

contents of each sump overboard into the ship channel. Sump and pump capacity are based upon a continuous rainfall of 4 inches per hour, and a 10-minute downpour at a rate of 8 inches per hour, with one of the three pumps acting as standby. A sump at the mid-point collects any water entering the tunnel drainage system, which is discharged by electric pumps to one of the main sumps.

#### TRAFFIC-CONTROL SYSTEM

Traffic lights are mounted at intervals of about 400 feet over each roadway lane. Control stations along the service walk permit setting all signals in either direction from the portal to any point in the tunnel on amber or red, leaving the off-going signals from this point to the other portal on green.

#### FIRE-ALARM SYSTEM

Fire alarm stations along the tunnel service walk can be used by the guards to actuate signals in the two crash truck stations and in the ventilation control room.

#### SERVICE TELEPHONE

A sound-powered service telephone system with stations in the tunnel along the service walk, in the ventilation control room, and in the crash truck stations provides intercommunication between these points for tunnel guards, crash-truck crews, and main operator. Outside telephone service is brought into the main control room.

#### ENGINEERING AND CONSTRUCTION

For the Texas Highway Department, D. C. Greer, state highway engineer; R. B. Alexander, bridge engineer; and J. Douglas, district engineer in Houston, exercised general supervision over the project. J. M. Page represented the Bureau of Public Roads. Parsons, Brinckerhoff, Hall & Macdonald was in charge of design and construction of the tunnel. Brown & Root, Inc. of Houston was the contractor for the sunken-tube tunnel. Farnsworth & Chambers, Inc., also of Houston, was the contractor for the remainder of the tunnel project.

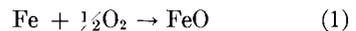
## Theory of Corrosion and Prevention of Paint Failures

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THIS paper discusses: (1) simplified presentation of the theory of corrosion of structural steel, outlining the electrical nature of corrosion, the electromotive series for metals and causes of difference in potential, galvanic cells and their action, mill scale (its composition, structure, why it accelerates corrosion), and mill-scale lifting; (2) the action of paint in preventing corrosion by inhibitors of corrosion, mechanical barriers, and sacrificial action of paint pigments; and (3) causes and prevention of paint failures—the types that occur in paint films on structural steel and methods of eliminating such failures.

●CORROSION has been defined as the destruction of a metal by chemical or electrochemical reaction with its environment (13). Two general types of corrosion occur: direct chemical oxidation and electrochemical. In direct oxidation, corrosion occurs by chemical

reaction of metal with a gas. In the case of iron, iron plus oxygen forms iron oxide:



Since there are various forms of iron oxide, the corrosion products should be specified.

In this case, ferrous oxide is the indicated reaction product; it may occur in deficiencies of oxygen at temperatures above 570 C. Iron also reacts directly with oxygen to form ferric oxide:



or to form another oxide known as magnetite:



A natural spontaneous tendency for metallic iron to react with oxygen to form oxides of iron exists because metallic iron has a high free-energy decrease when reacting with oxygen. Iron occurs as iron oxide in nature and requires a certain amount of energy to be expended to reduce it to the metallic state; therefore, there is a natural tendency for iron to react with oxygen and revert to its original state with the release of an equivalent amount of energy. When a fresh, clean surface of iron or steel is exposed to oxygen or the atmosphere, immediate oxidation of the surface takes place and a thin layer of iron oxide is formed. This will occur whether the atmosphere is wet or dry. The initial oxidation is by direct chemical reaction. The significant factor is that once the layer of oxide is formed, the rate of oxidation drops off and may stop completely. In some cases (for example, the stainless steels and low-alloy steels) the corrosion products (the oxide layer) become protective and may reduce the rate of corrosion to almost zero.

Temperature has a significant effect upon the rate of oxidation of metal surfaces. An increase in temperature increases the rate of oxidation and the thickness of the oxide layer that is formed. Mill scale, which will be discussed in detail later, results from corrosion of steel at elevated temperatures. In the case of steel or iron, corrosion by direct oxidation at normal temperatures is of little or no consequence. Bright, clean steel may be exposed to dry atmospheres for extremely long periods of time with no evidences of rusting and only a thin transparent film of iron oxide forms. A critical humidity does exist above which rusting will begin. Vernon (14) established that rusting does not occur below about 70 percent relative humidity at ordinary temperatures. When the humidity of the air reached or exceeded 70 percent, rusting begins. This rusting

is believed to occur by electrochemical reaction rather than by direct oxidation.

Some gaseous impurities in the air, such as sulfur dioxide, in the presence of water rapidly increase the rate of corrosion. Little or no direct reaction occurs between steel and dry sulfur dioxide, even in the presence of oxygen. With slight quantities of moisture present, rapid and serious corrosion occurs. Again this corrosion is electrochemical rather than a direct chemical reaction. Solids, such as particles of carbon and salts, may accelerate corrosion locally, and spots of rust may develop.

Serious corrosion of steel or iron occurs at normal temperatures only in the presence of both oxygen and water; this corrosion is electrochemical. In direct oxidation, electrons are given up by the iron and taken up by the oxygen through direct sharing or transfer; but in electrochemical corrosion, iron gives up electrons which must flow through a metallic or conducting path to another area where electrons combine with other ions and an electric current is generated in the process.

In Figure 1 an electrochemical cell is illustrated. This is in reality a voltaic cell or battery; it is also called a galvanic cell. An anode and cathode must be present and must be immersed or in contact with a conducting solution or electrolyte. This electrolyte may be a salt solution, as in the illustration, or it may be an acid, a base, or a molten salt. For current to flow and corrosion to occur, the anode must be connected to the cathode by a low-resistance path of metal or a conducting solution. The anode forms the area at which oxidation of the metal occurs. Oxidation here is defined as the giving up of electrons.

In the case illustrated, the anode is iron, and in the process of corrosion one atom of iron will oxidize by giving up two electrons to form a ferrous ion. (An ion is a particle which may be charged negatively or positively.) The ferrous ion goes into solution and has a positive charge as indicated. The reaction occurs at the surface of the anode. The negatively charged electrons remaining create an excess negative charge on the anode, which is therefore electrically negative. Electrons travel through the anode and the metallic connecting path to the cathode.

In this case, a copper cathode is illustrated,

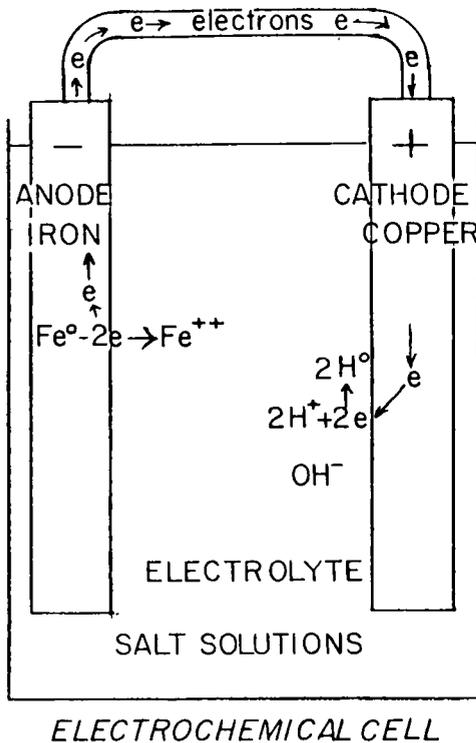


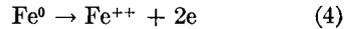
Figure 1. Electrochemical cell in operation.

but the cathode could be carbon, or platinum, or iron, or a number of other materials. Water in the electrolyte ionizes to form hydrogen and hydroxyl ions. These are indicated  $H^+$  and  $OH^-$  respectively. At the cathode, hydrogen ions react with the excess electrons to form hydrogen atoms. In some cases, these hydrogen atoms will combine to form hydrogen molecules. In other cases the hydrogen atoms will react with excess oxygen present in solution to form more water.

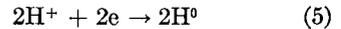
In the case of formation of hydrogen molecules, hydrogen gas plates out on the cathode and a layer of hydrogen soon builds up over the entire cathode. If this hydrogen remains on the cathodic area, the cathode is insulated and polarization occurs. As a result of the polarization, the flow of current gradually diminishes and may cease altogether.

Since practically all of the corrosion which occurs at normal temperatures is electrochemical and occurs in the presence of both oxygen and water, the reactions which take place will be summarized here. Iron corrodes

in a series of reactions which occur in steps. In the simplest case, iron gives up electrons to form ferrous ion:



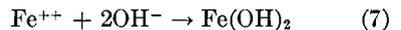
In acidic solutions, hydrogen ions react with the free electrons at the cathode to form elemental hydrogen:



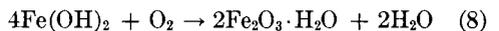
Hydrogen ions and hydroxyl ions exist in solution by dissociation of water:



As a result of the reactions which occur in Equations 4 and 5, an excess of ferrous ions and hydroxyl ions exist in solution with significant and far-reaching effects. The excess of hydroxyl ions occurs around the cathode because of the depletion of hydrogen ions. As a result, the cathodic area is alkaline and adjacent oil paints are detrimentally saponified to form soluble soaps. Ferrous ions and hydroxyl ions migrate through the solution and at some point will come into contact. The result of combination of ferrous ions with hydroxyl ions is indicated in equation 7:



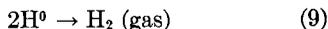
Because the reaction product is insoluble, the reaction goes essentially to completion and ferrous hydroxide is precipitated from solution. A continuous process may occur if the deposited hydroxide does not insulate the anodic or cathodic area completely. Ferrous hydroxide is an unstable compound and, in the presence of excess oxygen, will react to form the familiar rust, which is a form of ferric hydroxide. The composition of rust is not too well known and may vary depending upon the amount of moisture and oxygen present and upon the conditions of formation of the rust. Generally, rust is considered to be ferrosiferic hydroxide:



The yellowish-red rust commonly formed in moist atmospheres or water is therefore a hydrated ferric oxide, which is similar to the ferric oxide formed in direct chemical reaction except that water of hydration is combined into the compound. Under conditions where the supply of oxygen is limited, a greenish

hydrated ferric oxide may be the resulting product or even a black hydrated iron oxide with the approximate composition  $\text{Fe}_3\text{O}_4$ .

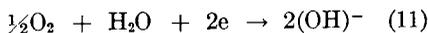
Positive hydrogen ions react with excess electrons at cathodic areas as indicated in Equation 5. Elementary hydrogen formed may combine to form molecular hydrogen



with the evolution of hydrogen gas. The evolution of hydrogen in this form is common in acidic solutions. In aerated solutions that are nearly neutral, the reaction of any hydrogen formed is



and reaction occurs with excess oxygen to form liquid water. Excess oxygen in essentially neutral solutions also accepts electrons at the cathode to form a surplus of hydroxyl ions in solution:



Because free oxygen reacts with the corrosion products formed at the cathode, corrosion proceeds undiminished as long as the supply of free oxygen exists. When free oxygen is no longer available, corrosion slows down and may cease completely.

Atmospheric corrosion at normal temperatures takes place by the preceding mechanism, since above the critical humidity sufficient water is present to maintain an electrolyte in contact with the metal. Electric currents flow from anodic areas to cathodic areas on the surface of the metal. These areas are generally small and quite close together; corrosion appears to take place uniformly over the surface. Actually, the surface consists of innumerable anodes and cathodes. Where anodic areas are small and pronounced currents exist, pits develop.

The potential difference which exists between the anode and cathode determines the rate of current flow and, in turn, the amount of metal that will be corroded. There is a very definite relationship between the amount of metal wasted away and the amperes of current flowing. One ampere-hour of current will dissolve 1.04 grams of iron to form ferrous ions. It is quite fortunate that as the current density increases, polarization increases and the difference in potential which causes corrosion then decreases.

TABLE I  
ELECTROMOTIVE SERIES

	Metal	Normal Electrode Potential, volts
Noble end	Gold	+1.42
	Platinum	+1.2
	Silver	+0.800
	Mercury	+0.799
	Copper	+0.345
	Hydrogen	0.000
	Lead	-0.126
	Tin	-0.136
	Nickel	-0.250
	Cadmium	-0.402
	Iron	-0.440
	Chromium	-0.710
	Zinc	-0.762
	Aluminum	-1.670
Base end	Magnesium	-2.34

The potential which exists between the anode and the cathode depends primarily upon the position of the metals in the electromotive series. The elements of the electromotive series fall into two groups, known respectively as electronegative (base) and electropositive (noble). Between these two groups lies the element hydrogen. The hydrogen electrode is used as a reference and has been arbitrarily assigned a zero potential. Zinc, for example, has a greater solution potential than iron when placed in an electrolyte. A potential difference will exist between them of 0.762-0.440 equalling 0.322 volts. The actual potentials will vary with the solutions and their concentration. Table 1 (13) lists only the potentials of metals in standard or normal solutions. The sign associated with the potentials is only of relative significance.

Many possible variations exist in electrochemical or galvanic cells. Almost any combination of metals may occur, and as indicated previously, even hydrogen gas may be an electrode. It is not necessary that the anode and cathode be of different materials. Both the anode and the cathode may be of iron or of steel and a current generated. If an iron anode is immersed in a solution of a given concentration and another iron anode is immersed in another solution of a different concentration, a potential difference will exist because of the difference in concentration of the solutions. The solution may be of uniform concentration, but there may be a difference in the amount of oxygen dissolved at the anode in comparison to the cathode. If a difference in dissolved oxygen exists, a concentration

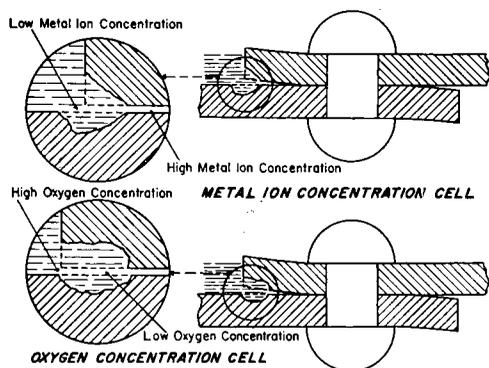


Figure 2. Diagram of concentration cells which occur in practice.

TABLE 2  
GALVANIC SERIES

(Corroding end—Anodic)

Magnesium  
Aluminum  
Duralumin

Zinc  
Cadmium

Iron  
Chromium—Iron (Active)  
Chromium—Nickel  
Iron (Active)

Soft Solder  
Tin  
Lead

Nickel  
Brasses  
Bronzes  
Nickel—Copper Alloys  
Copper

Chromium—Iron (Passive)  
Chromium—Nickel—Iron (Passive)

Silver Solder

Silver  
Graphite  
Gold  
Platinum

(Protected end—Cathodic)

cell will also exist and current may be generated.

Figure 2 illustrates practical examples of concentration cells. In one case, a difference in the concentration of dissolved metal salts exists. As a result, corrosion occurs in the region of high metal-ion concentration. In the other case, an oxygen-concentration cell exists, and because of a low oxygen concentration in the crevice, the area is anodic to the remaining area and corrosion occurs. Here, corrosion occurs in the area deficient in oxygen.

Note that in the electromotive series alumi-

num is very anodic in comparison to hydrogen, and therefore one might conclude that aluminum should be easily and quickly corroded. However, upon exposure to oxygen, aluminum forms a layer of aluminum oxide which is quite protective and may completely stop further corrosion. Table 2 lists the galvanic series determined from the results of actual service and test (11). The materials in any one group are so similar in potentials in actual service that they may be safely coupled without developing any serious galvanic effects. Materials in different groups have sufficient difference in potential to generate electric currents. Position may vary slightly depending on local conditions.

When materials are far apart in the table, currents are possible and severe corrosion may be expected. In galvanic corrosion, severe damage may occur by reason of the fact that corrosion is limited to one spot; for example, the total amount of metal that corrodes may be small, but the anodic area may be small and corrosion localized in the form of a pit, which will perforate the wall of a vessel in time.

The anode in a current-producing cell is negative and the cathode is positive by the method of designation used here. The flow of current, as normally visualized or represented, is opposite to the flow of electrons. By convention, current flows from the anode into the electrolytic solution and then to the cathode. This convention is the most widely used, but is rather arbitrary and opposite to the actual flow of electrons.

In any case where an electric current leaves a metal surface which is corrodible, destruction or loss of metal occurs at the point where the current leaves the metal and enters the electrolyte (which may be water, concrete, soil, etc.).

Figure 3 illustrates stray current electrolysis which, in this case, shows damage occurs to buried metal by a stray current resulting from a direct current trolley system. Note that in this illustration the current is leaving the positive area and that the positive area is the anodic area. This is in contrast to a current-producing cell, as illustrated in Figure 1. The signs assigned to the anode and cathode are reversed in a current-consuming cell from those in a current-producing cell. Because of the extreme confusion which exists in designating areas as positive and negative, it is

better practice to think of them as anodic or cathodic.

Severe damage has occurred because of stray-current electrolysis. Perforation of steel members occurs easily and may result in complete failure of a structure. There is great danger in coating anodic areas where strong currents may exist, because breaks in the coating permit electric current to leave the metal at those points; all of the corrosion is concentrated at small spots. When steel is enclosed in concrete, if stray currents pass from the steel to the concrete and in turn to the ground or leave the circuit by some method, corrosion products accumulate around the steel in proportion to the amount of current that flows; in time, they may spall or fracture the concrete from the tremendous pressure developed.

It is obvious that corrosion of the anode takes place but that the cathode is protected by means of the electric current which flows. This is the basis for a method of protection of metal by application of an electric current which maintains the metal to be protected in a cathodic state. Cathodic protection is the result. The current may be supplied by two methods: the first is through use of sacrificial anodes of magnesium, aluminum, or zinc, which are permitted to corrode and protect what would normally be anodic areas. In the second method, a source of direct current is connected to anodes and current flows from the anodes to the areas to be protected. In this case the anodes may consist of inert conducting materials, such as graphite, scrap iron, or other metal. If the metal anode is corrodible, it will be gradually wasted away by passage of the current. Noble-metal anodes, such as gold or platinum, do not show any deterioration by passage of a current. Aluminum anodes are often used with impressed current from an external source in cathodic protection systems.

Figure 4 shows a cathodic protection system utilizing a rectifier, connected to a source of alternating current, to provide direct current to a ground-bed system of anodes to protect a buried pipeline by maintaining it at a cathodic potential to the corrosive earth.

In summing up this presentation of the basic theory of corrosion and its application in practice, it is important to caution against either under estimating or over estimating the losses from corrosion and the necessity for

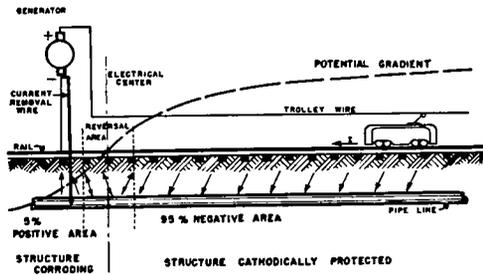


Figure 3. Stray-current electrolysis, which can damage structures buried in the soil or in contact with an electrolyte.

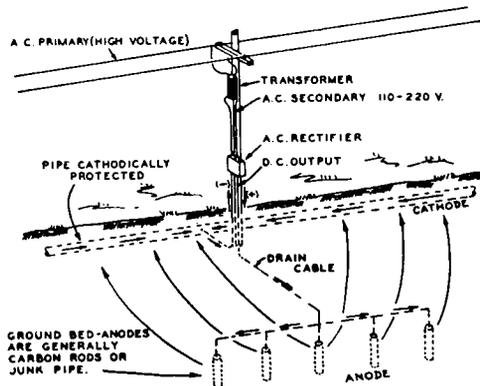


Figure 4. Diagram of a typical cathodic protection system using applied current. A sacrificial system would utilize only a sacrificial anode and the external current source would be eliminated.

protective coatings. It is often difficult to economically justify the use of protective coatings on structural steel exposed to the atmosphere under normal conditions. While it is true that corrosion is serious and that a uniform loss of metal may be expected, the overall rate of corrosion of steel in such exposure may be so low that a small corrosion allowance would be adequate to protect the structure from corrosion over its expected useful life. The increase in metal cost may be less than the cost of painting over years. Serious corrosion of structural steel generally occurs in localized regions. This is often due to faulty designs which allow water to accumulate or be trapped along with dissolved salts (such as brine) and permit dangerous concentration cells to cause serious localized metal loss.

## MILL SCALE

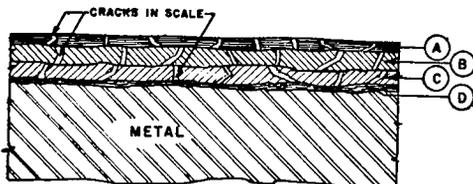
The protection of steel structures exposed to the atmospheres or immersed in water would be comparatively simple were it not for the mill scale found on structural steel. Mill scale consists of oxides of iron which are formed on steel because of the rolling operation. The steel is heated to high temperature and rolled while hot. Direct oxidation of the steel occurs during this process. Most of the scale which forms during the actual rolling operation is knocked off in subsequent passes through the rolls and by operations designed to remove this rolling scale. After being rolled to the desired shape and thickness, steel is allowed to cool. During the cooling operation, the mill scale ordinarily encountered on structural steel forms. The steel is then shipped to the fabricator. During the process of cooling, handling, storage, and shipping, the mill scale becomes cracked to varying degrees, some of the steel surface begins to rust, and some of the mill scale is loosened.

The composition of mill scale is illustrated in Figure 5. There are three principal layers which occur in mill scale, but these layers do not have sharp boundaries. The outer layer consists of ferric oxide,  $\text{Fe}_2\text{O}_3$ , which is a stable oxide of iron and has the highest concentration of oxygen, approximately 30 percent by weight. This material undergoes no further oxidation under ordinary conditions. Under the layer of  $\text{Fe}_2\text{O}_3$  which is comparatively thin, is a layer of  $\text{Fe}_3\text{O}_4$ , essentially magnetite. This material contains about 28 percent oxygen. It may undergo further oxidation under proper conditions to  $\text{Fe}_2\text{O}_3$ . The bulk of the layer of mill scale is composed of ferrous oxide,  $\text{FeO}$ , containing about 22 percent oxygen. This material is unstable and is easily

oxidized to ferric iron, which results in an increase in volume, since ferric oxide has a greater volume per weight of iron contained than ferrous oxide. This change in volume is sufficient to cause fracture of the mill scale and spalling of the scale from the surface. A fourth layer is often present and consists of a mixture of metallic iron with ferrous oxide. This is actually the surface of the steel substrate. The actual thickness of mill scale on structural steel depends upon rolling conditions; it varies from about 2 mils to 20 mils, but generally it will range from 2 to 5 mils. It is believed that the very thick patches of mill scale which occur are fragments of the scale which formed during rolling operations and were not removed, but which were subsequently overcoated with another layer of iron oxide. On structural steel the outer layer of  $\text{Fe}_2\text{O}_3$  is very thin. The bulk of the mill scale is reported (6) to consist of  $\text{Fe}_3\text{O}_4$ , roughly 10 to 15 percent, and of  $\text{FeO}$ , roughly 85 percent.

Since mill scale consists of oxides of iron, there is a reduced tendency for oxidation of the surface to occur. Mill scale may be protective to the steel surface under special conditions, but these special conditions, unfortunately, cannot always be relied upon to prevent further corrosion. If the mill scale is intact, it constitutes a good base for painting and will give long, satisfactory paint life when exposed to mild atmospheres; the paint life may equal or surpass that on blast-cleaned or pickled steel. This statement is true for intact mill scale, a surface condition which is seldom encountered in actual practice due to fabricating procedures.

The reasons for the erratic, costly, corrosion-accelerating performances of mill scale which occur on actual structures may be understood by examining the fundamental chemical and physical changes that take place. To begin with, mill scale is cathodic to steel. It has a more noble potential than mild steel and an electric current is generated between the underlying steel and the mill scale at breaks in the scale when an electrolyte moistens the surface. The steel corrodes and protects the mill scale. The potential difference generated between steel and mill scale may reach 0.2 to 0.3 volts, but the true potential difference is difficult to measure and may exceed these values. This galvanic couple is almost as powerful a generator of electric current as a



Mill scale is composed of several layers: A.  $\text{Fe}_2\text{O}_3$   
B.  $\text{Fe}_3\text{O}_4$ , C.  $\text{FeO}$  D.  $\text{FeO} + \text{Fe}$ .

Figure 5. The structure and composition of a typical mill scale on structural steel.

steel to copper couple. Figure 6 illustrates the corrosion that occurs in the presence of water at a break in mill scale. If the steel is immersed in water, a rust tubercle develops and a pit is formed; a similar but slower action occurs upon exposure of steel with mill scale to atmospheres above the critical humidity. This electrochemical cell is identical in operation to the one illustrated in Figure 1. The only difference is that here mill scale is the cathode while in the other electrolytic cell copper is the cathode. If the break in mill scale is small in area, such as a crack or small piece of scale broken off, the corroding current is concentrated at one point and a pit forms. This is a characteristic corrosion phenomenon which occurs when a small active anode is coupled to a large cathodic area. Generally, the same amount of corrosion occurs in the small localized area as would have occurred over a large area of anode; since the total metal removed is proportional to the amount of electric current flowing, rapid eating away of metal occurs and a pit forms which may lead to perforation and failure of the structure. This same action occurs even when the mill scale is painted if sufficient moisture can permeate the paint film.

Once pitting begins, it may accelerate further corrosion because of rust which forms adjacent to the pit. In addition to the original mill-scale-to-steel galvanic couple, concentration cells may develop because of oxygen deficiency below the rust.

Upon exposure of mill scale to the atmosphere, a weathering process occurs. This weathering process is an undercutting of the outer layers of mill scale by corrosion of the underlying steel and the innermost ferrous oxide layer. The undercutting of the mill scale, in turn, loosens the outer layers of mill scale and carries away the scale and any paint remaining. This undercutting and resulting corrosion is the familiar "mill-scale lifting" that has ruined many costly paint jobs. It is directly attributable to the fact that the mill scale was originally not intact and that the method of cleaning and painting was inadequate to prevent corrosion at discontinuities in the mill scale.

Rust cannot be considered as an alternative substrate for paint. While it is sometimes possible to obtain long, economical paint life over intact mill scale, there has never been any

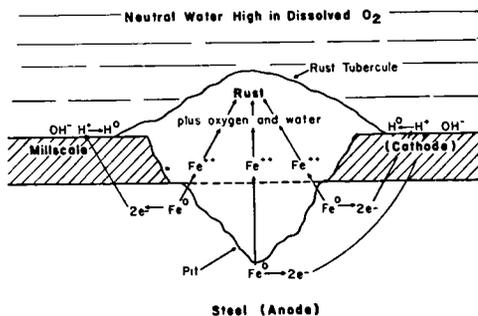


Figure 6. Formation of pits and rust tubercles. This may occur when immersed in water or may occur in atmospheres above the critical humidity.

method devised of painting over rust which results in long paint life. Rust is a hydrated form of ferric oxide; as a result, it is moist and has a hygroscopic nature, i.e., it tends to absorb further moisture from the atmosphere, further increasing its electrochemical characteristics. Rust is generally contaminated with corrosive agents in the atmosphere, such as sulfur dioxide and sulfates in industrial atmospheres and chlorides in marine atmospheres.

Because of the cathodic relationship of mill scale to steel, devastating corrosion often occurs when mill-scale-coated steel is immersed in a strong electrolyte, such as sea water or brine solutions. A crack or break in the mill scale may result in extremely fast corrosion and serious pitting. Under these conditions the probability of failure is so high that it is almost imperative that mill scale be completely removed from steel before painting and exposure.

#### PREVENTION OF CORROSION

Corrosion may be prevented, but a careful analysis of the cost of the method of protection must be made. The most-obvious method of preventing corrosion is to use corrosion-resistant materials. Materials such as various stainless steels and monel have high corrosion resistance for even the most-corrosive environments. However, even these materials are subject to serious localized attack if improperly used. For that reason, one of the most-fundamental prerequisites to satisfactory elimination or reduction of corrosion is proper design. Such design should reduce potential sources of failure by eliminating

joints and crevices where water or moisture may be trapped or where oxygen or other concentration cells may be formed, eliminating the formation of galvanic couples by not permitting electrical contact between dissimilar materials, and building structures so that it is possible to properly maintain them.

The highly corrosion-resistant alloys are much more expensive than mild steel or the low alloys. While the cost of fabricating a steel structure from stainless or monel may be fantastically high, there are cases where the low alloys containing lesser amounts of chromium and nickel will be economical because of their increased corrosion resistance. These low alloys have a much greater resistance to atmospheric corrosion than mild steel or copper steel, because principally the oxides that are formed upon first exposure are much more protective than the oxides on mild steel. Copper-bearing steels have a better corrosion resistance than mild steel when exposed in the atmosphere. However, for immersion in water, there is little or no advantage in using copper-bearing or low-alloy steels. Wrought iron has little or no advantage in corrosion resistance over mild steel. English investigations have shown that while some of the foreign wrought iron appears to have a slight improvement in corrosion resistance, the American wrought iron has poorer resistance than mild steel.

Aluminum has shown good resistance to corrosion when properly used. Here, the choice of the alloy to be used and the design of the structure in which it is to be used is critical for long and proper service.

For the majority of steel structures that will be erected in the near future, it is certain that mild or copper-bearing steel will continue to be the main construction material. For that reason, the balance of this paper will deal with the prevention of corrosion of such steel.

One of the best methods of protecting steel and iron from corrosion is by means of galvanizing. The cost is economical for small pieces that can be easily cleaned and handled in the shop and for light-weight sheets or plates that would have a limited life unless so protected. In galvanizing, one of the methods of prevention of corrosion is readily apparent; it is the sacrificial action which results from electrical contact of a less-noble metal which is expended to protect steel. Zinc is sacrificed

at discontinuities in the coating and the underlying metal is protected. This is a form of cathodic protection.

In addition to protecting by sacrificial action, galvanizing protects steel by imposing an impermeable barrier to moisture and oxygen. This constitutes another method of protecting steel from corrosion. As long as a barrier is maintained which will not permit the passage of oxygen and water to the steel surface, corrosion will be impossible. In the case of galvanizing, the zinc coating is easily corroded; since it is expensive, it is important to obtain the most-economical use of this coating. In normal unpolluted rural atmospheres, a galvanizing of 2 ounces per sq. ft. of surface is expected to have a normal life of about 20 years. This thin coating lasts for that long a period because the corrosion products formed on the surface of the zinc in such atmospheres are protective and the rate of corrosion slows down after the initial exposure. When zinc is exposed in industrial atmospheres, the corrosion products are less protective; as a result the zinc will fail in comparatively short periods of time. For that reason galvanized metal exposed in industrial atmospheres requires protection in the form of a protective coating, such as paint, to obtain long life. Galvanizing exposed to marine atmosphere has a life longer than in industrial atmospheres, because the corrosion products resulting from the chloride contamination in the atmosphere are more protective than those which result from sulfate contaminants in industrial atmospheres.

Corrosion may also be prevented by the addition of corrosion inhibitors to the corrosive medium or the metal surface. The real mechanism of corrosion through the use of inhibitors is not too well known and is quite complex. Only a few of the more-obvious aspects will be covered here. Most inhibitors prevent corrosion by forming films over the anodic or cathodic areas, or over both. For example, in the case of chromates which are used to prevent corrosion, a soluble chromate salt, such as potassium or sodium dichromate, is dissolved in water. It ionizes to form metal ions and chromate ions. The chromate ions are responsible for the inhibition. It is generally believed that a layer of chromate ions is adsorbed on the surface of the anode and retards corrosion by making the surface rela-

tively inert. When insufficient chromate is available to form a complete film over the anode and to maintain this film completely intact, holes appear in the chromate film; as a result, those areas are subject to corrosion. Since the area corroding is then relatively small in comparison to the total anode and cathode areas, intense, rapid acceleration of corrosion may occur. Any inhibitor which suppresses corrosion by coating the anode must be maintained at a level sufficient to keep the film intact. Cathodic inhibitors, which are safer to use but less effective, coat the cathodic areas and suppress corrosion in that manner.

Since all serious corrosion occurring at normal temperature is electrochemical in character, it seems reasonable to insert an insulating barrier between the anode and cathode to eliminate corrosion by suppressing the flow of current. This method works out well in practice and is one of the best methods of protecting surfaces. Materials such as rubber, vinyls, and coal tar, which are very impermeable and have a low absorption of water and salt and a high electrical resistance, are used. They effectively suppress the flow of current over the surface of the metal and by this method eliminate corrosion.

Paint is the most-widely used method of suppressing the corrosion of structural steel. Corrosion is retarded by paint in a number of ways. These methods are adaptations of the procedure just described. One of these ways is through the formation of a mechanical barrier on the surface of the steel which excludes moisture and oxygen. Unfortunately no paint or similar material is completely impermeable to the passage of oxygen and water. As a result, even the best paints fail to protect steel, by eventually failing to prevent the passage of these corrosive agents.

Mayne (10) and others have shown that paint films will permit the passage of sufficient water and oxygen to permit uninterrupted corrosion of steel. The actual mechanism of the passage of the water through paint films is not known. It was long felt that the paint film was porous and that oxygen and water diffuse through the film. However, late studies (2) have shown that a properly pigmented and applied paint film does not contain any discrete pores large enough for molecules of gas or water vapor to pass through. The basic

principles that apply to the diffusion of fluids through permeable membranes seem to apply in the case of paints also. Therefore, it is easily understood why increasing the thickness of the paint film decreases its permeability. This has been found true in a number of tests and studies. Actual experience with coatings and paints supports this belief. When a paint or coating protects steel by acting as a mechanical barrier only, it is found generally necessary that either a very-impermeable membrane or film, relatively speaking, must be used, or else a very-thick film must be applied. Successful barrier-type coatings utilize both of these features. The excellent service of coal-tar enamels is believed to be due to the thickness at which they are applied and to the relative impermeability of the coatings. They usually are about  $\frac{3}{32}$  inch thick.

Good adhesion is another necessary fundamental property of coatings, if they are to be of value in protecting steel. Barrier-type coatings must have good adhesion to the substrate, otherwise the moisture and oxygen that penetrate the film will displace the molecules of the coating from the surface and rusting will take place at the interface. This rusting will continue to spread, undercutting the protective coatings, and before long the entire coating may be removed in large patches or sheets. A coating with good adhesion to a clean metal substrate will resist undercutting and separation from the metal, even though it has no rust-inhibitive properties.

A good priming paint for steel, in addition to having excellent adhesion and mechanical resistance to passage of corrosive agents, must have rust-inhibitive properties. Chromate pigments are used in paints to provide the same rust-inhibitive properties as chromate inhibitors. Salts such as sodium chromate or sodium dichromate are not of value as paint pigments, because they are too soluble. If used in paint pigments, they will effectively eliminate corrosion for a short period of time, but since they are very soluble in water, they will leach out of the paint film over a period of time, leaving a hole or discrete pore in the film which will permit the passage of water and oxygen. Once the chromate has all washed out, it will no longer protect the surface. However, chromate pigments are in use which are extremely resistant to leaching because of low solubility. Enough chromate ion does go

into the solution to act as an inhibitor for the amount of moisture which will penetrate the paint film. At the same time, not enough is dissolved from the pigment, under ordinary circumstances, to permit the paint film to become porous. This type of paint pigment is usually mixed with other pigments, such as iron oxide or extenders, to decrease permeability and, at the same time, to improve the mechanical strength of the film. This type of rust-inhibitive primer is effective in suppressing corrosion of steel. It should be properly formulated with a synthetic resin vehicle of sufficient wetting ability to properly adhere to the surface that is going to be coated. Linseed oil paints are relatively permeable to the passage of water and salt. For this reason they do not make a satisfactory primer with the comparatively soluble chromate pigments, such as zinc yellow (often referred to as zinc chromate). However, when the film is fortified by more-resistant synthetic resins, such as the alkyds or phenolics, the primer has sufficient impermeability to resist leaching for a long period of time. If these primers are going to be exposed for long periods of time to weather, high humidity, condensation, or immersion in water, they should be topcoated with comparatively impermeable paints.

Another type of protection is afforded by paints with the so-called sacrificial pigments. Sacrificial pigments can be incorporated into paint and are used in the case of the zinc-dust paints. Here, the paint must have a high concentration of zinc dust in order to be effective. This is believed to be due to the electrical contact that is necessary between the particles of the pigment. Zinc-dust paints will, in this manner, provide electrochemical protection to the steel if the steel is exposed at small discontinuities, such as breaks and scratches. However, such electrochemical protection will not extend more than a fraction of an inch from the coating.

It is well known that corrosion in alkaline solutions is less than in neutral or acidic solutions. Water solutions of a number of rust inhibitive pigments are slightly alkaline. The popular conception is that alkalinity is by no means the most-important criteria in the rust-inhibitive pigment. Red-lead pigment mixed with water gives a slightly alkaline reaction. When mixed with linseed oil and allowed to

dry, the film shows an initial acidic reaction. This acid reaction in the film gradually approaches neutrality. This acidity is not of the type commonly experienced in terms of inorganic acids, such as muriatic acid or sulfuric acid, but rather in terms of organic acids formed in the drying process of the linseed oil. Experimental work indicates that soluble hydrolysis products of certain lead compounds can inhibit the corrosion of steel. A more-simplified explanation for the corrosion-inhibitive properties of red lead is based on the fact that the lead pigment reacts with the oil fraction to form lead soaps. These soaps result in a dense, tough film of low water permeability. The result is that a film is formed which is rust inhibitive and, at the same time, acts as a good mechanical barrier to the passage of water and oxygen. The actual mechanism probably also involves the formation of thin oxide films and the anodic absorption of organic-acid molecules and soluble lead compounds.

Paint films may retard corrosion by interposing a barrier of high electrical resistance between the cathode and the anode. Vinyl films for example, have high electrical resistance. It has been found that when such paints fail, the electrical resistance decreases greatly; their resistance is decreased by diffusion of sodium chloride through paint films.

In summation, it might be said that a suitable metal-protective paint must be one with rust-inhibitive properties, low permeability to corrosive agents, low absorption of water, high dielectric resistance, and the ability to wet the surface to which it is applied. All of these properties are not essential to any one particular coating; however, most successful coatings are those that have a majority of these properties. The mechanism and principles by which paints retard corrosion are discussed by Evans (4), Jordan (9), Mayne (10), and Elm (3).

#### PAINT FAILURES AND THEIR PREVENTION

The minimizing of paint failure is not difficult provided the underlying causes of corrosion and paint failures are understood. Then, good painting practice coupled with common sense and practical experience will serve to reduce the probability of failure to a remote chance. A few years ago the Steel Structures Painting Council was organized to prevent

the costly, premature paint failures which were occurring on numerous bridges and other structures. During the past three years the council has been active in studying present good practice in cooperation with a number of technical associations. The results of their findings in regard to what constitutes present good practice and what should be done to minimize paint failures are now appearing in the form of a series of specifications dealing with surface preparations, pretreatments, paint application, paints, and complete paint systems. A summary of present good painting practice has been published in the *Steel Structures Painting Manual (1)*. The essential features of those findings will be summarized in concluding this paper.

Typical conditions on a badly neglected painted bridge are illustrated in Figure 7. Note that the knee brace on the left has been distorted by rust forming in the joint between the upper end of the angle and the steel plate. Proper design of steel structures should eliminate the possibility of water entering such joints and developing sufficient pressure from rust to spread the joint. The paint has been allowed to deteriorate through lack of maintenance to the point where extensive and expensive preparation of the surface to remove rust and the residue of old paint is necessary. This expensive repainting could have been prevented by a minimum amount of maintenance based over a number of years. A serious loss in thickness of the web of the plate girder has occurred at the floor line where the wet accumulation of dirt has set up electrochemical cells.

All paints fail eventually; a paint failure is a premature termination of the useful life of the paint. The most outstanding factors which govern the performance of paint are: (1) proper design of the structure to be painted; (2) proper surface preparation; (3) correct application of paint; (4) use of paint materials which are properly formulated and capable of performing the required service.

Design has already been touched on briefly and will not be discussed in detail, since it is beyond the scope of this discussion. Surface preparation, however, is believed to be the most important of the factors involved. It has often been said that three fourths of the life of the paint is determined by the surface preparation. The effect of surface preparation

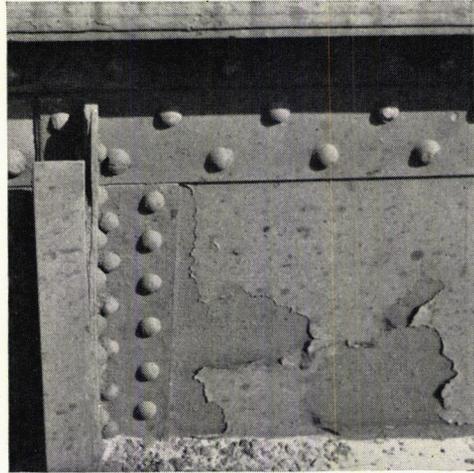


Figure 7. Example of paint failure occasioned by delaying painting too long and by improper design, which permits rust to form in the knee brace between the angle and the plate.

TABLE 3  
EFFECT OF SURFACE PREPARATION ON THE DURABILITY OF PROTECTIVE PAINTING SCHEMES

Surface Preparation	Durability, years	
	4-Coat Scheme (2 coats of red lead paint and 2 coats of red iron oxide paint)	2-Coat Scheme (2 coats of red iron oxide paint)
Intact mill scale .....	8.2*	3.0
Weathered and wirebrushed .....	2.3	1.2
Pickled.....	9.5*	4.6
Sandblasted .....	10.4	6.3*

\* Indicates that at the most recent inspection the painting scheme had not failed on all the surfaces concerned.

on the durability of paint is clearly shown in Tables 3 and 4, reported by Hudson (7, 8).

Pickling or sandblasting lengthens the life of paint many times over the life on rusted or weathered steel. Weathered surfaces, even though wire-brushed, are extremely poor surfaces to paint. Intact mill scale, when painted with a rust-inhibitive priming paint and suitably top-coated, lasted almost as long as on pickled or sandblasted steel. But when the intact mill scale was not protected with a rust-inhibitive primer it lasted only about a third as long. The second table brings out the interesting fact that a micaceous iron ore paint

TABLE 4  
METHOD OF SURFACE PREPARATION FOR  
PAINTING

Painting Scheme (Two coats)	Life of Painting Scheme, years		
	Over Weather- ed Surface	Over Pickled Surface	Over Weather- ed and Heated Surface
Black bituminous.....	2.6	13.1*	2.2
Lead chromate.....	2.7	14.5*	7.5
Micaceous iron ore.....	0.6	15.0	0.6
Red lead.....	1.1	13.1*	5.9
Red oxide.....	1.8	8.1*	2.8
Red oxide and zinc chromate.....	3.7	9.6*	5.3
White lead.....	2.2	7.0	1.7
Average.....	2.1	11.5	3.7

\* Back surface had not failed after fifteen years' exposure.

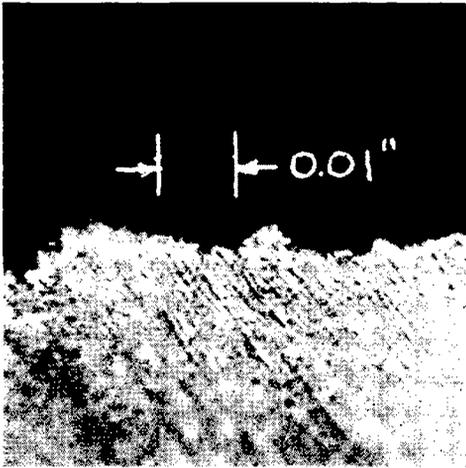


Figure 8. Excessively roughened surface anchor pattern profile caused by grit blasting with too-large abrasive.

lasted on weathered steel surfaces only 0.6 years but on a pickled surface, even without a rust-inhibitive pigment, it lasted for 15 years.

These results show that complete removal of mill scale results in better performance of paint. Because of the excessive cost of complete removal of mill scale, it is often economical to paint over the scale. This practice is successful if the atmosphere in which the steel is to be exposed is not unduly corrosive, but extremely careful cleaning of the surface is necessary to remove all cracked, loose, and broken scale. The exceedingly detrimental effect of rust is shown in the preceding tables, and it is imperative that rust be removed

down to sound metal before painting. It is possible, however, to paint over slight residues of rust which are almost impossible to remove by methods short of blast cleaning or pickling, provided primers with good wetting power are used. These are, without exception, slow drying.

The anchor pattern produced by the surface preparation must be conducive to good paint adhesion and bonding. Solvent cleaning improperly done may leave a residue of oil and grease in a thin film over the entire surface. Such a residue interposes a nonpolar layer between the polar metal surface and the paint; a decrease in the attractive force between paint and surface results. If the film is thick, there may be a complete lack of paint adhesion. Excessive power wire-brushing may burnish the surface to be painted, particularly in the case of mill scale, to the point where paint cannot properly adhere to the surface. Power tools, such as rotary descalers, chipping hammers, and scalers, may leave sharp ridges in the metal surface which cannot adequately be coated with paint. This same danger exists when blast cleaning with large abrasives. Excessive grit size produced the 10-mil anchor pattern illustrated in Figure 8. The peaks produced are sharp, and it is almost impossible to obtain adequate film thickness of conventional paints over the peaks. Pin points of rust soon appear over the peaks and accelerate failure of the paint. Pickling operations may leave residues of hydrochloric or sulfuric acid on the metal surface, unless properly rinsed and passivated. These residues of free acid will react with the metal to form sulfates and chlorides, but the residual salts are strong stimulators of corrosion. Human sweat is another strong stimulator of corrosion, and hand prints on clean metal surfaces may cause localized paint failure and corrosion.

Closely coupled with the surface preparation are pretreatments of the surface which are used to further reduce the possibility of paint failure. Cold phosphate and hot phosphate treatments are used to convert clean, rust-and-scale-free steel surfaces to insoluble, crystalline layers of iron and zinc phosphate. The resulting phosphate has an increased corrosion resistance because of its relative inertness and high electrical resistance. These crystalline surface-conversion coatings also improve paint performance by forming a good surface anchor

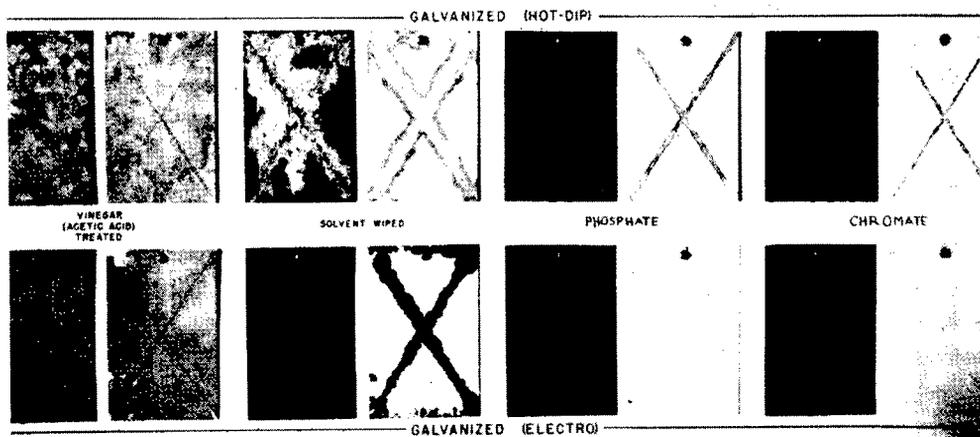


Figure 9. Paint will stick to properly prepared galvanized iron as illustrated here. Panels on the left were treated with vinegar (acetic acid) and also by solvent wiping. Panels on the right were treated by phosphate and by chromate solutions. The white panels were primed with a white enamel and baked. Black panels were primed with black automotive enamel and baked. The panels were exposed for 100 hours to salt spray except those which were treated by vinegar, which were exposed for only 25 hours.

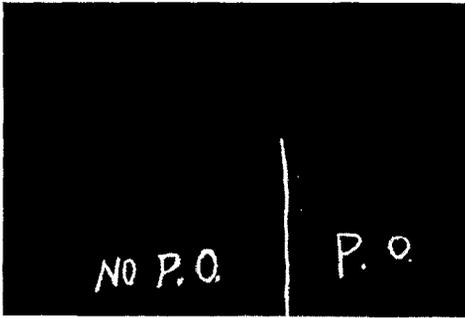
for the coating. Because the surface is uniform, local corrosion through dissimilar surface conditions is minimized.

Galvanized iron and steel show frequent paint failure. The failure is due to poor adhesion of paint. A host of nostrums and home remedies have been advanced as pretreatments for galvanizing. Practically all of these have little merit, and many of them are dangerous because they cause destruction of the zinc. The phosphate pretreatments convert the surface of galvanizing to a satisfactory paint anchor. Figure 9 illustrates the effect of phosphate and chromate pretreatments of galvanized metal. Similar results are obtained on plain steel. Note the great improvement in paint adhesion and performance of the chromate and phosphate pretreatments over solvent wiping or treating with vinegar. Wash-primer pretreatment is another effective method of improving adhesion of paint to galvanized metal. The only conventional paints which have shown merit in painting over new, galvanized metal without pretreatment are the zinc-dust-pigmented primers. In the event pretreatment is not feasible, it is necessary that galvanizing be weathered for periods of at least 6 months prior to painting, unless zinc-dust primers are used.

The wash-primer pretreatment improves adhesion of paint to metal and improves the performance of paint. It should be applied

over scale- and rust-free metal. Again, as in the case of blast cleaning or pickling, the advantage to be obtained in the use of these pretreatments must be weighed against the increase in cost. For mild atmospheric exposure conditions, where ordinary cleaning and painting methods have proved feasible, it is difficult to economically justify the increased expense of pretreatment.

Cracked and broken mill scale has been shown to be a poor base for paint. Even when cleaning is conscientiously carried out, a certain amount of mill-scale lifting and localized paint failure is almost inevitable. This may not be serious, and economical protection of the steel may be obtained if spot maintenance of the paint system is undertaken at the necessary times. After a period of time, the surface should become stabilized with no further mill scale lifting. Badly cracked and broken mill scale should be removed prior to painting. In the event this is impossible, a wetting-oil pretreatment is advantageous. Figure 10 shows the improvement obtained by using a penetrating (wetting) oil prior to painting. The paint used was a good structural-steel primer with moderate wetting ability for rusty, dirty surfaces. The wetting oil is believed to have saturated the surface and sealed the cracks in the mill scale and thus prevented rusting. Without the pretreatment, the paint did not have sufficient



**Figure 10.** The effect of using a wetting or penetrating oil is shown. Note the improvement in performance after a year of exposure of a high-quality structural-steel primer on a mill-scale-covered tank in which the mill scale was cracked in fabrication.

reserve of oil to saturate the surface and still maintain the necessary balance between pigment and vehicle. Wetting-oil pretreatments are sometimes used when quick-drying primers are specified so that adhesion of the paint to insufficiently cleaned surfaces is improved.

Application of paint is second in importance to surface preparation in determining the service life to be expected of a paint system. Perhaps the most-important and most-essential feature of good application is to obtain adequate film thickness. Improper thinning of paint makes it difficult, if not impossible, to obtain adequate thickness. Thinning decreases the viscosity, makes the paint easier to apply, and increases coverage; therefore, there is frequent, detrimental overthinning of paint. Paint should be applied at the viscosity recommended by the formulator or manufacturer of the paint. It will generally be procured at the proper viscosity for brush application. Spraying may require further dilution with thinner, but large amounts are seldom required. Most paints that are of satisfactory viscosity for brushing may be applied by spray. In cold weather the viscosity of paint increases, brushing is hard work, and painters add thinner. A dry paint film of too low thickness results. In cold weather, paints should be warmed prior to use rather than thinned.

Since paint-film thicknesses is the most critical factor of application, it should be checked carefully. Two methods are available for checking thickness. The first is to compute the dry film thickness based upon the coverage

obtained in square feet per gallon after making due allowance for paint losses. The second method is to utilize paint-film-thickness meters. Two types are available; the wet-film-thickness gauge, which permits paint to be checked for thickness immediately upon application, and the dry-film-thickness gauge. Priming coats of paint for steel structures should have a minimum of  $1\frac{1}{2}$  mils of paint per coat; 2 mils are more desirable and often possible. Intermediate and finish coats should have a minimum of 1 mil, and  $1\frac{1}{2}$  mils are preferable. Unconventional paints such as the lacquer type or the thick bituminous coatings obviously do not fall within these ranges. Sufficient coats of paint should be applied so that at least 4 mils of dried paint are obtained, while 5 mils is considered to be more desirable.

The other factors of application which affect paint performance are well known and will not be gone into in detail. The first detailed guide for adequate inspection of cleaning and painting only recently has been published; it is *Good Painting Practice (1)*.

The surface should be clean and dry when painted. If some time has elapsed since cleaning, the surface should be checked to make sure that no further deposits of dirt or other contaminants have occurred. If the surface is blast-cleaned or pickled, painting should take place prior to the formation of any rust on the surface. Great care should be exercised that contaminants and corrosion stimulators, salts, dew, etc., should not contaminate the surface prior to painting or between coats of paint.

Painting should take place in dry weather with the relative humidity lower than 85 percent and the temperature above 40 F. The surface should be at least above the freezing point of water and should be dry. Painting should not take place when rain or snow is imminent. If there is danger of freezing before paint is dry, then painting should be delayed.

Preceding coats of paint should be dry before further coating. There is, however, a danger of the paint becoming too dry for satisfactory repainting. Fresh linseed-oil paints, upon drying too long, may be difficult to wet with subsequent coats of paint, and crawling may ensue. Crawling is the gathering of paint with exposure of unwetted substrate. Phenolic paints are notorious for drying too hard for satisfactory recoating. Poor adhesion of subsequent coats results. When paints are too dry

and hard for satisfactory recoating the surface should be lightly abraded with fine steel wool, sandpaper, or rubbed with rags wetted with solvent. The addition of powerful solvents such as methyl isobutyl ketone or cellosolve to subsequent coats of paint has been advantageous in promoting adhesion under these circumstances. However, care must be exercised that the added solvent does not act as a paint remover and lift the preceding coats of paint.

Proper drying conditions are advantageous in obtaining long paint life. Obviously it is difficult to control drying conditions in the field. However, in shop painting of steel, drying conditions can be better controlled. Where possible, paint should not be exposed until it is dried thoroughly. If painted steel is to be immersed in water, the longer the paint is dried before immersion, the better the service that results.

Finally, the paint itself will be considered. The first requirement for a paint system is that the material be adequate to perform the services expected in the environment and on the type of structure to be protected. A suitable selection must be made of primer, intermediate, and topcoats. The primer must have the correct pigments for inhibiting corrosion; the vehicle must have sufficient wetting ability to develop proper adhesion to the type of surface being painted, and *this factor is critical in deciding paint performance*. If the primer is used as a shop coat, it must be capable of protecting the steel from the time of shipment to the time it is erected and field coated. For large bridges or structures, this condition imposes a terrific burden upon the shop coat. Despite the fact that the shop coat may apparently have successfully withstood this preliminary exposure, it may be badly deteriorated and an unsatisfactory base for the subsequent coats of paint. Only the highest quality paint should be considered as a shop coat under these circumstances.

When field coating or finish coating takes place at relatively short periods after the priming, the primer need not have as great weather resistance. The second coat of paint should be one which has some degree of rust-inhibiting properties, but it should also have inertness and increased resistance to the passage of water and oxygen. Since it must wet only the primer, the wetting characteristics

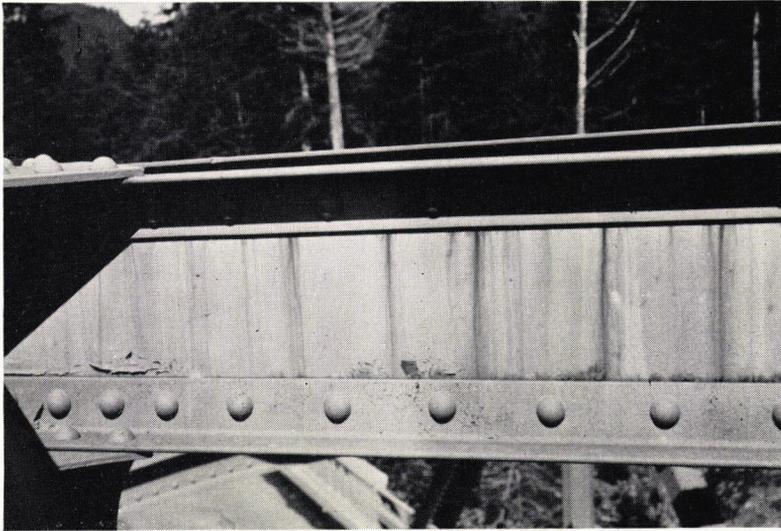
need not be as strong as those of the primer; faster-drying synthetic paints are generally satisfactory. The paint then has improved durability.

The outer coats of paint must be pigmented so that the color retention is good when color is important. They must be inert to the atmosphere in which they will be exposed and must serve to protect the paint system from the effects of ultra-violet light and the weather.

The vehicle obviously must be one which will have long durability in the environment to which it is exposed. If this environment is rural or marine atmosphere, then linseed oil, alkyd, or phenolic paints are adequate. If the environment is a strong chemical one, then oleoresinous paint may be completely unsatisfactory and synthetics such as vinyls, chlorinated rubber, or epoxys may be necessary, or inerts such as bitumen may be required.

Typical failures are illustrated in Figure 11, showing the upper lateral of a highway bridge. Rust stains are showing from rust which has formed in the upper joint. These should have been made so that the joints were tight, or else the cracks should have been sealed during the painting operations. Paint is scaling at the joint along the edge of the lower angle with the web due to poor coverage of paint in this interstice. Peeling and flaking of paint is occurring on the center and left side due to poor adhesion of paint. This poor adhesion may have been caused by many reasons.

Loss of adhesion is perhaps the most-prevalent type of premature failure of the paint itself. Paint adhesion to clean metal surfaces has been discussed; blast cleaning or roughening of the surface increases the total surface area and therefore the total adhesion. Excessive thinning of paint has one advantage; it improves the adhesion of paint to the metal surface. Under difficult painting conditions, excessive thinning with a high-boiling thinner, such as kerosene, may sufficiently improve the adhesion to make the addition of an extra coat of paint to obtain the required film thickness economical. This type of treatment is similar to the wetting-oil treatment. In fact, wetting oils are often added to paint primers to improve adhesion. When steel is immersed, the excess alkalinity which occurs at cathodic areas saponifies oil-containing paint and may completely loosen the paint film. The problem of intercoat adhesion of paints is one that re-



**Figure 11.** Rust stains from rusting in joints of upper laterals. Failure of paint on web and lower angle is due to poor coverage of the joint along the edge of the lower angle, while blistering and flaking on the center and left is due to poor adhesion of paint.



**Figure 12.** Blistering.

quires specialized knowledge and advice. It is best to avoid such complications by following the recommendations of the paint manufacturer.

The second-most-prevalent type of paint failure is corrosion at discontinuities in the coating. Holidays, skips, breaks, scars, and other gaps in the coating system cause anodic areas where corrosion may occur. If the structure is exposed in a very-corrosive environment or immersed in an electrolyte, rapid cor-

rosion may occur with perforation of the metal. Rusting, which begins at breaks in the coating, tends to undercut the coating and thus spread. While it is almost impossible to avoid all discontinuities in a paint system, they may be kept to a minimum by good application technique. The greater the number of coats of paint, the lower the probability of discontinuities overlapping with areas that receive no paint protection whatsoever. Strip painting of edges, crevices, filets, rivets, etc. is recommended.

Blistering is a frequent type of paint failure which occurs on steel immersed in water or exposed to high humidity and condensation. Blistering is illustrated in Figure 12. In this case the blisters are filled with water. Rusting usually accompanies blistering, but some paints have sufficient inhibitive powers to almost eliminate rust in the blisters. Blistering is often caused by the use of primers with slightly soluble pigments in fresh water. Osmotic pressure drives water through the semipermeable paint and causes blisters. This situation occurs to a lesser degree in salt water because of the dissolved salts. Blistering may also be caused by solvents which are trapped in a paint film by drying of the outer surface of the paint. Hydrogen is often ab-

sorbed in steel and occasionally causes blistering. Blistering caused by immersion in water may be minimized by utilizing the less-soluble pigments or using impermeable paints. The very-permeable paints also do not blister, since the water easily escapes through the paint.

Typical failures of paint films are illustrated in Figures 13 to 16; they include checking, alligatoring, cracking, flaking, scaling, peeling, lifting, wrinkling, and chalking.

*Checking* is the slight breaking in the paint film in which the breaks do not penetrate to the underlying metal. *Alligatoring* is the pronounced wide cracking that develops over the entire surface. These, as in the case of checking, do not penetrate to the underlying surface. *Cracking* is the breaking of paint film in which the cracks extend to the underlying surface. These types of eventual film deterioration should be considered as paint failures only when the paint has failed to give its expected service. These failures are caused by stresses which develop gradually during the drying and aging period of the paint. When these stresses inside the paint film exceed the strength of the film, fine cracks form which then develop into alligatoring or cracking. Premature paint failure of this type may be minimized by avoiding the application of excessively thick coats of paint, particularly those that dry on the surface very rapidly, and by avoiding the application of topcoats before the undercoats are properly dry for recoating. The application of hard-drying, short-oil topcoats over oil primers or long-oil-resin primers is a source of failure in this regard.

*Flaking* is actual detachment of pieces of the dry paint film either from the underlying metal or from paint previously applied. Flaking is generally preceded by cracking or checking and results from loss of adhesion. Flaking is a term usually reserved for the failure when the pieces that are detached are less than  $\frac{1}{4}$  inch in diameter. *Scaling* is a more severe form of flaking in which the loosened pieces of paint are larger. *Peeling* is an aggravated form of failure similar to flaking and scaling.

*Lifting* is a softening and expansion of the paint by the solvents of a newly applied paint. It generally results in a wrinkling, raising, or lifting of the paint so that it is easily removed from the surface. When lifting occurs, the paint system that is used should be examined

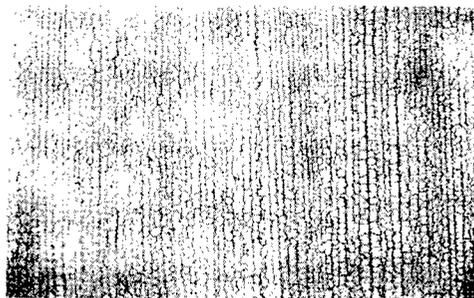


Figure 13. Checking.

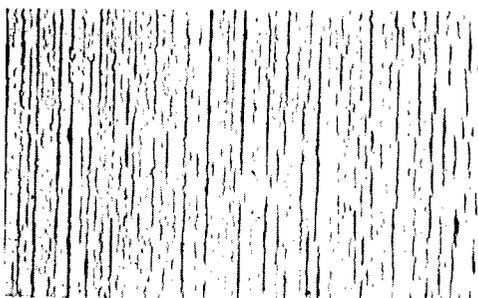


Figure 14. Cracking.



Figure 15. Flaking.

carefully to determine whether an improper choice of the coat of paint that is doing the lifting was made. In the event that it is necessary to use paints with strong solvents as outer coats, then barrier coats must be utilized between the paints that will be lifted and the outer coats. These barrier coats may be shellac

or resins soluble only in alcohol. Lifting may be minimized by utilizing oxidizing type of primers which are permitted a long time to dry before recoating.

*Wrinkling* is the formation of furrows and ridges in the surface of a paint. It occurs because the surface dries more rapidly than the underlying portion of the paint film or because preceding coats of paint have not completely dried. Wrinkling is minimized by applying the paints in thin coats, by proper choice of drier in the paint, by permitting undercoats to dry thoroughly before applying succeeding coats, and by correct formulation of the paint.

*Chalking* is the forming of a loose powder evolved at the surface of the paint or just beneath the surface. It may be detected by rubbing the film with tips of fingers or a piece of black cloth. Chalking is a natural condition, and it occurs because of the decomposition of the outer layer of paint exposed to the weather. The degree of chalking may be controlled by proper choice of pigment and vehicle. Paints may be made to chalk more rapidly where it is desired to gradually remove the paint film during its service life. This has two advantages. In the first place, light-colored paints are kept bright and clean in appearance. Secondly, it tends to avoid the excessive build up of dry paint films. Dried paint films continue to undergo stress and strain during aging. After a period of time, when the dry-film thickness becomes excessive, they tend to become brittle and crack and flaking follows. When this condition develops, extensive repair work is necessary to properly prepare the old surface for repainting. Often complete removal of the paint becomes necessary.

In summing up this discussion on the prevention of paint failures, it is desirable to say a few words concerning proper maintenance of paint systems. To obtain the most-economical service out of paint systems it is almost always desirable to maintain the integrity of the paint system by frequent spot cleaning and repainting. If local breakdown occurs, this type of cleaning and painting reduces the spread of rust and maintains the appearance at low cost. When the underlying metal is stabilized and no further rusting or breakdown of the paint takes place, gradual erosion of the outer paint film occurs. If contrasting colors of paint are used in the system, the degree of erosion of the finish paints may be followed by color changes

in the system. When it is apparent that the outer coat of paint is wearing thin, then it is time to protect the investment in the cleaning and priming by applying at least one additional coat of paint. If this is done at frequent intervals, one coat of paint is adequate. At the same time, appearance is maintained at the highest level at the lowest cost. When it is extremely expensive to repaint because of staging or because it is extremely costly to take a structure out of service for cleaning and painting, then it may be advantageous to get the maximum life out of a paint system even though spotty corrosion occurs. Under this system of painting, complete cleaning and painting occurs at every repaint.

In conclusion, economical protection of steel structures is possible by means of paint although in some cases the value of the appearance must be taken into consideration in justifying the expense. A knowledge of the fundamentals of corrosion and the mechanism of protection by means of paint will help to minimize the probability of paint failure. Much of the material contained herein is from the manual previously referred to (1). A valuable source of theoretical and practical information is the book by Speller (12); an outstanding text on paint failures has been written by Hess (5).

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## Hydraulic Theory for Design of Storm-Water Inlets

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THE capacity of many storm-water inlets can be found by comparing the flow into the inlet with the flow into a wide opening. In this manner, formulas are derived for the design of curb-opening inlets without gutter depression, grate inlets, and combination inlets, with or without gutter depression. The formulas have been substantiated with numerous test data.

The characteristics of other types of inlet are also mentioned. It is found that the most-efficient types are the combination inlet and the grate inlet. In both cases, the grate should have only longitudinal bars. When the street grade is steep and gutter depression is considered undesirable, a curb opening with diagonal notches in the gutter may be used.

● A RESEARCH project in the Johns Hopkins University is being sponsored by Baltimore City, Baltimore County, and the Maryland State Roads Commission to investigate problems of storm drainage. The work is being done under the direction of the Department of Sanitary Engineering with the cooperation of the Department of Civil Engineering. Of the many problems in the program, one subject of study is the capacity of storm water inlets. Four papers on the subject have been published (1, 2, 3, 4) and a booklet (5) is to be published shortly. In this paper, the comparative merits of different

types of inlet are discussed, and formulas for the capacity of several types of inlet are derived. The derivation is released for publication for the first time and is believed to be helpful to highway engineers in understanding the hydraulic behavior of inlets.

The derived formulas for inlet capacity have been substantiated with numerous test data from models of 1-to-2 and 1-to-3 scales. The model results have also been checked with tests in the field. For the description of the model and the experimental data, the reader is referred to the references at the end of this paper.