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Design and Qualification of Cured-in-Place Liners for the Rehabilitation of ASME Safety Class 3 Piping Systems

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Technical Report

Design and Qualification of Cured-in-Place Liners for the Rehabilitation of ASME Safety Class 3 Piping Systems

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Final Report, December 2006

EPRI Project Manager
A. Machiels

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

dba George Antaki

NOTE

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CITATIONS

This report was prepared by

dba George Antaki
133 Birch River Road
Aiken, SC 29803

Principal Investigator
G. Antaki

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REPORT SUMMARY

This report presents an evaluation of a rehabilitation technique that consists of the insertion of a non-metallic, corrosion-resistant lining in degraded buried ASME Safety Class 3 piping systems. The report documents current design rules for the rehabilitation of corroded or damaged buried steel pipe by insertion of a cured-in-place (CIP) liner and identifies gaps in technology that need to be filled for the application of the CIP liner to seismically qualified ASME Safety Class 3 piping systems.

Background

Buried service water piping systems experience internal and external corrosion that can result in leaks and/or ruptures and corrosion and biofilm deposits such as tubercles that can reduce flow to less than design requirements. A rehabilitation technique that has proven useful in the repair of waterworks suffering from these problems is the rehabilitation of buried piping by the insertion of a non-metallic, corrosion-resistant liner. The technique has gained widespread acceptance because of its many advantages:

- It is a trenchless method, which does not require uncovering the buried pipe.
- The liner is inserted in one sweep, allowing the rehabilitation of hundreds of feet of pipe in a single day.
- The process results in a single, continuous corrosion-resistant liner, which covers the corroded or damaged host pipe and its joints.
- The corrosion resistance of the liners has been proven in a wide range of water services, including sewer applications.
- The liner can be sized to accommodate internal pressure and external groundwater and soil pressures.

This report investigates one particular trenchless liner insertion technique, the inversion of a CIP resin-impregnated liner.

Objective

To assess the potential use of cured-in-place liners for rehabilitation of corroded Safety Class 3 service water systems, including the liners' ability to withstand seismic ground movements.

Approach

The project team produced an overview of the CIP lining process and reviewed current design rules for cured-in-place liners. In the United States, the design rules for CIP liners consisting of a resin-impregnated felt tube coated with a permanently bonded polyethylene layer are provided by three standards:

- ASTM F 1216, "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of Resin-Impregnated Tube."
- ASME Section XI, Division 1, Code Case N-589-1, "Nonmetallic Cured-in-Place Piping."
- A third standard, ASTM F 2207, "Standard Specification for Cured-in-Place Lining System for Rehabilitation of Metallic Gas Pipe," addresses a related inversion lining technique that uses a woven elastomer jacket with an impregnated adhesive epoxy resin. The epoxy resin adheres to the host pipe after inversion and curing.

The project team reviewed the design methods of these three standards and identified gaps in technology that need to be addressed for the application of cured-in-place methods to seismically qualified ASME Section III Safety Class 3 buried pipe.

Results

This investigation of the CIP liner found that:

- The rehabilitation of buried corroded steel pipe using CIP liners has a good cost and reliability track record in the waterworks industry.
- The research team did not identify published data on the seismic behavior of CIP lined pipe or more generally on the bending behavior of the CIP liner tube.

To pursue the use of the CIP liner for seismically qualified Safety Class 3 applications, twelve gaps in technology will have to be addressed. The report includes recommendations for further research needed in order to develop a complete set of design rules and design properties.

EPRI Perspective

EPRI is presently funding a simple exploratory bending test of a CIP liner tube. The assessment of the bending capability of the CIP liner tube subjected to strains comparable to those that would occur in a design basis earthquake will indicate whether the liner is a viable option for meeting seismic design rules. If the test proves successful, i.e., if the liner absorbs the simulated seismic bending in a ductile manner, without failing, then estimates will be developed to address the other identified gaps in technology.

Keywords

Service water system
Buried pipe
Repair
Cured-in-place liner
Safety applications

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1 INTRODUCTION

1.1 Background

Buried service water piping systems experience internal and external corrosion that can result in leaks and/or ruptures, and corrosion and biofilm deposits (e.g., tubercles) that can reduce flow to less than design requirements.

In order to restore the integrity of these buried pipes and extend their safe operating life, this report evaluates a rehabilitation technique which has proven successful in the repair of waterworks: the rehabilitation of buried pipe by the insertion of a non-metallic, corrosion-resistant liner. The technique has gained widespread acceptance because of its many advantages:

- It is a trenchless method, which does not require uncovering the buried pipe.
- The liner is inserted in one sweep, allowing the rehabilitation of hundreds of feet of pipe in a single day.
- The process results in a single, continuous corrosion resistant liner, which covers the corroded or damaged host pipe and its joints.
- The corrosion resistance of the liners has been proven in a wide range of water services, including sewer applications.
- The liner can be sized to accommodate internal pressure and external groundwater and soil pressures.

One particular trenchless liner insertion technique, the inversion of a cured-in-place (CIP) resin-impregnated liner, is investigated in this report.

1.2 Objectives

The objectives of this report are to:

- Describe the CIP lining process, its application, its advantages and limitations (Chapter 2).
- Present and explain the current design rules for the rehabilitation of corroded or damaged buried steel pipe by inversion of a CIP liner (Chapter 3).
- Identify the “Gaps in Technology” for the application of the CIP liner to seismically qualified ASME III Division 1 Class 3 buried piping systems (Chapter 3).
- Provide example applications of the current design rules for sizing CIP liners (Appendices A, B and C).

- Calculate the seismic wave passage ground strain (motion) that the CIP liner would have to accommodate (Appendix D).
- Provide an overview of other trenchless lining techniques currently used in the rehabilitation of buried liquid and gas pipelines (Appendix E).

1.3 Scope

The scope of this report is the CIP inverted liner used for the trenchless rehabilitation of corroded or damaged buried steel service water lines.

1.4 Approach

Following the description of the CIP lining method (Chapter 2), the report reviews and discusses the design rules published in current design standards, and identifies Gaps in Technology for application to seismically qualified Service Water Systems (Chapter 3).

A two-step approach is proposed. In the first step a simple bend test would be used to investigate the viability of the CIP liner as a seismically qualified rehabilitation technique. If the test is successful, a plan would be developed to resolve the Gaps in Technology identified in the report. A set of minimum tests that is believed to be required to resolve the Gaps in Technology is identified in Section 4. Supporting documentation and example applications are provided in Appendices.

2
AN OVERVIEW OF THE CIP LINING PROCESS

2.1 Description

The repair of buried pipes by a CIP liner is a trenchless technology commonly used to rehabilitate damaged or degraded waterworks. It is also used to rehabilitate gas pipelines with an extruded elastomer coat acting as a gas barrier.

The liner is inserted into the host pipe by an inversion process. One end of the tube is clamped around an inversion ring and inserted from an existing access point. The liner is then inverted as it progresses through the host pipe, driven by hydrostatic pressure from a water column, or by steam or compressed air (Figures 2-1 through 2-5).

The liner consists of two parts:

- A fabric (felt) impregnated with thermosetting resin. After inversion, the resin impregnated fabric is cured and hardens. It constitutes the outer layer, in contact with the host pipe (but not adhering to it), providing permanent form and strength.
- A plastic outer layer (elastomer liner) bonded to the fabric which enables the liner to be handled before and during installation. After insertion by inversion, the plastic layer constitutes the inner layer, in contact with the fluid inside the pipe, providing a corrosion-resistant barrier.

Following installation (Figure 2-6), the layers from the inside (water) towards the outside (ground) will consist of: (1) water – (2) elastomer lining – (3) hardened woven liner – (4) host pipe – (5) ground. There are three types of CIP liners on the market:

- Liners for gravity flow application.
- Liners for limited pressure service (below 80 psi).
- Liners for high pressure service (up to 200 psi or more).

2.2 Installation

The installation of a CIP liner generally consists of the following steps:

- Obtaining access to terminal ends (existing manhole, valve box, or new dig to cut pipe).
- Camera inspection of pipe condition to characterize cleanliness and damage.
- Internal cleaning of the pipe.

- Camera inspection for cleanliness and damage.
- Liner inversion.
- Curing.
- Camera inspection.
- Pressure or leak testing.

2.3 Advantages and Limitations of CIP Linings

The advantages of CIP repairs include:

- There is no need to excavate the line other than at the two terminal points (liner launch and receiving ends) and at locations of branches and elbows with a bend greater than 45º.
- A leak-tight barrier is formed to prevent both line losses (out-leakage) and infiltration (in-leakage).
- A corrosion resistant liner is installed, protecting the host pipe from further internal degradation.
- The liner has the ability to bridge discontinuities such as wall loss or damaged joints.
- Repair time is reduced as the liner can typically be inserted and cured within a day.
- Generally there is no reduction in flow capacity as the reduced flow area is compensated by a reduction in friction losses due to the smoothness of the liner.

The limitations of CIP repairs include:

- There are limits on fluid temperature and pressure.
- Openings need to be remotely cut for branch lines (lateral tie-ins) or preferably, tees and branches need to be cut out and replaced.
- The presence of bends could limit the insertion process or cause wrinkles (Figure 2-7).
- The liner needs to be custom fabricated where there are changes in pipe diameter.
- The quality of the liner, its seams and the impregnation process affect the quality and smoothness of the final installation (Figure 2-6).
- The importance of installer qualification.
- Limited non-destructive testing to assure adequacy of the installed liner.

Figure 2-1
Liner Lowered into Position

Figure 2-2
Water-Filled Liner at Launching Point

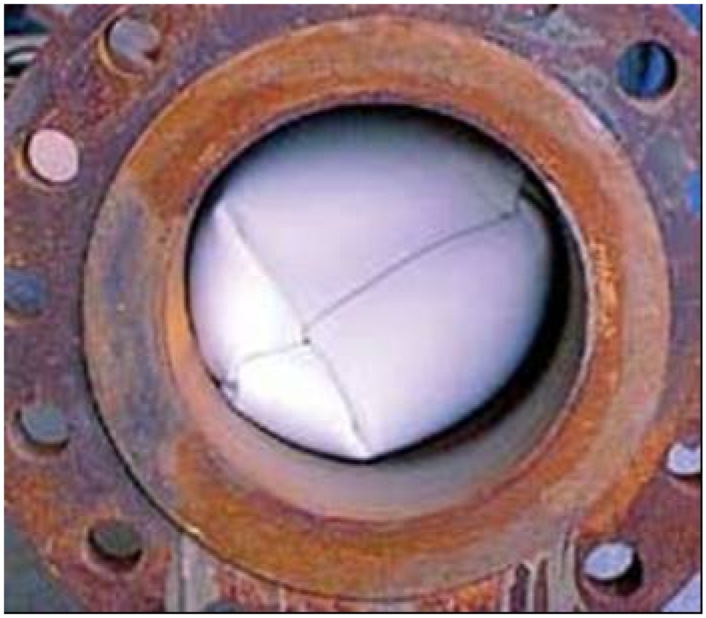

Figure 2-3
Inverted Liner Progresses as it Unfolds in Host Pipe

Figure 2-4
Inverted Liner Progresses as it Unfolds in Host Pipe

Figure 2-5
Water-Filled Liner

Figure 2-6
Illustration Before-and-After Liner Insertion

Figure 2-7
Liner Showing Installation Wrinkles

3
REVIEW OF EXISTING DESIGN RULES

3.1 Design Process

The design process consists first in defining the design input, which includes:

- Host pipe material, components, size and layout.
- Host pipe condition (fully or partially deteriorated, see Section 3.2).
- Design loads (pressure, temperature, flow rates, ground and surface loads, seismic wave passage and anchor motion).
- Design life of the CIP liner.
- CIP physical and mechanical properties.

Given the design input, the two aspects of design qualification are:

- Hydraulic design (pressure drop and flow rate, given the reduced inner diameter and the reduced friction coefficient), not addressed in this report.
- Mechanical design by analysis for selecting the wall thickness of the CIP liner.

This report addresses the mechanical design of the CIP liner.

3.2 Design Loads

For the purpose of design, there are two types of CIP liner applications: (1) CIP liner for partially deteriorated host pipe and (2) CIP liner for fully deteriorated host pipe. The meaning of “partially deteriorated” and “fully deteriorated” refers to the applied loads that the liner and the host pipe are expected to sustain. Table 3-1 summarizes the design loads in each case.

Table 3-1
Component Relied Upon to Sustain Load

Load	Partially Deteriorated Host	Fully Deteriorated Host
Internal pressure	Liner as membrane[(1)]	Liner as cylinder[(2)]
Groundwater ext. pressure	Liner	Liner
Internal vacuum	Liner	Liner
Soil and surface	Host pipe	Liner
Seismic	Liner	Liner

Notes:
(1) Liner acts as a membrane in bending and tension, bridging missing and badly corroded host pipe areas. This type of liner has also been referred to as Interactive Liner since the system integrity relies on the liner interacting with the host pipe.

(2) Liner acts as a pipe under hoop stress. This type of liner has also been referred to as Independent Liner since it does not rely on the host pipe for pressure design.

3.3 Design Rules

In the United States, the design rules for CIP liners are provided in three standards:

- ASTM F 1216, "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of Resin-Impregnated Tube" [1].
- ASME XI Division 1, Code Case N-589-1, "Nonmetallic Cured-in-Place Piping" [2].

A related standard, applicable to another type of CIP liner is:

- ASTM F 2207, "Standard Specification for Cured-in-Place Lining System for Rehabilitation of Metallic Gas Pipe" [3].

The design methods from these three standards are reviewed in Sections 3.4, 3.5 and 3.6, with technical commentary in Section 3.7, concluding in the Gaps in Technology identified in Section 3.8.

3.4 ASTM F 1216 Design Equations

ASTM F 1216 [1] addresses design for internal and external pressure, soil loads and surface (live) loads, for a partially deteriorated and a fully deteriorated host pipe, as defined in Table 3-1. It does not address seismic design. A MathCad shell with a numerical example is provided in Appendix A.

3.4.1 ASTM F 1216 Nomenclature

B’ = coefficient of elastic support = 1 / (1 + 4 exp(-0.065 H)), in-lb

C = ovality reduction factor

D = mean inside diameter of original pipe, in

d = diameter of hole or opening in original pipe wall, in

E_L = long-term (time corrected) modulus of elasticity for CIPP, psi

E_s’ = modulus of soil reaction, psi (see ASTM Practice D 3839)

H = height of soil above top of pipe, ft

H_w = height of water above top of pipe, ft

I = through-wall moment of inertia of CIPP per unit length of wall = $t^3/12$, in^3

K = enhancement factor of the soil and existing pipe adjacent to the new pipe (a minimum value of 7.0 is recommended where there is full support of the existing pipe)

N = factor of safety

P = ground water load, psi

q = percentage ovality of original pipe

q_t = total external pressure on pipe, psi

R_w = water buoyancy factor (0.67 min) = 1 – 0.33 (Hw/H)

SDR = standard dimension ratio of CIPP

t = thickness of CIPP, in

σ_L = long term (time corrected) flexural strength for CIPP, psi

σ_{TL} = long term (time corrected) tensile strength for CIPP, psi

ν = Poisson ratio (0.3 average)

3.4.2 Gravity Flow in Partially Deteriorated Host Pipe

$$P = \frac{2 \times K \times E_L}{1-\nu^2} \times \frac{1}{(SDR-1)^3} \times \frac{C}{N}$$

$$C = \left[\frac{1-\frac{q}{100}}{\left(1-\frac{q}{100}\right)^2} \right]^3$$

P = ground water load, psi

K = enhancement factor of the soil and existing pipe adjacent to the new pipe (a minimum value of 7.0 is recommended where there is full support of the existing pipe)

E_L = long-term (time corrected) modulus of elasticity for CIPP, psi

ν = Poisson ratio (0.3 average)

SDR = standard dimension ratio of CIPP

C = ovality reduction factor

q = percentage ovality of original pipe

N = factor of safety

If the original pipe is oval, the CIPP design shall have a maximum SDR (minimum thickness) as calculated by the following formula

$$1.5 \times \frac{q}{100} \times \left(1+\frac{q}{100}\right) \times SDR^2 - 0.5\left(1+\frac{q}{100}\right) \times SDR = \frac{\sigma_L}{P \times N}$$

σ_L = long term (time corrected) flexural strength for CIPP, psi

Table 3-2 provides the maximum allowable height of ground water above the invert for K = 7, E = 125,000 psi (50 year modulus), ν = 0.3, C = 0.64 (5% ovality), and N = 2”.

Table 3-2
Groundwater Limits [5]

Inside Diameter of Original Pipe (in)	Nominal CIPP Thickness (in)	Maximum Allowable Height of Ground Water Above Invert (ft)
8	0.236	40.0
10	0.236	20.1
12	0.236	11.5
15	0.354	20.1
18	0.354	11.5
18	0.472	27.8
24	0.472	11.5
24	0.591	22.8
30	0.591	11.5
30	0.709	20.1

3.4.3 Gravity Flow in Fully Deteriorated Host Pipe

In addition to the equations of 3.4.2 for Gravity Flow in Partially Deteriorated Host Pipe, the following equations shall be met if the host pipe is fully deteriorated:

$$q_t = \frac{C}{N} \times \sqrt{32 \times R_w \times B' \times E_s' \times \frac{E_L \times I}{D^3}}$$

q_t = total external pressure on pipe, psi

R_w = water buoyancy factor (0.67 min) = 1 – 0.33 (Hw/H)

H_w = height of water above top of pipe, ft

H = height of soil above top of pipe, ft

B’ = coefficient of elastic support = 1 / (1 + 4 exp(-0.065 H)), in-lb

E_s’ = modulus of soil reaction, psi (see ASTM Practice D 3839)

E_L = long term modulus of elasticity for CIPP, psi

D = mean inside diameter of original pipe, in

I = through-wall moment of inertia of CIPP per unit length of wall = $t^3/12$, in^3

The CIPP design shall have a maximum SDR (minimum thickness) as calculated by the following formula:

$$\frac{E \times I}{D^3} = \frac{E}{12 \times SDR^3} \geq 0.093$$

E = initial modulus of elasticity, psi

3.4.4 Pressure Condition in Partially Deteriorated Host Pipe

If

$$\frac{d}{D} \leq 1.83 \times \sqrt{\frac{t}{D}}$$

d = diameter of hole or opening in original pipe wall, in

t = thickness of CIPP, in

then

$$P = \frac{5.33}{(SDR - 1)^2} \times \left(\frac{D}{d}\right)^2 \times \frac{\sigma_L}{N}$$

If

$$\frac{d}{D} > 1.83 \times \sqrt{\frac{t}{D}}$$

the defect is large; the host pipe is considered fully deteriorated and Section 3.4.5 applies.

3.4.5 Pressure Condition in Fully Deteriorated Host Pipe

In addition to the equations of A1.2 Gravity Flow in Partially Deteriorated Host Pipe, the following equations shall be met.

$$P = \frac{2 \times \sigma_{TL}}{(SDR - 2) \times N}$$

σ_{TL} = long term (time corrected) tensile strength for CIPP, psi

3.5 ASTM F 2207 Design Equations

ASTM F 2207 [3] addresses design for internal pressure of a CIP liner membrane spanning a missing hole (through-wall corrosion) in the host pipe, as illustrated in Figure 3-1. It does not address seismic design. The solution is based on test data which shows the material to be anisotropic and bi-linear as shown in Figure 3-2. A MathCad shell with a numerical example is provided in Appendix B. The design equations presented here are provided in [3, 4]:

3.5.1 Nomenclature

D = pipe diameter, in

E_{1-45} = primary (elastic) modulus in the 45-degree orientation per unit width, lb/in

E_{1-a} = primary (elastic) modulus in the axial orientation per unit width, lb/in

E_{1-h} = primary (elastic) modulus in the hoop orientation per unit width, lb/in

E_{2-45} = secondary (plastic) modulus in the 45-degree orientation per unit width, lb/in

E_{2-a} = secondary (plastic) modulus in the axial orientation per unit width, lb/in

E_{2-h} = secondary (plastic) modulus in the hoop orientation per unit width, lb/in

h = projection of liner, in

L = length of defect in axial direction, in

N_a = axial load per unit width, lb/in

N_h = hoop load per unit width, lb/in

N_{u-a} = ultimate axial load per unit width, lb/in

N_{u-h} = ultimate hoop load per unit width, lb/in

p = applied pressure, psi

r_a = radius of curvature of liner in axial direction, in

r_h = radius of curvature of liner in hoop direction, in

S_{12-1} = primary interaction compliance coefficient, in/lb

w = length of defect in hoop direction, in

$\varepsilon_{i\text{-}a}$ = axial strain (i = 1 primary (elastic) and i = 2 secondary (plastic)), in/in

$\varepsilon_{i\text{-}h}$ = hoop strain (i = 1 primary (elastic) and i = 2 secondary (plastic)), in/in

ε_y = yield strain, in/in

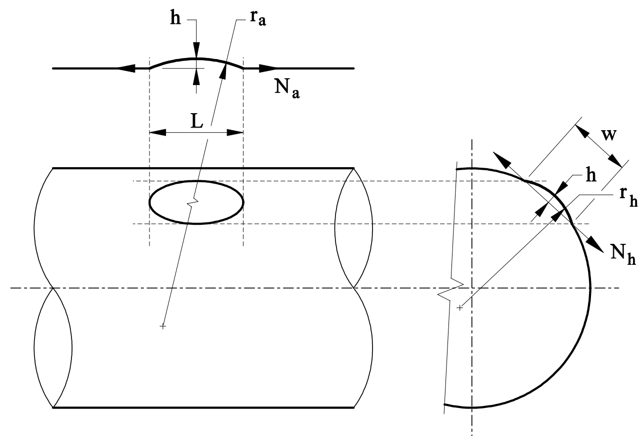

Figure 3-1
Illustration of Nomenclature

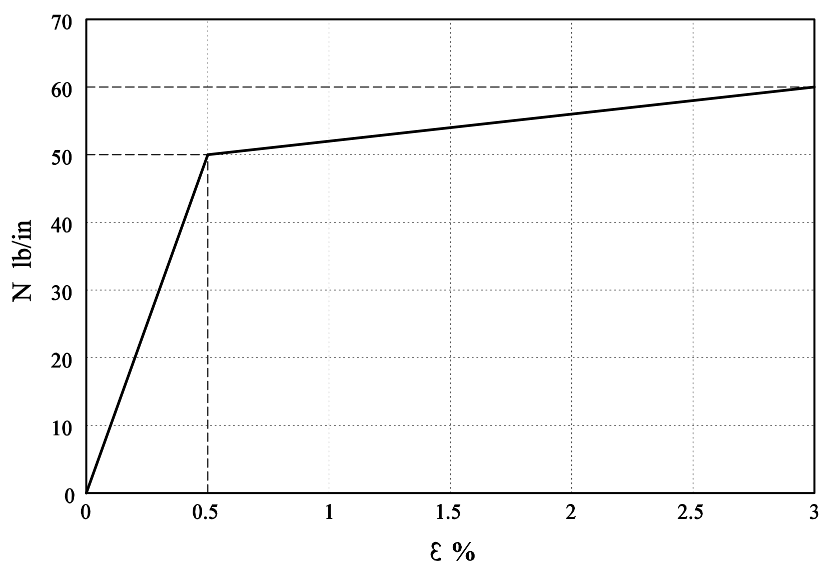

Figure 3-2
Bi-Linear Approximation of Liner Load-Strain Properties

3.5.2 Equations

Consider the CIP liner membrane bridging a hole, which in practice would be a localized pin hole caused by corrosion. Referring to Figure 3-1, the condition for equilibrium is:

$$\frac{N_h}{r_h} + \frac{N_a}{r_a} = p$$

The strains in the axial and hoop direction, as a function of the deformed liner shape are:

$$\varepsilon_a = \frac{2 \times r_a}{L} \times \sin^{-1}\left(\frac{L}{2 \times r_a}\right) - 1$$

$$\varepsilon_h = \frac{2 \times r_h \times \sin^{-1}\left(\dfrac{w}{2 \times r_h}\right)}{D \times \sin^{-1}\left(\dfrac{w}{D}\right)} - 1$$

The constitutive equations are:

$$\varepsilon_{i-h} = \frac{1}{E_{i-h}} \times N_h + S_{12-i} \times N_a$$

$$\varepsilon_{i-a} = \frac{1}{E_{i-a}} \times N_a + S_{12-i} \times N_h$$

where:

$$S_{12-1} = \frac{0.5}{E_{1=45}} + 0.25 \times \left(\frac{1}{E_{1-h}} + \frac{1}{E_{1-a}}\right)$$

$$S_{12-2} = \frac{0.5}{E_{2=45}} + 0.25 \times \left(\frac{1}{E_{2-h}} + \frac{1}{E_{2-a}}\right)$$

The onset of yield condition is:

$$(\varepsilon_a^{\,2} + \varepsilon_h^{\,2})^{1/2} = \varepsilon_y$$

The geometric compatibility equations are:

$$r_a = \frac{L^2}{8 \times h} + \frac{h}{2}$$

$$r_h = \frac{w^2}{8 \times h} + \frac{h}{2}$$

The failure interaction criteria are:

$$\frac{N_h}{N_{u-h}} = 1$$

$$\frac{N_a}{N_{u-a}} = 1$$

$$\left(\frac{N_h}{N_{u-h}}\right)^2 + \left(\frac{N_a}{N_{u-a}}\right)^2 = 1$$

3.5.3 Solution to Equations

By substitution, the equations that relate the load per width of liner to the internal pressure and the dimensions of the hole (through-wall corrosion loss) are obtained.

$$\frac{N_h}{\frac{w^2}{8\times h}+\frac{h}{2}}+\frac{N_a}{\frac{L^2}{8\times h}+\frac{h}{2}}=p$$

$$N_h=\frac{1}{\frac{1}{E_h\times E_a}-S_{12}{}^2}\times\frac{1}{E_a}\times\{\frac{\left(\frac{w^2}{4\times h}+h\right)\times\sin^{-1}\left(\frac{w}{\frac{w^2}{4\times h}+h}\right)}{D\times\sin^{-1}\left(\frac{w}{D}\right)}-1\}-$$

$$S_{12}\times\{\frac{\left(\frac{L^2}{4\times h}+h\right)\times\sin^{-1}\left(\frac{L}{\frac{L^2}{4\times h}+h}\right)}{L}-1\}$$

$$N_a=\frac{1}{S_{12}{}^2-\frac{1}{E_h\times E_a}}\times S_{12}\times\{\frac{\left(\frac{w^2}{4\times h}+h\right)\times\sin^{-1}\left(\frac{w}{\frac{w^2}{4\times h}+h}\right)}{D\times\sin^{-1}\left(\frac{w}{D}\right)}-1\}-$$

$$\frac{1}{E_h}\times\{\frac{\left(\frac{L^2}{4\times h}+h\right)\times\sin^{-1}\left(\frac{L}{\frac{L^2}{4\times h}+h}\right)}{L}-1\}$$

3.6 Code Case N-589-1 Design Equations

3.6.1 Status of Code Case N-589-1

The design equations of ASME Code Case N-589-1, “Class 3 Nonmetallic Cured-in-Place Piping” [2], address all design loads, including seismic loads. However, Code Case N-589-1 was not approved by the US Nuclear Regulatory Commission. NRC Regulatory Guide 1.193 [6] cites the following four reasons:

1. The installation process provides insufficient controls on wall thickness measurement.
2. There are no qualification requirements for installers and installation procedures such as those for welders and welding procedures.

3. Fracture toughness properties of the fiberglass are such that the cured-in-place piping (CIPP) could crack during a seismic event.
4. Equations 4 and 5 in the Code Case contain "i" term [a stress intensification factor] that is derived from fatigue considerations. Stress intensification factors, however, have not been developed for fiberglass materials.

A MathCad shell with a numerical example for Code Case N-589-1 is provided in Appendix C.

3.6.2 Nomenclature

A = cross sectional area of CIPP, in^2

B' = coefficient of elastic support = 1 / (1 + 4 exp(-0.065 H)), in-lb

C = ovality reduction factor

D_o = outside diameter of CIPP (inside diameter of host pipe), in

E_F = time-temperature corrected flexural modulus of elasticity of CIPP, psi

E_s' = modulus of soil reaction, psi

H = height of soil above top of host pipe, ft

H_w = height of ground water above top of host pipe, ft

i = stress intensification factor (SIF). The product 0.75i shall never be taken as less than 1. The SIF for CIPP in a straight host pipe shall be taken as 1. The Owner is required to determine, through testing in accordance with Appendix II, the value of the applicable SIF.

K = buckling enhancement factor for the soil and host pipe adjacent to CIPP. A value of 7.0 shall be used.

k = occasional load factor = 1.2

M_A = resultant moment loading on cross section due to weight and other applicable sustained loads, in-lb. Because CIPP is continuously supported by the existing soil system or the partially deteriorated pipe, the M_A term can usually be neglected.

M_B = resultant moment loading on cross section due to applicable occasional loads, such as thrusts from relief and safety valve loads, from pressure and flow transients, and seismic inertia, in-lb. For seismic inertia, use only half of the range. The effects of seismic displacements shall be included in [thermal expansion] equation.

N_E = 2 (design factor)

N_S = 4 (design factor)

P_D = internal design pressure, psi

P_{mo} = maximum operating pressure, psi

q_t = total external pressure, psi

R_w = water buoyancy factor (0.67 minimum) = $1 - 0.33(H_w/H)$

r_m = mean radius of CIPP, in

S_α = axial loading on cross section due to seismic displacements or other applicable occasional loads, lb

S_T = time-temperature corrected ultimate tensile strength of CIPP, psi

t_n = nominal CIPP wall thickness, in

t_r = required CIPP design wall thickness, in

Z = section modulus of CIPP, in$^3 \approx \pi\, r_m^{\,2}\, t_n$

ν = Poisson ratio = 0.3, or as determined in accordance with ASTM D 2105

3.6.3 Internal Pressure

For a partially or fully deteriorated host pipe, the required wall thickness shall be

$$t_r = \frac{D_o}{\dfrac{2 \times S_T}{P_D \times N_S} + 1}$$

t_r = required CIPP design wall thickness, in

P_D = internal design pressure, psi

D_o = outside diameter of CIPP (inside diameter of host pipe), in

S_T = time-temperature corrected ultimate tensile strength of CIPP, psi

N_S = 4 (design factor)

3.6.4 External Pressure

For a fully deteriorated pipe, the required wall thickness shall also comply with the following equation:

$$t_r = 0.721 \times D_o \times \sqrt[3]{\frac{\left(\frac{N_E \times q_t}{C}\right)^2}{E_F \times R_w \times B' \times E_s'}}$$

N_E = 2 (design factor)

q_t = total external pressure, psi

C = ovality reduction factor

E_F = time-temperature corrected flexural modulus of elasticity of CIPP, psi

E_s’ = modulus of soil reaction, psi

R_w = water buoyancy factor (0.67 minimum) = 1 – 0.33(H_w/H)

H_w = height of ground water above top of host pipe, ft

H = height of soil above top of host pipe, ft

B’ = coefficient of elastic support = 1 / (1 + 4 exp(-0.065 H)), in-lb

For a partially deteriorated pipe, the required wall thickness shall also comply with the following equation:

$$t_r = \frac{D_o}{\sqrt[3]{\frac{2 \times K \times E_F \times C}{q_t \times N_E \times (1-\nu^2)}} + 1}$$

K = buckling enhancement factor for the soil and host pipe adjacent to CIPP. A value of 7.0 shall be used

ν = Poisson ratio = 0.3, or as determined in accordance with ASTM D 2105

3.6.5 Longitudinal Stresses Sustained and Occasional Loads

$$\frac{P_{mo} \times D_o}{4 \times t_n} + 0.75i \times \frac{M_A + M_B}{Z} + \frac{S_\alpha}{A} \le k \times \frac{S_T}{4}$$

P_{mo} = maximum operating pressure, psi

t_n = nominal CIPP wall thickness, in

i = stress intensification factor (SIF). The product 0.75i shall never be taken as less than 1. The SIF for CIPP in a straight host pipe shall be taken as 1. The Owner is required to determine, through testing in accordance with Appendix II, the value of the applicable SIF.

M_A = resultant moment loading on cross section due to weight and other applicable sustained loads, in-lb. Because CIPP is continuously supported by the existing soil system or the partially deteriorated pipe, the M_A term can usually be neglected.

M_B = resultant moment loading on cross section due to applicable occasional loads, such as thrusts from relief and safety valve loads, from pressure and flow transients, and seismic inertia, in-lb. For seismic inertia, use only half of the range. The effects of seismic displacements shall be included in [thermal expansion] equation.

A = cross sectional area of CIPP, in^2

k = occasional load factor = 1.2

S_α = axial loading on cross section due to seismic displacements or other applicable occasional loads, lb

Z = section modulus of CIPP, $in^3 \approx \pi r_m^3 t_n$

r_m = mean radius of CIPP, in

t_n = nominal CIPP wall thickness, in

3.6.6 Thermal Expansion and Contraction

$$i\frac{M_C}{Z} + \frac{S}{A} \le \frac{S_T}{2}$$

M_C = resultant moment loading on cross section due to thermal expansion or contraction, in-lb

S = axial loading on cross section due to seismic displacements, if included, and thermal expansion, lb

3.7 Commentary

3.7.1 ASTM F 1216 Commentary

The design equations of ASTM F 1216 have several shortcomings.

1. All Sections: The standard addresses internal and external pressures. It has no provisions for bending loads, in particular bending due to soil movement from seismic wave passage, necessary for safety class 3 seismic design.
2. Section 3.4.2: This formula evaluates the liner under uniform radial hydrostatic pressure from the ground water that infiltrated the host pipe. However, the $1/SDR^3$ relationship assumes that the liner buckles freely, as if there was no host pipe. The experimentally-based enhancement factor K is then introduced to increase the buckling pressure to account for the restraining effect of the host pipe and surrounding soil.
3. Section 3.4.2: The long-term modulus of elasticity of the liner could be either
   (a) Its compressive creep modulus if the liner fits tightly to a round host pipe, and therefore will deform symmetrically, radially inward, or
   (b) Its flexural creep modulus if the liner is oval (not tight fitting to the host pipe) and will bend
4. Section 3.4.2: The basis of the theoretical relationship between the initial ovality q and the long-term flexural strength, and its experimental confirmation, needs to be documented.
5. Section 3.4.3: Here the liner is treated as a buried pipe deflecting under soil and surface loads, as if the host pipe has vanished. This is conservative to an extreme. Reportedly, the Australian Code AS 2566 "Buried Flexible Pipelines – Part 1: Structural Design" Australian / New Zealand Standard has more realistic approach. The Australian standard and its British equivalent, WRc/WAA "Sewerage Rehabilitation Manual" UK Water Research Centre / Water Authorities Association should be reviewed.
6. Sections 3.4.2, 3.4.3 and 3.4.4: There is no mention of the effects of cyclic internal pressure (pressure fluctuations in service) or cyclic external pressure (ground water level changes or cyclic surface traffic load).
7. Sections 3.4.2 to 3.4.5: There is no mention of anisotropy of the material (if any) in contrast to ASTM F 2207 where anisotropy is a key aspect of the design equations.
8. The ASTM F 1216 is based on linear buckling. Unlike ASTM F 2207 it does not address a bi-linear behavior of the CIP liner.

3.7.2 ASTM F 2207 Commentary

In this method, the liner is sized for internal pressure only. The shortcomings include:

1. The host pipe is relied upon for other loads such as soil, surface, ground water. Seismic design or, more generally, bending loads, are not addressed.
2. The design equations require the knowledge of the three-directional (axial, hoop and diagonal at 45 degrees) anisotropic and bi-linear mechanical properties of the liner.

3. The design solution is given in the form of a load per unit width of liner, not directly in required liner thickness.
4. The design equations apply to the liner membrane bridging a postulated hole. In actual applications of external pitting, the hole size will often be unknown, or the host pipe may be lined before a through-wall hole has developed. So it becomes unclear what should be the postulated hole size (w and L in Figure 3-1).

3.7.3 ASME Code Case N-589-1 Commentary

In addition to the deficiencies noted in NRC Regulatory Guide 1.193, other shortcomings include:

1. Section 3.6.3: The internal pressure formula does not account for any benefit provided by the host pipe. This is grossly conservative.
2. Section 3.6.4: The same comment applies to external loads design (ground water and soil) as for ASTM F 1216.
3. Section 3.6.5: The NRC Comment regarding fracture behavior of the CIPP material is valid.
4. Section 3.6.5: The longitudinal stress equation is that of a liner above-ground, with no host pipe. The above-ground behavior reflected in M_A, and the assumption of no host pipe reflected in PD/4t need to be explained through an example. In fact, it is not clear how to calculate M_A in a liner continuously supported by the host pipe.
5. Section 3.6.6: The expansion and contraction behavior of the liner needs to be better described to clarify how the thermal stresses originate and therefore what should be the corresponding equations.
6. Sections 3.6.5 and 3.6.6: The NRC comment regarding the stress intensification factor "i" is valid. In particular, is the stress intensification factor concept valid for a CIP liner? If not, do cyclic stresses need to be considered in the CIP liner design?

3.8 Gaps in Technology

From the above commentary, the following gaps in technology are noted:

- Assess whether the CIP liner has sufficient ductility to absorb bending caused by seismic wave passage. This would be the first priority in order to assess the viability of the CIP liner as a seismically qualified option. While seismic induced soil bending strains are plant-specific, an estimated strain is provided in Appendix D.
- Confirm that the M/Z equation for pipe bending is also applicable to a CIP liner, and whether an axial force needs also be considered.
- Assess whether a stress intensification factor "i" is needed, what form it should take, and how it should be developed; including consideration of ripples in the liner and their effect on stress concentration (NRC comment).

- Investigate the CIP design and sizing equations in Australian Code AS 2566 and UK Code WRc/WAA, and compare to the US approach (ASTM F1216, ASTM F 2207 and ASME Code Case N-589-1).
- Assess whether the material is anisotropic (as in ASTM F 2207) or whether the design may be based on an isotropic approach (as in ASTM F 1216).
- Determine whether the material behaves in a linear-buckling mode as in ASTM F 1216, or a bi-linear mode as in ASTM F 2207, (Figure 3-2).
- If ASTM F 2207 does apply, the solution should be developed in the form of a required liner thickness rather than the more cumbersome form of load per unit width.
- If ASTM F 2207 does apply, the design equations would need to be developed for loads other than internal pressure. This will be a challenge given that the material would have to be evaluated as anisotropic in three directions (axial, hoop and diagonal at 45 degrees) and non-linear.
- The Code Case N-589-1 internal pressure wall thickness equation needs to be investigated to determine if it results in unreasonably thick liners for several typical plant pipe sizes and pressures.
- The fracture toughness and risk of brittle fracture need to be addressed (NRC comment).
- The design life of the CIP liner needs to be investigated in the case of soil-induced corrosion (outer diameter corrosion). Unless the soil-induced corrosion is arrested (which may be hard to prove), the liner may have to be designed in all cases as if the host pipe is fully deteriorated.
- The existing design rules apply to ambient temperatures in the order of 70°F. If the line is to be used for intake or discharge of warmer water, the mechanical properties will have to be developed accordingly, including short and long-term (creep rupture) properties.
- The mechanical properties currently available are for quasi-static loads (pressure, ground water, soil). Properties will have to be developed at seismic strain rates.

4 RECOMMENDATIONS

4.1 Summary of Technology

It is evident from this investigation of the CIP liner that:

- The rehabilitation of buried corroded steel pipe using CIP liners has a good cost and reliability track record in the waterworks industry.
- In the United States, there are three standards that address CIP liners (ASTM F 1216, ASTM F 2207, and ASME Code Case N-589-1). The design approach and equations of these three standards vary, including differences in the treatment of mechanical properties of the CIP liner (isotropic vs. anisotropic, linear vs. non-linear).
- This research did not identify published data on the seismic behavior of CIP lined pipe, or more generally on the bending behavior of the CIP liner tube (a single report of bending test, undocumented).
- In order to pursue the use of the CIP liner for seismically qualified safety-class 3 applications, Gaps in Technology identified in section 3.8 will have to be addressed.

4.2 Recommendation

Because the CIP liner rehabilitation technology is successful in waterworks applications similar to buried Service Water Systems, the method should be further investigated for application to the rehabilitation of buried safety-class 3 service water lines. It is recommended that the investigation proceed in two steps:

<u>Step-1</u>. First, a simple exploratory bending test of a CIP liner tube should be conducted, prior to any other investigation. The assessment of the bending capability of the CIP liner tube subject to bending moments comparable to those that would occur in a design basis earthquake would indicate whether the liner is a viable option for seismic design. The strain that CIPP should be capable of reacting is estimated in Appendix D.

<u>Step-2</u>. If the test proves successful (the liner absorbs the simulated seismic bending well, in a ductile manner, without failing), then an estimate should be developed to address the “Gaps in Technology” identified in Section 3.8.

Based on the current work to qualify high-density polyethylene for ASME Class 3 applications, it is likely that the required testing would include:

4.2.1 Full-Range Stress Strain Properties

The full-range stress strain curves of the selected CIPP material will need to be developed for the temperature range of interest. These curves will provide part of the bases for the Code allowable stresses and strains, and the engineering properties that can be used for design of CIP piping systems. This includes the allowable stress at temperature, the modulus of elasticity at temperature, and the effect of aging on the properties. Results also provide the full-range stress-strain curve in the event that a user decides to use the wave passage method to qualify the pipe for the seismic load or to perform a nonlinear analysis for a given load. The possible differences in properties between axial and hoop directions will need to be investigated.

The response of piping to the seismic event is dependent on the modulus of elasticity. The modulus in turn is dependent on the strain rate. It is possible that some additional testing at seismic strain rates will be needed to determine an appropriate modulus.

4.2.2 Frequency of Cycling Effect on Fatigue Life

Cyclic loads will cause the material to heat up and change properties (e. g., yield stress, modulus of elasticity, fatigue properties, etc). In normal usage, either the frequency of loading is of a very long duration (e.g., thermal cycling associated with changes to water or ground temperature) or of such limited number of cycles (e.g., seismic) that the effect is not significant. However, with fatigue testing, there are many thousands of cycles applied over a relatively short period of time, so the effect can be significant. The effect may be different at room and at elevated temperatures. A parametric analysis would need to be performed to select the test frequency for all future work.

4.2.3 Fatigue Curves

Fatigue testing would be required to develop the stress amplitude versus cycles to failure curve (commonly referred to as a S-N curve) for cyclic loads. It would need to be performed in accordance with the guidance of the ASME Section III Code and address the temperatures of interest.

4.2.4 Effect of Aging on Fatigue Properties

The effects of thermal aging on CIP fatigue properties would need to be determined. These tests could be conducted using standard tensile specimens that will be cut from CIP pipe[1]. One set of tests would need to be run on new material and one set would need to be run on thermally aged material.

4.2.5 Stress Intensification and Flexibility Factors for 45º Bend and Flanged Joint

Assuming that stress intensification factors are applicable for CIPP, Code acceptable SIFs would need to be developed for a 45º bend and a flanged joint in accordance with the guidance of the

[1] Thermal aging of pipe specimens to use in fatigue tests would be very expensive and is judged to be not necessary.

ASME Section III Code. For the bend, differences in behavior between in-plane and out-of-plane directions would need to be investigated. Flexibility factors for such components would also need to be developed.

4.2.6 Strength Test of Flange

The objective of this test would be to compare the strength of the flanged joint to the pipe. It would likely consist of a static bend test where the flange would be bolted to a test bed and the test specimen subjected to an increasing bending load until leakage or fracture of the pipe, flange adapter, flange or bolts.

4.2.7 Long-Term Creep Rupture Tests

No creep rupture data were found for CIP material. This task would measure the long-term creep of pressurized pipe specimens at a variety of temperatures. The tests may need to be performed on both new and thermally aged material.

4.2.8 Crack Propagation

No data on resistance of CIP to slow or rapid crack propagation were found. Such data will likely be required for the temperature range of interest. The effect of aging on crack propagation will likely need to be determined.

5 REFERENCES

1. ASME F1216, "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of resin-Impregnated Tube".
2. ASME Boiler and Pressure Vessel Code, Section XI, Division 1, Code Case N-589-1, "Nonmetallic Cured-in-Place Piping".
3. ASTM F2207, "Standard Specification for Cured-in-Place Lining System for Rehabilitation of Metallic Gas Pipe".
4. "The Long-term Performance of the Starline[R] 200 Liner for Gas Distribution Systems", Francini, R.M, Pimputkar, S.M., Wall, G., Oliver, M., Battelle, Columbus, for Gas Research Institute (GRI), December, 2000.
5. ASTM F 1216-98, Table X1.1, "Maximum Groundwater Loads for Partially Deteriorated Gravity Pipe Condition".
6. US Nuclear Regulatory Commission, Regulatory Guide 1.193, Revision 1, August 2005, "ASME Code Cases Not Approved for Use".

A
ASTM F1216 EXAMPLE

One of the standards for the design of CIP pipe is ASTM F 1216 - 05 [1]. For the case of a partially deteriorated host pipe (soil and surface loads are supported by the host pipe), the CIPP liner must resist the external hydrostatic ground water pressure.

An example using "Inliner Technology" parameters is provided below. The solution is based on a MathCad shell reproduced here for ease of use and verification, hence the decimals.

<u>Nomenclature:</u>

Bp = coefficient of elastic support

C = ovality correction factor

D = pipe outside diameter, in

Dmin = minimum pipe outside diameter if oval pipe cross section, in

dmax = maximum hole size or opening in host pipe, in

E = modulus of elasticity of CIP, short-duration load, psi

EL = modulus of elasticity of CIP, long-duration load, psi

Es = soil modulus, psi

Hs = burial depth, ft

Hw = distance from top of the water table down to top of pipe, ft

K = enhancement (stiffening) factor of soil support to the existing pipe, a minimum value of 7.0 is recommended in ASTM F 1216-05 where there is full support of the existing pipe

N = safety factor

nu = Poisson ratio of CIPP liner

Ps = soil load, psi

Pt = total soil load, psi

Pwp = pressure on the pipe due to the ground water, psi

Rw = water buoyancy

q = ovality

SR = stiffness ratio

t = minimum wall thickness of CIP, gravity flow service, in partially deteriorated pipe, to resist external hydrostatic pressure, in

tb = minimum wall thickness of CIP, gravity flow service, in fully deteriorated pipe, to resist external hydrostatic pressure and soil load, in

tPL = minimum wall thickness of CIP, pressurized service, with large hole (larger than dmax), in

tPS = minimum wall thickness of CIP, pressurized service, with small hole (smaller than dmax), in

w = soil density, lb/ft^3

σb = through-wall bending stress in CIP liner in partially deteriorated pipe, psi

σL = long-term (time-corrected) flexural strength for CIP liner in partially deteriorated pipe, psi

σFD = through-wall bending stress in CIP liner in fully deteriorated pipe, psi

σFD = long-term (time-corrected) flexural strength for CIP in fully deteriorated pipe, psi

σTL = long term tensile strength of liner, psi

A.1 Gravity Flow Partially Deteriorated Host Pipe

In the first part of this example, a CIP liner in a 36.5 inch ID, partially deteriorated pipe, is sized to sustain the groundwater hydrostatic pressure for 50 years. The required CIP liner thickness is calculated to be 0.66 inch.

Hw (ft) is the distance from the top of the water table down to bottom of pipe = 14.0

Pwp is the pressure (psi) on the pipe due to the ground water (water table). Water density = 62.4 lb/ft^3 = 0.433 psi / ft depth = 6.062 psi

D is the pipe outside diameter = 36.5”

Dmin is the minimum pipe outside diameter (ovalized) = 35.8”

q is the ovality in percent, defined on the basis of OD as is the practice in piping design, and in terms that can be directly measured in the field, whereas ASTM F 1216 Appendix X1 defines it in terms of mean and minimum ID.

$$q := 100\frac{(D - Dmin)}{D}$$

q = 1.918

C is the ovality reduction factor

$$C := \left[\frac{\left(1 - \frac{q}{100}\right)}{\left(1 + \frac{q}{100}\right)^2}\right]^3$$

C = 0.842

E is the modulus of the CIP (psi) for short-duration loads

E = 30,0000 psi

EL is the modulus of the CIPP for long duration load, taken in this example as 1/2 the short term modulus E

EL = E/2 = 1.5 x 10^5 psi

t (in) is the minimum wall thickness required to resist the external hydrostatic pressure

K is the enhancement (stiffening) factor of the soil and existing pipe = 7

nu is the Poisson ratio = 0.3

N is a safety factor = 2

$$t := \frac{D}{\left[\frac{(2 \cdot K \cdot EL \cdot C)}{Pwp \cdot \left(1 - nu^2\right) \cdot N}\right]^{\frac{1}{3}} + 1}$$

t = 0.66

σb (psi) is the through-wall bending stress due to initial ovality subject to external pressure

DR is the dimension ratio = D/t = 55.317

$$\sigma b := \left[\left[1.5 \cdot \frac{q}{100} \cdot \left(1 + \frac{q}{100}\right) \cdot DR^{2}\right] - 0.5 \cdot \left(1 + \frac{q}{100}\right) \cdot DR\right] \cdot Pwp \cdot N$$

σb = 745.931 psi

Compare the through-wall bending stress σb to the long-term flexural strength σL of the CIP = 2500 psi

A.2 Gravity Flow Fully Deteriorated

In the second part of this example, the same 36.5 inch ID pipe is now fully deteriorated, so the CIP liner has to be sized to sustain soil loads as well as groundwater hydrostatic pressure for 50 years. The required CIP liner thickness is calculated to be 0.84 inch.

Pwp (psi) is the hydrostatic pressure

Ps (psi) is the soil load

Hs (ft) is the burial depth = 15 ft

w is the soil density = 130 lb/ ft^3

Rw is the water buoyancy

$$Rw := 1 - 0.33\left(\frac{Hw}{Hs}\right)$$

Rw = 0.692

$$Ps := \frac{w \cdot Hs \cdot Rw}{144}$$

Ps = 9.371 psi

Pt is the total soil load

Pt = Pwp + Ps = 15.433 psi

Bp is the coefficient of elastic support

$$Bp := \frac{1}{1 + 4\exp(-0.065 \cdot Hs)}$$

Bp = 0.399

tb is the minimum CIPP thickness to prevent buckling under soil and groundwater loads

Es is the soil modulus = 1000 psi

$$tb := \left[0.375 \cdot \frac{\left(Pt \cdot \frac{N}{C}\right)^2 \cdot D^3}{EL \cdot Rw \cdot Bp \cdot Es} \right]^{0.33}$$

tb = 0.841

Check for minimum stiffness

SR is the stiffness ratio must be larger than 0.093

$$SR := \frac{E}{12 \cdot \left(\frac{D}{tb}\right)^3}$$

SR = 0.306 is larger than 0.093

Check the through-wall bending stress in a fully deteriorated pipe σbFD

$$\sigma bFD := \left[\left[1.5\cdot\frac{q}{100}\cdot\left(1+\frac{q}{100}\right)\cdot\left(\frac{D}{tb}\right)^2\right]-0.5\cdot\left(1+\frac{q}{100}\right)\cdot\left(\frac{D}{tb}\right)\right]\cdot Pt\cdot N$$

σbFD = 1.021 x 10^3 psi

Compare to the long-duration load capacity of the CIPP system σLFD = 2500 psi

A.3 Pressure Flow Partially Deteriorated Host Pipe

The maximum hole or opening size in the host pipe that can be treated by a flat-plate CIP liner approximation is

$$dmax := D\cdot 1.83\cdot\left(\frac{t}{D}\right)^{0.5}$$

dmax = 8.981 in

If the actual hole or opening in the host pipe is smaller than dmax, then the required CIP wall thickness is

σL = 2500 psi

P = 100 psi

d = 6 in

$$tPS := \frac{d}{\left(\frac{5.33}{P}\cdot\frac{\sigma L}{N}\right)^{0.5}+1}$$

tPS = 0.655 in

If the actual hole or opening in the host pipe is larger than dmax, then the required CIP wall thickness is

σTL = 1500 psi

$$tPL := \frac{D}{\left(\frac{2 \cdot \sigma TL}{P \cdot N}\right) + 2}$$

tPL = 2.147 in

B
ASTM F2207 EXAMPLE

Determination of the Design Pressure for Cured-in-Place Liners in Partially Deteriorated Pipe. The solution is based on a MathCad shell reproduced here for ease of use and verification, hence the decimals.

Nomenclature: (Note: Tables X1.1, X1.2 and X1.3 refer to table numbers in ASTM F2207).

D = inner diameter of pipe, in

Ea1 = primary modulus in the axial direction (adhesive dominated region), axial stiffness of liner (E1 in Table X1.1), lb/in

Ea2 = secondary modulus in the axial direction (fiber-elastomer dominated region), axial stiffness of liner (E2 in Table X1.1), lb/in

Eh1 = primary modulus in the hoop direction (adhesive dominated region), hoop stiffness of liner (E1 in Table X1.2), lb/in

Eh2 = secondary modulus in the hoop direction (fiber-elastomer dominated region), hoop stiffness of liner (E2 in Table X1.2), lb/in

E(45)1 = primary modulus in the 45 degree orientation (fibers at 45 deg. from load), lb/in

h = radial projection of pressurized domed liner beyond pipe, in

hy = radial projection h at yield pressure, in

L = length of hole bridged by liner, in

LPW = load per unit width, lb/in

Naf = axial failure load / width (Pmax / Wc in Table X1.1), lb/in

Nay = axial yield load / width, lb/in

Naabp = actual axial burst pressure / width (experimental average Pmax / Wc in Table X1.1), lb/in

Nahbp = actual hoop burst pressure / width (experimental average Pmax / Wc in Table X1.2), lb/in

Nhf = hoop failure load / width (Pmax / Wc in table X1.2), lb/in

Nhy = hoop yield load / width, lb/in

Nmaxhoop = maximum hoop / width in the liner

Pf = internal pressure at failure, psi

Py = internal pressure at yield, psi

S121 = primary interaction compliance factor (Table X1.3), where S121 = 0.5/E(45)1 + 0.25 (1/Eh1 + 1/Ea1), in/lb

S122 = secondary interaction compliance factor (Table X1.3), where S122 = 0.5/E(45)2 + 0.25 (1/Eh2 + 1/Ea2), in/lb

S212 = interaction compliance factor (Table X1.3), in/lb

Temp = operating temperature, deg.R (529.67 deg.R = 70°F)

tf = life, years

w = circumferential width of hole bridged by liner, in

εa = axial strain

εh = hoop strain

εay = axial strain at yield, intercept of primary and secondary axial load / width vs. strain lines

εhy = hoop strain at yield, intercept of primary and secondary hoop load / width vs. strain lines

εy = yield strain (Tables X1.1 and X1.2)

Conditions

Source: ASTM F 2207 - 02 Standard Specification for Cured-in-Place Pipe Lining System for Rehabilitation of Metallic Gas Pipe, ASTM International, Section A1.4.
Source: GRI-00/0237 Final Report, The Long-Term Performance of the Starline (R) 200 Liner for Gas Distribution Systems, Battelle Columbus for GRI.

1. Equilibrium of liner subject to internal pressure (ASTM Eq. (A1.13))

Nh / rh + Na / ra = p

Nh = hoop load / width
Na = axial load / width
ra = radius of curvature of liner in hoop direction
rh = radius of curvature of liner in axial direction
p = internal pressure

2. Strain displacement (ASTM Eq. (A1.14) (A1.15))
Deformed liner approximated by a circular arc

εh + 1 = 2 rh asin (w / 2 rh) / D asin (w / D)
εa + 1 = 2 ra asin (L / 2 ra) / L

3. Constitutive equations (ASTM Eq. (A1.16) (A1.17))
Applies separately in primary (Eh1, Ea1, S121) and secondary (Eh2, Ea2, S122) regions

εh = Nh / Eh + S12 Na
εa = Na / Ea + S12 Nh

4. Compatibility equations (ASTM Eq. (A1.118) (A1.19))

ra = L^2 / 8 h + h / 2
rh = w^2 / 8 h + h / 2

5. Failure criteria (ASTM Eq. (A1.20) (A1.21) (A1.22))

Nh / Nhf = 1
Na / Naf = 1
$(Nh / Nhf)^2 + (Na / Naf)^2 = 1$

6. Conditions 1 and 4 lead to (ASTM Eq. (A1.26))

Nh / [(w^2 / 8 h) + h / 2] + Na / [(L^2 / 8 h) + h / 2] = p

7. Yield criterion

$\varepsilon h^2 + \varepsilon a^2 = \varepsilon y^2$

$L := 1.197$

$Naf := 74.7$

$Ea1 := 3350$

$S121 := -3.95 \cdot 10^{-5}$

$w := 1.197$

$Nhf := 215.543$

$Ea2 := 39.4$

$S122 := -0.00152$

$D := 1.68$

$\varepsilon y := 0.00895$

$Eh1 := 8325.5$

$S212 := 0.00026$

$Eh2 := 733.8$

Step 1 - Pressure at yield Py and liner projected height at yield hy are calculated by solving Conditions 6 and 7
The guess values can be approximated from the measured data in Tables X1.1 and X1.2.

$Py := 10$

$h := 0.06$

Given

$$Py = \frac{1}{\left(\frac{1}{Ea1\cdot Eh1} - S121^2\right)\cdot\left(\frac{w^2}{8\cdot h} + \frac{h}{2}\right)}\cdot\left[\frac{1}{Ea1}\cdot\left[\frac{\left(\frac{w^2}{4\cdot h} + h\right)\cdot asin\left(\frac{w}{\frac{w^2}{4\cdot h} + h}\right)}{w} - 1\right] \ldots + -S121\cdot\left[\frac{\left(\frac{L^2}{4\cdot h} + h\right)\cdot asin\left(\frac{L}{\frac{L^2}{4\cdot h} + h}\right)}{L} - 1\right]\right] \ldots$$
$$+ \frac{1}{\left(\frac{1}{Ea1\cdot Eh1} - S121^2\right)\cdot\left(\frac{L^2}{8\cdot h} + \frac{h}{2}\right)}\cdot\left[-S121\cdot\left[\frac{\left(\frac{w^2}{4\cdot h} + h\right)\cdot asin\left(\frac{w}{\frac{w^2}{4\cdot h} + h}\right)}{w} - 1\right] \ldots + \frac{1}{Eh1}\left[\frac{\left(\frac{L^2}{4\cdot h} + h\right)\cdot asin\left(\frac{L}{\frac{L^2}{4\cdot h} + h}\right)}{L} - 1\right]\right]$$

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

$$\begin{pmatrix} Py \\ hy \end{pmatrix} := Find(Py, h) \qquad \begin{pmatrix} Py \\ hy \end{pmatrix} = \begin{pmatrix} 29.645 \\ 0.058 \end{pmatrix}$$

The axial yield LPW in the liner Nay is

$$\mathrm{Nay} := \frac{1}{\frac{1}{\mathrm{Ea1}\cdot\mathrm{Eh1}} - \mathrm{S121}^2}\cdot\left[-\mathrm{S121}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot hy} + hy\right)\cdot\mathrm{asin}\left(\frac{w}{\frac{w^2}{4\cdot hy} + hy}\right)\right]}{w} - 1\right] \ldots \\ + \frac{1}{\mathrm{Eh1}}\left[\frac{\left(\frac{L^2}{4\cdot hy} + hy\right)\cdot\mathrm{asin}\left(\frac{L}{\frac{L^2}{4\cdot hy} + hy}\right)}{L} - 1\right]\right]$$

Nay = 29.455

The hoop yield LPW in the liner Nhy is

$$\mathrm{Nhy} := \frac{1}{\left(\frac{1}{\mathrm{Ea1}\cdot\mathrm{Eh1}} - \mathrm{S121}^2\right)}\cdot\left[\left[\frac{1}{\mathrm{Ea1}}\cdot\left[\frac{\left[\left(\frac{w^2}{4\cdot hy} + hy\right)\cdot\mathrm{asin}\left(\frac{w}{\frac{w^2}{4\cdot hy} + hy}\right)\right]}{w} - 1\right] \ldots \\ + -\mathrm{S121}\cdot\left[\frac{\left(\frac{L^2}{4\cdot hy} + hy\right)\cdot\mathrm{asin}\left(\frac{L}{\frac{L^2}{4\cdot hy} + hy}\right)}{L} - 1\right]\right]\right]$$

Nhy = 62.375

The radius of curvature of the liner in the axial direction is ra = 1/2 (L^2/4h + h). The strain in the axial direction, at yield, is

$$\varepsilon ay := \frac{\left(\frac{L^2}{4 \cdot hy} + hy\right) \cdot \operatorname{asin}\left(\frac{L}{\frac{L^2}{4 \cdot hy} + hy}\right)}{L} - 1$$

$\varepsilon ay = 6.329 x 10^{-3}$

The radius of curvature of the liner in the hoop direction is rh = 1/2 (w^2/4h + h). The strain in the hoop direction, at yield, is

$$\varepsilon hy := \frac{\left(\frac{w^2}{4 \cdot hy} + hy\right) \cdot \operatorname{asin}\left(\frac{w}{\frac{w^2}{4 \cdot hy} + hy}\right)}{w} - 1$$

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

ASTM F2207 Example

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 the liner tested. The guess values can be approximated from the measured data in Tables X1.1 and X1.2, as follows:

$$Pf := 100$$

$$h := 0.06$$

$$\varepsilon a := 0.005$$

$$\varepsilon h := 0.005$$

Given

$$\varepsilon a = \frac{\left(\frac{L^2}{4\cdot h} + h\right)\cdot \operatorname{asin}\left(\frac{L}{\frac{L^2}{4\cdot h} + h}\right)}{L} - 1$$

$$\varepsilon h = \frac{\left(\frac{w^2}{4\cdot h} + h\right)\cdot \operatorname{asin}\left(\frac{w}{\frac{w^2}{4\cdot h} + h}\right)}{D\cdot \operatorname{asin}\left(\frac{w}{D}\right)} - 1$$

$$Pf = \frac{\frac{1}{\left(\frac{1}{Ea2\cdot Eh2} - S122\cdot S212\right)}\cdot\left[\frac{1}{Ea2}\cdot(\varepsilon h - \varepsilon hy) - S212\cdot(\varepsilon a - \varepsilon ay)\right] + Nhy}{\frac{w^2}{8\cdot h} + \frac{h}{2}} \ldots$$

$$+ \frac{\frac{1}{\left(\frac{1}{Ea2\cdot Eh2} - S122\cdot S212\right)}\cdot\left[(-S122)\cdot(\varepsilon h - \varepsilon hy) + \frac{1}{Eh2}\cdot(\varepsilon a - \varepsilon ay)\right] + Nay}{\frac{L^2}{8\cdot h} + \frac{h}{2}}$$

$$Nhf = \frac{1}{\left(\frac{1}{Ea2\cdot Eh2} - S122\cdot S212\right)}\cdot\left[\frac{1}{Ea2}\cdot(\varepsilon h - \varepsilon hy) - S212\cdot(\varepsilon a - \varepsilon ay)\right] + Nhy$$

$$\begin{pmatrix} \varepsilon h \\ \varepsilon a \\ Pf \\ hf \end{pmatrix} := \mathrm{Find}(\varepsilon h, \varepsilon a, Pf, h)$$

$$\begin{pmatrix} \varepsilon h \\ \varepsilon a \\ Pf \\ hf \end{pmatrix} = \begin{pmatrix} 0.221 \\ 0.359 \\ 433.31 \\ 0.462 \end{pmatrix}$$

Nf is the failure LPW in the liner

$$Nh := \frac{1}{\left(\frac{1}{Ea2 \cdot Eh2} - S122 \cdot S212\right)} \cdot \left[\frac{1}{Ea2} \cdot (\varepsilon h - \varepsilon hy) - S212(\varepsilon a - \varepsilon ay)\right] + Nhy$$

Nh = 215.543

$$Na := \frac{1}{\frac{1}{Ea2 \cdot Eh2} - S122 \cdot S212} \cdot \left[(-S122) \cdot (\varepsilon h - \varepsilon hy) + \frac{1}{Eh2} \cdot (\varepsilon a - \varepsilon ay)\right] + Nay$$

Na = 52.527

X2.2 Maximum Stress Criteria Conclusion: Liner "Life tf (years) and Max Operating Pressure" [ASTM Eq. (X1.2)]

tf: = 50

Temp: = 529.67

Nahbp: = 312.8

Naabp: = 74.7

$$Nmaxhoop := Nahbp \cdot \left[0.700 \cdot tf^{-0.00402} \cdot \exp\left[41.905 \cdot \left(\frac{1}{Temp} - \frac{1}{529.67}\right)\right]\right]$$

Nmaxhoop = 215.543

C
ASME CODE CASE N-589-1 EXAMPLE

Nomenclature:

D = outside diameter, in

NS = safety factor

Pd = design pressure, psi

tr = required CIP thickness, in

σTL = long-time tensile strength of liner, psi

D = 20 in

NS = 4

Pd = 100 psi

σTL = 1500 psi

$$tr := \frac{D}{\left(2 \cdot \frac{\sigma TL}{Pd \cdot NS}\right) + 1}$$

tr = 2.353

$$RW := 1 - 0.33 \cdot \frac{Hw}{Hs}$$

Rw = 0.692

$$tbcc := tb \cdot \left(\frac{NS}{N}\right)^{\frac{1}{3}}$$

tbcc = 1.06

$$tcc := \frac{D}{\left[\frac{(2 \cdot K \cdot EL \cdot C)}{Pwp \cdot \left(1 - nu^2\right) \cdot NS}\right]^{\frac{1}{3}} + 1}$$

tcc = 0.453

D
SEISMIC STRAINS IN BURIED PIPE

Nomenclature:

A_p = net cross sectional area of pipe

C = apparent wave velocity

C_a = soil adhesion

D = pipe outer diameter

E_{sct} = secant modulus of elasticity of pipe

F_{max} = maximum force transmitted between ground and pipe

H = depth of burial to top of pipe

K_o = coefficient of soil pressure at rest

L_w = dominant wave length

PGA = peak ground acceleration

PGV = peak ground velocity

W_p = unit weight of pipe and contents

α_a = axial seismic coefficient for ground strain

α_b = bending seismic coefficient for ground strain

σ_n = average pressure between soil and pipe

γ = soil unit weight

ε_a = maximum strain transmitted between ground and pipe

$\varepsilon_{a\text{-}max}$ = maximum seismic induced axial strain in buried pipe and liner

$\varepsilon_{b\text{-}max}$ = maximum seismic induced bending strain in buried pipe and liner

$\varepsilon_{b\text{-}max}$ = maximum seismic induced bending strain in buried pipe and liner

ε_g = maximum strain in ground

Φ_a = apparent angle of pipe wall friction

κ = curvature of pipe

Maximum Total Strain

Maximum total strain in buried pipe and liner due to seismic wave passage

$\varepsilon_{max} = \varepsilon_{a\text{-}max} + \varepsilon_{b\text{-}max}$

$\varepsilon_{a\text{-}max}$ = maximum seismic induced axial strain in buried pipe and liner

$\varepsilon_{b\text{-}max}$ = maximum seismic induced bending strain in buried pipe and liner

Maximum Axial Strain

Maximum seismic induced axial strain in buried pipe and liner

$\varepsilon_{a\text{-}max} = \max \{\varepsilon_g ; \varepsilon_a\}$

Maximum strain in the ground due to passage of sinusoidal seismic wave

$$\varepsilon_g = \frac{PGV}{\alpha_a \times C}$$

C = apparent wave velocity

PGV = peak ground velocity

α_a = axial seismic coefficient for ground strain

ε_g = maximum strain in ground

Coefficient	Compression Wave	Shear Wave	Rayleigh Wave
α_a	1.0	2.0	1.0

Upper bound in long straight pipe (limited by pipe-ground break-out)

$$\varepsilon_a = \frac{F_{max} \times L_W}{4 \times E_{sct} \times A_P}$$

A_p = net cross sectional area of pipe

E_{sct} = secant modulus of elasticity of pipe

F_{max} = maximum force transmitted between ground and pipe

L_w = dominant wave length

ε_a = maximum strain transmitted between ground and pipe

$$F_{max} = \pi \times D \times (C_a + \sigma_n \times \tan \Phi_a)$$

D = pipe outer diameter

C_a = soil adhesion

σ_n = average pressure between soil and pipe

Φ_a = apparent angle of pipe wall friction

$$\sigma_n = \gamma \times H \times \frac{1 + K_o}{2} + \frac{W_p}{\pi \times D}$$

H = depth of burial to top of pipe

K_o = coefficient of soil pressure at rest

W_p = unit weight of pipe and contents

γ = soil unit weight

Maximum Bending Strain

$$\varepsilon_{b-max} = \frac{\kappa \times D}{2}$$

ε_{b-max} = maximum seismic induced bending strain in buried pipe and liner

κ = curvature of pipe

$$\kappa = \frac{PGA}{(\alpha_b \times C)^2}$$

C = apparent wave velocity

PGA = peak ground acceleration

α_b = bending seismic coefficient for ground strain

Coefficient	Compression Wave	Shear Wave	Rayleigh Wave
α_b	1.6	1.0	1.0

Example

shear wave passage

C = 2000 ft/sec

PGV = 25 in/sec

α = 2.0

$$\varepsilon_g = \frac{PGV}{\alpha \times C} = \frac{25}{2 \times (2000 \times 12)} = 0.0005 = 0.05\%$$

D = 6" pipe = 6.625 in = 0.55 ft

H = 5 ft

K_o = 1.0 max

W_p = 30.4 lb/ft

γ = 120 lb/ft^3

$$\sigma_n = \gamma \times H \times \frac{1+K_o}{2} + \frac{W_p}{\pi \times D} = 120 \times 5 \times \frac{1+1}{2} + \frac{30.4}{\pi \times 0.55} = 617 \text{ lb/ft}^2 = 4.3 \text{ psi}$$

C_a = 950 lb/ft^2 = 6.6 psi stiff soil

σ_n = 4.3 psi

Φ_a = 15 degrees, rusted steel in stiff soil

$$F_{max} = \pi \times D \times (C_a + \sigma_n \times \tan \Phi_a) = \pi \times 6.625 \times (6.6 + 4.3 \times \tan 15) = 161 \text{ lb/in}$$

A_p = 5.58 in^2 (6 in sch.40 cross section)

E_{sct} = 28 10^6 psi

F_{max} = 161 lb/in

L_w = 750 ft

ε_a = maximum strain transmitted between ground and pipe

$$\varepsilon_a = \frac{F_{max} \times L_W}{4 \times E_{sct} \times A_P} = \frac{161 \times (750 \times 12)}{4 \times (28 \times 10^6) \times 5.58} = 0.0023 = 0.23\%$$

$\varepsilon_{a\text{-max}} = \max\{\varepsilon_g ; \varepsilon_a\} = \max\{0.05\% ; 0.23\%\} = 0.05\%$

C = 2000 ft/sec

PGA = 80 in/sec^2

α_b = 1.0 shear wave

$$\kappa = \frac{PGA}{(\alpha_b \times C)^2} = \frac{80}{(1 \times 2000 \times 12)^2} = 1.4\ \ 10^{-7}\ 1/\text{in}$$

$$\varepsilon_{b-max} = \frac{\kappa \times D}{2} = \frac{1.4 \times 10^{-7} \times 6.625}{2} \approx 0$$

$\varepsilon_{max} = \varepsilon_{a\text{-max}} + \varepsilon_{b\text{-max}} = 0.05\% + 0\% = 0.05\%$

E
OTHER LINER REHABILATION TECHNIQUES

E.1 Slip Lining

Slip lining is the insertion of a new pipe (of smaller diameter) in the degraded host pipe, by pulling (winch cable) or pushing (grip). Polyethylene, fiberglass reinforced plastic, and polyvinyl chloride plastic (PVC) are commonly used as slip liners. The annular space between the slip liner and the host pipe can be grouted, which provides two benefits:

- The grout prevents infiltration of ground water
- The grout reinforces the liner

The slip liner can provide full structural strength. The issue is loss of flow area.

Figure E-1
Slip Lining of Pipe

Source: Flexpipe Systems

One variation of the slip liner is a woven product that can be sized for internal pressures up to 250 psi. It has no strength for bending loads or external pressure. The Insituform product is called Thermopipe. Diameters are currently limited to ~12" (limiting factor is development cost versus market size). One option for small to mid diameter pipes under high pressure might be to use a combination of two products: a CIP Liner to resist bending moments and external pressure (e.g., ground water, soil pressure, traffic) and the woven type slip lining to withstand high internal pressures.

E.2 Modified Slip Lining Folded U-Liner

A butt-fused polyethylene pipe is folded and strapped into a U-shape liner and pulled into the host pipe. Once in place, the U-shaped liner is pressurized, snapping its straps to revert back to its circular cross section, forming a close fit with the host pipe. Folding can be done on site or in factory with the liner shipped to the site folded and rolled.

The lining is limited in thickness, thus a folded u-liner is usually not structural (pressure boundary only)

Figure E-2
PE Liner Pulled Through Former

Source: Proline Technologies

Figure E-3
Strapped PE Pipe Ready for Insertion

Source: Proline Technologies

E.3 Modified Slip Liner Diameter Reduction

A butt-fused PE pipe is pulled through rollers which neck down the pipe to a slightly lower diameter to allow it to be pulled into the host pipe. Once in place, the tension applied to the liner is released. The liner recovers its original diameter, forming a close fit with the host pipe.

Current diameter reduction machines are limited to a pipe thickness of ~1” which equates to ~150 psi for diameters up to 24”, less for larger diameters. The liner can provide full structural strength.

Figure E-4
Roll-Down System

Source: Proline Technologies

Figure E-5
Roller Reduction Box

Source: United Pipeline Systems

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3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94304-1338 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com