DESIGN CONSIDERATIONS

X1.1 Terminology:

X1.1.1 Filament reinforced lining—A lining made of reinforced lining materials with high tensile strength filament, such as carbon fiber and glass fiber. The reinforcement filaments are used to prevent creep rupture of lining materials and significantly increase the lining structure strength and creep resistance along the hoop and longitudinal directions.

Note X1.1 The composite lining in this document is specifically referred to Manufactured In-place Composite Pipe (MICP). MICP is a Close Fit Lining (CFL) which is reinforced by helically wound continuous carbon fiber. The fiber is designed and orientated that it will mainly reinforce the lining strength in hoop direction. MICP can also be reinforced with axially applied continuous carbon fiber in addition to helical orientation.

X1.2 Working Load Consideration of Manufactured In-place Composite Pipe (MICP)

X1.2.1 Note to designer: The design strategy of composite lining is to consider all the applicable working scenarios and determine the required lining thickness under each condition, then use the maximum thickness value of calculation results to finalize the design. The following design considerations are inclusive of equations for a multitude of installation environments and/or parameters. Designers should be aware that not all the equations are applicable to each specific project. The designer is advised that each project should be examined on case by case basis in an effort to avoid utilizing these design considerations as ‘standardized design methodology’. Designing for external loading on the lining system exemplifies this advisory. If the designer can assess or assume that the existing host pipe has a high probability continuing to either fully or partially resist external loading during and after the expected design life of the lining system, then the designer shall utilize proper equations provided in this design consideration to afford the most cost and time effective solution. By example, typically reinforced concrete pressure pipe’s failure mode is the fracturing wires therein reducing its resistance to internal pressure and conversely, little or no deterioration to the concrete cylinder has occurred. In this instance the designer needs to consider that there is a high probability the pipe will continue to resist soil loads and probably external water loads as well for the design life of the lining. Therefore, in such instances the designer should reduce or sometimes even eliminate the buckling forces on the liner system or in some cases simply decrease the safety factor for external loading. This also should be considered by the designer for steel and cast-iron pipes when external corrosion has not been a failure mode.
of the existing host pipes. These design considerations have been made inclusive of equations and descriptions thereof to facilitate liner design for any working condition and the designer shall consider all factors on a case by case basis for each lining project.

X1.2.2 The lining design shall consider the lining movement and thermal stress caused by the fluctuations of lining working temperature if applicable.

X1.2.3 Semi-structural MCIP is an interactive lining bonded to the host pipe internal diameter whose hoop strength may be less than that required to support the maximum operating pressure (MOP) for the pressure pipe, but that can withstand abrasion and independently withstand vacuum, and pressure loads at holes or gaps. Structurally independent linings need to hold external hydrostatic loads due to groundwater, soil, and live load if applicable, as well as, withstand the long-term internal pressure, all scenarios are independent of the host pipe. The distribution and orientation of reinforcement fiber in the composite have a major influence on the overall material strength of the lining. With respect to orientation, since the major stress on most of the pipes is along the pipe hoop direction, the fiber filaments shall be oriented close to the lining hoop direction as shown in Figure X 1 to maximize the composite lining structure strength. If fiber filament winding is applied to reinforce the lining material, the lining must have enough wall thickness and
strength to withstand the bending and shear stresses caused by the fiber constrains and internal pressure on the unreinforced areas of the lining material.

![Diagram of Carbon fiber filament winding reinforced composite lining](image)

**Figure X1.1: Carbon fiber filament winding reinforced composite lining**

X1.2.4 Additionally, the lining thickness must also be verified to ensure the lining has enough strength to withstand the axial stresses caused by Poisson’s ratio effect and thrust load. If the lining is not supported or surrounded with soil but suspended as beam structures, the lining thickness must also be verified for overcoming the bending stress, shear stress, and buckling caused by gravity.

Note X1.2 —The lining may have different thicknesses and physical properties due to the type and amount of filament reinforcement. The supplier shall submit design calculations to the user for review and approval. Suppliers shall submit test results from third-party organization for all required material tests for the completion of lining thickness calculus. All calculus inputs shall be equivalent to all corresponding testing data provided by third-party organization.

X1.3 Thermal Stress Effect

X1.3.1 If MICP is to be immersed in fluids over 120 °F, the thermal expansion and stress shall be verified for the lining system. MICP shall be designed to accommodate axial movement due to temperature fluctuations, when applicable:

\[ L_C = \alpha \cdot L \cdot \Delta T \] (X1.1)
where: \( L_C \) = length change of the lining system, in (mm),
\( L \) = continuous length of the installed lining system, in (mm),
\( \alpha \) = coefficient of thermal expansion and contraction in/in/°F (mm/mm/°C) per Test Method E289,
\( \Delta T \) = temperature fluctuations, °F (°C).

X1.3.2 MICP that is affixed at the ends of the host pipe or bonded to the host pipe shall be checked for thermal stresses when applied in a working environment with temperature fluctuations that exceed normal ambient or processing temperatures. The lining system must have sufficient tensile/compression strength to withstand the thermal stress.

\[
\sigma_{TL} \geq \alpha \cdot E_{TL} \cdot \Delta T
\]

where: \( E_{TL} \) = long-term tensile modulus of elasticity of rigid lining material under normal working temperature (psi) per Test Method D2990,
\( \sigma_{TL} \) = long-term tensile strength of rigid lining material at maximum working temperature (psi) per Test Method D2990.

Note X1.3 — If the working temperature is over 100°F, the lining material properties under elevated working temperature shall be tested and used in the design consideration.

X1.4 Semi-Structural MICP

X1.4.1 Lining Buckling Resistance for Hydraulic Load

X1.4.1.1 Semi-structural MICP is designed to support the hydraulic loads due to groundwater, since the soil and surcharge loads can be supported by the original pipe. The groundwater level shall be determined by the user and the thickness of the MICP shall be sufficient to withstand this hydrostatic pressure without collapsing. The lining thickness shall be determined as

\[
t_{1a} = \frac{D}{\sqrt[3/3]{\left(\frac{2KE_{LC}}{N_e(p_{water}+p_v)}\right)^{1/3}+1}}
\]

where: \( t_{1a} \) = minimum thickness of rigid lining material for overcoming the hydrostatic load, in (mm),
\( p_v \) = vacuum pressure, psi (Mpa),
\( N_e \) = design factor of safety for external load,
$K$ = enhancement factor of the soil and existing host pipe adjacent to the new lining (a minimum value of 7.0 is recommended where there is full support of the existing pipe),

$D$ = inside diameter of host pipe, in. (mm),

$\nu$ = Poisson’s ratio of the lining material (dimensionless) per Test Method D638,

$E_L$ = long term flexural modulus of elasticity of SIPP rigid lining material at maximum working temperature (psi),

$C$ = ovality reduction factor (dimensionless), $C = \left(\frac{1-q/100}{[1+q/100]^2}\right)^3$

$P_{water}$ = hydrostatic pressure, $P_{water} = \frac{\delta_w (H_w + D/2)}{144}$

$H_w$ = Height of groundwater above the host pipe, ft (m),

$\delta_w$ = water density, lb/ft$^3$(KN/m$^3$).

X1.4.2 Lining Thickness for Perforations on Host Pipe

X1.4.2.1 Semi-structural MICP is designed to withstand the internal pressure in spanning across any holes or perforations in the host pipe. The minimum required lining thickness shall be determined as

$$t_{2a} = \frac{D}{\left[\left(\frac{B}{d}\right)^2\left(\frac{33\sigma_L}{PN_i}\right)\right]^Z + 1}$$

where:

$t_{2a}$ = minimum thickness of rigid lining material for overcoming the internal load, in (mm),

$\sigma_L$ = long-term flexural strength of rigid lining material per Test Method D790, psi (MPa),

$N_i$ = design factor of safety for internal load,

$d$ = diameter of hole or perforation on host pipe, in. (mm),

$P$ = internal pressure load inside host pipe, psi (MPa).

X1.4.2.2 The thickness $t_{2a}$ shall be verified to meet the following requirement in Eq. X1.5 to ensure the MICP provides a circular flat plate fixed at the edge and it is subject to transverse pressure only. If the hole or perforation size does not meet the requirement, the lining cannot be
considered in flat plate loading but in ring tension or hoop stress, then the lining shall be designed as structurally independent lining.

\[
\frac{d}{D} \leq 1.83 \left(\frac{t_{2a}}{D}\right)^{1/2}
\]

(X1.5)

X1.5 Structurally Independent MICP

X1.5.1 Lining Buckling Resistance for External Load

X1.5.1.1 The external pressure on host pipe caused by live load and water should be calculated as

\[
q_t = 0.433 \cdot (H_w + \frac{D}{12}) + \frac{\delta_s H R_w}{144} + W_s
\]

(X1.6)

Where:

- \( q_t \) = total external pressure on pipe, psi (Mpa),
- \( \delta_s \) = unit weight of soil overburden, lb/ft\(^3\) (KN/m\(^3\)),
- \( H \) = depth from ground surface to top of pipe, ft (m),
- \( R_w \) = water buoyancy factor = 1 - 0.33(Hw/H) (≥ 0.67),
- \( W_s \) = live load, psi (MPa).

Note X1.4 —Live load can be calculate based on AASHTO Standard Specifications for Highway Bridges, 12th Edition.

X1.5.1.2 Vacuum pressure shall also be considered for lining buckling resistance calculation if applicable. If the host pipe will be around to provide rigid encasement to the lining during the design/service life and water can infiltrate into the host pipe through cracks or other defects on the pipe wall, the lining will be exposed to external load caused by water and vacuum pressure only and the minimum lining thickness for overcoming the external load shall be calculated as

\[
t_{1b1} = D \left[ \frac{(0.433(H_w + \frac{D}{12}) + P_v)N_e(1-v^2)}{E_{CL} \cdot C} \right]^{1/2}
\]

(X1.7)

where:

- \( t_{1b1} \) = minimum thickness of rigid lining material for overcoming the buckling force when lining is encased with rigid host pipe, in (mm),
- \( E_{CL} \) = long-term flexural modulus of elasticity of MICP material, dependent on the existence of filament or fabric reinforcement, psi (MPa).
Note X1.5 — If the host pipe will always exist and provide rigid encasement to the lining during the design/service life, as well as, the lining is closely bonded to the pipe interior and no water/air will infiltrate through host pipe wall to apply external pressure to the lining external surface, the lining will not be exposed to any external pressure load during the design/service life. Therefore, in the lining design consideration the designers do not need to consider the buckling of lining caused by external load or the designers can simply reduce the safety factor to optimize the lining design and save lining material and cost.

X1.5.1.3 If the host pipe is or will be fully deteriorated and the MICP will be supported by surrounding soil during the design/service life, the minimum lining thickness for overcoming the external load shall be calculated as

\[ t_{1b2} = \left( \frac{\left[ (q_L + P_V) N_p \right]^2 D^3 \cdot 12}{32 \cdot R_W \cdot B^3 \cdot M_{sn} \cdot E_{CL} \cdot C} \right)^{1/3} \]  

(X1.8)

where:
- \( t_{1b2} \) = minimum thickness of rigid lining material for overcoming the buckling force when lining is surrounded with soil, in (mm),
- \( M_{sn} \) = constrained soil modulus, psi (Mpa),
- \( B' \) = coefficient of elastic support = \( 1/(1+4e^{-0.065H}) \).

X1.5.1.4 If the lining is not surrounded with soil or any constrain support but immersed with fluid, the minimum lining thickness for overcoming the external load shall be calculated as

\[ t_{1b3} = \left[ \frac{4 N_p (q_L + P_V) (1 - \nu^2)}{(1 - S_r) E_{CL}} \right]^{1/3} \frac{D}{2} \]  

(X1.9)

where:
- \( t_{1b3} \) = minimum thickness of rigid lining material for overcoming the buckling force when lining is not surrounded with soil, in (mm),
- \( S_r \) = geometrical imperfection reduction factor, the default value is 0.4.

X1.5.1.5 The long-term flexural modulus of elasticity of MICP material is dependent of the rigid lining material thickness and reinforcement filament inside the lining. The flexural modulus shall be determined as

\[ E_{CL} = f E_L = \frac{E_L L_{pp} t_b^3 + 4 A_f E_f t_b^2 - 12 A_f E_f t_c t_b + 12 A_f E_f t_c^2}{t_b^2 (A_f E_f + E_L L_{pp} t_b)} E_L \]  

(X1.10)

where:
- \( f \) = reinforcement factor of flexural modulus,
- \( L_{pp} \) = overall filament pitch of reinforcement fiber under tension when lining material deflect or bend,
- \( t_b \) = rigid lining material thickness,
\[ E_f = \text{fiber tensile modulus per Test Method C1557, psi (Mpa)}, \]
\[ A_f = \text{fiber cross section area, in}^2. \text{ (mm}^2), \]
\[ t_c = \text{overall distance between lining surface and reinforcement fiber under tension.} \]

X1.5.2 Lining Resistance for Internal Pressure Load

X1.5.2.1 If the lining has no reinforcement filaments in the structure, the minimum lining thickness for overcoming the maximum allowable operating pressure (MAOP) shall be obtained as (this equation is only for comparison purposes of reinforced and unreinforced lining systems for designer’s discretion):

\[
t_{2b1} = \frac{D}{\frac{2\sigma_{TL}}{F.N_i} + 1} \quad (X1.11)
\]

where: \( t_{2b1} \) = minimum thickness of rigid lining material for overcoming MAOP without filaments reinforcement, in. (mm).

X1.5.2.2 If the lining is reinforced with filament winding in the structure, the minimum lining thickness for overcoming the maximum allowable operating pressure (MAOP) shall be obtained as

\[
t_{2b2} = \frac{N_i PDL_p - 2 \min(E_f A_f \varepsilon_{\theta_{\max}}, A_f \sigma_f)}{[2L p \min(E_{TL} (\varepsilon_{\theta_{\max}} + \varepsilon_{\theta_S}), \sigma_{TL}) + N_i P L_p]} \quad (X1.12)
\]

where: \( t_{2b2} \) = minimum thickness of rigid lining material for overcoming MAOP with filaments reinforcement, in. (mm),

\( L_p \) = overall fiber winding pitch distance, in. (mm),

\( \varepsilon_{\theta_{\max}} \) = maximum allowable tensile strain of the filament fiber, per Test Method C1557,

\( \sigma_f \) = carbon fiber tensile strength per Test Method C1557, psi (Mpa),

\( \varepsilon_{\theta_S} \) = material shrinkage in curing process per Test Method D6289, in/in. (mm/mm).

Note X1.6 — The equation offered is useful when continuous fibers are circumferentially wound and oriented on host pipe. Modifications may be required if the filament winding angle is beyond certain range.
X1.5.2.3 Bending stress with filament reinforcement—If the lining material is combined with a reinforcing filament winding, when the lining is loaded under internal pressure the lining material between the filament pitches will be under bending along the radial direction. The minimum material thickness for overcoming the stress caused by bending shall be determined by the following equation:

\[ t_{2b3} = \sqrt{\left(\frac{N_i P}{2 \sigma_l}\right) L_p} \]  \hspace{1cm} (X1.13)

where: \( t_{2b3} \) = minimum thickness of rigid lining material for overcoming the maximum allowable bending stress, in. (mm),

Note X1.7 —The equation X1.13 is applicable wherein there is potential for bending stress event to govern SIPP lining material thickness determination.

X1.5.2.4 Shearing stress with filament reinforcement—If the lining material is combined with a reinforcing filament winding, when working under internal pressure shear stress will be imposed on the unconstrained lining material. The minimum thickness of the lining material for overcoming shear stress shall be determined by the following equation:

\[ t_{2b4} = N_i \frac{\tau_L D - \sqrt{\tau_L^2 D^2 - 4 \tau_L \sigma_{\theta_{\max}} E_f A_f}}{\tau_L} \]  \hspace{1cm} (X1.14)

where: \( t_{2b4} \) = minimum thickness of rigid lining material for overcoming the maximum allowable shear stress, in. (mm),

\( \tau_L \) = long-term shear strength of lining material at maximum working temperature, psi (Mpa), \( \tau_L = LR^* \tau \),

\( \tau \) = Shear strength of lining material, initial at maximum working temperature, psi (Mpa), per Test Method D732,

\( LR \) = Long-term retention of mechanical properties at maximum working temperature (%), \( LR = \sigma_T / \sigma_{T L} \), \( \sigma_T \) = Tensile strength of the lining material, initial at maximum working temperature, psi (Mpa).

Note X1.8 —The equation X1.14 is applicable wherein there is potential for shear stress event to govern the lining material thickness determination.
X1.5.2.5 Poisson’s Ratio Effect—As the lining material is pressurized, it stretches radially and shrinks lengthwise because of the Poisson’s ratio effect. Therefore, if the lining material is affixed to the pipe at the two or more locations, the internal pressure load can cause stress along axial direction. The minimum lining thickness for withstanding the axial stress shall be determined as

\[(4\sigma_{TL} + 8\nu N_i P) t_{2b5}^2 - (8\nu N_i PD + 4D \sigma_{TL}) t_{2b5} + 2\nu N_i PD^2 = 0\]  

where:

\[a = (4\sigma_{TL} + 8\nu N_i P)\]

\[b = -(8\nu N_i PD + 4D \sigma_{TL})\]

\[c = 2\nu N_i PD^2\]

\[t_{2b5} = \frac{-b - \sqrt{b^2 - 4ac}}{2a}\]

where: \(t_{2b5}\) = minimum thickness of rigid lining material as determined by Poisson's effect, in. (mm).

X1.5.2.6 Thrust Load Effect—If the lining is not fixed at the ends or elbows, the lining system will be subjected to thrust load caused by internal pressure, the minimum lining thickness shall be determined as

\[t_{2b6} = \frac{D}{\sqrt{\frac{\sigma_{TL}D^2}{N_i P + \sigma_{TL}}} + \frac{12D^2 \sigma_{TL}}{l_{sp}^2 N_e}}\]  

where:

\(t_{2b6}\) = minimum thickness of rigid lining material for withstanding thrust load, in. (mm).

X1.5.3 Suspended Pipe Lining

X1.5.3.1 If the pipe is suspended, bending moments will happen on the lining system between the supports due to gravity. The minimum lining thickness for withstanding the stress on lining material caused by bending moment can be determined as

\[4(\rho_m - \rho_l) t_{3b1}^2 + \left(4\rho_l D - 4\rho_m D - \frac{12D^2 \sigma_{TL}}{l_{sp}^2 N_e}\right) t_{3b1} + \rho_m D^2 = 0\]  

\[a = 4(\rho_m - \rho_l)\]

\[b = \left(4\rho_l D - 4\rho_m D - \frac{12D^2 \sigma_{TL}}{l_{sp}^2 N_e}\right)\]

\[c = \rho_m D^2\]
\[ t_{3b1} = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \]

where:
\( t_{3b1} \) = minimum thickness of rigid lining material for withstanding stress caused by bending moment, in. (mm).

\( \rho_l \) = lining material density, lb/in\(^3\) (KN/m\(^3\)),

\( \rho_m \) = conveyed material (liquid or gas) density, lb/in\(^3\) (KN/m\(^3\)),

\( L_{sp} \) = suspended lining length, ft (m).

X1.5.3.2 Gravity and bending moment on the lining can also result in buckling of lining material wall. The minimum lining thickness for providing required buckling resistance can be determined as

\[ 4 \left( \rho_m - \rho_l - \frac{6D\psi E_{TL}}{t_{3b2}^2 N e \sqrt{3(1-\nu^2)}} \right) t_{3b2}^2 + (4\rho_l D - 4\rho_m D)t_{3b2} + \rho_m D^2 = 0 \quad \text{(X1.18)} \]

\[ a = 4 \left( \rho_m - \rho_l - \frac{6D\psi E_{TL}}{t_{3b2}^2 N e \sqrt{3(1-\nu^2)}} \right) \]
\[ b = (4\rho_l D - 4\rho_m D) \]
\[ c = \rho_m D^2 \]
\[ t_{3b2} = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \]

where:
\( t_{3b2} \) = minimum thickness of rigid lining material for withstanding lining wall buckling caused by gravity, in. (mm),

\( \psi \) = knockdown factor or reduction factor.

X1.5.3.3 Gravity on the lining will cause shear stress on the lining material. The minimum lining thickness for overcoming the shear stress can be determined as

\[ 4(\rho_m - \rho_l)t_{3b3}^2 + \left( 4\rho_l D - 4\rho_m D - \frac{4D\tau_{TL}}{L_{sp} N e} \right)t_{3b3} + \rho_m D^2 = 0 \quad \text{(X1.19)} \]

\[ a = 4(\rho_m - \rho_l) \]
\[ b = \left( 4\rho_l D - 4\rho_m D - \frac{4D\tau_{TL}}{L_{sp} N e} \right) \]
\[ c = \rho_m D^2 \]
\[ t_{3b3} = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \]
where: \( t_{3b2} \) = minimum thickness of rigid lining material for withstanding lining wall buckling caused by gravity, in. (mm),

\( \psi \) = knockdown factor or reduction factor.

X1.6 Flow Capacity Calculation

X1.6.1 Flow Capacity Calculation of Portable Water Main—Uniform pipe flow rate over the lining materials in potable water mains is calculated by the Hazen–Williams Equation using the physical properties of the pipe.

\[
Q_1 = kC_{hw}R^{0.63}S^{0.54} \times A
\]  

(X1.20)

where: 

\( A \) = flow area, ft\(^2\) (m\(^2\)),

\( Q_1 \) = flow rate obtained using Hazen-Williams equation, ft\(^3\)/s (m\(^3\)/s),

\( k \) = conversion factor for the unit system (k = 1.318 for US customary units, k = 0.849 for SI units),

\( C_{hw} \) = roughness coefficient,

\( R \) = hydraulic radius, ft (m),

\( S \) = slope of the energy line, ft/ft (m/m).

X1.6.2 Flow Capacity Calculation of Non-Portable Water Main—Uniform pipe flow rate over the lining materials in other applications exclusive of potable water mains is calculated by the Manning’s Equation with the flow area and pipe slope.

\[
Q_2 = \frac{1.486}{n} AR_H^{2/3} S^{1/2}
\]  

(X1.21)

where: 

\( Q_2 \) = flow rate obtained using Manning’s equation, ft\(^3\)/s (m\(^3\)/s),

\( n \) = Manning’s Roughness Coefficient,

\( R_H \) = hydraulic radius, ft (m), \( R_H = D/4 \) for pipe flowing full.

X1.7 Lining Design Summary—Eqs. X1.1-1.2 can be used to determine the thermal effects on the lining. Semi-structural lining shall be designed using Eqs. X1.3-1.5 to withstand the external hydrostatic pressure and internal pressure over perforations. For structurally independent lining, the lining material installed in a pressure pipe is designed to withstand all external loads and the...
full internal pressure. Eqs. X1.6-1.10 shall be used to calculate the overall external load and the minimum thickness of rigid lining material for required lining buckling resistance. Eqs. X1.11-1.16 shall be applied to determine the required thickness of rigid lining material for internal pressure load. If the lining is not surrounded with soil but suspended, Eqs. X1.17-1.19 shall be used for the design consideration of lining thickness to overcome the normal and shear stresses on lining caused by gravity and also provide enough buckling resistance for the lining. Eqs. X1.20-1.21 shall be used to predict the flow capacity of the host pipe after the lining is applied. In general, designers shall always calculate the required lining thickness for overcoming external and internal pressure loads. Particular cases, such as thermal effect and stresses on lining caused by gravity may be considered if applicable or required by the user. Advanced design requirements, such as lining fatigue and service life under cyclic load or frequently changing loading conditions, need special design consideration and it is currently not included in this document.
X2.CHEMICAL&CORROSIVE-RESISTANCE TESTS

X2.1  **Scope:**

X2.1.1  This appendix covers the test procedures for chemical-resistance and corrosive-resistance properties of SIPP lining materials. Minimum standards are presented for standard pipe applications.

X2.2  **Procedure for chemical & corrosive-resistance testing:**

X2.2.1  Chemical resistance tests shall be completed in accordance with Practices D543. Exposure shall be for a minimum of one month at 73°F (23°C). During this period, the SIPP lining material test specimens shall lose no more than 20% of their initial flexural strength and flexural modulus when tested in accordance with Section 8 of this practice.

X2.2.2  Leach tests for health effects of drinking water system shall be completed in accordance with NSF/ANSI 61. Any chemicals that leach from lining materials into drinking water shall be analyzed and a toxicological evaluation of chemical concentrations shall be evaluated to ensure that they are below levels that may cause potential adverse human health effects. For applications other than standard pipelines, it is recommended that chemical-resistance tests be conducted with actual samples of the fluid flowing in the pipe. These tests can also be accomplished by depositing lining material test specimens in the active pipe.

X2.2.3  For sewer force mains applications, Table X2.1 presents a list of chemical solutions that serve as a recommended minimum requirement for the chemical-resistant properties of lining material in standard sanitary sewer applications.

X2.2.4  For gas pipe application, the jacket and the elastomer skin materials shall be compatible with the liquids listed in Table X2.2 and tested in accordance with Practice D543, Practice A, Procedure I. Neither tensile strength nor elongation of any of the components shall change more than 20%. Weight of the test specimen after testing shall not have increased by more than 14% or decreased by more than 3%. This test shall be a qualification test to be performed once for each class or pressure rating of installed pipe lining.

*Note X2.1 —These tests are only an indication of what will happen because of short-term exposure to these chemicals. For long-term results, additional testing is required.*
### TABLE X2.1 Minimum Chemical Resistance Requirements for Sewer Applications

<table>
<thead>
<tr>
<th>Chemical Solution</th>
<th>Concentration, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water (pH 6–9)</td>
<td>100</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>5</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>10</td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>10</td>
</tr>
<tr>
<td>Gasoline</td>
<td>100</td>
</tr>
<tr>
<td>Vegetable oil</td>
<td>100</td>
</tr>
<tr>
<td>Detergent</td>
<td>0.1</td>
</tr>
<tr>
<td>Soap</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### TABLE X2.2 Chemical Resistivity List of Reagents for Gas Application

<table>
<thead>
<tr>
<th>Liquids</th>
<th>Test Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (External and Internal)</td>
<td>Freshly prepared distilled water (in accordance with Practice D 543)</td>
</tr>
<tr>
<td>Gasoline (External)</td>
<td>Gasoline-Automotive Spark-Ignition Engine Fuel per Specification D4814</td>
</tr>
<tr>
<td>Gas Condensate (Internal)</td>
<td>70 % volume isooctane + 30 % volume toluene</td>
</tr>
<tr>
<td>Methanol</td>
<td>20 % volume methanol + 80 % volume distilled water</td>
</tr>
<tr>
<td>Triethylene Glycol</td>
<td>10 % volume triethylene glycol + 90 % volume distilled water</td>
</tr>
<tr>
<td>Brine Solution</td>
<td>10 % mass NaCl solution made up with a balance of distilled water</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>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</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>10 % volume isopropanol + 90 % volume distilled water</td>
</tr>
<tr>
<td>Sulfuric Acid</td>
<td>5 % weight (of total solution) H$_2$SO$_4$ in distilled water</td>
</tr>
<tr>
<td>Surfactants</td>
<td>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</td>
</tr>
<tr>
<td>Mercaptans</td>
<td>2 % volume tertiary butyl mercaptan + 98 % volume mineral oil, white, USP</td>
</tr>
</tbody>
</table>
Explanation of Equation Derivations

This document explains the majority derivation process of the equations in the Appendix X1.

1. **Equation X1.1**

   [Diagram: Change in length of a rod due to thermal expansion.]

   Linear expansion means change in one dimension (length) as opposed to change in volume (volumetric expansion). To a first approximation, the change in length measurements of an object due to thermal expansion is related to temperature change by a "linear expansion coefficient". It is the fractional change in length per degree of temperature change. Assuming negligible effect of pressure, we may write

   \[ \alpha = \frac{1}{L} \frac{dL}{dT} \]

   where \( L \) is a particular length measurement and \( T \) is the rate of change of that linear dimension per unit change in temperature.

   The change in the linear dimension can be estimated to be

   \[ \Delta L = \alpha \Delta TL \]

   This equation works well if the linear-expansion coefficient does not change much over the change in temperature \( \Delta T \), and the fractional change in length is small \( \Delta L/L \ll 1 \). If either of these conditions does not hold, the equation must be integrated.

2. **Equation X1.2**

   Material will expand or contract depending on the material's thermal expansion coefficient. If the material is free to move, the material can expand or contract freely without generating stresses. Once this material is attached to a rigid body at one end, thermal stresses can be created. This
stress is calculated by multiplying the change in temperature, material's thermal expansion coefficient and material's young's modulus (see formula below). $E_L$ is young's modulus, $\alpha$ is thermal expansion coefficient, $T_o$ is temperature original, and $T_f$ is the final temperature.

$$\sigma = E_L \alpha (T_o - T_f) = E_L \alpha \Delta T$$

As the temperature increases the stress will be in compression due to the constraints, this is when $T_f$ is greater than $T_o$. The opposite happens which cooling, when $T_f$ is less than $T_o$, the stress will be in tension.

3. **Equation X1.3**

This equation is derived from Eq. X1.1 in ASTM F1216 Appendix X1.

4. **Equation X1.4**

This equation is derived from Eq. X1.6 in ASTM F1216 Appendix X1.

5. **Equation X1.5**

This equation is from Eq. X1.5 in ASTM F1216 Appendix X1.

6. **Equation X1.6**

This equation is from Eq. X1.3 in ASTM F1216 Appendix X1.

7. **Equation X1.7**

This equation is derived from Glock’s equation:

$$P_e = \frac{E_L}{1 - \nu^2} \left( \frac{t}{D} \right)^{2.2}$$

Where: $D =$ host pipe inside diameter (in)

$E_L =$ lining material long-term modulus (psi)

$t =$ lining thickness (in)

$\nu =$ lining material Possion’s ratio

$P_e =$ external load on the lining (psi)
Consider the safety factor and geometry imperfection of ovality, Glock’s equation can be modified as
\[ N_e P_e = \frac{C E_L}{1 - v^2} \left( \frac{t}{D} \right)^{2.2} \]

Where: \( C = \) ovality reduction factor
\[ C = \left[ 1 - \frac{q}{100} \left( 1 + \frac{q}{100} \right)^2 \right]^3 \]
\( q = \) percentage ovality of original pipe (see F1216 for more details)
\( N_e = \) safety factor

8. **Equation X1.8**

Most buried pipe design uses the Luscher’s buckling equation:
\[ N_e P_e = \frac{2 (B/R_w M_{sn} E_L I)^3}{R^{1.5}} \]
\[ B' = 1 / (1 + 4 e^{-0.065 H}) \]
\[ R_w = 1 - 0.33 \left( \frac{H_w}{H} \right) \]
\[ I = t^3/12 \]

Where: \( B' = \) coefficient of elastic support
\( R_w = \) water buoyancy factor (≥ 0.67)
\( I = \) moment of inertia of pipe wall \( t^3/12 \)
\( R = \) pipe radius (in)
\( M_{sn} = \) constrained soil modulus (psi)
\( H_w = \) height of water above top of pipe (ft)
\( H = \) height of soil above top of pipe (ft)
\( N_e = \) safety factor
\( P_e = \) external load on the lining (psi)
By considering the safety factor, the minimum required lining thickness for buckling can be derived from Luscher’s buckling equation as

\[
t = \left[ \frac{(P_e \cdot N_e)^2 \cdot D^3 \cdot 12}{32 \cdot R_W \cdot B' \cdot M_{sn} \cdot E_L \cdot C} \right]^{\frac{1}{3}}
\]

This equation is also available in ASTM F1216 Appendix X1, Eq. X1.3.

9. Equation X1.9

If the lining is not surround and supported by soil, the lining can be assumed as a long free pipe, the buckling equation of a long pipe can be expressed as

\[
N_e P_{cr} = \frac{E_L}{4(1 - v^2)} \left( \frac{t}{R} \right)^3
\]

\(P_{cr}\) is the buckling pressure, \(N_e\) is safety factor. If consider the geometry imperfection, the equation can be modified as

\[
N_e P_{cr} = \frac{E_L}{4(1 - v^2)} \left( \frac{t}{R} \right)^3 (1 - S_r)
\]

\(S_r\) is the geometry imperfection factor which is equal to 0.4 in default (the most severe situation of eccentricity, non-uniform thickness, ovality, etc).

Assume that \(P_{cr} = q + P_v\), from the equations above the minimum lining thickness without soil support for overcoming buckling pressure can be derived as

\[
t = \left[ \frac{4N_e(q + P_v)(1 - v^2)}{(1 - S_r)E_L} \right]^{1/3} D \frac{1}{2}
\]

Where: \(q = \text{external load on the lining (psi)}\)

\(P_v = \text{vacuum pressure (psi)}\)

\(P_e = \text{external load on the lining (psi)} (P_{cr} = P_e = q + P_v)\)

10. Equation X1.10

This equation shows the influence of filament reinforcement on the flexural modulus of composite lining. As shown in the follow figure, MICP will deflect when under external pressure. The major
The bending of the lining wall happens at the poles of the long axial of the elliptical shape. The lining material can be considered as a beam under bending for simplification purposes.
If filament reinforcement is added in the lining, the flexural modulus of lining material will increase, and the lining will have lower deflection. It is assumed that the reinforcement filament only increases material strength under tension, fiber and lining material are bonded together and there is no slipping between these two components.

Assume that $\sigma$ is the stress caused by bending and $\sigma = a \cdot t$. The beam width, which is along the pipe axial direction, is under unit length $w = 1$. The bending moment on the beam can be divided as three components:

$$M_1 = \int_0^{h-h_0} t \cdot at \, dt = \frac{a}{3} (h-h_0)^3$$

$$M_2 = \int_0^{h_0} t \cdot at \, dt = \frac{a}{3} (h_0)^3$$

$$M_3 = F_f (h_0 - t_c)$$

$$M = M_1 + M_2 + M_3$$

Where $F_f = \text{tensile force provided by fiber}$, $F_f = \sigma_f \cdot A_f \cdot n$

$\sigma_f = \text{tensile stress on the fiber}$

$A_f = \text{fiber cross section area, in}^2. \text{ (mm}^2)$

$n = \text{fiber amount in unit width of pipe, } n = 1/L_p$

Since the fiber and rigid lining material are bonded together, fiber and rigid material shall have the same tensile strain, thus
\[ \varepsilon_f = \varepsilon, \sigma = E \cdot \varepsilon, \sigma_f = E_f \cdot \varepsilon_f \quad \text{yields} \quad \sigma_f = \frac{E_f}{E} \cdot \sigma \]

At the location of the filament, the stress on the rigid lining material becomes

\[ \sigma = a \cdot t = a(h_0 - t_c) \]

Thus

\[ \sigma_f = \frac{E_f}{E} \cdot \sigma = \frac{E_f}{E} \cdot a(h_0 - t_c) \]

\[ F_f = \sigma_f \cdot A_f \cdot n = \frac{E_f}{E} \cdot a(h_0 - t_c) \cdot A_f \cdot n \]

From the equilibrium of force, the tension and compression forces on the beam cross section shall equal to each other

\[ F_R = F_L + F_f \]

\[ \frac{a}{2} (h - h_0)^2 = \frac{a}{2} (h_0)^2 + \frac{E_f}{E} \cdot a(h_0 - t_c) \cdot A_f \cdot n \]

From this equation it can be obtained that

\[ h_0 = \frac{E L_p h^2 + 2 A_f E_f t_c}{2 A_f E_f + 2 E L_p h} \]

Since \( M = M_1 + M_2 + M_3 \), the slope \( a \) can be derived as

\[ a = \frac{12 M (A_f E_f + E L_p h)}{E L_p h^4 + 4 A_f E_f h^3 - 12 A_f E_f h^2 t_c + 1212 A_f E_f h t_c^2} \]

The unreinforced area moment of inertia of the beam was

\[ I = \frac{w h^3}{12} \]

The new area moment of inertia of the beam becomes

\[ I' = \int_0^1 \int_{-h_o}^{h-h_o} y^2 \, dy \, dx = \frac{1}{3} ((h - h_0)^3 - (h_0)^3) \]

The reinforcement factor of flexural modulus is obtained as
In the design process, the lining thickness becomes $t = h$. For a single layer of filament reinforcement, the overall fiber pitch is $L_{pp} = L_p$. For multiple layers of filament reinforcement, the overall fiber pitch is obtained by calculating the actual pitch of filaments under tension at the poles of long axial of the elliptical shape. The distance $t_c$ can be obtained by taking the average of the distances between lining surface and filaments under tension.

11. Equation X1.11

This equation is derived from the equation X1.6 in ASTM F1216 as

$$P = \frac{2\sigma_{TL}}{(DR - 2)N_i}$$

$DR$ is the dimension ratio. From this equation the minimum lining thickness for overcoming internal pressure can be derived as

$$t_{2b1} = \frac{D}{\left(\frac{2 \cdot \sigma_{TL}}{P \cdot N_i}\right) + 2}$$

In the appendix, the calculation was taken more conservatively so the equation was modified as

$$t_{2b1} = \frac{D}{\left(\frac{2 \cdot \sigma_{TL}}{P \cdot N_i}\right) + 1}$$

12. Equation X1.12

The figure below shows the cross-section area of a carbon fiber reinforced lining. Assume the lining can hold the internal pressure, there will be an equilibrium of force along the lining hoop direction where the lining material and carbon fiber are under tensile stress. Assume the lining thickness is $t$, diameter is $D$, internal pressure is $P$, and the lining material has a shrinkage strain $\varepsilon_s$ when cure. Since the carbon fiber will not take compression stress but tensile stress, assume the lining material and carbon fiber will both elongate in the hoop direction with the same expansion ratio if the lining is under internal pressure and the carbon will expand a hoop strain of $\varepsilon_\theta$, then
the lining material will have hoop strain of $\varepsilon_\theta + \varepsilon_s$ (because the lining material shrinks during curing, the carbon fiber will not expand when the lining material expansion strain is less than the shrink strain). Since the lining material and carbon fiber will break if the hoop strain is too high, in the equilibrium we will consider using the minimum value of material tensile strength or the multiplication of material modulus and strain.

The distribution and orientation of reinforcement fiber in the composite have a major influence on the overall material strength of the lining. With respect to orientation, since the major stress on most of the pipes is along the pipe hoop direction, the fiber filaments shall be oriented close to the lining hoop direction to maximize the composite lining structure strength. In the modeling, since the orientation of carbon fiber is almost perpendicular to the pipe axial direction because of the large pipe diameter and small fiber pitch, it is assumed that the fiber reinforcement is mainly effective on the lining hoop direction and the reinforcement effect along the lining axial direction can be ignored.

For a certain length of lining between the centers of two pitches, the equilibrium can be written as

$$N_i P * (D - t)L_p = 2tL_p * \min(E_{TL}(\varepsilon_\theta + \varepsilon_s), \sigma_{TL}) + 2\min(E_f A_f \varepsilon_\theta, A_f \sigma_f)$$

Where: $L_p =$ fiber winding pitch distance, in. (mm)
\( E_{TL} \) = long-term tensile modulus of elasticity of MICP material under normal working temperature, psi (Mpa), per Test Method D2990

\( \sigma_{TL} \) = long-term tensile strength of MICP material under normal working temperature, psi (Mpa), per Test Method D2990

\( E_f \) = fiber tensile modulus per Test Method C1557, psi (Mpa)

\( A_f \) = fiber cross section area, in² (mm²)

\( \varepsilon_\theta \) = maximum allowable hoop strain of the filament fiber, per Test Method C1557

\( \sigma_f \) = carbon fiber tensile strength per Test Method C1557, psi (Mpa)

\( \varepsilon_s \) = material shrinkage in curing process per Test Method D6289, in/in. (mm/mm)

The minimum lining thickness of reinforced lining can be derived from the above equation as

\[
t = \frac{N_iPD_Lp - 2\min(E_f A_f \varepsilon_{\theta max}, A_f \sigma_f)}{[2L_p \min(E_{TL}(\varepsilon_{\theta max} + \varepsilon_s), \sigma_{TL}) + N_i PL_p]}
\]

13. Equation X 1.13

On the cross-section of lining material between two fiber filaments, the material will bend because of the internal pressure. Assume that the influence of material stress along hoop direction caused by bending can be ignored. Consider the carbon fiber as a rigid line confinement, the maximum stress caused by material bending happens at the material under the fiber center. The material bending can be simplified as bending beam between two fixed ends, the maximum bending stress on the material can not be higher than the material strength, therefore
Where:  

\[ W = \text{the pressure per unit length}, \quad W = N_l \times P \times b \]  

\[ I = \text{area moment of inertia}, \quad I = \frac{b t^3}{12} \]  

\[ b = \text{unit length of lining material along hoop direction} \]  

From the equations above, it can be derived that the minimum lining thickness for overcoming the bending stress between the fibers is obtained as

\[ t \geq \sqrt[3]{\frac{N_l P}{2 \sigma_L}} L_p \]  

**14. Equation X1.14**

On the cross-section of lining material where carbon fiber contact with the material, the lining material will be under shear stress because of the internal pressure load. Assume that the tension force on the carbon is \( F \), and the carbon fiber is regarded as line body, the shear force on the lining material and tension force on the carbon fiber will result in an equilibrium as
Where:

\[ \varepsilon_{\theta_{\text{max}}} = \text{fiber material maximum tensile strain} \]

\[ t = \text{lining material shear strength} \]

From the equations above, the minimum required lining thickness for overcoming the shear stress caused by reinforcement filaments and internal pressure can be derived as

\[
t = \frac{\tau_L D - \sqrt{\tau_L^2 D^2 - 4 \tau_L \varepsilon_{\theta_{\text{max}}} E_f A_f}}{\tau_L}
\]

15. Equation X1.15

As the lining material is pressurized, it stretches radially and shrinks lengthwise because of the Poisson’s ratio effect. Therefore, if the lining material is affixed to the pipe at the two or more locations, the internal pressure load can cause stress along axial direction. For a cylinder pipe with internal pressure and fixed ends, the stress along axial direction caused by Poission’s ratio effect...
has been investigated as (P.L., Gould, “Introduction to LINEAR ELASTICITY”, Springer, Second Edition, pp. 119)

\[ \sigma_{zz} = \frac{2\nu (P_i R_i^2 - P_o R_o^2)}{R_o^2 - R_i^2} \]

Where:

- \( P_i \) = internal pressure (psi)
- \( P_o \) = external pressure (psi)
- \( R_i \) = pipe inside radius (in), \( R_i = (D - 2t)/2 \)
- \( R_o \) = pipe outside radius (in), \( R_o = D/2 \)
- \( \nu \) = lining material Possion’s ratio

Assume that the external pressure can be ignored, also multiply the internal pressure with a safety factor, the equation above can be rederived as

\[ \sigma_{zz} = \frac{2\nu N_i P_i (D - 2t)^2}{D^2 - (D - 2t)^2} \]

The lining thickness \( t \) can be solved as

\[
(4\sigma_{TL} + 8\nu N_i P) t^2 - (8\nu N_i PD + 4D\sigma_{TL}) t + 2\nu N_i PD^2 = 0
\]

\[
a = (4\sigma_{TL} + 8\nu N_i P)
\]

\[
b = -(8\nu N_i PD + 4D\sigma_{TL})
\]

\[
c = 2\nu N_i PD^2
\]

\[
t = \frac{-b - \sqrt{b^2 - 4ac}}{2a}
\]

**16. Equation X1.16**

If the lining is not fixed at the ends or elbows, the lining system will be subjected to thrust load caused by internal pressure. The material tensile strength and internal pressure load result in an equilibrium as

\[
\sigma_{TL} \left( \frac{\pi D^2}{4} - \frac{\pi(D - 2t)^2}{4} \right) = N_i P \frac{\pi(D - 2t)^2}{4}
\]
The equation above can be solved to determine the minimum lining material wall thickness for overcoming the tensile load caused by internal pressure as

\[ t = \frac{D - \sqrt{N_i P + \sigma_{TL} D^2}}{2} \]

17. Equation X1.17

If the pipe is suspended, bending moments will happen on the lining system between the supports due to gravity. Assume that the suspended lining length is \( L_{sp} \). The cross-section areas of lining material and conveyed material are
\[ A_L = \frac{\pi D^2}{4} - \frac{\pi(D - 2t)^2}{4} \]
\[ A_m = \frac{\pi(D - 2t)^2}{4} \]

Where:  
\( A_L \) = cross-section areas of lining material (in^2)  
\( A_m \) = cross-section areas of conveyed material (in^2)

The weights of lining material and conveyed material are
\[ W_l = \rho_l A_l L_{sp} \]
\[ W_m = \rho_m A_m L_{sp} \]
\[ W = W_l + W_m \]

Where:  
\( \rho_l \) = lining material density (lb/in^3)  
\( \rho_m \) = conveyed material density (lb/in^3)  
\( W_l \) = lining material weight (lb)  
\( W_m \) = conveyed material weight (lb)  
\( W \) = total material weight (lb)

The lining can be treated as a beam with fixed ends under uniform load, the maximum stress on the lining material can be determined as
\[ \sigma_m = \frac{WL_{sp} D}{12 I} \leq \frac{\sigma_{TL}}{N_e} \]

Where:  
\( I \) = area moment of inertia,  
\[ I = \frac{\pi}{4} \left( \frac{D}{2} \right)^4 - \left( \frac{D - 2t}{2} \right)^4 \approx \pi \left( \frac{D}{2} \right)^3 t \]

From the equations above, the minimum lining thickness for overcoming the bending stress on the lining material caused by gravity can be obtained as
\[ 4(\rho_m - \rho_l)t^2 + \left( 4\rho_l D - 4\rho_m D - \frac{12D^2\sigma_{TL}}{L_{sp}^2N_e} \right)t + \rho_m D^2 = 0 \]
\[ a = 4(\rho_m - \rho_l) \]
\[ b = \left(4\rho_l D - 4\rho_m D - \frac{12D^2\sigma_{TL}}{L_{sp}^2 N_e}\right) \]
\[ c = \rho_m D^2 \]
\[ t = \frac{-b-\sqrt{b^2-4ac}}{2a} \]

18. Equation X1.18

Continue with the model in Equation X1.17, the lining can be treated as a beam with fixed ends under uniform load, the maximum buckling stress on the lining material can be determined as

\[ \sigma_{cr} = \frac{\psi E}{\sqrt{3(1-\nu^2)}} \frac{t}{r} \]

This equation is from the reference papers:

- Buckling of Thin-Walled Long Steel Cylinders Subjected to Bending. Available from: https://www.researchgate.net/publication/275376868_Buckling_of_Thin-Walled_Long_Steel_Cylinders_Subjected_to_Bending

When apply with safety factor, this equation can be rederived as

\[ \sigma_{cr} = \frac{N_e \psi E}{\sqrt{3(1-\nu^2)}} \frac{t}{r} \leq \frac{W L_{sp}}{12I} \frac{D}{2} \]

From the equations above, the minimum lining thickness for overcoming the buckling on the lining material caused by gravity can be obtained as

\[ 4 \left(\rho_m - \rho_l - \frac{6D\psi E_{TL}}{L_{sp}^2 N_e \sqrt{3(1-\nu^2)}}\right) t^2 + (4\rho_l D - 4\rho_m D)t + \rho_m D^2 = 0 \]

\[ a = 4 \left(\rho_m - \rho_l - \frac{6D\psi E_{TL}}{L_{sp}^2 N_e \sqrt{3(1-\nu^2)}}\right) \]
\[ b = (4\rho_l D - 4\rho_m D) \]
\[ c = \rho_m D^2 \]
\[ t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \]

19. Equation X1.19

For a hollow circular cross section, if the shear force on the cross section surface is \( V \), the maximum shear stress is

\[ \tau_{\text{max}} = \frac{VQ}{Ib} = \frac{4V}{3A} \left( \frac{r_2^2 + r_2r_1 + r_1^2}{r_2^2 + r_1^2} \right) \]

For a thin wall pipe, the wall thickness is relatively small compared to the pipe radius, thus

\[ r_2 \approx r_1, \quad \frac{r_2^2 + r_2r_1 + r_1^2}{r_2^2 + r_1^2} \approx \frac{3}{2} \]

When apply with safety factor

\[ \frac{\tau_{\text{max}}}{N_e} = \frac{VQ}{Ib} = \frac{4V}{3A} \left( \frac{r_2^2 + r_2r_1 + r_1^2}{r_2^2 + r_1^2} \right) \approx \frac{4V}{3A} \cdot \frac{3}{2} = \frac{2V}{A} \approx \frac{2V_{\text{yields}}}{2\pi rt} \rightarrow V = \frac{\tau_{\text{max}}}{N_e} \pi rt \]

Continue with the model in Equation X1.17, the shear force on the lining is

\[ V = \frac{1}{2}(W_l + W_m) \]

Combine the equations above, the required thickness of rigid lining material for overcoming the shear stress is determined as

\[ 4(\rho_m - \rho_l)t^2 + \left( 4\rho_lD - 4\rho_mD - \frac{4D\tau_L}{L_{sp}N_e} \right) t + \rho_mD^2 = 0 \]

\[ a = 4(\rho_m - \rho_l) \]

\[ b = \left( 4\rho_lD - 4\rho_mD - \frac{4D\tau_L}{L_{sp}N_e} \right) \]

\[ c = \rho_mD^2 \]

\[ t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \]

20. Equation X1.20

This equation is derived directly from Hazen–Williams Equation.

21. Equation X1.21
This equation is derived directly from Manning’s Equation.

**Lining Pressure Rating**

The long-term lining pressure rating can be obtained by reversely derived Eq.X1.8 as

\[
P_{\text{rating-L}} = N_i P = \frac{2L_p t_{2b2} \cdot \min(E_{TL}(\varepsilon_{\theta max} + \varepsilon_{\theta s}), \sigma_{TL}) + 2 \min(E_f A_f \varepsilon_{\theta max}, A_f \sigma_f)}{(D - t_{2b2})L_p}
\]

where:
- \( t_{2b2} \) = minimum lining thickness at MAOP with filaments reinforcement, in. (mm),
- \( L_p \) = fiber winding pitch distance, in. (mm),
- \( E_{TL} \) = long-term tensile modulus of elasticity of SIPP lining material under normal working temperature, psi (Mpa), per Test Method D2990,
- \( \sigma_{TL} \) = long-term tensile strength of SIPP lining material under normal working temperature, psi (Mpa), per Test Method D2990,
- \( E_f \) = fiber tensile modulus per Test Method C1557, psi (Mpa),
- \( A_f \) = fiber cross section area, in². (mm²),
- \( \varepsilon_{\theta max} \) = maximum allowable hoop strain of the filament fiber, per Test Method C1557,
- \( \sigma_f \) = carbon fiber tensile strength per Test Method C1557, psi (Mpa),
- \( \varepsilon_{\theta s} \) = material shrinkage in curing process per Test Method D6289, in/in. (mm/mm).

The short-term lining pressure can be obtained by using the equation above but replacing the long-term lining material properties with short-term lining material properties as

\[
P_{\text{rating-S}} = N_i P = \frac{2L_p t_{2b2} \cdot \min(E_T(\varepsilon_{\theta max} + \varepsilon_{\theta s}), \sigma_T) + 2 \min(E_f A_f \varepsilon_{\theta max}, A_f \sigma_f)}{(D - t_{2b2})L_p}
\]

where:
- \( t_{2b2} \) = minimum lining thickness at MAOP with filaments reinforcement, in. (mm),
- \( L_p \) = fiber winding pitch distance, in. (mm),
\( E_T \) = short-term tensile modulus of elasticity of SIPP lining material under normal working temperature, psi (Mpa), per Test Method D638,

\( \sigma_T \) = short-term tensile strength of SIPP lining material under normal working temperature, psi (Mpa), per Test Method D638,

\( E_f \) = fiber tensile modulus per Test Method C1557, psi (Mpa),

\( A_f \) = fiber cross section area, in\(^2\), (mm\(^2\)),

\( \varepsilon_{\theta_{max}} \) = maximum allowable hoop strain of the filament fiber, per Test Method C1557,

\( \sigma_f \) = carbon fiber tensile strength per Test Method C1557, psi (Mpa),

\( \varepsilon_{\theta_s} \) = material shrinkage in curing process per Test Method D6289, in/in. (mm/mm).