

White Paper

Performance Guideline for Buried Steel Structures

Introduction

Historically, structural plate corrugated steel pipe structures have been fabricated from galvanized steel. Galvanized steel has a history of long life when installed in proper environments; however durability remains a concern in installations with more challenging environmental conditions. Since 1974, corrugated metal products have been manufactured from polymer coated sheet in order to improve durability in these challenging installations. Recently, similar polymer coatings have been applied to structural plate corrugated steel pipe and deep corrugated structural plate.

The Corrugated Steel Pipe Institute (CSPI) developed a Guideline to assist practitioners in selecting appropriate structure type, end protection details and the optimum coating and plate thickness combination to enable corrugated steel plate structures to meet design service life specifications. Consideration of the application exposure, location and the site specific environmental conditions are key parameters when estimating the material service life of buried flexible steel structures. The guideline is intended to supplement local knowledge of the performance of buried plate structures.

This white paper provides technical data and assumptions which support the Estimated Material Service Life (EMSL) approach presented in the CSPI Guideline. The EMSL approach uses established models to estimate metal loss in soil, water and atmospheric environments. Models considered and selected for each of the environments are discussed in the following sections of this white paper.

This white paper was prepared by Elzly Technology Corporation under contract to CSPI. Elzly is a consulting engineering firm specializing in corrosion and corrosion control for civil works, industrial structures and military equipment. Their experience includes more than 20 years studying the durability of corrugated metal structures and the benefits of various coatings. Elzly has a broad technical perspective on the use of protective coatings, metal plating, corrosion resistant metal alloys and chemical corrosion inhibitors.

Estimated Material Service Life (EMSL) Approach

The Canadian Highway Bridge Design Code¹ does not dictate a specific durability estimation procedure. Rather, the code provides minimum corrosion protection requirements and references a variety of durability estimation procedures in the commentary. The commentary discusses coatings, cathodic protection, engineered backfill and increased metal thickness as approaches to improving structural durability. For durability estimation, the commentary refers the reader to the California Method² and

¹ CAN/CSA-S6-06 - Canadian Highway Bridge Design Code

² California Test 643, Method for Estimating the Service Life of Steel Culverts (<http://www.dot.ca.gov>)

variants thereof. For loss models, the reader is referred to those proposed by the University of British Columbia and AASHTO. In addition to the metal loss models which are compatible with the *AASHTO LFRD (Load and Resistance Factor Design) Bridge Design Specifications*³ and that proposed in a study by the University of British Columbia⁴ the UK Design Manual for Roads and Bridges⁵ also provides a metal loss model.

To estimate structural plate service life for galvanized plate, the loss models may be used to calculate estimated metal loss from each side of the structural plate. Figure 1 illustrates the approach. This estimated metal loss is added to the nominal required structural steel thickness as a “corrosion allowance”.

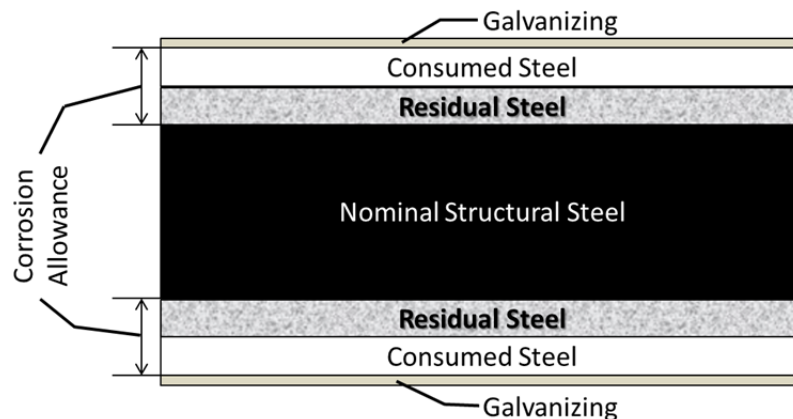


Figure 1. Schematic of the EMSL approach.

In Figure 1, the nominal structural steel is the layer required to resist the applied load without yielding. The corrosion allowance is comprised of consumed steel (steel lost to corrosion) and residual steel (part of the corrosion allowance that is not lost to corrosion for whatever reason). The design approach makes the simplification that corrosion occurs at some general uniform rate and does not take into account the special circumstance of corrosion pitting. Since pit penetrations have a limited impact on the overall remaining cross section, the service life of a corrugated plate structure is related to the remaining tensile capacity and not necessarily the maximum pit depth. Metal loss is idealized as uniformly distributed over the surface at some depth deeper than the actual average yet shallower than the deepest pit which may occur. This results in a conservative model of the corrosion impact.

In the case of structural plate corrugated steel pipe and deep corrugated structural plate, the plate surface may be exposed to water, soil or atmosphere. Thus, different corrosion models may need to be considered for either side of the structure. Generally, the worst case will involve water on one side and soil on the other or soil on both sides. Exceptional instances of extreme conditions such as sulfate

³ NCHRP REPORT 675, *LRFD Metal Loss and Service-Life Strength Reduction Factors for Metal-Reinforced Systems*.

⁴ Durability of Buried Galvanized Steel Structures in British Columbia, Tom Galtung Dosvig, University of British Columbia, April 1995.

⁵ UK Design Manual for Roads and Bridges BD 12/01 Volume 2, Section 2, Part 6 Design of Corrugated Steel Buried Structures with Spans Greater than 0.9 Metres and up to 8.0 Metres

reducing bacteria (SRB) or highly corrosive chemistries would result in higher corrosion. The model does not determine corrosion rates for these extreme conditions. Instead, the model includes environmental limits within which the extreme conditions are unlikely.

The corrosion allowance is a calculated estimate of the average metal loss expected over the Design Service Life (DSL). By adding a corrosion allowance to the thickness required to resist applied dead and live loads we can ensure the structure meets the design requirements throughout the DSL. A protective coating can be added to the structure, or portions of the structure, to reduce the estimated corrosion allowance. If applicable, the guideline recommends the designer assume no metal loss for a period of time on polymer coated pipe (this period of time is referred to as the add-on life).

A corrosion allowance is calculated for each environment (water, soil and atmosphere) to which the structure is exposed. Corrosion acts from both the inside and outside of a structure; only one corrosion allowance for each side of a plate is to be summed to determine the required total corrosion allowance. For example, for submerged plates on a creek crossing, it may be appropriate to use the water corrosion allowance inside and soil allowance outside.

Water-side Corrosion

Water side corrosion is the most complicated of the environments in which a corrugated structural plate structure must perform. For water side corrosion, the engineer must consider water chemistry (pH, resistivity, chlorides, sulfates, and hardness) and flow rate (aeration and abrasion).

- pH level – pH is a measure of the acidity or alkalinity of the water. In acidic solutions, pH is less than 7 ($\text{pH} < 7$) and for basic solutions pH is greater than 7 ($\text{pH} > 7$). A solution with $\text{pH} = 7$ is considered neutral. As pH becomes more acidic, metallic corrosion generally increases. Caustic (basic) pH is generally not corrosive to steel but can be corrosive to other materials such as aluminum or zinc.
- Resistivity (ohm-cm) – resistivity is an indication of water's inability to carry an electrical current. It is a function of the concentration of Total Dissolved Solids (TDS) or salt ions in the water. ASTM D-1125 can be used to measure resistivity of water.
- Chlorides (Cl) – chlorides are highly soluble compounds commonly found in deicing salts, seawater and evaporation pools. Chloride ions are the most likely contributor to low resistivity values. Chlorides promote the corrosion of unprotected steel because of their effect on resistivity, depassivating effect and hygroscopic nature (in atmospheric exposures). ASTM D-512 can be used to measure chloride ion content in water.
- Sulfates (SO_4) – soluble sulfates occur naturally. They are also commonly found in polluted air and are deposited on soil and in water. They contribute to lower pH levels in water (acid rain). Sulfate may decrease resistivity and support sulfate reducing bacteria in anaerobic conditions, both of which promote the corrosion of unprotected steel. ASTM D-516 can be used to measure soluble sulfate in water.

- **Total Hardness** – hardness is indicated by the amount of calcium carbonate (CaCO_3) dissolved in the water and will determine the buffering capacity or ability of the water to neutralize acidity from rainwater and other sources. Natural soft water has a low concentration of CaCO_3 which, despite high resistivity, may indicate a corrosive potential for galvanized steel. Hard water is rich in CaCO_3 which neutralizes acidity and forms a protective scale on galvanized steel. ASTM D-1126 can be used to measure total hardness of water.
- **Aeration & Flow** – Well aerated, flowing water increases the corrosion rate of metals because it (1) ensures that the maximum possible amount of oxygen is available to support the corrosion reaction and (2) tends to prevent stable protective oxide films from forming on the surface. The higher flow rates associated with higher abrasion levels will tend to increase metallic corrosion.
- **Abrasion** – Table 1 shows four abrasion levels which have been defined based on the type of bedload present and the anticipated maximum flow velocity.⁶

Table 1 – Abrasion Flow Parameters

Abrasion Level	Bedload Description	Anticipated Flow Velocity (m/s)
1	Non Abrasive – No bedload (e.g. storm sewers, stormwater detention systems, arches)	Negligible
2	Low Abrasive – Minor bedloads of sand and gravel	0 - 1.5
3	Moderately Abrasive – Moderate bedloads of sand and gravel	1.5 - 4.5
4	Severely Abrasive – Heavy bedloads of sand, gravel and rock	1.5 - 4.5

Flowing bedload will wear the soft zinc coating through to the hard “alloy layer” which is an alloy of steel and zinc that is actually harder than the underlying steel. Abrasion velocities should be evaluated on the basis of frequency and duration. Consideration should be given to a frequent storm such as a two year event or mean annual discharge. Choosing a less conservative (i.e., less frequent) flow condition for a design basis may extend the calculated service life but will also increase the risk of erosion failure in the bottom of the structure. Selection of the correct abrasion level is less critical for structures without a metal invert.

Table 2 shows a number of existing guidelines for water side corrosion of galvanized corrugated steel pipe. The first three are from the UK Design Manual for Roads and Bridges. The fourth is guidance from the New Mexico DOT and the fifth is guidance provided by the Corrugated Steel Pipe Institute. The UK Design Manual is the only source that provides a quantitative calculation of corrosion allowance. However, the UK Design Manual does not take into account water conditions which are known to be

⁶ *Pipe Selection Guide*, available from National Corrugated Steel Pipe Association, Washington, DC.

corrosive in Canadian installations of galvanized pipe. Specifically, experience has shown that water hardness less than 80 ppm or water resistivities greater than 8000 Ω -cm can significantly shorten the life of galvanized structures. Furthermore, moderate levels of abrasion (defined as moderate bedloads of sand and gravel with an anticipated maximum flow velocity above 4.5 m/s) are not considered suitable for uncoated galvanized structures.

Table 3 shows the effluent corrosivity classification scheme developed by modifying the UK models with hardness parameters and upper resistivity bounds. The scheme includes three classifications based on five characteristics. The overall classification should be based on the most severe condition and limiting property. For example, if the chloride ion is 125 ppm and the soluble sulfates are 10 ppm, the environment would be rated as “aggressive.”

For non-aggressive and aggressive corrosivity classifications, galvanizing and steel corrosion rates can be estimated using the equations in Table 4. Galvanized steel is not recommended for use in very aggressive environments.

Table 2 - Guidelines for Water Side Corrosion of Galvanized Corrugated Steel Pipe

Source	pH	Chloride, ppm	Sulfate, ppm	Hardness, ppm	Resistivity, Ω -cm*	Corrosion Loss or Service Life
UK non-aggressive	6.0-9.0	≤ 50	≤ 240	N/A	N/A (>2000)	Galvanizing – 4 $\mu\text{m}/\text{yr}$ Steel – $22.5 \cdot t^{0.67} \mu\text{m}/\text{yr}$
UK aggressive	5.0-6.0	50-250	240-600	N/A	N/A (667-2000)	Galvanizing – 14 $\mu\text{m}/\text{yr}$ Steel – $40.0 \cdot t^{0.80} \mu\text{m}/\text{yr}$
UK very aggressive	<5.0 or >9.0	>250	>600	N/A	N/A (<667)	Not Recommended without coating
New Mexico DOT	6.0-8.5	<250	<250	N/A	>1000	50 years
CSPI guidelines	5.8-9.8	<150	<200	>80	2000-8000	25 to 100 years (Varies with steel thickness and environment)

N/A – information not provided

* Resistivity values for the UK criteria are not provided in the document but were estimated by the author based on the specified chemistry limits.

Table 3 - Corrosivity Classification for Water and Effluent

Corrosivity Classification	pH	Chloride ion (ppm)	Soluble sulfates (ppm)	Hardness ppm CaCO_3	Resistivity (ohm-cm)
Non-Aggressive	$6 \leq \text{pH} \leq 9$	≤ 50	≤ 240	>80	2000-8000
Aggressive	$5 \leq \text{pH} < 6$	>50 and ≤ 250	>240 and ≤ 600	>80	2000-8000
Very Aggressive	<5 or >9	>250	>600	<80	<2000 or >8000

Table 4 – Zinc and Steel Corrosion Rates for Non-Aggressive and Aggressive Waters

Rate of corrosion of zinc ($\mu\text{m}/\text{year}$)		Calculation for thickness of sacrificial steel ($M, \mu\text{m}$) ⁽¹⁾	
<i>Non-Aggressive</i>	<i>Aggressive</i>	<i>Non-Aggressive</i>	<i>Aggressive</i>
4	14	$M = 22.5 * (t - 16 \text{ years})^{0.67}$	$M = 40.0 * (t - 4.57 \text{ years})^{0.80}$

Note (1): t = Design Service Life in years. These formulae assume a zinc thickness of $64 \mu\text{m}$ per side (coating mass of $915 \frac{\text{g}}{\text{m}^2}$)

Table 5 provides the calculated steel corrosion allowance for various DSLs. Note that these loss rates assume that the inside surface of the galvanized steel is continuously immersed. For plates which are only seasonally exposed to water, this corrosion allowance is conservative. For the soil side surface of plates exposed to water via saturated soil, the soil side corrosion rates discussed in Table 7 shall be used as the water associated with saturated soil is not rich in oxygen, a key component of the water side corrosion process.

Table 5 – Calculated Water Side Steel Corrosion Allowance

DSL (years)	Steel Corrosion Allowance (μm) ⁽¹⁾	
	<i>Non-Aggressive</i>	<i>Aggressive</i>
25	98	447
50	239	847
75	346	1203
75⁽²⁾	66	145

Notes:

(1) The steel corrosion allowance is the thickness of steel that must be considered as an add-on to the thickness calculated as a structural requirement

(2) The steel corrosion allowance for a 75 year DSL when polymer coated is used at a Level 3 (Moderate) abrasion condition.

Soil-side Corrosion

Corrosion of steel in soils has been studied extensively. Most models of soil corrosion are based on data from a National Bureau of Standards (NBS) study of metal loss from steel and galvanized specimens that were buried under a variety of soil conditions for more than 50 years. There is broad agreement with the observation by Romanoff⁷ that metal loss rates follow an exponential rate of the form $X = Kt^n$. This equation implies that corrosion rate decreases with time. There are a number of models for projecting soil corrosion for steel structures. Table 6 summarizes several of the models.

The models vary in their assumptions. Models 1 & 2 employ an exponential equation which accounts for the beneficial effects of galvanizing. For simplicity, models 9 through 15 replace the exponential equation with a linear rate and delay the initiation of corrosion to account for the life of the galvanizing. Models 17 and 18 incorporate both delayed initiation and an exponential corrosion rate. As noted in the table, most of the models have been developed for galvanized steel. However, models 3, 4, 9 and

⁷ M. Romanoff, "Underground Corrosion," NBS Circular 579, U.S. Dept. of Commerce, 1957.

10 are for uncoated steel and would thus require modification (such as an initial offset) to be relevant for galvanized steel.

Table 6 – Summary of Corrosion Loss Models from the Literature

Key	Corrosion Loss (X) Formula	Ref ⁸	Notes
1	$X (\mu\text{m}) = 25 * t(\text{years})^{0.65}$	(1)	Average loss for galvanized steel based on NBS work
2	$X (\mu\text{m}) = 50 * t(\text{years})^{0.65}$	(1)	Maximum loss for galvanized steel based on NBS work
3	$X (\mu\text{m}) = 40 * t(\text{years})^{0.80}$	(1)	Average loss for carbon steels based on NBS work
4	$X (\mu\text{m}) = 80 * t(\text{years})^{0.80}$	(1)	Maximum loss for carbon steels based on NBS work
5	$X (\mu\text{m}) = 25 * t(\text{years})^{0.65}$	(1)	Maximum loss from Electrochemical Test Cell Data at 25% Saturation. (Darbin et al, 1988)
6	$X (\mu\text{m}) = 2.8 * t(\text{years})^{0.65}$	(1)	Minimum loss from Electrochemical Test Cell Data at 25% Saturation. (Darbin et al, 1988)
7	$X (\mu\text{m}) = 50 * t(\text{years})^{0.60}$	(1)	Maximum loss from Electrochemical Test Cell Data at 50% and 100% Saturation. (Darbin et al, 1988)
8	$X (\mu\text{m}) = 5.5 * t(\text{years})^{0.60}$	(1)	Minimum loss from Electrochemical Test Cell Data at 50% and 100% Saturation. (Darbin et al, 1988)
9	$X (\mu\text{m}) = 80 * t(\text{years})^{0.80}$	(3)	Nominal sacrificial steel requirement for plain steel in good quality fill
10	$X (\mu\text{m}) = 13 * t(\text{years})$	(3)	Nominal sacrificial steel requirement for plain steel in high quality fill
11	$X (\mu\text{m}) = (t_f - 10 \text{ years}) * 28$	(3)	Nominal sacrificial steel requirement for marginal quality fill. Assumes 86 μm galvanizing is present and t_f is a design life less than 50 years.
12	$X (\mu\text{m}) = (t_f - 10 \text{ years}) * 28$	(3)	Caltrans guidance for “Neutral & Alkaline” fills (minimum resistivity > 1,000 $\Omega\text{-cm}$; pH > 7) with 86 μm galvanizing
13	$X (\mu\text{m}) = (t_f - 10 \text{ years}) * 33$	(3)	Caltrans guidance for “Acidic” fills (minimum resistivity > 1,000 $\Omega\text{-cm}$; pH < 7) with 86 μm galvanizing
14	$X (\mu\text{m}) = (t_f - 6 \text{ years}) * 71$	(3)	Caltrans guidance for “Corrosive” fills (minimum resistivity < 1,000 $\Omega\text{-cm}$) with 86 μm galvanizing
15	$X (\mu\text{m}) = (t_f - 30 \text{ years}) * 13$	(3)	Caltrans guidance for “Select Granular” fills (clean, free draining gravels with less than 5% fines and resistivity > 1,000 $\Omega\text{-cm}$) with 86 μm galvanizing
16	$X (\mu\text{m}) = (t - 10.5 \text{ years}) * 12$	(6)	AASHTO model assuming 64 μm galvanizing
17	$X (\mu\text{m}) = 22.5 * (t - 16 \text{ years})^{0.67}$	(7)	UK guidance for Non-Aggressive soils; 64 μm galvanizing
18	$X (\mu\text{m}) = 40.0 * (t - 4.6 \text{ years})^{0.80}$	(7)	UK for Aggressive soils and 64 μm galvanizing

CSPI Technical Bulletin 13 recommends the more conservative AASHTO method (Model 16) designed for buried MSE retaining wall soil mats.⁹ This method applies assumed loss rates to the zinc coating and carbon steel to determine the steel corrosion allowance required for a given design service life. As a point of comparison, Technical Bulletin 13 also incorporates the UK loss rate for non-aggressive soils

⁸ References can be found at the end of this white paper

⁹ AASHTO LRFD Bridge Construction Specifications, Article 7.6.4.2, Soil Reinforcements

(Model 17). The less conservative UK model results in a smaller corrosion allowance than the AASHTO model.¹⁰ The two corrosion allowance criteria represent a range of valid engineering models which may be used for soil side corrosion. Table 7 shows basis for the loss rate calculation while Table 8 shows the resulting corrosion allowance for common design lives.

Table 7 – Zinc and Carbon Steel Soil Side Loss Rates

Material	Period	AASHTO Standard Loss Rate/year/side (μm) ³	UK Non-Aggressive Loss Rate/year/side (μm) ⁴
Zinc Coating	First 2 years	15	4
	Subsequently	4	4
Carbon Steel	After Zinc Depletion	12	$M=22.5 t_s^{0.67}$

Note: M is the UK steel corrosion allowance, after zinc depletion, per side in μm (rather than a loss rate / year / side). M is calculated as $M = 22.5 * t_s^{0.67}$, where t_s is the additional design service life in years after zinc depletion (for a zinc thickness of 64 μm per side, t_s = design service life – 16 years)

Table 8 – Calculated Soil Side Steel Corrosion Allowance per Side

DSL (years)	AASHTO Steel Corrosion Allowance (μm per side)	UK Steel Corrosion Allowance (μm per side)
25	174	98
50	474	239
75	774	346

Note: The steel corrosion allowance is the thickness of steel that must be considered as an add-on to the thickness calculated as a structural requirement.

Engineered backfill materials that encase buried plate structures are selected based on known physical (structural) properties but they must also meet specified chemical properties to minimize structure corrosion. Backfill must be a free draining granular material, devoid of organics and have chemical properties as indicated in Table 9.

Table 9 – Backfill Material Chemistry

Backfill Material Property	Test Method		Galvanized Limits	
	AASHTO	ASTM	UK Method	AASHTO
pH	T289-91	G-51	6 – 9	5 – 10
Resistivity	T288-91	G-57	> 3000 ohm-cm	> 3000 ohm-cm
Chlorides	T291-91	D-512	< 50 ppm	< 100 ppm
Sulfates	T290-91	D-516	< 240 ppm	< 200 ppm
Organics	T267-86	NA	< 1%	< 1%

Note: The UK method imposes the additional constraints on the plasticity index (PI) of material passing through a 425 μm sieve and the level of oxidizable sulfides (OS).

¹⁰ UK Design Manual for Roads and Bridges BD 12/01 Volume 2, Section 2, Part 6 Design of Corrugated Steel Buried Structures with Spans Greater than 0.9 Metres and up to 8.0 Metres

The pH of soil is used as an indicator of the soil corrosivity. Some metals are more sensitive to the pH of their environment than others. As pH becomes more acidic, metallic corrosion generally increases. Caustic (basic) pH is generally not corrosive to steel but can be corrosive to other materials such as aluminum or zinc. The referenced test methods cover procedures for determining the pH of a soil using conventional pH meters and probes.

Soil resistivity is a measure of a soil's ability to support electrochemical corrosion by migration of charged species necessary to balance corrosion reactions. Lower resistivity generally correlates to higher corrosion rates. The referenced test methods cover the equipment and procedures for measurement of soil resistivity both in-situ and on samples removed from the ground.

Chloride ions are the most likely contributor to low resistivity values and will promote the corrosion of unprotected steel. Sulfates (SO_4) are generally considered to be more benign than chloride ions for metallic corrosion. However, the presence of sulfates does pose a risk for metallic materials in the sense that sulfates can be converted to highly corrosive sulfides by anaerobic sulfate reducing bacteria. Because sulfate represents only one of the fractions in which sulfur can exist in the soil, the extraction and quantification of soil sulfur can be a complex process. AASHTO Method T-290-91 describes a chemical titration method for measuring water soluble sulfate concentrations.

Organic material in the backfill can initiate the formation of anaerobic pockets of soil which could be contaminated with sulfate-reducing bacteria, thereby initiating microbial attack in the form of severe pitting. Low organic content is also required for structural purposes. Total organic content should be limited to 1 percent by weight of the total soil fraction as determined in accordance with AASHTO T-267.

Figure 2 shows seven of the models for corrosion of galvanized steel in clean backfills (solid lines) as well as the two models recommended in the design guidance for calculating the required steel corrosion allowance (dashed lines). The data suggest the models recommended by the guideline bracket the high and low levels of estimated steel loss in clean backfill.

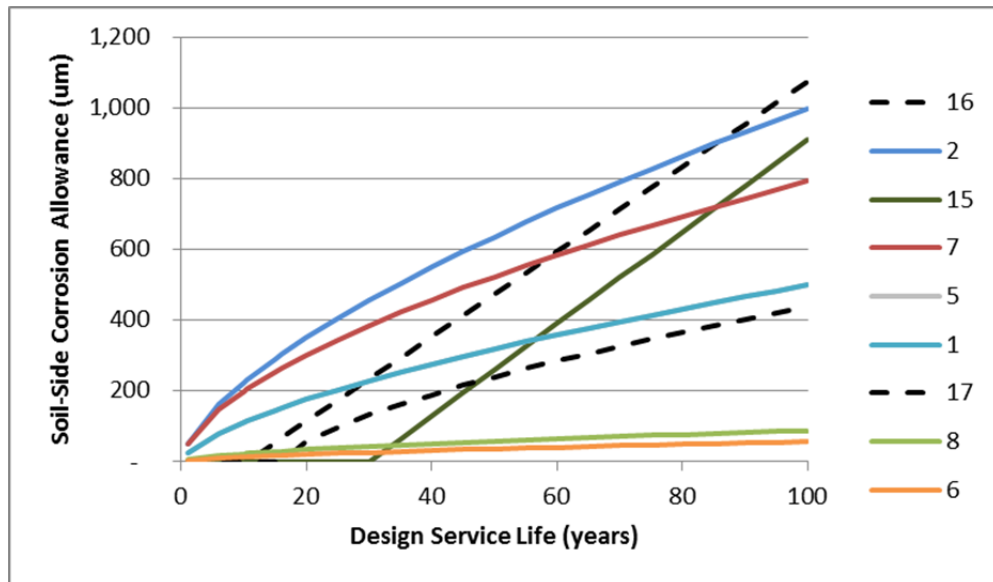


Figure 2. Alternative corrosion allowance models. The legend at right lists the model number from Table 6 in order of decreasing 100-year corrosion allowance.

Engineered backfill materials are typically imported and their properties may be vastly different than native materials. Engineered backfill envelopes isolate the structure from native materials of unknown properties. Performance of galvanized steel in lower quality backfills or native materials is considered by the Caltrans models. Figure 3 shows the projected steel loss in backfills which are more corrosive than the high quality backfill recommended in the guideline. The required corrosion allowance increases dramatically in lower quality backfill materials. The Caltrans data suggests corrosion allowances 2 to 7 times greater would be required in these backfills. Alternatively, the models suggest the service life may be shortened by 50% to 80% of the DSL. Model 11 for galvanized steel in marginal backfill material is consistent with the Caltrans predictions for neutral and alkaline soils (model 12).

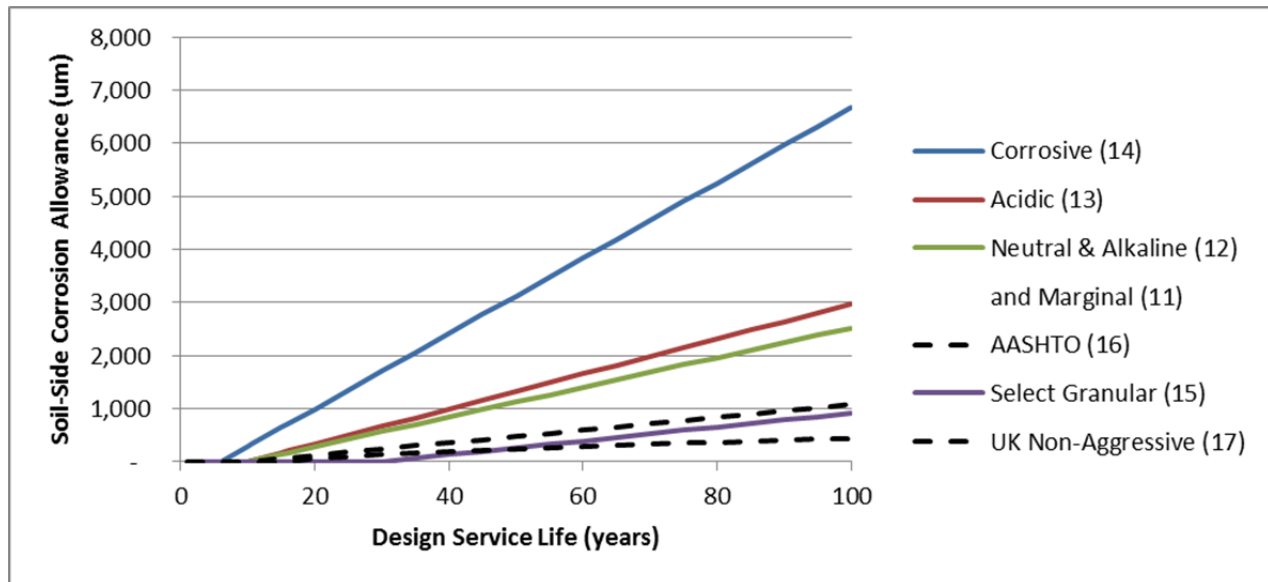


Figure 3. Corrosion allowance models for a range of soil conditions including select backfill.

Atmospheric Corrosion

Atmospheric corrosion of steel and zinc has been extensively studied. Experience suggests that atmospheric corrosion is generally not a significant concern for corrugated plate products in installations where the soil and water conditions are suitable for service. However, atmospheric corrosion may be considered for structures subject to concentrated industrial gases or coastal areas with high levels of airborne salinity. ISO standards for classification of environments^{11, 12} and data from the ISO CORRAG program¹³ are useful if the designer wishes to quantify atmospheric corrosion in the EMSL approach.

Atmospheric corrosion categories are specified in International Standard ISO 9223.¹¹ They are based on Time of Wetness (TOW), sulfur dioxide concentration, and chloride concentration. To determine the atmospheric corrosion category (designated as C1, C2, C3, C4 or C5), a table is consulted which relates the TOW class (designated T1 through T5, based on hours per year of surface wetness), sulfur dioxide class (designated P0 through P3, based on sulfation plate measurements) and chloride class (designated S0 through S3 based on chloride candle measurement).

Based on this methodology, TOW is the major influence in atmospheric corrosivity. The harshest environments (C4 and C5) have TOW classes of T4 and T5, which corresponds to greater than 30% of the time, which is usually not the case.

¹¹ ISO 9223:1992 Corrosion of metals and alloys -- Corrosivity of atmospheres -- Classification.

¹² ISO 9224: Corrosion of metals and alloys- Corrosivity of atmospheres- Guiding values for the corrosivity categories.

¹³ ISOCORRAG International Atmospheric Exposure Program: Summary of Results, 2010 ASTM International, West Conshocken, PA.

Increasing classifications for sulfur dioxide and chlorides also increase the corrosion category. In addition to high TOW, C4 and C5 classifications are associated with chloride deposition rates above 61 mg/m²/day, typically found in marine environments. Finally, C4 and C5 classifications are associated with sulfur dioxide concentrations above 41 mg/m². Such concentrations would be associated with close proximity to industrial pollution sources. For reference, typical ambient air quality guidelines for sulfur dioxide would be an annual average on the order of 0.03 mg/m³. Point source emissions (e.g., power plant stack emissions) might have on the order of 2,000 mg/m³.

Based on an ISOCORRAG study "International Atmospheric Exposure Program", corrosion allowances have been calculated for various environments in each of the corrosivity categories.¹⁴ Table 10 calculates the corrosion allowance which would be required for atmospheric corrosion to meet various DSL in varying environmental corrosivity classifications. Note that applications which are neither marine nor industrial would probably have a classification of C1, C2, or C3 and thus not require a corrosion allowance.

Table 10 – Atmospheric Side Corrosion Allowance for Various Environments

		C1	C2	C3	C4	C5
Steel Corrosion Rate (um/yr)		<=0.3	0.3-4.9	4.9-10	10-16	16-39
Zinc Corrosion Rate (um/yr)		<=0.05	0.05-0.4	0.4-1.1	1.1-2.2	2.2-4.4
Steel Corrosion Allowance to reach DSL (μm)¹⁵	25 years	0	0	0	0	0-410
	50 years	0	0	0	0-330	330-1,400
	75 years	0	0	0-170	170-730	730-2,400
	100 years	0	0	0-420	420-1,100	1,100-3,300

Polymer Coated Structural Plate

Polymer coatings were first introduced for corrugated steel pipe (CSP) applications in the 1970's. These coatings offered a promising means of increasing the corrosion and abrasion resistance of CSP. At the time several different types of polymer coatings were available. Of these polymer coatings, Dow "Trenchcoat" proved to be the best performing and presently is the only polymer coating remaining in production for CSP. The heavy gauge protective film is a tough, rugged film that is laminated to the inside and outside of galvanized sheet metal prior to forming CSP, providing a corrosion and abrasion barrier on the finished product. The film is comprised of two layers that have an overall nominal thickness of 250 μm (10 mils). The product is fully described in ASTM A742, *Polymer Precoated Sheet for Sewers and Drains* and included in CSA G401, *Corrugated Steel Pipe Products*.

¹⁴ Dagmar Knotkova, Kreislova, Katerina, Dean, Jr. Sheldon W. *ISOCORRAG International Atmospheric Exposure Program: Summary of Results*. ASTM International. May 2010.

¹⁵ Corrosion allowances assume 86μm galvanizing.

Numerous laboratory and field studies have been conducted on this product.¹⁶ These studies have been conducted by independent engineering firms, DOT's, CSP Fabricators, NCSPA members and the coating suppliers. Field experience since 1974 has been documented to validate service life projections in excess of 80 years for the product.¹⁶

As the Trenchcoat product is not designed for application on corrugated plate products, considerable effort was put into the development of a similar product. The corrugated plate coating is a similar chemistry as the Trenchcoat product. Both products are EAA (ethylene acrylic acid copolymer) materials with comparable material characteristics. The corrugated plate coating is applied at a slightly higher film thickness (400 µm versus 250 µm). The materials also have similar performance characteristics. Table 11 shows some of the material characteristics based on manufacturers' data.

Table 11 – Material Data for Alternative EAA Coatings

Property	Structural Plate Coating	Trenchcoat
Chemistry	Thermoplastic ethylene acrylic acid copolymer	ethylene acrylic acid copolymer
Cured Film Thickness	250µm minimum, 400µm average	250µm
Condensing Humidity Resistance	5000+ hours	6 months (~4300 hours), no attack or loss of adhesion
Salt Spray Resistance	3000+ hours	1000 hours
Color	Black	Black
Tensile Yield, Mpa	8	10.7
Tensile Strength, Mpa	20	20.7
Percent Elongation	610	470
Shore D Hardness	54	46

Comparative testing of polymer coated structural plate has been performed by Transports Québec, Service des Matériaux d'Infrastructures in accordance with Méthode LC 21-102, "Aggregates' Resistance To Polishing: Sand-Blasting Method." The test involves subjecting test panels to abrasive impact from Ottawa sand. The sand was blasted on the surface at a rate of 570 g/minute for four cycles at 43.3 minutes per cycle. Figure 4 shows the measured coating thickness loss during the course of the testing. As can be seen, the EAA copolymer on the corrugated plate product outperformed the Trenchcoat. Both EAA materials out-performed the metallic coatings (galvanized and aluminized).

¹⁶ For example, see Ault "Performance of Polymer Coated Corrugated Steel Pipe" 2003 Transportation Research Board, Washington, D.C.

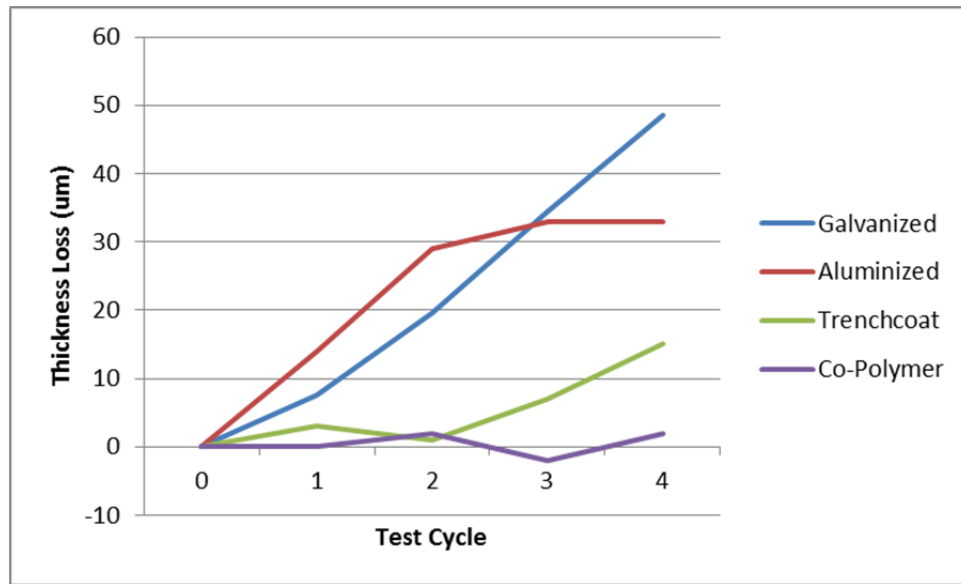


Figure 4. Performance of coatings in sand-blasting test.

Acceptance test methods for polymer coated sheet quality described in ASTM A742 are applicable to polymer coated plate with the exception of adhesion testing. The adhesion test method described in ASTM A742 relies on bending coated sheet which is not practical for most coated structural plate (due to the increased thickness). An alternative knife cut adhesion test would be more suitable for structural plate. The adhesion test requirement has been modified to include the Transports Québec abrasion resistance test described above. Table 12 contains a preliminary list of acceptance tests required for polymer coated structural plate. These are included for guidance only; a full performance specification was under development at the time this white paper was prepared.

Table 12 - Guidance for Structural Plate Coating Acceptance Testing

Property	Test Method	Requirement
Adhesion	ASTM D3359	Rating of "5A" or better
Impact	ASTM D2794	No break after a 4.0J impact on a 15.88 mm punch
Thickness	ASTM D1005	250µm minimum, 400µm average
Holidays	ASTM G62	Less than 22 holidays per square meter
Abrasion Resistance	LC 21-102	Max 0.43 g
Imperviousness	ASTM D543	No loosening or separation
Freeze-Thaw Resistance	ASTM A742	No effect after 100 cycles
Weatherability	ASTM G23	No effect after 100 hours
Resistance to Microbial Attack	ASTM G22	No Effect

It is critical to note product performance is dependent on coating chemistry **and** application process. Simply selecting a generically similar coating does not guarantee success. However, the combination of primer, protective coating and processing steps does seem to provide a structural plate coating which

provides performance similar to Trenchcoat in laboratory testing and short-term field tests. Longer field service history will help to substantiate the long-term performance of the coating.

Polymer coatings behave as barriers between the metal and the environment. The effective lifetime of a polymer coating is the time which it prevents significant exposure of the metal substrate to a corrosive environment. Table 13 provides three alternative recommendations for environmental limits which are published by the Trenchcoat film manufacturer. Because the polymer coatings are similar chemistry, it is reasonable to adopt these recommendations for polymer coated structural plate.

Abrasion or chemical attack is another probable mode to breach the barrier coating. Research suggests that polymer coatings can provide an effective life of 80 plus years depending on the abrasion condition. Table 14 shows the recommended “add-on” life to assume for each of three abrasion levels. Polymer coatings will tend to resist the effects of abrasion as long as they remain adhered to the steel substrate. Given the similar performance of Trenchcoat and the structural plate coating in the abrasion and corrosion tests described above, it seems reasonable to expect a similar add on life from the structural plate coating. Additional field experience will validate the laboratory test data.

Table 13 – Environmental Limits for Polymer Coated Steel (Water and Soil Exposure)

Environmental Parameter	Suggested Limits for Polymer Coated Steel		
	50 Year EMSL	75 Year EMSL	100 Year EMSL
pH Range	3 to 12	4 to 9	5 to 9
Resistivity	> 250 Ω -cm	> 750 Ω -cm	> 1,500 Ω -cm

Note: For polymer coating performance, resistivity is considered to be a suitable proxy for specific salt concentrations (chloride, sulfate)

Table 14 – Effective Protective Life of Polymer Coating

Abrasion Condition	Effective Polymer Coating Life (years)
Level 1, Non-Abrasive – very low velocities and no bedload	80+
Level 2, Low Abrasive – Minor bedloads of sand and gravel with 1.5 m/s maximum flow velocity	80+
Level 3, Moderately Abrasive – Moderate bedloads of sand and gravel with 4.5 m/s maximum flow velocity	70
Level 4, Severely Abrasive – Heavy bedloads of sand, gravel and rock with maximum flow velocity in excess of 4.5 m/s	Not Recommended

Field experience with galvanized structures suggests that galvanized fasteners are not the life-limiting component of the structure. As a result, it is expected that galvanized fasteners could be used with polymer coated plate in a broader range of environments than galvanized plate is suitable. Fasteners are available which will provide better corrosion and wear resistance than galvanizing. Generically described as duplex coatings, inorganic dip-spin coatings or metallic ceramic coatings, these products

have found widespread acceptance in manufacturing industries. Use of coated fasteners is recommended in the most extreme environments.

Summary

The durability of galvanized structural steel plate is adequate to provide a long life in the proper environment. Polymer coated structural plate has been developed for use in more challenging environments. CSPI has developed a guideline which provides a methodology for identifying environments where polymer coated structural plate is a cost-effective material to meet the desired DSL. This white paper describes the technical background for the CSPI guideline, allowing the engineer to perform additional detailed analysis or consider uniquely challenging applications.

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