WSA XXX Water Industry Standard for Cured-in-place pipes (CIPP) used for the renovation of drinking water pipes

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PREFACE

This Standard was prepared by the Water Services Association of Australia (WSAA). It was published on the **[to be included in published version]**.

The objective of this Standard is to provide performance requirements for cured-in-place pipe (CIPP) intended for the renovation of pipeline systems used for the supply of drinking water.

NOTE: Products complying with this Standard may also be suitable for the renovation of water pipes used for other applications such as recycled water, fire services and irrigation.

Selection, design, installation and commissioning requirements are covered by WSAA Manual for selection and application of cured-in-place pipe (CIPP) and spray liners for use in water pipe.

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FOREWORD

This Standard addresses the performance requirements of Cured-in-place pipe (CIPP) materials and finished products used in the renovation of drinking water pipelines. It is intended to provide manufacturers and specifiers with a means of demonstrating fitness for purpose.

This Standard differs from those applicable to conventionally installed piping systems in that it is required to verify certain characteristics of the components as manufactured as well as in the installed condition. In accordance with ISO terminology these have been identified as the "M" stage for the collective materials used to fabricate the liner and the "I" stage for the liner as installed.

ISO terminology has also been adopted for describing the structural classification with Class A being fully structural, Classes B and C being semi-structural and Class D providing an internal barrier layer (refer to appendix B for class requirements).

The service life of products conforming to this Standard will be dependent upon the condition of the host pipe, the quality of the liner material and its application and the service conditions. The material and process selection should therefore be in accordance with the requirements of the asset owner with respect to extending the service life of the host pipeline.

Neither the type of polymer used nor the reinforcement is specified in the Standard. All materials used are required to meet the performance requirements of this Standard including effect on drinking water.

As part of its product appraisal process, WSAA may request details of previous successful installations or require contractors to undertake trial installations. In addition to the test records described in this Water Industry Standard, WSAA may ask suppliers to include:

- The host pipe diameter and length, material and service conditions;
- The water off time (time from water off to supply restoration);
- Disinfection regime;
- Contractor details and date of installation;
- Results of pressure or leak tests;
- Where relevant, details of any subsequent rectification work applied to the renovation; and
- All quality control testing undertaken including CCTV examination of the lined pipe, joints and liner ends.

1. SCOPE AND GENERAL

1.1 SCOPE

This Standard specifies the performance requirements and test methods for products used in the renovation of pipelines conveying drinking water, by cured-in-place pipes (CIPP). It is applicable to the CIPP lining of host pipes including but not limited to asbestos cement, cement mortar lined metallic pipes, metallic pipes and reinforced concrete.

The Standard is applicable to fully structural, Class A, and semi-structural, Class B and Class C, liners as defined in Appendix B. Note the Class D classification is provided for information only. It is not covered by this Standard.

It is applicable to lining systems typically comprising of a fibrous carrier impregnated with a thermosetting resin and intended to be installed in accordance with the WSAA Manual for selection and application of cured-in-place (CIPP) and spray liners for use in water pipe.

The pipe liner, in the form of a resin-impregnated tube may be pulled directly into the host pipe or inverted as it is inserted. Water pressure, swabs, steam or air may be used to inflate the tube so it expands tightly against the host pipeline before being cured in place.

Curing may be carried out by the application of heat, UV radiation, visible light, or at ambient temperature.

The diameter range for which a CIPP product can be used shall be established as part of the product appraisal process.

The service temperature range for which a CIPP product can be used shall be established as part of the product appraisal process.

NOTES:
(i) No minimum pressure rating is specified for CIPP products as the appropriate pressure rating will be stipulated by the Water Agency on a case-by-case basis.

(ii) This Standard does not set requirements for abrasion resistance or impact resistance.

1.2 CONFORMITY REQUIREMENTS

Methods for demonstrating conformity with this Standard shall be in accordance with Appendix A.

Product certification, when required, shall be undertaken in accordance with WSA TN-08.

Note: The word ‘shall’ is used in this Standard to designate a mandatory requirement.

1.3 LIMITATIONS

This Standard applies to CIPP lining products which are either Class A (fully structural) or which rely on a degree of structural integrity of the host pipe to both withstand external loads and resist internal pressure, Class B and C (semi-structural). Refer to appendix B for liner class details.

1.4 NORMATIVE REFERENCES

The following are the normative documents referenced in this Standard:

AS

681.1 Elastomeric seals- Material requirements for pipe joint seals used in water and drainage applications Part 1: Vulcanized rubber.

1145.4 Determination of tensile properties of plastics materials - Test conditions for isotropic and orthotropic fibre-reinforced plastic composites

1199.1 Sampling procedures for inspection by attributes — Part 1: Sampling schemes indexed by acceptance quality limit (AQL) for lot-by-lot inspection.

1646 Elastomeric seals for waterworks purposes.

1210 Pressure Vessels

2345 Dezincification resistance of copper alloys

4321 Fusion-bonded medium-density polyethylene coating and lining for pipes and fittings

3894.9 Site testing of protective coatings - Determination of adhesion

4041 Pressure piping

4087 Metallic flanges for waterworks purposes.

AS/NZS

2566.1 Buried flexible pipelines – Structural Design

2566.2 Buried flexible pipelines - Installation

3500 Set (Parts 0-4) Plumbing and drainage Set

3571.2 Plastics piping systems - Glass-reinforced thermoplastics (GRP) systems based on unsaturated polyester (UP) resin Pressure and non-pressure water supply (ISO 10639:2004, MOD)

4020 Testing of products for use in contact with drinking water.

4158 Thermally-bonded polymeric coating on valves and fittings for water industry purposes.

AS ISO/IEC
17025 General requirements for the competence of testing and calibration laboratories.

ASTM

D570 Standard Test Method for Water Absorption of Plastics

D638 Standard Test Method for Tensile Properties of Plastics

D790 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced. Plastics and Electrical Insulating Materials

D1599 Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings

D2290 Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe

D2369 Standard Test Method for Volatile Content of Coatings

D2992 Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings

D3039 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

D3567 Standard Practice for Determining Dimensions of “Fiberglass” (Glass-Fiber-Reinforced Thermosetting Resin) Pipe and Fittings

D4541 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

D7028-07 Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA)

D7234 Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers

E831 Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis.

F1216 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube

F1743 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled In-Place Installation of Cured-In-Place Thermosetting Resin Pipe (CIPP)

AWWA
Structural Classifications of Pressure Pipe Linings – Suggested Protocol for Product Classification

EPA (USA)

Method 24 Determination of volatile matter content, water content, density, volume solids, and weight solids of surface coatings

Method 1311 Toxicity Characteristic Leaching Procedure

ISO

62 Plastics — Determination of water absorption

527-4 Plastics — Determination of tensile properties — Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites

899-1 Plastics — Determination of creep behaviour — Part 1: Tensile creep

3126 Plastics piping systems — Plastics components — Determination of dimensions

7509 Plastics piping systems — Glass-reinforced thermosetting plastics (GRP) pipes — Determination of time to failure under sustained internal pressure

8513 Plastic piping systems — Glass-reinforced thermosetting plastics (GRP) pipes — Determination of longitudinal tensile properties

8521 Plastic piping systems — Glass-reinforced thermosetting plastics (GRP) pipes — Determination of the apparent initial circumferential tensile strength

ISO 8521:1998, Plastic piping systems – Glass-reinforced thermosetting plastics (GRP) pipes – Determination of the apparent initial circumferential tensile strength

10639 Plastics piping systems for pressure and non-pressure water supply — Glass-reinforced thermosetting plastics (GRP) based on unsaturated polyester resin (UP) — Specifications for pipes, fittings and joints.

10928 Plastics piping systems — Glass-reinforced thermosetting plastics (GRP) pipes and fittings — Methods for regression analysis and their use.

11295 Classification and information on the design and applications of plastics lining systems used for renovation and replacement.

11296-4 Plastics piping systems for renovation of underground non-pressure drainage and sewerage networks — Part 4: Lining with cured-in-place pipes

11297-4 Plastics piping systems for renovation of underground drainage and sewerage networks under pressure — Part 4: Lining with cured-in-place pipes

11298-1 Plastics piping systems for the renovation of underground water supply networks – Part 1 General

11298-4 Plastics piping systems for the renovation of underground water supply networks – Part 4 Lining with cured-in-place pipes

13002 Carbon fibre — Designation system for filament yarns

13003 Fibre-reinforced plastics — Determination of fatigue properties under cyclic loading conditions

11359-2 Plastics – Thermomechanical analysis (TMA) – Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature

14125 Fibre-reinforced plastic composites — Determination of flexural properties

15306 Glass-reinforced thermosetting plastics (GRP) pipes — Determination of the resistance to cyclic internal pressure

WSAA
TN-08 Product conformity assessment requirements.

1.5 TERMS AND DEFINITIONS

For the purpose of this standard, the following terms and definitions apply.

1.5.1 Carrier material
porous component of the liner, which carries the liquid resin system during insertion into the pipe being renovated and forms part of the installed lining system once the resin has been cured.

1.5.2 Composite
combination of cured resin system, carrier material and/or reinforcement excluding any internal or external membranes.

1.5.3 Curing
process of resin polymerization, which may be initiated or accelerated by the use of heat or exposure to light.

1.5.4 Declared value
limiting value of a characteristic declared in advance by the lining system supplier, which becomes the requirement for the purposes of assessment of conformity.

1.5.5 Design thickness

the minimum thickness of the resin impregnated carrier material plus any reinforcing layer(s) intended for use in design calculations.

1.5.6 Independent pressure pipe liner
a liner capable, on its own, of resisting without failure all applicable internal loads throughout its design life.

1.5.7 Inversion
process of turning a flexible tube or hose inside out by the use of fluid (water or air) pressure.

1.5.8 Inverted-in-place insertion
method whereby the impregnated lining tube is introduced by inversion to achieve simultaneous insertion and inflation.

1.5.9 Lining tube

the combined components of the liner prior to curing, i.e. all of the following that apply in the product used: carrier material, reinforcing layer(s), internal and/or external membrane, mixed uncured resin applied to carrier material.

1.5.10 Liner
lining tube after installation and curing is completed.

1.5.11 Lining with cured-in-place pipes
lining with a flexible tube impregnated with a thermosetting resin, which produces a pipe after resin cure.

1.5.12 Membrane

a thin layer of material that can be used as a component of the lining tube. Membranes can be internal or external and can be permanent or semi-permanent.

1.5.13 Permanent membrane
internal or external membrane designed to retain its integrity through the processes of lining tube insertion and resin system cure, and to provide functions for the operational life of the CIPP liner.

1.5.14 Semi-permanent membrane
internal or external membrane designed to retain its integrity through the processes of lining tube insertion and resin system cure, but not relied on to retain its integrity at the “I” stage.

1.5.15 Reinforcing Layer

a layer that forms part of the lining tube and provides additional strength and stiffness to the installed liner.

1.5.16 Renovation
work incorporating all or part of the original fabric of the pipeline, by means of which its current performance is improved.

1.5.17 Renovated pipeline system
the existing pipeline system plus the installed liner used to renovate it.

1.5.18 Resin System

thermosetting resin including the curing agent(s) and any fillers or other additives in specified proportions

1.5.19 Simulated installation
the installation of a lining system into a simulated host pipeline, using representative equipment and processes, to provide samples for testing which are representative of the actual installation.

1.5.20 Simulated host pipeline
a section of pipeline, which is not part of an operational network, but which replicates the environment of the operational network.

1.5.21 Total thickness
the thickness of CIPP liner at the "I" stage comprising the thickness of all liner components.

1.5.22 Product stages
the liner material as installed and the component materials from which it is made can be considered at two distinct stages as follows:

1.5.22.1 "M" Stage
the stage as manufactured before any site processing or mixing of the components.

1.5.22.2 "I" stage
the stage as installed, that is, the final configuration of the material after site processing and installation.

1.5.23 Service conditions

1.5.24 Maximum service temperature
the maximum sustained temperature at which the CIPP system is intended to operate expressed in degrees Celsius (°C).

1.5.25 Nominal pressure (PN)
alphanumeric designation for the nominal pressure class, designated in bars, which is the maximum sustained hydraulic internal pressure for which the pipe is designed in the absence of other loading conditions. For example, PN12 indicates a nominal pressure of 12 Bar or 1,200 kPa.

1.5.26 Maximum allowable operating pressure
the maximum pressure that can be sustained, with a design factor, by the type or class of pipe for its estimated useful life under the anticipated working conditions.

1.5.27 Test pressure
hydrostatic pressure applied to the installed pipeline system in order to assess its integrity and water tightness.

1.5.28 Surface area-to-volume ratio
the surface area per unit length of the liner in direct contact with the drinking water divided by the volume of water per unit length.

1.6. SYMBOLS AND ABBREVIATED TERMS

The following symbols and abbreviations are used in the Standard:

AC asbestos cement

CIPP cured-in-place pipe
CI cast iron
EP epoxy resin
GRP glass reinforced thermosetting plastics
“I” as installed
“M” as manufactured
PA polyamide
PAN polyacrylonitrile
PEN poly (ethylene naphthalate)
PET poly (ethylene terephthalate)
PN nominal pressure
PPTA poly (p-phenylene terephthalamide)
PVC polyvinyl chloride
UP unsaturated polyester resin
VE vinyl ester resin

2. MATERIAL REQUIREMENTS “M” STAGE

This section specifies the requirements for the components that together make a lining tube.

CIPP products are comprised of a carrier material and a liquid resin that are combined during the installation process and then cured forming a liner. The CIPP product may also have an internal and/or external membrane and a reinforcing layer. The combination of these elements prior to curing is referred to as a ‘lining tube’ and after curing as a ‘liner’. Refer Figure 1.

The actual values of the properties for the materials at the “M” stage are to be stated by the supplier and shall be used for ongoing monitoring of quality, refer tables 1, 2 and 3.

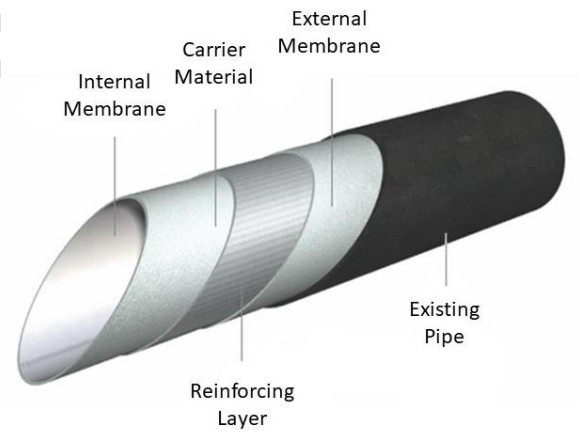

Figure 1. Typical wall construction of lining tube
Note: the reinforcing layer may be incorporated into the carrier material.

2.1. RESIN SPECIFICATION

The manufacturer shall:

(i) Nominate the chemical family of the CIPP resin and carrier material in accordance with Table 1.

(ii) Provide a specification for each resin component listing relevant properties with specified values and tolerances. The properties shall include those listed in Table 2. Any other properties relevant to the particular lining tube shall also be specified.

TABLE 1 MATERIALS FOR LINING COMPONENTS

Lining technique	Material component	Material type
Lining with Cured-in-place pipe (CIPP)	Resin system: — resin type — filler type — curing agent type	 UP, VE or EP[a] None, inorganic or organic Heat-initiated, light-initiated, UV initiated or ambient cure
	Carrier material/reinforcement	Polymeric fibres: PA, PAN, PEN, PET, PP or PPTA; Glass fibres of types 'E', 'C', 'R' and/or 'E-CR' conforming to ISO 10639 or AS3571.2; Carbon fibres of declared designation conforming to ISO 13002; or Combinations of the above fibres[b].
	Membranes	Unrestricted[c]

a Other resin systems can in principle be tested in accordance with this standard.
b Where a combination of fibres is used, the proportions by mass of each fibre type shall be declared to within 5 %.
c There are also no restrictions on the choice of thermoplastic materials used for membranes., however all materials shall comply with AS/NZS 4020.

2.2. **CARRIER MATERIAL AND REINFORING LAYERS**

The CIPP carrier material shall consist of one or more layers of flexible material, capable of carrying resin, and withstanding installation forces (including tensile), pressures and curing temperatures.

Reinforcing layers may be used as part of a lining tube to provide additional strength. Where used they shall be considered to form part of the design thickness when determining load capacity.

The manufacturer shall specify the composition of the carrier material and any reinforcing layers in accordance with Table 1.

The resin impregnated carrier material plus any reinforcing layers shall be uniform in thickness such that when installed the minimum design thickness shall be not less than specified and requirements for surface irregularities are met, see Section 3.3.

2.3. CIRCUMFERENCE OF THE LINING TUBE

The circumference of the lining tube should be dimensioned such that when installed it has full contact with the existing host pipe wall, unless otherwise required by the design. The manufactured length and thickness of the lining tube should include allowances for any longitudinal or circumferential elongations or contraction during installation.

- For Class A liners – Contact between liner and the host pipe is required primarily for connections and to prevent leakage. Lining through some sections of the host pipe without contact is acceptable, provided connections and water tightness can be achieved. Where adhesion to the host pipe's internal surface is required for water tightness, contact is required at all service connections, laterals and liner termination (ends). Where adhesion cannot be achieved mechanical fittings shall be used to ensure a seal.
- For Class B, Class C and Class D liners – full contact with pipe wall is required, as transfer of load to the host pipe is critical.
- A note on bends - some liners can be used through bends. The maximum bend angle is specified by the manufacturer (typically ≤45°). Where a liner is installed through a bend additional folds or wrinkles are likely to occur. Folds and wrinkles outside of tolerance are considered defects, as they introduce localised weak points in the liner, refer section 3.3 Surface Irregularities.

2.4. STORAGE AND TRANSPORT

The storage and transport of the components including shelf life and any storage temperature limitations shall be comply with the manufacturer's recommendations.

2.5. MARKING

Marking shall be applied to the outside of the lining tube as delivered to the installation site or in the case of pre-packaged lining tubes, on the outside of the packaging. Marking shall include:

- reference to this Standard;
- manufacturer's name and/or trademark;
- nominal outside diameter;
- wall thickness;
- resin system;
- certification licence number;
- manufacturer's information providing traceability to the production period and production site; and
- application, i.e. Drinking Water.

2.6. FITTINGS AT THE "M" STAGE

2.8.1. Fittings for use in water supply shall comply with the requirements of the Water Supply Code of Australia (WSA 03). Water Agencies may require products and materials to be "approved" and/or product and material suppliers to be "accredited" and may have limitations on some products. Unless otherwise approved by the Water Agency, only Water Agency "approved" products and materials shall be used. See Water Agency websites for details.

2.8.2. Fittings for use in conjunction with CIPP linings shall have a service life expectancy not less than the lining system(s) with which they are intended to be used.

2.8.3. Fittings shall comply with AS/NZS 4020. A scaling factor, where applied, shall be determined in accordance with Appendix B of AS/NZS 4020. Successful evaluation of a fitting shall qualify all products comprising the same materials and process, provided they have an equal or lower surface area-to-volume ratio.

2.8.4. Flanges shall have a drilling pattern in accordance with AS 4087.

2.8.5. Steel fittings shall made from stainless steel and shall comply with the stainless steel requirements in AS 4181 or shall be made to AS 1579 and coated with a fusion bonded polyethylene (FBPE) coating in accordance with AS 4321 and either a FBPE lining (AS 4321) or cement mortar lining in accordance with AS 1281. Ductile iron fittings shall made to AS/NZS 2280 and be protected against corrosion by a thermally bonded coating applied in accordance with AS/NZS 4158.

2.8.6. Brass fittings shall be low lead and resistance to dezincification and comply with AS 1565 and AS 2345.

2.8.7. Mild steel, ductile iron, GRP and PVC fittings shall comply with the relevant WSAA Product Specification.

3. MATERIAL REQUIREMENTS "I" STAGE

This clause specifies the requirements for the completed liner installation.

3.1. MATERIALS SPECIFICATION – LINER (I = INSTALLED AND CURED)

TABLE 2 PROPERTIES OF THE LINER (I = INSTALLED AND CURED)

Property	Test Method	Requirement
Glass transition temperature	ASTM D7028 ISO 11359-2	Recorded value
Water absorption	AS 4321 App. D	Recorded value
Contact with drinking water	AS/NZS 4020	Shall pass AS/NZS 4020 requirements
Minimum wall thickness	ASTM D3567 or ISO 3126	Not less than 87.5% of design thickness

A list of test requirements, including mechanical properties, and associated standards are listed in Appendix A, Table A1.

3.2. EFFECT ON DRINKING WATER

CIPP pipe shall comply with AS/NZS 4020 with a scaling factor of 1.0. Successful evaluation of a product shall qualify all lower surface area-to-volume ratios, i.e. larger diameters, of the same composition in the product range.

NOTE: The liner may be tested as a finished product using in-the-product exposure. Alternatively the resin may be tested alone as a coating. Both techniques are described in AS/NZS 4020, Appendix A.

3.3. SURFACE IRREGULARITIES

The liner shall not introduce surface irregularities in addition to those of the existing pipeline, which exceed a height of 2% of the nominal diameter of the pipeline or 6 mm, whichever is the greater. The height of irregularities shall be measured from the internal surface of the liner. If the CIPP liner has a surface irregularity a reduction factor of 0.5 (a factor of safety for liner imperfections, $N_i = 2$) shall be used in the design methodology for a CIPP liner.

3.4. SPANNING OF EXISTING HOLES AND GAPS

The ability of CIPP liners to span holes and gaps varies by product and class of liner. To determine the size of hole/gap that can be spanned by a Class B or Class C liner product the relevant equations in Appendix C, or the Pipe Evaluation Platform **[final site to be included in published version, currently available: https://pipes.monash.edu/]**, shall be used.

3.5. ACCEPTABLE BEND RADIUS

The supplier shall declare the minimum longitudinal radius the CIPP system is capable of negotiating without creating wrinkles or folds that will reduce the liner's load capacity under operational pressure, or reduce the expected life below the design life. Refer 3.3. Surface Irregularities.

3.6. OTHER MATERIALS

3.6.1. ELASTOMERIC SEALS

Elastomeric seals shall comply with AS 1646 and AS 681.1 and meet the requirements for contact with drinking water.

3.6.2. ADHESIVES AND SEALANTS

Adhesives, where used to fix and / or seal the liner to GRP, plastics or metallic components shall be compatible with the CIPP resin system and meet the requirements for contact with drinking water (AS/NZS 4020). Suppliers to provide a list of compatible products. End sealing using adhesives or sealants shall not occur directly to CML of pipes. GRP or PVC pipe material is recommended for this method of end sealing.

3.6.3. LUBRICANTS

Any lubricant used as part of the installation process that has direct contact with the conveyed water or liner shall comply with AS/NZS 4020.

3.6.4. EFFECT OF OTHER MATERIALS ON LINER CLASS

In order to classify a liner in accordance with the classifications system as described in Appendix B, the complete lining system shall be considered, including any fitting and other materials that are required install the liner.

Note: In order for a liner to conform to the Class A requirement of: “Can survive internally or externally induced failure of the host pipe”, it may be necessary to use an external membrane, or other measures, to ensure that the liner does not bond to the host pipe in order to survive a brittle pipe failure.

4. MECHANICAL PROPERTIES

4.1. GENERAL

A CIPP liner is expected to meet different structural performance requirements based on its class, see Appendix B for class and Appendix A for testing conformity. However, once installed, the liner and host pipe combined are required to withstand all stresses arising from the normal operation of the system, without leakage, and for the design life of the liner. In particular, the installed system shall have sufficient strength and stiffness to resist:

- external loading including soil and traffic loadings;
- ground water;
- internal water pressure; and
- pressure transients.

For Class A & B installations all the following tests are applicable except Clause 4.5, however if liner requires adhesion for sealing, e.g. at ends or service connections, Clause 4.5 shall be applicable.
For Class C all the following tests are applicable except Clause 4.6.
For Class D installations only Clause 4.5 is applicable.

NOTE: For the purpose of type testing, samples may be taken either from actual installations or from simulated installations.

4.2. TENSILE PROPERTIES

4.2.1. GENERAL

Tensile properties shall be determined using the methods given in any or all of the following standards: ASTM D3039; AS 1145.4 (Type 2 or 3); ASTM 2290; ISO 8521 (hoop); ISO 8513 (axial).

4.2.2. NUMBER OF SAMPLES FOR TYPE TESTING

Five samples of the same size and classification shall be used for each fibre direction (hoop and axial) conforming to 4.2.1. The fibre directions and fibre angle shall be clearly noted. Test samples shall be cut from liners having the same nominal size and layer thickness as field installed pipes, alternatively pieces can be cut from flat sheets of the same nominal size, thickness, fibre, resin and layer configuration and cut using either CNC machining or waterjet cutting. Gripping tabs or end tabs shall be ≥ 50 mm and no centring holes shall be used in the gripping areas.

4.2.3. REQUIREMENTS

The following properties shall be declared:

- Ultimate tensile strength of liner (σ_{th} and σ_{ta}) (total thickness), in MPa
- Tensile modulus of elasticity (E_{th} and E_{ta}), in GPa
- Poisson's ratio of the liner (ν_L), unitless

4.3. FLEXURAL PROPERTIES

4.3.1. GENERAL

Flexural properties shall be determined using the methods given in any or all of the following standards: ASTM D790; ISO 14125.

4.3.2. NUMBER OF SAMPLES FOR TYPE TESTING

Five pieces of the same size and classification shall be used for each fibre direction (hoop and axial) conforming to 4.3.1. The fibre directions and angle shall be clearly noted. Test pieces shall be cut from liners having the same nominal size, and layer thickness as field installed pipes, alternatively pieces can be cut from flat sheets of the same nominal size, thickness, fibre, resin and layer configuration and cut using either CNC machining or waterjet cutting.

4.3.3. REQUIREMENTS

The following properties shall be declared:

- Ultimate flexural strength of liner (σ_{fh} and σ_{fa}) (total thickness), in MPa
- Offset yield strength at 0.2% strain, in MPa
- Strain at failure or 5%, in %
- Flexural modulus of elasticity (E_{fh} and E_{fa}), in GPa

Flexural mechanical characteristics are not required for Class C or flexible liners. Flexural properties may be substituted with tensile properties.

If break occurs, treat the stress at break as the ultimate flexural strength (if highest strength).

4.4. BURST PRESSURE

4.4.1. GENERAL

Pipe burst pressure shall be determined using ASTM D1599 Procedure A.

Failure pressure can be converted into tensile stress by using Barlow's formula:

$$\sigma_{th} = \frac{P(D_L + T_L)}{2T_L}$$

Where σ_{th} is the hoop tensile stress in MPa, P is the internal pressure in MPa, D_L is the mean external diameter of the liner in mm and T_L is the minimum liner thickness in mm.

4.4.2. NUMBER OF SAMPLES FOR TYPE TESTING

One sample shall be used. Test samples shall be cut from liners consistent with field installation dimensions, including the same nominal diameter size and layer thickness conforming to 4.4.1.

4.4.3. REQUIREMENTS

The following properties shall be declared:

- Pipe burst pressure, in MPa
- Tensile strength, in MPa
- Liner thickness (minimum, maximum and average), in mm
- Liner diameter, in mm

The tensile strength from burst pressure testing shall not be less than 80% of the ultimate tensile strength in hoop direction from 4.2.3. If imperfections such as folds are present, tensile strength from burst pressure shall be used to determine the factor of safety for imperfections (N_i).

4.5. ADHESION

4.5.1. GENERAL

Adhesion tested on a variety of surfaces, including CML (if CML lined pipe) shall be determined using any or all of the following standards: ASTM D4541 for metal, ASTM D7234 for AC and CML, or Pull off adhesion testing to AS 3894.9 for all CIPP classes that require adhesion for sealing (e.g. at ends or service connections) or bonding to the host pipe (Class C).

The following properties shall be declared:

- Adhesive strength (σ_{ad}), in MPa
- Substrate the liner is adhered to

4.5.2. NUMBER OF SAMPLES FOR TYPE TESTING

Five samples of the same size and classification shall be used.

4.6. VACUUM

4.6.1. GENERAL

Vacuum pressure tests shall be conducted at -80 kPa to -95 kPa for a duration of 5 hours. Ends shall be sealed with external pipe end clamps.

4.6.2. NUMBER OF SAMPLES FOR TYPE TESTING

One sample consistent with field installation dimensions and host pipe material, including the same nominal diameter size and layer thickness conforming to 4.4.1 shall be used.

4.6.3. REQUIREMENTS

The testing in air in accordance with 4.6.1, the test sample shall not show signs of liner debonding.

4.7. THERMAL EXPANSION/CONTRACTION

4.7.1. GENERAL

Coefficient of thermal expansion and contraction, shall be determined using any or all of the following standards: ASTM E831, ISO 11359-2.

4.7.2. NUMBER OF SAMPLES FOR TYPE TESTING

One sample shall be used.

4.7.3. REQUIREMENTS

The following properties shall be declared:

- Coefficient of thermal expansion/contraction (α), in mm/mm/°C.

4.8. TENSILE RUPTURE STRENGTH

4.8.1. GENERAL

Tensile rupture strength properties shall be determined using any or all of the following standards and methods:
Method A: ASTM D2990; ISO 899-1 (tensile creep rupture) with ISO 10928 (regression analysis);
Method B: ASTM D2992-Hydrostatic Design Basis (HDB) long term testing (Procedure B); ISO 7509 (time to failure under sustained internal pressure), with ISO 10928 (regression analysis), AS 3571.2.

4.8.2. NUMBER OF SAMPLES FOR TYPE TESTING

≥18 pieces of the same size and classification shall be used for hoop direction only. The tests pieces shall conform to 4.2 (Method A) and 4.4 (Method B). Minimum time to failure points shall correspond to those from the above standards (4.81). The fibre directions and angle shall be clearly noted (Method A).

4.8.3. REQUIREMENTS

The following properties shall be declared:

- Tensile rupture strength of liner ($\sigma_{thl,r}$ and $\sigma_{tal,r}$) (total thickness), in MPa
- Tensile rupture strength of liner (structural: fibre + resin only), in MPa
- Stress vs. time curve (log-log plot)
- 97.5% lower confidence limit line
- Regression and lower confidence lines shall be extrapolated to a minimum of 438,000 hours

The properties shall be taken from the lower confidence level of 97.5%.

4.9. TENSILE CREEP MODULUS

4.9.1. GENERAL

Tensile creep modulus properties shall be determined using any or all of the following standards:
Method A (creep): ASTM D2990; ISO 899-1 (tensile creep).
Method B (stepped isothermal method): ASTM D6992 (SIM)[1]
The test samples shall conform to 4.2.1. Method A is the preferred method; however, Method B can be used for testing at different stress/pressure levels provided the liner has conducted Method A testing for a minimum of 3,000 hours for comparison (minimum 1 piece).

4.9.2. NUMBER OF SAMPLES FOR TYPE TESTING

≥3 pieces of the same size and classification for each pressure/stress level. Samples shall be testing at a stress within the elastic range, similar to the stress experienced in the field (use 4.4.1 to determine stress). The fibre directions and angle shall be clearly noted.

4.9.3. TIME INTERVAL AND TEST DURATION

For Method A, measurements should be recorded at the minimum following time intervals: 1, 6, 12, 30 minutes, 1, 2, 5, 10, 30, 60, 100, 300, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 80000, 90000, and 10,000 hours. Testing shall be conducted for a minimum of 10,000 hours.
For Method B, measurements should be recorded at the following time intervals: 2 readings per second during the initial loading ramp and minimum of two readings per minute during constant load portions. Dwell time steps shall be run for a minimum of 10,000 seconds. A minimum of six different temperature steps should be used below the glass transition temperature (Tg) of the material.

4.9.4. REQUIREMENTS

The following properties shall be declared:

- Tensile creep modulus of liner (E_{thl} and E_{tal}) (total thickness), in GPa
- Creep retention factor (CRF), where $CRF = \frac{E_{thl}}{E_{th}}\ or\ \frac{E_{tal}}{E_{ta}}$
- Creep modulus vs. time curve (log-log plot)
- Master creep modulus versus log time curve at the step one reference temperature (Method B only)
- Master Creep strain vs. log time curve at the step one reference temperature (Method B only)
- Results shall be extrapolated to a minimum of 438,000 hours

[1] Note that this standard was developed for geosynthetics materials. It is considered to be applicable to thermo-setting materials. However, further testing may be required to confirm its applicability.

4.10. FLEXURAL CREEP MODULUS

4.10.1. GENERAL

Flexural creep modulus properties shall be determined using any or all of the following standards: ASTM D2990; ISO 899-2 (flexural creep).

The test samples shall conform to 4.3.1
Note: Flexural creep modulus and tensile creep modulus may be substituted if only one test method is conducted.

4.10.2. NUMBER OF SAMPLES FOR TYPE TESTING

≥3 pieces of the same size and classification for each pressure/stress level. Samples shall be tested at a stress within the elastic range, similar to the stress experienced in the field (use 4.4.1 to determine stress). The fibre directions and angle shall be clearly noted.

4.10.3. TIME INTERVAL AND TEST DURATION

Measurements should be recorded at the minimum following time intervals: 1, 6, 12, 30 minutes, 1, 2, 5, 10, 30, 60, 100, 300, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 80000, 90000, and 10,000 hours. Testing shall be conducted for a minimum of 10,000 hours.

4.10.4. REQUIREMENTS

The following properties shall be declared:

- Flexural creep modulus of liner (E_{fhl} and E_{fal}) (total thickness), in GPa
- Creep retention factor (CRF), where $CRF = \frac{E_{fhl}}{E_{fh}}\ or\ \frac{E_{fal}}{E_{fa}}$
- Creep modulus vs. time curve (log-log plot)
- Results shall be extrapolated to a minimum of 438,000 hours

4.11. FATIGUE STRENGTH

4.11.1. GENERAL

Fatigue strength properties shall be determined using any or all of the following standards:
Method A (fatigue strength): ASTM D2990; ISO 13003 with ISO 10928 (regression analysis).
Method B (cyclic hydrostatic strength): ASTM D2992 (Procedure A)
The test pieces shall conform to 4.2.1 (Method A) and 4.4.1 (Method B).

4.11.2. NUMBER OF SAMPLES FOR TYPE TESTING

≥18 pieces of the same size and classification shall be used. Minimum number of cycles to failure points shall correspond to those from the above standards (4.11.1). The fibre directions and angle shall be clearly noted.

4.11.3. REQUIREMENTS

The following properties shall be declared:

- Tensile fatigue strength (hoop) of the liner ($\sigma_{thl,f}$) (total thickness), in GPa
- Fatigue stress vs. number of cycles to failure (log-log plot)
- 97.5% lower confidence limit line
- Regression line and lower confidence line shall be extrapolated to a minimum of 10,000,000 cycles

For anisotropic materials tensile properties shall be tested in the hoop direction only. The properties shall be taken from the lower confidence level of 97.5%.

4.12. TESTING AND CONDITIONING TEMPERATURES

All mechanical characteristics specified in this document shall, unless otherwise specified, be determined at a temperature of 23 ± 2 °C. For long-term service temperatures greater than 25 °C, type tests shall, unless otherwise specified, be carried out within 5 °C of, but at not less than the design service temperature in order to establish de-rating factors to be used in design.

Humidity has been shown to reduce modulus and strength properties. As the liners are expected to be saturated indefinitely, the wet factor results shall be used when determining liner properties, i.e. dry samples are not recommended.

Test samples shall be tested underwater (with immersion period) (for 4.8, 4.9, 4.10, 4.11), or samples shall be saturated based on ASTM D570 or ISO 62 saturation times an immediately tested (for short-term tests, 4.2, 4.3, 4.4). Alternatively, a wet strength reduction factor, ϕ_s, shall be used where testing is conducted for strength properties (4.2, 4.3, 4.4, 4.8, 4.11) on dry samples and compared with wet samples.

$$\phi_s = \frac{\sigma_{t,wet}}{\sigma_{t,dry}}$$

where $\sigma_{t,wet}$ is the wet tensile strength of the liner (MPa) and $\sigma_{t,dry}$ is the dry tensile strength (MPa). The wet strength reduction factor shall be a factor from 0 to 1.

For creep modulus (4.9, 4.10), test samples shall be tested underwater (with immersion period). A wet creep reduction factor, ϕ_c, shall be used if samples are conducted dry, to compare with wet samples.

$$\phi_c = \frac{E_{l,wet}}{E_{l,dry}}$$

$E_{l,wet}$ is the wet creep modulus of the liner (GPa) and $E_{l,dry}$ is the dry creep modulus of the liner (GPa). The wet creep modulus reduction factor shall be a factor from 0 to 1.

The use of tensile/flexural and hoop/axial shall be consistent for both wet and dry properties to determine strength and creep reduction factors.

4.13. TEST REQUIREMENTS

When tested in accordance with the methods given in Table A1, the mechanical characteristics of pipe samples taken from actual or simulated installations shall conform to this table.

Where requirements are specified in Sections 4.2 to 4.12 and Table A1 are declared values, these declarations shall be documented for each liner product, with supporting test data or references to such data, in the installation manual for that product.

The extensions into the lateral pipe of Class A, B and C lateral connection collars shall be considered as pipes.

Declared values refer to the 97.5% lower confidence limit value of the test results as determined from the results of tests on a set of the specified number of test samples.
Other international or national Standard tests may be applied where the test conditions are identical to the nominated methods or sufficiently similar as to produce essentially equivalent results.
For anisotropic materials properties shall be tested in both the hoop and axial directions unless otherwise noted.
Note: Axial (longitudinal) directions are interchangeable. Hoop (circumferential) directions are interchangeable.

5. SAMPLING

The supplier shall document the method used for acquiring samples for testing for installation quality control purposes. The samples may be obtained by means of one of the following methods:

(i) a simulated installation;

(ii) an installation;
(iii) off-cuts formed by confining an otherwise free section of liner during inflation and curing to the same perimeter as the internal diameter of the pipe being lined; or

(iv) any other method that can be demonstrated to replicate the characteristics of samples cut from the actual pipe wall.

For the purpose of three-point bending flexural test in accordance with Table A1, the orientation of samples shall be longitudinal.

The test requirements and associated standards are listed in Section 4.2 to 4.12 and Appendix A, Table A1.

6. ADDITIONAL CHARACTERISTICS

6.1. RECONNECTION TO THE EXISTING NETWORK

The supplier shall provide detailed written instructions regarding the type of end seals and any connection fittings to be used when connecting the cured lined pipe to the existing water network.

All terminations are to be water tight when tested in accordance with AS/NZS 2566.2, Section 6. Refer Manual for selection and application of cured-in-place pipe (CIPP) and spray liners for use in water pipe for additional requirements.

The following methods of end sealing are considered unacceptable:

(a) caulking directly to CML, CML must be completely removed to ensure bond to host pipe material if caulking;

(b) piped on epoxy resin; or

(c) hydrophilic liners installed prior to the CIPP liner.

6.2. RECONNECTION OF EXISTING SERVICES

The supplier shall provide detailed written instructions regarding the reestablishment of existing services after the CIPP has been cured. Reconnection requirements may vary based on the host pipe material and required class of the liner. Reinstated service connections shall be water tight when tested in accordance with AS/NZS 2566.2, Section 6.

Where adhesion to the host pipe is required to achieve water tightness at existing service connections the supplier shall provide detailed surface preparation instructions.

Where mechanical tappings are required to achieve water tightness at existing service connections fittings shall comply with the requirements of this Water Industry Standard.

6.3. CONNECTION OF NEW SERVICES

The supplier shall provide detailed written instructions regarding the connection of new services to pipeline renovated using CIPP product including any safety requirements. The method of connecting new services may vary based on the host pipe material and class requirements of the liner.

6.4. CONNECTION OF NEW OFFTAKES

The supplier shall provide detailed written instructions regarding the connection of new offtakes to pipeline renovated using CIPP product. The method of connecting new offtake may vary based on the host pipe material and class requirements of the liner.

6.5. REPAIR OF RENOVATED PIPELINE

The supplier shall provide detailed written instructions regarding the repair of pipelines renovated using CIPP product. The method of repair may vary based on the host pipe material and class requirements of the liner.

6.6. OTHER

The supplier shall nominate any other requirements for the successful installation of their product.

7. PRODUCT DOCUMENTATION

7.1. GENERAL

Technical information relating to the CIPP lining system and correct installation methods shall be readily available to aid the user and installer. The information may be in the form of a technical manual or equivalent document and be written in plain English and supplemented by figures and diagrams as applicable. The information provided shall satisfy the requirements of a warranty as referenced in the Plumbing Code of Australia (PCA) and those requirements of the AS/NZS 3500 series of Standards.

The information shall consider the requirements in the WSAA Manual for selection and application of cured-in-place pipe (CIPP) and spray liners for use in water pipe. Where deviation from the requirements of this manual is necessary this shall be highlighted for the review and approval of the asset owner.

7.2. PRODUCT DATA

Product data shall be available that identifies critical product characteristics and as a minimum include:

a) Diameter range for application.
b) Pipe length range for application.
c) Safety Data Sheets (SDS).
d) The structural capabilities of the product in accordance with Appendix B and C.
e) OHS requirements.
f) Any derating factors to be applied to physical characteristics measured under laboratory conditions when designing a pipeline renovation.

7.3. INSTALLATION INSTRUCTIONS

The manufacturer shall provide installation instructions including, but not limited to, details of:

a) Equipment to be used.
b) Preparatory works, e.g. obstruction removal, surface cleaning.
c) Handling and installation details.
d) The mixing ratio of the components by mass or volume as appropriate, including the acceptable ratio tolerance.
e) The temperature band within which the components and blend shall be maintained.
f) Working time, i.e. the time within which the mixed resin system shall be installed.
g) Curing times and whether these are thickness dependent.
h) Maximum and minimum curing temperatures.
i) Any restrictions on the site ambient conditions that might adversely affect the application of the lining.
j) Minimum and maximum thickness to be applied with each pass and time interval permitted between multiple passes.
k) Liner termination procedure required to avoid leakage.
l) Procedure to avoid leakage at connections including tapping bands and under pressure cut-ins.
m) Final inspection and testing.
n) Requirements for new offtakes and new services.
o) Requirements for repair of lined pipeline.

NOTES:

1. Where appropriate, a derating factor may be applied to short-term physical properties in order to estimate long-term characteristics. Where the material properties are temperature sensitive, a temperature-derating factor may be required when the renovated pipe is subjected to elevated service temperatures.

Where material properties are sensitive to water saturation or humidity, a water derating factor shall be required.

2. When pipes have CML water can migrate through the CML when under pressure. Additional steps may be required to prevent leakage when CML is present.

APPENDIX A - MEANS FOR DEMONSTRATING CONFORMITY WITH THIS STANDARD

(Normative)

A1 SCOPE

This Appendix sets out a means for consistent demonstration of conformity with this Standard through the use of a minimum sampling and testing frequency plan. Where variations to this plan are made, demonstration of conformance with the minimum requirements may be necessary.

A2 RELEVANCE

The long-term performance of pipeline systems is critical to the operating efficiency of water agencies in terms of operating licences and customer contracts. The long-term performance of plumbing systems is similarly critical to the durability of building infrastructure, protection of public health and safety and protection of the environment.

A3 DEFINITIONS

A3.1 Acceptable quality level (AQL)

When a continuous series of lots or batches is considered, the quality level which, for the purpose of sampling inspection, is the limit of a satisfactory process average (see AS 1199.1).

NOTE: The designation of an AQL does not imply that a manufacturer has the right knowingly to supply any non-conforming unit of product.

A3.2 Material or compound batch

A clearly identifiable quantity of a particular material or compound.

A3.3 Production batch

A clearly identifiable collection of units, manufactured consecutively or continuously under the same conditions, using material or compound to the same specification.

A3.4 Lot

A clearly identifiable subdivision of a batch for inspection purposes.

A3.5 Sample

One or more units of product drawn from a batch or lot, selected at random without regard to quality.

NOTE: The number of units of product in the sample is the sample size.

A3.6 Sampling plan

A specific plan, indicating the number of units of components or assemblies to be inspected or tested.

A3.7 Process verification test (PVT)

A test performed by the manufacturer on materials, components, joints or assemblies at specific intervals to confirm that the process continues to be capable of producing components conforming to the requirements of the relevant Standard.

NOTE: Such tests are not required to release batches of components and are carried out as a measure of process control.

A3.8 Batch release test (BRT)

A test performed by the manufacturer on a batch of components, which has to be satisfactorily completed before the batch can be released.

A3.9 Type testing (TT)

Testing performed to prove that the material, component, joint or assembly is capable of conforming to the requirements of the relevant Standard.

A4 MINIMUM SAMPLING AND TESTING FREQUENCY PLAN

A4.1 General

Tables A1 and A2 set out the minimum sampling and testing frequency plan for a manufacturer to demonstrate compliance to this Standard. Where variations to this plan are made, demonstration of conformance with the minimum requirements may be necessary.

A4.2 Testing

Testing shall be conducted by a testing laboratory or facility that fulfills the requirements of AS/NZS ISO/IEC 17025, General requirements for the competence of testing and calibration laboratories.

NOTE: AS ISO/IEC 17025 can apply to first-party, i.e. manufacturer or supplier, second-party or third-party testing laboratories and facilities.

A4.3 Retesting

In the event of a test failure, the products manufactured since the previous test(s) conforming to the requirements outlined in Table A1 shall be quarantined as a batch. A further set of samples shall be selected randomly from the quarantined batch using a sampling plan to AS 1199.1. If the retest requirements are met, the batch may be released and compliance with this Standard for the quarantined batch may be claimed.

Should a failure on retesting occur, then the quarantined batch shall be rejected and claims and/or marking indicating conformity to this Standard shall be suspended until the cause of the failure has been identified and corrected.

A4.4 Rejection after retest

In the event of a quarantined batch being rejected after retesting, it may be subjected to 100% testing for the failed requirement(s), and only those items found to comply may be claimed and/or marked as conforming with this standard.

TABLE A1 MINIMUM SAMPLING AND TESTING FREQUENCY PLAN

Characteristic	Clause	Requirement	Test Method	Frequency
MATERIAL PROPERTIES FOR RESIN SYSTEM				
Resin type	Table 1	UP, VE, or EP	Declared value	At any change in material formulation, design or process
Filler type	Table 1	None, inorganic or organic	Declared value	
Curing agent type	Table 1	Heat-initiated, light-initiated, or ambient cure	Declared value	
PROPERTIES OF CURED LINER				
Glass transition temperature	Table 2	Recorded value	ASTM D7028-07	At any change in material formulation, design or process
Water absorption	Table 2	Recorded value	AS3862	
PERFORMANCE REQUIREMENTS				
Mean wall thickness	Table 2	Not less than the design thickness	ISO 3126	At any change in material formulation, design or process
Minimum wall thickness	Table 2	Not less than 87.5% of design thickness	ISO 3126	
Water tightness	2.3 6.1 6.2	Installed liner, terminations and connections to existing network are water tight	AS/NZS 2566.2, Section 6	As per water agency testing frequency requirements
Contact with drinking water	Table 2 3.2 3.6.1 3.6.2	All system components meet standard requirements	AS/NZS 4020	At any change in material formulation, design or process
Elastomeric seals	3.6.1	Compliance with AS 1646 and AS 681.1	Product certification to AS 1646 and AS 681.1	
Mechanical Type Tests (TTs)				
Performance	4.2	Tensile properties	ASTM 3039 AS 1145.2 (Type 2 or 3) ASTM 2290 ISO 8521 (hoop) ISO 8513 (axial)	At any change in material formulation, design or process. Test results considered valid for 5 years.
	4.3	Flexural properties	ASTM D790 ISO 14125	
	4.4	Resistance to short-term hydraulic pressure (for Class C, and Class B and A)	ASTM D1599	
	4.5	Adhesion (for Class C, and Class B and A if adhesion is required for sealing or bonding to host pipe)	ASTM D4541 ASTM D7234 AS 3894.9	

Characteristic	Clause	Requirement	Test Method	Frequency
	4.6	Vacuum (for Class B and A)	See Section 4.6	
	4.7	Thermal expansion/contraction	ASTM D696 ASTM E289 ASTM E831 ISO 11359-2	
	4.12	Wet strength reduction factor	ASTM D570 ISO 62 or testing underwater and compared with testing in air	
Type tests (TTs) long-term				
Performance	4.8	Tensile rupture strength	ASTM D2990 ISO 13003 ASTM D2992	At any change in material formulation, design or process. Test results considered valid for 10 years.
	4.9	Tensile creep modulus	ASTM D2990 ISO 899-1 ASTM D6992	
	4.10	Flexural creep modulus	ASTM D2990 ISO 899-2	
	4.11	Fatigue strength	ISO 13003, ASTM D2992	
	4.12	Wet creep reduction factor	ASTM D570 ISO 62 or testing underwater and compared with testing in air	

APPENDIX B - STRUCTURAL CLASSIFICATION OF LINERS

(Normative**)**

Piping systems used for the renovation of pressure pipelines are classified in ISO 11295 in accordance with their structural performance as follows.

B1 CLASS A

i. Can survive internally or externally induced failure of the host pipe.
ii. The long-term pressure rating is equal to or greater than the maximum allowable operating pressure of the renovated pipeline.
iii. The liner has sufficient inherent ring stiffness to be self-supporting when depressurised.
iv. Is capable of spanning gaps and holes long-term at the maximum allowable operating pressure.
v. Provides an internal barrier to the corrosion, abrasion and/or tuberculation / scaling of the host pipe and to the contamination of the pipe contents by the host pipe. Generally it also reduces the surface roughness for improved hydraulic performance.

B2 CLASS B

i. The liner has sufficient inherent ring stiffness to be self-supporting when depressurised.
ii. Is capable of spanning gaps and holes long-term at the maximum allowable operating pressure.
NOTE: The liner becomes sufficiently close fit during installation or during initial operation for transfer of the internal pressure stress to the host pipe.
iii. Provides an internal barrier to the corrosion, abrasion and/or tuberculation / scaling of the host pipe and to the contamination of the pipe contents by the host pipe. Generally it also reduces the surface roughness for improved hydraulic performance.

B3 CLASS C

i. The liner relies on adhesion to the host pipe to be self-supporting when depressurised.
ii. Is capable of spanning gaps and holes long-term at the maximum allowable operating pressure.
NOTE: The liner becomes sufficiently close fit during installation or during initial operation for transfer of the internal pressure stress to the host pipe.
iii. Provides an internal barrier to the corrosion, abrasion and/or tuberculation / scaling of the host pipe and to the contamination of the pipe contents by the host pipe. Generally it also reduces the surface roughness for improved hydraulic performance.

B4 CLASS D (Note this Class of pipe is not included in this WSAA Standard)

i. The liner relies on adhesion to the host pipe to be self-supporting when depressurised.
ii. Provides an internal barrier to the corrosion, abrasion and/or tuberculation / scaling of the host pipe and to the contamination of the pipe contents by the host pipe. Generally it also reduces the surface roughness for improved hydraulic performance.

APPENDIX C - DESIGN METHODOLOGY FOR A CIPP LINER

(Normative)

SCOPE

This Appendix sets out a means for consistent demonstration of conformity with this Standard to determine either: (a) the minimum liner thickness required for a liner for the intended service life or (b) predict the service life of a lined pipe. The following limit states (Figure 2) are used for each class of liner (See Appendix B).

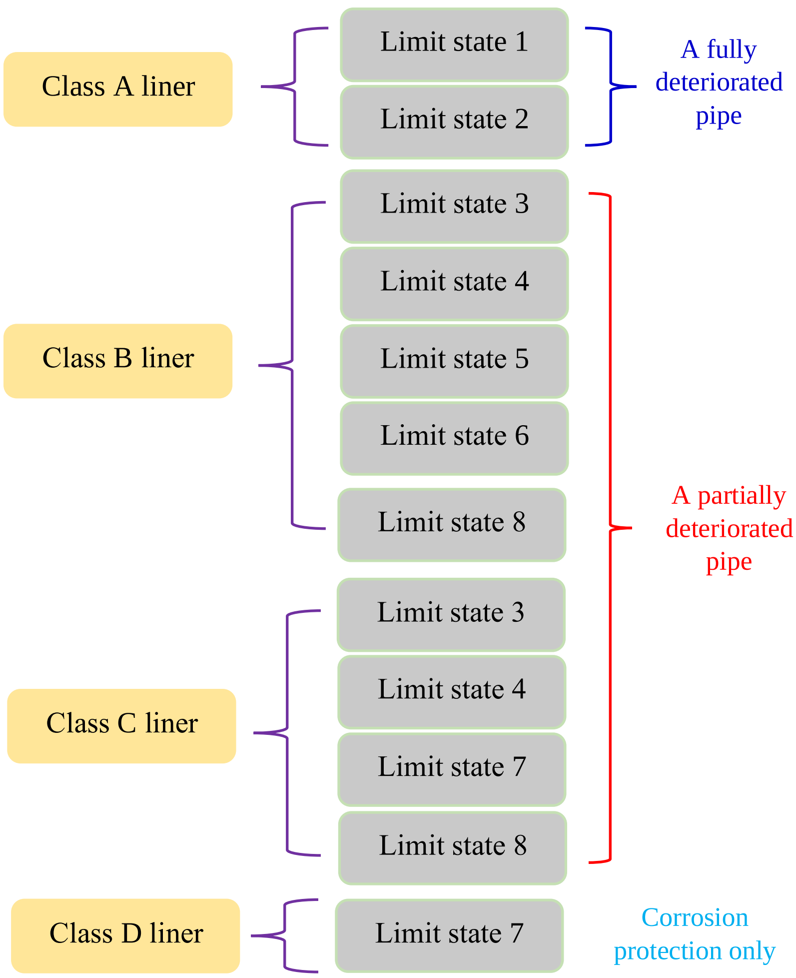

Figure 2. Lined pipe analysis for different classes of linings

FULLY DETERIORATED HOST PIPE

LIMIT STATE 1: INTERNAL PRESSURE (HOOP FAILURE)

For internal pressure check, the maximum stress in the liner σ_{max} (MPa) shall not be larger than the tensile strength of the liner in the hoop direction

$$\sigma_{max} \leq \sigma_{thl} \tag{1}$$

where σ_{thl} is the long-term strength (hoop) of the liner and is the lesser value of either: the tensile rupture strength[2] (hoop) $\sigma_{thl,r}$ or fatigue strength[3] (hoop) $\sigma_{thl,f}$ determined by Section 4.8 or 4.11 respectively (MPa).

The maximum stress shall be determined as follows (ASTM F1216 2016)

$$\sigma_{max} = \frac{P_{max} \cdot \left(\frac{D_L}{T_L} - 1\right) \cdot N}{2} \tag{2}$$

where P_{max} is the maximum allowable pressure, which is the larger of the operating pressure P (MPa) and the sum of the operating pressure P and cyclic surge pressure P_C (MPa) divided by 1.4 $(P + P_C)/1.4$ (AWWA M45 2013), D_L is the external diameter of the liner (mm), T_L is the design wall thickness of the liner (mm), N is a factor of safety, which considers the effect of liner imperfections (Section 3.3) and uncertainty in parameters involved in analysis.

LIMIT STATE 2: BUCKLING UNDER EXTERNAL LOADS (SOIL, HYDROSTATIC LOADS, LIVE LOADS) EXCLUDING INTERNAL PRESSURE

This limit state applies when the pipe is out of service, e.g. pressure in the pipe is removed for maintenance or the pipe is under vacuum pressure, or when the total external pressure is greater than the operating pressure, P. For buckling check, the total external pressure on pipes q_t (MPa) shall be no larger than the liner capacity for total external pressure q_{tc} (MPa)

$$q_t \leq q_{tc} \tag{3}$$

The total external pressure on pipes q_t (MPa) shall be determined as follows (ASTM F1216 2016)

$$q_t = \frac{9.81 \cdot H_w + \gamma_s \cdot H \cdot R_W}{10^6} + w_q \tag{4}$$

where H_w is the height of water above pipe, measured from pipe crown (mm), γ_s is the soil unit weight (kN/m^3), H is the pipe burial depth (mm), R_W is the water buoyancy factor (unitless) and shall be determined using Equation (5)

$$R_W = 1 - 0.33 \cdot \frac{H_w}{H} \geq 0.67 \tag{5}$$

where w_q is the live load (pressure) at the burial depth (MPa) from AS 2566.1 (1998), Equation 4.7.2(1). It should be noted that if $q_t \leq P$, the internal operational pressure governs the design (Equation (2)) (AWWA 2019) and buckling under external loads does not need to be checked.

The liner capacity for total external pressure q_{tc} shall be calculated using Equation (6)

$$q_{tc} = \frac{1}{N}\left[\frac{8 \cdot R_W \cdot B' \cdot E_s \cdot C \cdot CRF(\beta t) \cdot E_{LB} \cdot {T_L}^3}{3 \cdot D^3}\right]^{\frac{1}{2}} \tag{6}$$

[2] Note the value of σ_{thl} can be taken at a time corresponding to the estimated service life. For example, if a liner service life is 50 years, and in that time 50 years of continuous or intermediate pressure (fluid or ground pressure) will be applied on the liner, a σ_{thl} value corresponding to 50 years would be conservative. Alternatively, an estimated duration of internal operating pressure can be used. Note: see 4.12 for testing temperature.

[3] Note the value of $\sigma_{thl,f}$ can be taken at a time corresponding to the likely number of recurring cyclic surge pressure cycles estimated for service life. For example, if we predict that a minimum of two surge pressure cycles occur during a day (pump start-up and pump shutdown) the minimum pressure transient cycles to be experienced by a liner in a 50-year service life would be 36,500. From this number we can estimate the $\sigma_{thl,f}$ of the liner.

$$B' = \frac{1}{1 + 4e^{\frac{-0.213H}{10^3}}} \tag{7}$$

where E_s is the soil modulus[4] (MPa) (AS 2566.1 1998), C is the ovality reduction factor and it is defined as follows

$$C = \left[\left(1 - \frac{\Delta}{100}\right) \Big/ \left(1 + \frac{\Delta}{100}\right)^2\right]^3 \tag{8}$$

where Δ is the ovality of the original pipe (%)[5], $CRF(\beta t)$ is the creep retention factor (Section 4.9 and 4.10) at time βt, β is the fraction of liner service life when out of service[6], t is the design lifetime of liner (years), E_{LB} is the lesser of: the short-term flexural modulus of elasticity (hoop) of the liner (E_{fh}) (GPa) (Section 4.3) or short-term tensile modulus of elasticity (hoop) of the liner (E_{th}) (GPa) (Section 4.2).

PARTIALLY DETERIORATED HOST PIPE

LIMIT STATE 3: HOLE SPANNING

A through-wall hole (defect) may form at a zone of graphitization, by a corrosion pit that penetrates through the pipe wall, or at a disconnected service line.

For hole spanning checks, the maximum stress in the liner σ_{max} (MPa) shall be no larger than the tensile strength of the liner σ_t (MPa).

$$\sigma_{max} \leq \sigma_{tl} \tag{9}$$

where σ_{tl} is the long-term strength of the liner and is the lesser value of either: the tensile rupture strength, which can be either in the axial $\sigma_{tal,r}$ or in the hoop $\sigma_{thl,r}$ directions (MPa), or fatigue strength (hoop) of the liner $\sigma_{thl,f}$ (MPa).

σ_{max} shall be determined using the hole spanning equation (Fu et al. 2021a) as follows

$$\frac{\sigma_{max}}{P_{max}} = \frac{1.45 \cdot \left(\frac{E_p}{CRF(\mathrm{t}) \cdot E_L}\right)^{-0.183} \cdot \left(\frac{T_L}{D}\right)^{-1.13} \cdot (1 - 0.068 \cdot f) \cdot N}{\left[1 + 21.94 \cdot \exp\left(-20.63 \cdot \frac{d}{D}\right)\right]\left[\frac{T}{D} + 2 \cdot \left(\frac{T}{D}\right)^{-0.052}\right]} \tag{10}$$

where E_p is the modulus of elasticity of host pipe material (GPa)[7], and E_L is the greater value of either: the short-term modulus of elasticity of the liner in the hoop direction (E_{th}) or axial direction (E_{ta}). D and T are the internal diameter and wall thickness of the host pipe, f is the

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[4] E_s can be taken from the higher range of values of E'_e and E'_n in Table 3.2 (AS 2566.1 1998) due to the soil being in its natural state (trenchless installation with still in-situ soil and host pipe can be assumed as soil is in a dense state).

[5] A percentage ovality of the original pipe equals:

$$.100 \times \frac{(Mean\ internal\ diamter - Minimum\ internal\ diamter)}{Mean\ internal\ diameter}$$

or

$$100 \times \frac{(Maximum\ internal\ diamter - Mean\ internal\ diamter)}{Mean\ internal\ diameter}$$

[6] A fraction of time out of service is used in this case as in most cases the lined pipe will not be subjected to both vacuum and external loads over a significant period of time, for example 14 days maximum. The creep modulus ($CRF \cdot E_L$) will not experience vacuum and soil loads (host pipe will support a lot of these loads) for the whole service life. Also, the elastic creep modulus will tend to recover when the internal pressure is removed.

[7] If no testing results are available the following standard values shall be used for modulus of elasticity of host pipe materials: Asbestos cement - 15 GPa, Cast iron - 100 GPa, Mild steel - 200 GPa, Ductile iron – 165 GPa.

friction coefficient of the interface between the host pipe and the liner[8], d is the diameter of the hole (defect) in the host pipe.

LIMIT STATE 4: GAP SPANNING

Gaps in deteriorated cast iron pipes may exist due to past pipe repairs, joints or formed due to axial soil movements induced by thermal effects, thrust and/or horizontal vehicle loads etc. In addition, ring fractures or joint failures may occur in pipes subjected to axial tension and/or bending and these ring fractures and failed joints can be considered as gaps with zero width.

For gap spanning checks, the maximum stress in the liner σ_{max} shall be no larger than the tensile strength of the liner σ_t.

$$\sigma_{max} \leq \sigma_{tal,r} \tag{11}$$

where σ_{max} can be a combination of axial, or principal, short-term or long-term tensile stress, $\sigma_{tal,r}$ is the tensile rupture strength (axial) of the liner (MPa).

Three sub-limit states are considered, namely, liner covering existing gap under internal pressure, formation of gaps for lined pipes under internal pressure and lined pipes with ring fractures under internal pressure and bending as shown in Figure 3.

[8] The friction coefficient ranges between 0 to 0.577 and depends on the adhesion of the liner to the host pipe (or CML). The recommended ranges of friction coefficients for the interfaces between host pipes and polymeric liners are as follows: AC or CML 0.1–0.2 and Metallic 0.3–0.4.

4-1 Liner covering existing gaps under internal pressure

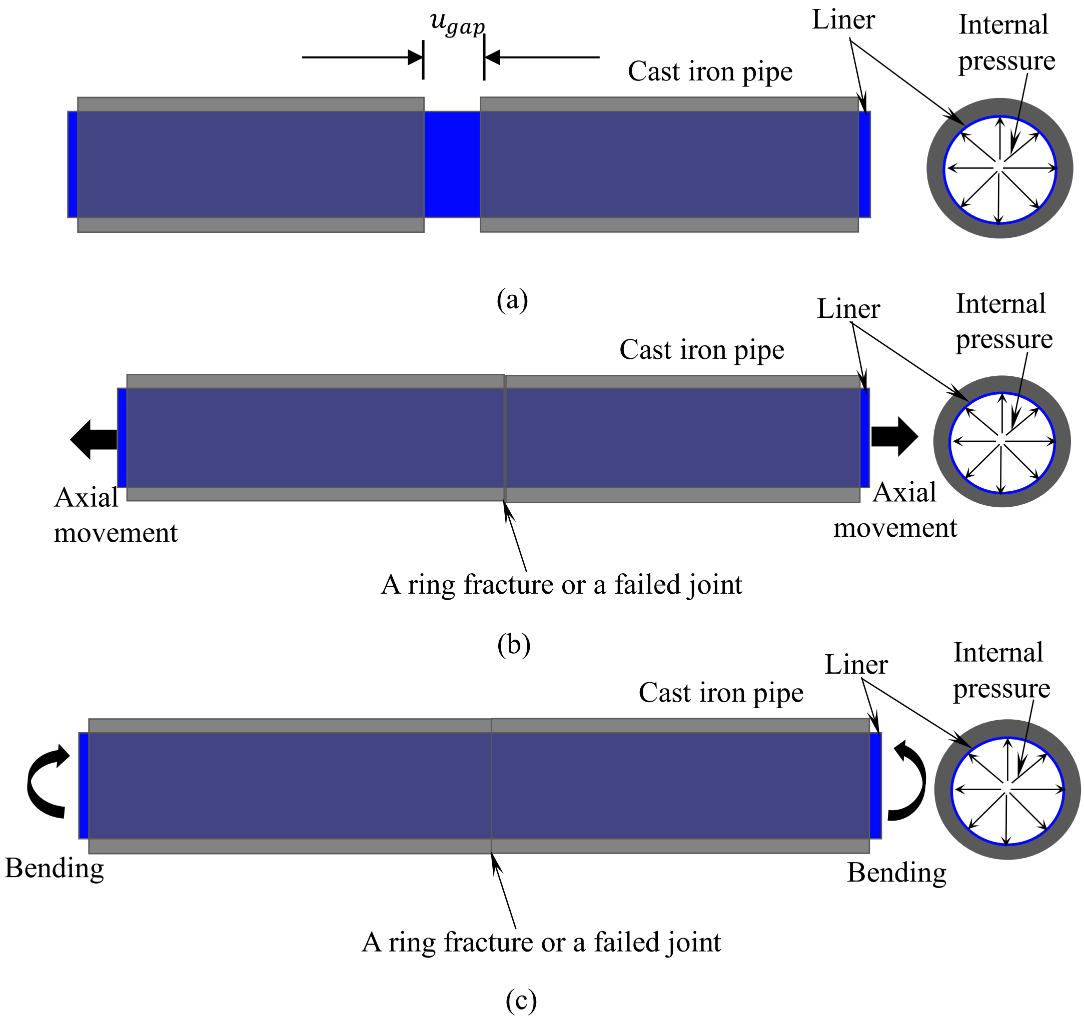

Figure 3. Pressurised cast iron pipes lined with polymeric liners: a) Liner covering existing gaps under internal pressure; (b) Formation of gaps for pressurised lined pipes under axial movements; (c) A lined pipe with a ring fracture under internal pressure and bending

The existing gaps are considered to be formed due to pipe repairs, joints or other causes. When an existing gas is present in a host pipe, the maximum stress in the liner σ_{max} can be determined using the equation as follows (Fu et al. 2021b)

$$\frac{\sigma_{max}}{P_{max}} = \frac{2.33 \cdot \frac{u_g}{T_L} \cdot (1 + 0.52 \cdot f - 0.15 \cdot f^2) \left(1 - 0.02 \cdot \left(\frac{E_p}{CRF(\mathrm{t}) \cdot E_L}\right)^{0.5}\right) \cdot N}{1 + 0.39 \cdot exp\left(-2.7 \cdot \frac{CRF(\mathrm{t}) \cdot E_L}{P_{max} \cdot N}\right)} \tag{12}$$

where u_g is the existing gap width of host pipe (mm) and E_L is the greater value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}). Note: Equation (12) is only valid for a gap width of up to 35 mm. For gap widths greater than 35 mm, the pipe should be treated as fully deteriorated (see fully deterioration pipe - Limit state 1).

4-2 Formation of gaps for pressurised lined pipes under axial movements

After a ring fracture has developed in the host pipe, a gap might be formed due to thermal effects, thrust, horizontal vehicle loads or other loads. During the gap formation process, the maximum stress in the liner $\sigma_{a,max}$ (MPa) will develop and can be calculated by the following equation (Fu et al. 2021b)

$$\frac{\sigma_{a,max}}{P_{max}} = 31.5 \cdot \left(\frac{u_{gp}}{T_L}\right)^{0.5} \cdot f^{0.4} \cdot \left(\frac{CRF(\mathrm{t}) \cdot E_{ta}}{P_{max} \cdot N}\right)^{0.43} \cdot \left(\frac{E_p}{CRF(\mathrm{t}) \cdot E_{ta}}\right)^{-0.02} \cdot N \tag{13}$$

where u_{gp} is the gap formed due to the axial movement or axial pulling force (mm) and E_{ta} is the short-term tensile modulus of elasticity (axial) of the liner (GPa).

4-3 Lined pipes with ring fractures under internal pressure and bending

The limit state applies when there is a ring fracture or failed joint in the host pipe and the lined pipe is under combined internal pressure and bending. The bending can be caused by ground movements from reactive soils or frost or other sources.

The maximum stress in the liner for a lined pipe with a ring fracture under internal pressure and bending shall be calculated using the following equation (Fu et al. 2021b)

$$\frac{\sigma_{a,max}}{P_{max}} = \frac{\left(\frac{T_L}{D}\right)^{-0.246} (1 + 0.53 \cdot f - 0.3 \cdot f^2)\theta^{0.82} \left(\frac{CRF(t) \cdot E_{ta}}{P_{max} \cdot N}\right)^{0.81} \left(\frac{E_p}{CRF(t) \cdot E_{ta}}\right)^{0.053} \cdot N}{\frac{T}{D} + 0.043 \cdot \left(\frac{T}{D}\right)^{-0.508}} \tag{14}$$

where θ is the rotation angle of the pipe (°)[9]. Note that this formula was derived based on linear elastic liner properties and therefore underestimates the local capacity of CIPP liners with biaxial stress strain curves.

LIMIT STATE 5: BUCKLING UNDER EXTERNAL PRESSURE

For this limit state, pressure pipes are considered to be depressurized periodically either due to routine maintenance or cyclical events. Note that this is for partially deteriorated host pipe. The polymeric liner is considered to take only the groundwater load while the host pipe takes the soil and surcharge load.

For buckling under external pressure check, the groundwater load P_G (MPa) shall be no larger than the groundwater load capacity P_{GC} (MPa)

$$P_G \leq P_{GC} \tag{15}$$

The external pressure capacity shall be determined by the following equation (ASTM F1216 2016)

$$P_{GC} = \frac{2000 \cdot K \cdot CRF(\beta t) \cdot E_{fh}}{(1 - \nu_L^2)} \cdot \frac{C}{\left(\frac{D}{T_L} - 1\right)^3} \tag{16}$$

where K is the enhancement factor of the soil and existing pipe adjacent to the liner. A minimum value of 7 for K shall be used where there is full support of the existing pipe (ASTM F1216 2016), E_{fh} is the short-term flexural modulus of elasticity in the hoop direction (GPa), ν_L is the Poisson's ratio of the liner.

For rigid host pipes, the applied external pressure on the liner P_G shall be determined as follows

[9] The recommended range of rotation angle is 0–1°. For a rotation angle greater than 1°, a Class A liner or flexible liner is recommended.

$$P_G = \left(\frac{9.81 \cdot (H_w + D_M)}{10^6} + P_v\right) \cdot N \tag{17}$$

where H_w is the height of groundwater above pipe (mm), measured from pipe crown, D_M is the mean diameter of the host pipe (mm), P_v is the vacuum pressure (MPa)[10].

For flexible host pipes, 50% of the live load is considered to be transferred to the liner (AWWA 2019). This is a conservative estimate since host pipes are assumed to be structurally sound for a Class B design and most host pipes are rigid.

The applied external pressure for flexible pipe shall be determined as follows:

$$P_G = \left(\frac{9.81 \cdot (H_w + D_M)}{10^6} + P_v\right) \cdot N + w_q \cdot N/2 \tag{18}$$

LIMIT STATE 6: THERMAL EFFECTS

When both liner ends are anchored, the lining system shall have sufficient strength in the axial direction to withstand thermal end loads as follows

$$10^3 \cdot \alpha \cdot E_A \cdot \Delta T \cdot N \leq \sigma_A \tag{19}$$

where α is the coefficient of thermal expansion (mm/mm/°C), E_A is the liner tensile or compressive modulus in the axial direction (GPa), ΔT is the temperature change or maximum range of temperature experienced by the liner during service (℃)[11], σ_A is the short-term tensile or compressive strength of the liner in the axial direction (MPa). Note either tensile or compression can be used but not a combination of the two.

LIMIT STATE 7: ADHESION CHECK

Note that a pipe might be depressurised due to routine maintenance, normal operation or cyclical events such as pressure transients. Therefore, given these circumstances, adhesion between the host pipe and liner needs to be checked.

For the adhesion check, the external pressure on the liner P_N (MPa) shall be no larger than the adhesion strength of the liner to host pipe substrate σ_{ad} (MPa).

$$P_N \leq \sigma_{ad} \tag{20}$$

where P_N shall be determined for two different load combinations as follows

7-1 Combination of external water pressure and vacuum

The external pressure on the liner P_N is the same as P_G as determined in Equation (17).

7-2 Combination of external water pressure and thermal loads

The external pressure on the liner P_N shall be determined as follows

$$P_N = \frac{\gamma_w \cdot (H_w + D_M) \cdot N}{10^6} + 10^3 \cdot \alpha \cdot E_{fh} \cdot \Delta T \tag{21}$$

[10] Vacuum pressure ranges from 0 MPa (no vacuum) to 0.1 MPa (high vacuum). If pipe is subjected to vacuum loading a suggested value of 0.1 MPa shall be used if measurements are not available.

[11] The temperature change, fluctuations or maximum range of temperature expected to occur in the host pipe and liner during service. The difference between the maximum and minimum temperature.

LIMIT STATE 8: UNIFORM REDUCTION OF PIPE WALL THICKNESS (FOR AC PIPES ONLY)

Due to lime leaching, the effective wall thickness of AC pipe will reduce over time. Consequently, the maximum stress in the liner σ_{max} will increase over time. To ensure safety, the maximum stress in the liner σ_{max} (MPa) shall not exceed the tensile strength of the liner σ_{thl}.

$$\sigma_{max} \leq \sigma_{thl} \tag{22}$$

The maximum stress in the liner σ_{max} shall be determined as follows

$$\sigma_{max} = \frac{E_L P_{max} D_L}{2(E_p T + E_L T_L)} \tag{23}$$

It should be noted that the maximum stress in the AC pipe σ_p (MPa) shall not exceed the tensile strength of the AC host pipe material $\sigma_{t,AC}$ (MPa)[12].

$$\sigma_p \leq \sigma_{t,AC} \tag{24}$$

If this condition is not met then the liner shall be designed as a standalone liner, i.e., the host pipe is considered to be fully deteriorated.

The maximum stress in the AC pipe σ_p shall be determined as follows

$$\sigma_p = \frac{E_p P_{max} D_L}{2(E_p T + E_L T_L)} \tag{25}$$

Notation

C Ovality reduction factor

CRF Creep retention factor

$CRF(t)$ Creep retention factor at design lifetime t

$CRF(\beta t)$ Creep retention factor at time βt

d Diameter of the hole (defect) in the host pipe (mm)

D Internal diameter of the pipe (mm)

D_L External diameter of the liner(mm)

D_M Mean diameter of the host pipe (mm)

E_A Short-term tensile or compressive modulus of the liner in the axial direction (GPa)

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[12] The tensile strength of the AC host pipe material shall be determined from either standards (BS486 1933, AS A41 1959, AS 1171 1977) or AC pipe testing. If no testing results are available the following standard values shall be used:

- for AC pipes buried before 1959, use 15.5 MPa (BS486, 1933)
- for AC pipes buried between 1959 and 1970, use 22.1 MPa (AS A41 1959)
- for AC pipes buried after 1970, use 23.5 MPa (AS 1171, 1977)

E_L Short-term modulus of elasticity of the liner (GPa) and is the greater value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}).

E_{LB} Short-term modulus of elasticity of the liner (GPa) for buckling and is the lesser value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}).

$E_{l,dry}$ Dry creep modulus of the liner (GPa)

$E_{l,wet}$ Wet creep modulus of the liner (GPa)

E_{fa} Short-term flexural modulus of elasticity (axial) of the liner (GPa)

E_{fal} Flexural creep modulus (axial) of the liner (GPa)

E_{fh} Short-term flexural modulus of elasticity (hoop) of the liner (GPa)

E_{fhl} Flexural creep modulus (hoop) of the liner (GPa)

E_p Modulus of elasticity of host pipe material (GPa)

E_s Soil modulus (MPa)

E_{ta} Short-term tensile modulus of elasticity (axial) of the liner (GPa)

E_{tal} Tensile creep modulus (axial) of the liner (GPa)

E_{th} Short-term tensile modulus of elasticity (hoop) of the liner (GPa)

E_{thl} Tensile creep modulus (hoop) of the liner (GPa)

f Friction coefficient of the interface between the host pipe and the liner (unitless)

H Pipe burial depth (mm)

H_w Height of water above pipe, measured from pipe crown (mm)

K Enhancement factor

N Factor of safety

P_{max} Maximum allowable pressure (MPa)

P Operating pressure (MPa)

P_c Recurring cyclic surge pressure (MPa)

P_G Groundwater load (MPa)

P_{GC} Groundwater load capacity (MPa)

P_N External pressure on the liner (MPa)

P_v Vacuum pressure (MPa)

q_t Total external pressure on pipes

q_{tc} Liner capacity for total external pressure

R_W Water buoyancy factor (unitless)

t Design lifetime of liner (years)

T Pipe wall thickness allowing for uniform corrosion (mm)

T_L Liner design thickness (mm)

u_g Existing gap width of host pipe (mm)

u_{gp} Gap formed due to axial movement or pulling force (mm)

w_q Live load (pressure) at the burial depth (MPa)

α Coefficient of thermal expansion/contraction (mm/mm/°C)

β Fraction of liner service life when out of service

γ_s Soil unit weight (kN/m^3)

Δ Ovality of the original pipe (%)

ΔT Temperature change (°C)

θ Rotation angle (°)

ν_L Poisson's ratio of liner (unitless)

σ_A Short-term tensile or compressive strength of the liner in the axial direction (MPa)

σ_{ad} Adhesion strength of the liner to host pipe substrate (MPa)

$\sigma_{a,max}$ Maximum stress (axial) in the liner (MPa)

σ_{fa} Short-term flexural strength (axial) of the liner (MPa)

σ_{fh} Short-term flexural strength (hoop) of the liner (MPa)

σ_{max} Maximum stress in the liner (MPa)

σ_p Maximum stress in the AC host pipe (MPa)

$\sigma_{t,AC}$ Ultimate tensile strength of AC (MPa)

σ_t Tensile strength of the liner (MPa)

$\sigma_{t,dry}$ Dry tensile strength of the liner (MPa)

$\sigma_{t,wet}$ Wet tensile strength of the liner (MPa)

σ_{ta} Short-term tensile strength (axial) of the liner (MPa)

$\sigma_{tal,r}$ Tensile rupture strength (axial) of the liner (MPa)

σ_{tl} Long-term strength (hoop) of the liner and is the lesser value of either: the tensile rupture strength, which can be either in the axial $\sigma_{tal,r}$ or in the hoop $\sigma_{thl,r}$ directions (MPa), or fatigue strength (hoop), $\sigma_{thl.f}$ (MPa)

σ_{th} Short-term tensile strength (hoop) of the liner (MPa)

$\sigma_{thl,r}$ Tensile rupture strength (hoop) of the liner (MPa)

σ_{thl} Long-term strength (hoop) of the liner and is the lesser value of either: the tensile rupture strength (hoop), $\sigma_{thl,r}$ (MPa) or fatigue strength (hoop), $\sigma_{thl.f}$ (MPa)

$\sigma_{thl.f}$ Fatigue strength of the liner (MPa)

ϕ_c Wet creep reduction factor

ϕ_s Wet strength reduction factor

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