

Performance of Hot-Dip Galvanized Steel Products

In the Atmosphere, Soil, Water, Concrete, and More



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Introduction

Corrosion and repair of corrosion damage are multi-billion dollar problems. Estimates show metallic corrosion costs the United States approximately \$297 billion annually, or about 3% of the national GDP. Although corrosion is a natural phenomenon, and can never be completely eliminated, utilizing adequate corrosion protection systems in harsh environments can drastically reduce the costs. Hot-dip galvanizing after fabrication is a cost effective, maintenance-free corrosion protection system that lasts for decades even in the harshest environments. For more than 100 years, hot-dip galvanized steel has been utilized extensively to combat corrosion in major industrial environments including petro-chemical, transportation, and public utilities.

The zinc of the hot-dip galvanized coating is more corrosion resistant than bare iron and steel. Similar to steel, zinc corrodes when exposed to the atmosphere; however, zinc corrodes at a rate approximately 1/30 of that for steel. Also like steel, zinc corrodes at different rates depending on its environment. Therefore, the performance of hot-dip galvanized steel varies from environment to environment. Environments in which galvanized steel is commonly used include indoor and outdoor atmospheres, the storage of hundreds of different chemicals, in fresh water, sea water, soils, concrete, and/or in conjunction with other metals, treated wood, or extreme temperatures. Because of the many years galvanizing has been used for corrosion protection, a wealth of real-world, long-term exposure data on zinc coating performance in a wide variety of environments is available. Because hot-dip galvanized steel is used in so many different applications, it is important to understand what factors affect its performance in each of these environments.



Steel Corrosion and Protection

The Corrosion Process

Elements are rarely found in a pure metal state. Rather, they are found in chemical combinations with one or more nonmetallic elements. These chemical combinations are commonly known as ore.

Significant energy must be expended to reduce the ore to pure metal. This energy can be applied via metallurgical or chemical means. Additional energy also may be used in the form of cold-working or heating and casting to transform the pure metal into a working shape. Corrosion can be viewed simplistically as the tendency for a metal to revert to its natural, lower energy state, ore. From a thermodynamic perspective, the tendency to decrease in energy is the main driving force behind metallic corrosion.

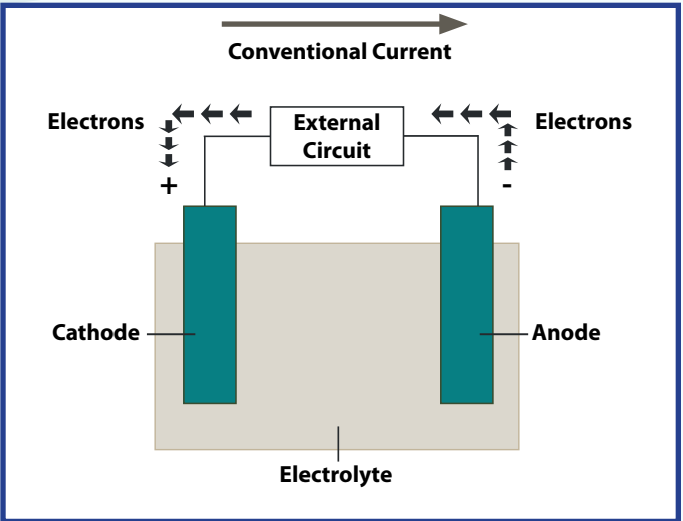


Figure 1: Bi-metallic couple

Galvanic Corrosion

There are two primary types of galvanic cells that cause corrosion: the bi-metallic couple and the concentration cell. A bi-metallic couple (Figure 1) is like a battery, consisting of two dissimilar metals immersed in an electrolyte solution. An electric current (flow of electrons) is generated when the two electrodes are connected by an external, conductive path.

A concentration cell consists of an anode and cathode of the same metal or alloy and a return current path. The electromotive force is provided by a difference in concentration of the surfaces through the external path. There are four elements necessary for corrosion to occur in a galvanic cell:

- Anode-** The electrode where galvanic reaction(s) generate electrons. Corrosion occurs at the anode.
- Cathode-** The electrode that receives electrons. The cathode is protected from corrosion.
- Electrolyte-** This is the conductor through which current is carried. Electrolytes include aqueous solutions or other liquids.
- Return Current Path-** This is the metallic pathway connecting the anode to the cathode. It is often the underlying metal.



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All four elements, anode, cathode, electrolyte and return current path, are necessary for corrosion to occur. Removing any one of these elements will stop the current flow and galvanic corrosion will not occur. Substituting a different metal for the anode or cathode may cause the direction of the current to change, resulting in a switch as to the electrodes experiencing corrosion.

The Galvanic Series of Metals (Figure 2) lists metals and alloys in decreasing order of electrical activity. Metals nearer the top of the table often are referred to as less noble metals and have a greater tendency to lose electrons than the more noble metals found lower on the list.

CORRODED END Anodic or less noble (ELECTRONEGATIVE) Magnesium Zinc Aluminum Steel Lead Tin Nickel Brass Bronzes Copper Stainless Steel (passive) Silver Gold Platinum PROTECTED END Cathodic or more noble (ELECTROPOSITIVE)	Cathodic protection can occur when two metals are electrically connected. Any one of these metals or alloys will theoretically corrode while offering protection to any other that is lower in the series, so long as both are electrically connected. However, in actual practice, zinc is by far the most effective in this respect.
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Figure 2: Galvanic Series of Metals

Corrosion of Steel

The actual corrosion process that takes place on a piece of uncoated steel is very complex. Factors such as variations in the composition/structure of the steel, presence of impurities due to the higher instance of recycled steel, uneven internal stress, and/or exposure to a non-uniform environment all affect the corrosion process.

It is very easy for microscopic areas of the exposed steel to become relatively anodic or cathodic to one another. A large number of such areas can develop in a small section of the exposed steel. Further, it is highly possible several different types of galvanic corrosion cells are present in the same small area of an actively corroding piece of steel.

As the corrosion process progresses, corrosion products might tend to build up in certain areas of the metal. These corrosion products have different elemental compositions than their original state. The new compositions exposed on the surface lead to changes in the anodic and cathodic areas. As the change in anodic and cathodic areas occur, previously uncorroded areas of the metal can be attacked and corrode. This eventually will result in overall corrosion of the steel surface (Figure 3).

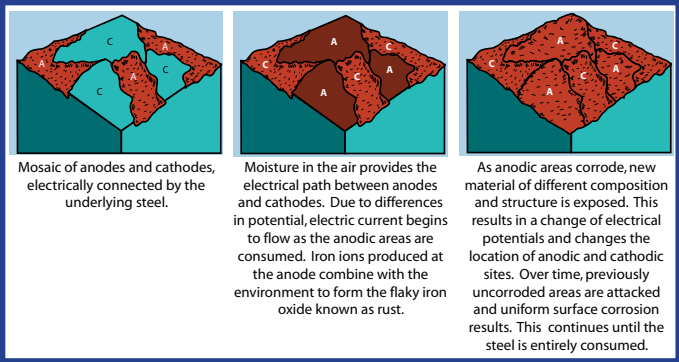


Figure 3: Changes in cathodic and anodic areas

The rate at which metals corrode is controlled by factors such as the electrical potential and resistance between anodic and cathodic areas, pH of the electrolyte, temperature, and humidity.

The corrosion products of steel are oxide particles and have a distinctive brown/red color: rust. Just a small amount of these particles can cause an uncoated steel surface to appear corroded. Steel corrodes naturally when exposed to the atmosphere, but the corrosion process accelerates when concentration cells are active on the surface.

How Zinc Protects Steel from Corrosion

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

Barrier Protection

Barrier protection is perhaps the oldest and most widely used method of corrosion protection. It acts by isolating the base metal from the environment. Two important properties of barrier protection are adhesion to the base metal and abrasion resistance. Paint is one example of a common barrier protection system.

Zinc Patina

The barrier and cathodic protection prevent corrosion of the steel itself. The zinc metal is protected by the formation of a patina layer on the surface of the coating. The zinc patina is formed by the conversion of zinc metal into corrosion products through interaction with the environment. The first products formed include zinc oxide and zinc hydroxide. Later in the corrosion cycle these products interact with carbon dioxide in the environment to form zinc carbonate. The zinc carbonate is a passive, stable film that adheres to the zinc surface and is not water soluble so it does not wash off in the rain or snow. This zinc carbonate layer corrodes very slowly and protects the zinc metal underneath. The formation of the zinc carbonate turns the zinc coating to a dull gray color. The long term corrosion protection of the zinc coating depends on the formation of the patina layer.

Cathodic Protection

Cathodic protection is an equally important method for preventing corrosion. Cathodic protection requires changing an element of the corrosion circuit by introducing a new corrosion element, thus ensuring the base metal becomes the cathodic element of the circuit.

There are two major variations of the cathodic method of corrosion protection. The first is the sacrificial anode method. In this method a metal or alloy anodic to the base metal to be protected is placed in the circuit and becomes the anode. The protected base metal becomes the cathode and does not corrode. The anode corrodes, thereby providing the desired sacrificial protection. Zinc is anodic to iron and steel; thus, the galvanized coating provides cathodic corrosion protection as well as barrier protection.

The other form of cathodic protection is called the impressed current method. In this method, an external current source is used to impress a cathodic charge on all the iron or steel to be protected. While such systems generally do not use a great deal of electricity, they often are very expensive to install and maintain.



The Hot-Dip Galvanizing Process

The hot-dip galvanizing process consists of three basic steps: surface preparation, galvanizing, and inspection.

Surface Preparation

Surface preparation is the most important step in the application of any coating. In most instances, incorrect or inadequate surface preparation is the cause of a coating failure before the end of its expected service lifetime.

The surface preparation step in the galvanizing process has its own built-in means of quality control because zinc will not metallurgically react with an unclean steel surface. Any failures or inadequacies in surface preparation will immediately be apparent when the steel is withdrawn from the molten zinc, because the unclean areas will remain uncoated and immediate corrective action must be taken.

Surface preparation for galvanizing consists of three steps: degreasing, chemical cleaning and fluxing.

Degreasing - A hot alkali solution, mild acidic bath, or biological cleaning bath removes organic contaminants such as dirt, paint markings, grease, and oil from the steel surface. Degreasing baths cannot remove epoxies, vinyls, asphalt, or welding slag; thus, these materials must be removed by grit-blasting, sand-blasting, or other mechanical means before the steel is sent to the galvanizer.

Chemical Cleaning - A dilute solution of hot sulfuric acid or ambient temperature hydrochloric acid removes mill scale and iron oxides (rust) from the steel surface. As an alternative to or in conjunction with chemical cleaning, this step can also be accomplished using abrasive cleaning, air blasting sand, metallic shot, or grit onto the steel.

Fluxing - The final surface preparation step in the galvanizing process serves two purposes. It removes any remaining oxides and deposits a protective layer onto the steel to prevent any further oxides from forming on the surface prior to galvanizing.

Flux is applied in two different ways; wet or dry. In the dry galvanizing process, the steel or iron is dipped or pre-fluxed in an aqueous solution of zinc ammonium chloride. The material is then dried prior to immersion in molten zinc. In the wet galvanizing process, a layer of liquid zinc ammonium chloride is floated on top of the molten zinc. The iron or steel being galvanized passes through the flux on its way

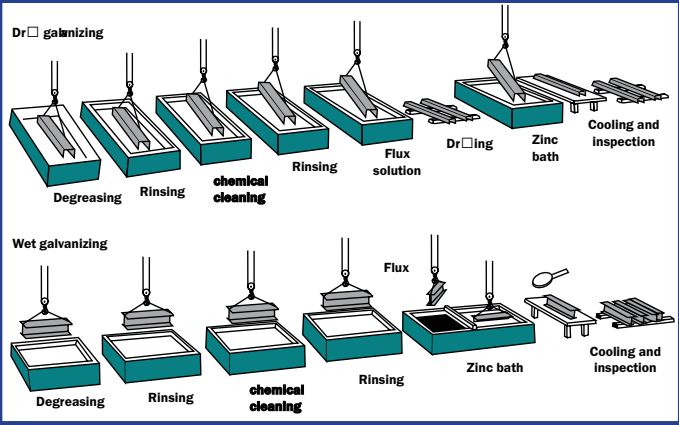


Figure 4: Hot-dip galvanizing process

Galvanizing

In the true galvanizing step of the process, the material is completely immersed in a bath of molten zinc. The bath contains at least 98% pure zinc and is heated to approximately 840 F (449 C). Zinc chemistry is specified by ASTM B 6.

While immersed in the kettle, the zinc reacts with the iron in the steel to form a series of zinc/iron intermetallic alloy layers. Once the fabricated items coating growth is complete, they are withdrawn slowly from the galvanizing bath, and the excess zinc is removed by draining, vibrating, and/or centrifuging.

The metallurgical reaction will continue after the articles are withdrawn from the bath, as long as the article remains near bath temperature. Articles are cooled either by immersion in a passivation solution or water or by being left in open air.

Hot-dip galvanizing is a factory-controlled process performed under any climate conditions. Most brush- and spray-applied coatings depend upon proper climate conditions for correct application. Dependence

on atmospheric conditions often translates into costly construction delays. The galvanizer's ability to work in any climate conditions provides a higher degree of assurance of on-time delivery; furthermore, no climate restrictions means galvanizing can be completed quickly and with short lead times.

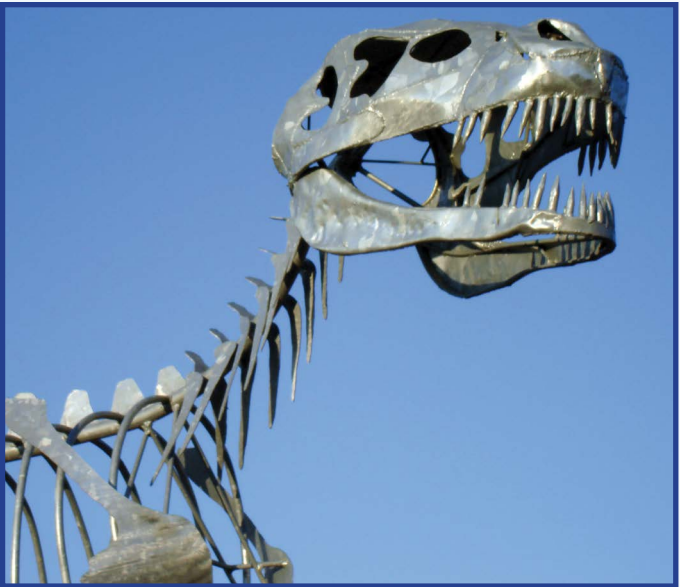


Withdrawal of a steel article from the zinc bath.

Inspection

The inspection of hot-dip galvanized steel is simple and fast. The two properties of the coating closely scrutinized are coating appearance and coating thickness. A variety of simple physical and laboratory tests may be performed to determine thickness, uniformity, adherence, and appearance.

Products are galvanized according to long-established, accepted, and approved standards of ASTM, the Canadian Standards Association (CSA), the International Organization for Standardization (ISO), and the American Association of State Highway and Transportation Officials (AASHTO). These standards cover everything from minimum required coating thicknesses for various categories of galvanized items to the composition of the zinc metal used in the process.



This sculpture was hot-dip galvanized to keep it beautiful in a corrosive outdoor environment.

The inspection process for galvanized items also requires minimal labor. This is important because the inspection process required to assure the quality of many brush- and spray-applied coatings is highly labor-intensive and requires expensive skilled labor.

Once a job has been delivered and accepted at the galvanizer's plant, there is one point of responsibility for ensuring the material leaves the plant properly galvanized. That point of responsibility is the galvanizer.



Physical Properties of Hot-Dip Galvanized Steel

The Metallurgical Bond

Galvanizing forms a metallurgical bond between the zinc and the underlying steel or iron, creating a barrier that is part of the metal itself. During galvanizing, the molten zinc reacts with the iron in the steel to form a series of zinc-iron alloy layers. *Figure 5* is a photomicrograph of a typical galvanized coating microstructure consisting of three alloy layers and a layer of pure metallic zinc.

The galvanized coating is tightly bonded to the underlying steel, at approximately 3,600 pounds per square inch (psi). Other coatings typically offer bond strengths of 300-600 psi, at best.

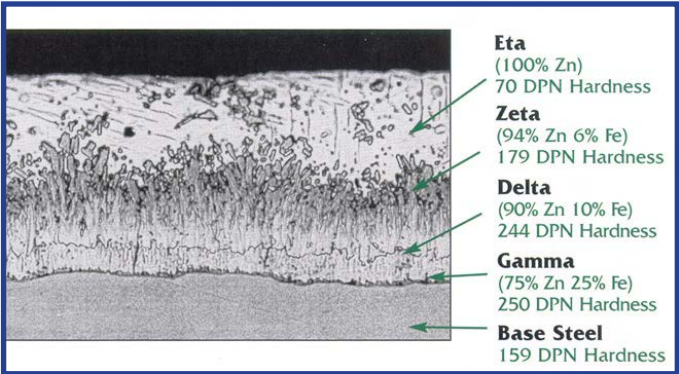


Figure 5: Photomicrograph of galvanized coating

Impact and Abrasion Resistance

The coating microstructure displayed in *Figure 5* also indicates the hardness of each layer, expressed by a DiamondPyramidNumber(DPN). TheDPNis a progressive measure of hardness, which means the higher the number the greater the hardness. Typically, the Gamma, Delta, and Zeta layers are harder than the underlying steel. The hardness of these inner layers provides exceptional protection against coating damage through abrasion. The Eta layer of the galvanized coating is quite ductile, providing the coating with some impact resistance.

Hardness, ductility, and bond strength combine to provide the galvanized coating with unmatched protection against damage caused by rough handling during transportation to and/or at the job site as well as during its service life. Furthermore, because galvanizing provides more than just barrier protection, even if the impermeable coating is physically damaged, it will continue to provide cathodic protection to the exposed steel. Exposed areas of steel up to 1/4" in size will be protected from corrosion by the surrounding zinc until all of the coating is gone (*Figure 6*).

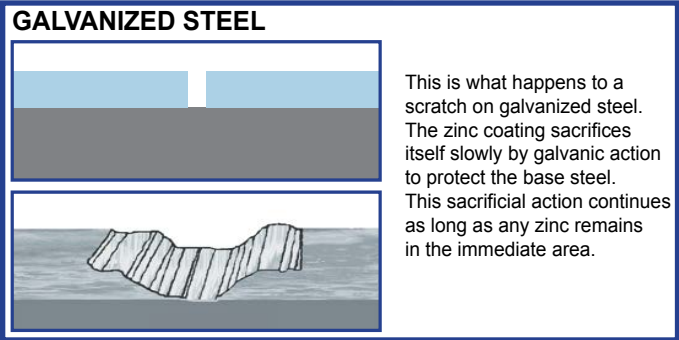


Figure 6: Zinc protects scratched base steel

The toughness of the galvanized coating is extremely important, since barrier protection is dependent upon coating integrity. Other coatings damage easily during shipment or through rough handling on the job site. Furthermore, all organic forms of barrier protection, such as paint, are permeable to some degree (pinholes), which means electrolytes in the environment will begin to damage even an intact coating. *Figure 7* shows how corrosion will begin and immediately progress at a scratch or gap in a paint coating.

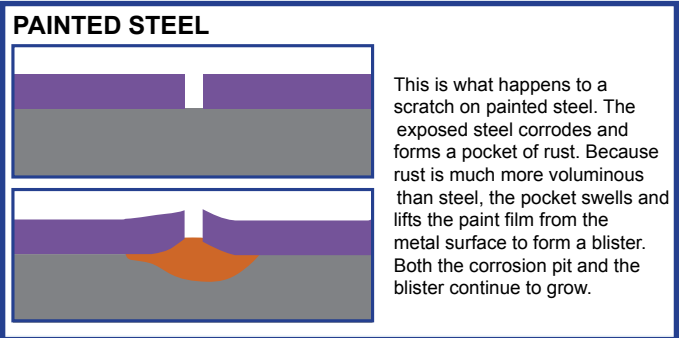


Figure 7: Underfilm corrosion causes paint to peel and flake

Complete, Uniform Coverage

The metallurgical reaction that occurs between zinc and steel is a diffusion process, which means the coating grows perpendicular to all surfaces. Therefore, the galvanized coating is at least as thick at the corners and edges as on the rest of the article (*Figure 8*). Additionally, since hot-dip galvanizing is a total immersion process, both the outside and inside of hollow structures are coated.

Brush- or spray-applied barrier coating systems have a natural tendency to thin at corners and edges, and provide no coverage, and thus, no corrosion protection on the inside of hollow structures such as pipe and tubes.

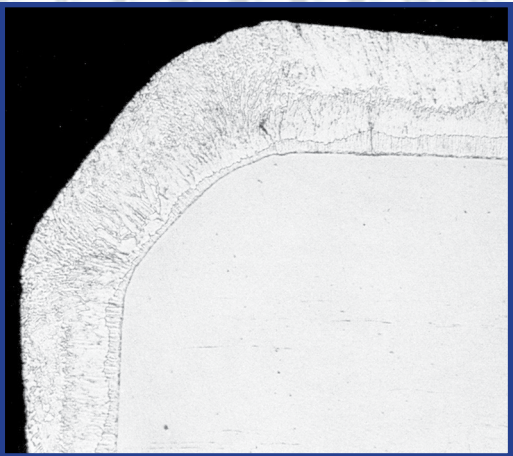
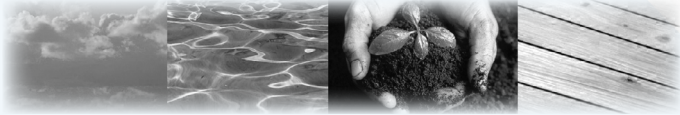


Figure 8: Full Corner Protection

Coating damage is most likely to occur at edges and often corrosion beings in the interior of hollow structures, so these areas are where added protection is needed.



Performance of Galvanized Coatings

Galvanized coatings have proven performance under numerous environmental conditions. The corrosion resistance of zinc coatings is determined primarily by the thickness of the coating but varies with the severity of environmental conditions.

The predictability of the lifetime of a coating is important for planning and budgeting for required maintenance. Measurements of the actual rate of consumption of the galvanized coating during the first few years of service often provide good data for projecting remaining life until first maintenance. Due to the build-up of zinc corrosion products, which in many environments are adherent and fairly insoluble, the corrosion rate may slow as time progresses. Therefore, predictions of service life to first maintenance based on initial corrosion rates of zinc coatings are often conservative.

In the Atmosphere

Zinc, like all metals, naturally corrodes when exposed to the atmosphere. The corrosion products that form on the surface provide a passive, impervious barrier that slows the corrosion of the zinc. Three different products build on the surface over time to develop what is collectively known as the zinc patina. Zinc oxide is the initial corrosion product on the surface and is formed by a reaction between the zinc coating and oxygen in the atmosphere. When the zinc oxide interacts with moisture, it can be converted to zinc hydroxide. The zinc hydroxide and zinc oxide further react with carbon dioxide in the air to form zinc carbonate. The zinc carbonate particles form a layer of tightly adherent and relatively insoluble particles on the surface. The layer, or patina, is primarily responsible for the long-lasting corrosion protection provided by the galvanized coating in most atmospheric environments.



This Candelabra structure towers over Miami.

Since 1926, ASTM Committees A05 (*Metallic Coated Iron and Steel Products*), G01 (*Corrosion of Metals*) and others have been collecting records of zinc coating behavior under various atmospheric conditions. These atmospheric exposure tests are conducted throughout North America to obtain corrosion rate data for zinc. The corrosion behavior of the galvanized coating in various atmospheric environments is influenced by many factors such as: prevailing wind direction, type and density of corrosive fumes and pollutants, amount of sea spray, number of wetting and drying cycles, and the duration of exposure to moisture. Although there is a range in observed corrosion rates, actual observed rates rarely exceed 0.3 mils per year. Furthermore, when exposed indoors, the life of the galvanized coating will be significantly longer than outdoor exposure.

The real world data collected was used to develop the **Zinc Coating Life Predictor (ZCLP)**. The ZCLP estimates the **time to first maintenance** (TFM) of hot-dip galvanized coatings based on the factors that highly influence corrosion rates. TFM is the life until 5% of the surface is showing iron oxide (red rust). At this point, it is unlikely the underlying steel has weakened or the integrity of the structure is compromised. However, it is appropriate to select a brush- or spray- applied corrosion protection system to apply to extend the life of the steel product.

The continual collection of data since the 1920's has shown a substantial improvement in corrosion rates recently due to anti-pollution campaigns. Therefore, the projected times to first maintenance provided by the ZCLP are conservative estimates for the 21st century. Using the ZCLP, *Figure 9* was developed to plot the time to first maintenance of hot-dip galvanized coatings in five exposure conditions:

Industrial environments are generally the most aggressive in terms of corrosion. Air emissions may contain some sulfides and phosphates that cause coating consumption. Automobile, truck and plant exhaust are examples of these emissions. Most city or urban areas are classified as moderately industrial.

Tropical Marine environments are found in climate regions where the temperature rarely, if ever, falls below the freezing point of water. The high humidity in combination with the chlorides in the air from the nearby water makes these climates almost as corrosive as industrial environments. The warmer temperatures of the tropical marine atmosphere raise the activity level of the corrosion elements on the surface of the zinc coating. Other factors that affect marine corrosion rates are wind speed and direction as well as proximity to the coast.

Temperate Marine environments are less corrosive than tropical marine environments due to the lower temperature and humidity levels in the temperate region. Chlorides, wind speed, wind direction, and distance from the sea also affect the corrosion rate of zinc coatings in temperate marine atmospheres.

Suburban atmospheres are generally less corrosive than moderately industrial areas. As the term suggests, they are found in the largely residential perimeter communities of urban or city areas.

Rural atmospheres are the least aggressive of the five types. This is due to the relatively low level of sulfur and other emissions found in such environments.

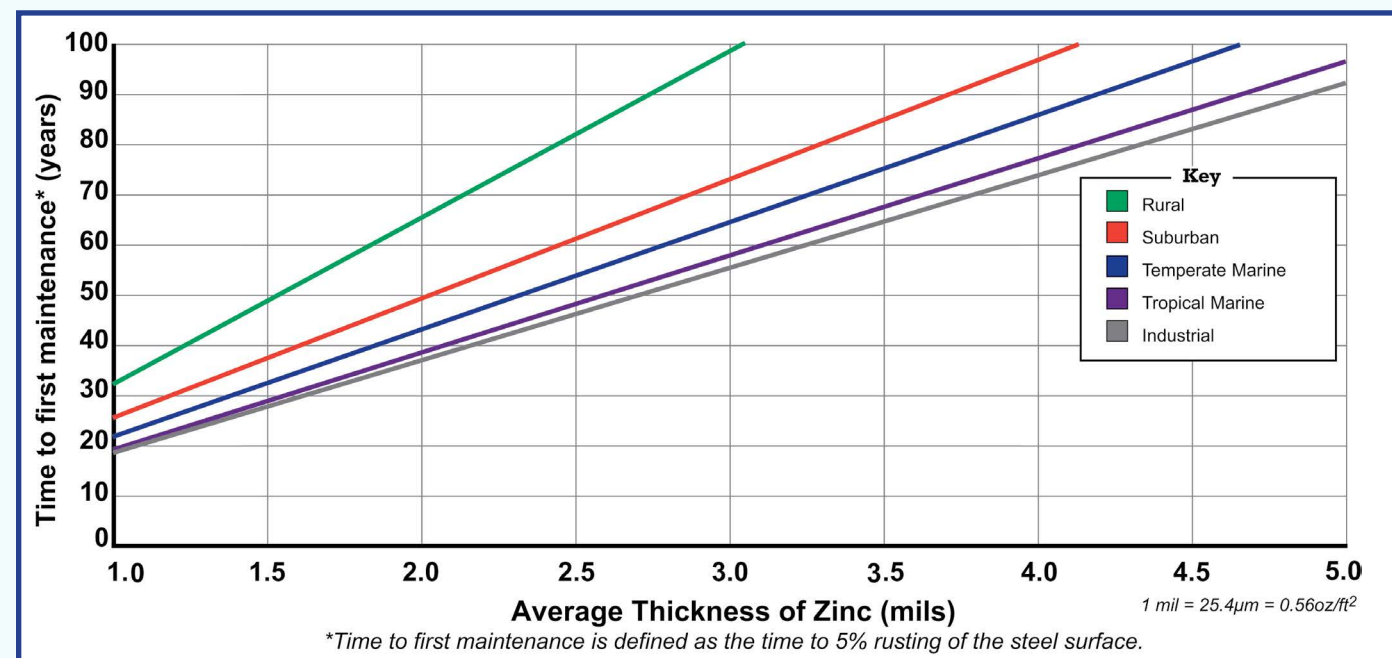


Figure 9: Time to First Maintenance

In Soils

More than 200 different types of soils in North America have been identified and are categorized according to texture, color, and natural drainage. Coarse and textured soils, such as gravel and sand, permit free circulation of air, and the process of corrosion may closely resemble atmospheric corrosion. Clay and silt soils have a fine texture and hold water, resulting in poor aeration and drainage. The corrosion process in such soils may resemble the corrosion process in water.

The National Corrugated Steel Pipe Association (NCSPA) has funded tests conducted by Corpro Companies on buried hot-dip galvanized steel since 1930, resulting in data indicating the zinc coating on the exterior of the pipe is critical to long-term performance. And although the NCSPA focus is on "life to first perforation," the estimate of service life utilized here is years to complete corrosion of

the zinc coating plus an additional time of 25%, to account for partial corrosion of the steel member. This provides the project engineer with information to determine time to replacement or maintenance for non-critical items such as ground rods and reinforced earth wire to more critical structural components such as pilings, utility poles, and guardrail posts. The research suggests a linear relationship between galvanized coating thickness and performance and the existence of four basic and distinct soil conditions, each with a different effect on buried hot-dip galvanized steel. As *Figure 10* shows, there are critical limits for pH, water content, and chloride concentration which determine the durability of the galvanized coating. In between the limits, as pH, water content and chloride concentration vary, so too does the corrosion rate of the hot-dip galvanized steel coating. Since most galvanized structural steel has at least 3.9 to 5 mils of zinc coating, estimated service life in the harshest soil is 35 to 50 years and in less corrosive soil 75 years or more.

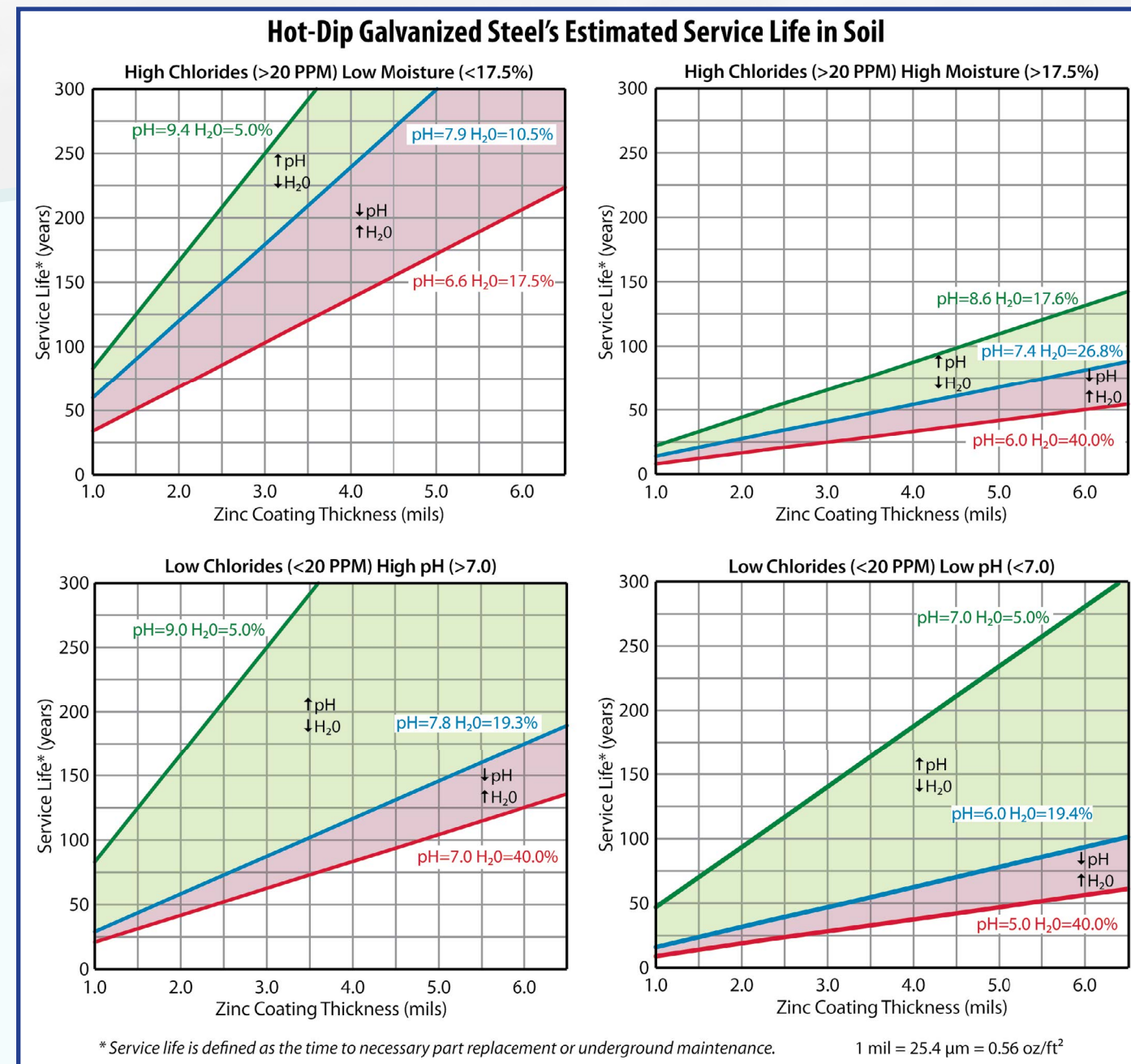


Figure 10: Estimated Service Life in Soil

In Fresh Water

Galvanizing is successfully used to protect steel in fresh water exposure. Fresh water refers to all forms of water except sea water. Fresh water may be classified according to its origin or application. Included are hot and cold domestic, industrial, river, lake and canal waters. Corrosion of zinc in fresh water is a complex process controlled largely by impurities in the water. Even rain water contains oxygen, nitrogen, carbon dioxide and other dissolved gases, in addition to dust and smoke particles.

Ground water carries micro-organisms, eroded soil, decaying vegetation, dissolved salts of calcium, magnesium, iron, and manganese, and suspended colloidal matter. All of these substances and other factors such as pH, temperature, and motion affect the structure and composition of the corrosion products formed on the exposed zinc surface. Relatively small differences in fresh water content or conditions can produce relatively substantial changes in corrosion products and rate. Thus, there is no simple rule governing the corrosion rate of zinc in fresh water. However, one trend data supports is hard water is much less corrosive than soft water. Under conditions of moderate or high water hardness, a natural scale of insoluble salts tends to form on the galvanized surface. These combine with zinc to form a protective barrier of calcium carbonate and basic zinc carbonate which slow the corrosion rate.

Galvanized coatings provide considerable protection to steel immersed in sea water and exposed to salt spray. The factors that influence the corrosion of zinc in fresh water also apply to sea water. However, it is the dissolved salts (primarily sulfides and chlorides) in sea water that are the principal determinants of the corrosion behavior of zinc immersed in sea water. Given the high level of chloride in sea water, a very high rate of zinc corrosion might be expected. However, the presence of magnesium and calcium ions in sea water has a strong inhibiting effect



These vineyard aerators use a duplex coating of hot-dip galvanizing and paint to protect against tropical sea water and salt spray exposure.

on zinc corrosion in this type of environment. Results from accelerated laboratory tests sometimes use a simple sodium chloride (NaCl) solution to simulate the effects of sea water exposure on galvanized steel and should be viewed skeptically. Real world results often differ significantly from accelerated laboratory tests.

In Chemical Solutions

A primary factor governing galvanized coating corrosion behavior in liquid chemical environments is the solution's pH. Galvanizing performs well in solutions of pH above 4.0 and below 12.5 (Figure 11). This should not be considered a hard and fast rule because factors such as agitation, aeration, temperature, polarization, and the presence of inhibitors also may change the corrosion rate. Within the pH range of 4.0 to 12.5 a protective film forms on the zinc surface and the galvanized coating protects the steel by slowing corrosion to a very low rate. The protective film's exact chemical composition is somewhat dependent upon the specific chemical environment.

Since many liquids fall within the pH range of 4.0 to 12.5, galvanized steel containers are widely used in storing and transporting many chemical solutions. Figure 12 shows an abbreviated list of some commonly used chemicals successfully stored in galvanized containers.

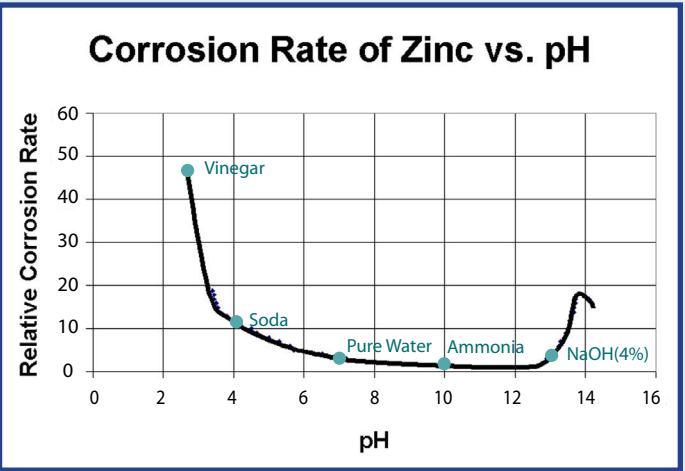


Figure 11: Effect of pH on corrosion of zinc

Hydrocarbons Benzene (benzole) Toluene (toluole) Xylene (xyole) Cyclohexene Petroleum ethers Heavy naphtha Solvent Naphtha	Nitriles (cyanides) Diphenylacetoneitrile p-chlorobenzglycyanides		Butyl	butyrate sobutyrate caproate propionate succinate titanate*	Amine and Amine Salts Pyridine Pyrrolidine Methylpiperazine Dicarbethoxypiperazine 1-benzhydryl-4-methylpiperazine 2-4-diamino-5-(4-chlorophenyl-6) ethlpyrimidine Hydroxyethylmorpholine (hydroxyethyldiethylenimideoxide) p-aminobenzenesulphonylguanidine Butylamine oleate Piperazine hydrochloride monohydrate Carbethoxypiperazine hydrochloride (dry)
	Esters Allyl	butyrate caproate formate propionate butyrate sobutyrate caproate caprylate propionate succinate		Propyl	butyrate isobutyrate caproate formate propionate benzoate butyrate caproate
		Ethyl		Iso-Butyl	benzoate butyrate caproate formate propionate
		Amyl		Iso-Propyl	benzoate caproate formate propionate
		Methyl		Cyclohexyl	butyrate *and other unspecified titanates
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)	Benzyl	Phenols Phenol Cresols (mehtylphenols) Xylenols (dimethylphenols) Biphenol (dihydroxybiphenyl) 2, 4-dichlorophenol p-chloro-o-cresol Chloroxylenols		Amides Formamide Dimethylformamide
		Octyl			
					Miscellaneous Glucose (liquid) Benzilideneacetone p-chlorobenzopheone Sodium azobenzenesulphonate Melamine resin solutions Crude cascara extract Creosote Chloroflourocarbons

Figure 12: Chemicals successfully stored in galvanized containers (partial list)

In Contact with Treated Wood

Pressure treated wood is often used for construction areas that will be exposed to the weather or in high moisture areas. The chemicals used to treat this wood were revised in 2003 to remove some of the potential harmful elements in the treatment. The change in chemical formulations increased the corrosivity of the wood when in contact with metal parts. The two most popular chemicals for wood pressure treatment are alkaline copper quaternary (ACQ) and copper azole (CA), which are both active corrosion materials.

Only two corrosion protection systems are recommended for use with these pressure treatment chemicals: hot-dip galvanized steel and stainless steel. The hot-dip galvanized coating provides a thicker layer of zinc than other zinc-coated fasteners. Hot-dip galvanized steel can withstand the harsh chemicals and slow the corrosion rate. Common metal parts used with pressure treated wood are connector plates, joist hangers, bracing plates, and fasteners of all types. All of these parts should be either hot-dip galvanized or fabricated using stainless steel to withstand the corrosivity of the treated wood.

In Concrete

Concrete is an extremely complex material. The use of various types of concrete in construction has made the chemical, physical, and mechanical properties of concrete and their relationship to metals a topic of ongoing studies. Steel wire or reinforcing bars (rebar) often are embedded in concrete to provide added strength.

Since rebar is not visible after it is embedded in concrete, corrosion protection is very important to retain structural integrity. Galvanized rebar has demonstrated corrosion protection for many years in corrosive atmospheres such as Bermuda. As the corrosion products of zinc are much less voluminous than those of steel, the cracking, delamination, and spalling cycle of concrete is greatly reduced when using galvanized rebar. Laboratory data support, and field test results confirm, reinforced concrete structures exposed to aggressive environments have a substantially longer service life when galvanized rebar is used as opposed to uncoated steel rebar.



Magistrate Court and Hamilton Police Station in Bermuda utilizes hot-dip galvanized reinforcing steel to combat the corrosive tropical environment. All infrastructure in Bermuda requires hot-dip galvanized rebar.

The bond strength between galvanized rebar and concrete is excellent. However, it often takes slightly longer to develop than the bond between uncoated rebar and concrete. According to laboratory and field tests, the bond between galvanized rebar and concrete is in fact stronger than the bond between uncoated rebar and concrete (Figure 13) or epoxy-coated rebar and concrete.

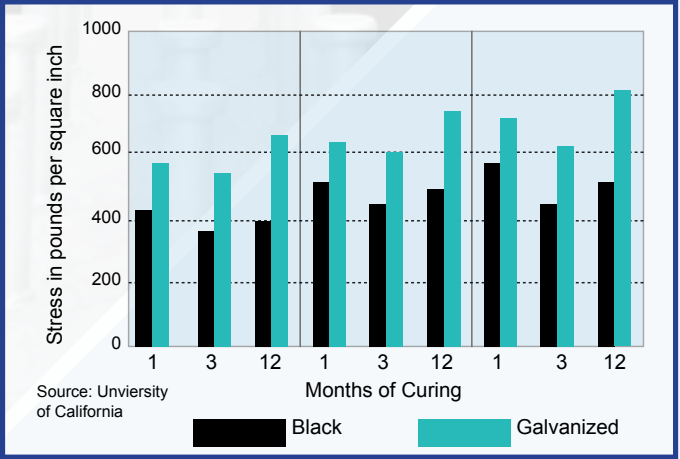


Figure 13: Bond strength to concrete: black vs. galvanized reinforcing steel

A comparison of the qualitative and quantitative characteristics of galvanized rebar and epoxy-coated rebar is shown in Figure 14.

Hot-Dip Galvanized Rebar	Performance & Condition	Epoxy-Coated Rebar
No	Special Handling	Extensive
No	Subject to UV Damage	Yes
No	Touch-up After Placement	Yes
Equivalent to Black Bar	Overlap Length	Additional Steel Required
No	Holidays/Pinholes	Yes
Yes	Fabricate after Coating	Yes
Excellent	Bond to Concrete	Poor
No	Underfilm Corrosion	Yes
Yes	Cathodic Protection	No
Excellent	Abrasion Resistance	Poor
All	Installation Conditions	Temperature > 50 F

Figure 14: Hot-Dip Galvanized Rebar vs. Epoxy-Coated Rebar

Information and additional studies about the uses and behavior of galvanized reinforcement in concrete can be found in:

- Galvanized Steel Reinforcement in Concrete
- Hot-Dip Galvanized Reinforcing Steel: A Specifier's Guide
- Hot-Dip Galvanized Steel – A Concrete Investment

Download any of these publications from the AGA (www.galvanizeit.org/publications) or learn more at www.galvanizedrebar.com.



The lightning mitigation system towers were galvanized to withstand the extreme high temperatures at launch.

In Extreme Temperatures

Galvanized coatings perform well under extreme cold and hot temperatures. Hot-dip galvanized coatings do not show any significant differences in corrosion rate in temperatures below -40 F. In higher temperatures, the coating can be affected. In long-term, continuous exposure, the recommended maximum temperature is 392 F (200 C). Continuous exposure to temperatures above this can cause the outer free zinc layer to peel from the underlying zinc-iron alloy layer. However, 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.



The Quick Chill Cooler expansion was hot-dip galvanized to help meet USDA food processing requirements and to withstand the extreme cold environment.

In Contact With Other Metals

Where zinc comes into contact with another metals, the potential for corrosion through a bi-metallic couple exists. The extent of the corrosion depends upon the position of the other metal relative to zinc in the galvanic series (Figure 2, page 2), and to a lesser degree on the relative size of the surface area of the two metals in contact.

The behavior of galvanized coatings in contact with various metals is summarized in Figure 15. The information given is provided as a guide to avoid situations where corrosion may occur when galvanized surfaces are in contact with another metal.

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

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

General notes: Ratings in brackets are based on very limited evidence and 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

Figure 15: Additional corrosion of zinc and galvanized steel resulting from contact with other metals

The following provides more detail on other common metals used in construction that may come in contact with hot-dip galvanized steel.

Copper and Brass

If an installation requires contact between galvanized materials and copper or brass in a moist or humid environment, rapid corrosion of the zinc may occur. Even runoff water from copper or brass surfaces can contain enough dissolved copper to cause rapid corrosion. If the use of copper or brass in contact with galvanized items is unavoidable, precautions should be taken to prevent electrical contact between the two metals. Joint faces should be insulated with non-conducting gaskets; connections should be made with insulating, grommet-type fasteners. The design should ensure water is not recirculated and water flows from the galvanized surface towards the copper or brass surface and not the reverse.

Aluminum and Stainless Steel

Under atmospheric conditions of moderate to mild humidity, contact between a galvanized surface and aluminum or stainless steel is unlikely to cause substantial incremental corrosion. However, under very humid conditions, the galvanized surface may require electrical isolation from the aluminum or stainless steel.

Weathering Steel

When galvanized bolts are used on weathering steel, the zinc will initially sacrifice itself until a protective layer of rust develops on the weathering steel. Once this rust layer develops, it forms an insulating layer that prevents further sacrificial action from the zinc. The zinc coating has to be thick enough to last until the rust layer forms, usually several years. Most hot-dip galvanized bolts have enough zinc coating to last until the protective rust layer develops on the weathering steel, with only a minimal loss in coating life.



The Cincinnati Children's Hospital Parking Garage uses a combination of hot-dipped galvanized and stainless steel to create an aesthetically appealing exterior façade. The "ribbons of steel" design will remain beautiful for patients and medical staff well into the future.

Summary

The consistent performance of hot-dip galvanized steel in the atmosphere, soils, fresh water, salt water, chemical solutions, treated wood, concrete, extreme temperatures, and in contact with other metals have now been discussed in detail. In every category, galvanizing is an effective, durable, maintenance-free corrosion protection method. Galvanizing is specified for steel projects because of the versatility of zinc's barrier and cathodic protection, and because it performs well alongside all materials and in every environment. Because the applications of steel are many, hot-dip galvanizing will continue to be called upon to ensure long-lasting and maintenance-free corrosion protection.

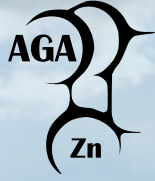
Pertinent Specifications

ASTM

A 123/A 123M	Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products
A 143/A 143M	Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement
A 153/A 153M	Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware
A 384/A 384M	Standard Practice for Safeguarding Against Warpage and Distortion During Hot-Dip Galvanizing of Steel Assemblies
A 385 - 2005	Standard Practice for Providing High Quality Zinc Coatings (Hot-Dip)
A 767/A 767M	Standard Specification for Zinc Coated (Galvanized) Steel Bars for Concrete Reinforcement
A 780/A 780M	Specification for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings
B6	Standard Specification for Zinc
D 6386	Standard Practice for Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Painting
E 376	Standard Practice for Measuring Coating Thickness by Magnetic Field or Eddy-Current (Electromagnetic) Test Methods

Canadian Standards Association

G 164-M	Hot-Dip Galvanizing of Irregularly Shaped Articles
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