DESIGN GUIDANCE FOR SELECTING A CULVERT LINER

I. Table of Contents

II. Table of Figures

III. GOALS FOR LINING CULVERTS

This guidance document assumes that a decision has been made by CT DOT to rehabilitate a culvert using a structural liner. Nonstructural liners will be allowed as a temporary method to stabilize an existing culvert quickly to provide time to initiate a project to address the proper rehabilitation or replacement of the culvert. A nonstructural liner may also be used in combination with a structural liner to achieve a smoother interior surface. Selecting a structural liner to rehabilitate a culvert is complicated. Selection requires consideration of many stakeholders. It is important to set some goals that the culvert liner must satisfy. These typically include:

A. Meets the Purpose and Need established for the project
B. Coordinates with other projects in Planning, Design or Construction phases
C. Considers the need for culvert extension for roadway widening or to minimize the height of endwalls
D. Is structurally adequate (shall be designed by LRFD Design Methodology)
E. Is hydraulically adequate (allowable headwater depth, effects of flooding both upstream and downstream, etc.)
F. Avoids potential erosion, piping, and scour
G. Is durable
H. Is capable of providing a 50-year minimum design service life unless the Department authorizes a lesser service life
I. Considers the minimum height inside of the lined culvert for inspection access (typically 5')
J. Is maintenance free, needs little maintenance, or does not hinder access for maintenance
K. Supports habitat/passage for fish and other species where applicable
L. Considers the need for a detour or stage construction
M. Considers construction access to the inlet and outlet
N. Considers geometry of channel and available length at inlet and outlet to set liner in channel before it is pushed or pulled into the host culvert.
O. Minimizes environmental impact from construction activities
P. Is constructible
Q. Considers worker safety for culvert entry and construction techniques
R. Considers water handling needs

IV. INFORMATION COLLECTION

The Preliminary Design phase begins with a Rehabilitation Study Report (RSR) to investigate culvert lining options and studying viable options to present alternates. Before viable options can be investigated, information about the culvert to be lined and the site where the culvert is located must be collected. Begin by collecting original construction plans, as-built plans, and plans for subsequent projects for rehabilitation or extension of the culvert. If the culvert conveys a watercourse, the previous hydraulic analysis and reports should be obtained as well. Bridge maintenance memos and responses shall also be obtained. The Bridge file contains several Bridge Safety Inspection Reports, load rating reports, and numerous other documents that are valuable sources of information. Other documents that may provide useful information are the Proposed Project Information (PPI) developed for the culvert and OEP Early Resource Screening information. These documents contain preliminary purpose and need as well as environmental concerns at the project location. This can provide an early notice of fisheries preliminary findings and recommendations.

The following information is typically available in the Bridge Safety Inspection Report, but if not, should be collected:

A. Age of culvert (year built)
B. Geographic location
C. Feature carried (if a roadway, include width of roadway, configuration of lanes and shoulders and position of roadway between inlet and outlet of culvert)
D. ADT and ADTT and classification of roadway carried by culvert
E. Feature conveyed through culvert (roadway, path, stream, etc.)
F. Structure type (Pipe, pipe arch, vertical or horizontal ellipse, box culvert, arch, etc.)
G. Shape and size (span, rise, diameter, etc.)
H. Material and thickness or gage (asphalt-coated corrugated steel, galvanized steel, masonry, etc.)
I. Maximum and minimum height of fill over culvert
J. Embankment slopes
K. Channel characteristics, including width, shape, depth, natural or paved bottom, etc.
L. Condition rating of the culvert, wingwalls, endwalls, etc.
M. Documented damage to the structure, including loss of coating systems, overall corrosion, loss of thickness at isolated locations and along invert, and perforations
N. Deflections and obstructions within the culvert
O. Voids below invert and behind culvert walls
P. Presence of erosion and scour at inlet and outlet or presence of a cutoff wall or protective apron
Q. Piping of water below invert
R. Flow depth measurements

V. ENVIRONMENTAL TESTING

When a culvert rehabilitation/replacement project is initiated, the bridge inspection report should be reviewed to determine if there is excessive corrosion in the culvert at and below the high-water mark inside the culvert. Reports for culverts along the same waterway upstream and downstream can also be reviewed to determine if they have experienced excessive corrosion. Excessive corrosion can be related to corrosion plus abrasion caused by the streambed material, but if the rate of deterioration has accelerated, consideration shall be given to perform environmental testing at the culvert site to determine the potential presence of corrosive elements. Such testing will typically be requested at project initiation and shall be performed before preparing RSR alternates for culvert lining to avoid selecting liner materials that could be vulnerable to corrosion at the site. A request for environmental testing is warranted when the watershed area upstream of the culvert contains any of the following:

- Past or present industries such as mines, tanneries, steel mills, pulp mills, textile plants, metal and plating industries, production of fertilizers, soap, paper, dyes, fungicides and insecticides
- Water discharge including sewage treatment, industrial wastewater, household wastewater, runoff from a heavily salted roadway, a hazardous waste site or naturally decaying material
- Farmlands that are likely being fertilized.
- Tidal or brackish water

The environmental testing shall be performed by a qualified environmental engineer using properly cleaned equipment and acceptable sampling methods and should include the following tests:

1. pH
2. Resistivity

3. Chloride concentration (testing not necessary in marine environments, but required in potentially brackish water)
4. Sulfate concentration (testing not necessary in marine environments, but required in potentially brackish water)

Sampling shall include:

- Water in the stream
- Water outfall from pipes that outlet upstream of the culvert
- Water from below the channel bottom

Since culvert liners are grouted within the host culvert, they are not as vulnerable to soil-side corrosion as the host culvert. Environmental testing should focus on water in and below the channel and water drainage/runoff that flows into the channel at or near the culvert. During low flow periods, water in the channel mixes with and is affected by subsurface water that interacts directly with the soil. This interaction may alter the pH and resistivity of the water and increase chloride and sulfate concentrations. These changes can produce an environment that is corrosive to the culvert liner.

The Designer shall consider the effect of pH and Resistivity on calculation of service life using the Culvert Liner Selection Worksheet. The effect of chlorides and sulfates is more difficult to quantify but understanding the role these factors play in corrosion and deterioration of the culvert liner is helpful in making a recommendation for a culvert liner in the RSR.

When environmental testing is not warranted or test results are not available during preparation of the RSR, the following assumptions can be made for input into the liner selection worksheet and to assist in determining service life of the liner material being considered:

1. pH:
   - Freshwater rivers: 6.5 (6.0 within pine forests)
   - Saltwater (marine environments): 8.0 (7.5 to 8.5)
   - Brackish water: 7.0 (6.0 to 8.5)
   - Stormwater runoff channels: 5.5 (5.0 to 6.0)
     Rainwater in Connecticut has a pH of about 5.0. These runoff channels may have very low flows or be dry a great deal of the year. Therefore, it is not reasonable to use the lowest pH to estimate service life.
2. Resistivity:
   - Freshwater rivers: R = 4,000 ohm-cm
   - Stormwater runoff channels: R = 5,000 ohm-cm
   - Rivers with direct runoff upstream from heavily salted roads: R = 2,500 ohm-cm
   - Brackish water: R = 200 to 2,000 ohm-cm
   - Saltwater (marine environment): R = 25 ohm-cm

3. Chlorides:
   - Freshwater rivers: 100 ppm or higher chloride concentration in water with a pH of 7.3 or lower can cause corrosion of metal culvert liners. pH may not matter at Abrasion Level 3 and higher.
   - Brackish water: Assume chlorides are at a sufficient concentration to promote corrosion if the tidal influence is anticipated at the culvert site.
   - Saltwater (Marine environment): Assume chlorides are at a sufficient concentration to promote corrosion.

Chlorides are present at culverts in a marine environment or brackish water in areas of tidal influence. Water in marine environments typically has a higher pH than in rivers and streams containing fresh water. When the pH is above 7.3, resistivity has a much greater influence than pH on the corrosion rate of metal culvert liners. Resistivity in saltwater can be very low compared to freshwater. This can significantly shorten the service life of metal culvert liners. A steel liner with a protective polymeric or Type II aluminum coating are protected by their barrier coatings from corrosion and can provide an acceptable service life if abrasion does not destroy the coating first. Galvanized steel and aluminum liners are more vulnerable in saltwater environments and should generally not be specified.

Chlorides may also be present at culverts that receive surface water runoff from roads treated heavily with de-icing salts in the winter. Surface water can seep into roadway embankments and migrate into streams. Drainage outlets can deposit water from catch basins close to the inlet of a culvert. Freshwater streams usually have a pH lower than 7.3. When pH is low and chlorides reduce resistivity, the protective oxidative layer that forms on metal can be dissolved, and corrosion can accelerate. When pH is 7.3 or lower, the equation for service life is a function of both pH and resistivity. At lower pH and resistivity levels, the effect of both variables dramatically shortens the service life of metal culvert liners. Understanding the environment for which the culvert liner is designed is very important.

The presence of de-icing salts is not a year-round phenomenon. Heavy spring rains and melting snow often wash away salts or dilute the concentration in the water that passes through the culvert. Because of the limited seasonal use of de-icing salts, and the fact that corrosion reactions decrease in the colder temperature, corrosion of culvert liners due to chlorides from road salt does not significantly shorten the service life of a culvert. Testing of chloride concentration and resistivity during low flow periods will give the best indication of how chlorides in the water will affect corrosion of a metal culvert liner. Designers shall use judgment when considering how the seasonal fluctuation of chlorides impacts the determination of service life.

4. Sulfates:
   100 ppm or higher Sulfate concentration in water can cause corrosion of metal culvert liners. When pH is below 7.0 and sulfate concentration is 1,500 ppm or more, Designers shall specify low-permeability concrete for invert liners. Type II cement is recommended to resist sulfates.

   Sulfates are mineral salts containing sulfur. Sulfate ions are detrimental to the passive oxide film that protects steel from corrosion. The sulfates do not chemically react to form the corrosion product but are an activator of corrosion. Once the corrosion reaction begins, even if conditions return to those favoring passivation of the metal, corrosion still progresses. Sulfates can act synergistically with chlorides to further accelerate corrosion on metal surfaces. Hydrogen sulfide when present in water makes the water acidic and causes rapid corrosion – even in the absence of oxygen.

   The decay of plants and animals and some industrial processes produce these salts. Mines, tanneries, steel mills, pulp mills, and textile plants also release sulfates in the environment. Industrial wastewater, household wastewater, runoff from a hazardous waste site or naturally decaying material can put sulfates into waterways, rivers, lakes and streams. Water that flows through rock or soil containing gypsum could contain significant sulfate concentration. Water that contains sulfates seeps through soil and contaminates groundwater. Fertilizer applied to fields on farmlands supplies sulfates that can be carried by surface runoff to drainage channels, streams and rivers.

Sulfates can lower the pH of water, causing corrosion to metals. If sufficient acidic water is available, it can neutralize the pH of concrete, leading to corrosion of reinforcing steel. Sulfates can combine with the lime in cement to form calcium sulfate (gypsum), which creates structural weakness in concrete culverts and liners and shortens the life of the concrete.

VI. SITE VISIT AND DESIGN INSPECTION

A site visit is a required step in the Preliminary Design phase and is critical for preparing contract documents. A Design Inspection collects information that is relevant to structural evaluation of the culvert, to the presentation of alternates, and to the preparation of contract documents for a construction project.

Determine if it is safe to enter the culvert. Contact Bridge Safety for confined space requirements. Culverts that are determined to be unsafe to enter may still be able to be surveyed using 3-D laser scanning technology by setting the instrument up at the inlet and outlet ends.

For culverts that are safe to enter, perform a design inspection. The inspection shall include confirmation of all information collected as well as the physical condition of the culvert. It shall include observations of all conditions that affect the proper functioning of the culvert and the rehabilitation of the culvert. Bridge Safety can provide guidance on safety of entering culverts.

Document or verify the following during the design inspection:

A. Roadway width and approach geometry.
B. Ease of access to inlet and outlet.
C. Presence of utilities, roadway drainage, roadway barrier, noise barrier and any other potential obstacle to access or constructability.
D. Proximity of residences, businesses and private property and their access to the roadway near the culvert.
E. Depressions, sinkholes and cracks in the roadway or ground above the culvert, erosion, scour, undercutting of the stream banks and other embankment instability concerns.
F. The presence of regulated areas and potentially sensitive habitats.
G. Identify the presence of sediment, rocks and other debris on the bottom of the culvert. Document the size and type of material present and the depth of material in the culvert.
H. Section loss due to corrosion, abrasion, or other environmental factors. Include general section loss and isolated section loss. Identify the presence and locations of perforations. Section loss will be used to determine the capacity of the culvert to support earth and other loads. If debris is present in the bottom of the culvert, then it may need to be removed to observe and measure damage to the invert. If it is not possible or practical to remove debris during the design phase, the designer shall document the decision to not remove debris. In such cases the designer shall make conservative assumptions regarding the condition of the invert and review those assumptions with the Department for approval. Removal of debris by the construction contractor and inspection of the invert during construction may be an alternative to confirm assumptions made during design. During design, the designer shall develop an alternate plan for rehabilitation should the proposed method of rehabilitation be determined during construction to not be feasible. The Department will decide whether to proceed with the proposed alternate and if the

alternate plan is reasonable to implement by change order. It may be necessary to re-advertise the project if the condition is determined during construction to be considerably worse.

I. Isolated deformations, deflection and distortion. Settlement of the soil beside the culvert or excessive live load can cause deflection or deformation of the culvert. Noncircular culverts are particularly sensitive to bending distortion. A large rock in the backfill can apply a concentrated load on a culvert wall, deforming it unsymmetrically in a localized area. Voids in the backfill or unbalanced compaction during installation can cause unsymmetrical loading on a culvert cross section. Some deformations are caused by the failure of bolts at a seam, which leads to cusping of the culvert plates.

J. Cross sectional measurements of the culvert along its length. Before measuring cross sections, it is recommended to lay out a survey baseline through the culvert to which cross sections may be referenced. Cross sections should be developed at regular intervals along the baseline and at additional, critical locations identified by the designer. Most culverts deflect under load and do not have the same size or shape as when they were first installed. Deflections will vary along the length due to differences in loading. Identify and measure bolt heads, which reduce the available inside dimensions for lining. Removal of debris in the culvert may be required to obtain measurements. Document if the cross section is uniform or changes along the culvert length. Note also if there is a horizontal curvature, sharp bends or angle points in the alignment that would limit the length of liner that can be installed. If any portion of the culvert must be removed to install a liner, note where the removal will begin and end along the length and/or cross section and how much material must be removed.

K. Profile of the culvert invert. High embankments in the middle of the culvert length cause greater settlement in the culvert than at the ends. This can create a sag in the profile of the culvert invert. Elevations along the invert along the entire length of culvert can help a designer determine if there is a sag.

L. Joints (type and condition), if present, between culvert sections. Indicate if the joint is leaking and take note if soil or sediment is washing through the joint.

M. Presence of coatings remaining (usually missing at the bottom) and where along the perimeter the coatings have been worn away. Identify limits of corrosion and abrasion around the perimeter for use in designing a liner for abrasion.

N. Voids in the bedding or backfill. Often, voids in the bedding can be seen through perforations in the invert, but if not visible, voids can be detected by hammer-tapping the culvert to detect a hollow sound). Pay particular attention to voids at the bottom corners of pipe arches. Loss of bearing at the corners can quickly result in failure of the culvert.

O. Average flow condition/depth and high water marks.

P. Observation of whether water flows below the invert instead of/in addition to flowing through the culvert. Flow through the bedding is called "piping," and may create voids below the invert.

Q. Baffles, roughness rings or other instream fish passage or energy dissipation features inside the culvert.

R. Configuration of inlet and outlet. Document wingwall and headwall configuration and condition, mitered or square culvert ends, presence of tapered inlet, flow diversion walls/deflectors, endwalls, slope protection, cutoff walls, aprons, nosing between multiple culvert barrels, debris collection, rock weirs, composition of the channel bed material, sedimentation or erosion of the channel, scour holes, vegetation, etc. Document the inlet configuration for potential hydraulic improvement.

S. Determine if water is salty/brackish (riverine or tidal condition).

T. Test water for pH and resistivity as this can affect the longevity of culvert liners.

U. Width of channel upstream and downstream (Bankfull width). Is the water channelized or does it overflow the banks and cover a floodplain? Does water rise quickly in a flood event or is there a short timeframe in which water can be handled before it overtops a cofferdam?

VII. DETERMINATION OF ABRASION LEVEL

Classify the abrasion level at the culvert on a scale of 1 to 6 as defined in Appendix B, with "1" being the least severe and "6" the most severe. Abrasion Level will be needed during the selection of culvert liner material. Abrasion Level will be used to determine the appropriateness of material and in the calculation of target design service life. Abrasion level is one of the most important determinations in culvert liner selection. Abrasion level directly affects the rate at which liner material wears and helps determine if a liner material is suitable at all. Wear rates typically outpace corrosion rates at Abrasion Level 4 and above. If careful evaluation of a site can lead to a determination of Level 3 abrasion or lower, abrasion typically does not control the selection of a liner material. Although particle size is extremely important, availability of a moderate volume of abrasive aggregate of the specified size and smaller in the channel bed can be the difference between classification of abrasion as Level 3 or 4.

Before the abrasion level at a specific culvert can be classified, the type and volume of bedload available to cause abrasion shall be investigated. This can be performed by visual examination during a site visit. It is recommended that a geotechnical engineer, accompanied by a hydraulic engineer and the Designer inspect the channel and culvert bottom to identify the type (including angularity) and size of aggregates present. Before visiting the site, the hydraulic engineer shall perform or obtain a preliminary hydraulic analysis to determine the velocity and depth of flow through the culvert during a two-year event. Determine the size aggregate that will likely be moved by the two-year flow (a table is available in Appendix B labelled "Bed Materials Moved by Various Flow Depths and Velocities"). Particle size is the most useful property in determining if bed material will move during specific flow conditions. In the field, observe the available volume of that particle size and smaller that can be moved by a two-year flow and classify the volume as:

- No bed load
- Minor
- Moderate
- Heavy

Presence of material by itself should not be the sole determinant of bed load volume. In addition to observing the volume of aggregate at or below a specified size that is available in the stream bed to move during a 2-year event, the following observations will help in determining whether the available bed material will be likely to move and cause abrasion:

- The slope of the channel profile
- Roughness of the channel
- The cross sectional shape of the channel
- Angularity and size distribution of bedding material
- Compaction level of bed material
- Bed armoring
- Evidence of historical scour/erosion/deposition/bank cutting
- Obstacles to flow (or lack thereof), such as rocks, rock weirs, scour holes, debris in the channel, paved inverts, etc.

It is important to observe the channel just upstream of the culvert as well as a significant reach of channel upstream, since that material can be transported downstream to the culvert being rehabilitated. Hydraulic Engineering Circular, HEC-20 – Stream Stability at Highway Structures provides guidance in qualitatively determining sediment transport characteristics of the watercourse at the culvert being lined or replaced.

It is not anticipated that a sieve analysis will be needed for the purpose of determining abrasion level, however, a bar probe may be used to examine the channel bottom and determine the layer depth of channel bottom material contributing to the determination of volume. Penetration of the bar into the channel bed (or lack of penetration) can provide insight into the ability of the material to armor the channel bottom, potentially reducing erosion and sediment transport. However, armor materials often appear in a shallow layer over sand or finer material. Transport of this material can expose the fine bedding material below it which also must be considered in evaluating the bed load volume since its particle size is less than the size of particles in the armor layer.

Observe and document abrasion within the existing culvert (and nearby culverts, if possible). If scour holes are present, look for deposition of abrasive materials in the scour hole as well, since the velocity may have slowed enough over the scour hole to deposit the material that has caused abrasion.

VIII. STRUCTURAL CULVERT LINER MATERIAL OPTIONS

Structural liner materials can first be evaluated for abrasion and corrosion at the given culvert site to determine liners that may be eliminated from consideration. With a list of viable structural liner options, designers can begin to eliminate options based on other goals discussed in Section I above. Liner materials that are appropriate for environmental conditions for the desired service life and for other goals can be preliminarily sized for structural capacity to support the height of fill and all live loads that the culvert is expected to carry. A structural culvert liner shall be designed as if in direct burial without composite action with the host culvert. Although the grout in the annular space between the host culvert and the liner adds stiffness and strength to the liner, the maximum stiffness of the grout used in design calculations shall not exceed that of well-compacted, well-graded angular sand and gravel backfill. The culvert liner shall be designed for the known soil envelope around the host culvert. If the soil modulus of the backfill envelope is not known, it may be selected from Table 1 in Appendix B assuming Type III soil. The capacity of the liner shall be determined in accordance with AASHTO LRFD Bridge Design Specifications, Section 12 – Buried Structures and Tunnel Liners.

Be sure to check if the liner can support all Design, Legal and Permit Vehicles. Structural liners spanning 6’ or more shall be load rated in accordance with the CT DOT Bridge Load Rating Manual and a load rating report shall be submitted during the design phase by the 90% plan submission.

For most culverts when fill heights exceed 8’ to 10’, live loads will not be distributed to the culvert but will bridge the culvert through soil arching and be applied to the compacted soil columns on both sides of the culvert. For these situations, a Capacity/Demand Ratio shall be computed in accordance with the Department’s Bridge Load Rating Manual for the culvert to confirm that the liner has sufficient capacity to support the dead load of the soil prism above. For each liner span and height of fill, a preliminary design of the liner shall be performed to confirm that the liner can support the loads.

If a liner cannot perform structurally under live load, consider constructing a distribution slab beneath the roadway pavement to span the culvert and distribute load to the soil beside the culvert instead of to the crown of the culvert. Removing live load from the structure won’t increase the service life of a culvert liner, but it can increase the number of options that are structurally acceptable. Designers should note that a distribution slab may interfere with buried utilities and roadway drainage. Preliminary thickness of distribution slabs may be estimated as 1” thickness for every foot of span. Precast concrete slabs may be specified to expedite installation. Such slabs should be designed with a longitudinal key, dowels or other mechanical connection between slabs to transfer live load to adjacent slabs transversely. A 6” thick minimum compressible layer of lightweight fill or foam should be placed just below the center half of the distribution slab so load is distributed to the ends of the slab instead of bearing directly above the crown of the culvert. If a concrete distribution slab is considered to remove live load effect from the liner be sure to include the extra cost of installing a distribution slab in the RSR alternative.

Structural culvert liner options are categorized as follows:

A. Thermoplastic/Thermosetting Resin
   1. High Density Polyethylene (HDPE)
      a. Solid Wall
      b. Corrugated
         i. Smooth Interior
         ii. Corrugated Interior
      c. Profile Wall - Smooth Interior
   2. Polyvinyl Chloride (PVC) – Solid Wall
   3. Fiberglass – Solid Wall

B. Metal
   1. Steel-Reinforced Polyethylene (SRPE)
   2. Aluminum
      a. Spiral Rib Smooth Interior
      b. Corrugated
      c. Structural Plate
      d. Tunnel Liner
   3. Steel - Uncoated or coated (Coatings include galvanized, aluminized, and polymeric)
      a. Solid Wall
      b. Corrugated (spiral or annular ribs)
         i. Smooth Interior
         ii. Corrugated Interior
      c. Structural Plate (galvanized)
      d. Tunnel Liner

C. Concrete

A. THERMOPLASTIC/THERMOSETTING RESIN

Availability

Thermoplastic, fiberglass and PVC culvert liners are available as shown in Table VI.1 below:

Table VIII.1– THERMOPLASTIC / THERMOSETTING RESIN LINER AVAILABILITY

WALL TYPE	INTERIOR	MAX. SPAN	WALL THICKNESS	AVAILABLE STIFFNESS*
PVC				
Solid Wall	Smooth	15” O.D.	0.44”	NA
Profile Wall	Smooth	48” I.D.	0.19” Inner Wall	NA
Fiberglass				
	Smooth	Any reasonable span	Custom	NA
HDPE				
Solid Wall	Smooth	63” O.D.	O.D./Dimension Ratio	SDR 41 SDR32.5 SDR 26
Corrugated	Corrugated or Smooth	60” Nom. I.D.	Varies by diameter See AASHTO M294	Varies by diameter See AASHTO M294
Profile Wall	Smooth	120” I.D.	Varies by Dia. and Ring Stiffness Coefficient (RSC)	RSC 160 RSC 250 RSC 400

*Liner stiffness:

SDR = Standard Dimension Ratio = O.D./Wall Thickness

RSC = Ring Stiffness Constant = load applied between parallel plates needed to deflect the pipe 3%, measured in pounds per foot per percent deflection (CT DOT requires RSC 160 min. stiffness)

Pipe stiffness of corrugated liner is measured at 5% deflection in psi, and varies by diameter

PVC liner pipe is only available in standard diameters up to approximately five feet with a smooth inner wall type. Wall thickness is also standard and not customizable.

Fiberglass liner is available in any shape and span and can be ordered to custom lengths. Fiberglass liner can be customized to fit any culvert within tight tolerances if desired. In addition, the thickness of fiberglass liner can be custom designed to resist abrasion and support all required loads.

HDPE liner, like PVC, is available in standard sizes only. Solid wall and corrugated HDPE are available in limited maximum diameters, but profile wall HDPE is available in a wide range of standard diameters. Solid wall HDPE is available in the same limited span range as corrugated HDPE but offers various thicknesses for the same diameters. Corrugated HDPE offers both smooth wall and corrugated wall types, which may make it more desirable in certain applications. Corrugated HDPE may offer cost advantages for lining small diameter culverts that are not subjected to live load or moderate to high abrasion. Most HDPE selected for culvert lining will be profile wall because of the wider range of sizes and choices for stiffness (stiffer pipe offers a thicker inner wall). Profile wall HDPE pipe is available in open and closed profiles. It is recommended to specify closed profile. Closed profile pipe includes an inner and an outer wall. This offers extra protection against abrasion perforating the liner and additional structural capacity if the inner liner becomes perforated.

Selecting the size of the liner is often critical for meeting hydraulic requirements. Designers shall account for known deformations in the host culvert and anticipate continued deformation until the liner is installed and select a liner that will easily clear these obstacles. The outside diameter of bell and spigot type joints shall also be accounted for so they will also clear obstructions in the host culvert. Host culverts that are metal with bolted seams have additional obstructions from nuts or bolt heads inside the structure. When possible, it is recommended to create a template of the liner and pull it through the culvert to demonstrate that the specified size liner will be able to be installed.

Liners made of different materials are not all supplied in the same standard dimensions or increments. Solid wall liners are typically specified by outside diameter whereas corrugated and profile wall liners are specified by inside diameter. To make matters even more complicated, corrugated liner is specified by a nominal inside diameter while profile wall inside diameter is actual. Designers shall check the availability of the desired liner dimension before assuming that material may be specified. Availability varies between suppliers, so check with more than one supplier before assuming that a product is not available in the desired material and size.

Designers looking for the advantages that HDPE, PVC and fiberglass have to offer may also consider steel-reinforced HDPE liner. This material is addressed under metal liners, but comes with a thinner wall, which may allow a larger diameter to fit in the host culvert.

Abrasion and Corrosion Resistance

Abrasion Levels 1 to 3:

HDPE, PVC and Fiberglass are all suitable materials. Abrasion is negligible.

Abrasion Levels 4 to 6:

- PVC liner abrades two times faster than steel
- HDPE liner abrades at a rate 2 to 5 times faster than steel
- Fiberglass liner abrades 12 to 30 times faster than steel.

Smooth liners facilitate higher flow velocities and allow abrasive bedload to move faster through the culvert. Abrasion of smooth liners is more uniform along the invert. Corrugated liner wears faster along the upstream face of the corrugations due to more direct impact from abrasive bed load. Corrugations tend to cause stones to tumble and bounce through the culvert, impacting the liner with more energy.

HDPE, PVC and fiberglass liners do not corrode. They are generally unaffected by pH, Resistivity, chlorides and sulfates. Before a Designer selects one of these liner materials, the longterm section loss due to abrasion must be considered. After calculating the loss of thickness, the Designer shall evaluate the liner's capacity to resist loads with the reduced section properties. Corrugated and profile wall liners have relatively thin walls to begin with. Although they have sufficient section properties to resist short-term loads, the reduction in long-term material properties, coupled with losses due to abrasion makes them vulnerable to failure due to buckling. Grout around the liner helps resist global buckling, but local buckling may still be a failure mechanism. Liners with closed profiles can resist local buckling better than liners with open profiles.

Hydraulics

HDPE, PVC and fiberglass liners are all available with smooth inner walls. Installing a smooth liner inside a corrugated metal host culvert, even though the inside diameter is smaller, may provide a hydraulically acceptable solution. In some cases where the flow through the culvert is inlet-controlled, the constriction created by the liner can adversely affect the hydraulic capacity of the lined culvert. In these instances, consider designing an improved inlet. Improved inlets may be created by beveling the grout in the annular space at the upstream end of the liner. Alternatively, structures can be installed at the upstream end to funnel water into the liner. Fiberglass can be used to create special structures to create improved entry conditions. Such structures can be used at the leading end of the liner as an integral extension of the liner.

In some cases it is desirable to slow the flow of water down before it exits the culvert. HDPE in diameters up to 60” offers a corrugated inner wall. Corrugations can be used to slow the flow velocity to reduce erosion of the stream bed at the outlet. Corrugated interior pipe shall not be used in Abrasion Levels 4 to 6 without considering the service life of the liner.

Baffles or sills can also be installed in the invert to slow the flow of water and to encourage sedimentation of natural stream bed materials in the culvert. The diameter and length of sections of liner play a role in accessibility to install baffles. Longer sections of liner require a minimum diameter of approximately 48 inches to provide sufficient access to attach baffles or sills in the middle of the length. Due to maximum diameter limitations, long lengths of PVC, solid wall HDPE and corrugated HDPE liner should not be used if baffles would be installed in the middle of the length. Long lengths of profile wall HDPE in smaller diameters should also not be used if baffles must be installed in the middle of the length. Baffles in HDPE, PVC and fiberglass pipe can be damaged by larger stones and debris moving at high velocities. Before selecting a liner material, check with the supplier of the liner to ensure that baffles can resist the forces and impact loads that are expected and provide the desired service life.

Installation Methods and Constructibility

HDPE, PVC and fiberglass liners are installed by slip lining or segmental construction methods. When slip lining is the method of installation, check with the supplier of the liner to determine the maximum length that can be installed by this method. Slip lining requires joining the segments outside of the host culvert as the liner is pushed or pulled through the culvert. Liners that are pulled through require joining methods that will not allow the sections of liner to be separated as the liner is pulled. HDPE, PVC and GRP liners all offer high quality joints. If pushing the liner into the host culvert, care shall be taken not to crack or buckle the liner by pushing too hard. Corrugated and profile wall liner are vulnerable to buckling, and solid wall liner (especially PVC) is vulnerable to cracking if pushed too hard. Bells of bell-and-spigot type joints – particularly corrugated HDPE liner - can snag on corrugations, nuts or deformations in the host culvert. The Designer shall select a diameter that will facilitate installation without snagging but should also review the Contractor’s proposed method of installation carefully to ensure that steps are taken to avoid snagging. Corrugated HDPE does not perform well being pulled into the culvert because of the fit of the joints. They can also pull apart in long runs due to thermal contraction.

Grouting HDPE, PVC and fiberglass liners is a critical operation. It starts by specifying lightweight cellular grout where possible. Reducing grouting pressure and buoyant forces on the liner during installation can prevent damage to the liner and shifting of the liner within the host culvert. Thin walls such as provided by corrugated and profile wall liner are particularly vulnerable to grouting pressure. Grouting is typically a contractor's responsibility, but contract documents shall require that grout ports be installed in the liner to verify that grout has achieved specific depths and that the grout pour should stop. Controlling the height of the grout lift can avoid sudden failures. The Contractor shall insist that the supplier install grout ports as indicated on the working drawings.

Segmental lining is often selected due to physical constraints related to the culvert site. Shorter segments are needed when there is a limited lay-down area at the inlet or outlet end to assemble a long length of slip liner. Shorter lay down areas can be caused by natural bends in the channel, steep profiles, and placement of water handling cofferdams close to the inlet of the culvert. Deformities or obstructions within the host culvert can also discourage installation by slip lining methods in lieu of shorter segments that can be pulled or pushed in lengths that can clear obstructions.

Weight or size may also drive the need to install the liner using the segmental method. This may affect transportation, access to deliver the liner to the end of the culvert, or even the ability to move the liner into position within the host culvert. Heavier liner such as fiberglass can be split into upper and lower halves to reduce the weight and size. Also, shorter lengths can be fabricated to reduce weight.

The tunnel lining method is typically used for steel and aluminum liners, but fiberglass has been used on rare occasions by some contractors and can be customized for this purpose.

Environmental

HDPE, PVC and fiberglass liners do not typically provide an ideal environment for fish and aquatic life. When it is desirable to establish a more natural stream bottom, one of these materials may be considered as a liner if placement of baffles and sills in the invert can be designed to encourage natural sedimentation. If high velocities during less frequent storm events could move large rocks through the lined culvert, baffles (and the liner itself) could be damaged. Designers shall consider this possibility before specifying baffles with HDPE and PVC. Fiberglass liner is solid and can accommodate stronger connections for baffles.

It may be necessary to import natural material into the culvert to establish a natural bottom. This should only be specified when the span and rise of the culvert will accommodate delivery and placement of the natural stream bed material within the lined culvert. Other features may need to be constructed to facilitate the natural sedimentation. Placement of boulders upstream of the culvert, or a series of rock weirs may need to be constructed to slow velocities enough to encourage deposition of material within the culvert.

Disruption of the environment to install the liner is another consideration. Access roads to transport large liners requires removal of trees and vegetation and upon completion, restoration of the environment. HDPE liners are particularly lightweight and can easily be delivered to the end of culverts with limited access.

The need for significant cofferdams for water handling can cause disruption over a large footprint of the stream bed and can limit the available room for setting a liner before it is moved into the host culvert. Solid wall products such as PVC and fiberglass can more easily be installed in a wet environment because due to their weight, they are less vulnerable to being moved by shallow depths of flowing water. This can allow for a smaller cofferdam or none at all.

Structural

In general, the most structurally vulnerable culvert liner is HDPE. The wall of the liner is not stiff enough to support the loads by itself – it must rely on the stiffness of a well-compacted soil envelope around the host culvert to resist the loads. To transfer loads to the structural liner, grout is placed between the host culvert and the liner. Although the liner may develop additional capacity through composite action with the grout and host culvert, the liner shall be designed as if in direct burial. For design of HDPE, PVC and fiberglass liners with height of cover less than 8', assume that the existing soil envelope is silty sand compacted to 85% unless specific information is available to use for design. HDPE is generally not suitable for use under shallow fills (< 3') with heavy, concentrated live loads above them. Although the AASHTO LRFD Bridge Design Specification states that the minimum height of cover is 12", Table 30.6-1 of the Construction Specification requires at least 36" of cover for culverts with a span of 3.5' or more to distribute loads from construction vehicles. In Connecticut, these construction vehicles are Legal Vehicles and can move freely along State roads. Before specifying a HDPE culvert liner under a roadway, check the height of cover to see if it meets the minimum.

When designing thermoplastic liners with Cover Height of 8' or greater, Table 1 of Appendix B may be used to select a constrained soil modulus. Unless actual soil backfill information is available, assume Class III soil and 95% compaction. 95% compaction assumes that the soil over and beside the culvert is well-compacted after many years of service. If it is suspected that there may be voids and/or active settlement in the backfill, then assume 85% compaction.

HDPE liners of the profile wall type offer a higher quality material than corrugated HDPE and have a more robust profile to support loads. Wall thicknesses of corrugated HDPE liner are thin and may buckle when loaded. Calculations show that corrugated HDPE liners generally do not perform well under the vehicular live loads they are expected to support in Connecticut. Heavy, concentrated loads over shallow fill shall be avoided. Corrugated HDPE may be suitable in installations that do not carry live load, but care shall be exercised during installation to ensure that construction loads do not fail the liner.

Under sustained loading, material properties change for thermoplastic and thermosetting resins. The stiffness of the plastic can drop to 20% to 25% of its initial value and yield strength can drop to less than half. With such reduced longterm properties, loading from high earth fills will cause continued longterm deflection of the structure. LRFD limits deflection to 5% of the span. Limiting deflection can reduce stress cracking. Designers shall check deflection under longterm properties. Although thermoplastic liner is quite flexible, large deflection of the liner wall is discouraged by the Design Specification. With reduced longterm stiffness, the thin wall is also prone to local or global buckling failure. Section loss due to abrasion can also weaken the wall of HDPE liner over time. Even though the abrasion rate is low and there is no corrosion, wall buckling due to a thinner wall over time caused by abrasion is a possible failure mechanism. The wall is substantially braced by the material in the annular space between host culvert and liner. However, the wall can still buckle inward where it is not supported by grout.

Thermoplastic and fiberglass liners rely heavily on the soil envelope around the host culvert to provide adequate stiffness for resisting applied loads, since the plastic wall itself typically lacks adequate stiffness -especially for corrugated HDPE liner. Soil stiffness depends on the type of soil and the level of compaction. Soil envelopes can be easily disturbed by voids, settlement or adjacent excavation for other drainage structures or utility installations. Disturbance due to excavation may be caused by third parties without any oversight by CT DOT. Restoration of the soil envelope by the third party may not be at the desired level of compaction. For this reason, and because in-situ soils are often used to backfill drainage structures, CT DOT recommends that the soil envelope be evaluated as silty sand with 85% compaction. In addition, the water table should be assumed to be 3' above the top of the culvert for design purposes. These design assumptions greatly reduce the capacity of thermoplastic and thermosetting resin culvert liners compared to designs prepared for ideal soil and compaction conditions but must be adhered to when designing thermoplastic and thermosetting resin materials for CT DOT culverts.

Of the liners in the thermoplastic and thermosetting resin category, fiberglass is the most versatile. This solid-wall liner can be fabricated to any shape, size, and thickness. The capacity can be increased by specifying a thicker wall, and a greater interior liner thickness can be specified to resist anticipated abrasion over the design service life. Thermosetting resin properties change over time under sustained loads, so designers are reminded to design the thickness using longterm properties. Large spans/rises can be fabricated as upper and lower halves and in shorter segments that can be transported and handled more easily. The segments are assembled in the field to create the full shape of the liner. Fiberglass liner can be custom made to tight tolerances to fit any culvert. When special sizes, shapes or custom fit aren't as critical, HDPE or PVC standard sizes and shapes should be considered as structural options to reduce weight and cost.

Steel-Reinforced Thermoplastic liner is technically categorized as a metal culvert liner. It offers greater stiffness than unreinforced thermoplastic liners, while providing a smooth, corrosion-resistant interior. Its light weight and long lengths allow it to be installed quickly. Due to a very thin plastic wall, steel-reinforced thermoplastic liner is recommended for Abrasion Levels 1 through 3 only. High performance bell-and-spigot or welded joints are available if desired to provide silt-tight or water-resistant joints.

B. METAL

i. STEEL-REINFORCED POLYETHYLENE (SRPE)

Availability

Table VIII.2 - SRPE LINER AVAILABILITY

WALL TYPE	INTERIOR	MAX. SPAN	WALL THICKNESS	AVAILABLE STIFFNESS*
Ribbed	Smooth inner wall	120” Nominal I.D.	Varies by diameter See AASHTO M335	NA

*SRPE is classified as a metal pipe by AASHTO because the steel ribs provide the primary structural capacity of the pipe while the HDPE inner wall is the conduit for water. Consult the manufacturer for physical properties of the pipe for design.

SRPE is available in standard diameters. Wall thickness cannot be customized. The smooth inner wall is reinforced by steel ribs that are encapsulated in HDPE and are integral with the inner liner. The profile is an open profile (there is no exterior wall). SRPE has a shallower wall profile than profile wall HDPE because its stiffness comes from the steel reinforcing ribs.

Abrasion and Corrosion Resistance

Abrasion Levels 1 to 3:

SRPE shall be specified for these levels only.

Abrasion Levels 4 to 6:

SRPE shall not be specified. The thin inner wall will abrade quickly at higher abrasion levels.

SRPE, like HDPE liner, does not corrode. Steel ribs are encased in HDPE so unless the encasement is damaged, the ribs are protected from corrosion. Encasement could be damaged by abrasion. HDPE can be repaired in the field, so all is not lost if localized damage occurs.

Hydraulics

SRPE has a very smooth interior and a low profile. Because of the shallow wall thickness and available sizes, SRPE has an advantage over HDPE to maximize the hydraulic capacity of the lined culvert.

Installation Methods and Constructibility

SRPE is lightweight, which is desirable for shipping and handling the liner. Pushing and pulling the liner in place takes less effort than heavier liners. SRPE can be damaged if forced into the host culvert. Special devices should be attached between the ribs at the bottom to prevent damage to the liner and support it as it is pulled along the skids into the host culvert. Snagging is one of the primary causes of damage during installation. Another source of damage is the grouting method. Because the lightweight pipe has such thin components, they are subject to buckling when loaded improperly. The pressure from grout can be too large for the thin walls if the density of the grout is high or if the grout lift itself is too high. Designers shall specify lightweight cellular grout where possible to minimize pressure. Grout ports shall be installed in the liner at appropriate heights to properly grout the annular space in lifts. Requests to not install grout ports, if proposed by the supplier during construction, should not be accepted.

Grouting of larger diameter SRPE shall take into account that a few of these sizes do not offer bell and spigot type joints. Instead, internal bands are used at the joints once the liner is in position within the host culvert.

Environmental

SRPE does not provide an ideal environment for fish and aquatic life. If a more natural stream bottom is desired, baffles may be installed in SRPE liner with inside diameter 48” or greater, which provides sufficient access to enter the pipe and install the baffles. SRPE liner can be ordered in lengths as short as 14’, so if baffles can be spaced at 14’ intervals, then they may be installed in smaller diameters as well. If high velocities during less frequent storm events could move large rocks through the lined culvert, baffles (and the liner itself) could be damaged. Designers shall consider this possibility before designing baffles with SRPE. Baffles (and the inner wall) can be repaired in the field.

Structural

SRPE behaves like a metal pipe due to the stiffness of the steel ribs encased in HDPE. Longterm properties need not be checked, since steel, not HDPE, is being subjected to the sustained load. Even though SRPE is stiffer than its unreinforced HDPE counterpart, the thin walls make the structure vulnerable to buckling failure. Designers are reminded to check this mode of failure to ensure that SRPE can adequately support all loads. SRPE relies less on the soil envelope for its capacity than unreinforced HDPE.

ii. ALUMINUM

Availability

Table VIII.3 - ALUMINUM LINER AVAILABILITY

WALL TYPE	INTERIOR	MAX. SPAN	WALL THICKNESS	AVAILABLE STIFFNESS
Corrugated	Smooth inner wall available	120” I.D. 144” Span for Pipe Arch	10 gauge	NA

Structural Plate	Annular ribs	316” I.D.	0.25”	NA
Tunnel Liner 2-Flange	Corrugated	As-designed	0.239”	NA
Tunnel Liner 4-Flange	Corrugated	As-designed	0.375”	NA

The most typical aluminum liners are spiral rib smooth interior, corrugated or profile wall. The strongest shape fabricated from aluminum is tunnel liner plate, which has corrugations. Aluminum is available in standard sizes for round pipes and pipe arches. Wall thickness can be selected by the Designer. A smooth inner wall is available by ordering Type IR aluminum pipe. Aluminum tunnel liner has a shallow wall profile that maximizes the hydraulic opening however, tunnel liner has a corrugated shape that will tend to slow the flow compared to a smooth liner.

Abrasion and Corrosion Resistance

Abrasion Levels 1 to 3:

Aluminum is a suitable material. Abrasion is negligible.

Abrasion Levels 4 to 6:

Aluminum can be considered in thicknesses up to ¼” for structural plate but will likely not give a suitable target design service life.

Moderate abrasion can remove the oxide coating that forms on the surface of aluminum liners. Exposing aluminum below the oxide layer will allow additional oxidation of the aluminum. Moderate and highly abrasive environments can also remove base metal, resulting in longterm reduction in section properties and reduced capacity of the liner.

Specifying extra thickness of aluminum can compensate for some loss of material, but for aggressive environments, aluminum may not be the best choice for a liner. Aluminum abrades quickly at Abrasion Level 4 and above. Designers may specify aluminum above Level 3 but must increase the thickness to provide the desired service life. When aluminum liner is used within a range of pH from 5.5 to 8.5 and Resistivity is above 1,500 ohm-cm aluminum forms an oxide coating that is resistant to corrosion. Outside of this pH range the protective oxide layer dissolves and stops protecting the aluminum. Chlorides above 100 ppm can provide a favorable environment for corrosion. For this reason, it is recommended to refrain from specifying aluminum liner in brackish water or marine environment.

Aluminum bolts could be specified for structural plate aluminum, but the strength of a galvanized bolt is usually preferred. The resistivities of these materials are close enough to not cause an adverse electrochemical reaction.

Hydraulics

Aluminum liner is offered with a smooth interior and a low profile. This type of liner can be one of the most hydraulically efficient liners when a strong liner is needed to maximize flow in existing culverts that were sized close to the desired hydraulic capacity. A smooth surface and maximized hydraulic area make this product desirable when deeper profile liners cannot deliver hydraulic results. Corrugated aluminum liner can be used to slow the water velocity before it exits the culvert.

Installation Methods and Constructibility

Aluminum is lightweight, which is desirable for shipping and handling the liner. Pushing and pulling the liner in place takes less effort than heavier liners. Aluminum can be damaged if care is not taken to restrict the height of grout lifts. The pressure from grout can be too large for the thin walls if the density of the grout is high or if the grout lift itself is too high. Bracing may be required inside the liner until grout has been placed. Designers shall specify lightweight cellular grout where possible to minimize pressure. Grout ports shall be installed in the liner at appropriate heights to properly grout the annular space in lifts.

Grout can react with the aluminum liner when placed in contact with the aluminum. This reaction is mild and lasts only through the hydration process until the cement cures. The miniscule section loss during this reaction is not of any structural consequence. Attempts to coat the outside wall of the aluminum liner with zinc chromate paint or bituminous coating have not worked well. The coatings were severely damaged during handling and installation and could not be touched up when the liner was in its final position. Touch up is time consuming and costly. Coating aluminum liner is not recommended.

Environmental

Aluminum does not provide an ideal environment for fish and aquatic life. If a more natural stream bottom is desired, baffles may be installed in aluminum liner to slow the flow and cause natural deposition of streambed material. Baffles would not typically be specified within a smooth-wall aluminum liner because the smooth wall is specified to increase flow while baffles are intended to slow the flow. Do not specify baffles in a liner with inside diameter less than 48" because access to enter the pipe and install the baffles would be difficult.

Structural

Aluminum liner is much stiffer than HDPE liners and its longterm material properties remain the same as its initial properties under sustained loads. While not as strong as steel, aluminum can support most heights of fill and loadings to which a culvert will be subjected. For very shallow fill, aluminum liner may not be able to support large, concentrated wheel loads. For height of cover greater than approximately 30 feet, aluminum liner may not be capable of supporting the soil prism. When aluminum culverts are installed in direct burial, external ribs can be used to increase the capacity of the culvert. However, when aluminum culvert liner cannot support the loads, it is generally impractical to attach external ribs without reducing the internal diameter excessively so the ribs can fit into the culvert. A stronger material such as steel may need to be considered.

iii. STEEL

Availability

Table VIII.4 - STEEL LINER AVAILABILITY

WALL TYPE	INTERIOR	MAX. SPAN	WALL THICKNESS	AVAILABLE STIFFNESS
Solid Wall	Smooth	As specified	1.25" Max. (Up to 2" Possible)	NA
Corrugated Galvanized	Smooth inner wall available	144" Round or Pipe Arch	8 gauge	NA
Corrugated Aluminized	Smooth inner wall available	144" Round or Pipe Arch	10 gauge	NA
Corrugated Polymer Coated	Smooth inner wall not available	144" Round or Pipe Arch	10 gauge	NA
Structural Plate	Annular ribs	316" I.D.	0.25"	NA
Tunnel Liner 2-Flange	Corrugated	As specified	0.239"	NA
Tunnel Liner 4-Flange	Corrugated	As specified	0.375"	NA

The most typical steel liners are spiral rib smooth interior, corrugated or profile wall. Although these are fabricated in standard sizes, special orders are possible with steel structural plate liner. Wall thickness is specified by the Designer. Solid wall steel liners can be custom designed and fabricated to fit any size or shape culvert and the Designer chooses the thickness. One of the strongest shapes fabricated from steel is tunnel liner plate, which has corrugations. Steel tunnel liner has a shallow wall profile that maximizes the hydraulic opening however, tunnel liner has a corrugated shape that will tend to slow the flow compared to a smooth liner. Steel tunnel liner corrugations can be filled with mortar to create a smooth interior surface. The mortar is anchored to the tunnel liner with studs or mesh secured by the bolts. The mortar is usually built up to cover the inside crests of the tunnel liner corrugations.

Abrasion and Corrosion Resistance

Abrasion Levels 1 to 3:

Steel is a suitable material. Abrasion is negligible.

Abrasion Levels 4 to 6:

Steel (coated or uncoated) can be considered. Additional thickness shall be considered to extend the design target service life.

Moderate abrasion can remove the oxide coating that forms on the surface of steel liners. Exposing steel below the oxide layer will allow additional oxidation of the steel. In moderate and highly abrasive environments the oxide coating can be removed and re-formed repeatedly. This is known as the abrasion-corrosion cycle and can lead to accelerated section loss. Abrasive environments also remove base metal, resulting in longterm reduction in section properties and reduced capacity of the liner.

Solid wall steel liners are typically designed with extra thickness to compensate for corrosion and abrasion and provide the desired service life. Some solid wall steel liners use a steel alloy that corrodes at about half the rate of conventional steel. Specifying extra thickness of steel can compensate for some loss of material, but coatings can also extend the service life of a steel liner. Galvanized steel has historically been used to extend the life of culverts. Aluminized steel has also been used and has been shown to provide a longer service life than galvanized steel when compared to one another in a less aggressive environment. Polymer coated steel combines a tough coating with the protection of galvanized steel below. Polymer-coated steel has been very effective in moderate to low abrasion environments, but the coating will abrade quickly in more aggressive environments. Polymer coating is available on steel up to 10-gauge thickness. Polymer coating can be damaged during shipping, handling and installation and must be repaired before installation of the liner.

Designers shall assume that polymeric coatings add twenty years of service life to a steel liner for Abrasion Levels 1 through 3, ten years for Level 4, five years for Level 5 and 0 years for Level 6. In some case histories, polymer coating has provided more than thirty years of corrosion protection to the steel liner at lower abrasion levels.

Asphalt coatings are also available but are considered to add only up to eight years to the service life of the steel. Asphalt coatings are unfriendly to the environment and are flammable. Thick concrete invert liners can offer the most protection against abrasion, but the concrete thickness raises the invert significantly and reduces the hydraulic area of the culvert. Thinner mortar coatings may be used for protection if anchored well to the liner. Mortar coating that fills the corrugations and creates a smooth interior also reduces the Mannings coefficient and can improve flow through the lined culvert. Greater velocity of flow can increase abrasion, however.

Steel liners perform better when pH is > 6.0 with resistivity above 2,000 ohm-cm.

Chlorides above 100 ppm can provide a favorable environment for corrosion. For this reason, it is recommended to refrain from specifying steel liner in brackish water or a marine environment. Sulfates at 100 ppm or more may cause a drop in pH that can accelerate corrosion in steel liners. Sulfates can adversely interact with chlorides to cause corrosion in metal. Sulfates lower the threshold at which chlorides cause corrosion. Aluminized liners may be considered for use in Abrasion Levels 1 and 2 when sulfate levels exceed 100, but only when pH is within allowable levels. When resistivity is above 1,500 ohm-cm, the recommended range of pH is between 5.0 and 7.2. When resistivity drops to 1,000 ohm-cm, the recommended range of pH is from 7.2 to 9.0. Polymer coated steel liners have performed well in Abrasion Levels 1, 2 and 3 in salty environments.

Hydraulics

Steel liner is offered with a smooth interior and a low profile. This type of liner can be one of the most hydraulically efficient liners when a strong liner is needed to maximize flow in existing culverts that were sized close to the desired hydraulic capacity. A smooth surface and maximized hydraulic area make this product desirable when deeper profile liners cannot deliver hydraulic results. Corrugated steel liner can be used to slow the water velocity before it exits the culvert. Baffles can also be installed in steel liners to slow the velocity.

Installation Methods and Constructibility

Steel is heavier than aluminum liners but offers much greater stiffness, which is desirable for shipping and handling the liner. Pushing and pulling the liner in place is less likely to cause damage to steel liner. Despite greater stiffness, steel can be damaged if care is not taken to restrict the height of grout lifts. The pressure from grout can be too large for the thin walls if the density of the grout is high or if the grout lift itself is too high. Bracing may be required inside the liner until grout has been placed. Designers shall specify lightweight cellular grout where possible to minimize pressure. Grout ports shall be installed in the liner at appropriate heights to properly grout the annular space in lifts. The liner must also be secured against buoyancy, so it is not displaced during grouting.

Environmental

Steel does not provide an ideal environment for fish and aquatic life. If a more natural stream bottom is desired, baffles may be installed in the steel liner to slow the flow and cause natural deposition of streambed material. Baffles would not typically be specified within a smooth-wall steel liner because the smooth wall is specified to increase flow while baffles are intended to slow the flow. Do not specify baffles in a liner with inside diameter less than 48” because access to enter the pipe and install the baffles would be difficult.

Structural

Steel is the strongest of liners and its long-term material properties remain the same as its initial properties under sustained loads. Steel liners can support most heights of fill and loadings to which a culvert will be subjected. For very shallow fill, steel liners subjected to large, concentrated wheel loads could be damaged. Designers shall consider this type of failure when checking the design.

Long-term strength can be achieved by designing the thickness of steel liners for losses due to abrasion and corrosion and still meet the desired service life. Uncoated, solid wall alloy steel liner plate will provide a strong liner that minimizes the liner thickness and maximizes the hydraulic area available. Some steel alloys have double the resistance to corrosion as conventional structural steel. These solid wall steel liners can be customized to a particular culvert size and shape. However, they are heavy and require field welding.

C. CONCRETE

Availability

Concrete is not typically used to line the entire circumference of a culvert. It is sometimes used to restore a culvert bottom that has become deteriorated, perforated or is completely missing. Concrete inverts that make the culvert hydraulically inadequate or have a negative impact on stream channel habitat may still be able to be specified if a supplemental culvert is installed that does provide these characteristics.

A dense, low-permeability concrete is desirable. Strength of the concrete is determined by the Designer based on structural capacity needed to rehabilitate the host culvert. A 4,400 psi concrete is the preferred minimum strength with a maximum aggregate size of 3/8” to facilitate pumping.

Abrasion and Corrosion Resistance

Abrasion Levels 1 to 3:

Concrete is a suitable material but is likely not the first choice for a liner. Abrasion is negligible.

Abrasion Levels 4 to 6:

Concrete has the fastest rate of abrasion of all materials but can provide a sacrificial invert to extend the life of the host culvert or protect the invert of a new liner.

Concrete is adversely affected by a combination of pH level below 7.0 and sulfate concentration above 1,500 ppm. When resistivity of the water is 1,000 ohm-cm or greater, sulfate is not a concern. The Designer shall specify a low-permeability concrete with a water/cementitious material ratio of 0.40 or lower. If sulfate concentration is above 2,000 ppm, Type II or V Portland cement shall be specified.

Hydraulics

A concrete invert is smooth, but the thickness typically reduces the capacity of the culvert. An improved inlet can increase the flow of water into the culvert when the culvert is inlet controlled. A hydraulic analysis is needed to determine if the flow in the lined culvert is adequate, a supplemental culvert is needed, or the culvert needs replacement. Often, the water velocity will increase due to the smooth concrete liner and a reduced hydraulic area. Sills or baffles may be designed to slow water velocity to address scour concerns at the outlet.

Installation Methods and Constructibility

If a concrete invert is selected, water shall be handled in a manner that allows concrete to be placed in the dry with sufficient time to gain the specified strength with proper curing in place. This typically requires placement of a temporary water handling cofferdam and pumping or diverting flow while the invert concrete is placed. Depending on the length of the host culvert, concrete may need to be pumped from one or both ends due to pumping distance limitations.

Voids behind the host culvert and at the invert must be filled to allow for the proper transfer of loads to the rehabilitated culvert.

Concrete can be cast in place, troweled on, or applied by low-pressure spray to restore a culvert invert or provide a smooth surface inside the culvert. Concrete can be mixed near the ends of the culvert or from the roadway above.

Environmental

Concrete inverts can be designed with low-flow channels and baffles or sills to encourage natural streambed material to be deposited to accommodate fish habitat and passage. Because of the thickness of the liner, creating a natural bottom can create an undesirable invert elevation and reduce hydraulic capacity. Close coordination between Hydraulic Designers and Environmental Planning is needed before proposing a concrete invert.

Structural

For concrete to restore the structural capacity of the culvert and protect the culvert against further deterioration, the concrete slab must be securely anchored to the culvert wall. If the as-built culvert did not have adequate capacity originally, the Designer may want to consider another option to rehabilitate the culvert. The slab shall be of sufficient thickness and reinforced to resist bending and axial forces imposed on it by the culvert walls as load is transferred from the walls to the concrete slab. Sufficient overlap with and anchorage to the host culvert wall will reduce prying forces at the edges of the concrete slab, allowing the concrete slab to act as a continuous, integral part of the culvert. Designers shall specify sufficient concrete cover above the reinforcing to allow for loss of material due to abrasion and erosion. Reinforcing should be galvanized, stainless or GFRP to avoid corrosion, minimize spalling and extend the life of the invert.

IX. NON-STRUCTURAL CULVERT LINERS

Most culvert liners are being proposed because a culvert condition has been identified as deficient or structurally incapable of supporting all required loads. However, not all culvert liners must be selected to provide full structural capacity. A culvert liner can be proposed to proactively protect the host culvert against corrosion, abrasion, and environmental attack to extend the service life of the culvert. It can also be used in conjunction with a proposed structural liner to provide a lower Mannings coefficient. In such an application, the non-structural liner must be selected to provide the desired service life. The three non-structural liners noted below will likely provide the desired service life when abrasion is classified as low. However, these liners may not provide the desired service life if installed improperly or under moderately abrasive conditions. A nonstructural liner can also be specified as a temporary measure until a structural solution is designed and implemented. For example, perforations in a culvert invert can allow bedding or backfill to be drawn into the culvert, creating voids, which can lead to structural failure of the culvert. Grouting the voids and installing a liner can prevent voids from developing or progressing. The non-structural liner must still be able to provide the service life anticipated for the temporary installation. Tools to assist in selecting non-structural liners are available in Appendices A and B.

Some examples of non-structural liners are:

A. Spiral wound HDPE or PVC
B. Centrifugally cast mortar or geopolymer
C. Cured in place resin.

The reason these are listed as “non-structural” is AASHTO LRFD Bridge Design Specification does not offer a method of calculating the capacity of these liners. To be considered a structural culvert liner, a culvert that qualifies to have a bridge number must also be load rated by the Load and Resistance Factor Rating (LRFR) method. Structural liners for culverts that are too small to be assigned a bridge number shall still be designed in accordance with AASHTO. Allowable Stress or Load Factor Design methodologies are not acceptable for structural liners on the National Bridge Inventory whose load rating will reported to FHWA.

A. SPIRAL WOUND

A continuous strip of HDPE or PVC extruded with a ribbed profile and wound mechanically with a machine that joins the edges to form a cross-sectionally closed shape. The liner can be made to conform to the shape of the host culvert. They can be expanded against the host culvert or fabricated as a fixed size and grouted between the liner and host culvert. Some profiles offer steel reinforcement embedded within the plastic.

Spiral wound liner can be installed while the host culvert carries water - up to 25 – 30% flow.

B. CENTRIFUGALLY CAST MORTAR OR GEOPOLYMER

Cementitious mortar or geopolymer liner applied by an electric or air powered rotating head. The host culvert must be clean and dry. All voids must be filled, and invert repaired to allow the machine to ride on skids through the culvert. Cementitious or geopolymer material is sprayed onto the culvert interior wall. Material is typically high strength and reinforced with fibers for tensile strength and to control cracking. When spraying over corrugations, hand finishing is often required if a smooth finish is desired. A number of states have experienced problems with cracking, leaking and debonding of the liner. This liner is difficult to install on culverts with discontinuities or sharp deformities.

C. CURED IN PLACE RESIN

Cured In Place Pipe (CIPP) is a term coined for a flexible tube material such as felt reinforced with fiberglass and impregnated with polyester resin. The tube is pulled through the culvert and expanded to tightly fit the interior of the host culvert. The resin is cured to a solid using heated water, steam, or ultraviolet light.

X. SELECTION OF CULVERT LINER WITH CONSIDERATION FOR METHOD OF INSTALLATION

There are three typical methods of structurally lining culverts: slip lining, segmental lining and tunnel lining. Each of these methods has limitations that will be discussed in the following paragraphs. All methods of structurally rehabilitating an existing culvert will not necessarily result in a hydraulically acceptable liner. Sometimes the strategy must be to address the structural needs of the host culvert and install a supplemental pipe or culvert to accommodate hydraulic needs.

A. SLIP LINING

Slip lining is typically the fastest and most economical method of culvert rehabilitation. Slip lining involves the insertion of a prefabricated structural liner that is smaller in cross section than the host culvert into the inlet or outlet end of the culvert. The liner is either prefabricated or assembled outside of the host culvert and pushed or pulled into the culvert. Longer culverts may require that a portion of liner be assembled, then moved partially into the host culvert while additional lengths are attached. This process is repeated until the liner is inserted completely into the host culvert. This technique is also used when there is insufficient length of channel at the inlet or outlet in which to stage the entire assembled liner before moving it into the culvert. After insertion of the liner, grout is pumped into the annular space between the host culvert and the liner.

Designers should look for the following conditions to be met for selecting a slip liner:

1. The host culvert is structurally safe to enter
2. Minimal obstructions exist within the host culvert to allow the free movement of a liner through the culvert
3. The dimensions and elevations of the host culvert are measured and documented
4. The Designer has verified that based on the documented measurements of the host culvert, the liner cross section will physically fit as it is pushed or pulled through the host culvert.
5. The length of culvert liner being pushed into the host culvert does not exceed the manufacturer's recommended push length for that type of liner.

B. SEGMENTAL LINING

Segmental lining involves the insertion of culvert liner segments into a host culvert to form a continuous liner. To form a continuous liner, the segments must be connected by gaskets, bands, bell and spigot joints, welding, fusion, or other acceptable joints. Grout bulkheads can also join liner segments of different sizes or shapes. Segmental lining is often specified where:

1. Sharp bends or misalignments occur in the host culvert that would prevent a slip liner from being inserted
2. Significant damage or isolated deformations of the host culvert exist, preventing a continuous slip liner to be inserted.
3. The channel alignment at the inlet or outlet has insufficient length to allow a slip liner to be set in the channel outside of the culvert.
4. Insufficient access is available to the culvert ends to deliver a long slip liner to the channel bed.

5. The size and/or weight of the liner is not conducive to transporting, handling or inserting a slip liner.
6. The push length for slip lining is less than the length of culvert to be lined.

To avoid using tunneling methods to remove obstructions, a cast-in-place concrete or grout transition segment can be formed and cast between two liner segments. This cast-in-place transition can facilitate the smooth flow of water from one segment size and shape to another. If necessary, different size segments can be inserted from opposite ends of the culvert to avoid the obstruction. However, if multiple obstructions exist, removal of obstructions may be necessary to line the full length of culvert. When the extent of removal of obstructions is determined to be too great to use the segmental lining technique, consider using a tunnel lining technique. Tunnel lining may also be partially used to eliminate obstructions and open the culvert for slip lining or segmental lining methods.

C. TUNNEL LINING

Tunnel liner plate is corrugated structural plate with right angle flanges for butt-type bolted seams on two sides or four edges of each rectangular plate. Four-flange plates create circumferential and longitudinal seams between plates. Two-flange plate uses bolted lap splices along the non-flanged edges to assemble rings. The flanged edges of the rings are butted together and bolted to join the rings to each another to extend the liner. Butted flange splices are weaker than lapped splices, so seam strength must be considered in the selection of liner plate. Tunnel lining ring segments are typically short in length – approximately 18" wide rings. The short segment length allows some flexibility to rotate the rings to navigate the liner around obstructions within the culvert to avoid removal of small obstructions in the host culvert. Removal may also be avoided by assembling a smaller ring at the obstruction if the reduction in hydraulic cross section can be tolerated. It is recommended to grout the smaller ring with a higher strength grout since the grout will be exposed to the flow of water. In the small separation between liner rings, grout from the annular space can be formed to create a smooth transition from the larger to the smaller liner ring if needed to improve the hydraulic flow. The downstream end of the smaller ring should not require a grout transition.

Tunnel lining is to be considered by the Designer when culvert failure is imminent, or other lining methods may cause failure of the culvert. Here are some of the conditions to look for:

- When any portion of the culvert cross section has changed shape excessively due to section loss and/or bending or buckling of the wall.
- When a bolted seam fails and cusping of the plates causes a sharp discontinuity in the culvert wall. Sometimes cracks form in the culvert plate from the bolt hole to the edge of the plate signaling impending failure before cusping of adjacent plates occurs.
- When large perforations or heavy section loss can be seen in the bottom accompanied by curling of the adjacent plates as the culvert walls are thrust downward into the bedding.
- When voids form in the bedding and/or backfill. Voids themselves are not warrants for tunnel lining, but when removal of portions of the host culvert are required, tunnel liner may offer a safe solution. Voids can be seen through perforations or detected by tapping the culvert wall and listening for a hollow sound. Voids indicate loss of support of the culvert that can lead to bending or buckling of the culvert wall.

Rings of tunnel liner plate are assembled progressively from the inlet or outlet end. Each ring of liner is bolted to the previous ring and adds to the support of the host culvert. Bulkheads may be constructed at desired intervals to grout the annular space between the tunnel liner and the host culvert for greater safety. Workers can install additional tunnel liner rings from inside the tunnel liner that has just been installed. Tunnel liner plate is considerably stronger than other types of liner and even when not yet grouted provides a safe place from which to construct the next ring. Grouting the tunnel liner in short segments can afford much greater safety to workers inside the liner.

Tunnel liner rings can be assembled while temporary water handling pipes conduct water through the culvert. Removal of material from the host pipe and excavation of backfill material should proceed in short segments within the culvert to allow tunnel liner rings to be assembled within the removal limits to minimize exposure time of the excavated areas. Depending on the extent of removal of the host culvert wall and soil before a segment of liner is installed, union workers with tunneling experience may be needed. The culvert span and rise, condition of culvert, backfill soil type and presence of voids, and height of water table are pieces of information that should be documented before attempting to determine if the work will be classified as "tunneling." Contract documents should identify tunneling needs when applicable. Designers should coordinate with Construction to determine the need for union tunnel workers. Typically, tunnel lining segments are short enough to not require special tunneling methods or workers.

Tunnel liner is available in galvanized steel or aluminum. Aluminum is more durable than galvanized steel – especially in low to moderate abrasion level environments. Neither material is durable under heavy abrasion from fast moving water carrying angular stone. Tunnel liner can be protected by applying a mortar lining to the invert along the portion of the cross section where abrasive action is anticipated. Mortar lining shall be anchored securely to the tunnel liner plate. When mortar lining is used, water velocity may increase, and erosion measures may need to be incorporated to protect the channel at the outlet of the culvert. Mortar lining will reduce the hydraulic opening, so a hydraulic analysis shall be performed to confirm that a mortar lining within a tunnel liner is an acceptable option.

XI. CONSTRUCTIBILITY

Constructibility plays an important role in selecting a culvert liner and lining method.

Access to the inlet and outlet ends of the culvert is needed:

- For trucks and equipment access
- For setting up cranes
- To deliver material
- For storing material
- For setting up water handling
- For removal of debris within the culvert
- For placement of the liner
- For grouting of the liner

The size and weight of liner segments can influence the selection of an alternate if site access makes it difficult to deliver and install the liner. Some liners can be fabricated in manageable segments, while others cannot. Delivering individual tunnel liner plates into the culvert for example could overcome access difficulties for delivery of larger liners but assembling plates inside of the culvert will take much longer to install the liner.

Inlet and outlet channel geometry can also affect the selection of a liner and method of lining. For example, a slip liner might be the most economical liner method, but if the channel turns a sharp bend just upstream or downstream of the culvert, there may be insufficient room to place a slip liner in the channel before moving it into the culvert. In another example, the profile grade of the channel may change sharply near the inlet or outlet, preventing a slip liner from being placed on a suitable alignment with the culvert invert. If site conditions require placing a water handling cofferdam near the inlet of the culvert, there may be insufficient room to place a liner before slipping it into the culvert. Any of these constraints could steer a designer toward selecting a culvert liner that can be installed by the segmental or tunnel lining methods instead of slip lining. This means more joints in the liner, more cost and more time to install the liner.

Handling water through the culvert during installation of the liner may be an important site requirement if other options are not available. The Designer shall indicate in the RSR how water is anticipated to be handled with each alternate presented. Consideration shall be given to the location and height of cofferdam and storm frequency at which the cofferdam would overtop. Channels with a tendency to flash flood may require special consideration in selection of liner and installation method to minimize the risk of injury or damage from a flash flood.

Another constructibility concern is insufficient survey of the host culvert. When the condition of host culvert does not allow entry for survey, a greater risk exists that the liner will not fit. In such cases tunnel lining methods must be selected or a replacement structure considered. Tunnel lining methods are slower and will affect the length of the construction schedule. There are few liners that can be specified with tunnel lining and the installation of these are slower than slip lining and segmental lining. Slower advancement of the liner comes with greater risk of storm events causing overtopping of the cofferdam and delays to the work. Temporary diversion of the water (if required) will cost more, take longer and may cause undesirable impacts to regulated areas and natural habitats.

XII. SERVICE LIFE

A report entitled, "Design Guide for Bridges for Service Life" (the Guide) was published in 2014 by the Transportation Research Board (TRB) at the Transportation Research Board website (http://www.trb.org/Design/Blurbs/168760.asp0x). This report provides information and guidance and defines procedures to systematically approach service life and durability for both new and existing bridges. The framework for this report is the SHRP2 Project R19A, "Bridges for Service Life Beyond 100 Years: Innovative Systems, Subsystems, and Components."

The Guide defines three terms that are important to understand:

- Service Life
- Design Life
- Target Design Service Life

Service Life is defined as "The time duration during which the bridge element, component, subsystem, or system provides the desired level of performance or functionality, with any required level of repair or maintenance."

Design Life is defined as "The period of time on which the statistical derivation of transient loads is based: 75 years for the current version of AASHTO LRFD Bridge Design Specifications, referred to throughout the Guide as "LRFD Specifications."

Target Design Service Life is "The time duration during which the bridge element, component, subsystem, and system is expected to provide the desired function with a specified level of maintenance established at the design or retrofit stage.

The approach to designing a new structure or a rehabilitation starts with public safety through structural adequacy. An important step in selecting a culvert liner is to eliminate options that are structurally inadequate to support the fill height and transient loads. As noted in the definition of "Design Life" above, the statistical derivation of transient loads is based on a design life of 75 years. While rehabilitating a culvert to last an additional 75 years is possible, it may not be practical or cost-effective. Steps taken to ensure a longer life may adversely affect other goals such as hydraulic capacity. There may be no available solutions that will provide such a long service life under the given conditions.

The Guide notes that “The service life of a given bridge element, component, subsystem, or system could be more than the target design service life of the bridge system.” A culvert’s target design service life is often defined as the time it takes for the culvert invert or wall to have its first perforation due to corrosion and abrasion. Despite the perforation, the soil envelope may still be able to distribute the loads to the culvert safely and the culvert wall may still have sufficient capacity to support the distributed loads. Why, then, should the target design service life be defined as the time it takes until the culvert first becomes perforated?

New culverts in direct burial that become perforated due to corrosion and/or abrasion expose bedding and backfill material that could be drawn into the culvert by flowing water or wash into the culvert when ground water infiltrates the culvert during low flows. Eventually, voids and sink holes will develop around and above the culvert and the structural capacity will eventually be affected by the loss of support. Unacceptable capacity will not likely occur at the time of first perforation. The time between first perforation and unacceptable structural capacity can vary widely among culverts. There is no reliable way to estimate the timeframe from first perforation to unacceptable capacity. Some culverts in Connecticut have lasted fifteen years or more after first perforation without showing signs of failing. Establishing the target design service life of a culvert in direct burial as “the number of years until the first perforation forms in the culvert invert or wall” is a reliable way to design the culvert “to provide the desired function with a specified level of maintenance established at the design or retrofit stage.” If a perforation forms, an assessment shall be made on a case-by-case basis how quickly the culvert should be repaired or replaced.

Rehabilitation does not have to be reactive; it can be proactive by lining the culvert at a pre-determined age before a perforation occurs. Such actions are classified as “preservation,” and can maintain culverts in a state of good repair. Preventative maintenance allows work to be performed on a schedule, which allows the cost of such work to be budgeted. The cost of preventative maintenance may be slightly higher than maintenance based on condition and needs, but it offers greater reliability and allows the owner to maintain the inventory in a state of good repair.

First perforation in a culvert liner does not expose the bedding and backfill the same way as with an unlined culvert in direct burial because the liner is surrounded by a grouted annular space. Perforation reduces section properties of the liner wall but grout in the annular space will provide some additional capacity of the liner. The contribution will depend on the strength and composition of the grout. In many cases, the host culvert is still actively contributing to the capacity through composite action with the grout. Therefore, the “time until first perforation” for a culvert liner should not necessarily define the target design service life of the culvert liner. In the design of culvert liners, Designers are directed to discount the composite action when designing the liner as a conservative design approach. There are too many site-specific variables that would make it difficult to define a generic approach to determining how much additional capacity from the host culvert and grout the Designer may assume in calculating the required capacity of the liner. Load rating engineers, however, may consider all known variables that contribute to composite action and distribution of load in assessing the capacity of a perforated culvert liner. With biennial or special inspections of the lined culvert, additional service life can be expected beyond first perforation.

The Guide emphasizes that “The end of service life for a bridge element, component, or subsystem does not necessarily signify the end of bridge system service life as long as the bridge element, component, or subsystem could be replaced or resume its function with a retrofit.” The culvert itself is a subsystem that contributes to the bridge system, which includes the culvert and the compacted backfill envelope. If the backfill integrity can be maintained, the culvert is a subsystem that can be retrofitted with a liner to allow the culvert to "resume its function." Therefore, when designing a new culvert, it would be wise to anticipate the future need for a liner and design the culvert opening to accommodate a liner.

The Guide recognizes that there may be multiple solutions to enhance or increase the service life of a culvert and that not all solutions must have a 75 or 100-year service life. The Guide states that Life Cycle Cost Analysis (LCCA) can help identify an optimum solution. See "Life Cycle Cost Analysis Guidance for CTDOT Bridge Projects" under "Guides" on the "Engineering and Construction Information Resources" web page. When all options have a similar service life with no maintenance, a LCCA may not be needed to compare options. Using LCCA, solutions that require periodic rehabilitation or preservation activities can be compared to solutions that require no rehabilitation or maintenance. The documentation of assumptions in developing the service life and LCC for each solution shall include rehabilitation or preservation activities that would extend the life of the liner. The Guide indicates that actions to extend the service life may be "based on assessment of condition and need, or they can be based on a program of preventive maintenance actions planned for similar elements on a group of bridges." A culvert that has served for 40 or 50 years and can be relined may be able to last another 40 or 50 years with no maintenance, thus extending the service life of the original culvert to 80 or 100 years. Relining comes at an expense and, in some cases, may not provide the desired hydraulic capacity. Should a supplemental pipe be proposed to provide the additional capacity required, the LCCA shall include the cost of the supplemental pipe in the estimate for a more appropriate evaluation of alternates.

The benefit of performing a LCCA is that it accounts for the different service lives of the various alternates. Consider the following example of three potential solutions to address a deteriorated culvert:

- Alternate 1: Culvert Replacement
- Alternate 2: Culvert Reline with a 16-gauge, aluminum, spiral rib, smooth liner that is hydraulically acceptable
- Alternate 3: Culvert reline with a 10-gauge, corrugated aluminum liner of a smaller diameter than Alternate 2 plus a supplemental 36" diameter jacked concrete pipe.

In the alternates above, Alternate 2 meets structural and hydraulic requirements, but abrasion and corrosion will greatly reduce the service life at this site. Alternate 2 is determined to have a relatively short service life but is considerably less costly than Alternates 1 and 3. Alternate 3 also meets structural and hydraulic requirements but the service life is greatly increased because a much thicker gauge liner is selected. The corrugated liner must have a smaller internal diameter than the smooth liner to fit within the host culvert. The corrugations also make the liner rougher than the smooth liner in Alternate 2, requiring that a supplemental pipe be jacked beside the culvert to meet hydraulic capacity needs.

Alternates 2 and 3 are both valid rehabilitation solutions. LCCA provides a tool that helps compare Alternates 2 and 3 to each other and to Alternate 1 to find an optimal solution. In addition to cost, other considerations like constructability, site-related concerns and perhaps availability of funds will influence the selection of a solution. Target design service life for a rehabilitation alternate need not meet the goal of 50 or 75 years, provided the evaluation shows the solution to be optimum for that site when compared to alternates that offer a longer service life.

XIII. CULVERT LINER SELECTION CHECKLIST

A. Identify all liner options that could perform structurally

B. Eliminate liner options that are undesirable based on:

1. Durability and Longevity

2. Hydraulics
3. Environmental and Regulatory Considerations
4. Method of Installation (Slip, Segmental, or Tunnel Liner)

C. Identify liner options for constructability considering the following:

1. Access
2. Site Constraints
3. Water Handling
4. Construction Schedule

D. Prepare Alternates, and Determine Service Life and Life Cycle Cost of Alternates

E. Select A Recommended Alternative

See Appendix A for lists of Advantages and Disadvantages for structural and non-structural liner material to assist in evaluating liner options. These lists should be included in the RSR for alternates that are presented. Standardizing the list of advantages and disadvantages will create better consistency between reports prepared by different designers.

Appendix B presents Culvert Liner Selection Aids.

Appendix C presents worked examples of culvert liner calculations for corrosion and abrasion.

APPENDIX A – ADVANTAGES AND DISADVANTAGES OF LINER OPTIONS

1. FIBERGLASS

Advantages:

- Cost-effective for specialized applications
- Low maintenance
- Durable
- Does not corrode
- Highly impact and abrasion-resistant (thickness of interior layer can be increased for abrasion)
- Chemical-resistant
- Lightweight – Short lengths or segments of a cross section are easily transported, handled and installed; Large sections available in split segments with tongue and groove joints to make them transportable and more easily handled
- Liner thickness can be customized to provide greater stiffness and strength and longer life
- Available in custom sizes and shapes, including short-radius bends and flared sections; lateral connections also available
- Fabricated to tight tolerances
- Manning's roughness coefficient as low as 0.009
- Self-cleaning; maintains smooth surfaces
- Capable of installing baffles or sills to slow water velocity and cause sedimentation
- Leak-free joints available

Disadvantages:

- Higher cost than high density polyethylene
- Heavier than high density polyethylene for comparable lengths
- Less abrasion-resistant material than high density polyethylene and pvc
- Low modulus of elasticity (stiffness)
- Low strength - additional capacity is gained at the expense of added weight and cost of material
- Material properties change significantly with time under sustained loads; longterm material properties are 50 - 65% of initial structural values for strength and stiffness. Data is good to 50 years but claims of 100-year service life have not been substantiated.
- Not available in profile wall and is therefore limited to the capacity of a solid wall liner

2. High Density PolyEthylene (HDPE) AND Polyvinyl Chloride (PVC)

Advantages:

- Cost-effective
- Low maintenance
- HDPE and PVC are not subject to chemical attack
- Material does not corrode
- Highly impact and abrasion-resistant
- Lightweight - Easily transported, handled and installed
- Available with smooth interior or corrugated interior
- Self-cleaning; maintains smooth surfaces
- Capable of installing baffles or sills to slow water velocity and cause sedimentation
- Long lengths are available, minimizing number of joints
- Leak-free joints available

Disadvantages:

- PVC available in diameters up to 48"
- PVC displays less resistance to abrasion than HDPE when pH < 4.0
- Low strength and stiffness (PVC is stronger and stiffer than HDPE)
- Relies on soil stiffness for capacity calculations
- Stiffness and strength drop drastically over time under sustained loads, making the wall susceptible to buckling and allowing excessive deflections
- Subject to stress cracking that may reduce longevity of HDPE. The existing test for antioxidants required for long-term service life of HDPE in AASHTO M 294 is inadequate, bringing into questions claims of service life of 75 to 100 years. Changes to M 294 have weakened cell classification requirements, potentially shortening the service life of HDPE pipe fabricated to this specification.
- Wall failure or buoyancy during grouting of annular space is a weakness with thin-walled HDPE liner. High groundwater table also increases buoyancy effects.
- Liner is flammable and subject to damage by brush fire and vandalism
- High thermal expansion affects long culverts with few joints or culverts with fused joints
- Poor weathering resistance

3. ALUMINUM

Advantages:

- Relatively strong – can support most fill heights and vehicle live loads
- Relies more on its own stiffness than on the soil envelope
- Material properties are constant over time
- Cost-effective
- Low maintenance
- Durable material in many environments
- Does not need protective coatings
- Impact and abrasion-resistant in low to moderately abrasive environments
- Gauge can be increased for longevity in moderately abrasive environments
- Lightweight - Easily transported, handled and installed
- Available in smooth or corrugated wall profiles
- Capable of installing baffles or sills to slow water velocity and cause sedimentation
- Long lengths are available, minimizing number of joints

Disadvantages:

- Low modulus of elasticity (stiffness) compared with steel
- May not be able to support large, concentrated loads under shallow fill
- Not suitable for highly abrasive stream flow conditions
- Not recommended for marine environments or where chloride concentration is high
- Should not be in direct contact with steel to avoid galvanic corrosion

4. STEEL

Advantages:

- Strongest of structural liners
- Very stiff without the soil envelope
- Resists grouting pressure with less bracing
- Material properties are constant over time
- Able to be coated for corrosion protection
- Polymer-coated steel and mortar lined steel can resist moderate abrasion
- Available in smooth or corrugated interiors
- Available in many gauges to provide extra thickness to compensate for abrasion and corrosion effects to meet service life goals
- Liner profile is thinner than other materials for same capacity
- Long lengths of liner are available, minimizing the number of joints
- Solid wall liner can be customized to any shape, size and thickness
- Solid wall liner has alloy to improve corrosion resistance. Thickness can be increased to account for longterm section loss due to corrosion.

Disadvantages:

- Heavier than other liners
- Coatings are vulnerable to more highly abrasive stream flow conditions
- Requires corrosion protection for longevity
- Galvanized coating is not suitable for a 75-year life without increasing the liner thickness
- Coated and uncoated steel may exhibit rust staining
- Few liner options are available with a smooth wall
- Solid wall requires welded joints and dry installation conditions
- Steel bands at joints are typically lower gauge and vulnerable to abrasion, requiring replacement before the target design service life

5. STEEL-REINFORCED THERMOPLASTIC

Advantages:

- Stronger than unreinforced thermoplastic liner
- Relies less on the soil envelope for stiffness
- Longterm solution for non-abrasive environments
- Resists grouting pressure with less bracing than for HDPE
- Material properties are constant over time
- Long lengths of liner are available, minimizing the number of joints
- High performance joints are available

Disadvantages:

- Susceptible to local buckling, which affects the capacity for the strength limit state
- Vulnerable to abrasive stream flow conditions due to the thin plastic wall
- Cannot include sills or baffles to slow velocity of flow and encourage sedimentation of natural stream bed material.

6. NON-STRUCTURAL LINERS

a. SPIRAL WOUND PVC OR HDPE

Advantages:

- Has the benefits of a slip liner but does not need long length of inlet or outlet channel from which to push or pull the liner.
- The liner can be installed while water is flowing in the host culvert.
- Minimal disruption to the public
- Minimal staging area is needed
- Smooth interior
- Essentially jointless
- Environmentally friendly (plastic is mechanically wound – avoiding contamination of water with styrene or thermal pollution
- The liner has structural capacity
- No shoring, excavating or backfilling
- The liner profile is relatively shallow, maximizing hydraulic area of the lined culvert

Disadvantages:

- Cannot be designed by LRFD or load rated by LRFR
- Non-round shapes are particularly susceptible to bending failure
- Liner thickness cannot be increased to provide a longer service life for abrasive environments
- Liner is flexible and vulnerable to deflection greater than 5% maximum specified by AASHTO. Gasketed seams may leak under excessive deflection.
- Thermoplastic long-term material properties drop dramatically compared to initial properties.
- Flammable – vulnerable to brush fires and vandalism.
- No owned spec exists to control product selection or prequalification

b. CENTRIFUGALLY CAST CONCRETE

Advantages:

- Fast installation
- Smooth interior surface is possible
- Staging does not typically disrupt the public

Disadvantages:

- Design methodology assumes (incorrectly) that the liner is designed for uniform radial external pressure. This is true for manholes, but not for horizontal culverts. Liner is not designed to resist eccentric loads.
- Fiber reinforcement may not adequately resist bending stresses.
- Thin liner is not suitable for direct burial due to potential for buckling failure.
- Uneven thickness of mortar – especially in corrugated structures and especially in non-round structures. Thickness is controlled by computer equipment that surveys the non-uniform cross section and controls the spray pressure and speed of the machine.
- Verification of mortar thickness is difficult
- Post installation troweling required for smoother liner
- Requires water handling for installation
- Liner mixes are proprietary. This makes it difficult to pre-design liner for design-bid-build. Inability to provide a load rating during design is not acceptable and shifts the responsibility to the Contractor. Requiring the Contractor to provide load rating calculations can lead to delays and claims.
- Poor record of success in multiple states (cracking, leakage, rust-staining, spalling)
- Difficult to assess the liner condition with so many signs of distress
- Impossible to assess the length of service life
- Abrasion resistance is different for each proprietary mix design
- Bond to host culvert is questionable
- Surface prep of host culvert is required.
- Should not be applied to failed culverts (cusped, deformed, voids, etc.)
- Invert recommended to be paved to allow the machine's skids to travel
- Requires significant work by hand methods in addition to the machine
- Length of liner dependent on material placement limitations
- Should not be applied with high ground water table percolating through culvert wall
- No owned spec exists to control product selection or prequalification

c. CURED IN PLACE RESIN

Advantages:

- Quick installation
- Forms a continuous, jointless liner
- Minimal disruption to the public
- Resists corrosion well
- Abrasion-resistant
- Smooth interior
- Conforms to any shape
- UV curing is fast, cost-effective and friendly to the environment

- Cured liner is suitable for potable water
- Liner does not shrink when cured
- Thickness can be increased

Disadvantages:

- Requires a dry pipe for installation
- Requires a machine using air or water pressure to install the liner within the host culvert
- Heated water or steam curing is not friendly to the environment and can be difficult to mitigate
- Cannot be designed by LRFD or load rated by LRFR
- Non-round shapes are particularly susceptible to bending failure
- Thermoplastic long-term material properties drop dramatically compared to initial properties.
- Liner is flexible and vulnerable to deflection greater than 5% maximum specified by AASHTO.
- Does not handle irregularities in host culvert well
- Contractor must consider the availability and location of a wet-out facility to apply the resin
- QA/QC plan is critical to success of the liner installation and performance
- No owned spec exists to control product selection or prequalification

APPENDIX B – CULVERT LINER SELECTION AIDS

In the absence of as-built information, the Table 1 may be used to select a constrained soil modulus for use in designing thermoplastic liners with Cover Height of 8' or greater. Unless actual soil backfill information is available, assume Class III soil and 95% compaction. 95% compaction assumes that the soil over and beside the culvert is well-compacted after many years of service. If it is suspected that there may be voids and/or active settlement in the backfill, then assume 85% compaction.

Table 0.1 - Constrained Soil Modulus

Secant Constrained Soil Modulus, M_s

	Constrained Soil Modulus at Various Depths, Compaction							
	Class I		Class II			Class III		
	Crushed Stone		GW, GP, SW, SP			GM, SM, ML(1), GC and SC with <20% passing the 200 sieve		
Cover Height	Compacted	Uncompacted	95%	90%	85%	95%	90%	85%
Feet	psi	psi	psi	psi	psi	psi	psi	psi
1	2350	1280	2000	1280	470	1420	670	360
5	3180	1440	2450	1440	510	1610	720	380
10	3900	1580	2840	1580	550	1730	750	400
15	4460	1660	3090	1660	590	1790	760	410
20	4980	1730	3270	1730	620	1840	770	420
25	5500	1800	3450	1800	650	1880	790	430
30	5900	1860	3610	1860	690	1920	810	450
35	6300	1920	3770	1920	720	1960	830	460
40	6700	1980	3930	1980	780	2010	860	480
45	7100	2040	4090	2040	790	2050	880	490
50	7500	2100	4250	2100	830	2090	900	510
55	7860	2180	4400	2180	860			
60	8220	2260	4550	2260	895			
65	8580	2340	4700	2340	930			
70	8940	2420	4850	2420	965			
75	9300	2500	5000	2500	1000			

Notes:

1) M_s values presented in the table assume that the native material is at least as strong as the backfill material. If the native material is not adequate, it may be necessary to increase the trench width. Refer to ASTM D2321 for additional information on over-excavation.

2) M_s may be interpolated for intermediate cover heights.

Table 0.2 – Recommended Abrasion Levels

Liner Material/Wall Type	Wall Profile	Available Sizes and Shapes	Material Spec	Max. Abrasion Level[1] Recommended	
Fiberglass	Solid	All (Can be custom made)	ASTM D3262	Level 6	
HDPE	Solid; Corrugated; Profile Wall	Round Round Round	AASHTO M326/ASTM F714 AASHTO M294 ASTM F894	Level 6	
PVC	Solid	Round		Level 4	
Aluminum	Spiral Rib Smooth Interior; Corrugated; Structural Plate; Tunnel Liner	Round, Pipe-Arch Round, Pipe-Arch Round, Pipe-Arch, Horiz. & Vertical Ellipses Round, Pipe-Arch and Underpass	AASHTO M 197 AASHTO M 196 AASHTO M 219 Alloy 5052-H141	Level 3 (A higher level may be considered if thickness is increased)	
Steel (Galvanized)	Spiral Rib Smooth Interior; Corrugated; Structural Plate; Tunnel Liner	Round, Pipe-Arch Round, Pipe-Arch Round, Pipe-Arch, Horiz. & Vertical Ellipses Round, Pipe-Arch and Underpass	AASHTO M 218 AASHTO M 218 AASHTO M 167 ASTM A1011	Level 5 (A higher level may be considered if thickness is increased)	
Steel (Aluminized, Type 2)	Spiral Rib Smooth Interior; Corrugated Tunnel Liner	Round, Pipe-Arch Round, Pipe-Arch Round, Pipe-Arch and Underpass	AASHTO M 274 AASHTO M 274 AASHTO M 274 ASTM A929	Level 5 (if thickness is increased)	
Steel (Polymer-Coated)	Spiral Rib Smooth Interior; Corrugated	Round, Pipe-Arch Round, Pipe-Arch	AASHTO M 246 AASHTO M 246	Level 5 (if thickness is increased)	
Steel (Uncoated)	Solid	All (Can be custom made)	ASTM A36, Grade B	Level 5 (if thickness is increased)	
Steel-Reinforced Thermoplastic	Corrugated Smooth Interior	Round	AASHTO M 335 and MP-40; ASTM D3350, Resin Class 345464C	Level 3	

Footnotes:

1. Abrasion levels are rated from “1” (no abrasion) to “6” (Heavy Abrasion)

The following information is referenced from the California Department of Transportation Highway Design Manual, Chapter 850 (Physical Standards).

https://dot.ca.gov/-/media/dot-media/programs/design/documents/chp0850-a11y.pdf

Table 0.3 - Classification of Abrasion Levels

Abrasion Level	General Site Characteristics	Possible Culvert Lining Options
1	Virtually no abrasive bed load Water velocity unlimited	All liners possible
2	Moderate bed load of sand or gravel 1 ft/s ≤ Velocity ≤ 5 ft/s	All liners possible Check nearby culverts for abrasion to be sure that abrasion is not a concern.
3	Moderate bed load of sand, gravel and small cobbles 5 ft/s < Velocity ≤ 8 ft/s	All liners possible. Steel should consider polymer coating, aluminized coating or galvanized coating and both should consider additional gauge thickness for target design service life. Aluminum should consider additional gage thickness for target design service life.
4	Moderate bed load of angular sands, gravels, and/or small cobbles/rocks 8 ft/s < Velocity ≤ 12 ft/s	Corrugated HDPE (Type S only), SDR HDPE, PVC, fiberglass, Steel should consider polymer coating, aluminized coating or galvanized coating and should consider additional gauge thickness. Aluminum not recommended.
5	Moderate bed load of angular sands, gravels, and rocks 12 ft/s < Velocity ≤ 15 ft/s	SDR HDPE, fiberglass, Steel should consider polymer coating, aluminized coating or galvanized coating and should consider additional gauge thickness.
6	Moderate bed load of angular sands, gravels, and rocks 15 ft/s < Velocity ≤ 20 ft/s (Note: If minor bed load, use Abrasion Level 3)	SDR HDPE (2.5" thick min.), fiberglass, Steel should be specified with additional gage thickness to yield the target design service life. Concrete not recommended for velocity >15 ft/s unless a larger, harder aggregate than the bed load is embedded in concrete liner. Consider culvert replacement with an armored channel bed or construct settling basins upstream of inlet to collect cobbles and rocks. This requires regular maintenance to remove collected materials.

Table 0.4- Bed Materials Moved by Various Flow Conditions

Bed Material	Grain Dimensions (inches)	Approximate Nonscour Velocities (feet per second)			
		Mean Depth (feet)			
		1.3	3.3	6.6	9.8
Boulders	more than 10	15.1	16.7	19.0	20.3
Large cobbles	10 – 5	11.8	13.4	15.4	16.4
Small cobbles	5 – 2.5	7.5	8.9	10.2	11.2
Very coarse gravel	2.5 – 1.25	5.2	6.2	7.2	8.2
Coarse gravel	1.25 – 0.63	4.1	4.7	5.4	6.1
Medium gravel	0.63 – 0.31	3.3	3.7	4.1	4.6
Fine gravel	0.31 – 0.16	2.6	3.0	3.3	3.8
Very fine gravel	0.16 – 0.079	2.2	2.5	2.8	3.1
Very coarse sand	0.079 – 0.039	1.8	2.1	2.4	2.7
Coarse sand	0.039 – 0.020	1.5	1.8	2.1	2.3
Medium sand	0.020 – 0.010	1.2	1.5	1.8	2.0
Fine sand	0.010 – 0.005	0.98	1.3	1.6	1.8
Compact cohesive soils					
Heavy sandy loam		3.3	3.9	4.6	4.9
Light		3.1	3.9	4.6	4.9
Loess soils in the conditions of finished settlement		2.6	3.3	3.9	4.3

Notes:

(1) Bed materials may move if velocities are higher than the nonscour velocities.

(2) Mean depth is calculated by dividing the cross-sectional area of the waterway by the top width of the water surface. If the waterway can be subdivided into a main channel and an overbank area, the mean depths of the channel and the overbank should be calculated separately. For example, if the size of moving material in the main channel is desired, the mean depth of the main channel is calculated by dividing the cross-sectional area of the main channel by the top width of the main channel.

The following information is from a Final Report (FHWA/CA/TL – CA01-0173, EA 680442) entitled, "Evaluation of Abrasion Resistance of Pipe and Pipe Lining Materials," published in September 2007.

https://rosap.ntl.bts.gov/view/dot/27517

Table 0.5 - Relative Abrasion Resistance Properties

Material	Relative Wear (dimensionless)
Steel	1
Aluminum	1.5 – 3
PVC	2
Polyester Resin (CIPP)	2.5 – 4
HDPE	4 – 5
Concrete (RCP 4000 – 7000 psi)	75 – 100
Calcium Aluminate (Mortar)	30-40
Calcium Aluminate (Concrete)	20 – 25
Basalt Tile	1
Polyethylene (CSSRP)	1 – 2

* Evaluation of Abrasion Resistance of Pipe and Pipe Lining Materials Final Report FHWA/CA/TL-CA01-0173 (2007).

The table above offers a comparison of abrasion resistance of a number of materials. All materials are compared to steel, where steel is the most resistant to abrasion. The rate of wear is very high in this study due to the extremely aggressive bed load of angular material and the high velocities.

The following tables present wear rates for various liner materials and are in no particular order.

Table 0.6 - Abrasion Wear Rates - Concrete

ABRASION OF CONCRETE LINER						
Abrasion Level	Velocity ft/s		Concrete Thickness (For 50-Year Life) Inches		Wear Rate Inch/Year	
	Low	High	Low	High	Low	High
4	8	12	2	4	0.04	0.08
5	12	15	4	13	0.08	0.26
6	15	20	13	15	0.18	0.30

Table 0.7- Abrasion Wear Rates - Steel

ABRASION OF STEEL LINER						
Abrasion Level	Velocity ft/s		Steel Thickness (For 50-Year Life) Inches		Wear Rate Inch/Year	
	Low	High	Low	High	Low	High
4	8	12	0.052	0.052	0.00104	0.00104
5	12	15	0.052	0.18	0.00104	0.0036
6	15	20	0.18	0.5	0.00218	0.01

Table 0.8 - Abrasion Wear Rates - Aluminum

ABRASION OF ALUMINUM LINER						
Abrasion Level	Velocity ft/s		Aluminum Thickness (For 50-Year Life) Inches		Wear Rate Inch/Year	
	Low	High	Low	High	Low	High
4	8	12	0.075	0.164	0.0015	0.00328
5	12	15	Provide invert protection		NA	NA
6	15	20	Provide invert protection		NA	NA

Table 0.9 - Abrasion Wear Rates - PVC

ABRASION OF PVC LINER						
Abrasion Level	Velocity ft/s		PVC Thickness (For 50-Year Life) Inches		Wear Rate Inch/Year	
	Low	High	Low	High	Low	High
4	8	12	0.1	0.1	0.002	0.002
5	12	15	0.1	0.35	0.002	0.007
6	15	20	0.35	1	0.005	0.02

Table 0.10 - Abrasion Wear Rates - HDPE

ABRASION OF HDPE LINER						
Abrasion Level	Velocity ft/s		HDPE Thickness (For 50-Year Life) Inches		Wear Rate Inch/Year	
	Low	High	Low	High	Low	High
4	8	12	0.125	0.25	0.0025	0.005
5	12	15	0.25	0.875	0.005	0.0175
6	15	20	0.875	2.5	0.0125	0.05

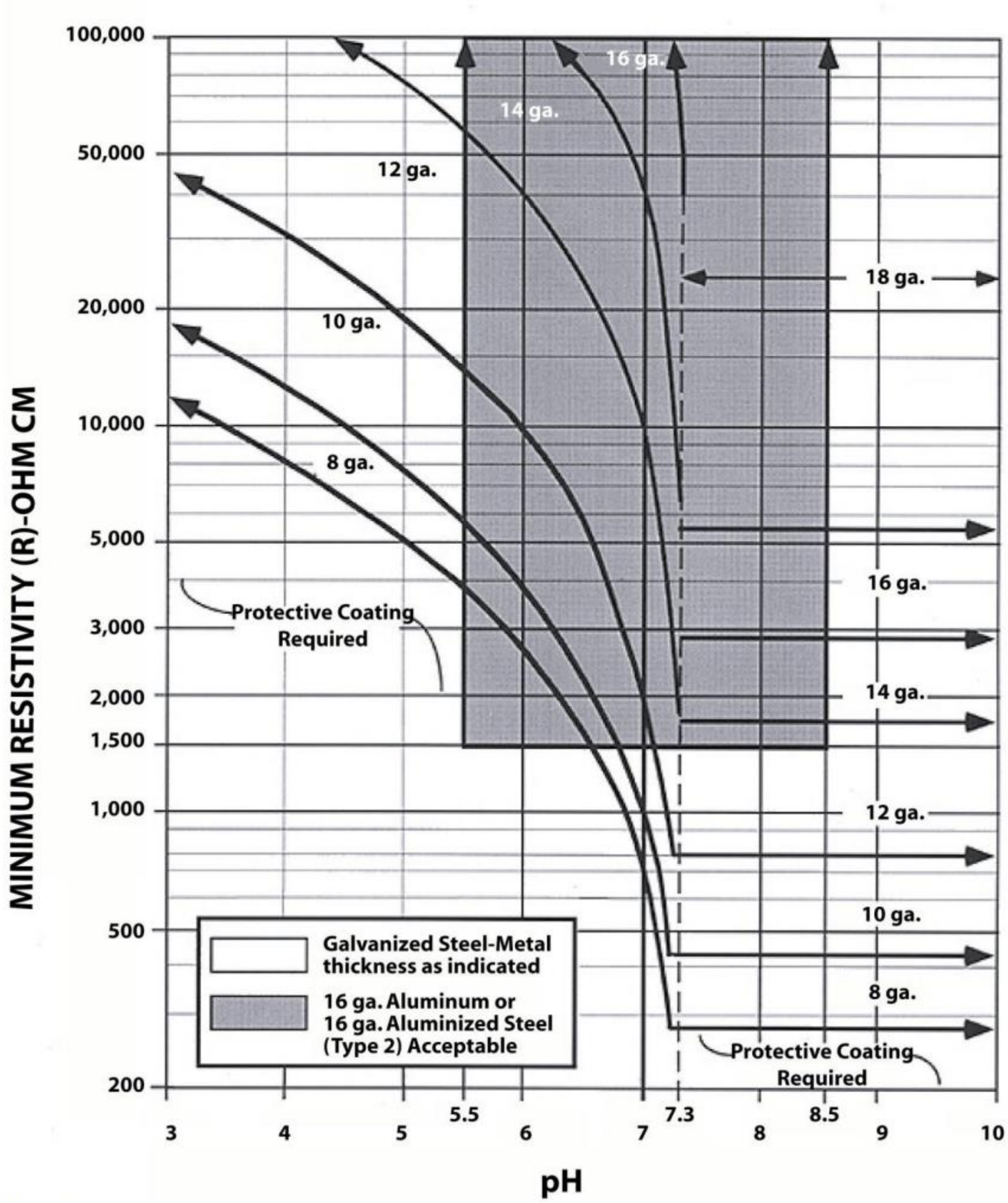
Table 0.11 - Abrasion Wear Rates - CIPP

ABRASION OF CIPP LINER						
Abrasion Level	Velocity ft/s		CIPP Thickness (For 50-Year Life) Inches		Wear Rate Inch/Year	
	Low	High	Low	High	Low	High
4	8	12	0.1	0.3	0.002	0.006
5	12	15	0.3	0.7	0.006	0.014
6	15	20	0.7	2	0.01	0.04

Polyester Resin Cured-In-Place Pipe (CIPP)

Figure 0-1 - Minimum Thickness of Metal for 50-year Service

Minimum Thickness of Metal Pipe for 50-Year Maintenance-Free Service Life (2)



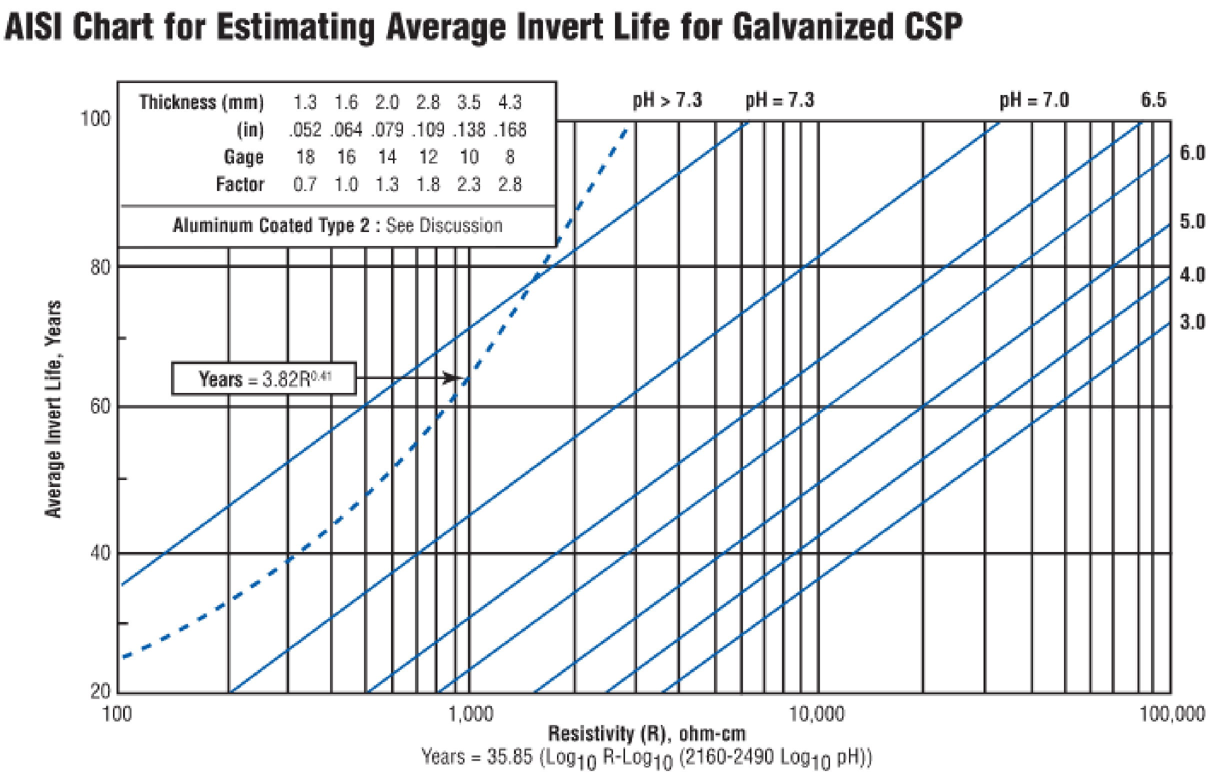
Notes:

(1) For pH and aluminum resistivity levels not shown refer to Fig. 855.3B steel pipes. (California Test 643)
(2) Service life estimate are for various corrosive conditions only.
(3) Refer to Index 852.3(2) and 852.4(2) for appropriate selection of metal thickness and protection coating to achieve service life requirements.

The following chart is referenced from the CSP Durability Guide, published by the National Corrugated Steel Pipe Association (NCSPA), May 2000. It directly applies to galvanized corrugated steel liner. To apply the AISI Chart to aluminized steel (Type 2), multiply the Average Life x 1.3. The chart is for corrosion only and does not consider the effects of abrasion.

http://pcpipe.com/wp-content/uploads/2019/05/NCSPA-CSP_Durability-Guide.pdf

Figure 0-2 - Estimating Service Life for Galvanized CSP



Steps in Using the AISI Chart

The durability design chart can be used to predict the service life of galvanized CSP and to select the minimum thickness for any desired service life. Add-on service life values are provided in the table on page 5 for additional coatings.

1) Locate on the horizontal axis the soil resistivity (R) representative of the site.
2) Move vertically to the intersection of the sloping line for the soil pH. If pH exceeds 7.3 use the dashed line instead.
3) Move horizontally to the vertical axis and read the service life years for a pipe with 1.6 mm (0.064 in.) wall thickness.
4) Repeat the procedure using the resistivity and pH of the water; then use whichever service life is lower.
5) To determine the service life for a greater wall thickness, multiply the service life by the factor given in the inset on the chart.

Table 0.12 - Corrosion Rates of Corrugated Steel

Corrosion Rates of Corrugated Steel Pipe (CSP)						
			Galvanized		Aluminized	
Gauge	Thickness, T (Inch)	Factor	Years, Y_G[1] to First Perforation	Corrosion Rate inch/year	Years, Y_A to First Perforation	Corrosion Rate inch/year
18	0.052	0.7	0.7 * Y_{G_16}	T_{18}/Y_{G_18}	1.3 * Y_{G_18}	T_{18}/Y_{A_18}
16	0.064	1	Y_{G_16}	T_{16}/Y_{G_16}	1.3 * Y_{G_16}	T_{16}/Y_{A_16}
14	0.079	1.3	1.3 * Y_{G_16}	T_{14}/Y_{G_14}	1.3 * Y_{G_14}	T_{14}/Y_{A_14}
12	0.109	1.8	1.8 * Y_{G_16}	T_{12}/Y_{G_12}	1.3 * Y_{G_12}	T_{12}/Y_{A_12}
10	0.138	2.3	2.3 * Y_{G_16}	T_{10}/Y_{G_10}	1.3 * Y_{G_10}	T_{10}/Y_{A_10}
8	0.168	2.8	2.8 * Y_{G_16}	T_8/Y_{G_8}	1.3 * Y_{G_8}	T_8/Y_{A_8}

Note: This table is for corrosion only and does not consider loss due to abrasion.

Footnote 1: Enter Resistivity, R, and pH into the following formula to calculate Years to first perforation of 16-gauge galvanized liner, Y_G: (Calculates value from Chart on previous page)

$$Y_{G\_16} = 35.85\ (\text{Log10 } R - \text{Log10 } (2160 - 2490 \text{ Log10 pH}))$$

Use the table below to select Y_{G_16} for a known pH and Resistivity. Enter Y_{G_16} in the table above to calculate the corrosion rates for galvanized and aluminized liners of various gauges.

Table 0.13 - Years to First Perforation for 16-gauge Galvanized Steel

Years to First Perforation for 16-Gauge Galvanized Steel Culvert Liner, Y_{G_16}												
	Resistivity											
pH	500	1000	1500	2000	3000	4000	5000	6000	7000	8000	9000	10000
4		6	13	17	24	28	32	34	37	39	41	42
5	3	14	20	24	31	35	39	41	44	46	48	49
6	13	23	30	34	41	45	48	51	54	56	58	59
6.5	20	31	37	42	48	53	56	59	61	63	65	67
7	34	45	51	56	62	67	70	73	75	77	79	81
7.3	60	71	78	82	88	93	96	99	101	104	105	107

APPENDIX C – WORKED EXAMPLES

1. Galvanized and Aluminized Steel Culvert Liner

The following discussion provides design guidance on how to use the AISI Chart in Figure B of Appendix B to graphically determine the service life of a selected culvert liner. Tables 7 and 8 in Appendix B provide a numerical calculation of years to first perforation. These calculations can be confirmed by the Liner Selection Worksheet that is available on State Bridge Design's web page.

For this example, it is determined that 16-gauge galvanized steel is needed for structural capacity. The liner will be grouted inside the host culvert, which is conservatively assumed to support no load. The AISI chart calculates time to first perforation. For corrugated galvanized steel experiencing no abrasion, first perforations can occur anywhere along the corrugations. Although capacity is reduced by a perforation, the grout, together with the host culvert will provide additional composite action and distribute loads to the bedding. Assume that the full design capacity of the liner is available at first perforation.

Little/no abrasion (Abrasion Levels 1 and 2),

Go to the AISI Chart for Estimating Average Invert Life for Galvanized CSP (or see Table 8above for 16-gauge galvanized steel culvert liner). For this example, assume that environmental testing was performed that indicates that the water has a pH of 6.0 and a resistivity of 2,000 ohm-cm. From the table, the Average Invert Life for a 16-gauge liner to first perforation is 34 years. If a life of 75 years is desired, consider a thicker gauge. There are two ways to calculate the thickness needed for a different gauge liner:

- Calculate the corrosion rate of 16-gauge liner:

  The corrosion rate is calculated by dividing the thickness of liner by the years of estimated service life: T_{16}/Y_{G_16} = 0.064 inch thick/34 years = 0.00188 inch/year

  Using the corrosion rate calculated above for the 16-gauge liner, calculate the desired thickness of liner to resist corrosion for 75 years: 75 years x 0.00188 inch/year = 0.141 inch. A 10-gauge liner is 0.138 inch thick < 0.141 inch (an 8-gauge liner would provide considerably more life).

- Use the inset of the AISI Chart in Figure B to directly calculate the life:

  The corrosion life of a 10-gauge galvanized steel liner is (34 years for a 16-gauge liner) x (a factor of 2.3 from the inset of the AISI Chart) = 78.2 years > 75 years.

  Note: the corrosion rate of 10-gauge galvanized plate is 0.138" thick/78.2 years = 0.00176 inch per year <0.00188 calculated for 16-gauge. 75 years x 0.00176 inch/year = 0.132" required < 0.138" for 10-gauge.

Moderate abrasion within the culvert (Abrasion Levels 3, 4 and 5),

Assume for this example that the type of streambed material is angular sands and gravels and the water velocity for a 2-year storm event = 12 fps. Classify this culvert as Abrasion Level 4. Select the thickness of the steel to account for material lost due to abrasion as well as corrosion. Since a 10-gauge was selected for corrosion alone, consider an 8-gauge liner.

8-gauge galvanized liner has a corrosion life of 2.8 x life of 16-gauge = 2.8 * 34 years = 94.2 years. The rate of corrosion is 0.168 inch / 94.2 = 0.00176 inch/year. Combining corrosion and abrasion rates for 8-gauge galvanized steel: 0.00104 inch/year + 0.00176 inch/year = 0.00280 inch/year. For a 75-year life a thickness of material must be 75 years *0.00280 inch/year = 0.21 inch > 0.168" 8-gauge galvanized steel liner.

Since 8-gauge is the thickest galvanized plate available, consider adding a concrete liner to help protect the 8-gauge galvanized steel liner. The 8-gauge galvanized steel liner is expected to last 0.0168 inch thick /0.0028 inch/year = 60 years. The concrete must last for 75 years – 60 years = 15 years.

From Table 6A - Abrasion of Concrete Liner in Appendix B, select the rate of abrasion of concrete for velocity = 12 fps to be 0.08 inch/year. 15 years x 0.08 inch/year = 1.2 inches of concrete is required to protect the 8-gauge galvanized steel liner.

Consider aluminized steel without a concrete liner. Aluminized steel is available in thicknesses up to 10 gauge. Select a 10-gauge aluminized steel liner. As seen previously, a 10-gauge galvanized liner without abrasion will last 78.2 years to first perforation. Aluminized 10-gauge will last 1.3 * 78.2 years = 101.7 years.

The corrosion rate of this liner is 0.138 inch / 101.7 years = 0.00136 inch/year.

Add the abrasion rate of 0.00104 inch/year for a total material loss of 0.00136 + 0.00104 = 0.00240 inch/year.

The calculated years to first perforation is: 0.138 inch / 0.00240 inch/year = 57.5 years. If a 75-year service life is desired, a concrete liner could be added. The required thickness of concrete liner is: (75 – 57.5) * 0.08 inch/year = 1.4".

2. Polymer-Coated Steel Culvert Liner

At Abrasion Level 4, polymer-coated steel is presumed to contribute an additional 10 years of service life to the culvert liner. The steel below the polymer is galvanized. Calculate the gauge required to provide a 75-year design service life. First, subtract the additional 10-year life that the polymer offers:

75 years – 10 year (polymer) = 65 years of life expected from the galvanized steel below the polymer coating. Note: Polymer-coated steel is available in thicknesses up to 10-gauge.

Next, determine the rate of section loss due to corrosion and abrasion:

> Corrosion: From the example above, a 10-gauge galvanized liner will corrode at the rate of 0.00176 inch/year
>
> Abrasion: The abrasion rate of steel is 0.0010 inch/year
>
> The combined wear rate = 0.00176 + 0.0010 = 0.00276 inch/year

Calculate the required thickness to last 65 years: 65 years x 0.00276 = 0.179 inch > 0.138 (10-gauge)

Since 10-gauge does not provide the required thickness, the thickest available polymer-coated liner will not be sufficient for a 75-year life. If the Department would accept a design service life of 50 years, or it can be shown that there will be adequate structural capacity at 75 years (remember that only a 16-gauge steel liner was required), the 10-gauge polymer-coated steel liner would be a possible alternate.

3. Aluminum Culvert Liner

Using the design situation in the example for the design of galvanized and aluminized steel liner, consider if aluminum liner can be proposed. pH is 6.0, Resistivity is 2,000 ohm-cm, Abrasion Level 4 with water velocity = 12 fps and a moderate bed load of angular sand and gravel.

Although aluminum liner is typically recommended for Abrasion Level 3 and lower, consider how it will perform in this situation. The service life will be shortened for Abrasion Level 4 and higher. Increasing the thickness is an option to increase service life if there is a compelling reason to consider aluminum.

From the Abrasion of Aluminum Liner table in Table 6C of Appendix B, the rate of abrasion is 0.00328 inch/year.

From Appendix B, Figure A, the corrosion rate is 0.064 inch/50 years = 0.0013 inch/year.

Calculate the years until first perforation of 0.25 inch-thick aluminum liner: 0.25 inch / (0.00328 + 0.0013inch per year) = 54.5 years. An aluminum liner of the maximum available thickness would perform for approximately 55 years until first perforation. If the life cycle cost for this liner for this service life is the lowest cost of the alternatives or is otherwise acceptable to the Department, aluminum could be considered an alternate in the RSR. The 0.25-inch-thick aluminum liner weighs less than the 10-gauge polymer-coated steel liner and offers five additional years of service life. If it were difficult to handle the steel in the field due to its weight or touching up the polymer coating was thought to add excessive time and cost, aluminum may provide a more constructable alternative. Before selecting the aluminum alternative, check the structural capacity at the end of service life to confirm it is adequate.

4. HDPE Culvert Liner

Since HDPE culvert liner will not corrode, consider abrasion only. From Table 6E – Abrasion of HDPE Liner the abrasion rate at a velocity of 12 fps (Abrasion Level 4) is 0.0050 inch/year. The required sacrificial thickness for a 75-year life is 75 x 0.0050 inch per year = 0.375 inch. This will require a smooth wall Standard Dimension Ratio (SDR) HDPE liner or a profile wall liner with an interior lining of at least 0.375”. SDR liner may be too heavy, too expensive, or may not be available at all. HDPE profile wall liner is lightweight, available and less expensive. Specify a minimum Ring Stiffness Coefficient (RSC) of 160. If the thickness is not adequate, select RSC 250 or stiffer.

5. Fiberglass Culvert Liner

Fiberglass resin abrades at a rate of six times that of HDPE. The interior layer of the wall thickness can be designed to be sacrificed for the service life of the culvert. At an abrasion rate of 0.030 inch/year, the interior layer shall be 75 years x 0.030 inch/year = 2.25” thick. The design of the fiberglass total wall thickness shall account for this sacrificial loss to ensure that the liner can support the desired loads at the end of its service life. Contact a supplier for preliminary design guidance.