Designation: F2207 – 06 (Reapproved 2013)

Standard Specification for Cured-in-Place Pipe Lining System for Rehabilitation of Metallic Gas Pipe[1]

This standard is issued under the fixed designation F2207; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers requirements and method of testing for materials, dimensions, hydrostatic burst strength, chemical resistance, adhesion strength and tensile strength properties for cured-in-place (CIP) pipe liners installed into existing metallic gas pipes, ¾ to 48 in. nominal pipe size, for renewal purposes. The maximum allowable operating pressure (MAOP) of such renewed gas pipe shall not exceed a pressure of 300 psig (2060 kPa). The cured-in-place pipe liners covered by this specification are intended for use in pipelines transporting natural gas, petroleum fuels (propane-air and propane-butane vapor mixtures), and manufactured and mixed gases, where resistance to gas permeation, ground movement, internal corrosion, leaking joints, pinholes, and chemical attack are required.

1.2 The medium pressure (up to 100 psig) cured-in-place pipe liners (Section A) covered by this specification are intended for use in existing structurally sound or partially deteriorated metallic gas pipe as defined in 3.2.10. The high pressure (over 100 psig up to 300 psig) cured-in-place pipe liners (Section B) covered by this specification are intended for use only in existing structurally sound steel gas pipe as defined in 3.2.10. CIP liners are installed with limited excavation using an inversion method (air or water) and are considered to be a trenchless pipeline rehabilitation technology. The inverted liner is bonded to the inside wall of the host pipe using a compatible adhesive (usually an adhesive or polyurethane) in order to prevent gas migration between the host pipe wall and the CIP liner and, also, to keep the liner from collapsing under its own weight.

1.2.1 Continued growth of external corrosion, if undetected and unmitigated, could result in loss of the host pipe structural integrity to such an extent that the liner becomes the sole pressure bearing element in the rehabilitated pipeline structure. The CIP liner is not intended to be a stand-alone pipe and relies on the structural strength of the host pipe. The operator must maintain the structural integrity of the host pipe so that the liner does not become free standing.

1.3 MPL CIP liners (Section A) can be installed in partially deteriorated pipe as defined in 3.2.10. Even for low pressure gas distribution systems, which typically operate at less than 1 psig, MPL CIP liners are not intended for use as a stand-alone gas carrier pipe but rely on the structural integrity of the host pipe. Therefore, the safe use of cured-in-place pipe lining technology for the rehabilitation of existing cast iron, steel, or other metallic gas piping systems, operating at pressures up to 100 psig, is contingent on a technical assessment of the projected operating condition of the pipe for the expected 30 to 50 year life of the CIP liner. Cured-in-place pipe liners are intended to repair/rehabilitate structurally sound pipelines having relatively small, localized defects such as localized corrosion, welds that are weaker than required for service, or loose joints (cast iron pipe), where leaks might occur.

1.3.1 HPL CIP liners (Section B) are intended for use only in existing structurally sound steel gas pipe as defined in 3.2.10. HPL CIP liners are not intended for use as a stand-alone gas carrier pipe but rely on the structural integrity of the host pipe. Therefore, the safe use of cured-in-place pipe lining technology for the rehabilitation of existing steel gas piping systems, operating at pressures up to 300 psig, is contingent on a technical assessment of the projected operating condition of the pipe for the expected 30 to 50 year life of the CIP liner.

1.4 The values stated in inch-pound units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D123 Terminology Relating to Textiles

---

[1] This specification is under the jurisdiction of ASTM Committee F17 on Plastic Piping Systems and is the direct responsibility of Subcommittee F17.60 on Gas.

Current edition approved Aug. 1, 2013. Published October 2013. Originally approved in 2002. Last previous edition approved in 2006 as F2207 – 06. DOI: 10.1520/F2207-06R13.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

D543 Practices for Evaluating the Resistance of Plastics to Chemical Reagents
D883 Terminology Relating to Plastics
D1598 Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure
D1600 Terminology for Abbreviated Terms Relating to Plastics
D1763 Specification for Epoxy Resins
D2240 Test Method for Rubber Property—Durometer Hardness
D2837 Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products
D3167 Test Method for Floating Roller Peel Resistance of Adhesives
D3892 Practice for Packaging/Packing of Plastics
D4848 Terminology Related to Force, Deformation and Related Properties of Textiles
D4850 Terminology Relating to Fabrics and Fabric Test Methods
F412 Terminology Relating to Plastic Piping Systems

2.2 *Other Standards:*
CFR 49 Part 192

3. Terminology

3.1 *General*—Definitions are in accordance with those set forth in Terminologies D123, D883, D4848, D4850, and F412. Abbreviations are in accordance with Terminology D1600, unless otherwise indicated.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *adhesive system*—the adhesive system is typically a two-part adhesive or polyurethane consisting of a resin and a hardener. The flexible tubing, after wet-out, is inserted into the pipeline to be rehabilitated using an inversion method. After the inversion is complete, the adhesive is cured using either ambient or thermal processes.

3.2.2 *cleaned pipe*—pipe whose inside wall, that which is bonded to the CIP pipe liner, has been cleaned down to bare metal and is free of tars, pipeline liquids, oils, corrosion by-products, and other materials that could impair the bonding of the liner to the pipe wall.

3.2.3 *composite*—the composite is the combination of the cured adhesive system, the elastomer skin, and the jacket.

3.2.4 *elastomer skin*—the elastomer skin is a membrane, typically made of polyurethane or polyester, allowing for both inversion of the liner during the installation process and pressure tight in-service operation. When the flexible tubing is inverted into the pipeline to be rehabilitated, the elastomer skin becomes the inside surface of the newly rehabilitated pipeline, directly exposed to the gas being transported.

3.2.5 *expansion ratio table*—a table of measured diameters of the flexible tubing at increments of pressure, supplied by the manufacturer. The expansion ratio is used to calculate the pressure required to fit the flexible tubing against the pipe wall and to determine the applicable range of pipe I.D. for a given diameter flexible tubing.

3.2.6 *flexible tubing*—the flexible tube is the tubing material inverted into the host pipe and is used to carry and distribute the adhesive. For a two-component system, the flexible tubing consists of a cylindrical jacket coated with an elastomer skin. For a three-component system, it is the same as the elastomer skin.

3.2.7 *high-pressure liner (HPL)*—a CIP liner only intended for structurally sound steel pipe in sizes 4 in. and larger with an MAOP greater than 100 psig up to 300 psig. High pressure liners (HPL) are only intended for steel pipe that has a maintained cathodic protection system with annual reads per local codes, such as CFR 49 Part 192, and other mandated maintenance, such as leak surveys. The PDB testing conducted on high pressure liners is intended for the extreme case if holes occur in the steel pipe that are not detected by the cathodic protection maintenance system. Corrosion monitoring per CFR 49 Part 192 shall be conducted annually to track changes in required readings and confirm there is no active corrosion

3.2.8 *jacket*—the jacket is a textile product that is manufactured into a cylindrical form. It is made of synthetic materials, typically polyester, and provides the tensile strength and flexibility necessary to resist the specified sustained pressure when installed in partially deteriorated pipe as defined in 3.2.10.

3.2.9 *medium-pressure liner (MPL)* —a CIP liner intended for all types of structurally sound or partly deteriorated metal pipes and for all applicable sizes of pipe with an MAOP of 100 psig or less. MPL liners are relatively flexible.

3.2.10 *partially deteriorated metallic pipe*—pipe that has either been weakened or is leaking because of localized corrosion, welds that are weaker than required for service, deteriorated joints (cast iron), etc. Partially deteriorated pipe can support the soil and internal pressure throughout the design life of the composite except at the relatively small local points identified above.

3.2.11 *three-component system*—a CIP pipe lining system comprised of three separate components, which are the elastomer skin, the jacket, and the adhesive.

3.2.12 *two-component system*—a CIP pipe lining system comprised of two separate components, which are the flexible tube and the adhesive.

3.2.13 *wet-out*—the process of placing the adhesive system into the flexible tubing and uniformly distributing it prior to the inversion process.

4. Materials

4.1 The materials shall consist of the flexible tubing, jacket, and the adhesive system. The combination of materials used in both the flexible tubing and the adhesive system shall depend on the desired design characteristics of the composite. All materials shall be compatible for natural gas service. Because CIP pipe liners are both multi-component and multi-material systems, it becomes necessary to specify minimum material performance requirements for the liner composite rather than specific material testing requirements for the individual components. These requirements are outlined in Section 5.

4.1.1 *Flexible Tubing*—For a two-component system, the flexible tubing consists of a jacket with an elastomer skin that functions as a gas barrier. For a three-component system, the elastomer skin is the flexible tubing. The elastomer skin in both systems is typically made of polyurethane or polyester. The flexible tubing is fit tightly against the inner surface of the existing pipe by diametrical expansion using air or water pressure and bonded to the inner pipe wall with an adhesive.

4.1.2 *Jacket*—The jacket is made of polyester or other synthetic materials compatible with the application. The jacket provides the necessary strength to the composite to meet the required design characteristics, for example, resistance to internal and external pressure, resistance to earth movement, and diametrical expandability.

4.1.3 *Elastomer Skin*—The elastomer skin holds the adhesive system inside the flexible tubing during the wet-out, inversion, and curing. During the inversion and curing, the elastomer skin holds the air, water, or steam pressure inside the flexible tubing. When the flexible tubing is inverted into the existing pipe, the elastomer skin becomes the inside surface of the lined pipe. Upon completion of the installation, the elastomer skin is directly exposed to the gas being transported and forms a gas barrier. The elastomer skin shall have a high chemical resistance to the materials it is in contact with as defined in 5.1.3. For two-component systems, the elastomer skin is extruded or otherwise placed on the outside of the jacket during the manufacture of the flexible tubing.

4.1.4 *Adhesive System*—The adhesive is a two-part system composed of a resin and a hardener. The adhesive formulation can be modified as necessary to meet the curing time, strength, and application requirements specified for the lining installation. The cured adhesive system, in combination with the flexible tubing, forms the composite. Either ambient or thermal curing of the adhesive system may be used.

5. Requirements

5.1 *Jacket and Elastomer Skin (Pre-Installation):*

5.1.1 *Workmanship*—Both the jacket and the elastomer skin shall be free from defects such as tears, bubbles, cracks, and scratches that could cause the liner to not be able to hold inversion and expansion pressures and, therefore, fail during installation. For two-component systems, the flexible tubing shall be rolled onto a reel designed to provide protection during shipping and handling. For three-component systems, the elastomer skin shall be rolled onto reels designed to provide protection during shipping and handling. The jacket may either be rolled onto reels or folded into boxes.

5.1.2 *Dimensions*—An expansion ratio table, as defined in 3.2.5, including nominal size and length, shall be attached to each roll of flexible tubing or jacket and elastomer skin prior to shipment from the manufacturer. All material dimensions and physical properties must at least meet the minimum specifications, requirements, or tolerances assumed in establishing the strength tests under Section 6.

5.1.3 *Chemical Resistance*—The jacket and the elastomer skin materials shall be compatible with the liquids listed in Table 1 and tested in accordance with Practice D543, Practice A, Procedure I. Neither tensile strength nor elongation of any of the components shall change more than 20 %. Weight of the test specimen after testing shall not have increased by more than 14 % or decreased by more than 3 %. This test shall be a qualification test to be performed once for each class or pressure rating of installed pipe liner.

NOTE 1—These tests are only an indication of what will happen as a result of short-term exposure to these chemicals. For long-term results, additional testing is required.

5.1.4 *Elastomeric Peeling Strength*—The peeling strength between the jacket and the elastomer skin shall meet or exceed 7.0 lb/in. (1.2 kg/cm) when measured in accordance with Test Method D3167.

5.1.5 *Physical Properties*—For two-component systems, the design pressure of the flexible tubing shall be sufficient to withstand the required installation, testing, and operating pressures and to form the required composite. For three-component systems, the design pressure of the elastomer skin or flexible tube shall be sufficient to withstand the installation inversion pressure and the design pressure of the combined jacket and elastomer skin shall be high enough to withstand the testing and operating pressures and to form the composite. For both systems the flexible tubing shall be flexible enough to allow installation using the inversion method.

5.2 *Adhesive System (Post-Installation and Cure):*

5.2.1 *General*—The adhesive system shall provide uniform bonding of the jacket to the I.D. of the host pipe. The adhesive shall provide protection against gas tracking between the composite and the host pipe when the installed cured liner (composite) is penetrated for any reason. For three-component

TABLE 1 Chemical Resistivity List of Reagents

Liquids	Test Composition
Water (External and Internal)	Freshly prepared distilled water (in accordance with Practice D543)
Gasoline (External)	Gasoline-Automotive Spark-Ignition Engine Fuel per Specification D4814
Gas Condensate (Internal)	70 % volume isooctane + 30 % volume toluene
Methanol	20 % volume methanol + 80 % volume distilled water
Triethylene Glycol	10 % volume triethylene glycol + 90 % volume distilled water
Brine Solution	10 % mass NaCl solution made up with a balance of distilled water
Mineral Oil	100 % White Mineral Oil USP, specific gravity 0.830 to 0.860, Saybolt at 100°F: 125 to 135 s, in accordance with Practice D543
Isopropanol	10 % volume isopropanol + 90 % volume distilled water
Sulfuric Acid	5 % weight (of total solution) H_2SO_4 in distilled water
Surfactants	5 % mass (of solution weight) dehydrated pure white soap flakes (dried 1 h at 105°C) dissolved in distilled water, in accordance with Practice D543
Mercaptans	2 % volume tertiary butyl mercaptan + 98 % volume mineral oil, white, USP

systems the adhesive system shall also provide uniform bonding of the elastomer skin to the jacket.

5.2.2 *Composite Liner Peeling Strength*

5.2.2.1 *Section A-For MPL liners,* the peeling strength of the composite liner from the wall of the cleaned pipe shall be tested in accordance with Test Method D3167 and shall not be less than 6.0 lb/in. (1.0 kg/cm).

5.2.2.2 *Section B-For HPL liners,* the peeling strength shall not be less than 10.0 lb/in. (1.7 kg/cm).

5.2.3 *Chemical Resistance*—The cured adhesive system shall have resistance to the chemicals listed in 5.1.3. The weight of the test specimen shall not increase by more than 14 % nor decrease by more than 3 % and it shall retain at least 80 % of both its hardness, when measured in accordance with Test Method D2240, and its peeling strength, when measured in accordance with Test Method D3167. This test shall be a qualification test to be performed once for each class of adhesives developed by each manufacturer.

5.3 *Composite (Post-Installation and Cure):*

5.3.1 *Mechanical Properties:*

5.3.1.1 *Peeling Strength*—The peeling strength of the composite shall be determined by the peeling strength of the adhesive system as required in 5.2.2.

5.3.1.2 *Strength Test*—The manufacturer shall conduct pressure tests to demonstrate the strength of the composite. The tests shall be conducted on properly lined partially deteriorated pipe as defined in 3.2.10. For a given pipeline operating pressure rating, the lined partially deteriorated pipe shall be tested at a minimum pressure of two times the certified MAOP of the pipeline for a minimum of one hour without leakage. The MAOP shall be determined as defined in 5.4. Nitrogen gas, air, or water may be used to conduct the strength tests.

5.3.1.3 *Flexibility Tests*—For flexible MPL liners, the manufacturer shall demonstrate the flexibility of each liner composite product as installed in partially deteriorated pipe by performing either a tensile test, see 6.1.4, or a bend test, see 6.1.5, while pressurized to the certified MAOP of the lined pipeline. For both of these tests, the liner composite shall not leak for a minimum period of 24 h. These tests are not considered as quality control tests and are not needed for acceptance of individual lots or runs.

5.3.2 *Chemical Resistance*—The composite shall be compatible with the liquids listed in 5.1.3, Table 1, and tested in accordance with Practice D543, Practice B. The level of applied stress in Practice B shall be determined by the manufacturer and reported along with the results of this test. Neither tensile strength nor elongation shall change more than 20 %. Weight of the test specimen after testing shall not have increased by more than 14 % or decreased by more than 3 %. This test shall be a qualification test to be performed once for each class or pressure rating of installed pipe liner.

NOTE 2—These tests are only an indication of what will happen as a result of short-term exposure to these chemicals. For long-term results, additional testing is required.

5.4 *MAOP (Post-Installation and Cure):*

5.4.1 The lined partially deteriorated pipe, as defined in 3.2.10, shall have an MAOP. The determination of the MAOP shall be based on the Pressure Design Basis (PDB) obtained in accordance with 6.1 and shall be the responsibility of the CIP pipe liner manufacturer.

$$\text{MAOP} = \text{PDB} \times 0.50$$

6. Test Methods

6.1 *Sustained Pressure Test:*

6.1.1 Lined partially deteriorated metallic pipe, as defined in 3.2.10, shall be used for all sustained pressure testing. For testing purposes and establishing pipeline MAOP, partially deteriorated pipe shall be simulated by a minimum full circumference gap between two pipe segments and a hole size as defined in the table below.

Nominal Pipe Diameter	Linear Pipe	Circumferential Gap Size	Minimum Diameter Hole Size
Section A			
¾ in.-3 in.	MPL	1 in.	½ nominal pipe diameter in pipe body
4 in.-10in.	MPL	1.5 in.	2 in.
12 in. and larger	MPL	2 in.	4 in.
Section B			
4 in. and larger	HPL	1 in.	2 in.

Note- The sustained pressure test is only used to establish the PDB rating, and does not imply the CIP liners can perform structurally as a stand-alone pipe.

6.1.2 Lined pipe samples are capped and tested to failure using either an extension of Test Method D1598, with suitable modifications in analysis and data validation or, the methodology developed and validated by Battelle for GTI, as outlined in Annex A of this specification, to develop a stress regression curve at 73°F.

6.1.3 *Pressure Design Basis*—Either an extension of Test Method D2837 which has been validated for CIP liners or, the methodology developed by Battelle for GTI, as outlined in Annex A of this specification, shall be used to determine the pressure design basis for CIP lined partially deteriorated pipe.

6.1.4 *Tensile Test*—Two contiguous pipe segments made of similar material to the pipe to be lined (steel, cast iron, copper, etc.), each 10 ft in length, shall be lined and, while at the certified pipeline MAOP, then pulled apart in tension until there is a minimum separation of 2 in. between the pipe segments.

6.1.5 *Bend Test*—Two contiguous pipe segments made of similar material to the pipe to be lined (steel, cast iron, copper, etc), each 10 ft in length, shall be lined and, while at the certified pipeline MAOP, then bent at the pipe joint to form a minimum separation of 2 in. between the pipe segments.

7. Manufacturing Quality Control

7.1 *Jacket and Elastomer Skin or Flexible Tubing*—For quality control and assurance purposes, tests of each diameter and size of the jacket and elastomer skin for three-component systems and of the flexible tubing for two-component systems shall be conducted at the beginning and end of each production run, and for each 10 000 ft of production or extrusion when a production run exceeds 10 000 ft.

7.2 *Adhesive System and Its Components*—Sampling shall be done for each production lot. The curing time and the adhesive strength, as specified in 5.2.2, shall be documented by the manufacturer. Measured values must be within prescribed tolerances given by the manufacturer.

7.3 *The Composite*—The sampling and tests shall be as specified by the purchaser.

8. Product Marking

8.1 The flexible hose shall be clearly marked throughout its length, at intervals not exceeding 5 ft (1.5 m), with the product designation, size, design ASTM Standard, and date of manufacture.

9. Packaging and Package Marking

9.1 *Jacket and Elastomer Skin:*

9.1.1 The elastomer skin shall be rolled onto a reel. The reel shall be strong enough to protect the materials from damage and all surfaces that contact the materials shall be appropriately coated to prevent damage to the elastomer skin. The loaded reels shall be sealed in plastic for protection during shipping. For three component systems, the jacket can be packaged as recommended by the manufacturer.

9.1.2 Shipping reels and boxes shall be marked with the name of the product, its type and size, lot or control number, and quantity contained as defined by the contract or purchase order under which the shipment is made.

9.2 *Adhesive System*—All packaging and package marking shall be in accordance with Specification D763, Section 10. All packing, packaging, and marking provisions of Practice D3892 shall apply to this specification. Material Safety Data Sheets (MSDS) shall be supplied and packaged with each shipment.

10. Keywords

10.1 composite; cured-in-place; flexible tubing; gas pipe renewal; inversion; rehabilitation

ANNEX

(Mandatory Information)

A1. DETERMINATION OF THE DESIGN PRESSURE FOR CURED-IN-PLACE LINERS IN PARTIALLY DETERIORATED PIPE

A1.1 Introduction

A1.1.1 The life of deteriorating buried gas distribution piping can be extended by lining the pipe. Rehabilitation technologies utilize the existing cavity and the structural support of the old pipe by inserting a liner into the old pipe. Cured-in-place (CIP) liners typically have an elastomeric layer in contact with the gas to inhibit permeation, and a fabric backing to contain the pressure. The liner is attached to the host pipe by an adhesive that cures and stiffens. Liners of this type can be characterized as having an elastomer-fabric-adhesive structure.

A1.1.2 When determining the "life" of a liner, it is necessary to specify the cause of failure, because different driving forces generally result in different estimates of "life." In the methodology described in this Annex, the stress field that causes failure is assumed to be the internal operating pressure. The "life" calculated on this basis is referred to as "stress rupture life."

A1.1.3 A traditional and well-established method of determining the long-term strength of unlined pipe is to pressurize the pipe (possibly at higher temperatures to accelerate the process) and note the time-to-failure. Repetition of this experiment using different pressures gives a graph of pressure versus time-to-failure. Judicious extrapolation of this data to longer times gives the desired result. If the desired service life ("design life") is specified, the data can be used to determine the expected internal pressure that can be safely sustained at that time. This is termed the "design pressure." Conversely, if the operating pressure is specified, the data can be used to determine the service life for which the lined pipe will sustain this internal pressure safely. The qualifier with respect to "safety" implies the use of a suitable safety factor. An alternative approach developed by Battelle for the Gas Technology Institute is presented here. Battelle's approach allows the number of test data to be reduced, and some tests to be performed on coupon specimen rather than full-scale host pipe.

A1.1.4 Pipe is lined because the integrity of the original host pipe is questionable. This means that the pipe has leaks (holes) or is expected to leak in the near future. Therefore, the long-term evaluation of lined pipe that fails because of internal pressure needs to consider the effect of:

Internal pressure,
Hole size,
Hole shape,
Host pipe diameter, and
Operating temperature.

A1.1.5 To extend traditional testing methods to lined pipe of different diameters and different holes, a large test matrix becomes necessary. This is likely to be time-consuming and expensive. By combining full-scale (or traditional) tests with coupon testing and a mathematical model, the procedure is able to reduce the amount of testing and extrapolate data on a more rational basis. This approach is described in the sections titled, "Material Characterization," and "Mathematical Modeling." It has been validated for two commercial liners, both of which had the elastomer-fabric-adhesive structure described earlier.

A1.1.6 The methodology described in this Annex documents the specifics of the mathematical model that was originally described in a Gas Research Institute (GRI) report.[3] The equations differ somewhat from those presented in the original report because of slight changes in nomenclature and rectification of minor errors. A stepwise procedure applicable to liners other than those tested and documented in the Gas Research Institute (GRI) report is also given herein.

A1.1.7 This Annex is formatted such that the methodology is described, and the roles of the materials characterization and mathematical modeling are clarified. Sections in this Annex (along with a brief description of the contents) are:

A1.1.7.1 *Stress Rupture Life Determination*—Defines empirical relationships between operating pressure, burst pressure, time-to-failure, and operating temperature, for a given hole shape and size, and pipe diameter based on measured data. If the model is applicable to the liner behavior, the burst pressure can be calculated from material properties as a function of hole shape and size, and pipe diameter. The model has been validated for two liners with the elastomer-fabric-adhesive structure.

A1.1.7.2 *Material Characterization*—Defines the material properties that are necessary, and indicates the manner of data acquisition and data processing.

A1.1.7.3 *Mathematical Modeling*—Lists the equations that comprise the model, and the physical origin of the equations.

A1.1.7.4 *Selection of the Failure Criterion and Computation of Burst Pressure*—Gives an overview of how the equations are to be processed, and specifies the input variables and the output variables.

A1.1.7.5 *Procedure to Estimate Design Pressure*—Gives a stepwise process to determine design pressure of a CIP liner.

A1.2 Stress Rupture Life Determination

A1.2.1 In full-scale stress-rupture tests, lined pipe of a specific diameter, with the host pipe having a hole of specific dimensions and a specific shape, is held under sustained internal pressure until the liner ruptures. When the rupture is immediate (under conditions of rapidly increasing internal pressure), the pressure at rupture is termed the "burst pressure" or the "ultimate strength." At pressures less than the burst pressure, failure is not immediate but occurs after a time period termed "time-to-failure." By repeating the test using different internal pressures, but keeping all other variables constant, an empirical relationship between the internal pressure and the time-to-failure is obtained (for a specific pipe diameter, hole shape, hole size, and operating temperature). By geometrically extrapolating the short-term data, one can obtain a design pressure corresponding to a desired design life. It is assumed that there is only one mode of failure in the short-term data set, and that the same mode of failure will be exhibited over the period of extrapolation. The entire procedure may have to be repeated to account for parameters such as hole size, hole shape, host pipe diameter and operating temperature.

A1.2.2 On the other hand, if the empirical data are used in conjunction with an applicable theoretical model, fewer tests are required, coupon testing can be substituted for some of the full-scale testing, and a more rational extrapolation basis can be used. The applicability of the model is determined by whether an equivalence can be demonstrated between tensile tests on coupons and stress-rupture tests on lined pipe with machined defects. This equivalence implies a unique relationship between load per width (LPW) and internal pressure for a specified hole size. The mathematical model described here demonstrates and quantifies such an equivalence for a particular class of liners.

A1.2.3 Whether the testing uses coupons or full-scale lined pipe, the number of specimens must be large enough so that the data are statistically valid. At least three to five LPW (or pressure) levels should be tested, with at least three replicates at each level. The temperature range should cover the expected temperature range of the liner in operation. The LPW (or pressure) levels need to be selected so that the specimen failure times are relatively evenly distributed over the full range of test times. This may require substantial trial-and-error because fiber composites tend to have a narrow range of LPW (or pressure) levels over which failure occurs. If the load is too high the failure is immediate; if the load is too low, failure times are very long. This emphasizes the importance of multiple test fixtures. The maximum duration of the testing is guided by the expected design life for the liner. In general, good practice suggests that data should not be extrapolated by more than two orders of magnitude when estimating the design life. This translates to tests with a maximum duration of 2500 h for a 30-year design life. The mode of failure must be the same for all specimens. If the mode of failure changes because of stress level or temperature, only data that have the same mode of failure can be analyzed together.

A1.2.4 For convenience, a dimensionless quantity, P, is defined as the ratio of the LPW to the ultimate LPW for tensile coupons, or the ratio of pressure to the burst pressure for a given size defect for full scale specimens. A power law curve is fit to isothermal data where t_f is the time to failure, and the constants a and b determined by regression analysis.

$$P = a \cdot t_f^b \tag{A1.1}$$

A1.2.5 If data at different temperatures are available, the form of the equation changes to:

$$P = a \cdot t_f^b \cdot e^{k'\left(\frac{1}{T} - \frac{1}{529.7}\right)} \tag{A1.2}$$

where T is the temperature in degrees Rankine, the constants a, b and k' are determined from the regression analysis, and e is the natural logarithm and has the value of 2.71828. The statistical level of confidence for the constants should be specified.

A1.2.6 Once the constants have been determined, Eq A1.1 or Eq A1.2 can be used with the specified design life to obtain the design pressure. This will give the maximum allowable LPW or pressure for a given pipe diameter and defect size at the design life. The next step is to extend this data set to any defect size and pipe diameter. This is done by relating coupon test data and hole dimensions to lined pipe burst pressure through material characterization and mathematical modeling.

---

[3] Francini, R. M., Pimputkar, S. M., Wall, G., and Battelle, M. O., *The Long-Term Performance of the Starline® 200 Liner for Gas Distribution Systems*, GRI-00/0237.

A1.3 Material Characterization

A1.3.1 *Coupon Preparation*—The flexible tubing is shipped "flattened out," and has folds or creases. (See Fig. A1.1.) The installed liner is to be slit open in such a way as to produce coupon samples that include the creases in some cases and coupons without the creases in other cases. The coupons are cut in several orientations: axially and in the hoop direction. If necessary some coupons can be cut oriented in the 45° direction. (See Fig. A1.2.)

A1.3.2 To represent normal installation conditions, the liner should be tested with the same thickness of adhesive that is present in a normal installation. One way to make test specimens that are representative of field conditions is to flatten the liner between two sheets of metal with the adhesive applied to the same side of the liner (the fabric side) as in practice, as shown in Fig. A1.3. If necessary, a release agent can be applied to the metal to facilitate removal of the specimens. A coupon cross section is shown in Fig. A1.4. Woven liners often have a crease where they have been flattened for spooling. Whether the crease affects liner properties significantly has to be determined by comparing tensile test data for samples with and without the crease. If the presence of a crease is significant, this has to be considered in formulating the test matrix.

A1.3.3 The approach described here applies directly to liners in which the hoop and axial fibers are orthogonal to each other. Tensile properties need to be determined in the hoop and axial orientations for the fabric as shown in Fig. A1.5. Fig. A1.6 shows a coupon being subjected to tensile stress. The specimen needs to be wide enough (0.75 to 1.00 in.) so that a representative number of fibers is included. (See Fig. A1.7) Based on measurements of the dimensions of the coupon, the load, and the strain in the direction of the load and transverse to the load, the LPW and the axial and transverse strains can be calculated and graphed.

A1.3.4 Fig. A1.8 shows a typical load/width-axial strain curve. Close to the origin, the curve is dominated by the strength of the adhesive, and away from the origin, the curve is dominated by the strength of the fiber-elastomer liner. The LPW-strain curve can be approximated by two straight lines (a bilinear curve) as shown in Fig. A1.9. The point of intersection of the two lines represents the yield point and the values at this point are the yield strain and the yield LPW. The slope represents the modulus of elasticity. Least-squares linear regression gives the equations for the bilinear approximation as:

$$y = m_{a1}x + c_{a1} \tag{A1.3}$$

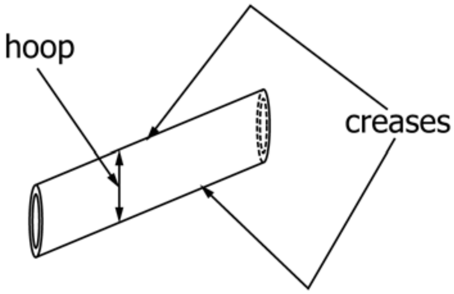

FIG. A1.1 Liner Before It is Slit Open

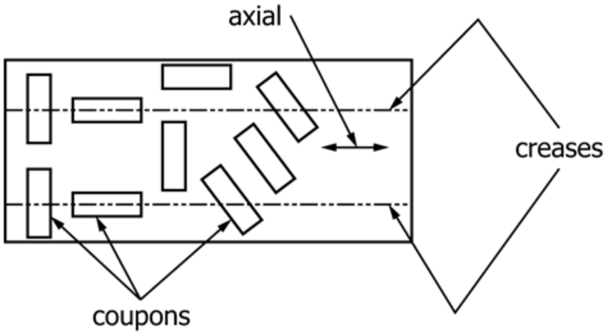

FIG. A1.2 Liner After It is Slit Open (Note the Orientation of the Coupons)

for the left-hand portion, and

$$y = m_{a2}x + c_{a2} \tag{A1.4}$$

for the right-hand portion.
The constants m_L and m_R represent the slopes of the lines, and the constants c_L and c_R represent intercepts on the *y*-axis.

A1.3.5 The next step is to plot the load versus the transverse strain. This will result in a plot that has a similar shape to that in Figs. A1.8 and A1.9, but the strain will be negative in most cases. The same procedure described above is used to fit the two parts of the curve to straight lines. The resulting regression of the two straight-line portions of these curves will give the following equations for the initial portion of the curve and secondary straight-line portions of the curve:

$$y = m_{t1}x + c_{t1} \tag{A1.5}$$

$$y = m_{t2}x + c_{t2} \tag{A1.6}$$

The constants m_{t1} and m_{t2} represent the slopes of the lines, and the constants c_{t1} and c_{t2} represent the intercepts on the *y*-axis.

A1.3.6 The procedure to determine material properties based on the bilinear approximation is as follows:

A1.3.6.1 The primary modulus is given by:

$$E_1 = m_{a1} \tag{A1.7}$$

A1.3.6.2 The secondary modulus is given by:

$$E_2 = m_{a2} \tag{A1.8}$$

A1.3.6.3 The primary Poisson ratio is given by:

$$\nu_{ah\_1} = \frac{-m_{t1}}{m_{a1}} \tag{A1.9}$$

A1.3.6.4 The secondary Poisson ratio is given by:

$$\nu_{ah\_2} = \frac{-m_{t2}}{m_{a2}} \tag{A1.10}$$

A1.3.6.5 The intersection of the lines, that is, the solution of Eq A1.3 and A1.4 gives the load/width at yield (on the *y*-axis) and the strain at yield (on the *x*-axis).

A1.3.6.6 The maximum value for the load/width is the ultimate load/width.

A1.3.7 The following properties need to be determined for the hoop and axial orientations:

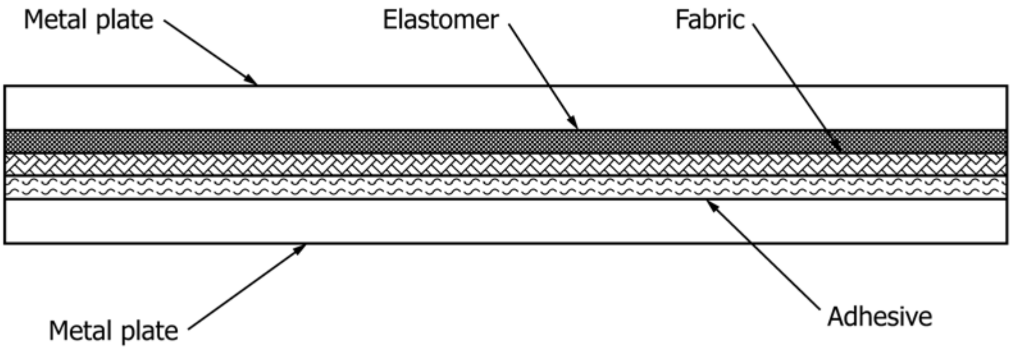

FIG. A1.3 Preparation of Tensile Specimen from Flattened Liner Material (Not to Scale)

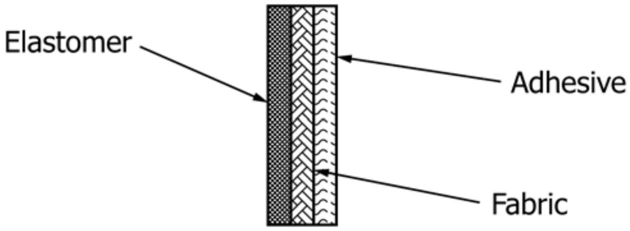

FIG. A1.4 Cross Section of Coupon (Not to Scale)

Yield strain (ε_y),
Load/width at yield (N_y),
Primary modulus (E_1),
Secondary modulus (E_2),
Primary Poisson ratio (ν_{12_1}),
Secondary Poisson ratio (ν_{12_2}) and
Ultimate load/width (N_{uts})

A1.3.8 The orientations in the axial and hoop orientations will be indicated by subscripts "*a*" and "*h*" on the parentheses respectively. For example, the yield strain the hoop direction will be represented by $(\varepsilon_y)_h$, and the secondary modulus in the hoop orientation will be denoted by $(E_2)_h$.

A1.3.9 At least five tests need to be performed in each orientation. The averaged values for each property and orientation are used in subsequent calculations. For convenience, material properties termed compliance coefficients can be defined as follows:

A1.3.9.1 The primary interaction compliance ($S_{12\text{-}1}$) is determined using the following equation:

$$S_{12-1} = \frac{-\nu_{12\_1}}{E_1} \tag{A1.11}$$

A1.3.9.2 The secondary interaction compliance ($S_{12\text{-}2}$) is determined using the following equation:

$$S_{12-2} = \frac{-\nu_{12\_2}}{E_2} \tag{A1.12}$$

A1.4 Mathematical Modeling

A1.4.1 This model applies to an elastomer-fabric liner whose shear stiffness is small compared with its stiffness in the axial and hoop directions. The purpose of this model is to use coupon test data, hole size data, and material property data to calculate the ultimate strength of the liner. This enables the calculation of service life or design pressure using Eq A1.1 or Eq A1.2 with greatly reduced full-scale testing of lined pipe. Some burst test data are necessary to select the appropriate failure criterion, and additional burst test data are necessary to validate the model.

A1.4.2 The model solves equilibrium equations, strain displacement equations, constitutive equations, and compatibility equations in conjunction with a failure model. Each is described below:

A1.4.2.1 *Equilibrium*—Static equilibrium of the exposed liner is expressed by the following equation:

$$\frac{N_h}{r_h} + \frac{N_a}{r_a} = p \tag{A1.13}$$

where:

N_h = hoop load/width,
N_a = axial load/width,
r_h = radius of curvature of liner in hoop direction,
r_a = radius of curvature of liner in axial direction, and
p = applied pressure.

A1.4.2.2 *Strain Displacement*—The defect is assumed to be uniquely characterized by two dimensions, *w* in the hoop direction, and *L* in the axial direction. For circular defects, $L = w$. It is assumed that the liner deforms into a circular arc at the hole in each of these directions, as shown in Fig. A1.10. The strains are then given by:

$$\varepsilon_h = \frac{2 \cdot r_h \cdot \sin^{-1}\left(\frac{w}{2 \cdot r_h}\right)}{D \ \sin^{-1}\left(\frac{w}{D}\right)} - 1 \tag{A1.14}$$

$$\varepsilon_a = \frac{2 \cdot r_a \cdot \sin^{-1}\left(\frac{L}{2 \cdot r_a}\right) - L}{L} \tag{A1.15}$$

where:

D = diameter of the host pipe.

A1.4.2.3 *Constitutive Equations*—The liner is assumed to be an orthotropic membrane without any shear stiffness. The relationship between stress and strain is then given by the following equations:

$$\varepsilon_h = \frac{1}{E_h} \cdot N_h + S_{12} \cdot N_a \tag{A1.16}$$

$$\varepsilon_a = S_{12} \cdot N_h + \frac{1}{E_a} \cdot N_a \tag{A1.17}$$

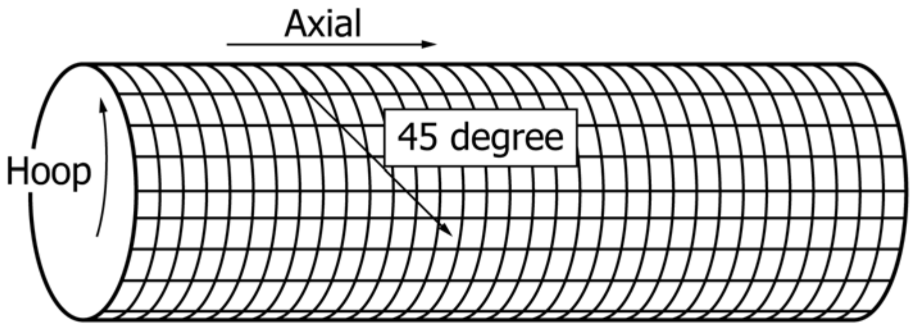

FIG. A1.5 Definition of Fiber Orientation for Tensile Testing

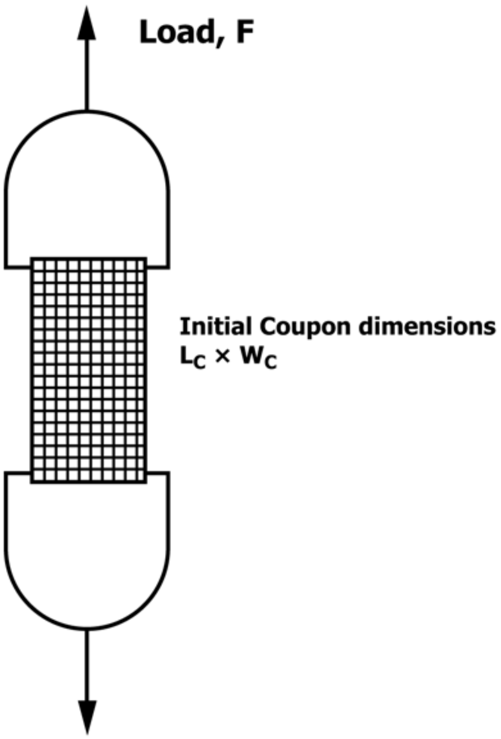

FIG. A1.6 Schematic of Tensile Test

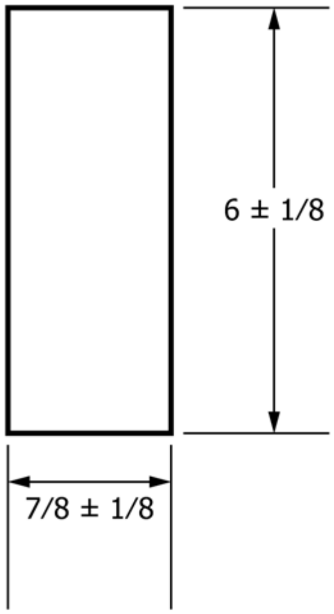

FIG. A1.7 Coupon Size

When using Eq A1.16 and A1.17, it is noted that the coefficients are different above and below the yield strain because of the bilinear approximation. The appropriate primary and secondary properties should be used.

NOTE A1.1—Strictly speaking, S_{12} in Eq A1.17 is S_{21}. Normally these are equal, but with a fabric they may not be. This will be determined during the material property testing described above. In the case that they are not, it must be taken into account when solving the series of equations.

A1.4.2.4 *Compatibility Equations*—As the liner bulges out of the defect, it is constrained to pass through the end-points of the defect. This requirement, in conjunction with the assumption that the shape of the liner in the axial and hoop directions is a circular arc, gives the following relationships for the radius of curvature of the bulge in each direction:

$$r_a = \frac{L^2}{8 \cdot h} + \frac{h}{2} \tag{A1.18}$$

$$r_h = \frac{w^2}{8 \cdot h} + \frac{h}{2} \tag{A1.19}$$

where:

h = height of the liner bulge beyond the pipe wall.

A1.4.2.5 *Failure Criteria*—Two failure criteria have been used successfully with liners. They are the maximum stress criterion and the interactive stress criterion. In the maximum stress criterion, failure occurs when either the hoop load/width reaches the ultimate hoop load/width or the axial load/width reaches the ultimate axial load/width. This means that failure occurs when:

$$\frac{N_h}{(N_{uts})_h} = 1 \tag{A1.20}$$

$$\frac{N_a}{(N_{uts})_a} = 1 \tag{A1.21}$$

In the interactive stress criterion, failure occurs when the following condition is reached:

$$\left(\frac{N_h}{(N_{uts})_h}\right)^2 - \frac{N_h N_a}{(N_{uts})_h^2} + \left(\frac{N_a}{(N_{uts})_a}\right)^2 = 1 \tag{A1.22}$$

Which failure criterion is more appropriate for a given liner is determined by comparing calculated burst pressure with measured values of burst pressure as described next.

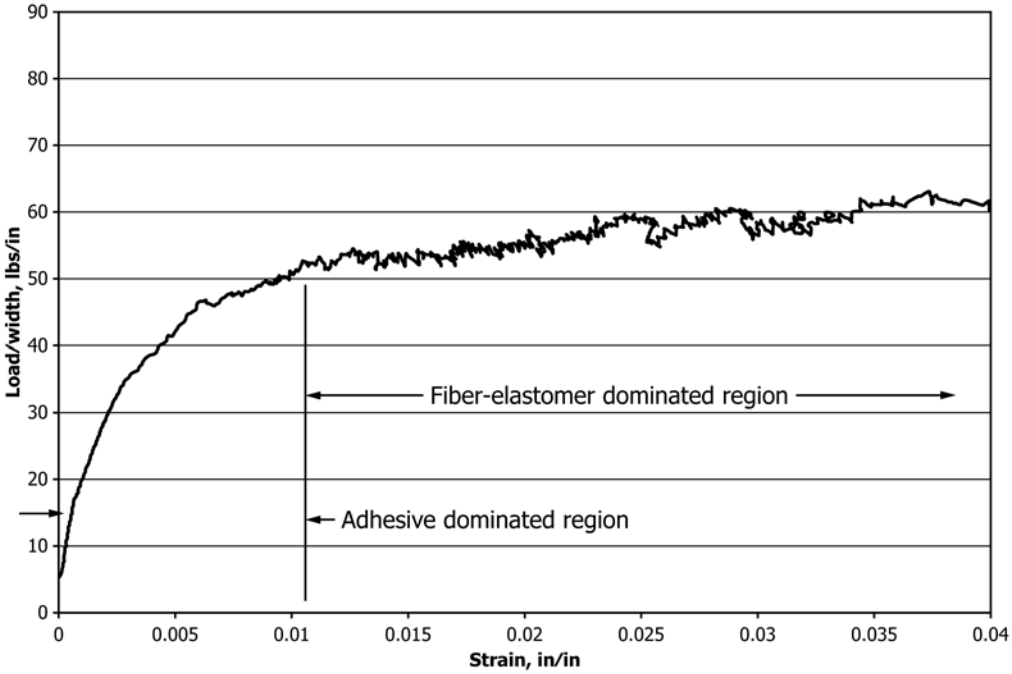

FIG. A1.8 Load/Width (N) versus Strain Showing Adhesive Dominance and Fiber-Elastomer Dominance

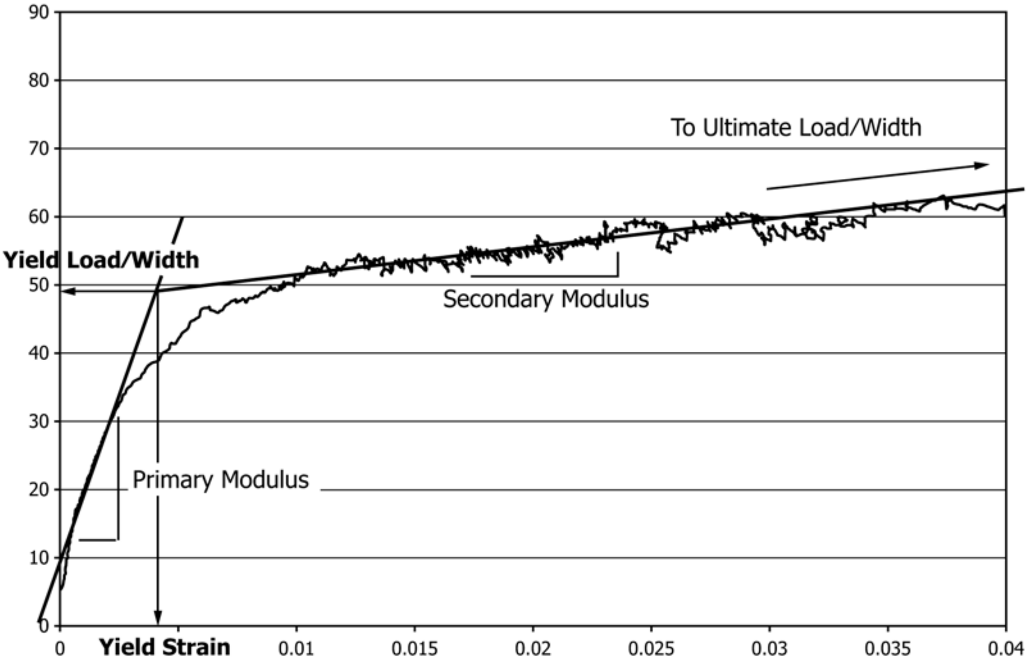

FIG. A1.9 Properties Defined on the Basis of the Bilinear Approximation

A1.5 Selection of the Failure Criterion and Computation of Burst Pressure

A1.5.1 After elimination of intermediates in Eq A1.11-A1.19, three equations remain with four unknowns (N_h, N_a, p, and h), assuming the property data, the pipe size (D) and the defect dimensions (L and w) are known. By specifying one of these variables, the other three unknowns can be determined. If the internal pressure, p, is specified, this can be written as:

$$N_h = f\left(p; L, w, D\right) \tag{A1.23}$$

$$N_a = f\left(p; L, w, D\right) \tag{A1.24}$$

$$h = f\left(p; L, w, D\right) \tag{A1.25}$$

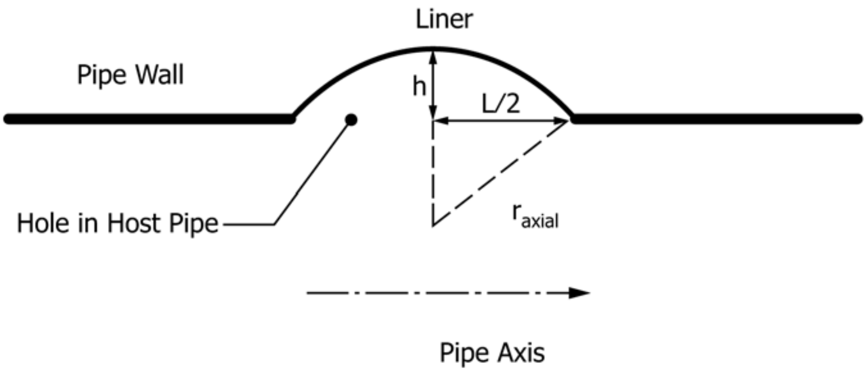

FIG. A1.10 Schematic and Nomenclature for Liner Bulging Out of Hole

A1.5.2 Therefore, for different values of the internal pressure, p, Eq A1.23-A1.25 can be used to calculate N_h and N_a.

A1.5.3 One way to do this is to eliminate r_a, r_h, ε_a, and ε_h and effectively obtain an equation in h and p. Then, if p is specified, h can be calculated using standard iterative techniques for solving nonlinear algebraic equations. The resulting set of equations is derived next.

A1.5.4 Eliminating r_a and r_h between Eq A1.13, Eq A1.18, and Eq A1.19 gives:

$$\frac{N_h}{\frac{w^2}{8h}+\frac{h}{2}}+\frac{N_a}{\frac{L^2}{8h}+\frac{h}{2}}=p \tag{A1.26}$$

A1.5.5 Solving Eq A1.16 and A1.17 for N_h and N_a, then eliminating ε_a, ε_h, r_a and r_h using Eq A1.14, Eq A1.15, Eq A1.18, and Eq A1.19 gives:

$$\begin{aligned}N_h=\frac{1}{\frac{1}{E_hE_a}-S_{12}^2}\Bigg(&\frac{1}{E_a}\left[\frac{\left(\frac{w^2}{4h}+h\right)\ \sin^{-1}\left(\frac{w}{\frac{w^2}{4h}+h}\right)}{D\ \sin^{-1}\left(\frac{w}{D}\right)}-1\right]\\ &-S_{12}\left(\left[\frac{\left(\frac{L^2}{4h}+h\right)\ \sin^{-1}\left(\frac{L}{\frac{L^2}{4h}+h}\right)}{L}-1\right]\right)\Bigg)\end{aligned} \tag{A1.27}$$

$$\begin{aligned}N_a=\frac{1}{S_{12}^2-\frac{1}{E_hE_a}}\Bigg(&S_{12}\left[\frac{\left(\frac{w^2}{4h}+h\right)\ \sin^{-1}\left(\frac{w}{\frac{w^2}{4h}+h}\right)}{D\ \sin^{-1}\left(\frac{w}{D}\right)}-1\right]\\ &-\frac{1}{E_h}\left(\left[\frac{\left(\frac{L^2}{4h}+h\right)\ \sin^{-1}\left(\frac{L}{\frac{L^2}{4h}+h}\right)}{L}-1\right]\right)\Bigg)\end{aligned} \tag{A1.28}$$

A1.5.6 By substituting for N_h and N_a from Eq A1.27 and Eq A1.28 in Eq A1.26, one gets an equation containing only h and p. Given p, the solution for h can be obtained by providing an initial guess for h, and then iterating using, for example, the Newton-Raphson method.[4,5]

A1.5.7 There are two steps to determining the failure pressure since the constitutive Eq A1.16 and A1.17 are bilinear. The first step is to determine the yield load/widths (N_y) and strains (ε_y). This is done by solving Eq A1.27, Eq A1.28 and Eq A1.26 along with a yield criterion of the form:

$$\varepsilon_h^2+\varepsilon_a^2=\varepsilon_y^2 \tag{A1.29}$$

where ε_y is the yield strain determined from the material testing. This results in the following yield values: N_{yh}, N_{ya}, ε_{yh}, and ε_{ya}. Eq A1.27 and A1.28 are then incremented from this point using the secondary moduli.

$$N_h=N_{yh}+\frac{1}{\frac{1}{E_hE_a}-S_{12}^2}\left(\frac{1}{E_a}\left(\varepsilon_h-\varepsilon_{yh}\right)-S_{12}\left\{\varepsilon_a-\varepsilon_{yh}\right\}\right) \tag{A1.30}$$

$$N_a=N_{ya}+\frac{1}{S_{12}^2-\frac{1}{E_hE_a}}\left\{S_{12}\left[\varepsilon_h-\varepsilon_{yh}\right]-\frac{1}{E_h}\left\{\varepsilon_a-\varepsilon_{ya}\right\}\right\} \tag{A1.31}$$

A1.5.8 The strain symbols have been substituted into Eq A1.27 and A1.28 to simplify them to the form given in Eq A1.30 and A1.31. These equations can be solved with Eq A1.20-A1.22 and can be used to determine when the liner ruptures. The calculated value of burst pressure should be compared with the measured value of burst pressure for the same hole size and shape. The failure criterion that predicts the measured value of burst pressure more closely should be used.

A1.5.9 Once the failure criterion is selected, a determinate set of equations exists. Therefore, burst pressure can be calculated as a function of defect dimensions.

A1.6 Procedure to Estimate Design Pressure—Summary

A1.6.1 The design pressure for a liner can be determined as follows (see Fig. A1.11):

A1.6.1.1 Conduct burst tests on lined pipe with the host pipe having holes of different dimensions.

A1.6.1.2 Determine the material properties of the liner as outlined in the section "Material Characterization."

---

[4] Hildebrand, F. B., *Introduction to Numerical Analysis* , McGraw-Hill, 1956.

[5] Gerald, C. F., and Wheatley, P. O., *Applied Numerical Analysis*, 5th ed., Addison-Wesley, 1994.

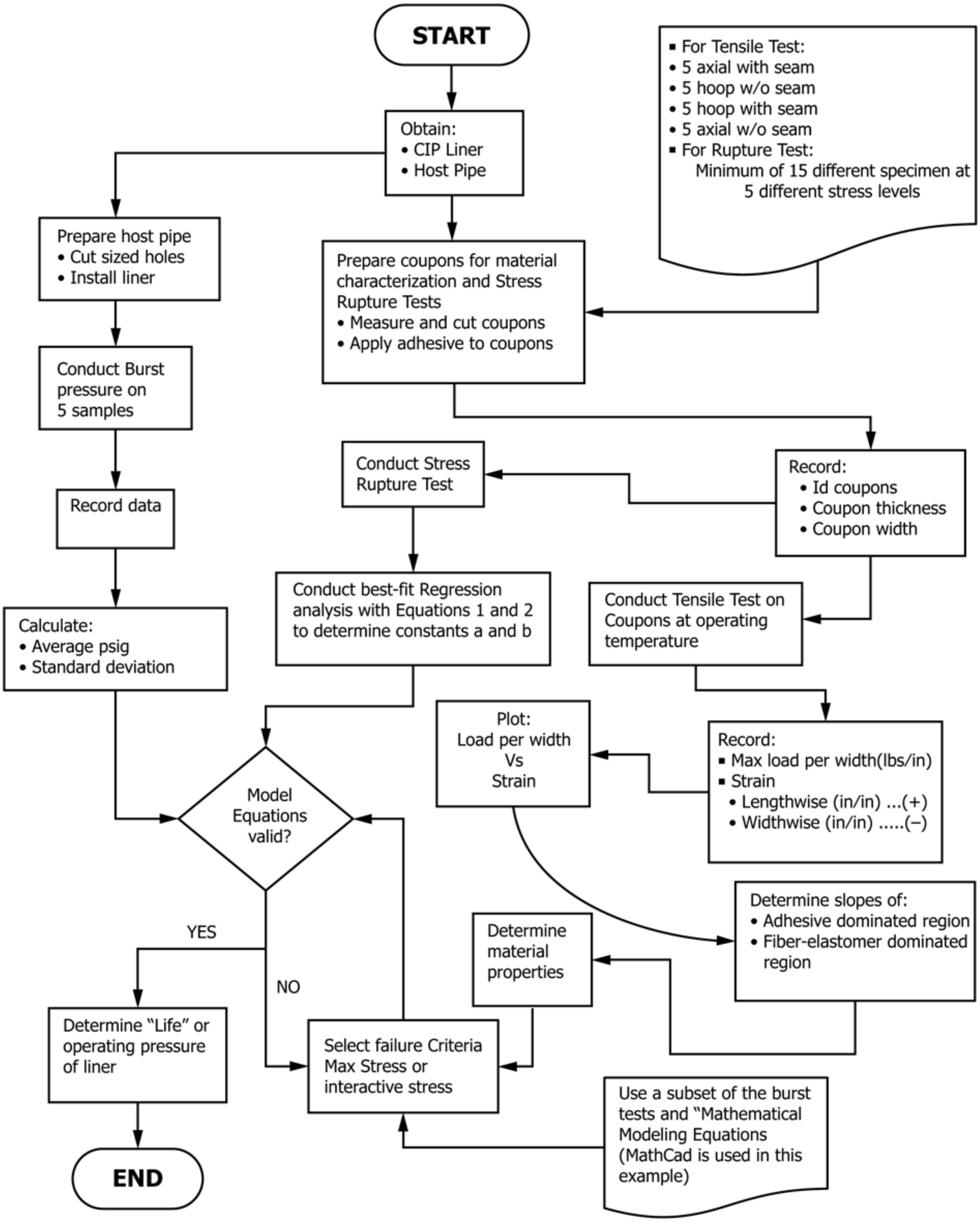

FIG. A1.11 CIP Liner Classification Flowchart

A1.6.1.3 Using a subset of the burst tests, and the equations in the section titled "Mathematical Modeling," select the appropriate failure criterion.

A1.6.1.4 Using the rest of the burst tests, validate the model equations and the choice of the failure criterion.

A1.6.1.5 Perform stress rupture tests on coupons, either at the operating temperature, or at a range of operating temperatures so that the constants in Eq A1.1 or Eq A1.2 can be determined.

A1.6.1.6 Use the validated model to determine the burst pressure (p_{ult}) for arbitrary hole dimensions and host pipe diameter.

A1.6.1.7 The calculated burst pressure as a function of hole dimensions and liner material properties, in conjunction with Eq A1.1 or Eq A1.2, will give the design pressure of the lined pipe when the design life is specified.

A1.7 Nomenclature

A1.7.1 *Symbols:* a = constant (1/h)
b = constant (dimensionless)
c_L , c_R = constants (left and right, respectively) for bilinear regression (lb/in.)
D = pipe diameter (in.)
h = height of linear bulge beyond pipe wall (in.)
k' = constant (°R)
E_1 = primary modulus (lb/in.)
E_2 = secondary modulus (lb/in.)
L = dimension of defect in axial direction (in.)
L_c = length of coupon (in.)
m_L , m_R = slope (left and right, respectively) for bilinear regression (lb/in.)
N_a = axial load/width (lb/in.)
N_h = hoop load/ width (lb/in.)
N_{uts} = ultimate load/ width (lb/in.)
N_y = load/width at yield (lb/in.)
p = applied pressure (psi)
P = ratio of the LPW to the ultimate LPW for tensile coupons, or the ratio of pressure to the burst pressure for a given size defect for full scale specimens (dimensionless)
r_a = radius of curvature of liner in axial direction (in.)
r_h = radius of curvature of liner in hoop direction (in.)
S_{12} = coefficient defined by Eq A1.11 or Eq A1.12 (lb/in.)
S_{21} = coefficient defined by Eq A1.11 or Eq A1.12 (lb/in.)
t_f = time to failure (h)
T = temperature (°R)
w = dimension of defect in hoop direction (in.)
W_c = width of coupon (in.)

A1.7.2 *Greek Symbols:* ν = Poisson's ratio (dimensionless)
ε_y = yield strain (dimensionless)

A1.7.3 *Subscripts:* a = axial direction (dimensionless)
h = hoop direction
–1 = left of (less than) yield point
12 = compliance coefficient
21 = compliance coefficient
45 = direction 45° to hoop and axial directions

APPENDIXES

(Nonmandatory Information)

X1. SAMPLE CALCULATION

X1.1 This sample calculation uses data derived for one of the current commercially available liners. See the reports published by the Gas Research Institute (GRI).[3,6] The equations used in this sample calculation are taken from these reports.

X1.2 Conduct burst tests on lined pipe with the host pipe having holes of different dimensions.

X1.2.1 Five specimens of lined pipe with a 1.197-in. diameter circular hole in the host pipe were used for burst testing. Failures occurred at 533.0, 575.8, 549.3, 539.1, and 476.1 psi. The average and the standard deviation for all five specimens were 534.7 psi and 36.6 psi, respectively.

X1.3 Determine the material properties of the liner as outlined in the section "Material Characterization."

X1.3.1 Straight-sided specimens were tested in the axial and hoop direction. The process for obtaining this information from the test data is described in the section on Material Characterization in the reference document. In particular, Fig. A1.9 shows how to determine this data from plotted tensile test results. The data resulting from these tests is shown in Tables X1.1 and X1.2.

X1.3.2 Using the data in Tables X1.1 and X1.2, S_{12} is calculated using Eq A1.11 and A1.12. These equations have the following form:

$$S_{12} = \frac{-\nu}{E} \qquad (X1.1)$$

X1.3.3 Substituting the values for the primary and secondary moduli (E) from the average values in Tables X1.1 and X1.2 gives the values for S_{12} as shown in Table X1.3.

NOTE X1.1—In the calculation of S_{12}, the primary value is dominated by the adhesive and so $S_{12} = S_{21}$. The secondary values of S_{12} and S_{21} are dominated by the cloth fiber and are not necessarily equal.

X1.4 Using a subset of the burst tests, and the equations in the section titled "Mathematical Modeling," select the appropriate failure criterion.

X1.4.1 Appendix X2 provides the printout of two MathCAD spreadsheets that calculate the burst pressures using the

---

[6] Francini, R. B., and Pimputkar, S. M. *Guidelines and Technical Information on Long-Term Performance of Cured-In-Place Liners for Rehabilitation of Gas Distribution Pipes*, GRI-98/0208.

maximum stress criterion of Eq A1.21 and A1.22 and the interactive stress criterion of Eq A1.22. These sheets solve Eq A1.26-A1.28 taking into account the bilinear nature of the stress strain curve. The results are shown in Table X1.4.

X1.4.2 Since the interactive stress criterion value is slightly closer to the actual test results (534.7 psi) and the result is conservative, it was chosen as the best criterion.

X1.5 Using the rest of the burst tests, validate the model equations and the choice of the failure criterion.

NOTE X1.2—Normally additional burst testing would be performed on lined pipe with different hole diameters and these results compared with the result of the failure calculations based on the defect hole dimensions from X1.4. Due to cost constraints, this was not done.

X1.6 Perform stress rupture tests on coupons, either at the operating temperature, or at a range of operating temperatures so that the constants in Eq A1.1 or Eq A1.2 can be determined.

X1.6.1 A series of stress rupture tests were carried out on the liner at different stress levels and temperatures. Best fit regressions were carried out using both Eq A1.1 and A1.2. There were not significant differences between the two results. However, since Eq A1.2 with temperature dependence gave slightly more conservative results it was chosen as the one to use for the design calculations. The results of the stress rupture testing and the best curve fit are shown in Fig. X1.1.

X1.6.2 The resulting equation for time to failure is:

$$\frac{N}{312.8} = 0.700 t_f^{-0.00402} e^{41.905\cdot\left(\frac{1}{T}-\frac{1}{529.7}\right)} \qquad \text{(X1.2)}$$

X1.6.3 Assuming a 50-year life for the liner at an operating temperature of 70°F, the resulting maximum N is 215.5 lbs/in. on the liner in the hoop direction. This is a reduction of 31 %. It is assumed that the axial failure N will be degraded by the same amount as the hoop failure pressure. This would result in an axial failure of 51.5 lbs/in.

NOTE X1.3—It would be better to carry out transverse stress rupture testing to determine this value. However, in the case of this particular liner, the failure is dominated by the hoop fiber strength and this was not necessary.

X1.7 Use the validated model to determine the burst pressure (p_{ult}) for arbitrary hole dimensions and host pipe diameter.

X1.7.1 The N values for a 50-year life from X1.6 are substituted for ultimate load per lengths and the calculations carried out in X1.4 to predict the burst pressure for the largest hole that exists in the pipe to be lined. For example, for a pipe with a maximum hole that is the same as that used in the calculation of X1.4, the maximum liner design pressure for a 50-year life at 70°F would be 342 psi. This is obtained by setting N_{hf} equal to the resulting maximum hoop LPW (215.5 lb/in.) in the mathematical model.

X1.8 The calculated burst pressure as a function of hole dimensions and liner material properties, in conjunction with Eq A1.1 or Eq A1.2 will give the design pressure of the lined pipe when the design life is specified.

X1.8.1 The calculation of X1.7 can be repeated for different design conditions.

TABLE X1.1 Axial Direction Tensile Results

ID No	t (in.)	W_c (in.)	P_{max}/W_c	ε_{yield}	P_{yield}/W_c	E_1	E_2	ν_1	ν_2
5in-1	0.051	0.584	68.8	0.0078	28.9	3390.4	60.7	-0.170	-0.150
5in-2	0.054	0.494	73.1	0.0082	37.9	3439.4	18.3	-0.240	-0.060
5in-3	0.057	0.523	81.9						
5in-4	0.050	0.765	74.0	0.0102	30.7	2542.0	13.9	-0.080	-0.020
5in-5	0.045	0.803	72.1	0.0076	39.8	3846.3	72.8	-0.050	-0.020
5in-6	0.051	0.807	78.4	0.0102	46.1	3532.1	31.5	-0.150	-0.050
Average			74.7	0.0088	36.7	3350.0	39.4	-0.138	-0.060
Standard deviation			4.7	0.0013	7.0	485.3	26.1	0.075	0.053

TABLE X1.2 Hoop Direction Tensile Results

ID No	t (in.)	W_c (in.)	P_{max}/W_c	ε_{yield}	P_{yield}/W_c	E_1	E_2	ν_1	ν_2
90-1	0.049	0.763	242.4	0.0090	101.8		518.0		0.110
90-2	0.050	0.752	335.6	0.0074	98.5	10444.4	1145.6		0.430
90-3	0.049	0.752	323.2	0.0093	88.5	7741.0	577.9	-0.300	0.160
90-4	0.049	0.502	342.6	0.0089	102.1	8797.5	707.7	-0.540	0.290
90-5	0.050	0.494	315.4	0.0106	96.5	6629.9	826.2	-0.190	0.070
90-6	0.049	0.504	317.5	0.0091	97.4	8014.8	627.3	-0.230	0.090
Average			312.8	0.0091	97.5	8325.5	733.8	-0.315	0.192
Standard deviation			36.0	0.0010	4.9	1416.5	228.5	0.157	0.141

TABLE X1.3 Primary and Secondary Interaction Compliance Coefficients

Orientation	S_{12_1}	S_{12_2}	S_{21_2}
Axial	-4.12×10^{-5}	-1.52×10^{-3}	
Hoop	-3.78×10^{-5}		2.62×10^{-4}
Average	-3.95×10^{-5}		

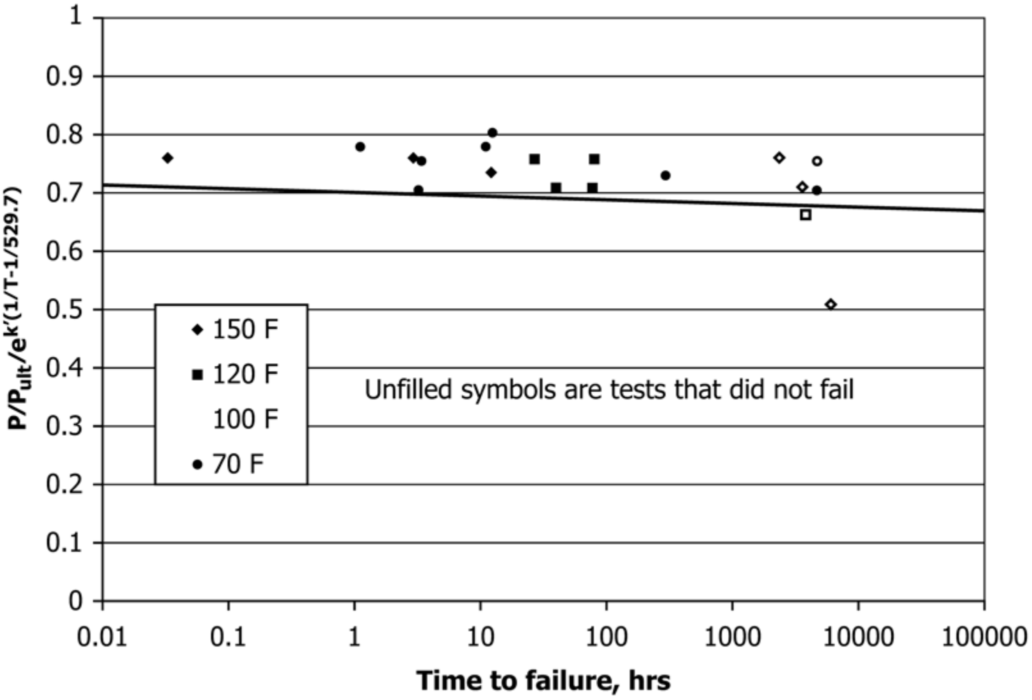

FIG. X1.1 Time to Failure

TABLE X1.4 Failure Pressure

Failure Criterion	Failure Pressure (psi)	Percent Difference from Actual
Maximum stress (Eq A1.17 and A1.18)	599.1	+12.0
Interactive stress (Eq A1.18)	472.2	-11.7

X2. CALCULATIONS OF BURST PRESSURE USING MAXIMUM STRESS AND INTERACTIVE CRITERIA (USING MATHCAD)

X2.1 Maximum Stress Criteria:

Input Data:
E_a is the axial stiffness in the liner
E_h is the hoop stiffness in the liner
S_{ah} is the compliance due to the Poisson effect (see Table X1.3)
P is the pressure on the liner
L is the length of the hole
w is the circumferential width of the hole
D is the inner diameter of the pipe
N_{af} is the axial failure load/width (see Table X1.1)
N_{hf} is the hoop failure load/width (see Table X1.2)
ε_y is the yield strain (see Table X1.1Table X1.2)

Output:
N_a is the axial load per unit width in the inner liner
N_h is the hoop load per width in the liner
r_a is the axial radius of curvature in the domed liner
r_h is the hoop radius of curvature in the domed liner

$L = 1.197$
$N_{af} = 74.7$
$E_{a1} = 3350$
$S_{12\_1} = -3.95 \cdot 10^{-5}$

$w = 1.197$
$N_{hf} = 215.543$
$E_{a2} = 39.4$
$S_{12\_2} = -0.00152$

$D = 1.68$
$\varepsilon_y = 0.00895$
$E_{h1} = 8325.5$
$S_{21\_2} = 0.00026$

$E_{h2} = 733.8$

Step 1:

Determine yield by using Eq A1.22-A1.24 with yield criteria of the form: $\varepsilon_a^2 + \varepsilon_h^2 = \varepsilon_y^2$. From this calculate N_{ay}, N_{hy}, ε_{ay}^2 and ε_{hy}, the yield load/width and strains in the axial and hoop orientations. The guess values can be approximated from the measured data in Tables X1.1 and X1.2.

Guess values to determine yield pressure

$P_y = 10$

$h = 0.06$

Given

$$P_y = \frac{1}{\left(\frac{1}{E_{a1}\cdot E_{h1}} - {S_{12\_1}}^2\right)\cdot\left(\frac{w^2}{8\cdot h}+\frac{h}{2}\right)}\cdot\left[\frac{1}{E_{a1}}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h}+h\right)\cdot\operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)\right]}{w}-1\right]-S_{12\_1}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot\operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L}-1\right]\right]\ldots$$

$$+\frac{1}{\left(\frac{1}{E_{a1}\cdot E_{h1}} - {S_{12\_1}}^2\right)\cdot\left(\frac{L^2}{8\cdot h}+\frac{h}{2}\right)}\cdot\left[-S_{12\_1}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h}+h\right)\cdot\operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)\right]}{w}-1\right]+\frac{1}{E_{h1}}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot\operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L}-1\right]\right]$$

$$\left[100\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h}+h\right)\cdot\operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)\right]}{w}-1\right]\right]^2+\left[100\left[\frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot\operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L}-1\right]\right]^2=(100\cdot\varepsilon_y)^2$$

$$\begin{pmatrix}P_y\\ h_y\end{pmatrix} = \operatorname{Find}(P_y, h) \qquad \begin{pmatrix}P_y\\ h_y\end{pmatrix} = \begin{pmatrix}29.645\\ 0.06\end{pmatrix}$$

$$N_{ay} = \frac{1}{\frac{1}{E_{a1}\cdot E_{h1}} - {S_{12\_1}}^2}\cdot\left[-S_{12\_1}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h_y}+h_y\right)\cdot\operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h_y}+h_y}\right)\right]}{w}-1\right]+\frac{1}{E_{h1}}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h_y}+h_y\right)\cdot\operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h_y}+h_y}\right)}{L}-1\right]\right]$$

$N_{ay} = 29.455$

N_{ay} is the axial yield LPW in the liner

$$N_{hy} = \frac{1}{\left(\frac{1}{E_{a1}\cdot E_{h1}} - {S_{12\_1}}^2\right)}\cdot\left[\left[\frac{1}{E_{a1}}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h_y}+h_y\right)\cdot\operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h_y}+h_y}\right)\right]}{w}-1\right]-S_{12\_1}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h_y}+h_y\right)\cdot\operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h_y}+h_y}\right)}{L}-1\right]\right]\right]$$

$N_{hy} = 62.375$

N_{hy} is the loop yield LPW in the liner

$$\varepsilon_{ay} = \frac{\left(\frac{L^2}{4\cdot h_y}+h_y\right)\cdot\operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h_y}+h_y}\right)}{L}-1 \qquad \varepsilon_{hy} = \frac{\left(\frac{w^2}{4\cdot h_y}+h_y\right)\cdot\operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h_y}+h_y}\right)}{w}-1$$

$\varepsilon_{ay} = 6.329 \times 10^{-3}$

$\varepsilon_{hy} = 6.329 \times 10^{-3}$

Step 2:

Determine the failure pressure using each of the failure criteria from Eq A1.16 and A1.17 or Eq A1.18 to see which best fits the burst data. Since the N-ε curve is assumed to be bilinear, the load/width and strain must be incremented from the yield point. The solution below uses Eq A1.18 which was determined to work best for for the liner tested. The guess values can be approximated from the measured data in Tables X1.1 and X1.2.

Guess values to determine failure pressure:

$P_f = 100$

$h = 0.06$

$\varepsilon_a = 0.005$

$\varepsilon_h = 0.005$

Given

$$\varepsilon_a = \frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot \operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L} - 1 \qquad \varepsilon_h = \frac{\left(\frac{w^2}{4\cdot h}+h\right)\cdot \operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)}{w} - 1$$

$$P_f = \frac{\frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{hy}}{\frac{w^2}{8\cdot h}+\frac{h}{2}} + \frac{\frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[-S_{12\_2}\cdot(\varepsilon_h - \varepsilon_{hy}) + \frac{1}{E_{h2}}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{ay}}{\left(\frac{L^2}{8\cdot h}+\frac{h}{2}\right)}$$

$$N_{hf} = \frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{hy}$$

$$\begin{pmatrix}\varepsilon_h\\ \varepsilon_a\\ P_f\\ h_f\end{pmatrix} = \operatorname{Find}(\varepsilon_h, \varepsilon_a, P_f, h) \qquad \begin{pmatrix}\varepsilon_h\\ \varepsilon_a\\ P_f\\ h_f\end{pmatrix} = \begin{pmatrix}0.355\\ 0.355\\ 598.725\\ 0.459\end{pmatrix}$$

N_f is the failure LPW in the liner

$$N_h = \frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{hy}$$

N_h = 312.8

$$N_a = \frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[-S_{12\_2}\cdot(\varepsilon_h - \varepsilon_{hy}) + \frac{1}{E_{h2}}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{ay}$$

N_a = 58.193

X2.2 Maximum Stress Criteria Conclusion: Liner "Life" and Max Operating Pressure:

t_f = 50
T_{emp} = 529.67
N_{ahbp} = 312.8
N_{aabp} = 74.7

$$N_{maxhoop} = N_{ahbp}\cdot\left[0.700\cdot t_f^{-0.00402}\cdot{}_{e}\,41.905\cdot\left(\frac{1}{T_{emp}} - \frac{1}{529.67}\right)\right]$$

This is the same as Eq A1.2

$N_{maxhoop}$ = 215.543
where:
t_f = life in years
T_{emp} = operating temperature 70°F which equates to 529.67°R
N_{ahbp} = actual hoop burst pressure (experimental average P_{max}/W_c from Table X1.2
N_{aabp} = actual axial burst pressure (experimental average P_{max}/W_c from Table X1.1
$N_{maxhoop}$ = maximum hoop LPW in the liner
e = 2.71828..., the base of natural logarithms

Substituting the value of $N_{maxhoop}$ for N_{hf} in the mathematical model solver results in a liner design pressure P_f of 384.776 psi. The maximum allowable operating pressure (MAOP) equals the design pressure multiplied by a factor of safety equal to 0.5, resulting in an MAOP of 192.3 psi. This result is for a 1.197 in. diameter hole in a 1.68 in. i.d. host pipe and assumes a 50-year life and a 70°F operating temperature.

X2.3 Interactive Criteria:

Input Data:
E_a is the axial stiffness in the liner
E_h is the hoop stiffness in the liner
S_{ah} is the compliance due to the Poisson effect (see Table X1.3)

Output:
N_a is the axial load per unit width in the inner liner
N_h is the hoop load per width in the liner
r_a is the axial radius of curvature in the domed liner

P is the pressure on the liner
L is the length of the hole
w is the circumferential width of the hole
D is the inner diameter of the pipe
N_{af} is the axial failure load/width (see Table X1.1)
N_{hf} is the hoop failure load/width (see Table X1.2)
ε_y is the yield strain (see Table X1.1Table X1.2)
r_h is the hoop radius of curvature in the domed liner

$L = 1.197$
$N_{af} = 74.7$
$E_{a1} = 3350$
$S_{12\_1} = -3.95 \cdot 10^{-5}$
$w = 1.197$
$N_{hf} = 215.543$
$E_{a2} = 39.4$
$S_{12\_2} = -0.00152$
$D = 1.68$
$\varepsilon_y = 0.00895$
$E_{h1} = 8325.5$
$S_{21\_2} = 0.00026$
$E_{h2} = 733.8$

Step 1:
Determine yield by using Eq A1.22-A1.24 with yield criteria of the form: $\varepsilon_a^2 + \varepsilon_h^2 = \varepsilon_y^2$. From this calculate N_{ay}, N_{hy}, ε_{ay}^2 and ε_{hy}, the yield load/width and strains in the axial and hoop orientations. The guess values can be approximated from the measured data in Tables X1.1 and X1.2.
Guess values to determine yield pressure
$P_y = 10$
$h = 0.06$
Given

$$P_y = \frac{1}{\left(\frac{1}{E_{a1}\cdot E_{h1}} - S_{12\_1}{}^2\right)\cdot\left(\frac{w^2}{8\cdot h}+\frac{h}{2}\right)}\cdot\left[\frac{1}{E_{a1}}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h}+h\right)\cdot\text{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)\right]}{w}-1\right]-S_{12\_1}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot\text{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L}-1\right]\right]\ldots$$

$$+\frac{1}{\left(\frac{1}{E_{a1}\cdot E_{h1}} - S_{12\_1}{}^2\right)\cdot\left(\frac{L^2}{8\cdot h}+\frac{h}{2}\right)}\cdot\left[-S_{12\_1}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h}+h\right)\cdot\text{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)\right]}{w}-1\right]+\frac{1}{E_{h1}}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot\text{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L}-1\right]\right]$$

$$\left[100\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h}+h\right)\cdot\text{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)\right]}{w}-1\right]\right]^2+\left[100\left[\frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot\text{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L}-1\right]\right]^2=(100\cdot\varepsilon_y)^2$$

$$\begin{pmatrix}P_y\\h_y\end{pmatrix}=\text{Find}\left(P_y, h\right) \qquad \begin{pmatrix}P_y\\h_y\end{pmatrix}=\begin{pmatrix}29.645\\0.06\end{pmatrix}$$

$$N_{ay}=\frac{1}{\frac{1}{E_{a1}\cdot E_{h1}}-S_{12\_1}{}^2}\cdot\left[-S_{12\_1}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h_y}+h_y\right)\cdot\text{asin}\left(\frac{w}{\frac{w^2}{4\cdot h_y}+h_y}\right)\right]}{w}-1\right]+\frac{1}{E_{h1}}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h_y}+h_y\right)\cdot\text{asin}\left(\frac{L}{\frac{L^2}{4\cdot h_y}+h_y}\right)}{L}-1\right]\right]$$

$N_{ay} = 29.455$
N_{ay} is the axial yield LPW in the liner

$$N_{hy}=\frac{1}{\left(\frac{1}{E_{a1}\cdot E_{h1}}-S_{12\_1}{}^2\right)}\cdot\left[\left[\frac{1}{E_{a1}}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot h_y}+h_y\right)\cdot\text{asin}\left(\frac{w}{\frac{w^2}{4\cdot h_y}+h_y}\right)\right]}{w}-1\right]-S_{12\_1}\cdot\left[\frac{\left(\frac{L^2}{4\cdot h_y}+h_y\right)\cdot\text{asin}\left(\frac{L}{\frac{L^2}{4\cdot h_y}+h_y}\right)}{L}-1\right]\right]\right]$$

$N_{hy} = 62.375$
N_{hy} is the loop yield LPW in the liner

$$\varepsilon_{ay}=\frac{\left(\frac{L^2}{4\cdot h_y}+h_y\right)\cdot\text{asin}\left(\frac{L}{\frac{L^2}{4\cdot h_y}+h_y}\right)}{L}-1 \qquad \varepsilon_{hy}=\frac{\left(\frac{w^2}{4\cdot h_y}+h_y\right)\cdot\text{asin}\left(\frac{w}{\frac{w^2}{4\cdot h_y}+h_y}\right)}{w}-1$$

$\varepsilon_{ay} = 6.329 \times 10^{-3}$
$\varepsilon_{hy} = 6.329 \times 10^{-3}$

Step 2:
Determine the failure pressure using each of the failure criteria from Eq A1.16 and A1.17 or Eq A1.18 to see which best fits the burst data. Since the N-ε curve is assumed to be bilinear, the load/width and strain must be incremented from the yield point. The solution below uses Eq A1.18 which was determined to work best for this particular liner. The guess values can be approximated from the measured data in Tables X1.1 and X1.2.
Guess values to determine failure pressure:
$P_f = 100$
$h = 0.1$
$\varepsilon_a = 0.005$
$\varepsilon_h = 0.005$
Given

$$\varepsilon_a = \frac{\left(\frac{L^2}{4\cdot h}+h\right)\cdot \operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h}+h}\right)}{L} - 1 \qquad \varepsilon_h = \frac{\left(\frac{w^2}{4\cdot h}+h\right)\cdot \operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h}+h}\right)}{w} - 1$$

$$P_f = \frac{\frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{hy}}{\frac{w^2}{8\cdot h}+\frac{h}{2}} + \frac{\frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[-S_{12\_2}\cdot(\varepsilon_h - \varepsilon_{hy}) + \frac{1}{E_{h2}}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{ay}}{\left(\frac{L^2}{8\cdot h}+\frac{h}{2}\right)}$$

$$\left[\frac{1}{N_{hf}}\cdot\left[\frac{\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)} + N_{hy}\right]\right]^2 - \frac{1}{N_{hf}}\cdot\left[\frac{\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)} + N_{hy}\right]\cdot\frac{1}{N_{hf}}\cdot\left[\frac{-S_{12\_2}\cdot(\varepsilon_h - \varepsilon_{hy}) + \frac{1}{E_{h2}}\cdot(\varepsilon_a - \varepsilon_{ay})}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)} + N_{ay}\right] \ldots = 1$$

$$+\left[\frac{1}{N_{af}}\cdot\left[\frac{-S_{12\_2}\cdot(\varepsilon_h - \varepsilon_{hy}) + \frac{1}{E_{h2}}\cdot(\varepsilon_a - \varepsilon_{ay})}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)} + N_{ay}\right]\right]^2$$

$$\begin{pmatrix}\varepsilon_h\\ \varepsilon_a\\ P_f\\ h_f\end{pmatrix} = \operatorname{Find}(\varepsilon_h, \varepsilon_a, P_f, h) \qquad \begin{pmatrix}\varepsilon_h\\ \varepsilon_a\\ P_f\\ h_f\end{pmatrix} = \begin{pmatrix}0.193\\ 0.193\\ 341.226\\ 0.331\end{pmatrix}$$

P_f is the failure pressure

$$N_h = \frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[\frac{1}{E_{a2}}\cdot(\varepsilon_h - \varepsilon_{hy}) - S_{21\_2}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{hy}$$

$N_h = 196.291$

$$N_a = \frac{1}{\left(\frac{1}{E_{a2}\cdot E_{h2}} - S_{12\_2}\cdot S_{21\_2}\right)}\cdot\left[-S_{12\_2}\cdot(\varepsilon_h - \varepsilon_{hy}) + \frac{1}{E_{h2}}\cdot(\varepsilon_a - \varepsilon_{ay})\right] + N_{ay}$$

$N_a = 44.822$

X2.4 Interactive Criteria Conclusion: Liner "Life" and Max Operating Pressure:

$t_f = 50$
$T_{emp} = 529.67$
$N_{ahbp} = 312.8$
$N_{aabp} = 74.7$

$$N_{maxhoop} = N_{ahbp}\cdot\left[0.700\cdot t_f^{\,-0.00402}\cdot{}_{e}\,41.905\cdot\left(\frac{1}{T_{emp}} - \frac{1}{529.67}\right)\right]$$

This is the same as Eq A1.2

$N_{maxhoop} = 215.543$
where:
t_f = life in years

T_{emp} = operating temperature of 70°F which equates to 529.67°R
N_{ahbp} = actual hoop burst pressure (experimental average P_{max}/W_c from Table X1.2
N_{aabp} = actual axial burst pressure (experimental average P_{max}/W_c from Table X1.1
$N_{maxhoop}$ = maximum hoop LPW in the liner
e = 2.71828..., the base of natural logarithms

Substituting the value of $N_{maxhoop}$ for N_{hf} in the mathematical model solver results in a liner design pressure P_f of 341.964 psi. The maximum allowable operating pressure (MAOP) equals the design pressure multiplied by a factor of safety equal to 0.5, resulting in an MAOP of 170.8 psi. This result is for a 1.197 in. diameter hole in a 1.68 in. i.d. host pipe and assumes a 50-year life and a 70°F operating temperature.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/