



# Standard Specification for Cured-in-Place Pipe Lining System for Rehabilitation of Metallic Gas Pipe<sup>1</sup>

This standard is issued under the fixed designation F 2207; 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 ( $\epsilon$ ) 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,  $\frac{3}{4}$  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 100 psig (689 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 cured-in-place pipe liners covered by this specification are intended for use in existing structurally sound or partially deteriorated metallic gas pipe as defined in 3.2.8. They 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.

1.3 CIP liners can be installed in partially deteriorated pipe as defined in 3.2.8. Even for low pressure gas distribution systems, which typically operate at less than 1 psig, 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.

1.4 *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:

- D 123 Terminology Relating to Textiles<sup>2</sup>
- D 543 Practice for Evaluating the Test Method for Resistance of Plastics to Chemical Reagents<sup>3</sup>
- D 883 Terminology Relating to Plastics<sup>3</sup>
- D 1598 Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure<sup>4</sup>
- D 1600 Terminology for Terms Relating to Plastics<sup>3</sup>
- D 1763 Specifications for adhesive Resins<sup>3</sup>
- D 2240 Test Method for Rubber Property—Durometer Hardness<sup>5</sup>
- D 2837 Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials<sup>4</sup>
- D 3167 Test Method for Floating Roller Peel Resistance of Adhesives<sup>6</sup>
- D 3892 Practice for Packaging/Packing of Plastics<sup>7</sup>
- D 4848 Terminology of Force, Deformation and Related Properties of Textiles<sup>8</sup>
- D 4850 Terminology Relating to Fabric<sup>8</sup>
- F 412 Terminology Relating to Plastic Piping Systems<sup>4</sup>

## 3. Terminology

3.1 *General*—Definitions are in accordance with those set forth in Terminologies D 123, D 883, D 4848, D 4850, and F 412. Abbreviations are in accordance with Terminology D 1600, unless otherwise indicated.

<sup>2</sup> Annual Book of ASTM Standards, Vol 07.01.

<sup>3</sup> Annual Book of ASTM Standards, Vol 08.01.

<sup>4</sup> Annual Book of ASTM Standards, Vol 08.04.

<sup>5</sup> Annual Book of ASTM Standards, Vol 09.01.

<sup>6</sup> Annual Book of ASTM Standards, Vol 15.06.

<sup>7</sup> Annual Book of ASTM Standards, Vol 08.02.

<sup>8</sup> Annual Book of ASTM Standards, Vol 07.02.

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### 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 *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 3.2.8.

3.2.8 *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.

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

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

3.2.11 *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 D 543, 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.<sup>9</sup>

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 D 3167.

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

5.2.2 *Composite Liner Peeling Strength*—The peeling strength of the composite liner from the wall of the cleaned pipe shall be tested in accordance with Test Method D 3167 and shall not be less than 6.0 lb/in. (1.0 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 D 2240, and its peeling strength, when measured in accordance with Test Method D 3167. 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 3.2.8. 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*—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 D 543, 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.<sup>9</sup>

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

<sup>9</sup> 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.

TABLE 1 Chemical Resistivity List of Reagents

Liquids	Test Composition
Water (External and Internal)	Freshly prepared distilled water (in accordance with Practice D 543)
Gasoline (External)	Gasoline-Automotive Spark-Ignition Engine Fuel per Specification D 4814
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 D 543
Isopropanol	10 % volume isopropanol + 90 % volume distilled water
Sulfuric Acid	5 % weight (of total solution) H <sub>2</sub> SO <sub>4</sub> 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 D 543
Mercaptans	2 % volume tertiary butyl mercaptan + 98 % volume mineral oil, white, USP

5.4.1 The lined partially deteriorated pipe, as defined in 3.2.8, 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 3.2.8, shall be used for all sustained pressure testing. For testing purposes and establishing pipeline MAOP, partially deteriorated pipe for nominal pipe diameters  $\frac{3}{4}$  to 3 in. shall be simulated by a minimum 1 in. full circumference gap between two pipe segments and a hole equal to a minimum of  $\frac{1}{2}$  the nominal pipe diameter in the pipe body. For nominal pipe diameters 4 to 10 in., partially deteriorated pipe shall be simulated with a minimum  $1\frac{1}{2}$  in. full circumference gap between two pipe segments and a minimum 2 in. diameter hole. For nominal pipe diameters of 12 in. or greater, partially deteriorated pipe shall be simulated by a minimum 2 in. full circumference gap and a minimum 4 in. diameter hole in the pipe body.

6.1.2 Lined pipe samples are capped and tested to failure using either an extension of Test Method D 1598, 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 D 2837 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 D 763, Section 10. All packing, packaging, and marking provisions of Practice D 3892 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

## (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.<sup>10</sup> 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

<sup>10</sup> 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.

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.

### 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

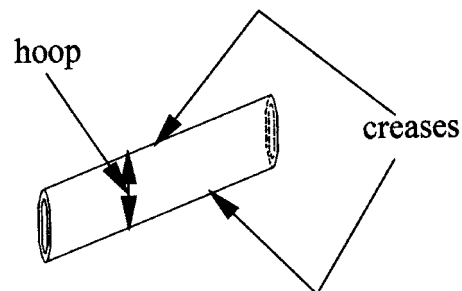


FIG. A1.1 Liner Before It is Slit Open