

## 3.7 DESIGNING AGAINST CORROSION

### 3.7.1 INTRODUCTION

In recent decades, attention has focused on body corrosion in automobiles, and significant advances have been made in the number and sophistication of corrosion-protection systems and techniques. This section examines some of the major environmental causes and categorizes the various types of corrosion that result. It highlights the broad range of countermeasures now available and briefly explores future needs.

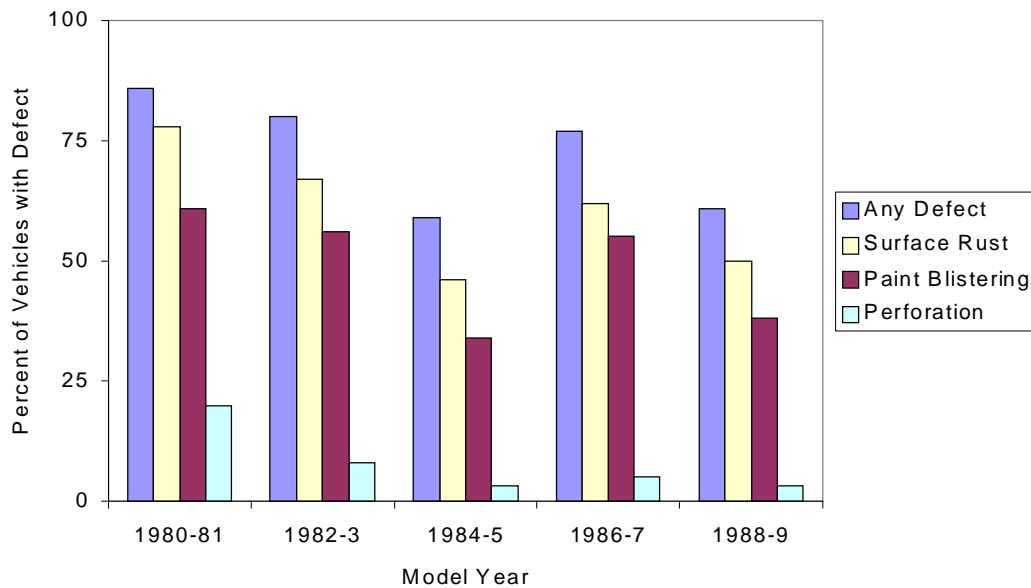
#### 3.7.1.1 Background

The automotive and steel industries have a long history of cooperative efforts, which have steadily improved the North American passenger vehicle. Some 50 years ago, car makers sought greater strength and durability in their vehicles and the steel producers responded by cold rolling very wide sheets of low-carbon steel, which opened the way to the greater safety of all-steel bodies. Later, better drawing steels were developed to accommodate designs with more complex body panel and fender shapes. More recently, steel producers expanded their offerings of higher-strength steels to shed pounds cost-effectively from components and assemblies for improved vehicle fuel economy.

Currently, the adoption by the major producers of high-technology methods of steel making, rolling, and annealing have resulted in the production of sheet steels with much more consistent properties.

Other cooperative efforts also have been undertaken. As road salt usage climbed in the United States and Canada, vehicle damage from corrosion increased. The auto industry and its suppliers responded with design changes and improvements in the materials used. These efforts began with galvanized steel rocker panels in the late 1950's, expanded to a broad range of coatings for other vulnerable components, and achieved an important turning point in vehicle corrosion protection. The cooperative efforts will continue as gains already achieved ([Figure 3.7.1.1-1](#)) form the basis <sup>1,2</sup> for further improvements and for "fine tuning" of protective systems and techniques through more selective - and more effective - use of each.

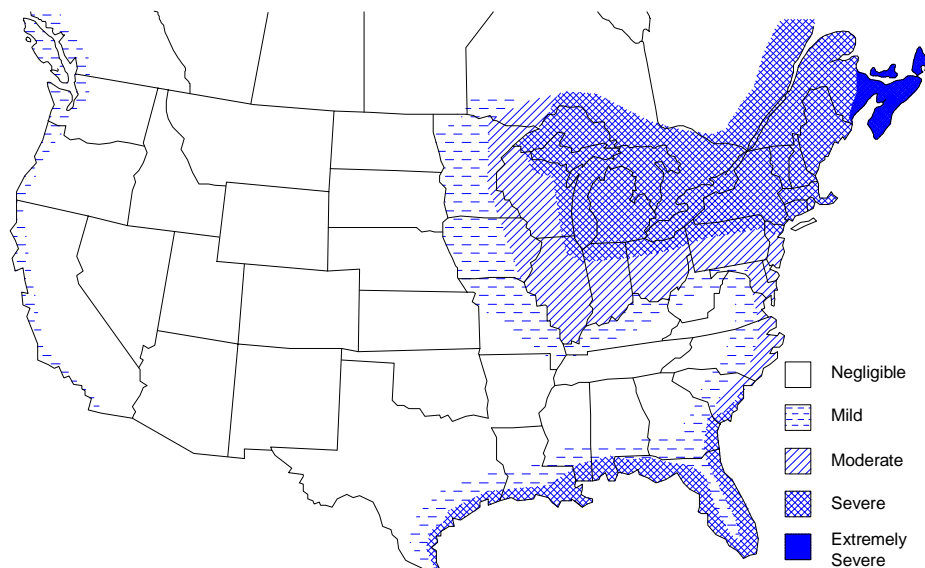
### 1995 SAE Parking Lot Survey Results



**Figure 3.7.1.1-1** Corrosion of automobiles as determined by SAE parking lot surveys, showing the decrease in corrosion of cars accompanying the increasing use of coated sheet. (Plotted from data given in Reference 1)

#### 3.7.1.2 Defining the Problem

Corrosion menaces most vehicles in the US and Canada to varying degrees. The worst car body and chassis damage occurs in the "salt belt" (Figure 3.7.1.2-1)<sup>3</sup>, an area that surrounds the Great Lakes and loops eastward through the northeastern states and the Canadian provinces of Ontario, Quebec, and the Maritimes.



**Figure 3.7.1.2-1** Vehicle corrosion environment in Canada and the United States

In this international zone, roughly 10 to 20 million tons of salt are applied to roads and streets each winter to depress the melting point of ice and snow and keep these thoroughfares open for traffic<sup>4</sup>. More judicious spread rates per mile have been offset by additional roads being de-iced. Today, motorists expect bare pavement all year round.

Vehicle corrosion results when lower body panels and under-vehicle components are exposed to road slush containing the de-icing chemicals<sup>5</sup>. The causes of corrosion, however, are not limited to wintertime activity, nor are they confined to vehicles driven in the "salt belt". Long after the snows have gone, dormant deposits of road salts on these vehicles can renew their corrosive action when rewetted by spring rains and road splash. While corrosion also occurs in vehicles in other northern states, damage usually is less severe where winter temperatures normally are too low for effective use of de-icing chemicals.

Alternative chemicals to sodium chloride are being evaluated to reduce the corrosion caused by highway de-icing salts, but they are more costly<sup>6</sup>.

Other environmental causes of corrosion across the country cannot be ignored. For example, air pollution in industrial centers poses a threat, particularly where levels of sulfur dioxide<sup>4</sup> and chloride are high. Dust control procedures<sup>7</sup> on rural roads also add to the threat in summer. And in coastal regions, year-round exposure to salt-laden spray, mist, and other airborne chemicals in combination with high humidity also can produce corrosion damage.

### **3.7.2 TYPES AND FORMS OF CORROSION**

Vehicle corrosion assumes several different forms or types, causing damage that ranges from minor to severe. An important first step in defining and dealing with the overall problem is to classify the several forms of corrosion attack and to qualify their effects.

#### **3.7.2.1 Uniform Corrosion**

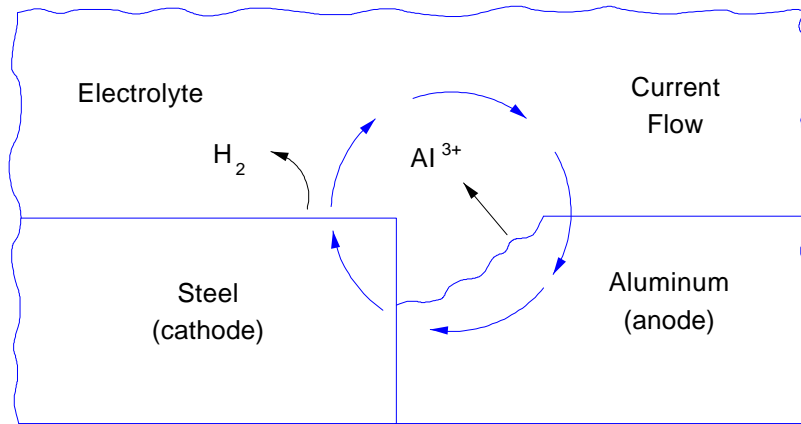
Uniform corrosion proceeds evenly over the entire exposed surface of an uncoated part and eventually causes a general thinning of the metal. It is the best known type of corrosion, but also is the least damaging. In automotive applications, uniform corrosion usually is not related to perforation or structural damage.

#### **3.7.2.2 Galvanic Corrosion**

Galvanic corrosion, sometimes referred to as two-metal or bimetallic attack, occurs when dissimilar metals are in contact in the presence of an electrolyte. The more active, or anodic, metal corrodes rapidly while the more noble, or cathodic, metal is not damaged. On the galvanic scale, aluminum and zinc are more active than low-carbon steel and, in the presence of a chloride-containing electrolyte, will corrode preferentially when in contact with steel ([Figure 3.7.2.2-1](#))<sup>8,9</sup>.

This form of corrosion has had a strong influence on limiting the use of aluminum in automotive applications that would be in direct contact with steel. To prevent an aluminum-to-steel contact, isolating techniques, such as nonconductive or barrier type spacers or sealers, are required.

The galvanic corrosion mechanism also can be turned into a benefit and it is widely employed as the primary protection system for steel. A thin zinc or zinc-alloy coating on steel will corrode preferentially and this sacrificial action provides long term protection for the substrate.

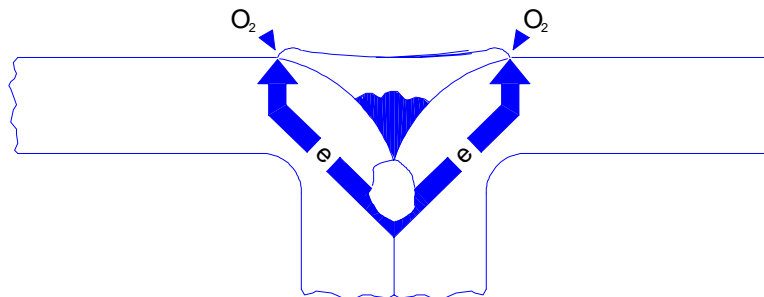


Galvanic corrosion occurs when two metals of dissimilar activity are placed in contact with one another in the presence of an electrolyte. The more active metal will react anodically and corrode in preference to the less active metal which, as the cathode, is protected.

**Figure 3.7.2.2-1** Galvanic or bimetallic corrosion

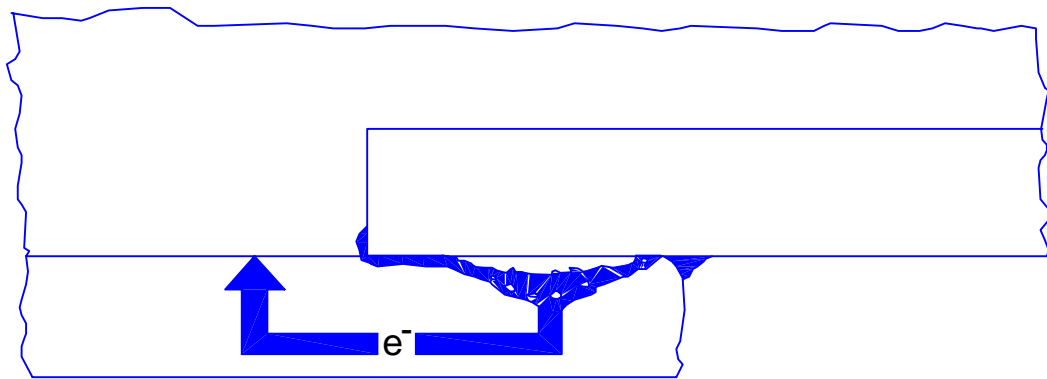
### 3.7.2.3 Crevice Corrosion

Crevice corrosion is the most damaging type encountered in the automobile because it's sharply focused on localized areas and usually is invisible in its early stages. The attack is swift, often resulting in unexpected or premature failure. Crevice corrosion attack is usually associated with small volumes of stagnant solution or electrolyte trapped in holes, on gasket surfaces, at joints ([Figure 3.7.2.3-1](#) and [Figure 3.7.2.3-2](#))<sup>8</sup> under fasteners, and in surface deposits or poutices ([Figure 3.7.2.3-3](#)).<sup>8</sup>



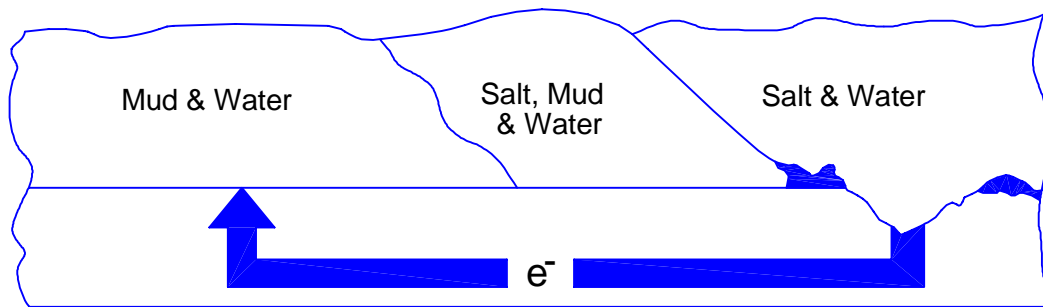
Crevice corrosion is caused by a gradient between the oxygen at the surface of the electrolyte and oxygen-starved electrolyte at the bottom of the crevice. Typical of weldments, sheet-metal joints, and rough surfaces where water may be trapped, the oxygen gradient also causes a rough microfinished surface to corrode faster than a smooth surface.

**Figure 3.7.2.3-1** Crevice corrosion at weld joint



Crevice corrosion also can occur between tightly sealed joints where the concealed metal surface is oxygen starved and electrolyte may seep between irregularities in the mating surfaces. This condition also occurs where moisture-bearing materials (such as felt) are in contact with the steel.

**Figure 3.7.2.3-2** Crevice corrosion at lap joint

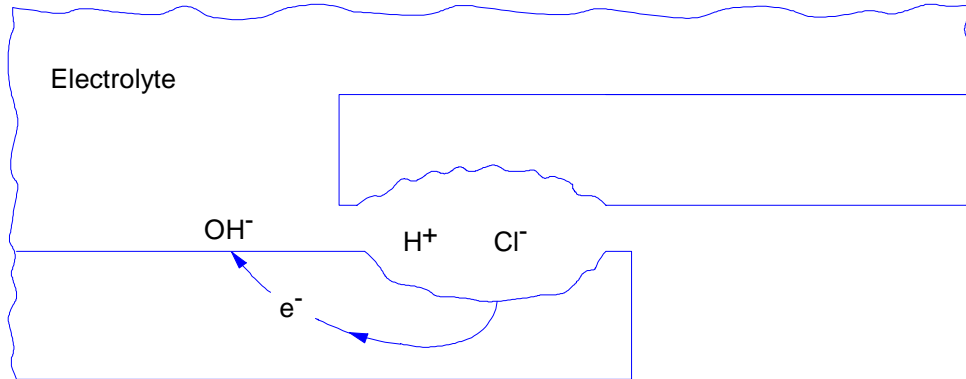


Electrolyte composition gradients are probably the most common cause of corrosion. Clumps of mud frequently collect under car fenders. The varying concentrations of salt and water encourage corrosion.

**Figure 3.7.2.3-3** Poultice corrosion

The mechanism of crevice corrosion will depend upon the type of metal and the conditions of exposure. Sometimes crevice corrosion can be explained on the basis of differences in metal ion concentration between the crevice and surrounding surfaces. Often, it is described as oxygen concentration cell corrosion, caused by oxygen availability at the surface of the electrolyte and oxygen starvation at the surface of the metal.

Other studies<sup>10,11</sup> have shown that although metal ion and oxygen concentration differences exist, the corrosion mechanism is more complex and can be explained by acid formation within the crevice. Although oxygen is depleted in the crevice, metal dissolution continues because the excess of positively charged metal ions is balanced by the migration of anions (especially chloride ions) from the bulk solution into the crevice (Figure 3.7.2.3-4).<sup>8</sup> The metal chloride concentration in the crevice increases. Hydrolysis of the metal chloride follows and the pH falls to approximately 3 within the crevice<sup>12</sup>. This sets up an autocatalytic anodic process in shielded areas.



Crevice corrosion showing acid formation and increased chloride ion concentration within the crevice.

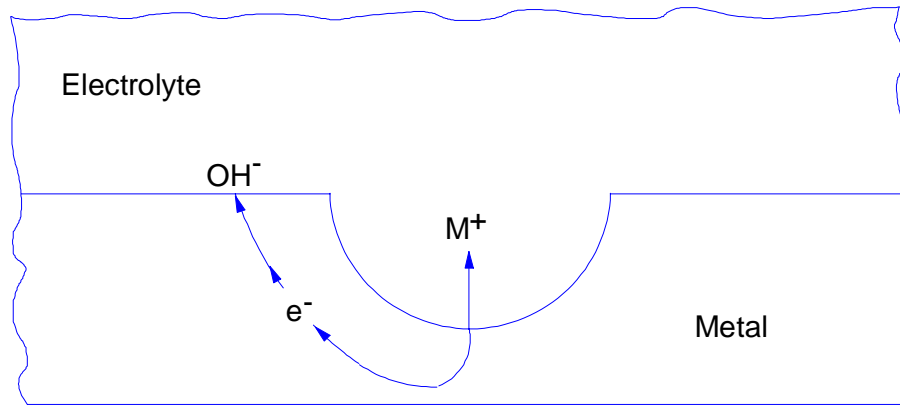
**Figure 3.7.2.3-4** Crevice corrosion at lap joint

Crevice corrosion remains a major problem because of current unitary manufacturing techniques where the body is a mass of box sections and joints<sup>13</sup>. It is almost impossible to eliminate the minute cracks between joined surfaces that are prime sites for crevice attack. The severity of crevice corrosion is evidenced by widespread inner-vehicle and under-vehicle corrosion and its resulting perforation of body panels and chassis components. This is caused by mud packs or pultices in a predominantly chloride medium.

Metals or alloys that rely on passive layers or oxide films for corrosion protection, for example aluminum alloys and stainless steels, are particularly susceptible to crevice attack in chloride media. The high concentration of chloride or hydrogen ions destroys the films, resulting in increased metal dissolution rates. These materials can be alloyed to improve their crevice corrosion resistance. In addition, designing to minimize crevices and maintenance to keep surfaces clean are used to combat the problem.

### 3.7.2.4 Pitting Corrosion

Pitting corrosion is a localized attack, usually caused by chlorides. The mechanism governing pit growth is similar to that of crevice corrosion. In fact, pits are "mini" crevices which usually have diameters equal to their depth. They can occur so closely spaced that they give the appearance of a roughened surface. This is a self-initiating form of crevice corrosion, in that the corrosion process creates the pit (or crevice) which propagates, at an accelerated rate, and eventually perforates the metal. Initiation of pits usually results from metal inhomogeneities, breaks in protective films, surface deposits, defects, or imperfections. (Figure 3.7.2.4-1).<sup>8</sup>



Similar to crevice corrosion, pitting corrosion occurs at localized areas where oxygen has been depleted, pH has become lowered and chloride has become enriched.

**Figure 3.7.2.4-1** Pitting corrosion

In summary, all four main types of corrosion occurring on an automobile involve destruction of the metal through reaction with the environment, and all are electrochemical in nature and require the presence of water. The presence of chlorides, as in de-icing salts, simply accelerate the attack.

### 3.7.3 CORROSION OF PAINTED STEEL

Corrosion of auto body components is usually classified according to initial location and direction of attack. When attack initiates at an interior surface or within a closed or semiclosed part, it is termed "perforation", or "inside-out" corrosion. Corrosion that initiates on visible exterior surfaces, usually at nicks or scratches in the paint, is called "cosmetic", or "outside-in" corrosion.

#### 3.7.3.1 Perforation Corrosion

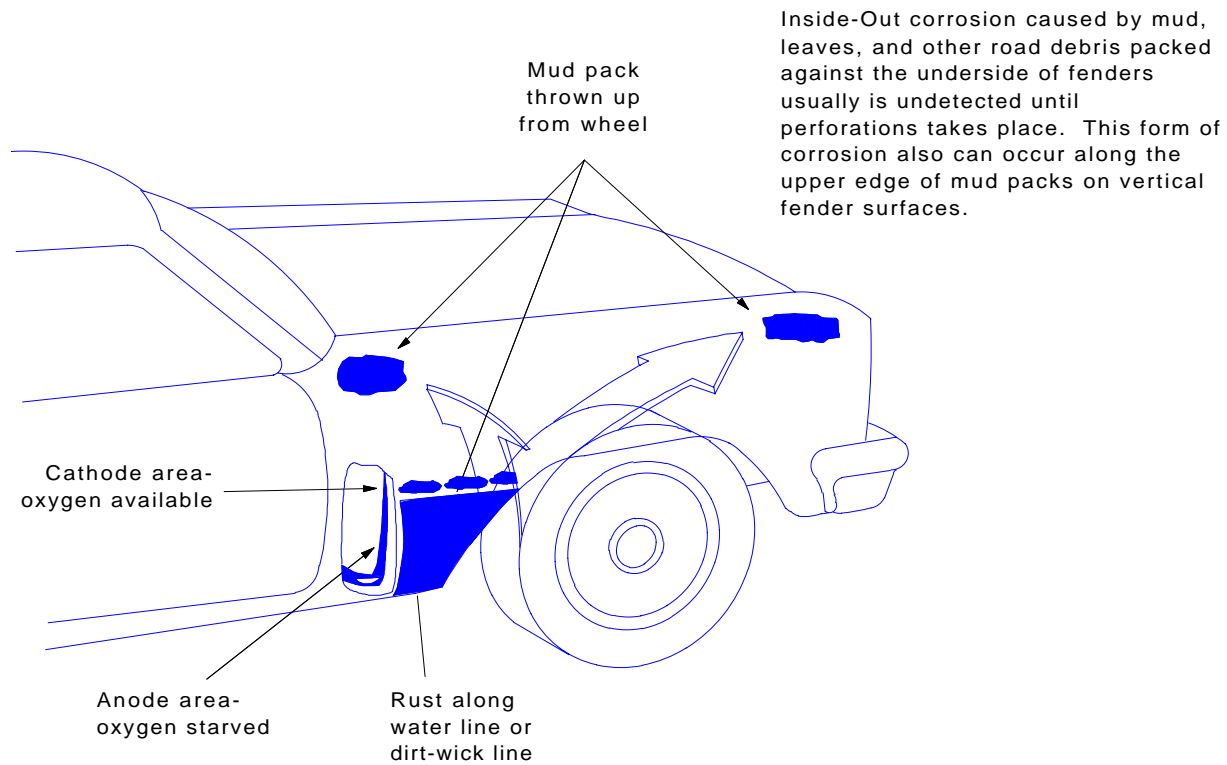
Perforation corrosion can lead to serious structural damage that may go undetected until it becomes visible on the external surface after penetrating the metal from within. Repair can be difficult and costly, often involving replacement of entire panels and sometimes requiring fabrication of new attachments or other custom work.

Much of the problem is caused by road debris collecting in packs or poultrices, which are trapped in pockets and corners and on ledges and vertical surfaces ([Figure 3.7.3.1-1](#)).<sup>8</sup>

The poultrices hold the salty electrolyte in intimate contact with the metal. This, and the lack of rapid runoff and thorough air-drying of the metal, accounts for corrosion occurring on vertical and upper interior surfaces. Plugging of drain holes is another cause of perforation corrosion. This leads to an accumulation of a damp, salty poultrice in the lower interior of doors, rocker panels, and tailgates that produces corrosion and eventual penetration of the sheet.

A major factor contributing to perforation corrosion is the inherent difficulty in adequately cleaning, phosphating, and applying primer to interior surfaces of body assemblies. By insuring

that all internal surfaces are completely protected, the use of precoated sheet has proven to be particularly effective in preventing perforation corrosion.



**Figure 3.7.3.1-1** Inside out Corrosion

### 3.7.3.2 Cosmetic Corrosion

Cosmetic corrosion begins at points of exterior damage to the paint system that locally expose the steel substrate. When bare metal is exposed to the environment, the main concern is poor appearance due to corrosion products, particularly red rust and stain, and the lateral spread of paint damage resulting from undercutting and blistering.

#### Scab Corrosion

Scab corrosion is a term applied to cosmetic corrosion when it occurs at exterior joints and crevices that trap moisture, dirt, and salts. Typical locations for this kind of corrosion are at the contact area between window moldings and cowl or tulip panels. Scab corrosion is not necessarily a galvanic reaction (caused by dissimilar metals), as it occurs frequently at joints of similar metals. Scab corrosion is minimized by use of a steel sheet with a zinc or zinc alloy coating on the exterior surfaces.

#### Filiform Corrosion

Filiform corrosion is a type of cosmetic corrosion that occurs under paint films on metallic surfaces. Although not immediately apparent, the attack appears as a network of threadlike filaments under the coating. It does not damage or destroy components, but it does have an adverse effect on appearance. Filiform generally occurs only within a range of relative humidity of about 55-85%.<sup>14</sup>

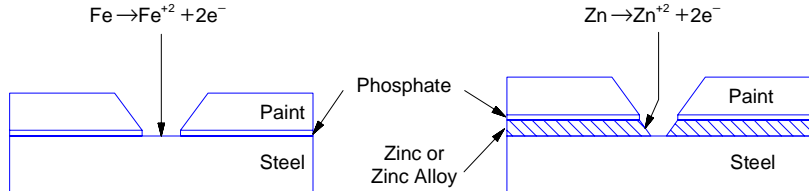
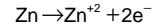
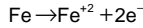
### 3.7.3.3 Mechanisms of Paint Undercutting

Mechanisms of paint undercutting have been the subject of considerable current research.<sup>15, 16</sup>

Figure 3.7.3.3-1 shows some of the factors involved during the undercutting corrosion of painted, cold-rolled, zinc, and zinc-alloy coated steel sheet at areas of localized paint damage.

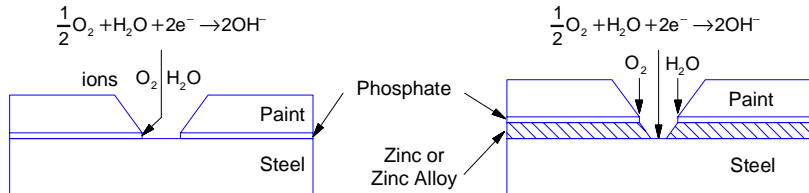
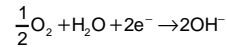
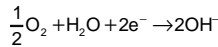
**Anodic Reaction**

Corrosion begins at exposed metal in the presence of electrolyte. Iron (in uncoated steel) or Zn (in pre-coated steel) gives up electrons to the base metal and ions are freed to the electrolyte. In zinc and zinc-alloy coated material, the exposed steel is protected galvanically.



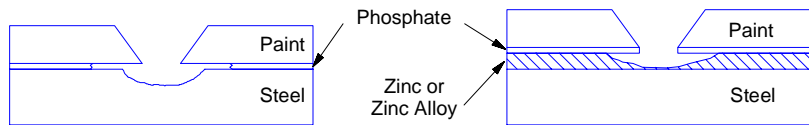
**Cathodic Reaction**

Hydroxyl ions are generated as a result of the cathodic reaction for both materials. With uncoated steel, OH<sup>-</sup> is produced on the steel surface.



**Mode of Attack**

With uncoated steel, the exposed steel substrate is attacked, while the phosphate film beneath the paint layer is dissolved by the high pH solution formed by the OH<sup>-</sup> ions. For zinc-coated steel, the coating dissolves the paint film and galvanically protects the exposed steel. Under very wet conditions, cathodic delamination may occur on coated surfaces.



**Corrosion Products**

In steel, iron oxide precipitates as a result of a series of chemical reactions and forms an unsightly red rust deposit. Zinc forms ZnO or Zn(OH)<sub>2</sub> or zinc hydroxy chloride depending on the type of corrosive environment. The white zinc corrosion product is less objectionable in appearance than red rust and also acts to protect the underlying steel.

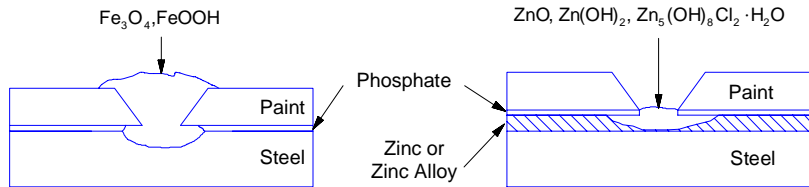
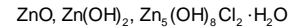
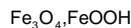


Figure 3.7.3.3-1 Corrosion processes at damaged paint site

In the case of cold-rolled sheet, exposure to wet conditions leads to anodic dissolution of the steel at the exposed area with the formation of unsightly red rust. The migration of water, oxygen, and ions through and under the paint film causes a cathodic reaction to take place beneath the paint adjacent to the damaged region. Electrons flow through the steel to balance the separated anodic and cathodic reactions. The high pH solution that is developed at the steel/paint interface causes a loss of paint adhesion, which is termed cathodic disbonding. Depending on the types of

paint system, pretreatment, and substrate, cathodic disbonding can proceed by one or more of several possible mechanisms, including:

1. Saponification of the paint resin, a degradation of the polymer by hydroxyl ions,
2. Dissolution of the phosphate layer, or
3. Reduction of an oxide layer on the metal surface.

During subsequent exposure to drying conditions, oxygen becomes available for increased cathodic activity at the area of initial damage, allowing anodic dissolution to spread into the delaminated region, thus leading to further attack by anodic undermining. Formation of voluminous rust beneath the film may lead to further damage caused by mechanical wedging.

Repeated exposure to wetting and drying cycles leads to a continuing attack of the steel substrate, formation of red corrosion products, and loss of paint adhesion.

With zinc and zinc-alloy coated steel, exposure to wet conditions does not result in rusting at the damaged site because of the sacrificial galvanic action of the zinc coating. In this case, as shown in [Figure 3.7.3.3-1](#), the zinc coating corrodes preferentially, acting as the anode in a galvanic couple, with the exposed steel acting as the cathode. While the steel is thus protected, there is some loss of paint adhesion due to anodic undermining as the zinc coating is consumed. There may be further loss of adhesion in advance of the dissolution front owing to cathodic disbonding.

Zinc ions that are produced by dissolution of the coating migrate to the exposed steel surface where they combine with hydroxyl ions from the cathodic reaction, thus forming a white precipitate. The white precipitate is generally less objectionable in appearance than red rust. It also serves to inhibit the cathodic reaction in this region and slows the rate of zinc dissolution. Red rust will eventually develop on the exposed steel once the available zinc in the coating is consumed.

During intervals of dryness, both anodic and cathodic reactions are halted and the spread of paint damage is stopped. This serves to explain why the degree of paint delamination for zinc and zinc-alloy coated steels exposed to actual service conditions is less than that of cold-rolled steel, even though the results are opposite when these materials are tested under conditions of continual wetness, such as in a salt-spray test.

### 3.7.4 PRECOATINGS

Application of a metal coating to both sides of the sheet steel for automobile body or chassis parts is one of the most effective methods of combating corrosion<sup>2</sup>.

Since the 1980's, there has been a major increase in the use of precoated steels in the North American automobile. The precoated sheet steels currently available are listed in [Table 3.7.4-1](#) with descriptions of the precoatings and typical automotive applications.

**Table 3.7.4-1** Precoated Steel Sheet for Automobiles

Coating	Description	Typical Applications
Hot-Dip Zinc	Galvanized sheet, produced by the hot-dip process. Available with regular spangle, minimized spangle and extra smooth surfaces. Wide range of coating masses available. Typical coating mass are 60-100 g/m <sup>2</sup> .	Inner and outer body panels, structural components.
Hot-Dip Zinc-Iron	Galvannealed sheet. Produced by heat treating hot-dip galvanized steel to form a zinc-iron alloy coating containing about 10% iron. Typical coating masses are 40-60 g/m <sup>2</sup> .	Inner and outer body panels, structural components.
Hot-Dip Aluminum-Silicon Alloy	Type 1 aluminum-coated. Coating is an aluminum-silicon alloy containing 8 to 12% silicon. Coating masses are class 25 (38 g/m <sup>2</sup> ) and class 40 (60 g/m <sup>2</sup> ).	Exhaust systems, catalytic converters, chassis components.
Hot-Dip Aluminum-Zinc Alloy	Galvalume sheet. Coating is an alloy of 55% aluminum, 1.5% silicon, balance zinc. Typical coating mass is 75g/m <sup>2</sup> .	Exhaust systems, air cleaner covers, core plugs, brake shields, floor pan covers.
Hot-Dip Lead-Tin Alloy	Terne is a lead-tin alloy containing 3 to 15% tin with a wide range of available coating masses. Hot dipping after flash electrodeposition of 1 to 1.5% nickel produces nickel terne.	Fuel tanks, fuel lines, brake lines, radiator and heater components, air cleaners.
Electroplated Zinc	Pure zinc coatings produced by electrodeposition. Range of coating masses available. Current use includes 30 to 100 g/m <sup>2</sup> . Typical costing masses are 60 and 70 g/m <sup>2</sup> . Available in one or two-side and differentially coated.	Inner and outer body panels.
Electroplated Zinc-Iron Alloy	Electrodeposited zinc-iron alloy coating containing 10 to 20% iron. Typical coating masses are 30-50 g/m <sup>2</sup> .	Inner and outer body panels.
Electroplated Zinc-Nickel	Electrodeposited zinc-nickel alloy coating containing 10 to 14% nickel. Typical coating masses are 20 to 40 g/m <sup>2</sup> .	Inner and outer body panels.
Electroplated Tin	Tinplate. Cold rolled sheet with a thin electrodeposited tin layer.	Oil filter and heater components.
Organic-Metallic Composite	Proprietary weldable organic coating and pretreatment applied by roll coating, usually to one side, over metallic-coated (usually electrodeposited) sheet. Typical combinations are 1 to 2 μm organic over zinc-nickel alloy, and a 5 - 10μm zinc-rich organic over zinc. Metallic coating can be one or two-side, but is usually one-side to provide barrier protection to the interior surfaces of outer body panels.	Inner and outer body panels, fuel tanks.

The principal precoated steels used in automotive applications today are metallic coated sheets, typically of either pure zinc or zinc alloy compositions. From 1981 to 1996, the shipments of coated sheet steel for North American consumption have shown a dramatic increase.<sup>17</sup> See [Figure 3.7.4.4-1](#)

Precoated steels are generally characterized by a coating mass designation. In general, corrosion resistance increases with coating mass<sup>18</sup>.

### 3.7.4.1 Hot Dipped Coated Steel

Hot-dip coatings are produced by a continuous process of immersing steel strip into a molten bath of the desired coating metal. The hot-dip process is currently the most cost-effective way to deposit heavy, corrosion-resistant coatings on a steel substrate. Recent advances in the production of uniform, lighter hot-dip coatings have made this process more attractive for exposed quality auto body panels. During the 1990's, steel companies throughout the world greatly increased their capacity to produce high quality coated sheet by installing modern, high-speed hot-dip coating lines.

The types of hot-dip coated sheet steels for applications in the automotive industry for body panels include pure zinc coatings and zinc-iron (Galvanneal) diffusion coatings.

#### Pure Zinc Coatings

Pure zinc coatings are available for automotive use with coatings ranging from approximately 20 to 160 g/m<sup>2</sup> per side. Heavier pure zinc coatings give the best galvanic or sacrificial corrosion resistance to cold-rolled steel substrates. Two-side hot-dip zinc-coated steels impart sacrificial protection from red rust to the exposed surface (cosmetic corrosion resistance) in applications such as rocker panels; and because hot-dip products are available in heavier coating masses, they are particularly suited to the inner surface of exterior body panels to prevent perforation corrosion.

#### Zinc-Iron (Galvanneal) Diffusion Coatings

Heating the strip immediately following its withdrawal from the zinc-coating bath produces zinc-iron coatings. This annealing process causes iron from the steel substrate to diffuse into the zinc coating. This results in an alloyed coating composed of approximately 10% iron (balance zinc). These coatings usually range in coating mass from 30-60 g/m<sup>2</sup>.

Zinc-iron coatings provide less sacrificial protection of exposed steel than pure zinc coatings; however, alloying zinc with iron lowers the corrosion rate of the coating. Zinc-iron alloy coatings are also more weldable. They are suited for exterior skin panels, inner panels, and structural components. Hot-dipped coated steels for use in automobile components other than body panels include aluminum-coated steels (type 1), aluminum (55%)/zinc, zinc/aluminum (5%), long terne, and nickel terne.

#### Aluminum-coated steels (Type 1)

Aluminum-coated steels (Type 1) contain 8-12% silicon in the coating. They have enhanced high-temperature corrosion performance and are primarily used for making parts of the automotive exhaust system, including intermediate pipes, muffler parts, and tail pipes. Aluminum-coated steels are also used for some structural components.

#### Aluminum (55%)/Zinc

Aluminum (55%)/Zinc-coated steels have similar applications involving high-temperature corrosion resistance. Typical applications include heat shields, mufflers, and underhood parts.

#### Zinc/Aluminum (5%)

Zinc/Aluminum-coated steels are claimed to offer some ductility and corrosion resistance advantages over pure zinc coatings.

**Long Terne**

Long Terne-coated steel has a coating of lead alloy containing nominally 8% tin. It protects against corrosion in gas tanks, fuel lines, and brake lines and does not contaminate gasoline or brake fluid. Less active than the steel substrate, it does not provide galvanic protection if the coating is penetrated. Nickel terne-coated steel includes an electrolytic flash coating of nickel (1 to 1.5 g/m<sup>2</sup>) underneath a conventional lead/tin coating for enhanced corrosion resistance. The use of terne is decreasing because of concerns about the effects of lead on the environment.

A variation of long terne-coated steel employs a subsequent prepainted organic coating on each surface for some fuel tanks. The outer surface has a zinc-rich organic coating to provide added exterior corrosion protection, while the inner surface has an aluminum-rich organic coating to augment the lead/tin coatings resistance to gasoline, and low concentrations of methanol and ethanol containing fuels.

**3.7.4.2 Electroplated Steel**

Steel sheet with an electroplated metallic coating is widely used for outer skin auto body panels because of enhanced coating thickness control, appearance, formability, and weldability. For production of automotive sheet steel, electroplating consists of a continuous, relatively low-temperature process in which a negatively charged steel strip is passed between positively charged anodes. Metallic ions of the desired coating elements, in an electrolyte solution, are reduced at the steel strip thereby plating the surface.

**Pure Zinc Coatings**

Electroplated zinc coatings range from approximately 20 to 100 g/m<sup>2</sup> per side for automotive body panel use. For outer body panels, 60 g/m<sup>2</sup> is the most popular.

**Zinc Alloy Coatings**

The most commonly produced zinc alloy coatings are zinc-iron (10 to 20% Fe) and zinc-nickel (10 to 14% Ni). These coatings are typically supplied for automotive applications in coating masses ranging from 20 to 50 g/m<sup>2</sup>. The advantages claimed for the zinc-alloy coating systems include better weldability and paint adhesion.

Several other binary and tertiary zinc-based alloy coatings for automotive use have been reported in the literature; however, none is being used extensively on commercial vehicles.

**Duplex Coatings**

Duplex coatings are designed to provide two-layer interaction. A thick bottom layer provides the bulk of the corrosion protection to the substrate, while the top layer, generally a flash coating (0.5 to 5 g/m<sup>2</sup>), enhances other desirable properties for automotive body sheet applications, such as weldability, paintability (cratering resistance), formability, and surface appearance. Examples of duplex coatings for automotive applications include 80 to 90% iron zinc over zinc-iron, and chrome-chrome oxide layers over pure zinc.

**3.7.4.3 Organic Precoated Steel**

For many years, Zincrometal (a registered trademark of Metal Coatings International), a weldable two-layer, one-side primer consisting of a zinc-containing chromium-oxide base layer with zinc-rich organic top layer on cold-rolled steel, was used extensively for making outer skin panels for automobiles. It provides enhanced passivation and corrosion protection from perforation corrosion and limited sacrificial protection to the substrate through the use of metal

powders in the organic layer. However, the need for better corrosion resistance and stamping performance led to the decline of Zincrometal in favor of two-side metallic coated steel sheet.

More recently, a variety of thin-film organic treatments, including zinc-rich primers, organic composites, and organic silicate composites, have emerged for use over zinc and zinc-alloyed coated sheet. These usually involve a treatment with a chromate corrosion-inhibiting layer and either a thin (5-10 $\mu$ m) zinc-rich organic or a very thin (1-2  $\mu$ m) clear organic layer.<sup>19,20</sup> The organic metallic-coated sheet steels were developed primarily for use in unexposed automotive applications. In these applications, additional corrosion protection is desired because full electrocoat primer coverage is often difficult to achieve due to inherent difficulties of cleaning and phosphating of interior surfaces and limited access of the electrocoat primer. Additionally, it is believed that the use of an organic layer will permit a decrease in metallic coating thickness while still providing equivalent corrosion protection.

#### 3.7.4.4 Precoated Steel Usage

Existing and projected precoated steel usage varies in the three main automobile producing areas in the world<sup>21</sup>.

##### Japan

The choice of corrosion protection used in Japan differs with the individual manufacturer. The most common automotive materials include:

1. Hot-dip zinc-iron alloy (galvanneal)
2. Electroplated zinc-nickel
3. Organic composite coatings over zinc-nickel
4. Electroplated zinc
5. Electroplated zinc-iron duplex (high iron flash topcoat on one side only, mainly for exposed parts)

Coating masses generally range from 15 to 45 g/m<sup>2</sup>.

Incentives for the Japanese auto makers to use zinc-alloy coatings of relatively low coating mass included welding equipment limitations and the high cost of electricity in Japan which made heavy coatings expensive. However, recent trends indicate that the coating masses for automotive steel in Japan are gradually increasing due to the need to provide added corrosion protection for the highly corrosive environments encountered in many North American markets. More future materials emphasis is being placed on exposed quality hot-dipped coated sheet, such as galvannealed coatings, to afford greater corrosion protection.

##### Europe

European car makers use a wide variety of methods to minimize corrosion damage and there is no consistent pattern of precoated steel usage. A few manufacturers have gone to an "all galvanized concept", while others use very little precoated steel, relying on corrosion resistance from organic coatings and waxes. Nevertheless, manufacturers have generally increased their consumption of coated sheet steel in recent years to where coated sheet accounted for about 43% of the mass of European auto bodies in 1987. This trend is expected to continue. The types of coated sheet products in use include:

1. Hot-dip zinc for unexposed parts

2. Electroplated zinc for exposed parts
3. Electroplated zinc-nickel
4. One-side zinc-rich prepainted electroplated zinc

The use of Zincrometal has declined and there are no major use of galvanized sheet.

### **North America**

The corrosion protection trend among domestic North American auto makers is widespread application of two-side precoated steel (90 percent of the body-in-white). The corrosion protection requirements are fairly well established by each manufacturer for the near future. Thus coated sheet product selection has emphasized manufacturability; i.e., forming, joining, and painting criteria. The coated sheet products used by the domestic North American manufacturers include both hot-dip and electroplated pure zinc and zinc-iron coatings in masses of 40 to 100 g/m<sup>2</sup> per side. The product mixes of the "transplant auto makers" are generally influenced by their parent company.

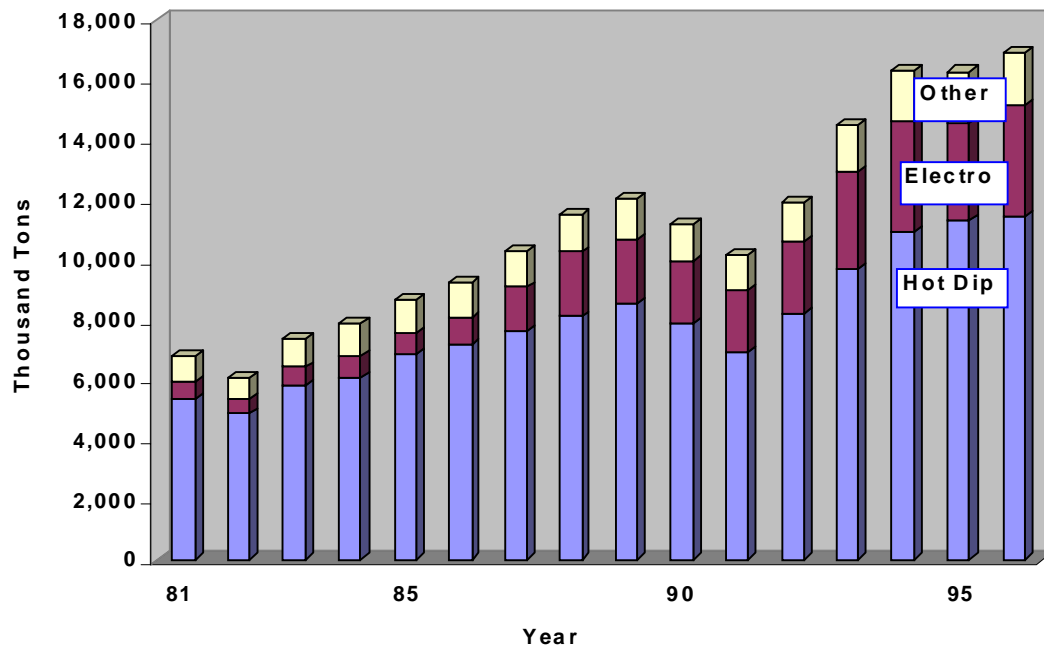
Future trends include reducing some coating masses, using organic films to enhance corrosion protection of metallic coated sheet products, and increasing applications of galvanized sheet.

The current and future higher usage of precoated steel by the North American manufacturers is a reflection of the philosophy that use of such materials is good technically, and a cost-effective way of providing durability in a highly corrosive environment ([Figure 3.7.4.4-1](#), [Figure 3.7.4.4-2](#), and [Figure 3.7.4.4-3](#)).

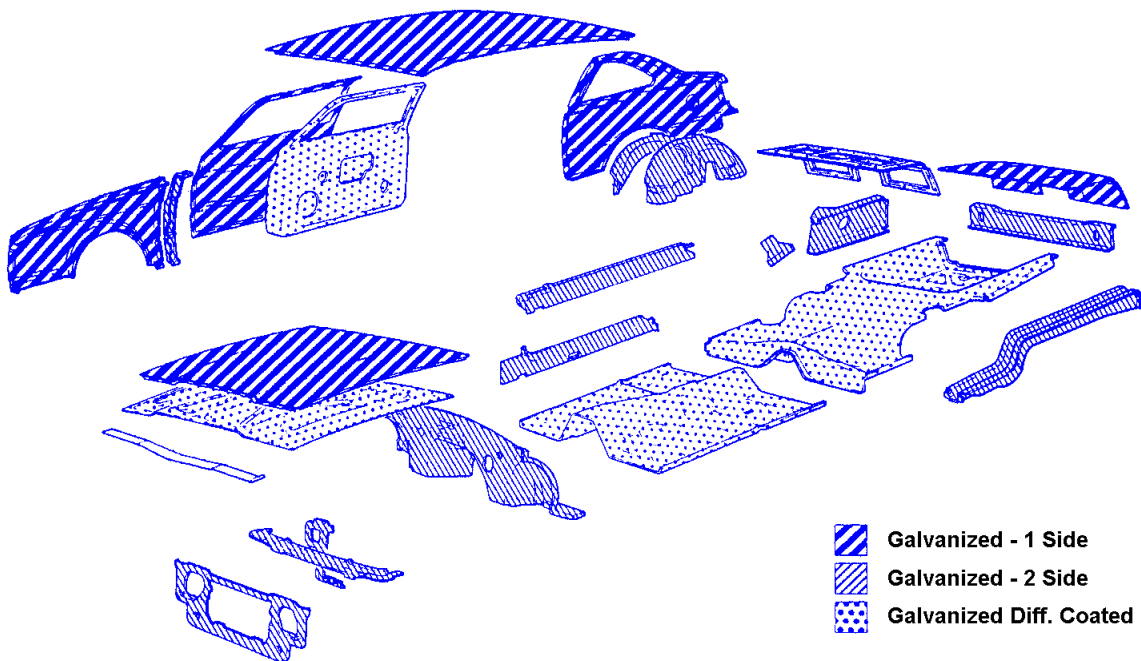
Coated sheet products used by the North American auto makers are generally:

1. 60 g/m<sup>2</sup> electroplated zinc for exposed panels
2. 60-70 g/m<sup>2</sup> hot dip zinc for unexposed panels
3. 40-50 g/m<sup>2</sup> hot-dip zinc-iron alloy (galvanized) for both exposed and unexposed panels

## US SHIPMENTS OF COATED SHEET



**Figure 3.7.4.4-1** U.S. shipments of coated steel sheet products, showing the increase in use of coated sheet steel products resulting by the automotive industry switch from bare cold rolled to coated sheet. (Plotted from data given in [Reference 22](#))



**Figure 3.7.4.4-2** 1989 TBird/Cougar body corrosion protection precoated and non-ferrous

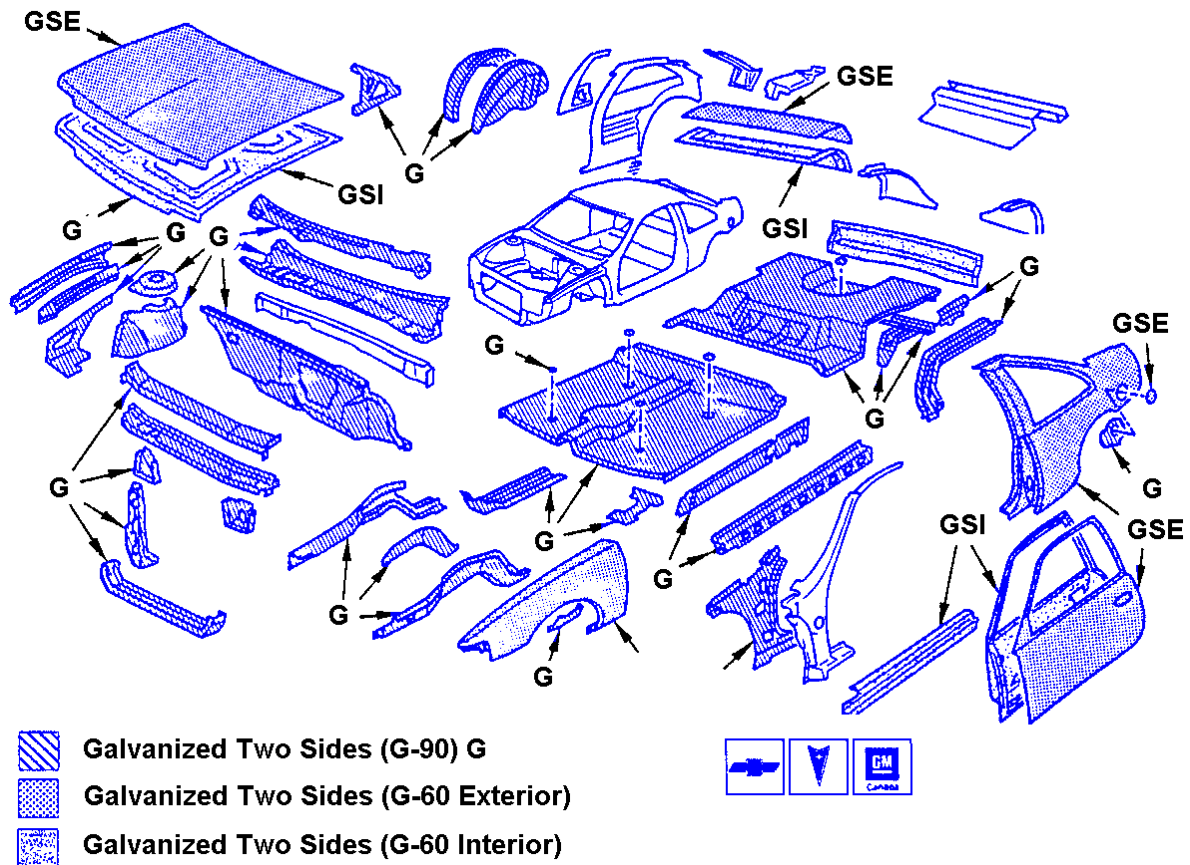


Figure 3.7.4.4-3 1990 GM-10 Coupe precoated metals

### 3.7.5 ASSEMBLY COATINGS FOR CORROSION PROTECTION

Several different types of coatings, such as zinc rich primers, waxes, and seam sealers, have historically been applied, after fabrication and during assembly, to provide supplemental corrosion protection of automobiles. Most of these coatings functioned by excluding the corrosive environment from the substrate; thus the protection provided was strictly barrier. The purpose of these coatings was to provide additional rather than sole protection against corrosion. The extensive usage of sacrificial galvanized steel has greatly diminished the need for many of these coatings.

Several different types of post coatings have been used successfully, but now have limited usage due to the increased use of galvanized steels.

#### Zinc-Rich Spray Primer

Zinc-rich spray primer is generally classified as a paint; however, it contains approximately 90% zinc by mass and should not be confused with the usual primers, surfacers, and topcoats used in painting an automobile. This material was applied to joints and interior surfaces after fabrication and prior to assembly. The industry had used this material as a spray-on 40 micron-thick protective coating for local protection during the last 25 years.

**Weld-Through Coatings**

Weld-through coatings were developed as an alternative material to the zinc-rich spray paint. They are gummy and weldable, and provide excellent protection even when applied to oily steel substrates. Welding fumes and handling of coated parts are disadvantages of this material.

**Corrosion-Preventive Wax**

Corrosion-preventive wax is a spray-on coating, applied by wands or automation, usually after painting. It is a solvent-based, perhaps aluminum-filled (for visibility) wax-containing corrosion inhibitor. Applied to a minimum dry film thickness of 50 microns, it develops a tack-free film after air curing that provides additional barrier corrosion protection in body cavities, seams, and hem areas. Typical applications have been the inside of the lower front fender, inside of doors, rear wheelhouse joints, and lower-quarter panel joints.

Two other types of assembly coatings that are still being used in numerous applications are chip resistant coatings and sound deadeners.

**Chip-Resistant Coatings**

Chip-resistant coatings are applied under the topcoat to the areas of the vehicle subject to stone chipping and road blast. They can be vinyl, urethane, or powder-spray coatings. The vinyl materials are applied to inner wheelhouse panels and lower exterior body side, and are used at about 400 microns thickness. The urethane and powder materials are spray applied and are used on the more visible portion of the vehicle, as well as on the leading edge of hood panels. Typical thicknesses used are 100 microns for the liquid urethane coatings and up to 250 microns for powder coatings.

**Sound Deadeners**

Sound deadeners are used primarily for sound deadening and not corrosion protection. Typically they are spray applied after paint, at about 800 microns thickness, on the inside of door panels, quarterpanels, wheel wells, and the tunnel area surrounding the driveshaft. Historically, these materials have deteriorated with age, hardened, cracked, or had poor adhesion, thus providing numerous corrosion sites. Newer versions of these materials, which include water-borne products, have improved adhesion, as well as greater resistance to cracking and flaking, than previously used materials. An example of current assembly coating on a vehicle is shown in [Figure 3.7.5-1](#).

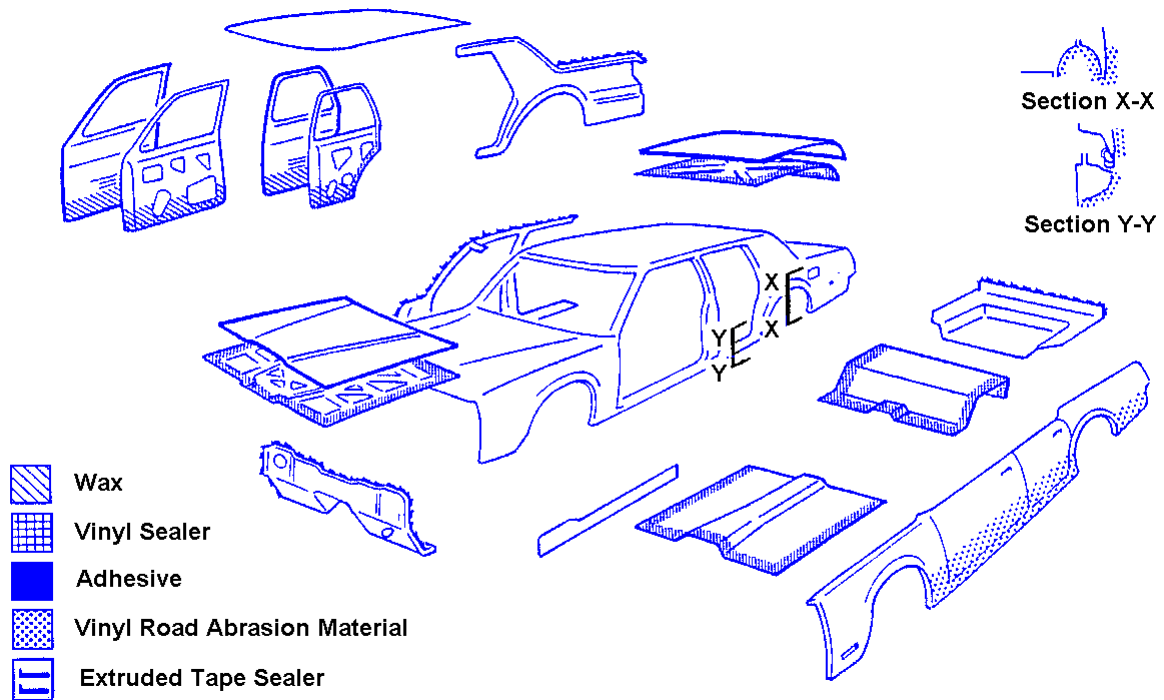


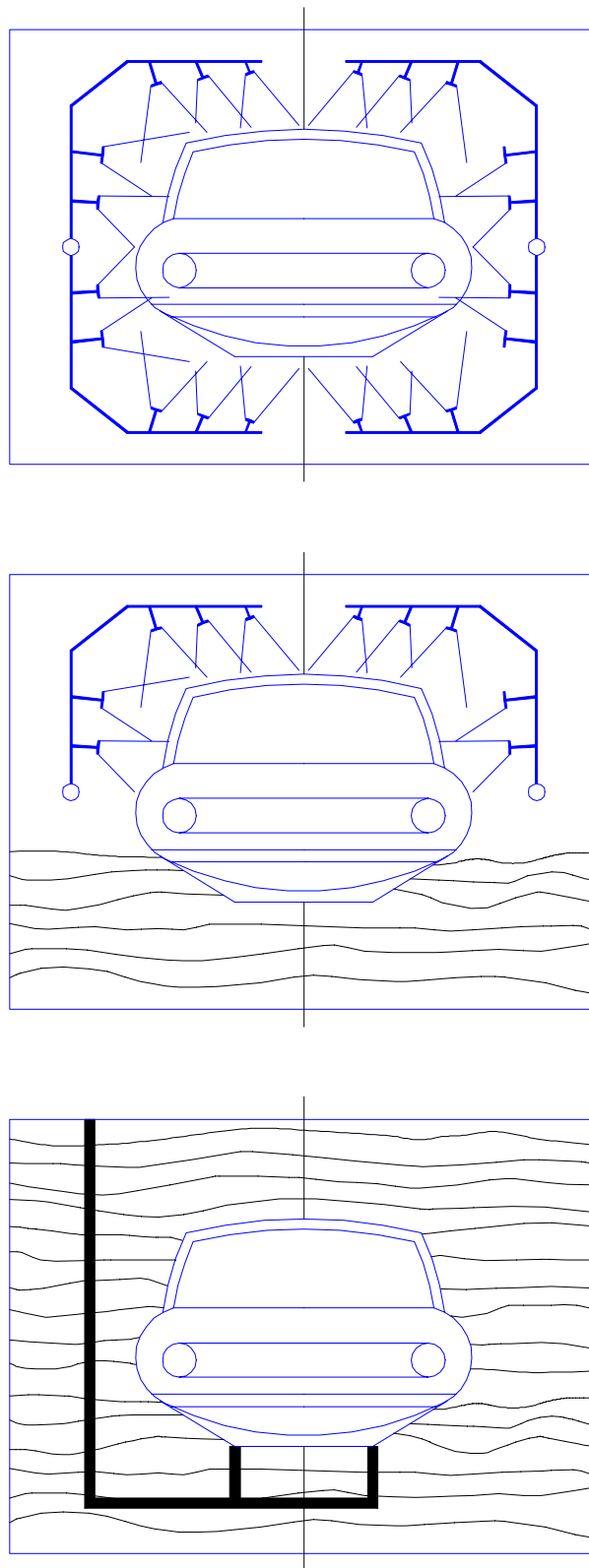
Figure 3.7.5-1 Assembly coatings

### 3.7.6 PHOSPHATE PRETREATMENT

The zinc phosphate pretreatment process reacts with the metal surface to form a nonmetallic crystalline coating<sup>23, 24, 25</sup>. The coating is resistant to alkaline corrosion by-products and inhibits underfilm corrosion<sup>26</sup>. It also serves as a nonconductive insulating layer to isolate corrosion sites and, by its structure, provides physical anchoring sites for the primer applied over it. Zinc phosphate coatings have been used successfully for years by the automotive industry to enhance the adhesion of organic finishes to the metal and to achieve superior corrosion resistance with these finishes. Phosphate coatings representing the latest technology will contain zinc, nickel, iron, and manganese as part of the chemical composition<sup>27</sup>. Phosphate baths have also been formulated to apply coatings equally well to all the different metallic surfaces represented in the car body today.

#### 3.7.6.1 Zinc Phosphate Coatings

The zinc phosphate coating can be applied to the car body at the assembly plant in either a spray or an immersion processing stage ([Figure 3.7.6.1-1](#)).



**Figure 3.7.6.1-1** In North America, phosphate coatings are applied by spraying, partial-immersion and full dip immersion systems

The method chosen for phosphate application usually determines the method used in the other stages. Although effective on exterior surfaces, spray application has difficulty reaching

enclosed and internal surfaces. Immersion application, on the other hand, can coat all surfaces of the car body, and thus this method also enhances inside out corrosion resistance. For this reason, immersion application is designed into new plants and into lines upgraded because of age or manufacturing changes. The typical processing sequence includes the following treatments:<sup>28</sup>

1. Body Shop Cleaning/Precleaning
2. Cleaning (2 Stages)
3. Rinsing
4. Rinse Conditioning
5. Phosphating
6. Rinsing
7. Post-treating
8. Deionized Water Rinsing

### **Cleaning**

At some assembly plants, additional cleaning is provided in the body shop to remove excessive dirt, grinding dust, and heavy oils. A precleaning step is used to remove sealer, chalk, and ink marks. Manual wiping or automatic spray application may be used. Alkaline cleaners containing builders and surfactants are used to remove processing and stamping oils and soils from the metal surface. Modern cleaners are formulated with inhibitors to reduce etching of the surfaces of reactive metals found in today's vehicles.

Recent developments in cleaner technology have led to lower operating temperatures. Where the usual cleaner temperature was about 140° F, the newer cleaners operate satisfactorily at 120° F. In addition to energy savings, the use of such cleaners also results in less sealer removal and redeposition in the cleaner sections. With increased interaction between oil suppliers and pretreatment companies, this scenario would help facilitate easily removable lubricants. This would result in cost savings as more lower temperature applications, aqueous cleaner recovery and recycling of the lubricant from the cleaning process.

### **Rinsing**

Rinsing removes the residual processing chemicals from the previous stages that would interfere with subsequent operations or compromise the performance of the coating system. The final deionized water rinse is especially critical to remove any salts that may contaminate the electrodeposition primer bath.

### **Conditioning**

Conditioning agents are colloidal suspensions of titanium phosphates (Jernstedt salts)<sup>29</sup> applied prior to phosphate deposition in a rinse step or separately in a spray riser. They nucleate crystallization of the phosphate coating, which results in a dense phosphate coating of small crystal size.

Recent developments include the use of liquid rinse conditioners for easier product delivery. Also, dust contamination from the usage of powders is eliminated.

### **Phosphating**

In the phosphating step, the metal surfaces react with an acidic solution containing zinc, nickel, and/or manganese as their acidic phosphate salts. The change in the pH at the

solution/metal interface causes solubility changes and the growth of phosphate crystals that are integral to the surface. Additives such as oxidizing agents serve to accelerate the deposition of a crystalline coating. Other additives may be needed to improve the treatment of zinc and aluminum surfaces. Because of automotive weight restrictions, aluminum is becoming an important component in the mix for pretreatment. Phosphating of aluminum requires use of new bath compositions. The baths are controlled by maintaining the required level of acidity, accelerator level, and metal concentrations. The use of coated steels has led to the development of products that replace part of the zinc in the zinc phosphate coating with nickel and/or manganese. Some European manufacturers have had success using electrodeposited zinc coated steels that were prephosphated at the production line. This approach reduces rusting in transit, lowers the use of lubricating liquids in the stamping plant, improves housekeeping in the stamping plant, and reduces chemical consumption at the assembly plant. Treatment of enclosed surfaces and hem flanges does not depend on the application method, and it is claimed that the treatment and performance of bimetallic couples is improved. When prephosphated sheet is processed in the assembly plant phosphate washer, cleaner strength must be controlled, and the two phosphate systems involved must be closely matched to avoid appearance and performance problems.

### Post-Treating

Although the most commonly used post-treatments contain chromium ions, new types have been developed that are based on organic monomers or polymers and/or inorganic salts. These newer types are of interest because of their environmental acceptability.

The need for the application of a post-treatment depends on total system requirements. Although this step is generally employed in the United States and Europe, Japanese car manufacturers do not use a post-treatment step<sup>30</sup>, except for manufacturing facilities located in the United States.

Future trends are to eliminate post-treatments and utilize DI water only.

### 3.7.6.2 Characterization of Phosphates

Phosphate coatings are characterized by composition, uniformity, coating mass per unit area, crystal size, and morphology. The coating mass is typically greater than 1.5 g/m<sup>2</sup> but less than 4 g/m<sup>2</sup>. Present-day phosphate systems aim for a crystal size of about 15 microns or less if applied by spray and 10 microns or less if applied by immersion. Crystal morphology is a function of conditioning, the application method, and phosphate bath composition. Immersion processing generally results in nodular crystals while spray processing gives plate-like crystals. Phosphate coatings containing a higher concentration of Fe (phosphophyllite)<sup>31</sup>, Ni, or Mn have been shown to outperform coatings containing only Zn (hopeite).<sup>32</sup>

The right combination of characteristics will yield the optimum paintable surface and form the foundation for the total corrosion resistant system applied to the metal surface.

### 3.7.6.3 Future Developments

Improvements in metal treatment technology are continuing. Among these are better performance, process simplification, automatic bath control, and on-line monitoring of coating characteristics. Increasingly restrictive environmental legislation will require waste minimization through the use of alternative compositions or ancillary processes. Analogous to these compositions are current research studies on nickel free baths which results in minimization of heavy metal additions to bath and sludge.

### 3.7.7 PAINTS AND PAINTING SYSTEMS

The North American automobile industry employs an electrocoat primer, in some instances a surfacer or guide coat, and a color topcoat system on car bodies. Major developments, particularly in the primers, offer significant improvements in corrosion protection.

In North America, the conversion from spray priming to cathodic electrodeposition of primer is complete. This rapid change occurred between 1976 and 1983, indicating the wide acceptance of cathodic electrodeposition epoxy primer for greatly improved corrosion resistance.

In electrophoretic deposition systems - variously called electrodeposition, electrocoating, E-Coat, and ELPO - the metal substrate is immersed in an aqueous bath and coated with a charged organic primer under the influence of an electrical field.

The advantages of electrodeposition include uniform coverage without pinholes, edge protection, penetration into enclosed areas, elimination of fire hazards and air pollution, and reduction of water pollution problems. In addition to adaptability to full automation, it offers more efficient utilization of the paint. Originally, cathodic electrocoated primers had poor stability and developed less "throwing power" than the anodic types, but both problems now have been solved. The major benefit of cathodic electrodeposition is the substantial improvement in corrosion resistance of the primed steel, particularly on marginal quality phosphated surfaces.

In the cathodic electrodeposition primer systems, the vehicle body is the cathode, and the dissolved metal ions tend to migrate in the same direction as the cationic resin, which coats the cathodic part. In addition to avoiding the possibility of anodic attack on the conversion coating or substrate, the electrodeposited cationic resins are alkaline in nature and tend to be inherently good corrosion inhibitors.

Electrodeposition of primer is at least a partial solution to the problems of tougher upcoming ambient air standards and energy conservation needs. It is much less polluting and, in many cases, also eliminates the need for the large dryoff oven after phosphating. The use of lead free electrodeposition primers contributes to the use of environmentally friendly coatings.

#### 3.7.7.1 Changes in Cathodic Electrodeposition Epoxy Primers

By 1985, most paint lines in North American automobile assembly plants converted to high build (30-35  $\mu\text{m}$  coating thickness) cathodic electrodeposition primers. In many plants this change resulted in the elimination of the primer surfacer or guide coat.

However, in the late 1980's, a trend developed away from the high-build electrocoats toward intermediate coating thickness of about 22  $\mu\text{m}$ . The use of a primer surfacer or guide coat has regained favor to optimize the appearance of the topcoat and to improve chip resistance. Further improvements in the cathodic electrocoat are designed for better stone chip resistance and lower bake temperatures.

#### 3.7.7.2 Improving Chip Resistance and Use of Color-Keyed Spray Primers

The continuing effort to improve field performance of paint systems has resulted in the addition of chip-resistant primers to the paint process. These may include either high-build products

sprayed on the cured electrocoat, or powder primers or slurries applied on the electrocoat prior to cure. Thin film primers are often painted on the front of hoods to provide additional stone protection.

To allow use of brighter topcoat colors or replace the use of expensive base coat material on less critical surfaces, some U.S. manufacturers are spray-applying color-keyed primers. These materials may be similar in color to topcoat color families, but are lower in cost and can produce significant paint cost savings. As a result of this process change, some automotive manufacturers are evaluating the use of medium build electrocoats (20-25  $\mu\text{m}$ ) in combination with color keyed primers to produce the 30-35  $\mu\text{m}$  primer film currently applied with high film build electrocoats.

### 3.7.7.3 Trends in Topcoats

Environmental regulations limiting the release of organic solvents have forced many changes in topcoat technology. Non-aqueous acrylic dispersion lacquers and thermoplastic acrylic lacquers have been eliminated due to their high solvent content. Currently, various topcoat systems are used for North American automobiles. They include:

1. Non-aqueous dispersion enamels
2. High solids solution enamels
3. High solids base coat/clear coat enamels
4. High solids base coat/two-component clear coats
5. Water borne base coats/enamel clear coats
6. Various combinations of the last three base coat/clear coat systems.

The non-aqueous dispersion enamels have almost been completely replaced by high solids solution enamels. Many plants have proceeded directly to base coat/clear coat technology for both metallic and non-metallic colors. These paints, in many cases, are applied directly over electrocoat primers. Base coat/clear coat systems provide attractive finishes with a deep luster that are more resistant to chalking, fading, and chemical spotting than are conventional enamels.

All base coat/clear coat systems, with the exception of waterborne base coats, are essentially applied wet-on-wet. Waterborne base coats are of interest because of their lower solvent content, and better orientation of the aluminum flakes. Two factors that are driving further changes in topcoats are stricter solvent emission regulations and chemical spotting problems due to atmospheric fallout. Lower emissions requirements have resulted in an emphasis not only on water borne base coats, but also on powder clear coats. These types of systems are currently being field tested on vehicles. To reduce problems of chemical spotting, many auto manufacturers have begun to use two-component clear coats as part of their paint system. These clear coats may be either urethane or non-urethane type materials. They require more sophisticated application techniques and equipment. Improvements in chemical resistance may also be obtained with certain powder clear coats.

The complete paint system film build with and without primer surfacers is shown in [Table 3.7.7.3-1](#). The total system film thickness may range from 85-110  $\mu\text{m}$ .

**Table 3.7.7.3-1** Typical Paint System Film Build

Topcoat	With Primer Surfacer	Without Primer Surfacer
Electrocoat and Primer	20-25 $\mu\text{m}$	30-35 $\mu\text{m}$
Primer Surfacer	15-25 $\mu\text{m}$	
Base coat	5-25 $\mu\text{m}$	15-20 $\mu\text{m}$
Clear coat	40 $\mu\text{m}$	40 $\mu\text{m}$

### 3.7.7.4 Autodeposition Coatings <sup>33</sup>

The automotive industry is showing increased interest in the use of autodeposition coatings for protecting steel and iron components. In the autodeposition coating process, a resinous coating is applied to a metal article as the result of chemical reaction of the metal surface with the coating solution. Since any surface that is wetted by the solution is coated, the system has unlimited "throwing power" into recessed or enclosed structures. Current commercial coatings are based on polyvinylidene chloride or acrylic resins. The PVDC coating process emits no volatile organic compounds (VOC), has no heavy metal effluent, and cures at 80° to 100°C. The acrylic coating process has low VOC emissions, requires a chromium rinse, and cures at 130° to 180°C. Current applications include various underhood and underbody components as well as housings, springs, and shafts.

Although current applications of autodeposition coatings are single-coat functional coatings for steel and iron components, developments for coating galvanized steel and primers for conventional and powder topcoats are being realized.

## 3.7.8 IMPROVING THE PROTECTION

### 3.7.8.1 Design Considerations

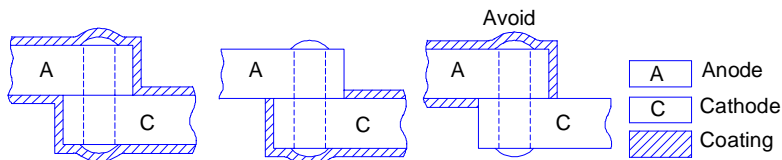
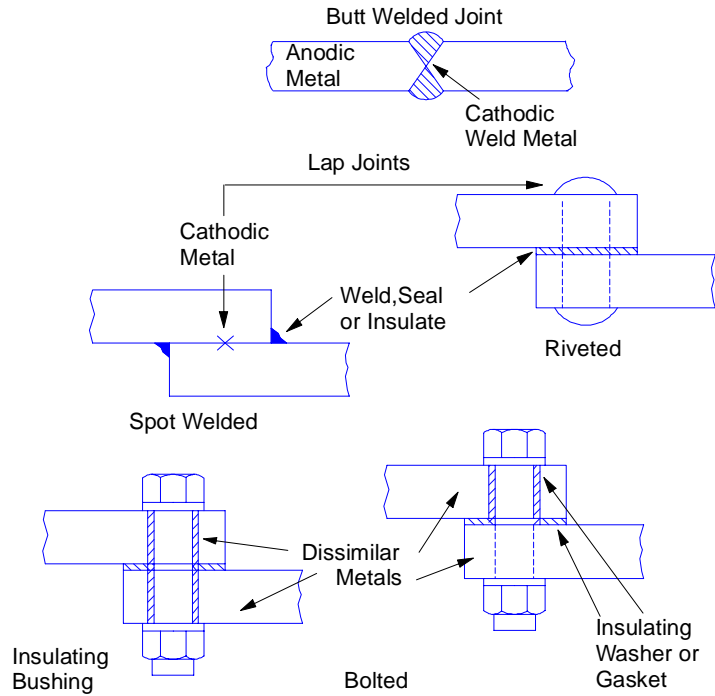
Design will continue to play an important role in controlling corrosion. As is widely recognized, the configuration of a part or assembly has an influence on - and often is the determining factor in - the type and severity of corrosion that occurs in service. It also determines the ease with which protective measures can be applied after assembly. Attention to design considerations becomes even more important wherever significant thickness reductions are involved.

For many years, preferred component configurations and assembly practices to minimize corrosion have been outlined and discussed in a growing body of design concept literature.<sup>34</sup> The importance of these factors - joints, closed sections and entrapment areas, and others - was again reviewed by Rowe in 1977<sup>35</sup> and the concepts detailed in [Figure 3.7.8.1-1](#) through [Figure 3.7.8.1-5](#) are based on his paper.

To minimize corrosion attack in butt welded and lap joints, the weld material (or rivet or bolt) should be less active than the larger area metals being joined.

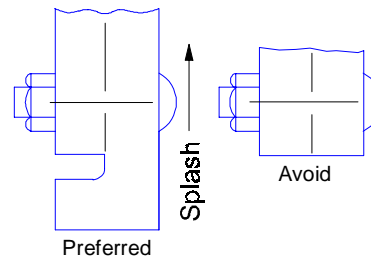
In lap joints, use of fillet welds, insulating material, or a seam sealer is recommended.

In bolting dissimilar materials, use of insulating washers or gaskets and bushings is required in a corrosive environment.

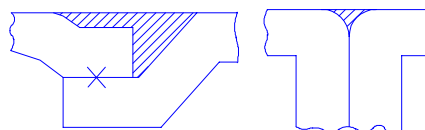


Coatings should be applied to both anode and cathode or to cathode only; never to the anode only. Damage to coating on anode would result in serious corrosion due to small anode-large cathode combination.

Joints exposed to direct splash should be protected by flanges. These may have to be angled to protect without creating entrapment sites.

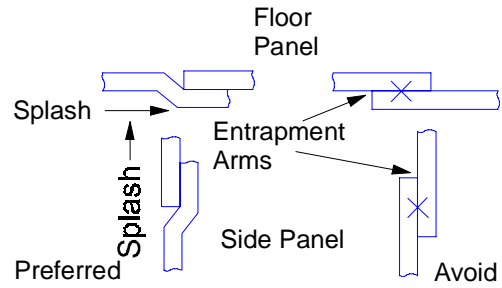


Entrapment sites in offset lap welds and standing seams should be eliminated with a sealer or a bead weld.

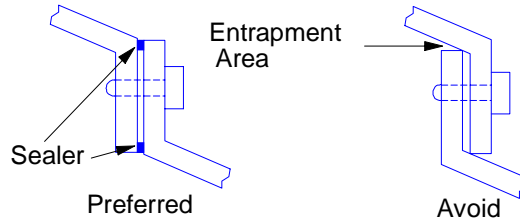


**Figure 3.7.8.1-1** Preferred design textures for joints and faying surfaces

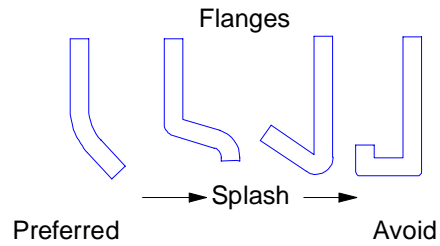
Orientation of floor panel and side panel lap joints is important in avoiding entrapment areas.



Design, and use of sealer minimizes entrapment areas.

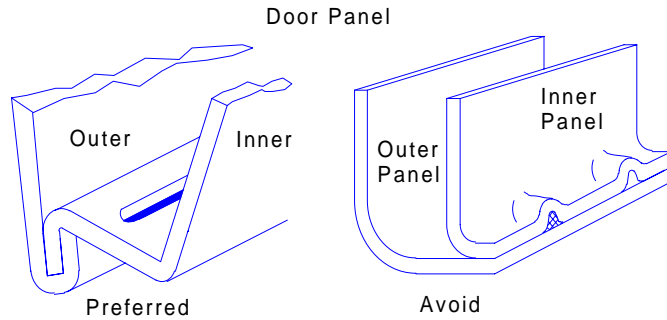


Flange orientation and design avoids entrapment of moisture and debris.

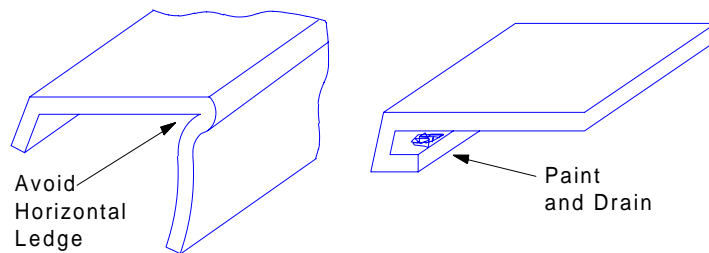


**Figure 3.7.8.1-2** Avoiding entrapment areas

Proper location of openings in lower doors can minimize chances of plugging and can enhance drainage. Design at right tends to plug with debris more easily than design at left.

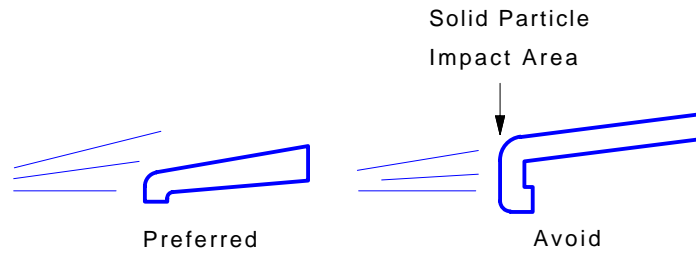


Horizontal catchment areas, as in fender at left, should be avoided. Hood section, at right, requires protective coating and drainage.

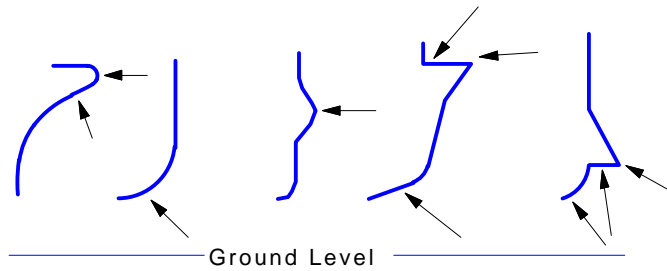


**Figure 3.7.8.1-3** Controlling entrapment areas

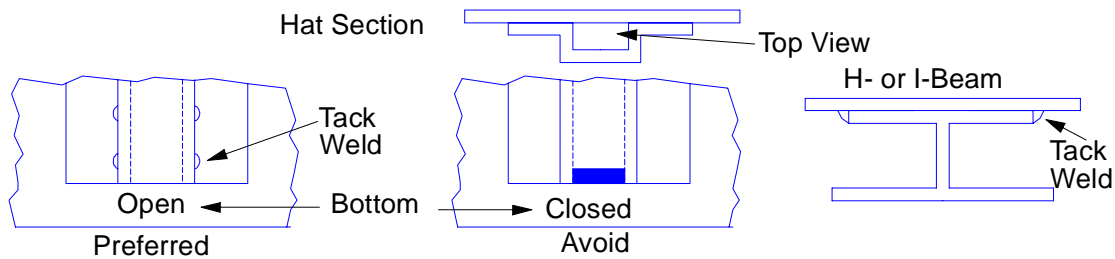
The vertical rise of components in the path of airborne solids should be minimized.



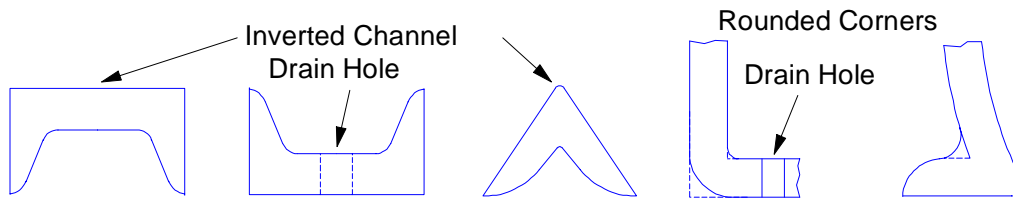
Sharp contours and certain directional design features should be minimized. (Arrows indicate areas of concern).



**Figure 3.7.8.1-4** Other design features



Hat section and H- or I-beam reinforcements are good designs but hat section should be open at bottom for easy drainage.



If not inverted, channels require drain holes to avoid entrapment areas; angle sections should have rounded corners, smooth tapers, and drain holes as indicated.

**Figure 3.7.8.1-5** Design and orientation of structural members and reinforcements

### 3.7.8.2 Aftermarket Rustproofing

The interest in aftermarket rustproofing to provide additional corrosion protection to North American-built vehicles has greatly diminished. The use of precoated steels, electrodeposition primer, and comprehensive post assembly coatings of waxes, sealers, urethane and vinyl have made aftermarket rustproofing unnecessary, according to most North American auto makers. Manufacturers of rust-inhibiting compounds are now supplying directly to the assembly lines.

The corrosion resistance is already built into today's vehicles.

### 3.7.8.3 Cathodic Protection

Cathodic protection of automobiles, in the form of sacrificial protection, is achieved using zinc coated steels to minimize body and chassis perforation corrosion, and stainless steel clad aluminum trim to control corrosion of steel body panels at trim areas.

Cathodic protection, in the form of impressed current protection, has been reported as not successful in controlling automobile body corrosion.<sup>36</sup> Field tests have demonstrated that the problems associated with automobile cathodic protection using anodes include the high resistivity of the non immersion environment.

## 3.7.9 CORROSION TEST METHODS

One of the most important and challenging tasks facing the corrosion and coatings engineers in automotive companies, steel companies, and other suppliers is that of evaluating coated steels and ranking candidate materials. Corrosion occurring over long service in the North American deicing salt/snow belt is difficult to simulate in a short time. Available methods include field surveys, on-vehicle testing, proving ground testing, atmospheric corrosion testing and laboratory testing. The ability of many of the currently methods to duplicate on-vehicle test results has been studied and ranked by the A/SP corrosion Task Force<sup>37</sup>.

### 3.7.9.1 Field Surveys

Field surveys involve inspection, often destructive, of the sheet steel components of actual vehicles with a well-defined history in a corrosive environment.

Obviously, if properly conducted with appropriate controls, this is the best and most direct way of comparing the performance of automotive materials. The environment is real, and component design and vehicle dynamics are taken into account.

However, it is time-consuming, tedious, expensive, and virtually confined to the automotive companies themselves. Faster, cheaper, yet dependable methods of evaluating materials are usually required.

### 3.7.9.2 On-Vehicle Testing

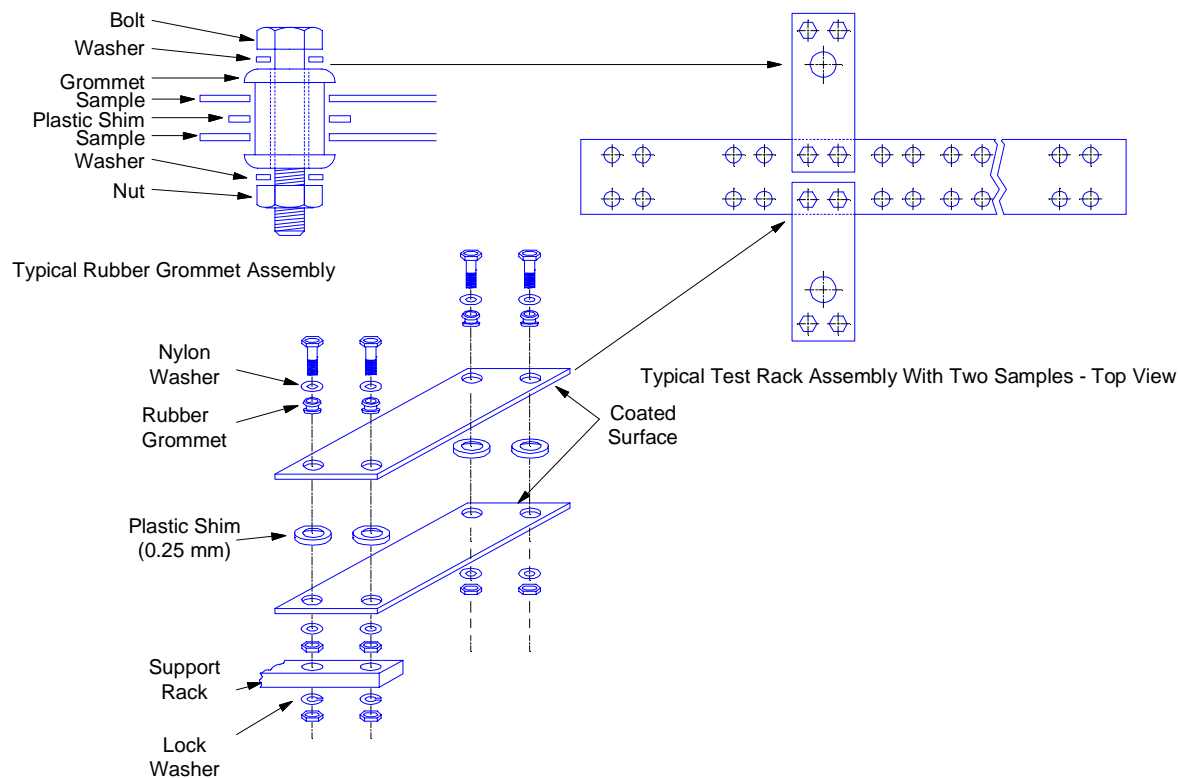
On-vehicle testing involves installing special racks with coupons on vehicles and subjecting the coupons to yearly inspections. An SAE Recommended Practice (J1293) was developed for under-vehicle corrosion testing in 1980, and updated in 1990 ([Figure 3.7.9.2-1](#)) following the work of an SAE Task Force of the Iron and Steel Technical Committee, Division 32.

It is now customary to carry out under-vehicle testing of the as-received metal precoated steels (compared with uncoated mild steel) as well as phosphated and cathodic primed metallic coated steels.

Measurements taken are usually percent surface area of base metal attack and density and depth of pitting. Although the measurements are relatively easy, the work is time consuming and tedious, and overall interpretation requires experience and good technical judgment.

On-vehicle testing of fully painted coupons of candidate materials on racks is also performed, with racks located on bumpers<sup>38</sup>, truck boxes<sup>18</sup>, and trailers.

Mobile testing is a good, relatively inexpensive method of testing that probably provides the closest simulation of actual service. As with field surveys, the test is lengthy, with at least two winters in a corrosive environment required for the under-vehicle testing, and considerably longer for the on-vehicle testing of the full paint system. In designing on-vehicle test programs, sufficient material should be provided to allow for possible attrition due to accidents, vandalism and changes in ownership.



**Figure 3.7.9.2-1** Under vehicle corrosion test assembly (SAE J1293)

### 3.7.9.3 Proving Ground Testing

Proving ground testing involves testing of prototype and production vehicles on the automotive company's proving grounds. Each automotive company has developed cycles to produce accelerated corrosion of vehicles. Test times can range from ten weeks to ten months, depending on the goal of the test proving ground. Corrosion/durability tests can simulate field experience in general metallic corrosion, cosmetic corrosion, and functional corrosion of various components and systems.<sup>39</sup> However, perforation corrosion is more difficult to accelerate.

In addition to testing of full vehicles in a realistic corrosive environment, the proving ground also tests components, assemblies, and painted test panels. These are either attached to test vehicles or towed on trailers.

For testing of perforation corrosion, a useful and practical method involves "mini-door" assemblies towed on trailers.<sup>40</sup> This allows simultaneous testing of a large array of simulated door enclosures, all subjected to the same environment at the proving ground. The mini-doors are subsequently taken apart, and both the amount and location of corrosion are determined. This has been used to quantitatively evaluate many different types and combinations of pre-coated steel in a way that would not be practical on full vehicles.<sup>41</sup>

#### **3.7.9.4 Atmospheric Corrosion Testing**

Atmospheric corrosion testing of the type used to rank coated steels for use in construction applications is used on a limited basis to rank automotive materials.

The outdoor scab test, also referred to as the modified Volvo test<sup>42</sup>, is often used for evaluating cosmetic corrosion resistance. In this test, test panels are placed outdoors on racks and sprayed with salt water twice weekly. Typical test times are one or more years.

#### **3.7.9.5 Laboratory Testing**

Laboratory testing includes salt spray (fog) testing per ASTM B117, laboratory cyclic testing and electrochemical testing.

##### **Salt Spray (Fog) Test ASTM B117**

Historically, the salt spray test has been one of the most widely used laboratory tests in automotive materials evaluation and development. However, it does not simulate the vehicle corrosion environment, either in the deicing salt/snow belt areas or coastal areas of North America, and accordingly often ranks materials differently than actual service exposure.

It is sometimes used for detecting marginal systems or highlighting poor quality samples of a system that is already known. While it may be relatively inexpensive and easy to carry out, agreement among different salt spray cabinets is often poor. Under no circumstance should it be used for research or materials development.

##### **Laboratory Cyclic Testing**

Cyclic laboratory corrosion tests involve repeated intervals of salt spray or salt water immersion, exposure to controlled humidity and temperature, and drying. Such tests provide a more realistic simulation of the environment experienced by road-driven vehicles, and they are being used increasingly in the evaluation of coated sheet products, phosphate pretreatments, and paint systems. As described in [Section 3.7.3.3](#), the mechanisms of corrosion and the relative behavior of materials under alternating wet-and-dry conditions are significantly different from what occurs under constantly wet conditions<sup>16</sup>.

In the past, each automotive company, and many of their suppliers, has developed its own cyclic corrosion test involving the use of different chemical conditions, temperatures, humidities, time periods, specimen size, configurations, and evaluation method. It has been reported that ranking of materials in the different tests does not correlate very well and little has been published on correlation between cyclic test results and actual service results.<sup>43</sup> Also the multiplicity of tests leads to confusion and problems.

A task force of the Auto/Steel Partnership, consisting of technical representatives of the major North American automakers, chemical suppliers, and steel sheet producers, has undertaken an effort to improve and standardize laboratory cyclic corrosion test. The SAE J2334 Cosmetic Corrosion Lab Test, developed by the Partnership and issued by SAE International in November 1998, shows excellent correlation to field corrosion in the North America snow belt<sup>38</sup>. The test includes two test cycles to accommodate both manual operation and automatic corrosion chamber testing. Development of a perforation corrosion test procedure by the Partnership is on going<sup>44</sup>.

### **Electrochemical Testing**

Because corrosion is generally an electrochemical process, electrochemical measurements can provide a great deal of information on rates and mechanisms of corrosion. Techniques such as linear polarization, potentiodynamic polarization, and electrochemical impedance spectroscopy are being used increasingly, spurred by the ongoing development of electronic instruments, computers and software. While these methods are particularly well-suited to fundamental studies, their application to materials evaluation has been limited by high equipment costs, need for skilled operators, and lack of standard practices.

Moreover, most electrochemical methods do little more than monitor the progress of corrosion. For purposes of materials testing, simpler means such as visual evaluation can often be conducted more quickly, at lower cost, and with greater certainty.

### **REFERENCES FOR SECTION 3.7**

1. T. C. Simpson, A. W. Bryant, G. Hook, R. A. Daley, R. J. Swinko, and R. W. Miller, "U. S. Automotive Corrosion Trends Over the Past Decade, Paper No. 394", in Corrosion and Corrosion Control of Aluminum and Steel in Lightweight Automotive Applications, NACE International, Houston, TX (1995).
2. Townsend, H. E., Coated Steel Sheets for Corrosion-Resistant Automobiles, *Materials Performance*, 30 (10), 60-65 (1991).
3. General Motors Milford Proving Grounds, "*Vehicle Corrosion Environment Canada and the United States*", Internal Document, October 1990.
4. Baboian, R., "Environmental Aspects of Automotive Corrosion Control", in Corrosion and Corrosion Control of Aluminum and Steel in Lightweight Automotive Applications, NACE International, Houston, TX (1995).
5. American Public Works Association, "*Vehicle Corrosion Caused by De-icing Salts*", Special Report #34, September 1970.
6. McCrum, R. L., "*Calcium Magnesium Acetate and Sodium Chloride as Highway Deicing Salts - A Comparative Study*", *Materials Performance*, Volume 28, Number 12, December 1989, pages 24-28.
7. "*Dust Control, Road Maintenance Costs, Cut with Calcium Chloride*" *Public Works* Vol. 121, No. 6, May 1990, pp. 83-84.

8. Townsend, H. E., Behavior of Painted Steel and Aluminum Sheet in Laboratory Automotive Corrosion Tests, Corrosion, 52 (1), 66-71 (1996).
9. Bittance, J. C., "Waging War on Rust, Part I: Understanding Rust", Machine Design, October 7, 1976, pages 108-113; Part II: "Resisting Rust," Machine Design, November 11, 1976, pages 146-152.
10. Rosenfeld, L. and Marshakov, J. K., "Mechanism of Crevice Corrosion", Corrosion Vol. 20, 1964, p. 115t.
11. France, Jr., W.D., "Crevice Corrosion in Metals", Localized Corrosion - Cause of Metal Failure, ASTM STP 516, American Society Testing & Materials, 1972, p. 164.
12. Hospadaruk, V., "Corrosion Fundamental and Their Application to Automobiles", Automotive Corrosion by Deicing Salts, R. Baboian, NACE, Houston 1981.
13. Fenton, J., "Long Term Corrosion Prevention", Automotive Engineer Vol. 9, No. 1, February/March 1984, p. 39.
14. Uhlig, H., "Filiform Corrosion, " Corrosion and Corrosion Control, Wiley, New York, 1971, p. 252.
15. Van Ooij, W. J., and Sabata, A., Corrosion 46 (2) p. 162-171 (1990).
16. Shastry, C. R., and Townsend, H. E., Corrosion 45 (2), p. 103-119 (1989).
17. Carson, C. G., and Peterson, P. T., "Challenges and Opportunities for Coated Steel Products", Proceedings of the USI 23rd Annual Meeting and Conference, Berlin, Federal Republic of Germany, October 1989.
18. Ostermiller, M. R., and Townsend, H. E., On-Vehicle Cosmetic Corrosion Evaluation of Coated and Cold-Rolled Steel Sheet, Proceedings of the Sixth Automotive Corrosion and Prevention Conference, P-268, Society of Automotive Engineers, Warrendale, PA (1993), pp. 65-83
19. Dorsett, T. E., Development of a Composite Coating for Pre-Coated Automotive Sheet Metal, SAE Paper 862027, December 1986.
20. Watanabe, T., et al., Development of Organic Composite Coated Steel Sheets with Bake Hardenability and High Corrosion Resistance, Proceedings of International Conference on Zinc and Zinc Alloy Coated Steel Sheet, GALVATECH '89, September 1989.
21. Ostermiller, M. R., Phiepho, L. L., Singer, L. and Raymond, L., "Advances in Automotive Corrosion Resistance," Proceedings of the Fourth International Conference on Zinc and Zinc-Alloy Coated Sheet, The Iron and Steel Society of Japan, Tokyo, pp. 678-685 (1998)
22. U.S. Shipments of Steel Mill Products", in Metal Statistics 1997, Ferrous Edition, American Metal Market, New York (1997).

23. Rausch, W., Die Phosphatierung von Metallen, (Eugene G. Lenz Verlag, 1974).
24. Lorin, G., Phosphating of Metals, (Finishing Publications, 1974).
25. Freeman, D. B., Phosphating and metal pre-treatment, (Woodhead-Faulkner, Cambridge, England, 1986).
26. Knaster, M. B. and Parks, J. M., Mechanism of Corrosion and Delamination of Painted, Phosphated Steel During Accelerated Corrosion Testing, Paper No. 860110, National SAE Meeting, 1986.
27. Mischke, P., Manganmodifizierung Stetzt Sich Durch, Industrie Anzeiger, 78/1987, p. 26.
28. Preparing Steel for Organic Coatings, Products Finishing Directory, 1989, p. 6.
29. Jernstedt, G. W., US Patent 2,310,239 Jernstedt, G. W., Trans. Electrochemical Society, 83, (1943), 361.
30. Simpson, M. W. and Zurilla, R. W., Phosphate Final Rinse Options, Pretreat 90, November 1990.
31. Richardson, M. D. W. and Freeman, D. B., Pretreatment and Cathodic Paint Performance - Use of the "*P/P&H Ratio*", Trans. IMF, 1986.
32. Kent, G. D. and Petschel, M., Polycrystalline Conversion Coatings, Products Finishing, September 1988.
33. Jones, T. C., and Fristad, W. E., Applications and Advances in Autodeposition Coatings," in Corrosion Prevention, SP-1265, Society of Automotive Engineers, Warrendale, PA, pp.1-10 (1997).
34. "*Prevention of Corrosion of Metals*", Handbook Supplement HSJ 447, Society of Automotive Engineers, Warrendale, PA 1981.
35. Rowe, L. C., "*The Application of Corrosion Principles to Design*", Paper No. 770292, presented at SAE Automotive Engineering Congress, Detroit, Michigan, February 1977.
36. Baboian, R., "*Cathodic Protection of Automobiles - Does It Work?*" Materials Performance, Vol. 26, No. 7, July 87, p. 82-88.
37. H. E. Townsend, D. D. Davidson, and M. R. Ostermiller, "Development of Laboratory Corrosion Tests by the Automotive and Steel Industries of North America", in Proceedings of the Fourth International Conference on Zinc and Zinc-Alloy Coated Sheet Steels", The Iron and Steel Institute of Japan, Toyko (1998), pp. 659-666.
38. M. W. Simpson, W. B. van der Linde, D. C. McCune, and H. E. Townsend, License-Plate Cosmetic Corrosion Tests of Automotive Coated Steel Sheet, NACE International Paper No. 98553 (1998).

39. Schumacher, W. A., "*Proving Ground Vehicle Corrosion Testing*", Automotive Corrosion & Prevention Conference, Dearborn Michigan, December 5-7, 1983.
40. Ostermiller, M. R., Piepho, L. L., Singer, L., Oldenburg, W. C., and Dorsett, T. E., "*Simulation of Perforation Corrosion Mechanism Using 'Mini-Door' Test Panels*", ASM World Conference, September 24-30, 1988, Published in Corrosion Resistant Automotive Sheet Steels, L. Allegra Ed., ASM International, Metals Park, Ohio.
41. Oldenburg, W., Dorsett, T., and Masterson, T., "*Perforation Corrosion Performance of Various Materials Using Mini-Door Test Specimens Correlated with Vehicle Road and Laboratory Test Results*", S.A.E. Automotive Corrosion and Prevention Conference, December 4-5, 1989, Paper No. 892579. Published in S.A.E. Publication, p. 228.
42. Stephens, M. L., Davidson, D.O., Soreide, L. E., and Shiffer, R. J. Paper No. 862013, Society of Automotive Engineers, Warrendale, Pennsylvania (1986).
43. Kent, Gary D., Hacias, Kenneth J., and Fotinos, Nicephoros A., "*Laboratory Evaluation of Automotive Conversion Coatings*", Paper No. 831812, SAE Automotive Corrosion and Prevention Conference, Dearborn, Michigan, December 5-7, 1983.
44. "SAE J2334, Cosmetic Corrosion Lab Test", SAE International, Warrendale, PA (1998).

