1,250	2,912	Rupture
7	1,050	89,155	Rupture

Table 10 - Cyclic Pressure Tests of the Flexpipe at Room Temperature

Test Sample	High Pressure (psi)	No. of Cycles to Failure	Failure mode
0	1,400	1	Rupture
1	1,050	4,750	Rupture
2	750	346,950	Leak
4-A	925	26,275	Rupture
5-A	1,100	3,640	Leak

Figure 19 - Primus Liner, short-term rupture test, test No. 1

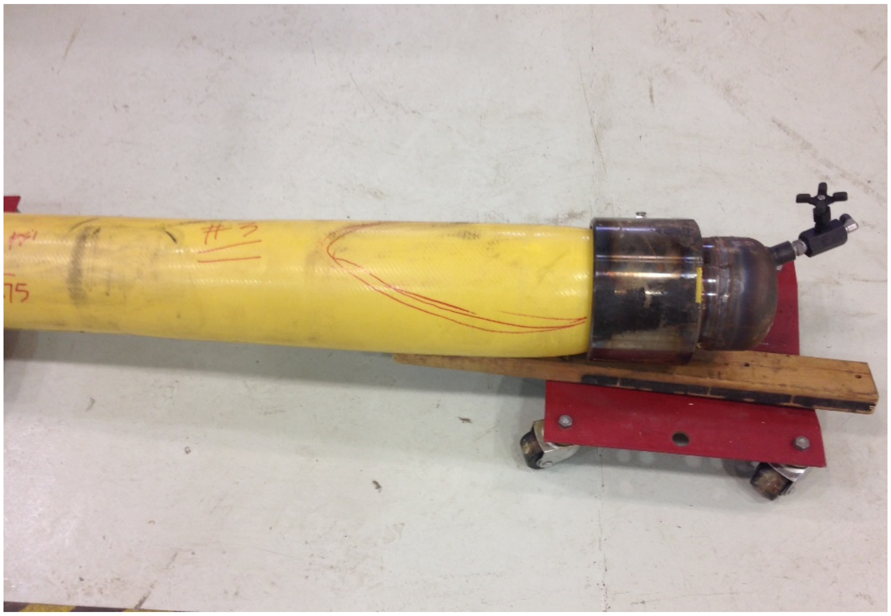


Figure 20 - Primus liner, sample leak at the bulge near the end connecter, test No. 3

Figure 21 - Primus Liner, sample rupture at long-term cyclic test No. 6

Figure 22 - Primus Liner, sample rupture at long-term cyclic test No. 7

Figure 23 - Flexpipe sample in short-term rupture test No. 1

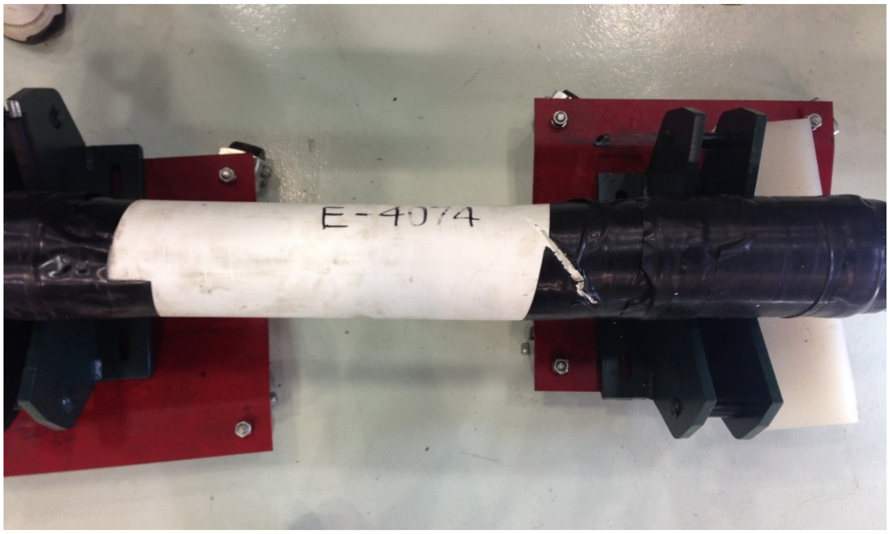


Figure 24 - Flexpipe sample leak in long-term cyclic test No. 2

Figure 25 - Flexpipe sample in long-term cyclic test No. 4-A

Cyclic Pressure Tests at Elevated Temperatures

The elevated-temperature tests utilize the time-temperature equivalence of the material to shift the results on the time-scale; thus allowing for an extrapolation of the hydrostatic pressure to longer time intervals. The time-temperature shift procedure is based on well documented methods for predicting the long term plastics behavior by accelerated testing at elevated temperature (19).

As noted by API 15S standard practice, the application of these principles to end fitting testing is, however, relatively new, and more industry experience is needed to evaluate the performance of the end fittings.

The elevated temperature tests were carried out in a thermostat-controlled water tank at controlled temperatures and with the water as the pressure media in the pipe samples as shown in Figure 26. Figure 27 and Figure 28 show the Primus and Flexpipe test specimens in the water path, respectively.

The end fittings were field type and were provided and installed by the manufacturers. The connections to the pressure lines were done at GTI to provide inlets and outlets to the pressurized water inside the samples.

A hydraulic pressure system was used for applying controlled hydraulic cyclic pressures to the test samples. Pressure gages were installed at each of the test specimens and a Data Acquisition system was used to control and monitor the cycles and the applied cyclic pressures.

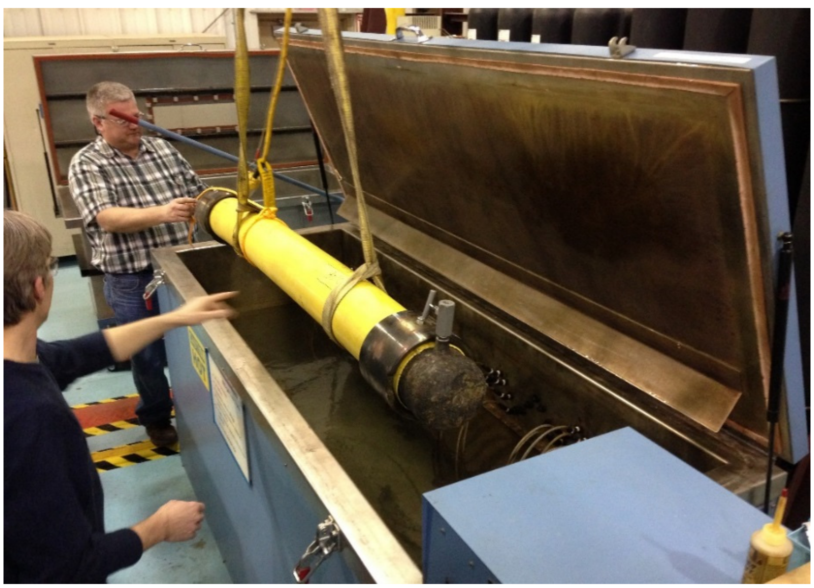


Figure 26 - Installation of the composite sample in the elevated-temperature tank

A summary of the testing procedure of the long-term cyclic pressure loading is as follows:

- The end closures were attached to the pipe sections, filled with water, and conditioned to the test temperature. The samples were connected to the pressuring device.
- The test samples were completely immersed in the elevated-temperature water tank.
- The samples were supported to prevent bending or deflection due to the weight of the pipe while under test.

- After conditioning the samples, the pressure was applied at various cyclic loading levels to produce multiple failure points in the log cycles-log pressure curves.
- The cyclic pressure, and number of cycles to failure were recorded. An example of the recorded output is shown in Figure 18.

The cyclic pressures values and temperature ranges were selected with the manufacturers based on the pressure capacity of their systems. Elevated-temperature tests were performed at 140^{o}F (60^{o}C), and 176^{o}F (80^{o}C).

The results of the cyclic tests at elevated temperatures are shown in Table 11 and Table 12 for the Primus and Flexpipe samples, respectively. Figure 29 to Figure 32 show the test specimens after the long-term tests.

Figure 27 - The Primus Liner in the elevated-temperature test

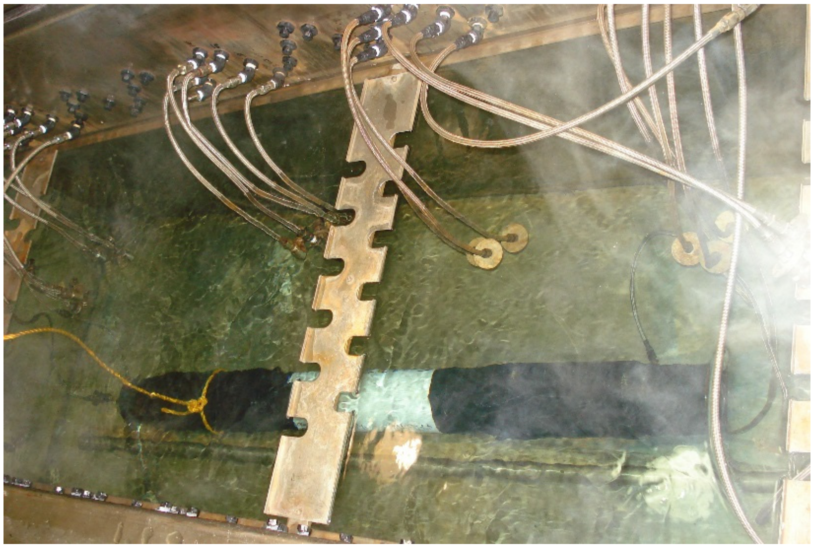


Figure 28 - The Flexpipe sample in the elevated temperature test

Table 11 - Cyclic Pressure Tests of the Primus Liner at 176^{o}F Temperature

Test Sample	High Pressure (psi)	Temperature (°F)	No. of Cycles to Failure	Failure mode
2	950	176	56,680	Leak
5	800	176	169,140	Leak
8	1,100	176	3,850	Leak
9	1,150	176	2,050	Rupture
10	1,050	176	13,590	Leak

Table 12 - Cyclic Pressure Tests of the Flexpipe at Elevated Temperature

Test Sample	High Pressure (psi)	Temperature (°F)	No. of Cycles to Failure	Failure mode
3	1,000	176	710	Rupture
4	750	176	7,680	Leak
1-A	1,000	140	1,680	Leak
2-A	800	140	18,680	Leak
3-A	900	140	9,850	Leak

Figure 29 - Primus sample at elevated temp cyclic test No. 2

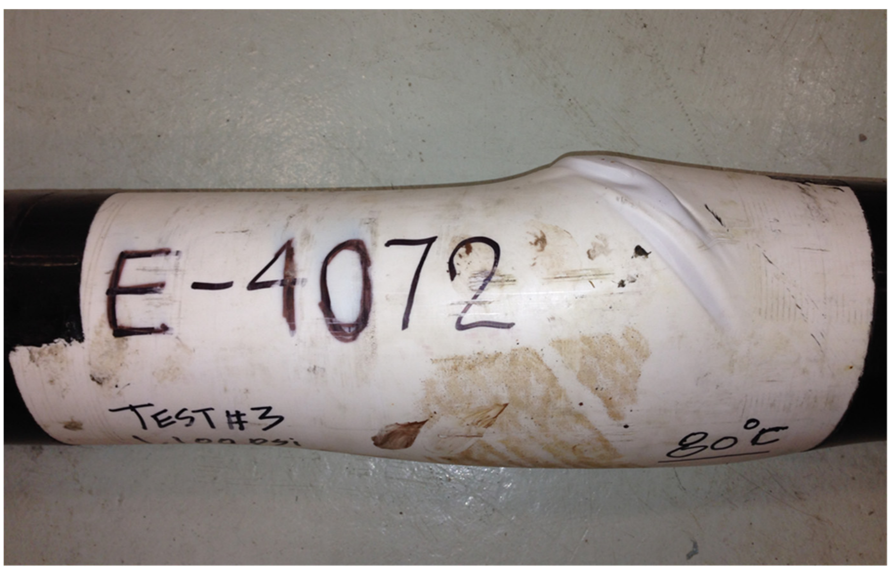


Figure 30 - Flexpipe sample after elevated temperature cyclic test No. 3

Figure 31 - Flexpipe sample after elevated temperature cyclic test No. 4

Figure 32 - Flexpipe sample after elevated temperature cyclic test No. 1-A

Chapter 4. Evaluation of Composites Long-Term Performance

The numbers of cycles to failure for the various cyclic pressures at room and elevated temperatures are plotted in the log-scale in Figure 33 and Figure 34 for the Primus and Flexpipe composites, respectively. The results in the figures show:

- Design service factors, such as the cyclic service de-rating factor (f_{cyclic}) and the fluid derating factor (f_{fluid}), are applied to determine the 'Maximum Service Pressure' (MSP) from the 'Maximum Pressure Rating' (MPR) for particular pipe applications (8):

  $MSP = MPR \times f_{cyclic} \times f_{fluid}$

  The cyclic service de-rating factor accounts for the effect of cyclic service conditions. Other service factors may also apply, such as those based on area classifications.

- The Long-term cyclic pressure of the composites was about 50 percent (i.e., a de-rating factor of 2) of the short-term burst strength at about 350,000 cycles. The estimation of the number of cycles during the life-time field operation may be used to estimate the life span of the composite. This procedure is presented later in this chapter.
- Composites failures at pressure levels above 60 percent of the short-term strength were mostly characterized by rupture failures; while failures at cyclic pressures below 60 percent short-term strength were mostly leaks. Most of these leaks were at the joints with the metal end caps which are typically used in the field to connect to the streel pipe segment.
- The long-term strength of the composites should be determined from tests performed at the temperature levels where the composite is expected to perform in the field.

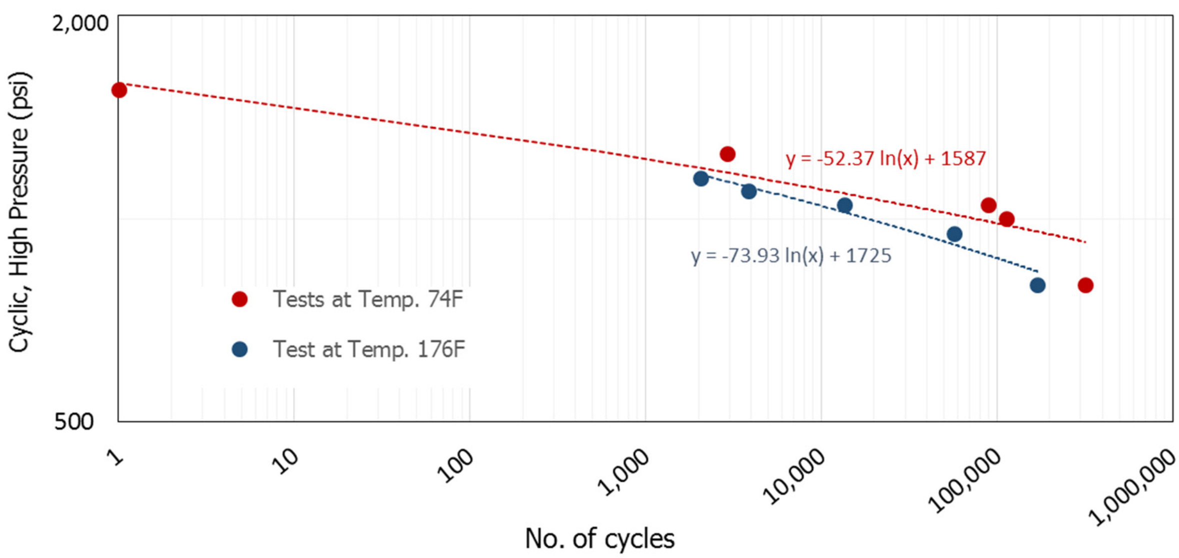


Figure 33 - Long-term cyclic pressure tests of the Primus Liner

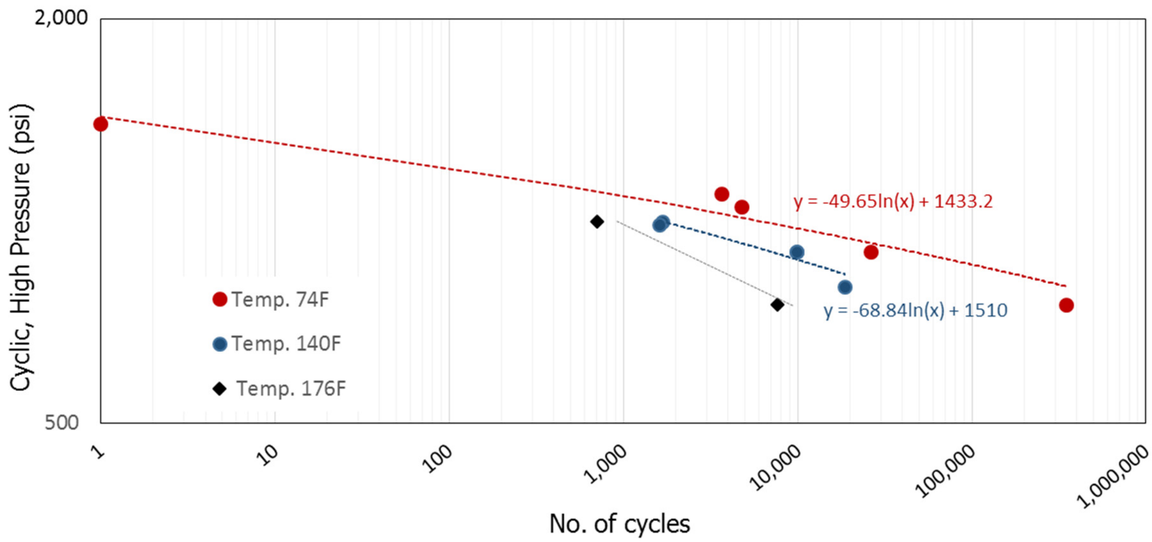


Figure 34 - Long-term cyclic pressure tests of the Flexpipe pipe

The results of cyclic pressure tests at elevated temperatures can be used to extrapolate the strength to longer time intervals. The determination of the long-term hydrostatic strength by extrapolation is presented in detail in reference (19). In this procedure, the extrapolated time (t_e) is calculated using the following equation:

$$t_e = k_e \times t_{max}$$

Where t_{max} is the maximum test time and k_e is the extrapolation time factor. The value of k_e is a function of the ΔT between the two applied temperatures. The extrapolation time factor in Table 13 may be used.

Table 13 - Estimated Values of k_e for various Temperature Differences (19)

ΔT °C	k_e
≥ 10 but < 15	2,5
≥ 15 but < 20	4
≥ 20 but < 25	6
≥ 25 but < 30	12
≥ 30 but < 35	18
≥ 35 but < 40	30
≥ 40 but < 50	50
≥ 50	100

The direct extrapolation from the temperature curves of 74°F and 140°F of the Flexpipe (Figure 34) were calculated for k_e and equals 4 as shown in Figure 35. This procedure assumed that no knee exits in the temperature curves. For the Primus liner, Figure 33 shows possible presence of a knee at cyclic pressure exceeding 100,000 cycles.

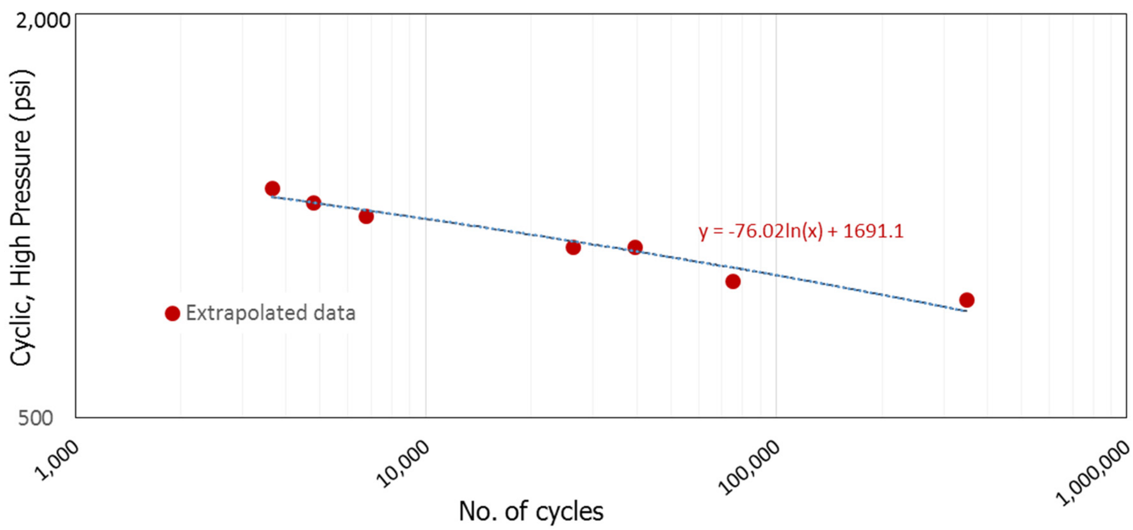


Figure 35 – Extrapolated data for the Flexpipe composite

The long-term life expectancy of the composite from the experimental data is estimated by dividing the number of experimental cycles to failure by the appropriate safety factor, as follows:

$$Remaining\ Design\ Cycles = \frac{Experimental\ Cycles\ to\ Failure}{Fatigue\ Design\ Factor}$$

The Fatigue Design Factor typically ranges between 10 and 20. The ASME Boiler & Pressure Vessel Code employs a safety factor of 2 on stress and 20 on experimental fatigue data to establish a design life, whichever generates the lower fatigue life (20).

The remaining design cycles are then converted to the number of years for an actual pipeline service life. The procedure is summarized as follows (21):

- Covert the operation pressure data from the field into a format that counts the number of pressure cycles for each pressure range. An example output of such pressure data is in the histogram plot shown in Figure 36.
- Use Miner's rule to combine the numbers of pressure cycles for the different pressure ranges to an equivalent number of cycles at the selected pressure. For example:

$$N_{350} = N_{25}\left[\frac{350\ psi}{25\ psi}\right]^{-3.74} + N_{75}\left[\frac{350\ psi}{75\ psi}\right]^{-3.74} + \ldots$$

The equation above can be used to convert the data from the experiment pressure range to the equivalent number of cycles at the field operating pressure. It is useful for applying test results to pipeline operation. As an example, to apply the results to a gas pressure system which operates at 200 annual cycles with pressure range of 36% SMYS, the test data must be converted into an equivalent number of cycles for a pressure range equal to 36% SMYS.

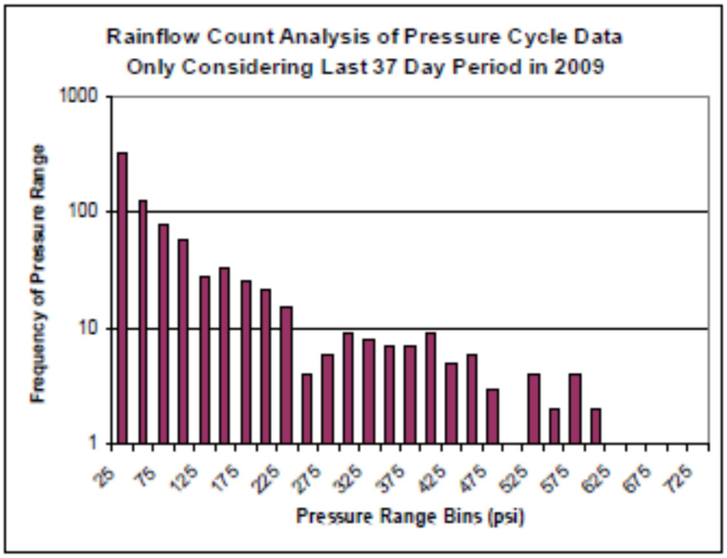


Figure 36 - Example of the frequency of pressure cycles (22)

An example of using the above procedure is as follows: A product tested at 110,000 cycles to failure at a pressure range of 72% SMYS. What is the 'Remaining Years of Service' in a system which operates at 400 annual cycles with a pressure range at 36% SMYS?

- From the experimental results: the Design Cycles equals 5,500 when a Fatigue Design Factor of Safety = 20 is applied.
- The test data is converted into an equivalent number of cycles for a pressure range equal to 36% SMYS. Using Miner's Rule, the composite samples that were cycled at 36% SMYS would have a 73,500 equivalent number of cycles when converted from the 72% SMYS data.
- The remaining design life is calculated by dividing the experimental fatigue lives by 400 annual cycles, resulting in about 183 years of service.

Chapter 5. Modeling the Pipe-High Pressure CIP Liner Interface

Introduction

Gas formation in the voids between the CIP liner and the pipe in high pressure systems may result in disbondment when the pipe is depressurized. Blistering could occur after the liner has been in service for a period of time and the pipe is depressurized for maintenance or emergency repair. This is especially of concern if a section of the liner is not fully bonded to the host pipe as shown in Figure 37(a). If the pipe is depressurized at a rate higher than the trapped gas can permeate back through the liner, the trapped gas may expand and possibly increase the disbondment of the liner as in Figure 37 (b).

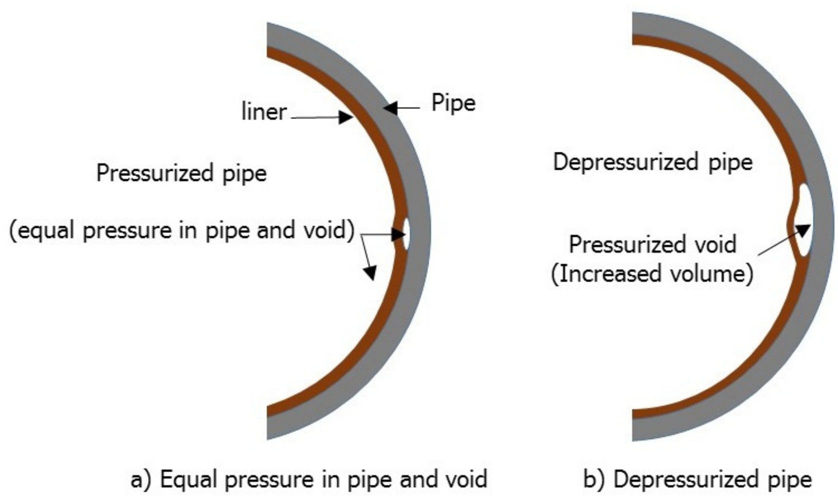


Figure 37 - Schematic of the increase in void volume after the pipe is depressurized

This chapter investigates the Cured-in-Place (CIP) liner-pipe interface mechanism and evaluates the bonding strength between the liner and the inner surface of the host pipe in high pressure applications.

A Finite Element Analysis (FEA) was performed to evaluate the bonding strength between the pipe and the liner at a void section when a rapid depressurization of high-pressure occurs. The analysis simulated initial disbonded areas of diameters between 1 to 4 inches in liners with internal pressure of 400 psig. Various liner and adhesive parameters were evaluated in the FEA analysis to determine the pressure limits when delamination occurs. The formation and results of the FEA analysis are presented in the chapter.

Validation laboratory tests were performed on a CIP structural liner rated at pressure 350-psig to evaluate the delamination of the liner when voids existed. The laboratory tests are presented in the following chapter.

Modeling the Pipe-Liner Interface

The Finite Element COMSOL program was used for modeling the disbondment of the CIP liner (23). The developed disbondment model simulated the mechanical aspect of the liner deformation and disbondment and it assumed an initial condition where a certain amount of gas is first trapped (under the operating pressure) in a void between the liner and pipe. Accordingly, the model does not address the gas diffusion phase through the liner.

The initial condition of the model assumes a defined 'void' area where the pressure drop inside the pipe causes an increased pressure in the void. Figure 38 shows the geometry of the pipe-liner model. The void is assumed circular with the liner disbonded from to the pipe. The initial void thickness between the liner and the pipe is assumed constant at 0.005 inch.

Using this approach enables the laboratory tests to be empirically verified by applying pressure inside the void. In addition, this approach enables running a parametric analysis for many initial pressures and void volume combinations.

The FEA model preforms a geometrically nonlinear, quasi-static stress analysis. The pipe, liner, and adhesive material can be linear or nonlinear, and/or non-isotropic. The adhesive between the liner and pipe is modeled using a thin elastic layer that defines the stress in the adhesive as a function of the extension. A damage function is added to the thin elastic layer to track the areas where disbondment occurs. Areas where the liner has disbonded have pressure applied to them. In addition to the thin elastic layer, there is a contact definition between the liner and pipe to realistically constrain the liner. The interfacial failure by delamination or disbondment is simulated with a Cohesive Zone Model (CZM) of the Solid Mechanics interface in the COMSOL software.

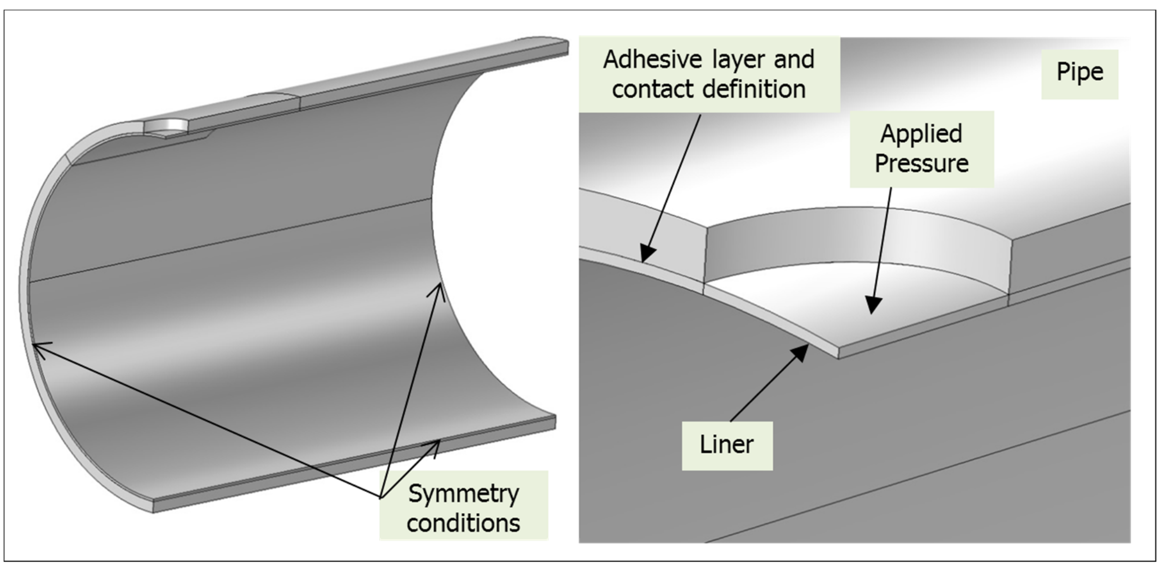


Figure 38 - Model geometry simulating an initial void condition

A key ingredient of the CZM model is a traction-separation law that describes the softening in the adhesive zone near the delamination tip. The CZM implemented in this model is described in detail in references (24) and (25).

The traction-separation law assumes the traction to increase linearly with the liner stiffness (K_p) until the opening crack reaches a failure initiation displacement (u_o). When the crack opens beyond u_o, the adhesive material softens irreversibly and it fails once the stiffness has decreased to zero. This occurs at the ultimate displacement u_f.

The values of u_o and u_f depend on whether the separation is normal or tangential to the interface. For the normal delamination mode (mode I), the failure initiation displacement is:

$$u_o = \frac{N_s}{K_p}$$

Where N_s is the normal tensile strength. The ultimate displacement is defined from the critical energy release parameter (G_I) as:

$$u_f = \frac{2\,G_I}{N_s}$$

Pipe-Liner Interface Parameters

The material properties used in the parametric study of the FEA are shown in Table 14. The pipe dimensions and internal pressure were assumed constant and the analysis was performed on various void sizes and liner and adhesive strength parameters. The critical energy was assumed to vary with the change of the tensile strength of the adhesive.

Table 14 - FEA Model Parameters

Parameter	Unit	Parameter Value
Pipe OD	inch	12.75
Pipe Wall Thickness	in	0.375
Pipe Internal Pressure	psig	400
Initial Void Thickness	inch	0.005
Initial Void Diameter	inch	1.0 - 2.5 - 4.0
Tensile Modulus - Liner	ksi	15,000 - 22,500 - 30,000
Liner Poisson's Ratio	-	0.4
Tensile Strength -Adhesive	psi	3000 - 4,500 - 6,000
Mode I Critical Energy Release	J/m^2	1,500 - 6,000
Mode II Critical Energy Release	J/m^2	1,875

Figure 39 shows the FEA mesh details. In order to reduce analysis time, a certain portion of the mesh around the initial void surface was defined with a thin elastic layer and the remainder of the model was defined with fixed displacements. Therefore, only the portion with the elastic layer had a refined mesh. The model however, is capable of simulating the adhesive layer on the entire bond area.

The adhesive disbondment between the liner and the pipe is represented in Figure 40 by the total displacements (in mm) which result from the increase in the pressure in the void due to rapid depressurization to 0 pressure inside the pipe. The output in the figure is for a 4-inch initial void diameter in the 12.75-inch OD diameter pipe, a linear tensile modulus of 15,000 ksi, and an adhesive tensile strength of 6,000 psi.

The stresses in the liner for the above parameters are shown in Figure 41. The figure shows the von Mises stresses in the liner at pressures 240, 260 and 400 psig in the void.

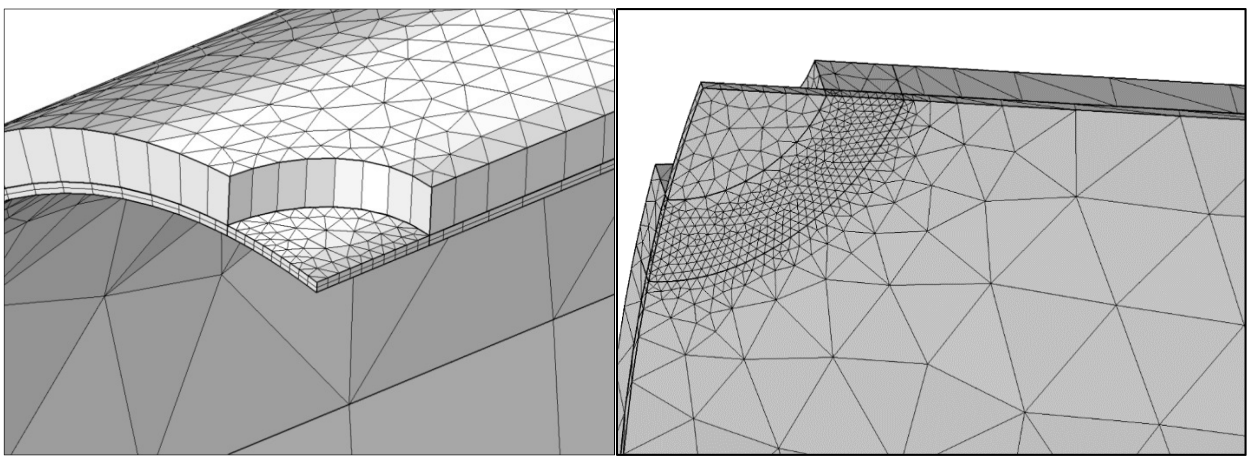


Figure 39 - FE mesh details above and below the initial void surface

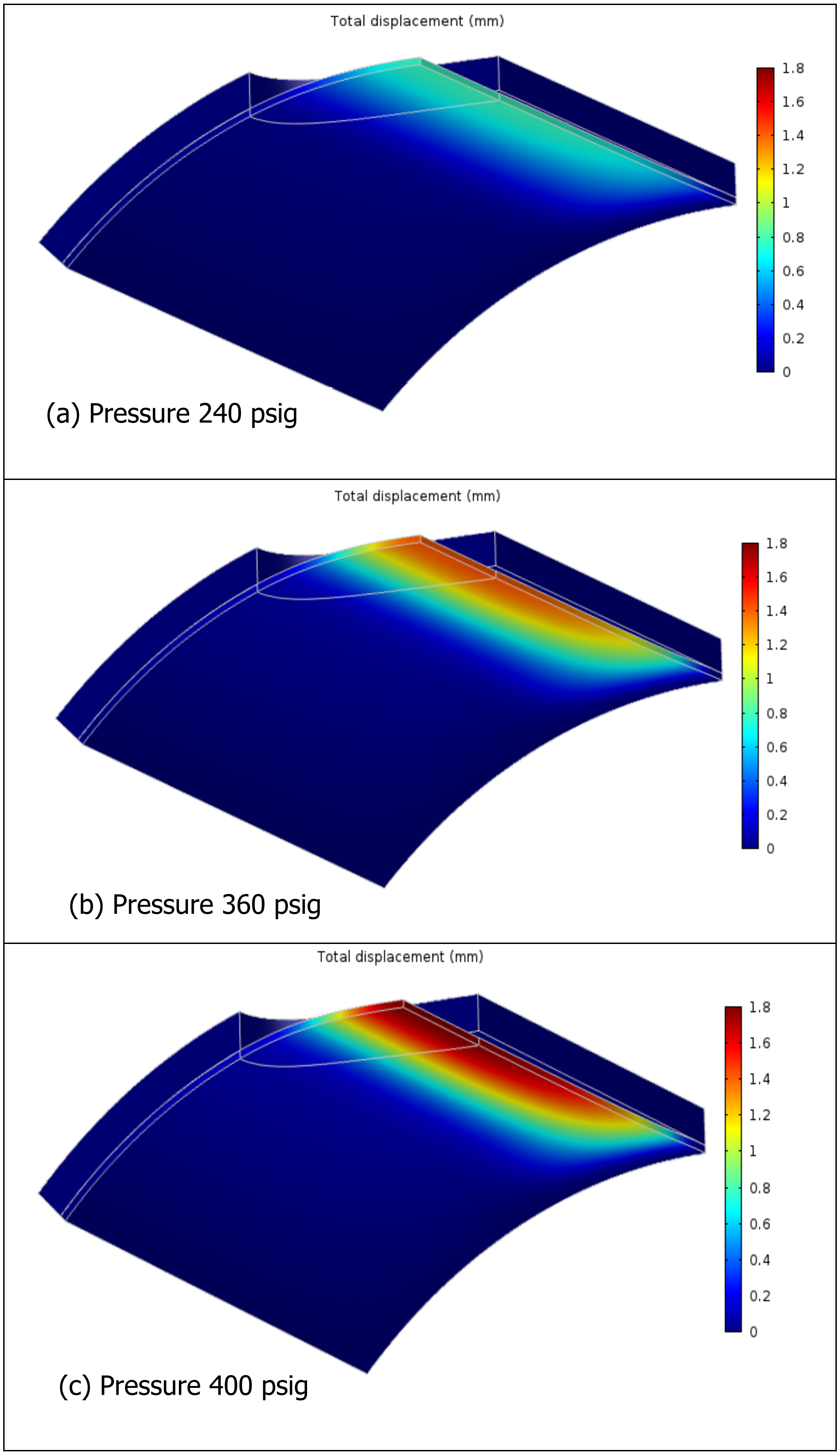


Figure 40 - Displacements between the metal surface and the liner at various void pressures

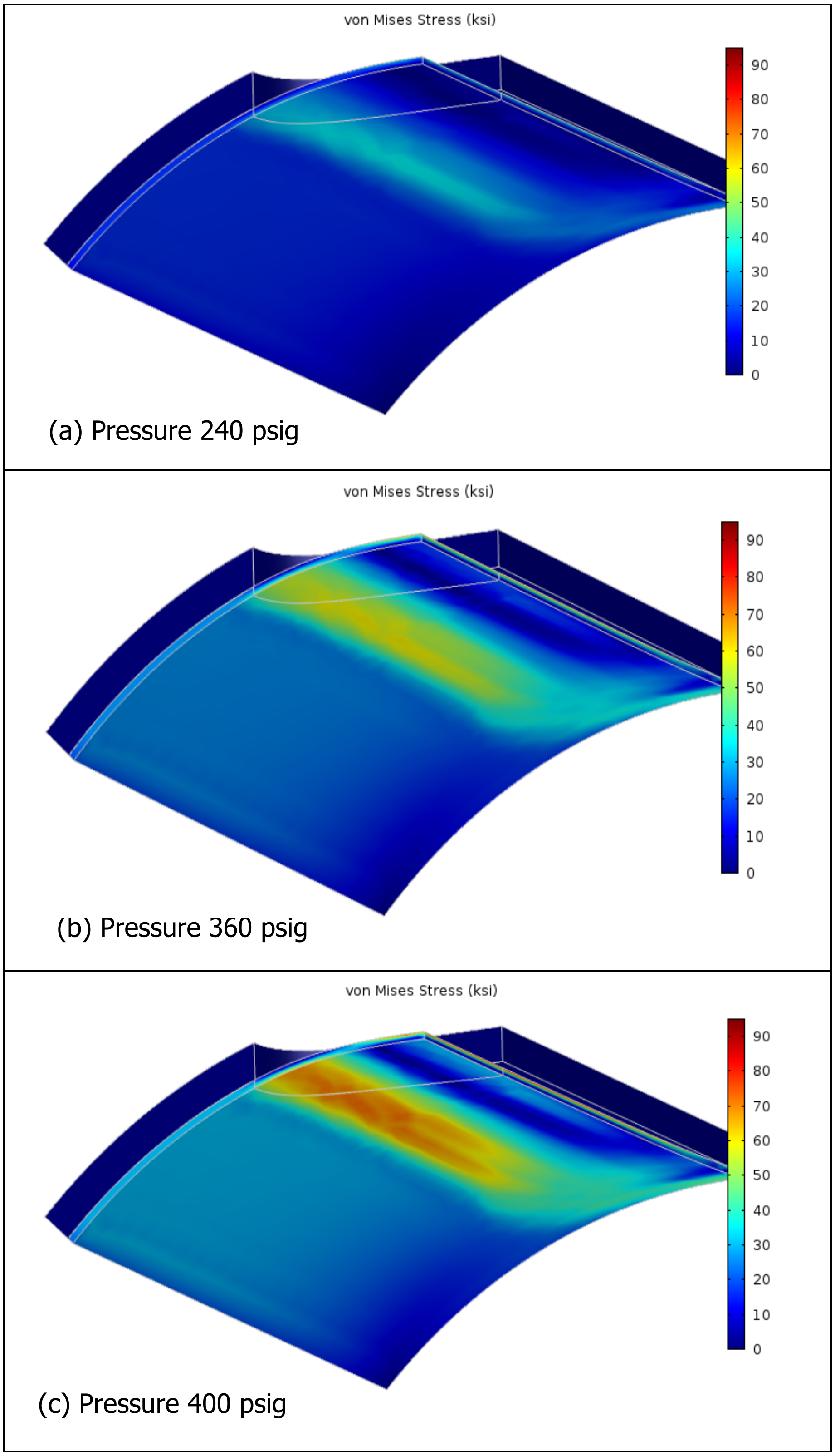


Figure 41 - Von Mises Stresses in the liner at various pressures in the void

Analysis of the Pipe-Liner interface

A linear elastic material definition was used for the liner and the adhesive layer. For the ranges of the liner and adhesive tensile moduli, which were analyzed in Table 14, there was a certain pressure beyond which a large disbondment "jump" occurred. Figure 42 shows the increase in the total void volume due to the increase of the internal pressure for an initial void diameter of 2.5 inches and an adhesive tensile strength of 4,500 psi. The figure shows the jumps in the void volumes, indicating disbondment, for various liners' tensile moduli.

Although the disbondment may initially occur due to the increase of the void pressure, the pressure of the trapped gas will eventually drop as disbondment increases, due to the large increase in the void volume. The determination of the gas pressure level where no further increase of disbondment occurs is done by overlaying the gas volume-pressure equilibrium curve of the trapped gas on the volume-pressure curve from an FEA analysis. The gas volume-pressure equilibrium curve is shown by a dotted line in the figure and it was calculated for methane gas with an initial void of 2.5-inch diameter and 0.005-inch thickness at 72^{o}F. The intersection of the two curves provides an estimate of the pressure where no further disbondment occurs.

Similar volume pressure curves are plotted in Figure 43 and Figure 44 for various adhesive strength and sizes of voids, respectively.

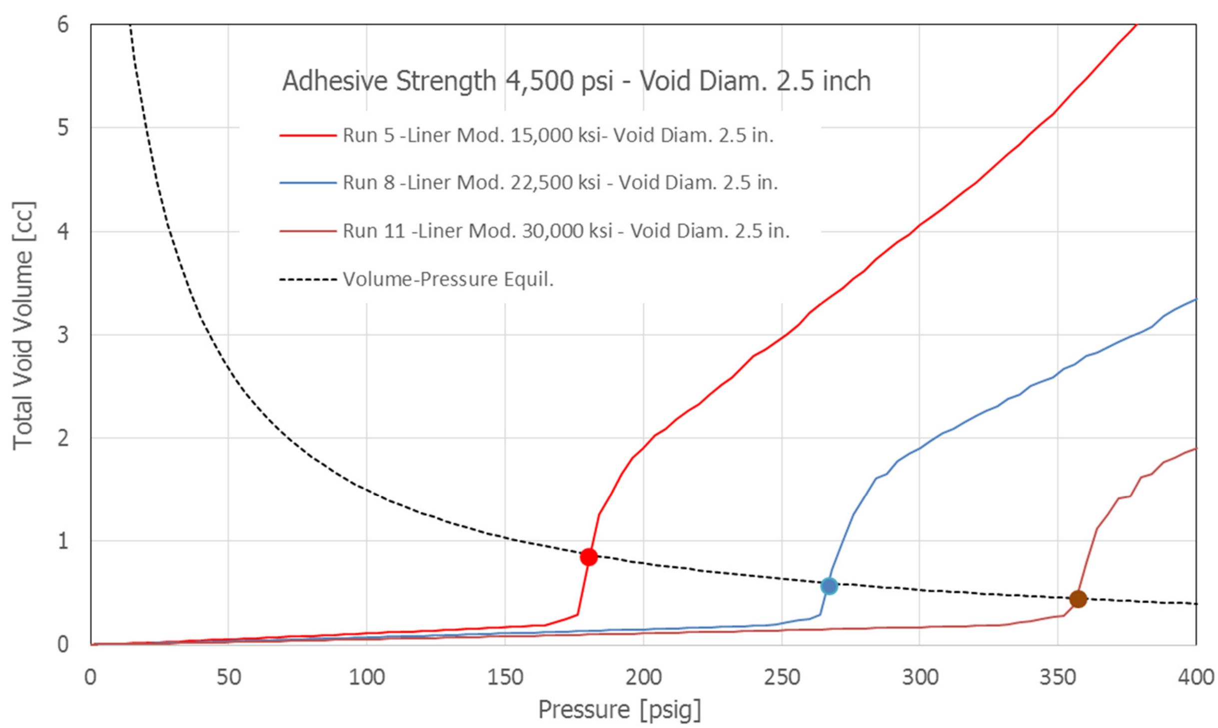


Figure 42 - Change of void volume with pressure for various liner tensile moduli

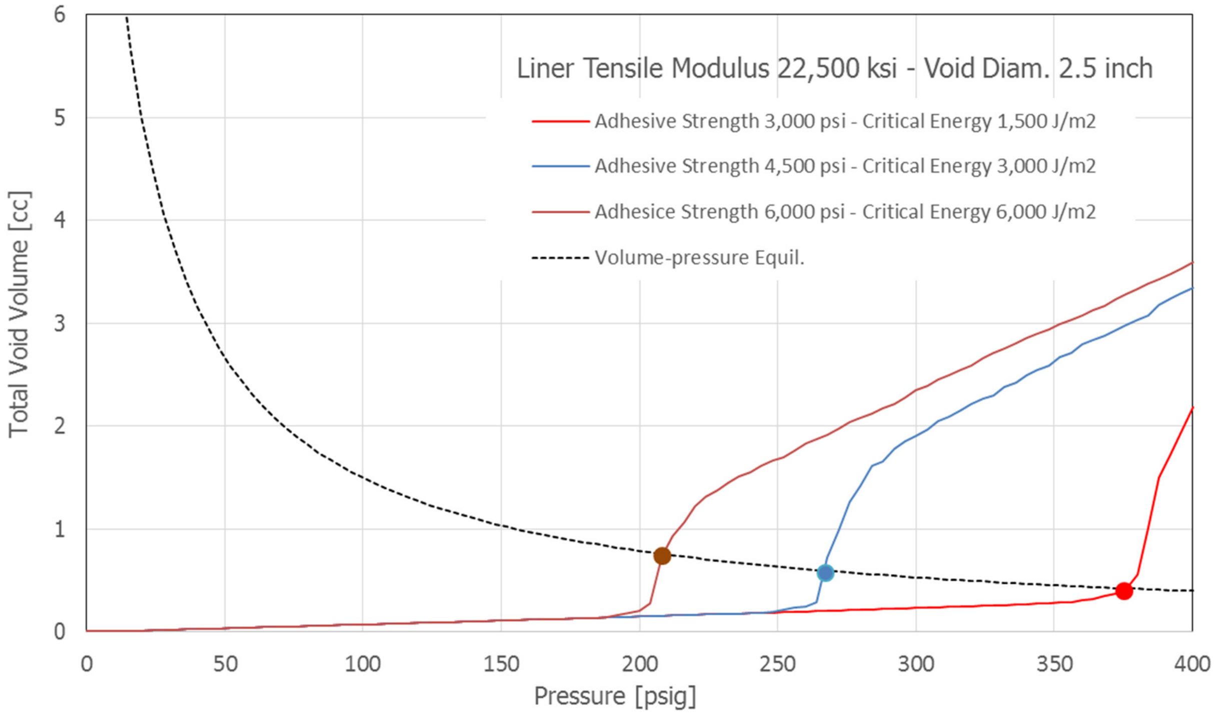


Figure 43 - Change of void volume with pressure for various adhesive strengths

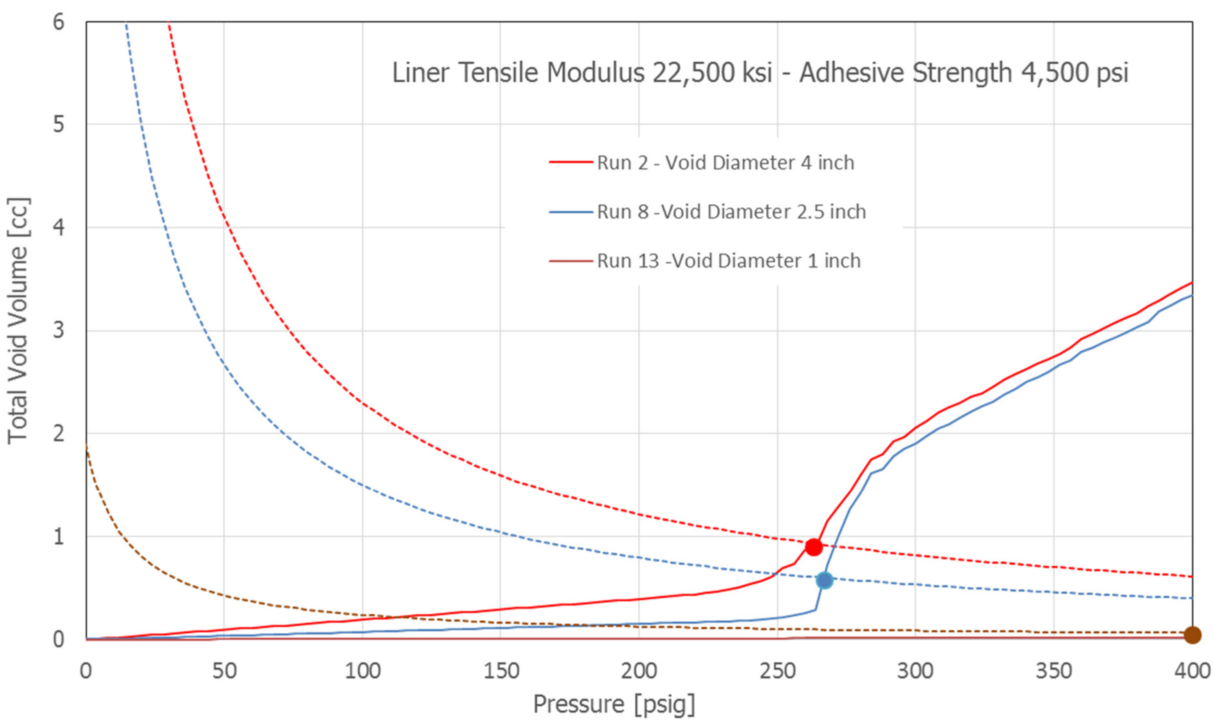


Figure 44 - Change of void volume with pressure for various void sizes

The above figures provide an estimate of the pipe pressure where depressurization to atmospheric pressure causes liner disbondment for certain initial void area, liner tensile modulus, and adhesive tensile strength.

An example of the application of the results of the above figures is as follows: a liner has a tensile modulus of 22,500 ksi and it is bonded to the host pipe with an adhesive of a tensile strength 4,500 psi. For an initial void diameter of 2.5 inches, Figure 42 shows that a disbondment of the liner would occur when the pipe is depressurized from about 270 psi to atmospheric pressure at room temperature.

Chapter 6. Large-scale Testing of High-Pressure CIP Liner

Introduction

The high-pressure CIP liners in the market today rely on the structural strength of the host pipe and can carry the internal pressure only in the limited gaps and voids sizes as specified by the manufacturers. Some new liner products (e.g.; Starline High-Pressure liners HPL-450) are designed to partially support deteriorated pipes with holes and gaps up to 2 inches in diameter.

Several ASTM Standards provide a framework and guidelines for most of the CIP liner products used in the pipe rehabilitation. These standards include:

- ASTM D5813 "Specification for Cured-In-Place Thermosetting Resin Sewer Pipe": The standard covers the requirements for the resins and fabric tube materials used for CIPP. The standard also outlines the test methods for evaluating installed CIPP.
- ASTM F1743 "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)": The Standard is an installation practice for the pulled-in-place method of installation.
- ASTM F1216 "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube".
- ASTM F2019, "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)".
- ASTM F2599, "Standard Practice for the Sectional Repair of Damaged Pipe By Means of an Inverted Cured-In-Place Liner".
- ASTM F2207, "Standard Specification for Cured-in-Place Pipe Lining System for Rehabilitation of Metallic Gas Pipe". The CIPP liners covered by this specification are installed into gas pipes of ¾ to 48 inches diameter. The MAOP of such renewed gas pipe shall not exceed a pressure of 300 psig.

The liner material used in large gas distribution pipes sizes is normally felted fabric (non-woven) and does not go around bends without wrinkling. Liners used for small pipe diameters with bends (e.g.; 4-inch pipes) are made from a woven fabric allowing it to go around bends with minimal wrinkling. Published data about the strength requirements of the fabrics and recommended design properties of the liners are shown in Table 15.

The material and quality control requirements for using high-pressure CIP liners in the rehabilitation of pipelines transporting natural gas and petroleum fuels include the following:

- Low gas permeation through the liner: Throughout the application life of liners, a low volume of gas would eventually permeate through the liner and either trapped between the liner the carrier pipe or leak to the surface.

- Ability to carry the internal pressure and stop leaks in pinholes and partially deteriorated joints as per the manufacture's allowable size of the holes and gaps.

Table 15 - Minimum Recommended Design Properties of CIPP

Test Property	Epoxy Resin Data	Epoxy Vinyl Ester Data	Isophthalic Polyester Data	Filled Isophthalic Polyester Data
Flexural Modulus, psi	250,000-300,000	350,000-450,000	250,000-350,000	400,000
Flexural Strength, psi	5,500	5,500	5,500	5,500
Tensile Strength, psi	3,000-5,000	3,000-5,000	3,000-5,000	3,000-5,000

A permeability test was performed with the high-pressure Starline CIP liner used in the rehabilitation of a large-scale (12-inch diameter) pipe sample. The test evaluated the time for the natural gas to permeate through the liner to the pipe wall.

Laboratory tests were then performed on the liner installed in order to evaluate gas formation in the voids between the liner and the pipe during the rapid depressurization of the high pressure systems. These tests evaluated the theoretical development of the disbondment between the liner and pipe which were developed in the previous section. Tests were also performed on pipe samples with various bends and simulated gaps in the steel pipe section.

Permeability Test

The principal characteristic of the liners used in the rehabilitation of gas pipelines is their intrinsically low permeability to a broad range of gases, vapors, and liquids. During the long-term operation of the liner-steel pipe system, gas migrates through the liner on a molecular basis by a diffusion process. A significant amount of time may be required for the gas to form in the voids between the liner and pipe wall and reach the pipe operating pressure.

The transmission of gas through a liner is subject to many factors (e.g., thickness and structure of the liner, the molecular weight of the gas, temperature, and internal pressure). Accordingly, the test procedure to simulate natural gas flow through the liner is selected to reflect actual service conditions as closely as possible. As such, the pressure at the simulated voids was kept equal to the pipe pressure to represent the long-term diffusion of the gas through the liner.

A summary of the testing procedure is as follows:

- A steel pipe specimen of 12-inch diameter and 36-inch length was tested. The pipe had two 1-¼ inch holes drilled at opposite sides of the pipe wall. Figure 45 shows a schematic and a view of the pipe specimen.
- The internal pipe surface was cleaned, lined, and allowed to cure. The lining of the pipe sample was performed by the liner manufacturer.

- The liner was inspected and areas of disbondment were marked prior to capping the pipe. The top cap had welded nipples for applying internal pressure with natural gas to 350 psig. A pressure gage was installed to monitor the pressure.
- The two holes in the pipe specimen were connected to pressurized nitrogen lines at equal pressure of 350 psi. Both the natural gas and nitrogen pressures were applied at equal increments.
- The natural gas was allowed to permeate through the liner (i.e., following Fick's law of diffusion) into the sample ports.
- A sample collection port was installed to collect gas samples and monitor the methane concentration at the back side of the holes.
- The gas samples were periodically drawn from the sample collection port and were analyzed with a gas chromatograph to determine methane concentration on the back side of the liner. The port was designed so that the sample collection does not affect the pressure level at the port.
- The equilibrium time for liner saturation was defined as the time it takes for the methane concentration to achieve a steady-state level through the liner.

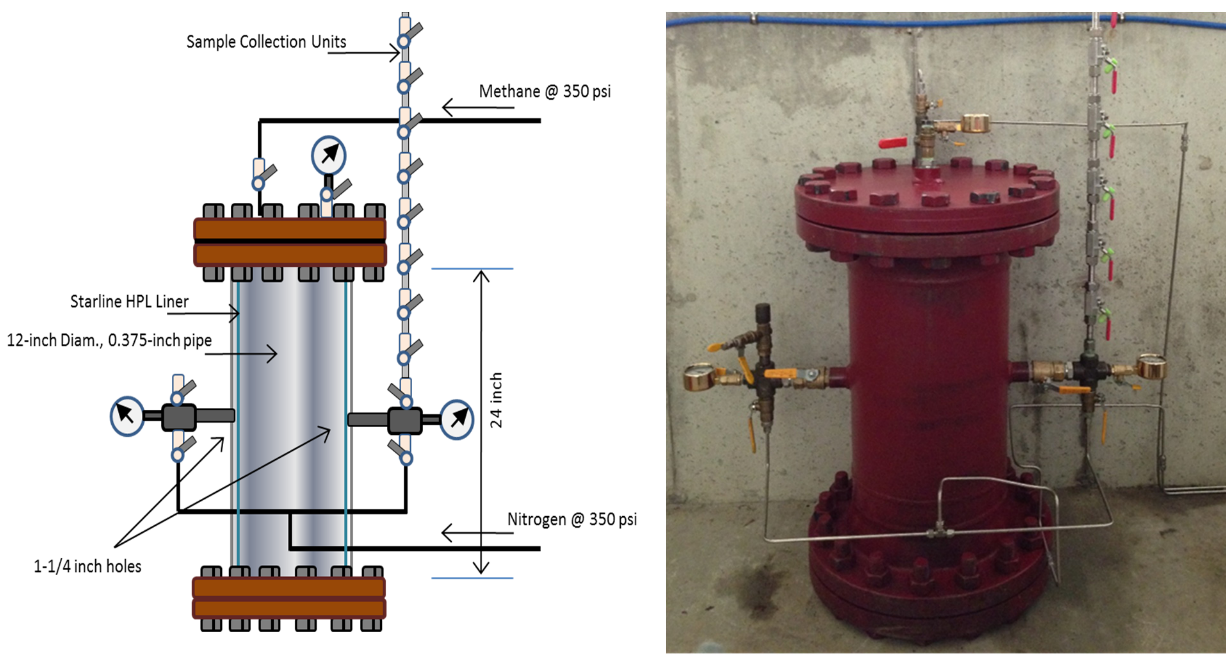


Figure 45 - The pipe specimen in the permeability test setup

The natural gas and the nitrogen pressures at both sides the two ports 'A' and 'B' were kept constant at 350 psi and were monitored during the test as shown in Figure 46. Figure 47 shows the measured methane concentrations outside the liner with time. Methane concentration was measured for 6 weeks to reach a steady-state flow through the 2-mm thick liner at pressure of 350 psi at room temperature.

Figure 46 - Pressure gage for monitoring internal pipe pressure in the specimen

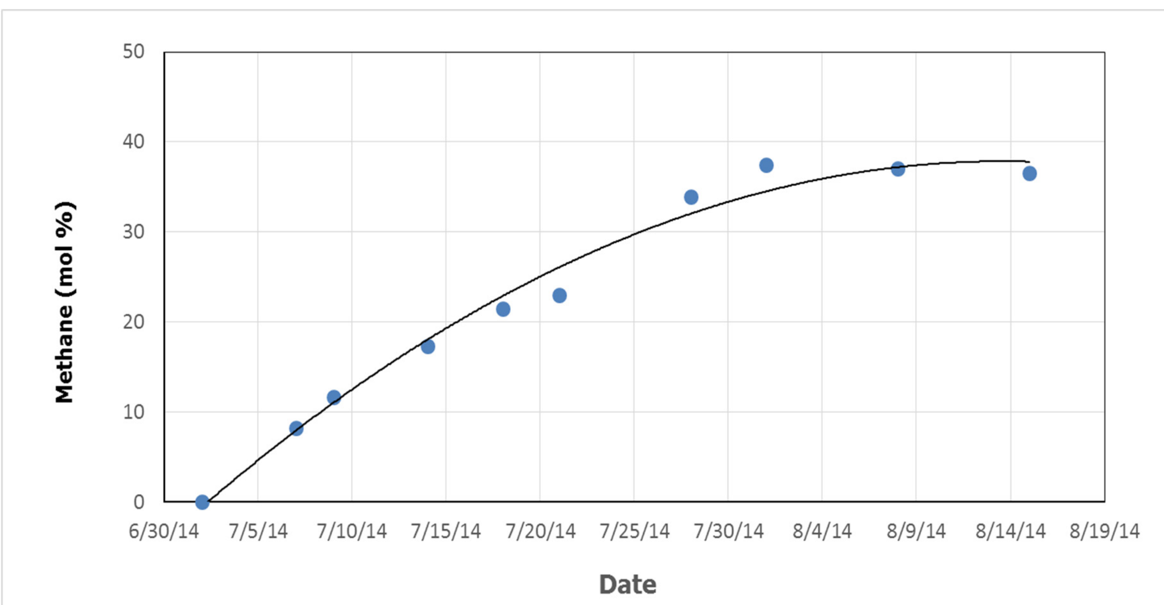


Figure 47 - Plot of methane concentration of the gas samples with time

Rapid Depressurization Tests

In high-pressure liners, the gas formation in wrinkles and un-bonded areas between the liner and pipe wall may cause disbondment when the pipe is depressurized. Disbondment could occur after the liner has been in service for a period of time and the pipe is depressurized for maintenance or emergency. This is especially of concern if a section of the liner is not fully laminated to the host pipe.

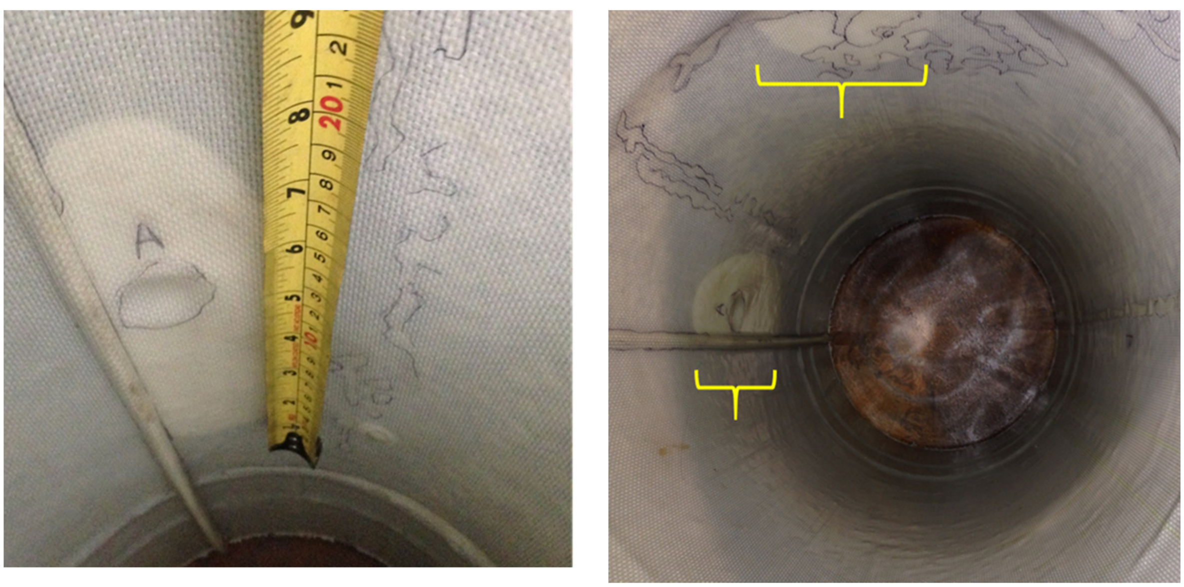
There is a current need by the natural gas utilities to investigate the potential disbondment of the high-pressure liners (i.e.; in applications up to 350 psig). For this purpose, a high-pressure liner was installed in a 12-inch diameter steel pipe section with simulated areas of disbondment, or "voids" between the liner and the pipe.

The pipe specimen was rapidly depressurized from 350 psig to atmospheric pressure over a period of 15 minutes; thus simulating pressure buildup in the voids. The sample was then disassembled and inspected for disbondment or damage. A summary of the testing procedure is as follows:

- The surface of the liner was uniform and bonded to the pipe. Small areas had lighter coloration indicating possible voids between the liner and the internal pipe surface. Figure 48 shows the areas of discoloration near ports 'A' and 'B' at both sides of the liner.
- The internal pipe pressure was kept at 350 psig for a duration of 6 weeks; which was sufficient to have gas permeation behind ports 'A' and 'B'.
- The internal pipe pressure was dropped form 350 psig to atmospheric pressure in 15 minutes. The complete depressurization of the pipe in such short period may not be a typical drop of line pressure in the field; however, it simulates the worst-case scenario for the pressure buildup in the voids.
- Following the pressure drop, the pipe caps were removed and the liner was inspected for disbondment or damage.
- No damage was observed through the visual inspection of the liner. Most of the initially marked voids in the liner had their marks unchanged, indicating no disbondment in these areas.
- The inspection after the test showed local small disbondment in the areas around port 'A' and at a part of the marked voids at the top section of the pipe. Figure 49 shows these two areas. The results of this test can be used to identify the limiting pressure that a liner can withstand without disbondment due to depressurization.

(a) (b)

Figure 48 - Discoloration of the liner showing areas of possible voids before the test



(a) (b)

Figure 49 - Local disbondment areas after rapid depressurization

Liners Installation in Pipe Bends

The liner material used in large gas distribution pipe sizes is normally flexible to allow for its installation in bends and elbows with minimum wrinkling. However, bends in the pipes generally cause wrinkles in the liners as shown in Figure 50 for 45- and 90-degree bends. Proper installation of the liner usually results in having the wrinkles filled with the adhesive material, with minimum voids.

A testing setup was built to evaluate the liner's installation through various degrees of bends and elbows. The liners were installed in 12-inch diameter pipe samples with bends of 22.5, 45, and 90-degrees. A schematic of the pipe samples is shown in Figure 51. In addition to the bends, the pipes had couplings with 1-inch and 2-inch circumferential voids where the liners carry the full internal pressure of the pipe without the steel host pipes.

The pipes were lined by the manufacturer of the Starline HPL-450 liner. It is a high pressure liner capable of carrying 450 psig internal pressure. The samples were shipped from the manufacturer location to GTI for the pressure tests. Figure 52 shows the pipe samples.

The liners were internally inspected to investigate the wrinkles at the bends. The inspection showed the wrinkles were fully bonded together with the adhesives, and without any visible voids or disbondment.

The samples were pressurized to pressures of 100, 200, and 350 psig. Rapid depressurization, (in a period of 15 minutes) was performed on the pipe samples after each of these pressure levels and the samples were inspected.

Each of these depressurization cycles was performed after the pressure was maintained in the samples for a duration of 6 weeks to allow for the gas to permeate through the liner under the internal pressure.

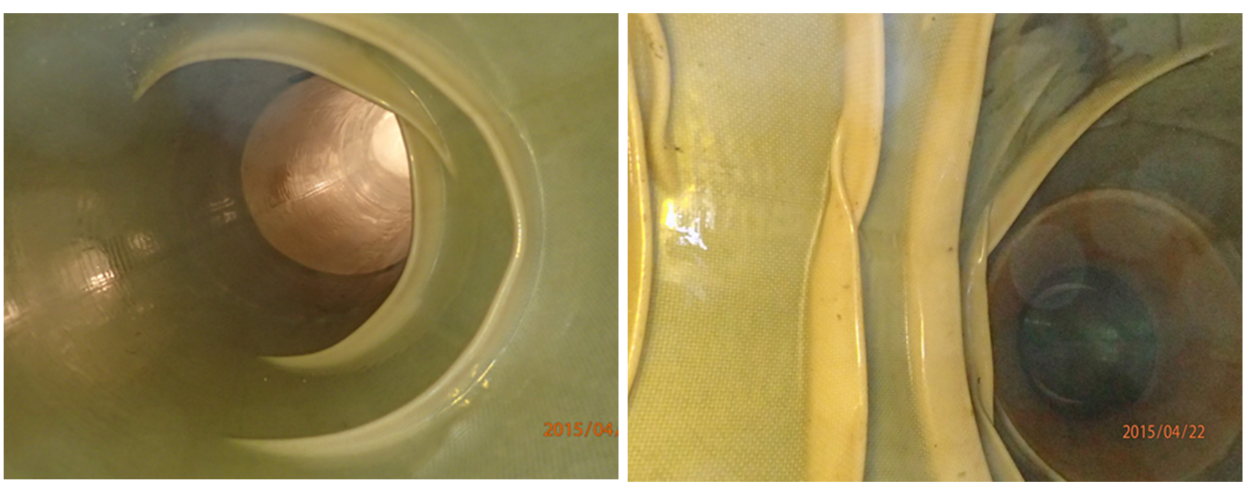


Figure 50 - The 45- and 90-degree bends at zero pressure

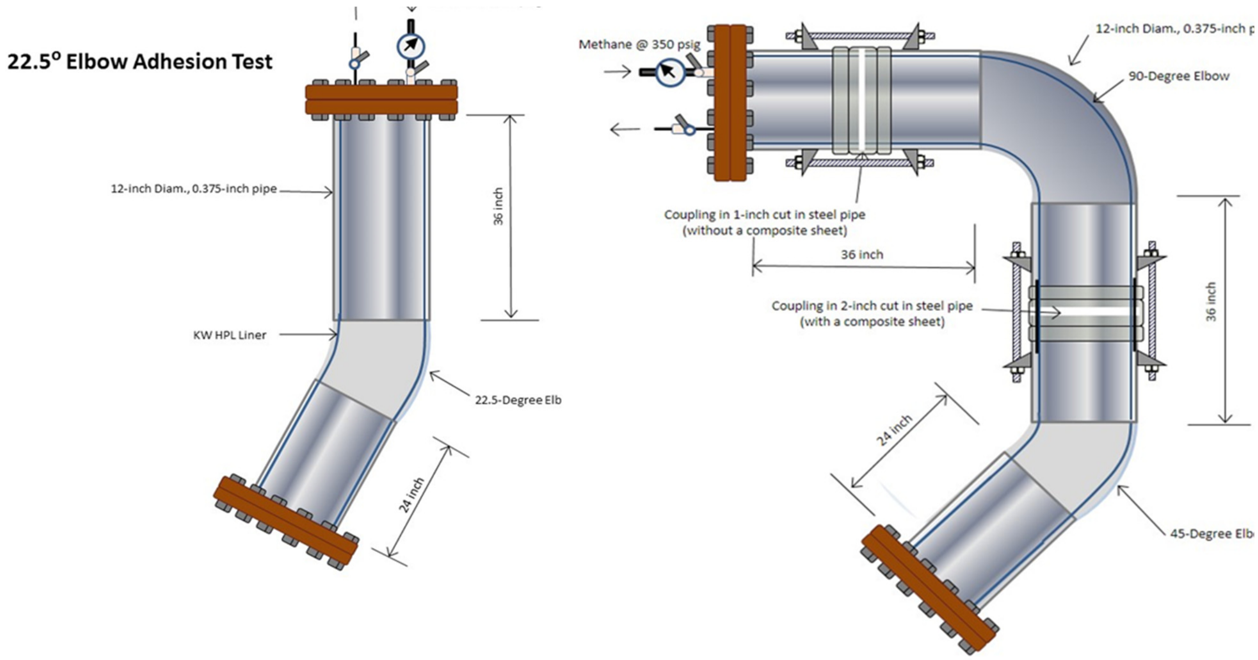


Figure 51 - Schematic of the large-scale pipe sample with bends

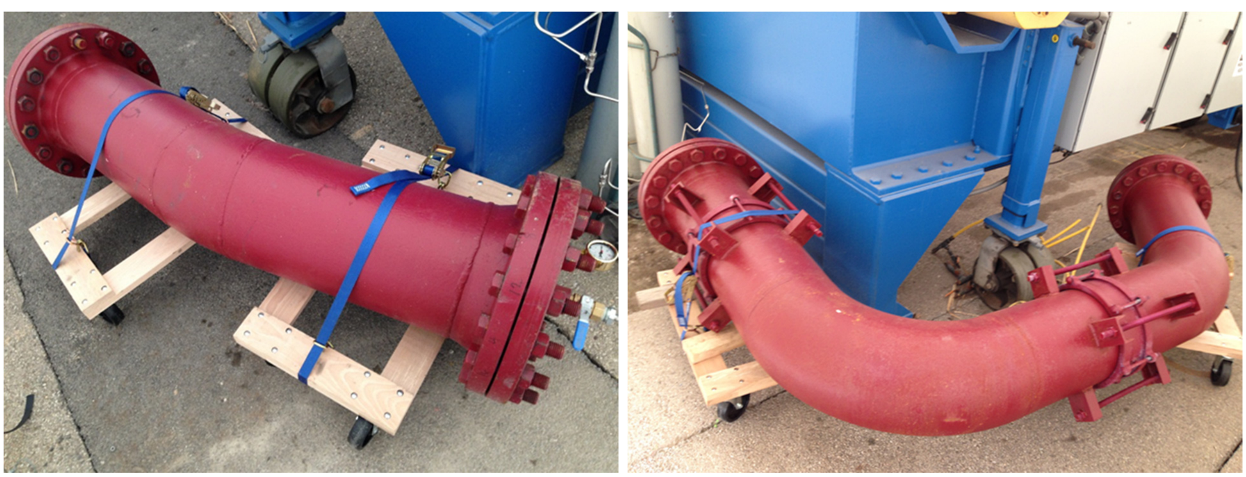


Figure 52 - Pipe samples with 22.5, 34, and 90-degree bends

After the rapid depressurization of the samples at each pressure, the samples were inspected to investigate if liner's disbondment was developed at the bends. The results show:

- No delamination or disbondment was observed after rapid depressurization of the samples from 100 and 200 psig to atmospheric pressure. Figure 53 shows a view of the bends after the pipes depressurized from 200 psig.

- A small disbanded circular area, of diameter about 1 inch, was observed at the bend after the samples depressurization from 350 psig to atmospheric pressure. Figure 54 shows the bend after the test.
- The results confirm the applicability of using liners in bends without significant disbondment. Liners may need to be inspected in bends to ensure that the wrinkles are fully bonded with the adhesive without any visible initial disbondment.

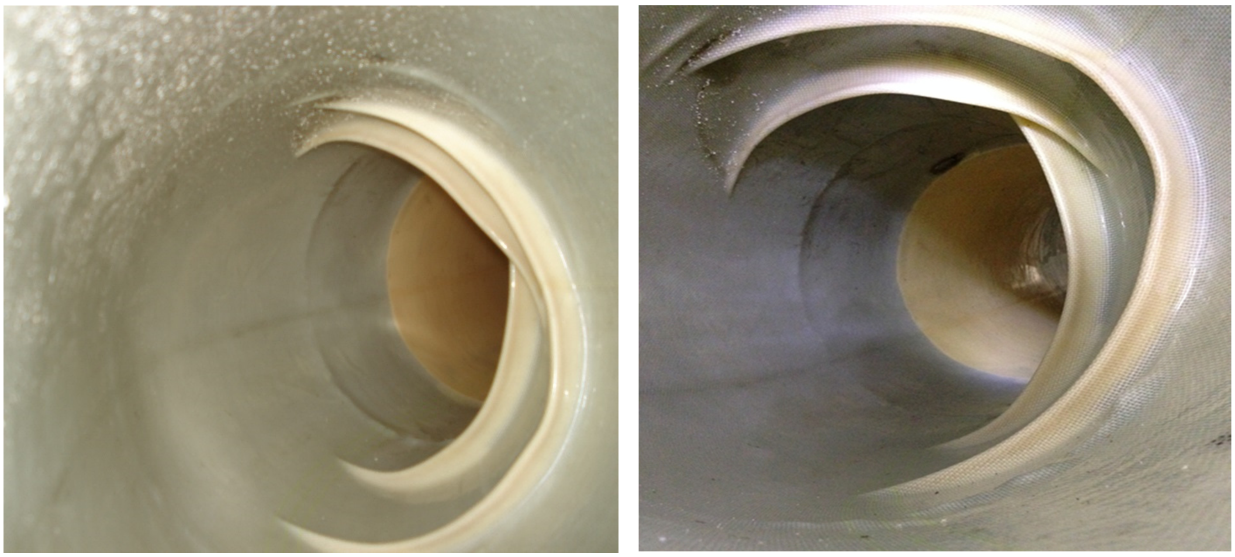


Figure 53 - The 45- and 90-degree bends, No effect of 200 psig depressurization

Figure 54 - Small delamination at the top after 350 psi depressurization

Chapter 7. Gap Analysis and Implementation Roadmap

Applicability of Composite Pipes and Liners

Several composite pipes and liners are currently being used in onshore and offshore oil and natural gas production applications. Many of these composites are spoolable pipes manufactured in various sizes and in continuous lengths up to 35,000 ft for the small diameter pipes. Most of these pipes have internal thermoplastic liner surrounded by laminates made of carbon, glass, or other fibers in an epoxy resin base as the pressure-carrying components of the composite. The use of these different materials allows for having high pressure ratings for these pipes for use in transmission lines.

The use of composite pipes and liners in the rehabilitation of natural gas and liquid transmission lines provides various advantages over the open-trench excavation and replacement of the deteriorating host steel pipes. These advantages include:

- Composites have proven their versatility and applicability in over 30 years of use in the transmission of oil and gas in production gathering and distribution pipelines,
- The various components of the composites allow for a wide range of applications and pipe sizes with various pressure ratings from 75 to 4,000 psi,
- Composite material provide high corrosion resistance, high strength-to-weight ratio, and high resistance to chemicals and aggressive environment,
- Small diameter composites are commonly spoolable to long length, thus facilitating the procedure of trenchless insertion with minimum number of excavation pits and with small footprint at the surface.

Although the material cost of the composite components can be sometimes higher than steel, the installation cost of these pipes is much less than for the steel pipe.

Although the use of these composites in the rehabilitation of gas transmission lines can provide a safe, practical, and economical alternative, some of the barriers that limit its implementation include (1):

- Composite pipe production in general is difficult to assess. The API recommended practice RP-15S (8) addresses the need for establishing quality control and inspection processes during manufacturing.
- Development of Non-Destructive Evaluation (NDE), quality control, and inspection procedures during the installation of the composite pipe and in-service,
- Understanding of behavior of large diameter composite pipes under varying loading and environmental conditions,

- Susceptibility to external damage from transportation, field installation, and third-party excavation,
- Need to evaluate the joints and valves used with the composite pipes in high pressure operations.

Although composite material have relatively high resistance to elevated temperature, the long-term cyclic pressure tests in this testing program has demonstrated significant reduction in their strength at elevated temperatures. Composites with thermoplastic components, such as HDPE, are susceptible to deformation and reduction in mechanical properties at elevated temperatures. Accordingly, the 49 CFR 192.123 code limits these pipes to 100 psi at operating temperatures up to 100ºF.

The mechanical properties of composites such as Fiber-Reinforced Pipes (FRP) are also reduced at elevated temperature; however, they are less susceptible than thermoplastics. Fiberglass based pipe pressure certifications are generally valid up to around 200ºF and there are composite pipes in the market that are rated to this elevated temperature. However, sufficient quality control during the manufacturing of these composites is required to insure that water does not reach the fiberglass-based components.

One of the parameters that needs to be further investigated in the composite system is the field joints and valves connections. There are several joining methods available for the composite pipes; including Butt-and-Wrap, O-Ring, Flush Thread, Threaded and Bonded, Flanged, Keyway (tongue and groove) Joint, and Socket Joints (1). Some of these joints, especially the wrapping joints, are labor and time intensive, requiring multiple applications of resin and reinforcing material with curing time between each application.

Maintaining a complete seal in natural gas pipelines at higher pressures is a challenge with some of these joining methods. Flanged connections are typically suitable for gas transmission lines and they are quick to install; but larger diameters are expensive and difficult to work with. In small-diameter spoolable composite pipes, the joints are minimized and can be laid at rates considerably higher than conventional steel pipes.

Implementation of Composite Systems in Gas Transmission Lines

A recent workshop was organized by GTI on July 2012 (26) to identify the current state of technology and future development needs for composite piping systems for transmission and distribution of liquid and gas pipelines. The workshop was attended by representatives from PHMSA, ASME, API, pipeline utilities, and several composites manufacturers. The objective of the workshop was to identify the requirements for the qualification of the composite systems and establish a roadmap for their standardization and implementation.

The conclusions from the workshop as well as from the literature review have shown three main areas of research which may enhance the acceptance and implementation of the use of composites in the rehabilitation of natural gas transmission systems. Figure 55 identifies these three areas.

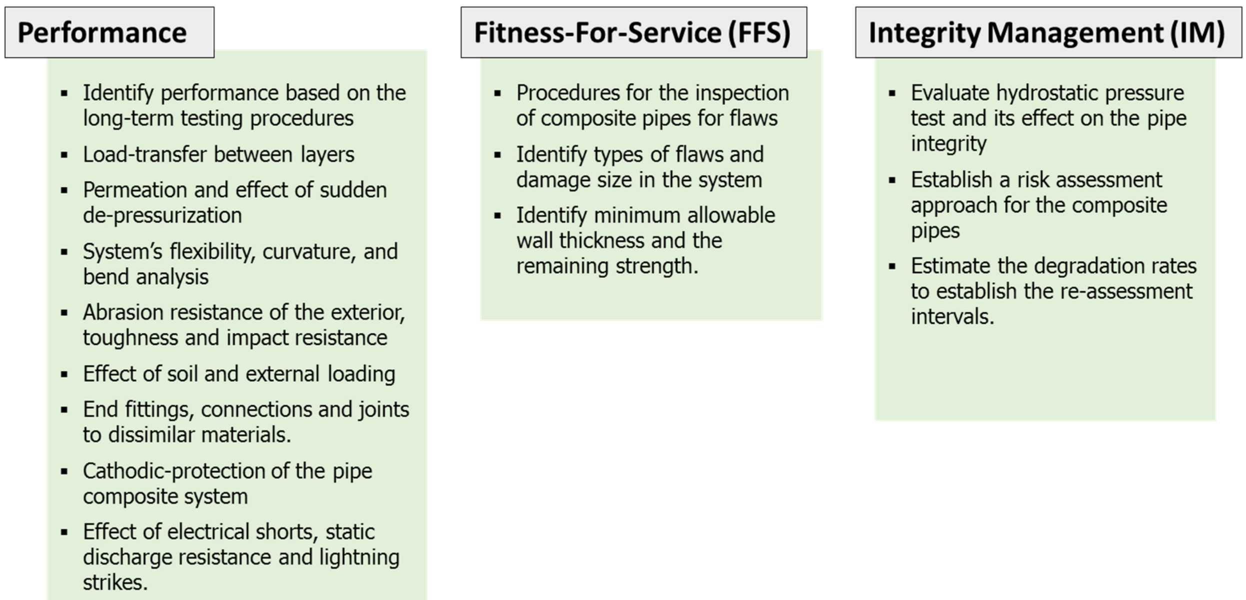


Figure 55 - Implementation requirements for composite pipes and liners

A) Performance Acceptance Requirements:

A performance specification defines the functional requirements of the composite, the environment in which it operates, and the criteria for verifying its compliance. The approach to address the development needs in this area includes:

- Qualify the performance based on hydraulic and cyclic loads in long-term testing at elevated temperatures and design pressures, and extrapolate to predict the life of the system. The specifications may define the range of temperature requirements.
- Incorporate the current standards and practices in API RP-15S (8), and ASME PCC2 (27) for the qualification of the systems.

This research project addressed this area by establishing the procedure long-term testing and evaluating the life expectancy of the products under various temperatures.

B) Fitness-For-Service Requirements:

The requirements for the FFS provide the ability to demonstrate the in-service integrity of the composite piping system when it contains a flaw. These requirements help ensuring the safety of the system while it continues to operate. The FFS assessment procedures also ensure that different applications of the composite system provide consistent life expectancy and they help optimizing the maintenance and operation of the pipeline.

The current FFS procedure in the API 579 (28) is based on steel pipelines. The approach for the implementation in the FFS requirements for composite pipes includes:

- Use the API 579 as a framework for establishing the specific FFS requirements for composite pipes. Composites may fall in Type-3 of the API 579 practice,
- Establish procedures for inspecting and categorizing flaws in composite pipes,
- Identify how the composite structure behaves under damage according to the material constitutive models,
- Define acceptance criteria and minimum allowable wall thickness,
- Include FFS procedures for coupling and joints for pullout, large deformations, and other damages.

C) Integrity Management:

Pipeline Integrity Management (IM) is a process for evaluating and reducing pipeline risks. Natural gas transmission companies conduct baseline evaluations of their pipelines according to the 49 CFR Part 192, Subpart O rules. Similarly, liquid pipeline IM is performed according to the 49 CFR Parts 195.450 and .452 rules.

The IM process specifies how pipeline operators must identify, prioritize, assess, evaluate, repair and validate the integrity of the pipeline in High Consequence Areas. The use of the composite piping systems in these regulated pipelines requires implementing the IM process for evaluating their integrity.

The approach for the implementation in the IM requirements for composite pipes and liners includes:

- Identify effective methods for the inspection of the composite pipes and liners. Currently, the applicable method which complies with the IM rule is the hydraulic pressure test.
- Establish a risk assessment approach for the composite pipes based on the ASME B31.8S procedure for steel pipelines.
- Investigate the applicability of non-destructive inspection methods (e.g., x-ray spectroscopy, electromagnetic, microwave). The market for using composite pipes may need to be large enough before pigging companies develop and incorporate the new inspection technologies in their machines.
- Establish the long-term assessment and inspection plan.

D) Construction and Maintenance:

Further issues related to the construction and maintenance of the composite pipeline systems were identified in the group discussion. These issues included the following needs:

- Establishing construction guidelines for connections and fittings with dissimilar pipes and the applicability to hot tap the pipes for service installations,
- The application of field repairs and installation of flow control devices.

Summary and Conclusions

The project performed an engineering assessment of structural composites and liners to determine their interaction with the host pipe and the characteristics required to carry the internal and external loads of a degraded host pipe. The focus of this work was on high-pressure composites and liners (up to 350 psig) installed using trenchless technology which can provide remediation to the pipe and its appurtenances. The results of the testing program and analysis are presented for the composite pipes and for the high-pressure liners as follows:

Composite Pipes:

The first task of the project reviewed the available composite pipes used in the rehabilitation of natural gas and liquid transmission lines. The rehabilitation of these lines is particularly problematic in congested pipeline systems in urban areas with very limited right of way space. Although most of the composite pipes are suitable for these rehabilitations, various characteristics govern their selection and use; including:

- Most of the composite pipes have standard diameters from 2 to 8 inches which may be suited for insertion into steel pipes with minimum diameters of 4 to 10 inches. Few composites manufacturers (e.g., Smart Pipe and Primus) produce pipes up to 16 inches.
- The pressure capacity of the composite pipe depends on its size. All the composites in the review were designed to carry operating pressures higher than 350 psig (with some composites up to 1,500 psig).
- Pipe bends and minimum radius are the major factors which govern the selection of the composite pipe. Most of the composite pipes have minimum bend radius from 20 to 150 inches, depending on pipe size, with limited insertion capabilities in multiple bends.
- Current composite pipes do not have hot tap-in connections to accommodate laterals, valves and other fittings. These connections are addressed by transitioning back to steel pipes with the necessary fittings.

The review of composite pipes covered the current requirements by the state regulators and the Office of Pipeline Safety (OPS) for granting special permits for use of these pipes where it is difficult to replace the existing pipes.

The long-term pressure rating of a composite pipes was evaluated in cyclic-pressure tests of pipes with standard end fittings at room temperature and at temperatures in excess of the standard operating temperature in the field. Cyclic pressure tests are commonly used in evaluating the strength of transmission pipes carrying non-compressible liquid and subjected to cyclic pressure loading during their operation.

Elevated temperature tests are used to extrapolate the long-term hydrostatic pressure by utilizing the time-temperature equivalence of the material. Extrapolation time factors were used to shift the results on the logarithmic time-scale.

Two composite pipes were evaluated in the long-term performance tests; namely 'Primus Liner' and 'Flexpipe'. The two composites could satisfactorily sustain line pressures of about 750 psig for extended durations of about 350,000 pressure cycles. The long-term life expectancy of these composites is estimated by dividing the number of experimental cycles to failure by the appropriate fatigue design factor. This factor typically ranges between 10 and 20. The ASME Boiler & Pressure Vessel Code employs a safety factor of 2 on stress and 20 on experimental fatigue data to establish a design life. The experimental results are then divided by the actual field number of cycles at equivalent pressure range to obtain the expected number of years of service.

Cured-in-Place (CIP) Liners

The high-pressure CIP liners in the market today rely on the structural strength of the host pipe and can fully carry the internal pressure in limited void sizes as specified by the manufacturers. Some new liner products (e.g.; Starline High-Pressure liners HPL-450) are designed to partially support deteriorated pipes with holes up to 2 inches in diameter.

The principal characteristic of the liners used in the rehabilitation of liquid and gas pipelines is their low permeability to a broad range of gases, vapors, and liquids. A permeability test was performed with the high-pressure Starline CIP liner used in a 12-inch diameter pipe sample. The test evaluated the time for the natural gas to permeate through the liner to the pipe wall. Methane concentration reached a steady-state condition at 350 psig pressure in a duration of six weeks.

The interface between the CIP liner and the pipe was evaluated in a FEA Analysis. The analysis was performed to evaluate the bonding strength between the liner and the pipe when a rapid depressurization of high-pressure occurs. Various liner and adhesive parameters were evaluated when the pipe is depressurized, thus causing a delamination of the liner. The gas pressure levels where disbondment occurred was established in graphs for various void sizes, liner tensile properties, and adhesive strengths.

Laboratory tests were performed on the liner in order to evaluate gas formation in the voids between the liner and the pipe during the rapid depressurization of the high pressure systems. These tests evaluated the theoretical FEA development of the disbondment between the liner and pipe. No damage was observed when the pressure was dropped from 350 psig to atmospheric pressure in 15 minutes. Most of the initially marked voids showed no disbondment due to the pressure drop except in two areas near an initial void in the liner.

Tests were also performed to evaluate the effect of rapid depressurization on liners installed in pipes with various degrees of bends and elbows. The liners were installed in 12-inch diameter pipe samples with bends of 22.5, 45, and 90-degrees. No delamination was observed after the rapid depressurization of the samples from 100 and 200 psig to atmospheric pressure. A small disbanded circular area was observed at the bend after depressurization from 350 psig to atmospheric pressure.

The results confirm the applicability of using liners in bends without significant disbondment; providing that tests are performed to identify the limiting pressure before disbondment occurs. Liners in bends should also be inspected to ensure that the wrinkles are fully bonded with the adhesive without any visible initial voids.

Implementation of Composite Pipes and Liners

The use of composite pipes and liners in the rehabilitation of natural gas and liquid transmission lines provides various advantages over the open-trench excavation and replacement of the deteriorating host steel pipes. These advantages include:

- The various components of the composites allow for a wide range of applications and pipe sizes with various pressure ratings,
- Composite material provide high corrosion resistance, high strength-to-weight ratio, and high resistance to chemicals and aggressive environment, and
- Small diameter composites are commonly spoolable to long length, thus facilitating the procedure of trenchless insertion with minimum number of excavation pits and with small footprint at the surface.

The material cost of the composite components can be sometimes higher than steel. However, the installation cost of these pipes is much less than for the steel pipe. Although the use of these composites in the rehabilitation of gas transmission lines can provide a safe, practical, and economical alternative, some of the barriers that limit its implementation include:

- The need for establishing quality control and inspection processes during manufacturing,
- Development of Non-Destructive Evaluation (NDE), quality control, and inspection procedures during the installation of the composite pipe and in-service,
- Determine the composites susceptibility to external damage during field installation and third-party excavation, and establish their fitness-for-Service evaluation procedure, and
- Need to evaluate the joints and valves used with the composite pipes in high pressure operations.

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