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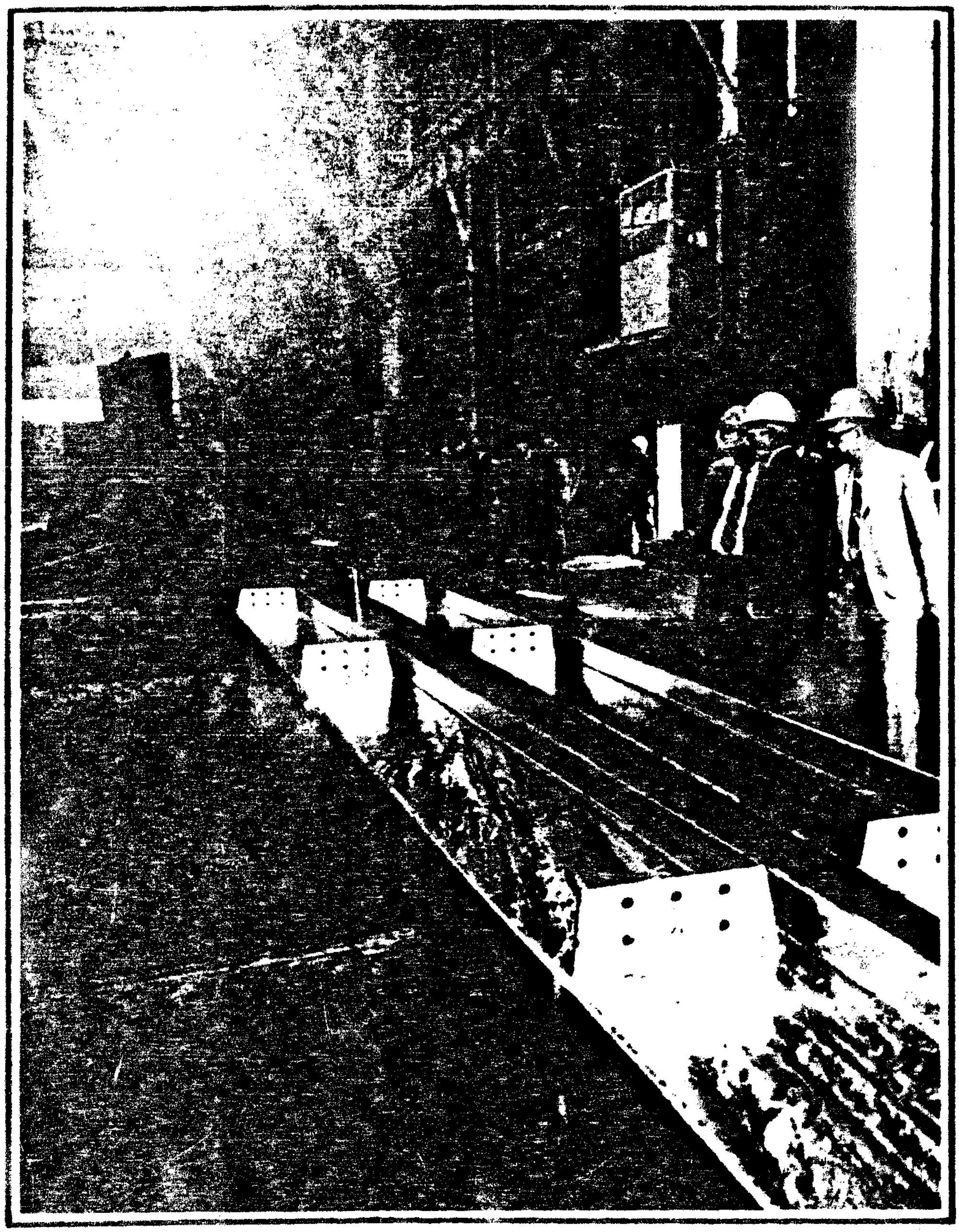

Hot Dip Galvanizing For Corrosion Protection Of Steel Products

AMERICAN HOT DIP GALVANIZERS ASSOCIATION

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The material included in this publication has been developed to provide accurate and authoritative information regarding iron and steel products hot dip galvanized after fabrication and is based on recognized engineering principles and inspection practices. This material is for general information only and is not intended as a substitute for competent professional examination and verification as to accuracy, suitability and/or applicability. The publication of the material contained herein is not intended as a representation or warranty on the part of the American Hot Dip Galvanizers Association, Inc. Anyone making use of this information assumes all liability arising from such use.

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INTRODUCTION

Corrosion and repair of corrosion damage are multi-billion dollar problems. Hot dip galvanizing after fabrication is a versatile corrosion control process which can help solve many of these problems in most major industrial applications. Chemical process industries, transportation and public utilities each have made extensive use of hot dip galvanized steel to combat corrosion and its problems.

Galvanized steel's values result from the relative corrosion resistance of zinc, which under most service conditions is considerably better than that of iron and steel. In addition to forming a physical barrier against corrosion, zinc applied as a hot dip galvanized coating cathodically protects exposed steel. Furthermore, galvanizing for protection of iron and steel is favored because of its low cost, its ease of application and the extended, maintenance-free service it provides.

This publication will assist designers, specifiers, material consultants, and fabricators to protect and improve their steel products. It outlines the nature of corrosion, the galvanizing process, and the properties and performances of galvanized coatings.

CORROSION AND PROTECTION OF STEEL

Corrosion of Steel

Rust, the term for corrosion products of iron, is the result of an electrochemical process. It occurs because of differences in electrical potential between small areas on the steel surface involving anodes, cathodes and an electrolyte. These differences in potential on the steel surface are caused by:

- variations in composition/structure;
- presence of impurities:
- uneven internal stress; and
- presence of a non-uniform environment.

These differences in the presence of an electrolyte, a medium for conducting ions, create corrosion cells. These corrosion cells consist of microscopic anodes and cathodes. As a result of differences in potential within the cell, negatively charged electrons flow from anode to cathode and iron atoms in the anode area are converted to positively charged iron ions.

The positively charged iron (Fe^{++}) ions of the anode attract and react with the negatively charged hydroxyl (OH^-) ions in the electrolyte to form iron oxide or rust. Negatively charged electrons (e^-) react at the cathode surface with positively charged hydrogen ions (H^+) in the electrolyte to form hydrogen gas. A simplified picture of what occurs in this corrosion cell is shown in Figure 1.

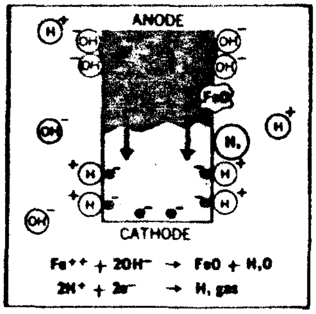


Figure 1.

Impurities present in the electrolyte make it an even better medium for the corrosion process. These impurities can be the constituents of the liquid in which the steel may be immersed or, as in the case of atmospheric exposure, can be the result of atmospheric sulfur oxides, atmospheric chlorides, and other contaminants or pollutants present in a damp atmosphere or dissolved in surface moisture.

As mentioned before, the anode and cathode areas on a piece of steel are microscopic. Greatly magnified, the surface might appear as the mosaic of anodes and cathodes pictured below, all electrically connected by the underlying steel.

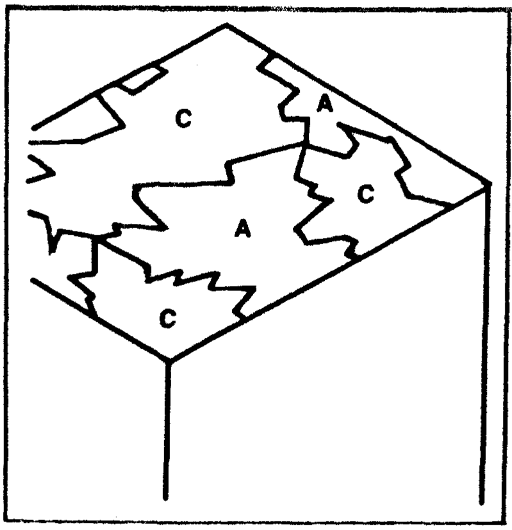


Figure 2.

The air's moisture provides the electrolyte and completes the electrical path between the anodes and cathodes on the metal surface. Due to the potential differences, a small electric current begins to flow as the metal is consumed in the anodic area. The iron ions produced at the anode combine with the environment to form the loose, flaky iron oxide known as rust.

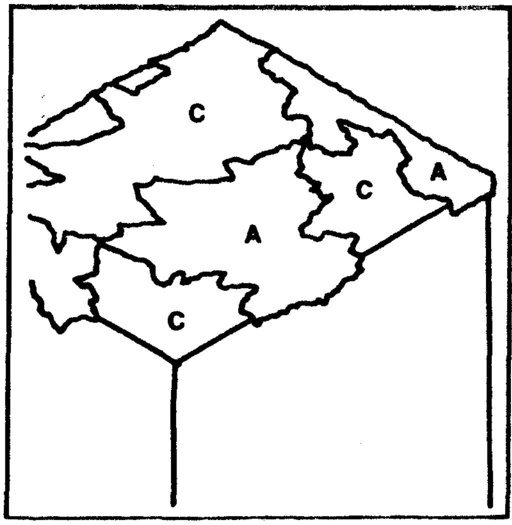


Figure 3.

As anode areas corrode, new material of different composition and structure is exposed. This results in changed electrical potentials and also changes the location of anodic and cathodic sites.

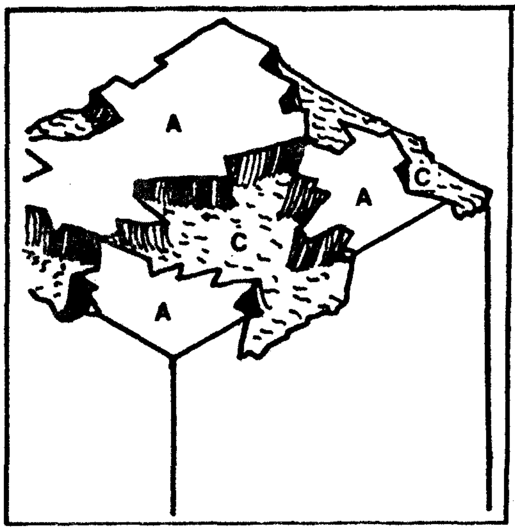


Figure 4.

The shifting of anodic and cathodic sites does not occur all at once. With time, previously uncorroded areas are attacked and a uniform surface corrosion is produced. These processes can continue until the steel is entirely consumed.

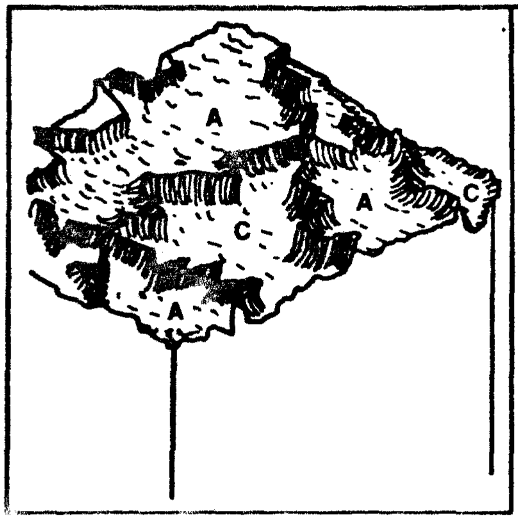


Figure 5.

How Zinc Protects Steel From Corrosion

The reason for the extensive use of hot dip galvanizing is the two-fold nature of the coating. As a barrier coating, it provides a tough, metallurgically bonded zinc coating which completely covers the steel surface and seals it from the corrosive action of its environment. In addition, the sacrificial action of zinc protects the steel even where damage or minor discontinuity occurs in the coating.

Barrier Protection

Zinc is a reactive metal that oxidizes in air to form a corrosion resistant film of zinc oxide. The zinc oxide layer is very thin, hard and tenacious and is the first step in the development of the protective corrosion product layer normally associated with the galvanized coating. When this surface has access to freely moving air in normal atmospheric exposure, the surface reacts with rainfall or dew to form zinc hydroxide. During drying, the zinc hydroxide reacts with carbon dioxide in the atmosphere and is converted into a thin, compact and tightly adherent layer of basic zinc carbonate.

It is this layer which provides the excellent barrier protection afforded by the galvanized coating. Because it is relatively insoluble, the basic zinc carbonate layer is weather-resistant and, once formed, minimizes further corrosion. After a period of time, this whitish-gray film tends to obscure the underlying zinc crystals on the surface of the galvanized coating.

The degree of protection obtained in a given case varies with the nature of the environment. The presence of chlorides and sulfur gases in the air modifies the composition of the carbonate layer by increasing its solubility so that it weathers more rapidly. Even so, the corrosion rate still is relatively low and the galvanized coating will have considerable service life.

Cathodic Protection

It is possible to measure the electropotentials of various metals in an electrolyte. From these measurements, a galvanic series for a particular set of conditions can be constructed. Such a galvanic series is shown in Table 1.

CORRODED END
Anodic or less noble
(ELECTRONEGATIVE)

Magnesium
Zinc
Aluminum
Cadmium
Iron or Steel
Stainless Steels (active)
Soft Solders
Lead
Tin
Nickel
Brass
Bronzes
Copper
Nickel-Copper Alloys
Stainless Steels (passive)
Silver Solder
Silver
Gold
Platinum

PROTECTED END
Cathodic or most noble
(ELECTROPOSITIVE)

Table 1.
Arrangement of Metals in Galvanic Series

Any one of these metals and alloys will theoretically corrode while offering protection to any other which is lower in the series, so long as both are electrically connected.

In actual practice, however, zinc is by far the most effective in this respect.

From the position of zinc and mild steel in the galvanic series, zinc is more anodic than steel. If zinc and steel are connected in the presence of the electrolyte, then the zinc will be consumed preferentially to protect the steel.

The galvanized coating is anodic to the base steel and will provide cathodic protection to exposed steel. Small areas of steel exposed at cut edges and drill holes or as the result of severe abrasion or impact, remain rust free due to the sacrificial action of the zinc coating.

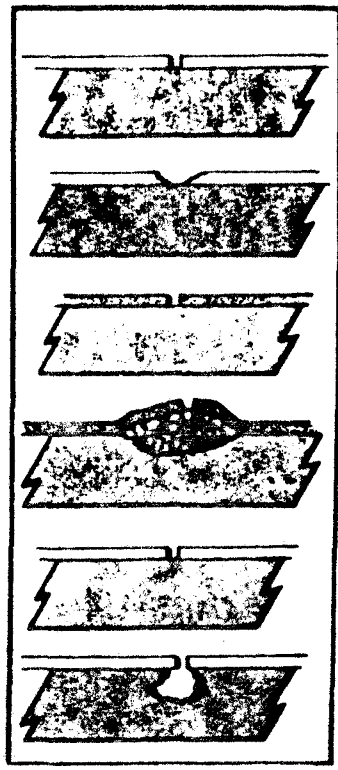


Figure 6.

This is what happens at a scratch on galvanized steel. The zinc coating sacrifices itself slowly by galvanic action to protect the basis steel. This sacrificial action continues as long as any zinc remains in the immediate area.

This is what happens at a scratch on painted steel. The exposed steel corrodes and forms a pocket of rust, which lifts the paint film from the metal surface to form a blister. Both the corrosion pit and the blister continue to grow.

This is what happens at a scratch on steel coated with a less active metal, such as copper. The exposed steel corrodes faster than it normally would to protect the more noble metal.

THE HOT DIP GALVANIZING PROCESS

The hot dip galvanizing process consists of three basic steps: a) surface preparation, b) fluxing, and c) galvanizing. Each of these steps is important in obtaining quality galvanized coatings.

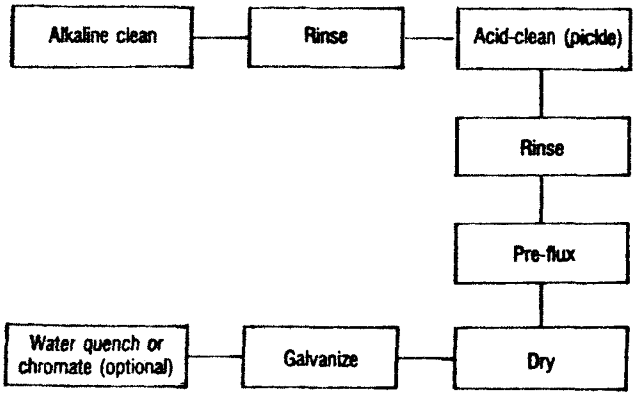


Figure 7.

Surface Preparation

It is essential that the material surface be clean and uncontaminated if a uniform, adherent coating is to result. Surface preparation is usually performed in sequence by caustic (alkaline) cleaning, water rinsing, acid pickling and water rinsing.

The caustic cleaner is used to clean the material of organic contaminants such as dirt, paint markings, grease, and oil, which are not readily removed by acid pickling. Scale and rust are normally removed by pickling in hot sulfuric acid (150°F) or hydrochloric acid at room temperature. Water rinsing usually follows caustic cleaning and acid pickling.

Surface preparation can also be accomplished using abrasive cleaning as an alternate to or in conjunction with chemical cleaning. Abrasive cleaning is a mechanical process by which sand, metallic shot, or grit is propelled against the material by air blasts or rapidly rotating wheels.

Fluxing

The final cleaning of the steel is performed by a flux. The method of applying the flux to the steel depends upon whether the "wet" or "dry" galvanizing process is used. Dry galvanizing requires that the steel be dipped in an aqueous zinc ammonium chloride solution and then thoroughly dried. This "preflux" prevents oxides from forming on the material surface prior to galvanizing. Wet galvanizing uses a molten flux layer that is floated on top of the bath metal. The final cleaning occurs as the material passes through this flux layer before entering the galvanizing bath.

Galvanizing

The material to be coated is immersed in a bath of molten zinc maintained at a temperature of about 850°F. A typical bath chemistry used in hot dip galvanizing is 1.2%Pb, 0.034%Fe, 0.002%Al, *and the balance Zn. The time of immersion* in the galvanizing bath varies, depending upon the dimensions and chemistry of the materials being coated. Materials with thick sections will take a longer time to galvanize than those with thin sections. Materials with a high silicon content *will produce thicker coatings for equal immersions in the* molten zinc than those with a low silicon content.

In addition to the effects of steel chemistry, the surface appearance and coating thickness are controlled by the galvanizing conditions. These include: a) variations in immersion time and/or bath temperature; b) rate of withdrawal from the galvanizing bath; c) removal of excess zinc by wiping, shaking or centrifuging; and, d) control of the cooling rate by water quenching or air cooling.

PHYSICAL PROPERTIES OF GALVANIZED COATINGS

The Metallurgical Bond

Hot dip galvanizing is a shop-applied coating which provides a combination of properties unmatched by other coating systems because it is *unique*, differing from all other coatings in the way it is bonded to the steel. The photomicrograph in Figure 8 shows a section of a typical hot dip galvanized coating. The coating consists of a progression of zinc-iron alloy layers *metallurgically bonded* to the base steel.

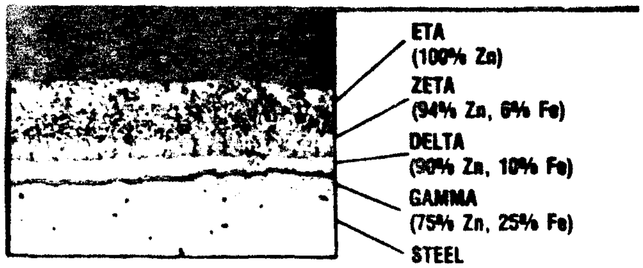


Figure 8.

The metallurgical bond formed by the galvanizing process ensures that no underfilm corrosion can occur. Paints, on the other hand, merely add to the steel a film which can be penetrated; as illustrated in Figure 6 once the film is broken, corrosion begins as if no protection existed.

Impact and Abrasion Resistance

Galvanizing's ductile outer zinc layer provides good impact resistance to the bonded galvanized coating. The photomicrograph in Figure 9 shows typical hardness values of a hot dip galvanized coating. The hardness of the zeta and delta layers actually is greater than that of the base steel and thus provides exceptional resistance to coating damage by abrasion.

Figure 9.

Photomicrograph shows hardness tests on a section of typical hot dip galvanized coating.

Eta layer
70 DPN hardness

Zeta layer
179 DPN hardness

Delta layer
244 DPN hardness

Base steel
159 DPN hardness

Corner and Edge Protection

Corrosion often begins on corners and edges, and it is here that galvanized coatings are the thickest—a natural result of the galvanizing process; whereas paint coatings, whether applied with brush or spray, are thinnest at corners and edges. Consequently, galvanized steel items have extra protection at the critical corner and edge areas.

Figure 10.

Galvanized coatings are slightly thicker at corners and edges.

A Galvanized Coating Is a Complete Coating

Because galvanizing is accomplished by total immersion, *all* parts of the steel fabrication become fully coated and protected, including areas inaccessible and hard to reach with paints. Furthermore, this integrity of any galvanized coating is assured because zinc will not metallurgically bond to unclean steel. Thus any uncoated area is immediately apparent as the work is withdrawn from the molten zinc. Adjustments are made on the spot, when required, so that a fully-protected item is delivered to the job site.

This assures the customer that he will not receive a coating which is not properly bonded to the steel surface. A sprayed or brushed coating can provide surprises because with improper surface preparation a coating can look good initially but fail in a relatively short time.

PERFORMANCE OF GALVANIZED COATINGS

A galvanized coating's protective life is determined primarily by the *thickness of the coating*, and the severity of the *exposure conditions*. Galvanized iron and steel have been used and evaluated in a variety of exposure conditions. These include: outdoor and indoor atmospheric environments, chemical environments, aqueous solutions, fresh and salt water environments, and soils. In all cases, the coating performance will vary according to the specific exposure conditions.

Atmospheric Exposure

Because the behavior of zinc and hot dip galvanized coatings during atmospheric exposure has been closely examined in tests conducted throughout the world, their performance in a specific environment can be predicted within reasonable limits.

Precise comparison of corrosion behavior in various environments is complicated by many factors. Some examples include prevailing wind direction; type and intensity of corrosive fumes and pollutants; the amount of sea spray; and the frequency and duration of moisture contact.

Most environments in which galvanized coatings are exposed contain some contaminants. Combined with the frequency and duration of moisture (fog, dew, rain, snow) these contaminants are the primary factors that determine the rate at which galvanized coatings are consumed.

Various atmospheric conditions are categorized as heavy industrial; moderate industrial (urban); suburban; rural; and marine. Within these broad classifications, corrosiveness differs at different locations in a single category.

Figure 11 shows the results of outdoor atmospheric exposure tests to measure protective life of galvanized coatings at various sites and environments in the United States. These sites are classified by the natures of their atmospheric environments.

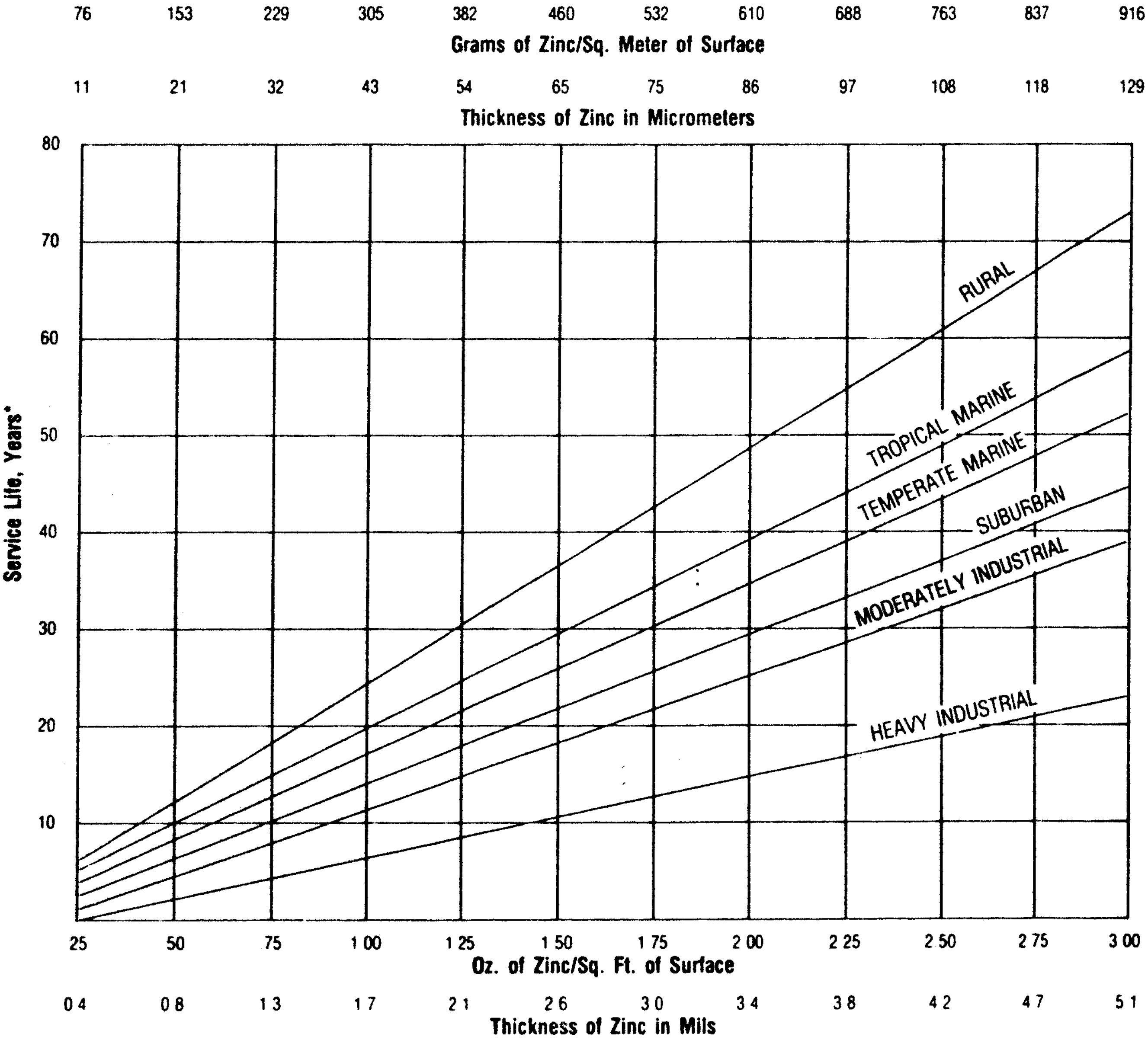
Many factors influence the corrosion of the zinc layer. Within the broad classification of the atmospheric environments, the following factors are most influential:

1. *Industrial & Urban Environments*. This classification of atmospheric exposure encompasses general industrial emissions such as sulfurous gases, corrosive mists and fumes inadvertently released from chemical plants, refineries, and similar processing plants.

   The most aggressive corrosion conditions can be expected in areas of intense industrial activity where the coating frequently is wetted with rain, condensation, or snow. In these areas, sulfur compounds combine with the moisture in the air and convert the normally impervious and adherent zinc oxide and basic zinc carbonates into zinc sulfite and zinc sulfate. Because these zinc-sulfur compounds are water soluable and have poor adhesion to the zinc surface, they are washed away by rain with relative ease. This process exposes a fresh zinc surface and starts a new corrosion cycle.
2. *Rural and Suburban Environments*. Compared to industrial environments, rural and suburban atmosphere settings are relatively mild, particularly if the exposures are well away from sea coasts and remote from industrial or urban activities.

Figure 11.

Life of Protection vs. Thickness of Zinc and Type of Atmosphere



*Service Life is defined as the time to 5% rusting of the steel surface.

Corrosion is relatively slow in rural or suburban atmospheres. Because the zinc corrosion products formed in these atmospheres tend to be adherent and usually are not washed off the zinc surface, their retention provides outstanding protection for the steel.

3. *Marine Environments*. Galvanizing's protection in marine environments is influenced by proximity to the coastline, coastal topography, and prevailing winds. In the marine air, chlorides from sea spray react with the normally protective film and produce soluble zinc chlorides. These zinc salts can be removed from the surface by rain or spray and expose a fresh zinc surface for further reaction. Under some conditions, the corrosion rate may be accelerated by wind blown sand which can remove corrosion products from the exposed surface.
4. *Indoor Exposure*. Typically, indoor galvanized coating life will be at least 2 to 3 times that for a similar outdoor exposure. Figure 12 shows anticipated life to first maintenance* of the galvanized coating under damp and dry conditions. The graph provides perspective of relative interior and exterior corrosion rates.

The atmospheric classifications are a guide to predicting corrosion rates for general environmental conditions. However, since applications and environments vary, the appropriate classification should be carefully selected on a job-by-job basis.

In each specific environment, different corrosion mechanisms determine the rate of corrosion. The results of the exposure tests reported by the American Society for Testing and Materials (ASTM), used to calculate the corrosion of steel and zinc at 38 North American locations as shown in Table 2, show that different locations and climates create significant variations in corrosion rates of zinc and steel. Furthermore, these results show that zinc is some twenty to thirty times more corrosion resistant than steel.

It should be noted that corrosivity can vary appreciably over very short distances, as shown by a comparison of the figures for the two Kure Beach sites. Although these sites are only 720 feet apart, the corrosion rate for zinc at the 80-foot site is roughly three times that at the 800-foot site. Similar variations in corrosivity can be found at various locations at a single industrial site.

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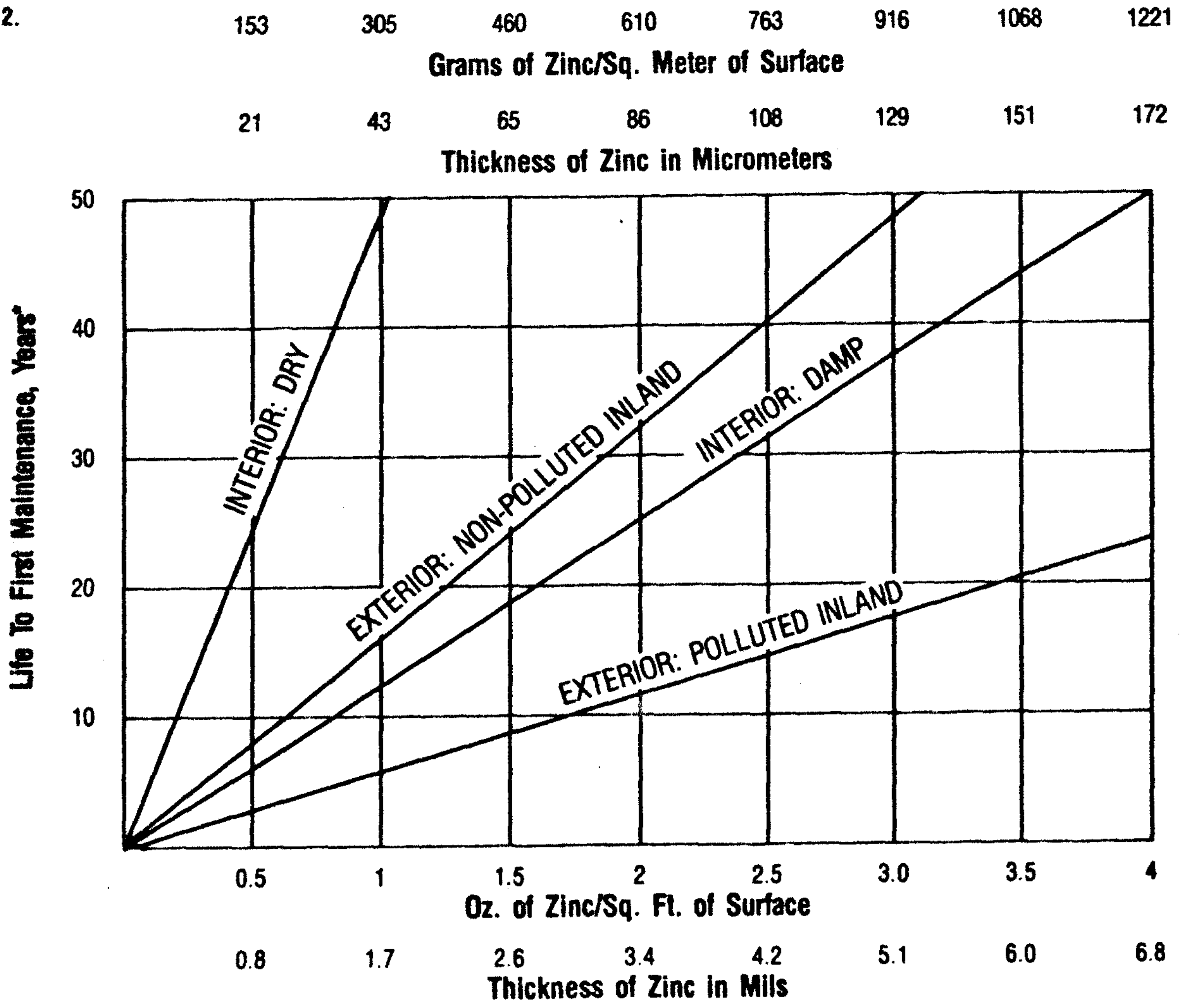
* *Life to first maintenance is calculated to allow substantial retention of the galvanized coating for subsequent painting.*

Figure 12.



***Life to first maintenance is calculated to allow substantial retention of the galvanized coating for subsequent painting**

Source: British Standard 5493: 1977 Table 3, Figure 1

Table 2.

Comparative Rankings of 38 Locations Based on Steel and Zinc Losses

			2-Year Exposure Grams Lost		
Zinc	*Steel*	*Location*	*Zinc*	*Steel*	*Steel : Zinc Loss Ratio*
1	1	Norman Wells, N.W.T., Canada	0.07	0.73	10.3
2	2	Phoenix, Ariz.	0.13	2.23	17.0
3	3	Saskatoon, Sask., Canada	0.13	2.77	21.0
4	4	Esquimalt, Vancouver Island, Canada	0.21	6.50	31.0
5	6	Fort Amidor Pier, Panama, C.Z.	0.28	7.10	25.2
6	8	Ottawa, Ontario, Canada	0.49	9.60	19.5
7	22	Miraflores, Panama, C.Z.	0.50	20.9	41.8
8	28	Cape Kennedy, ½ mile from Ocean	0.50	42.0	84.0
9	11	State College, Pa.	0.51	11.17	22.0
10	7	Morenci, Mich.	0.53	7.03	18.0
11	15	Middletown, Ohio	0.54	14.00	26.0
12	9	Potter County, Pa.	0.55	10.00	18.3
13	20	Bethlehem, Pa.	0.57	18.3	32.4
14	5	Detroit, Mich.	0.58	7.03	12.2
15	36	Point Reyes, Calif.	0.67	244.0	364.0
16	19	Trail, B.C. Canada	0.70	16.90	24.2
17	14	Durham, N.H.	0.70	13.30	19.0
18	13	Halifax (York Redoubt), N.S.	0.70	12.97	18.5
19	18	South Bend, Pa.	0.78	16.20	20.8
20	27	East Chicago, Ind.	0.79	41.1	52.1
21	29	Brazos River, Texas	0.81	45.4	56.0
22	23	Monroeville, Pa.	0.84	23.8	28.4
23	34	Dayton Beach, Fla.	0.88	144.0	164.0
24	32	Kure Beach, N.C. 800-foot Lot	0.89	71.0	80.0
25	17	Columbus, Ohio	0.95	16.00	16.8
26	12	Montreal, Quebec, Canada	1.05	11.44	10.9
27	16	Pittsburgh, Pa.	1.14	14.90	13.1
28	10	Waterbury, Conn.	1.12	11.00	9.8
29	25	Limon Bay, Panama, C.Z.	1.17	30.3	25.9
30	21	Cleveland, Ohio	1.21	19.0	15.7
31	24	Newark, N.J.	1.63	24.7	15.1
32	33	Cape Kennedy, 60 yds. from Ocean, 30-ft. Elev.	1.77	80.2	45.5
33	35	Cape Kennedy, 60 yds. from Ocean, Ground Level	1.83	215.0	117.0
34	31	Cape Kennedy, 60 yds. from Ocean, 60-ft. Elev.	1.94	64.0	33.0
35	26	Bayonne, N.J.	2.11	37.7	17.9
36	37	Kure Beach, N.C. 80-ft Lot	2.80	260.0	93.0
37	30	Halifax (Federal Building) N.S.	3.27	55.3	17.0
38	38	Galeta Point Beach, Panama, C.Z.	6.80	336.0	49.4

Source: "Corrosiveness of Various Atmospheric Test Sites as Measured by Specimens of Steel and Zinc," *Metal Corrosion in the Atmosphere*, ASTM STP 435.

Corrosion Performance In Liquids

When galvanized steel is used in contact with liquids, a different set of conditions determines its corrosion resistance. A liquid's degree of acidity or alkalinity is the factor of greatest importance; this is usually expressed on a logarithmic scale as the pH number.

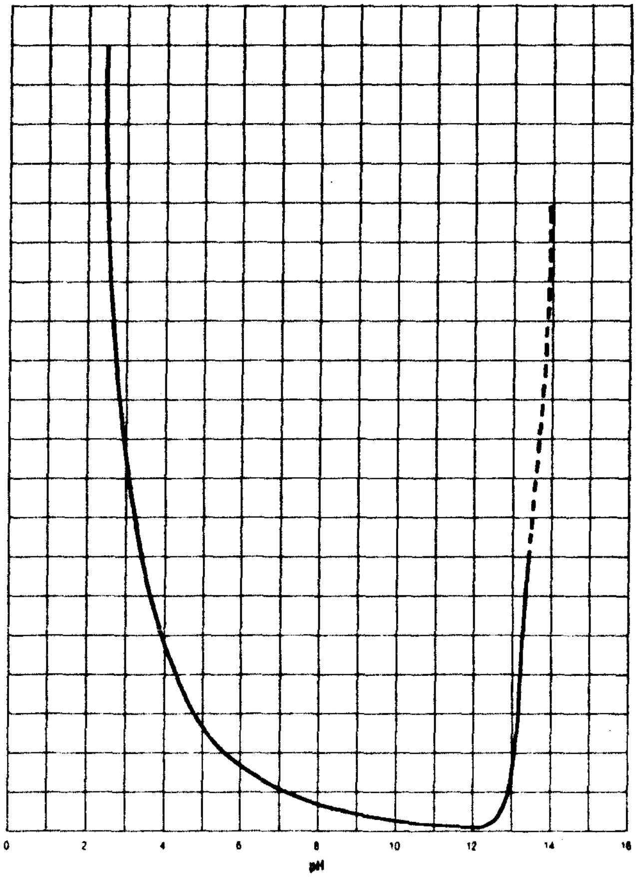
From the graph in Figure 13, it will be seen that the zinc coating dissolves in liquids with a pH below approximately 6 or above approximately 12.5. At intermediate pH values, a protective film is formed on the zinc surface and its corrosion is very slow. Since all alkalis, except the very strongest, and most types of water fall into this range, there is a very wide field of use for galvanized steel in the storing and conveying of liquids.

Separate sections are devoted to the corrosion resistance of hot dip galvanizing in contact with fresh water and sea water, so the discussion here is confined to its behavior in contact with chemicals and foods.

Most organic liquids, other than the stronger acids or substances likely to contain them, such as aldehydes, attack zinc only slightly so that it is suitable for storage tanks and equipment used in contact with motor fuels, creosote and phenols, trichlorethylene degreasing solutions, esters, etc. Galvanized steel is often used for the working parts of refrigerating equipment as it is highly resistant to corrosion by the refrigerants. In closed water cooling systems, salts such as chromates, borates and silicates are added to inhibit aqueous corrosion of zinc. Table 3 provides examples of some chemicals which have been stored successfully in galvanized containers.

Figure 13.

Effect of pH on Corrosion of Zinc



Source: B. Roetheli, G. Cox and W. Littreal, Metals and Alloys 3, 73 (1932)

Galvanized containers are not recommended for prolonged use in contact with foods. While a certain amount of zinc is essential for the human body and the small amount picked up from galvanized water pipes is perfectly safe, excessive amounts can be harmful. Thus galvanized steel may be unsuitable for vessels used for eating or cooking or for storing many liquid foods. For example, liquids such as milk or citrus juices are acidic. As a result of their reactions with a galvanized coating, they can pick up small quantities of zinc; if prolonged storage is involved, the amount of zinc dissolved in the liquid may effect the taste and could be in excess of recommended levels. On the other hand, galvanized steel is quite satisfactory for storing dry foods and for troughs which hold dry feed for animals.

Corrosion Performance In Fresh Waters

As it does in the atmosphere, a zinc coating's corrosion resistance in water depends on its initial ability to form a protective layer by reacting with its environment—in this case, a liquid. In water, this protective scale reduces access of oxygen to the zinc surface and this lessens the attack on the zinc coating.

The scale-forming ability of water depends principally on three factors: the hydrogen ion concentration (pH value), the total calcium content and the total alkalinity. If the pH value is below that at which the water would be in equilibrium with calcium carbonate, the water will tend to dissolve scale, rather than deposit it. Water with a high content of free carbon dioxide also tends to be aggressive towards zinc.

Galvanized coatings perform satisfactorily in waters of moderate or high carbonate hardness. Under such conditions, a natural scale of insoluble salts combines with the zinc corrosion products to form a protective barrier of calcium carbonate and basic zinc carbonate.

Temperature also affects the corrosion rate of zinc in water (see Figure 14). In distilled water at temperatures above about 130°F (55°C), the corrosion products that form on zinc have a coarse-grained structure and lose their adhesion to the zinc surface. Because they are easily dislodged, the zinc surface is exposed to renewed attack and, thus, rapid corrosion. Hard water in hot water systems will deposit an insoluble carbonate scale, nullifying the temperature effect.

The reaction sequence of corrosion in different types of water is complex and can be influenced by small variations in the composition of water. General rules for the corrosion sequence and the magnitude of the corrosion in different types of water are therefore difficult to lay down. Table 4 shows how different substances influence the corrosion rate of galvanized coatings. Table 5 gives approximate values for the magnitude of the corrosion in different types of water.

Table 3. Some chemicals which have been successfully stored in galvanized containers.

Hydrocarbons
Benzene (benzole)
Toluene (toluole)
Xylene (xylole)
Cyclohexene
Petroleum ethers
Heavy naphtha
Solvent naphtha
Alcohols
Methyl parafynol (methyl pentynol)
Morpholinoisopropanol
Glycerol (glycerin)
Halides
Carbon tetrachloride
Amyl bromide
Butyl bromide
Butyl chloride
Cyclohexyl bromide
Ethyl bromide
Propyl bromide
Propyl chloride
Trimethylene bromide
  (1,3-dibromopropane)
Bromobenzene
Chlorobenzene
Aroclors & Pyroclors
  (chlorobiphenyls)

Nitriles (cyanides)
Diphenylacetonitrile
p-chlorobenzglycyanide
Esters
Allyl butyrate
  caproate
  formate
  propionate
Ethyl butyrate
  isobutyrate
  caproate
  caprylate
  propionate
  succinate
Amyl butyrate
  isobutyrate
  caproate
  caprylate
Methyl butyrate
  caproate
  propionate
  succinate
Benzyl butyrate
  isobutyrate
  propionate
  succinate
Octyl butyrate
  caproate

Butyl butyrate
  isobutyrate
  caproate
  propionate
  succinate
  titanate*
Propyl butyrate
  isobutyrate
  caproate
  formate
  propionate
Iso-Butyl benzoate
  butyrate
  caproate
Iso-Propyl benzoate
  caproate
  formate
  propionate
Cyclohexyl butyrate
*and other unspecified titanates
Phenols
Phenol
Cresols (methylphenols)
Xylenols (dimethylphenols)
Biphenol (dihydroxybiphenyl)
2,4-dichlorophenol
p-chloro-o-cresol
Chloroxylenols

Amines and Amine Salts
Pyridine
Pyrrolidine
Methylpiperazine
Dicarbethoxypiperazine
1-benzhydryl-4-methylpiperazine
2,4-diamino-5- (4-chlorphenyl-6-)
  ethylpyrimidine
Hydroxyethylmorpholine
(hydroxyethyldiethylenimide oxide)
p-aminobenzenesulphonyl-
  guanidine
Butylamine oleate
Piperazine hydrochloride
  monohydrate
Carbethoxypiperazine
  hydrochloride (dry)
Amides
Formamide
Dimethylformamide
Miscellaneous
Glucose (liquid)
Benzilideneacetone
p-chlorbenzophenone
Sodium azobenzenesulphonate
Melamine resin solutions
Crude cascara extract
Creosote
Chloroflourocarbons

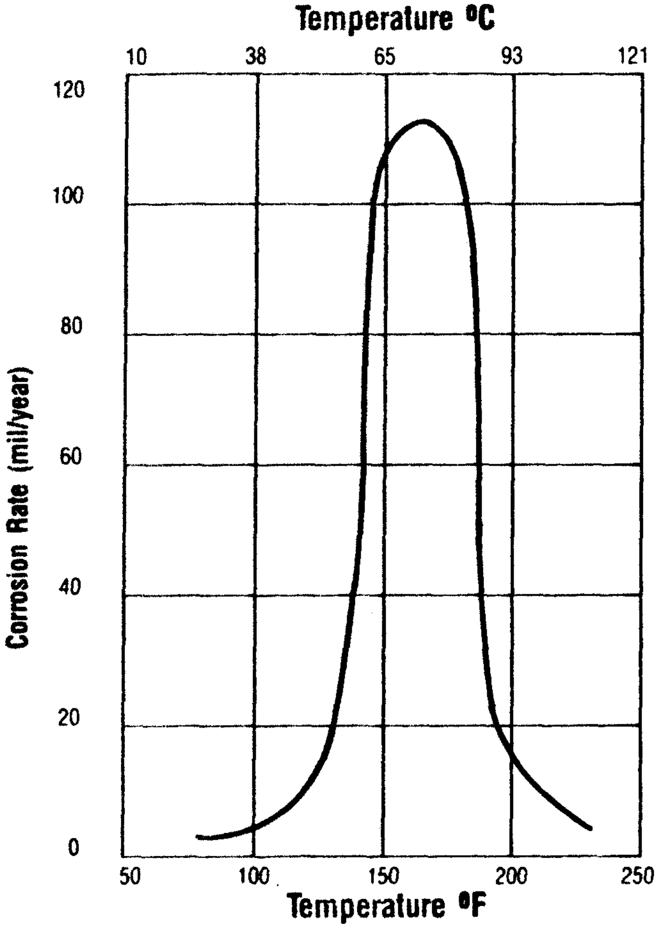


Figure 14 The influence of temperature on the corrosion rate of zinc in distilled, air-saturated water. (Note: The curve may have quite a different form in natural waters.)

Water type	Attacking substances	Passivating substances	Corrosion products		Relative corrosion rate
			solubility	adhesion	
Hard	O_2+CO_2	Ca+Mg	Very low	Very good	Very low
Sea	O_2+CO_2+Cl	Mg+Ca	Low	Very good	Moderate
Soft, with free air supply	O_2+CO_2	—	High	Good	High
Soft or distilled with poor air supply	O_2	—	Very high	Very poor	Very high

Table 4. *Corrosion of zinc in different types of water.*

Note: The different compositions of the corrosion products have not been included here since they are complex and dependent upon different compounds, salts, etc. that are present in all natural waters.

Water type	Approx material loss mils/year (um/year)
Sea water	
Global oceans, average	0.6-1.0 (15-25)
North Sea	0.5 (12)
Baltic Sea and Gulf of Bothnia	0.4 (10)
Fresh water	
Hard	0.1-0.2 (2-4)
Soft river water	0.8 (20)
Soft tap water	0.2-0.4 (5-10)
Distilled water	2.0-8.0 (50-200)

Table 5.

Approximate values for the magnitude of zinc corrosion with continuous exposure in different types of water.

Corrosion Performance In Seawater And Salt Spray

Sea salts are mainly sodium chloride with smaller amounts of manganese, magnesium and calcium salts. Typically, they have a pH of about 8. Compared to other metals and alloys, galvanized coatings provide considerable protection to steel when submerged and give galvanic protection until the zinc coating is consumed.

Anticipated galvanized coating life for material exposed in a *marine environment* and *immersed* in sea water is shown in Figure 15. Although anticipated galvanized coating life is shorter in seawater than in many other exposures, it is much greater than many other coating systems in this environment.

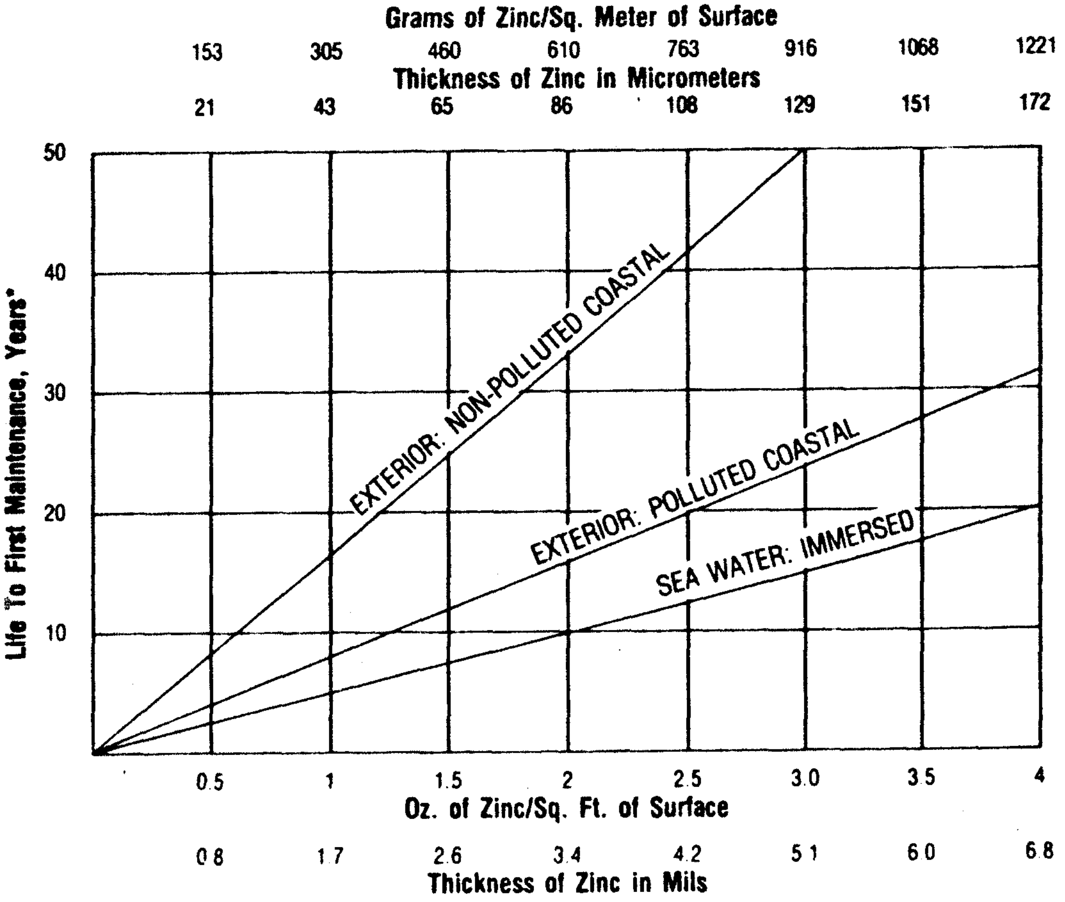
Corrosion Performance In Soils

The inground corrosion of a galvanized steel structure is largely a function of the soil in which it is located. Soils vary widely in the physical and chemical characteristics that determine corrosivity. Soils can contain weathered products, free or bound salts, acids and alkalis, mixtures of organic compounds, hydrogen, methane, oxidizing or reducing fungi and microorganisms, and the like. Depending upon their structures, various soils possess varying permeabilities to air and moisture. In soils, normal oxygen concentration is lower than in air but the carbon dioxide concentration is higher. Consequently, corrosion conditions in soil are very complicated and variations can be great between different locations, even those close to each other.

Soils with relatively coarse open textures are often aerated and under these conditions galvanizing's performance may approach that occuring in the atmosphere. Clay and silt-bearing soils of fine textures are likely to have high water-holding capacities which limit aeration and drainage. Consequently, these soil types produce higher corrosion rates on galvanized steel.

Soil resistivity is recognized as an indicator of inground corrosivity. A high-resistivity soil (i.e. poorly conducting) which

Figure 15.



*Life to first maintenance is calculated to allow substantial retention of the galvanized coating for subsequent painting

Source: British Standard 5493 1977 Table 3. Figure 1 lacks moisture or dissolved salts, or both, is generally less corrosive than a soil of lower resistivity. Dry soils having high electrical resistivity therefore are considered the soils least corrosive to buried galvanized steel.

Galvanic Behavior of Zinc in Contact With Other Metals

The interaction between different metals in contact is a complex corrosion problem. Moreover, it is often difficult to provide comprehensive data because of the many possible combinations of metals that can be in contact and the wide range of environments and conditions in which they may be installed.

The galvanic behavior of galvanized coatings in contact with various metals in atmospheric and immersion service is summarized in Table 6. The information given is provided as a guide to avoid situations in which corrosion may arise when galvanized surfaces are in contact with another metal.

Contact with Copper and Brass

When any installation requires contact between galvanized articles and either brass or copper, particularly in a moist environment, rapid consumption of the zinc coating can occur. Even run-off water from copper surfaces may contain sufficient dissolved copper to cause attack and rapid deterioration of a zinc coating. Where use of copper or brass together with galvanized steel in the presence of an electrolyte cannot be avoided, precautions should be taken to prevent electrical contact between the dissimilar metals. Joint faces should be insulated using non-conductive gaskets and connections should be made with insulating grommet-type fasteners. The design should be arranged so that water flows *from* the galvanized surface onto the brass surface and not the reverse. In such a system, the water should not be recirculated.

Contact with Aluminum and Stainless Steel

When either aluminum or stainless steel are in contact with a galvanized surface and the surface is exposed to air, galvanizing's performance is good. In very humid environments, however, the galvanized surface may require isolation by painting or joining compounds.

Corrosion Resistance of Fully Alloyed Galvanized Coatings

The corrosion protection and service life of galvanized coatings are not affected by differences in surface appearances. While some steels may produce freshly galvanized coatings with matte-gray and possibly mottled appearances, their corrosion protection is not impaired. Moreover, even when a reddish-brown discoloration develops prematurely on exposure of the coatings this is a mere aesthetic effect and should not be mistaken for corrosion of underlying steel.

Premature staining is a surface effect caused by corrosion of iron contained in the galvanized coating. Such a condition is more likely to develop when reactive steels (such as those containing relatively high silicon contents) are galvanized. While chemistry causes the zinc-iron alloy phase to extend throughout the galvanized coating, it does not reduce corrosion protection.

Long term exposure testing has shown that the corrosion resistance of galvanized coatings on the more reactive, silicon-bearing steels is similar to that of more galvanized coatings for equal thicknesses of coating and similar exposure conditions.

Performance at Elevated Temperatures

Galvanized coatings perform well under continuous exposure to temperatures up to 200°C (392°F). Exposure to temperatures above this limit can cause the outer free zinc layer to peel from the underlying zinc-iron alloy layer. Even so, the remaining zinc-iron alloy layer will provide good corrosion resistance and will continue to protect the steel for a long time, depending upon its thickness.

Table 6.

Additional Corrosion of Zinc and Galvanized Steel Resulting from Contact With Other Metals

	Environment				
	Atmospheric			Immersed	
Metal in contact	**Rural**	**Industrial/urban**	**Marine**	**Fresh water**	**Sea water**
Aluminum and alumnium alloys	0	0 to 1	0 to 1	1	1 to 2
Aluminum bronzes and silicon bronzes	0 to 1	1	1 to 2	1 to 2	2 to 3
Brasses including high tensile (HT) brass (manganese bronze)	0 to 1	1	0 to 2	1 to 2	2 to 3
Cadmium	0	0	0	0	0
Cast irons	0 to 1	1	1 to 2	1 to 2	2 to 3
Cast iron (austenitic)	0 to 1	1	1 to 2	1 to 2	1 to 3
Chromium	0 to 1	1 to 2	1 to 2	1 to 2	2 to 3
Copper	0 to 1	1 to 2	1 to 2	1 to 2	2 to 3
Cupro-nickels	0 to 1	0 to 1	1 to 2	1 to 2	2 to 3
Gold	(0 to 1)	(1 to 2)	(1 to 2)	(1 to 2)	(2 to 3)
Gunmetals, phosphor bronzes and tin bronzes	0 to 1	1	1 to 2	1 to 2	2 to 3
Lead	0	0 to 1	0 to 1	0 to 2	(0 to 2)
Magnesium and magnesium alloys	0	0	0	0	0
Nickel	0 to 1	1	1 to 2	1 to 2	2 to 3
Nickel copper alloys	0 to 1	1	1 to 2	1 to 2	2 to 3
Nickel-chromium-iron alloys	(0 to 1)	(1)	(1 to 2)	(1 to 2)	(1 to 3)
Nickel-chromium-molybdenum alloys	(0 to 1)	(1)	(1 to 2)	(1 to 2)	(1 to 3)
Nickel silvers	0 to 1	1	1 to 2	1 to 2	1 to 3
Platinum	(0 to 1)	(1 to 2)	(1 to 2)	(1 to 2)	(2 to 3)
Rhodium	(0 to 1)	(1 to 2)	(1 to 2)	(1 to 2)	(2 to 3)
Silver	(0 to 1)	(1 to 2)	1 to 2)	(1 to 2)	(2 to 3)
Solders hard	0 to 1	1	1 to 2	1 to 2	2 to 3
Solders soft	0	0	0	0	0
Stainless steel (austenitic and other grades containing approximately 18% chromium)	0 to 1	0 to 1	0 to 1	0 to 2	1 to 2
Stainless steel (martensitic grades containing approximately 13% chromium)	0 to 1	0 to 1	0 to 1	0 to 2	1 to 2
Steels (carbon and low alloy)	0 to 1	1	1 to 2	1 to 2	1 to 2
Tin	0	0 to 1	1	1	1 to 2
Titanium and titanium alloys	(0 to 1)	(1)	(1 to 2)	(0 to 2)	(1 to 3)

Key 0 Zinc and galvanized steel will suffer either no additional corrosion, or at the most only very slight additional corrosion, usually tolerable in service.

1 Zinc and galvanized steel will suffer slight or moderate additional corrosion which may be tolerable in some circumstances.

2 Zinc and galvanized steel may suffer fairly severe additional corrosion and protective measures will usually be necessary.

3 Zinc and galvanized steel may suffer severe additional corrosion and the contact should be avoided.

General notes: Ratings in brackets are based on very limited evidence and hence are less certain than other values shown. The table is in terms of additional corrosion and the symbol 0 should not be taken to imply that the metals in contact need no protection under all conditions of exposure.
Source: British Standards Institution pp 6484:1979 Table 23.

PERTINENT SPECIFICATIONS

American Society for Testing and Materials

A90	Methods of Test for Weight of Coating on Zinc Coated (Galvanized) Iron or Steel Articles
A123	Zinc (Hot-Galvanized) Coatings on Products, Fabricated from Rolled, Pressed, and Forged Steel Shapes, Plates, Bars and Strip
A143	Recommended Practice for Safeguarding Against Embrittlement of Hot Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement
A153	Zinc Coating (Hot-Dip) on Iron and Steel Hardware
A325	High-Strength Bolts for Structural Steel Joints, including Suitable Nuts and Plain Hardened Washers
A384	Recommended Practice for Safeguarding Against Warpage and Distortion During Hot Dip Galvanizing of Steel Assemblies
A385	Recommended Practice for Providing High Quality Zinc Coatings (Hot-Dip)
A386	Zinc Coating (Hot-Dip) on Assembled Steel Products
A394	Galvanized Steel Transmission Tower Bolts and Nuts
A780	Practice for Repair of Damaged Hot-Dip Galvanized Coatings
B6	Zinc (Slab Zinc)
E376	Recommended Practice for Measuring Coating Thickness by Magnetic-Field or Eddy-Current (Electromagnetic) Test Methods

Canadian Standards Association

G164-M	Hot Dip Galvanizing of Irregularly Shaped Articles

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