



The results and discussions demonstrate that uncoated weathering steels should not be exposed in the following conditions: marine or heavily industrial environment, high rainfall or humidity conditions, sheltered conditions, and some other bad design conditions. Therefore, for proper bridge design, the micro-environment as well as the macro-environment should be considered with caution and a study of previous experience by a corrosion engineer as a significant factor in preventing further corrosion.

CORROSION RESISTANCE OF WEATHERING STEELS

by

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# 1 Introduction

## 1.1 Background

The direct cost of steel bridge corrosion has been a major problem for state highway departments over the years. According to a recent report issued by the Federal Highway Administration, the total direct cost of metal corrosion in 26 industrial sectors is \$276 billion per year (Koch et al. 2002). Of that amount, highway bridges made of steel and concrete account for \$3.79 billion per year, which covers:

“Cost to replace structurally deficient bridges; and corrosion associated life-cycle cost for remaining (nondeficient) bridges, including the cost of construction, routine maintenance, patching, and rehabilitation. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion” (Koch et al. 2002, pp. 24)

To reduce both the initial and the maintenance painting costs, engineers in many states have increasingly been designing bridges made of bare, exposed weathering steel. However, after many years of experience, bridges in the snow belt states of the Midwest and Northeast, the Gulf Coast states, and the high rainfall and foggy regions along the West Coast have revealed problems caused by continuous wetness of the steel structure. Engineers are concerned about the long-term performance of weathering steel bridges.

Nevertheless, as with all new materials, much research has been conducted to find solutions for atmospheric corrosion to enhance the

successful application of weathering steel to bridges. The more economic benefit will be a savings in life cycle cost by eliminating the need for initial painting and periodic repainting of the entire superstructure. Research has also helped to identify design problems and corrosive microenvironments in which steel rusts excessively, such as: angle of exposure to the elements depending on the latitude of each site, skyward or groundward orientation, sheltered conditions with continuous moisture, and heavy concentrations of pollutants from rainfall or salt spray, dirt, and debris in industrial and marine environments.

This thesis summarizes the corrosion behavior not only of weathering steel, but also copper steel, and carbon steel (introduced in section 1.3) under localized microenvironment conditions. Additionally, the following parameters are investigated based on data reported by many researchers: angle of exposure, orientation, shelter, continuously moist conditions, industrial pollutants, deicing salts, galvanic corrosion, pitting and crevices.

## **1.2 Objectives**

For safety and economic reasons, controlling the corrosion damage to steel structures under service conditions has been a main concern of engineers. The unappealing sight of steel corrosion is not the only material damage. Excessive corrosion can lead to section loss and, thus, higher stresses in member sections. Therefore, the many factors, which affect the

corrosion behavior reported in the literature, have been reviewed, and much data analyzed.

Following up on an earlier the report by Albrecht and Naeemi (1984), this thesis illustrates the conditions that should be avoided to ensure successful performance of weathering steel for the infrastructure and also provides engineers with suggested guidelines for proper application of weathering steel in highway structures.

### **1.3 Type of Steel**

ASTM A242 and A588 weathering steels were used in most atmospheric exposure studies, along with copper and carbon steels as references. The alloying elements that contribute to the corrosion resistance of weathering steel are phosphorus (P), copper (Cu), nickel (Ni), Chromium (Cr), and Silicon (Si).

#### **1.3.1 A242 Steel**

A242 steel is a high-strength, low-alloy structural steel with “enhanced atmospheric corrosion resistance of approximately two times that of carbon structural steels with copper, which is equivalent to four times carbon structural steel without copper (0.02% Cu max.).”

The chemical compositions are listed in Table 1. 1. The 1968 ASTM A242 specification listed two grades: Type 1 and Type 2. While the contents of Cu and P are restricted, the steel producers are free to select the contents of Si, Ni, and Cr.

Type 1 steel, called simply A242, has higher corrosion resistance than Type 2 because it contains more phosphorous, 0.15 % P max.

Type 2 steel, replaced in 1968 by the A588 steel, has lower corrosion resistance than Type 1, because it contains less phosphorous, 0.04% P max, which improves weldability.

### **1. 3. 2      A588 Steel**

A new ASTM specification for weathering steel, first issued in 1968, was designated A588, “High-Strength Low-Alloy Structural Steel with 345 MPa Minimum Yield Point to 100 mm Thick.” A588 steel contains less phosphorous and is a leaner version of the A242 steel. It is less corrosive and is also easier to weld.

The A588 steel initially listed Grades A, B, C, D, E, F, G, H, J, and K, yet many grades also were deleted when steel companies went into bankruptcy or were bought by other steel companies. The latest edition of the A588 ASTM specification lists only four grades, A to C and K. See Table 1. 1.

### **1. 3. 3      Carbon Steel**

Carbon steel is alloyed with manganese, carbon, and trace amounts of sulfur, phosphorus, and copper (0.02% max.; copper steel is defined as having 0.02% Cu minimum). In all previous studies, carbon steel has been exposed along with weathering steel for comparison.

## **1. 4 Type of Environment**

The specimens were exposed in rural, industrial, and marine environments that are generally described as follows:

### **1. 4. 1 Rural Environments**

Rural environments are related to the countryside as opposed to the city: for example, most residential areas have farms. The air typically contains small amounts of sulfur oxides ( $\text{SO}_x$ ), carbon dioxide ( $\text{CO}_2$ ), and ammonia ( $\text{NH}_3$ ) respectively, from industrial waste, combustion products, and decomposition of fertilizer or animal excrement. Therefore, the rural environments are not generally aggressive against steel.

### **1. 4. 2 Industrial Environments**

Many factories located in industrial environments emit pollutants such as sulfur oxides ( $\text{SO}_x$ ), nitrogen oxides ( $\text{NO}_x$ ), and various industrial gases. Sulfur oxides ( $\text{SO}_x$ ) are the cause of acid rain. Industrial environments are sometimes called semi-industrial or severe industrial, depending on the corrosivity of the atmosphere.

### **1. 4. 3 Marine Environments**

Marine environments along coastal areas contain air-borne salt released into the atmosphere by waves breaking on the shoreline or by on-shore wind and fog. The aggressiveness of a marine environment depends on the nature of the wave action at the surf line, prevailing wind direction, shoreline topography, and relative humidity. The corrosion severity increases

rapidly as the distance from the shore decreases. Severe storms can carry salt spray far inland.

## 2 Angle of Exposure

Steel specimens corrode least at an angle equal to the latitude of the test site because they seem to receive sunshine directly, if horizontally exposed facing south. As an example, most published data on atmospheric corrosion in the United States are based on an angle 30 degree (deg) from the horizontal, while specimens in European countries are usually exposed at 45 deg facing south, owing to the higher latitudes.

Cosaboom et al. (1979) and Zoccola (1976) measured the thickness loss per surface of specimens mounted vertically, horizontally, and at a 30-deg angle. Komp et al. (1992) produced worldwide exposure test data for A588 grade A steel specimens, which were exposed at six sites at 45 deg and vertically.

Larrabee (1966) reported that the angle at which specimens are exposed to the environments relative to the horizontal, affected the degree of thickness loss induced by corrosion.

### 2.1 Cosaboom et al. (1979)

- Environment: Newark, NJ, industrial
- Test sites: Roof of DOT building  
Center-span girder of bridge No. 9 on I-78
- Steels: A242 steel (0.11% P, 0.29% Si, 0.66% Ni,  
0.52% Cr, 0.27% Cu)  
Carbon steel (0.007% P, 0.005% Si, 0.01% Ni,

0.02% Cr, 0.024% Cu)

- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical, horizontal, and 30 deg facing south
- Exposure time: 1968 – 1984 (16 years)

Cosaboom et al. (1979) explained that “the site was selected to expose the specimens to what were considered the most corrosive atmospheric conditions.” 30-deg specimens, which were close to the latitude of the site, were corroded less than horizontal and vertical specimens because they washed and dried within a short time after the rainfall, as shown in Fig. 2.1(a) Roof, N.J. DOT.

On the other hand, Fig. 2.1(b) Bridge Girder, I-78 shows that the difference between corrosion at the vertical and horizontal conditions at the bridge-mounted specimens is very small because these specimens were mounted on an interior beam located at the center-span of a bridge girder on I-78. According to Cosaboom et al. (1979), the bridge was opened to traffic after several years, and was found to be free from salt spray or exhaust fumes. Nevertheless, in comparison to the A242 steel specimens, carbon steel corroded more on the bridge than when it was located on the roof. According to Cosaboom et al. (1979), “carbon steel is highly sensitive to atmospheric conditions.”

## 2.2 Zoccola (1976)

Zoccola reported the result of corrosion tests conducted at the Eight-Mile Road Interchange near Detroit with two exposure conditions: vertical and horizontal.

- Environment: Detroit, MI, industrial
- Test sites: Roof of National Guard Armory  
Interior girder of Eight-Mile Road Bridge next to the wall
- Steels: A242 steel (Test 1: 0.077% P, 0.24% Si, 0.75% Ni, 0.56% Cr, 0.24% Cu)  
(Test 2: 0.08% P, 0.36% Si, 0.72% Ni, 0.64% Cr, 0.34% Cu)  
Carbon steel (Test 2: 0.011% P, 0.05% Si, --% Ni, --% Cr, 0.015% Cu)
- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical and horizontal
- Exposure time: 1966 – 1974 (8 years)

The horizontal specimens corroded more than the vertical specimens, unpredictably contrary to the test by Cosaboom et al. (1979) reported in section 2.1. Zoccola (1976) described how the test site was subjected to accumulated road dirt and salts on steel surfaces. There was a high retaining wall along the shoulder of the highway beneath the low-level service bridges and tunnel-like conditions in the underpass next to the wall. For this reason,

road spray, dirt and salts were carried by the air blast created by the heavy traffic on the expressway, and easily contaminated the horizontal specimen. The prolonged wetness caused by deposits, chlorides, and sulfates in close contact with the steel accelerates corrosion.

### **2.3 Worldwide Data**

U. S. Steel initiated a worldwide study, called the Cor-Ten Licensees Demonstration Program, to develop corrosion data for its Cor-Ten steel in 1972. The data from three countries out of the eight participating in this program were analyzed. Those three countries were the United States (US), the United Kingdom (UK), and Germany (G). The tests were conducted in rural, industrial and marine environments. More information about the steel compositions and sites is shown in Table 2.2.

The results of the study are presented as thickness loss curves in Figs. 2.3 to 2.8 organized by type of environment and type of steel. Each figure compares a 30 deg angle of exposure with a 90 deg angle of exposure, taking the average of the data for thickness loss curves, in three countries: US, UK, and Germany. Since the United Kingdom extends from 50 to 60 deg latitude, 90 deg specimens were corroded less than 30 deg in all three rural, industrial, and marine environments. The United Kingdom is located between the North Atlantic Ocean and the North Sea, where prevailing southwest winds over the North Atlantic, picking up a lot of moisture. Therefore, more corrosion thickness loss per surface occurs on the specimens in UK than in the US.

Moreover, the data from the specimens mounted at 90 deg in the German industrial atmosphere show similar behaviors to the 30 deg specimens in the United Kingdom.

## **2.4 Results and Discussion**

The experiments of Cosaboom et al. (1979), Zoccola (1976), and the worldwide data shows that weathering steel, A242 and A588 steels, corroded less than carbon steel in rural, industrial, and marine environments. In addition, the specimens facing south at 30-deg corroded less than vertical and horizontal specimens as shown in Fig. 2.1 (Cosaboom et al. 1979) and Fig. 2.3 to 2.8 from the worldwide data.

As generally expected, vertical specimens on the roof from Cosaboom et al. (1979) were less corroded than horizontal and 30-deg specimens under bald exposure. However, Zoccola (1976) did not confirm this expectation because the corrosion rates of horizontal specimens in both cases were higher than those of vertical specimens. Since there was a traffic way below the bridge, salt spray was kicked up by the traffic and accumulated more densely on the horizontal specimens than on the vertical specimens, owing to presence of water in the drainage. Nevertheless, microclimate conditions affecting the corrosion of steel might be studied as further research.

### 3 Orientation

Skyward or groundward orientation can affect the atmospheric corrosion rate of weathering steel. The skyward surface of steel specimens is generally expected to be wet a shorter time than the groundward surface, which receives no sunshine.

Larrabee (1944) and Zoccola (1976) painted one side and left unpainted the other side of each steel specimen tested, and then they exposed the specimens skyward and groundward. The thickness losses per surface were measured in rural and industrial environments in both experiments.

#### 3.1 Larrabee (1944)

- Environments: South Bend PA, semi-rural <sup>a</sup>  
Kearny NJ, industrial <sup>b</sup>
- Steels: HSLA steel (0.15% P, 0.89% Si, 0.04% Ni,  
1.00% Cr, 0.36% Cu)  
Copper steel (0.024% P, 0.025% Si, 0.02% Ni,  
0.02% Cr, 0.32% Cu)  
Carbon steel (0.019% P, 0.043% Si, 0.02% Ni,  
0.02% Cr, 0.024% Cu)
- Specimen size: 152 X 102 mm
- Angle of exposure: 30 deg facing south
- Orientation: Skyward and groundward



--% Cr, 0.015% Cu)

- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical and horizontal
- Exposure time: 1966 – 1974 (8 years)

According to Zoccola (1976), “the steel panels had been installed on the weathering steel beams of the Westbound Service Bridge, in a vertical position to simulate the beam web and horizontal-top and horizontal-bottom to parallel the beam flanges.” For comparison purposes, specimens were also located on the roof of a nearby building not affected by road spray, salts and soil. Plain carbon steel and Mayari R steel were placed at both sites in a later, second test (see Fig 3.2(a) and Fig 3.2(b)).

Zoccola (1976) described in detail the 3-bridge site at the complex interchange: two low-level service bridges, westbound and eastbound, and a high-level viaduct in between. Structural beams or plates of the bridges were all Mayari R steel. The exposed specimens were attached under the overpass stretching above the southbound section of the James Couzens Expressway. The southbound sections had a high-concrete retaining wall on one side and relatively close concrete abutments on the other side, whereas the northbound sections above the lanes were relatively open. The clear height of the service bridges was about 14.5 feet above the expressway. These northbound sections, moreover, were adjacent to the exit and entrance ramps that slowed traffic and released a great amount of road spray (Larrabee 1944).

In the results, successful performances were recorded for both the Mayari R steel specimens on the bridges above the expressway and for the building roof. On the roof was created a uniform, pleasing, protective, whereas flaking rust and road dirt and salts accumulated on the weathering steel beams of the two underpasses of the service bridges above the southbound lanes of the expressway, and on the 8-year corrosion specimens in one of the underpasses. Zoccola (1976) concluded that the accumulated deposits of road salts, debris, and corrosion products may be a reason for the severe corrosion of weathering steel, which was enough to keep the surfaces wet and trap chlorides and sulfates.

### **3.3 Results and Discussion**

The weathering steel panels performed with lower corrosion rate than other copper and carbon steels in the experiments of Larrabee (1944) and Zoccola (1976), as generally expected: the corrosion rate of the skyward specimens was lower than that of the groundward ones (Fig. 3.1 and Fig. 3.2(b)). The specimens, especially carbon and copper steels, corroded more in industrial Kearny, NJ, than in rural South Bend, PA. The thickness losses per surface of low-alloy steel in both rural and industrial atmospheres slowly increased; however, that of copper or carbon steel apparently grew especially at industrial Kearny, NJ, as seen in Fig 3.1.

On the other hand, the result of the corrosion rates in Fig. 3.2(a) Interior Girder was not clear: The thickness loss per surface on the skyward and

groundward specimens of carbon steel was very similar to each other. The corrosion rate of A242 steel on the skyward surface was even higher than on the groundward surface because the interior girder was located in the sheltered area where there was a high-concrete retaining wall on one side and abutments on the other side. As mentioned before in section 3.2, the location of the specimen could be considered as a significant factor in preventing further corrosion.

## 4 Shelter

The sheltered condition from wind, rain, and sunshine is contrasted with directly exposed conditions. The sheltered locations are between steel interior girders under the concrete deck, while the exposed location is on the open roof. This chapter provides information on how the conditions of shelter affect the severity of atmospheric corrosion of weathering steel in each rural, industrial, and marine area.

Larrabee (1966), Zoccola (1976), Cosaboom et al. (1979), and McKenzie (1978) conducted tests under both sheltered and open exposures to clarify the effect of shelter on the corrosion of weathering steel.

Sheltered racks were used for the experiment by Larrabee (1966) and Zoccola (1976), whereas Cosaboom et al. (1979) conducted experiments by attaching the specimens on an interior girder to achieve a sheltered effect, and on the roof to simulate an open exposure. McKenzie (1978) also examined specimens on an interior girder, and exposed a set of specimens, not on the roof, but in the open, facing prevailing winds.

### 4.1 Larrabee (1966)

- Environments: South Bend PA, semi-rural <sup>a</sup>  
Kearny NJ, industrial <sup>b</sup>
- Steels: HSLA steel (0.15% P, 0.89% Si, 0.04% Ni,  
1.00% Cr, 0.36% Cu)

Copper steel (0.024% P, 0.025% Si, 0.02% Ni,  
0.02% Cr, 0.32% Cu)

Carbon steel (0.019% P, 0.043% Si, 0.02% Ni,  
0.02% Cr, 0.024% Cu)

- Specimen size: 152 X 102 mm
- Angle of exposure: 30 deg facing south
- Orientation: Skyward and groundward
- Exposure time:
  - a. 1936 – 1959 (23 years)
  - b. 1936 – 1956 (20 years)

In the Larrabee (1966) experiment, groups of five specimens each were vertically exposed as shown in Fig. 4.1 (a). Specimens 1 and 2 were entirely sheltered and specimen 3 was partially sheltered. Baldly exposed specimens 4 and 5 were hit by wind, rain, and sunshine. The sheltered test racks were located in semi-rural South Bend, PA, and in marine Kure Beach, NC. The corrosion results at both sites are summarized in Table 4.1. The two bottom specimens facing south or west received more sunlight than did those higher specimens facing north: the longer exposure to sunlight seems to have resulted in a more protective rust layer on the bottom specimens. The corrosion rates of specimens 4 and 5 were obviously lower than those of the other three specimens. Specimens 2 and 3 were, on the other hand, more severely corroded due to prolonged wet periods under the shelter. Specimen 1 was in good condition, being sheltered from both water and sunshine.

The four-year data for carbon steel was plotted differently for the marine atmosphere, Kure Beach, NC in Fig. 4.1 (c) and Table 4.1. More seawater spray and deposits by hurricane-force winds led to extreme corrosion of the specimens facing east, contrary to the specimens facing west, which received the least amount of seawater spray during the first few months of the test period. Additionally, the rain washed the salt sprays from the rust of the bottom specimens, 4 and 5. They were the least corroded (Larrabee 1966).

## 4.2 Cosaboom et al. (1979)

- Environment: Newark, NJ, industrial
- Test sites: Roof of DOT building  
Center-span girder of bridge No. 9 on I-78
- Steels: A242 steel (0.11% P, 0.29% Si, 0.66% Ni,  
0.52% Cr, 0.27% Cu)  
Carbon steel (0.007% P, 0.005% Si, 0.01% Ni,  
0.02% Cr, 0.024% Cu)
- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical, horizontal, and 30 deg facing south
- Exposure time: 1968 – 1984 (16 years)

The data from Cosaboom et al. (1979) provided corrosion data for A242 and carbon steels in industrial Newark, NJ. The specimens were mounted vertically and horizontally on the interior and exterior girders of Bridge No. 9 on Interstate I-78, Section 5V, and on the roof of a nearby two-story building

occupied by the New Jersey Department of Transportation. There was a 6.5-year gap after construction until the bridge was opened and exposure of the weathering steel specimens began; therefore, there was no traffic either on or below the bridge during time that the bridge was closed. Vertical and horizontal specimens were used to imitate a web or a flange of the girder. In both vertical and horizontal cases, the bridge-sheltered specimens lost up to 65 percent more thickness of A242 and carbon steels than those baldly exposed on the building roof. Moreover, the vertical specimens corroded more on the interior girders than the exterior girders, while the horizontal specimens corroded almost the same on interior and exterior girders.

The corrosion loss per surface at mid-span of an interior girder was not different than corrosion loss per surface near the abutment because the bridge had been newly constructed and the test had been delayed for the initial 6.5 years without any traffic. As a result, there was no salt-contaminated water and accumulated debris near the abutments (Cosaboom et al. 1976).

### **4.3 Zoccola (1976)**

- Environment: Detroit, MI, industrial
- Test sites: Roof of National Guard Armory  
Interior girder of Eight-Mile Road Bridge next to the wall
- Steels: A242 steel (Test 1: 0.077% P, 0.24% Si, 0.75% Ni, 0.56% Cr, 0.24% Cu)

(Test 2: 0.08% P, 0.36% Si, 0.72% Ni,  
0.64% Cr, 0.34% Cu)

Carbon steel (Test 2: 0.011% P, 0.05% Si, --% Ni,  
--% Cr, 0.015% Cu)

- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical and horizontal
- Exposure time: 1966 – 1974 (8 years)

Zoccola examined the corrosion test with A242 and carbon steels in Detroit, Mich. The vertical specimens were attached on an interior girder of Eight-Mile Road over US highway 10 and the roof of the National Guard Armory, near the bridge. The bridge was opened to traffic in 1964; the freeway below, in 1965. Corrosion specimens were exposed in the tunnel-like underpass of the westbound service bridge above the southbound lanes of the expressway. (More detailed test information was mentioned in Chapter 3.)

A242 and carbon steels in Fig. 4.3 were both two times more corroded on sheltered interior girders than on open exposures. The A242 steel was less corroded than the carbon steel on the roof of the Armory, while there was poor behavior of A242 steel on an interior girder. It can be argued that this expressway demonstrated a major problem for weathering steel corrosion exposed to traffic fumes, road salt, and dirt which caused the specimens to develop heavy, flaky rust and a significant accumulation of deposits.

#### 4.4 McKenzie (1978)

- Environment: Iden bridge Sussex, UK, rural  
Loudwater Buckinghamshire, UK, rural  
Tinsley Yorkshire, UK, industrial  
Shoreham Sussex, UK, marine
- Test sites: (1) Open, facing the direction of prevailing wind  
(2) Underside of a thermally insulated beam
- Steels: A588 steel (0.01% P, 0.031% Si, 0.27% Ni,  
0.12% Cr, 0.22% Cu)  
Carbon steel (0.025% P, 0.28% Si, -- % Ni,  
0.57% Cr, 0.31% Cu)
- Angle of exposure: Vertical
- Exposure time: 5 years

In this last experiment, Albrecht and Naeemi (1984) plotted British data from Mckenzie (1978) at several test sites chosen in two rural areas, Iden and Loudwater; industrial Tinsley, and marine Shoreham by the Sea.

Duplicate specimens of each steel were removed from each exposure position annually for periods of up to five years. After derusting, corrosion rates were established by weight loss over the exposure period. The specimens were examined for pitting and in some cases measurements of pit depths. Environment conditions are shown in Table 4.2.

McKenzie (1978) concluded the corrosion rates were as follows (actual test sites are shown in Fig. 4.5 and Fig. 4.6):

- **Open exposure:** “the special mild steel corrosion rates and the Cor-Ten B rates are shown Fig. 4.2. Cor-Ten B corroded at a generally lower rate than the special mild steel and although there were signs of a reduction in corrosion rate with time, at none of the sites could the corrosion rate be considered negligible.” (Mckenzie 1978, pp. 4–5)
- **Comparison of open exposure and bridge sheltering:** “the corrosion time curves for Tinsley, Loudwater, Eastney and Iden are shown in Fig. 4.3. It is clear from these that the corrosion rates measured beneath a bridge can differ considerably from those measured in open exposure. At Tinsley and Loudwater, bridge sheltered corrosion rates for both steels were much lower than in open exposure over the period of the test. At the marine site however the opposite was found, indicating the particularly adverse effect of chlorides under sheltered conditions. At Iden, open exposure and bridge-sheltered rates were similar. There were also differences between the shapes of the corrosion time curves in open and bridge-sheltered exposure. In particular, at Loudwater, there was very little sign of a reduction in corrosion rate with time under bridge sheltering so that, for Cor-Ten B, the corrosion rate over the last two years of the test was higher than in open exposure.” (Mckenzie 1978, pp. 4–5)

## 4.5 Results and Discussion

Larrabee (1966): the use of sheltered racks gave us an idea of which locations may prevent corrosion. Perfectly sheltered specimen 1 was less corroded than specimens 2 and 3. Specimens 2 and 3 were severely penetrated by corrosion because of prolonged wet periods under the shelter. Additionally, the corrosion rates of specimens 4 and 5 were obviously lower than other specimens, as mentioned by Larrabee (1966).

Cosaboom et al. (1979) and Zoccola (1976): the specimens were mounted vertically and horizontally for each experiment, but only data on the thickness loss per surface from vertical specimens was taken for Fig. 4.3 (Zoccola 1976) because the performances of A242 and carbon steels were in line with expectations. The two experiments showed that A242 and carbon steels on interior girders were all less corroded than on roof locations. However, both A242 and carbon steel specimens performed in a similar fashion in sheltered conditions (see Fig. 4.3).

McKenzie (1978) found that open exposure corrosion rates were apparently higher than the sheltered exposure rates especially in the Tinsley, industrial environment. These results were quite contrary to other experiments. It appeared that the major influence on corrosion was the level of atmospheric sulfur compounds where the climate was misty and humid. Average atmospheric sulfur compounds in Tinsley (industrial) were almost five times other areas. The cause of corrosion in continuous moisture conditions with sulfur compounds will be discussed in the next chapter. Chloride was also an

important factor in the corrosion rate under sheltered conditions as shown in Fig. 4.4. In this instance, chloride built up and increased corrosion rates under the shelter. Therefore, we might conclude that this type of sheltering structure is not appropriate for the marine environment.

## 5 Continuously Moist Conditions

Wranglen (1972, p. 62) commented that “Atmospheric corrosion in general is the result of the conjoint action of two factors: oxygen and moisture (water in liquid form). If one of these factors is missing, corrosion does not occur. In dry air, as under the freezing point or a relative humidity (RH) less than about 60%, steel does not rust. Corrosion is therefore negligible in polar regions and in hot deserts. Indoors in heated, for example dry localities, steel does not rust either. In unheated premises, however, the humidity may be so high that rusting can occur”

Moisture also can be deposited by capillary action as well as direct precipitation. The porous rust coating and salt deposits on the steel surface absorb moisture due to capillary action promoted by pores and cracks in the rust coating as well as crevices and small pits.

At a relative humidity well below 100%, moisture can cause corrosion of the surface by acting as a thin and invisible film of electrolyte. The critical RH depends on the type of metal, surface contaminants, atmospheric pollutants, and the nature of the corrosion product. Above this critical RH, the atmospheric corrosion rate increases rapidly (Albrecht and Hall 2003).

### 5.1 Chemical Reaction of Steel Corrosion

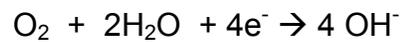
When the iron is exposed in a humid and clean rural atmosphere, the first oxidation product is a ferrous ion in the lowest oxidation state,  $\text{Fe}^{+2}$ . The ferrous ion can react with moisture and precipitate ferrous hydroxide due to

the presence of air dissolved in moisture. Albrecht and Naeemi (1984) indicated the chemical development suggested by Kunze (1974) and others as follows:

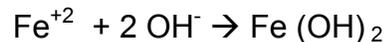
- i. The anodic iron dissolves in the condensed moisture film.



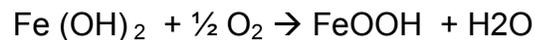
To counterbalance this reaction, the cathode accepts the electrons and passes them on to oxygen converted to hydroxyl 1 ion.



- ii. With free ferrous ions and free hydroxyl 1 ions in solution, the following reaction occurs:



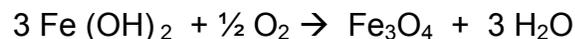
- iii. The fresh ferrous hydroxide is then oxidized by air to produce hydrated ferric oxide.



The following reactions may take place instead of those listed in steps ii and iii. The final product is hydrated ferric oxide in both cases.



- iv. When the supply of oxygen is not sufficient, the reaction takes place:



Or, as suggested by Hiller (1966),



The aforementioned humidity film reactions occur in clean rural environments. This process is rather slow. Moist air, including dust and pollutants, more actively and quickly rusts the iron (Evans 1972). The rapid corrosion in industrial atmospheres will be briefly discussed in section 5.3 and later in detail in Chapter 6.

## **5.2 Capillary Action**

Capillary action also effects the moist corrosion of weathering steels. It is a physical effect caused by the interactions of a liquid with the weathering steel surface. Moisture from direct precipitation of rain or snow can be deposited by capillary effect on the porous oxide coating, and absorbed by corrosion by-products or salt deposits on the surface. Pores in the oxide coating, cracks, and crevices can foster capillary action. Small pits, the space between the steel surface, and settled specks of dust also accelerate capillary action. Forces of attraction increase between water molecules and the solid surface to absorb condensation of water vapor on the surface of a solid (Tomashov 1966).

## **5.3 Relative Humidity**

Vernon conducted experiments that showed the effect of relative humidity on rusting. He examined carbon steel specimens in bell-jar atmospheres with controlled humidity, SO<sub>2</sub> content, and temperature. As shown in Fig. 5.2, little corrosion occurred in pure air below 100% relative

humidity; however, serious rusting was found on the specimen in the air with a certain critical humidity and even a small amount of sulfur dioxide.

When the SO<sub>2</sub> content was raised to 0.01 percent, the critical relative humidity dropped to 60 % and corrosion increased substantially. At 0.01 percent SO<sub>2</sub> content and increased relative humidity of 70, 75, and 99 percent, steel corroded 7, 8, and 12 times as much, respectively, than in 100 percent humidity. Air free of atmospheric content greatly reduced corrosion.

In addition, complex reactions between ferrous sulfate and corrosion salts produce further rusting. They are hygroscopic and so can trap further moisture on the steel surface. Table 5.1 shows that the effects of sea salt from evaporation at the sea surface decrease as the distance from the coast increases. When the location is up to 2 km from the coast, the amount of chloride in the air drops off rapidly (Chandler 1976). Table 5.2 also provides relative humidity values of the air in an enclosed space located above saturated solutions of various salts (Tomashov 1966). From the result on Table 5.2, the sodium chloride, a widely used deicing salt, becomes moist at 78 percent relative humidity; in other words, the sodium chloride at this level of humidity is can be hygroscopic and traps further moisture on the steel surface. The critical relative humidity depends on the type of metal, surface contaminants, atmospheric pollutants, and the nature of the corrosion product.

## 5.4 Larrabee (1966)

Larrabee (1966) focused on the consistency of high-strength low-alloy steel in the previous sheltered tests. Low-alloy steel lost more thickness per surface than either the low-carbon steel or the copper steel, probably because the rust films of all specimens periodically became dry. When these three steels remain continuously moist, especially with water of low pH, the high-strength low-alloy steels in open exposures did not perform well.

- Environments: South Bend PA, semi-rural <sup>a</sup>  
Kearny NJ, industrial <sup>b</sup>
- Steels: HSLA steel (0.15% P, 0.89% Si, 0.04% Ni,  
1.00% Cr, 0.36% Cu)  
Copper steel (0.024% P, 0.025% Si, 0.02% Ni,  
0.02% Cr, 0.32% Cu)  
Carbon steel (0.019% P, 0.043% Si, 0.02% Ni,  
0.02% Cr, 0.024% Cu)
- Specimen size: 152 X 102 mm
- Angle of exposure: 30 deg facing south
- Orientation: Skyward and groundward
- Exposure time: a. 1936 – 1959 (23 years)  
b. 1936 – 1956 (20 years)

HSLA and carbon steels in FIG. 5.1 were exposed in following test sites:

- (1) A railroad tunnel with continuously wet walls

(2) A second tunnel with dry walls

(3) On the roof of an office building in industrial Pittsburgh, PA.

The compositions of the steels are given in Table 3.3. The rust films formed in the wet tunnel were apparently not so protective as those formed during a similar period of time on steels fully exposed to the atmosphere. Larrabee (1966) consequently noted that the corrosion rates of the three steels in the wet tunnel were nearly linear and exhibited little tendency to decrease, as did the rates of steel on the top of the building. Furthermore, compared to copper steel and low-carbon steel, the high-strength low-alloy steel was not superior in corrosion resistance when it was exposed in the tunnels. In other words, although high-strength low-alloy steel performed better than copper steel when fully exposed to the outdoor atmosphere (roof of building), the copper steel actually lost less weight in the wet tunnel than did the high-strength low-alloy steel. The atmosphere in the wet tunnel was so severely corrosive that after one year of exposure the thickness loss per surface of the high-strength low-alloy steel was more than 11 times that of the same steel exposed on the roof (Larrabee 1966).

## **5.5 Results and Discussion**

As seen in the result of the experiments of Larrabee (1966), the amount of loss per surface between high-strength low-alloy steel and carbon steel was high in the wet tunnel. Larrabee (1966) also found that the difference between the amounts of corrosion of those two steels was relatively high on the building

roof, while barely discernable in the wet tunnel specimens. Additionally, the corrosion resistance of high-strength low-alloy steel was better than carbon steel.

It is important to know the fundamental reason why certain steels exhibit superior atmospheric corrosion resistance in certain environments. Alternate cycles of wetness atmosphere are necessary to develop a protective oxide coating on weathering steels; however, weathering steels do not exhibit superior corrosion resistance under continuously moist conditions, especially with water of low pH. For more understanding of the moist corrosion mechanism, not only must the chemical reactions, capillary action, and relative humidity of weathering steel be studied and supported, but also the chemical reactions with sulfur oxides in industrial atmospheres must be considered.

## 6 Industrial Pollutants

One of the factors effecting steel corrosion is industrial pollution produced by the burning fossil fuels. It is mentioned by Wrangler (1972, pp. 62) “atmospheric corrosion increases strongly if the air is polluted by smoke gases, particularly sulfur dioxide from fossil fuels, or aggressive salts, as in the vicinity of chimneys and marine environments. The atmospheric corrosion is therefore particularly strong in industrial and coastal areas. The corrosion is, furthermore, much higher if the metal surface is covered by solid particles, such as dust, dirt, and soot, because moisture and salts are then retained for a long time.”

The most corrosive pollutants from the industries are the sulfur oxides ( $\text{SO}_x$ ), which can also come from volcanoes and from other natural sources. Vernon (1931; 1939; 1935) first showed the effect of sulfur dioxide, in conjunction with relative humidity, on the corrosion of iron. He corroded carbon steel specimens in bell jar atmospheres with controlled humidity,  $\text{SO}_2$  content, and temperature. Even humid air at 100% relative humidity did not cause noticeable rusting in the absence of  $\text{SO}_2$ . When the  $\text{SO}_2$  content was raised to 0.01%, the critical relative humidity dropped to 60%. At 0.01%  $\text{SO}_2$  content and relative humidity of 70, 75, and 99%, iron corroded 7, 8, and 12 times more rapidly than in 100% humid air without  $\text{SO}_2$ .

Especially in the industrial environment, a large amount of sulfur oxides is emitted into the air, converted into strong acids, and then falls to the ground

as rain or snow. This chapter explains how carbon and weathering steels perform in an industrial atmosphere both theoretically and experimentally.

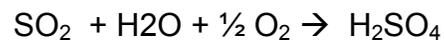
## 6.1 Acid Regeneration Cycle and Electrochemical Cycle

Sulfur oxides ( $\text{SO}_x$ ) are oxidized and hydrolyzed to sulfuric acid by acid regeneration and electrochemical cycles. The details are as explained below.

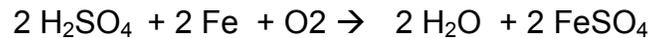
### 6.1.1 Acid Regeneration Cycle

It is commonly known that an acid regeneration cycle consists of the following steps:

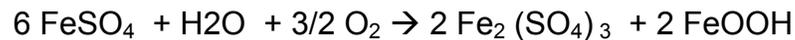
- i. Sulfuric acid forms in the presence of rust, with rust acting as a catalyst.



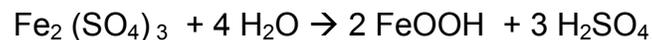
- ii. The chemical action of generated sulfuric acid forms ferrous sulfate.



- iii. Ferrous sulfate is oxidized to ferric sulfate and hydrated ferric oxide.



- iv. Ferric sulfate then hydrolyses to additional rust.



The last equation shows that all dissipated acid is theoretically regenerated. In fact, however, this acid regeneration cycle is restricted, and corrosion can continue on an electrochemical basis instead of by acid attack (Evans 1972). Kunze (1974) verified the electrochemical cycle in detail with a two-layer model.

### 6.1.2 Electrochemical Cycle

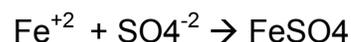
A two-layer model, as illustrated in Fig. 6.1, consists of an inner layer, bounded by the base metal and the oxidation-reduction front (red-ox front) inside the rust coating. The outer layer is bounded by the red-ox front and the atmosphere.

The two-layer model suggested by Kunze (1974) explains the rusting mechanism and involves an electrochemical cycle. The red-ox front separates the rust coating into an inner layer, where rust is electrochemically reduced, and an outer layer, where magnetite ( $\text{Fe}_3\text{O}_4$ ) is chemically oxidized to rust. The red-ox front moves inwards and outwards depending on the humidity level and the oxygen supply. The following is the general information:

- i. Some rust forms on the steel surface during the acid regeneration cycle by cathodic oxygen reduction.
- ii. An electrochemical cell is established. It involves oxidation, reduction, an anode (corroding metal), a cathode (existing rust), and an electrical current through the electrolyte (water solution).
- iii. The anodic ion dissolves in the condensed moisture and liberates electrons.

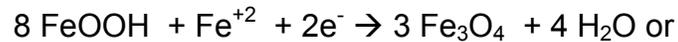


In the presence of sulfates in the rust, ferrous sulfate forms.

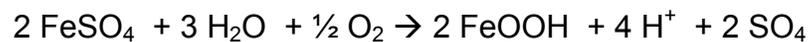


The electrons flow to the cathodic region near the red-ox front via the magnetite. As Schwarz pointed out in 1972, outer iron compounds containing  $\text{Fe}^{+2}$  and  $\text{Fe}^{+3}$  can also transmit the electrons.

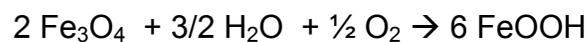
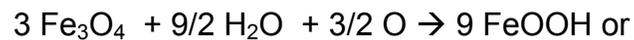
- iv. In the inner layer near the red-ox front, the cathodic region rust is reduced to magnetite by either of the following reactions:



- v. The first of the two reactions requires  $\text{Fe}^+$  ions, and the second,  $\text{H}^+$  ions. The latter come from hydrolysis of ferrous sulfate in the anodic region of the inner layer.



- vi. The magnetite that forms in the cathodic region reoxidizes again to rust.



These chemical reactions take place at the red-ox front, when enough oxygen from the air penetrates the outer layer and reaches the red-ox front. Formation of protective rust in the outer layer inhibits a continuous supply of oxygen and water to this front. As a result, the corrosion may slow down considerably.

## 6.2 Protective Mechanism of Weathering Steels

The atmospheric corrosion behavior of plain carbon steel and weathering steels is not different until a fully developed rust layer has formed on the steel (Horton 1965), as the previously explained mechanisms apply to steel in general. This chapter explains the reason weathering steel develops a protective rust layer.

The corrosion of metals, once initiated, proceeds by an electrochemical mechanism. Kunze (1974) and Misawa et al. (1971, 1973, 1974) have suggested theories about the formation of the protective oxide film on weathering steel.

According to Kunze (1974) mentioned earlier, the red-ox front separates the rust coating into an inner layer and an outer layer. Changing supplies of moisture and oxygen move the red-ox front inwards and outwards, so to speak, during the wet-dry cycles of natural weathering. The red-ox front moves outwards during the wet part of the cycle, and the diffusion of cations increases the supply of hydrogen ions as well as copper, chromium, and nickel cations. On the other hand, the red-ox front moves inwards during the dry part of the cycle. As it loses hydrogen ions, the pH value increases. This process of repeated wet-dry cycles builds the corrosion layer density, and prevents the outward diffusion of  $\text{Fe}^{+2}$  ions as well as slowing the thickness loss per surface due to moisture and oxygen. Therefore, both the anodic and the cathodic reactions slow down, and the rate of corrosion diminishes (Suzuki 1980).

Misawa et al. (1971, 1973, 1974) reported the remarkable differences in the rust coating. Low-alloy steel was uniformly rusted, and the rust-to-steel interface was even. On the other hand, the rust on plain carbon steel was not uniform and the rust-to-steel interface was not even. Misawa et al. (1971, 1973, 1974) attributed the uniformity to the presence of alloying elements. Horton (1965) had also found that the rust on low-alloy steels dried out more slowly than on carbon steel.

The presence of alloying elements influences the uniformity of the rust and slows the rate of drying, helping low-alloy steel to develop a durable, tightly adherent protective oxide rust coating with fewer cracks. Alternately, plain carbon steel has a nonuniform, porous rust coating with many cracks that let water, oxygen, and other contaminants freely penetrate. Fig. 2 and 3 each show a schematic representation of the oxide coating on carbon steel and low-alloy steel.

### **6.3 Schmitt (1967)**

- Environments: Seven different types of plants, industrial
- Steels:
  - A242 steel (0.075% P, 0.52% Si, 0.40% Ni, 0.74% Cr, 0.31% Cu)
  - A588 steel (0.013% P, 0.26% Si, --% Ni, 0.44% Cr, 0.31% Cu)
  - Carbon steel (0.012% P, 0.012% Si, 0.01% Ni, 0.03% Cr, 0.01% Cu)

- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical
- Exposure time: 1965 – 1967 (2 years)

Schmitt (1967) tested three types of steel specimens, A242, A588, and carbon steels, in several industrial environments around the chemical plants listed on Table 6.1. The two-year exposure data for specimens are plotted in Fig. 6.1.

Fig. 6.2 shows that the corrosion at the sulfur plant (curve 1) was much more severe than at the other plants. Although chlor-alkali (curve 2) is second most corrosive, it obviously had less effect than other chemical plants on the A242 and A588 weathering steels. The loss per surface of carbon steels was twice that of weathering steels at each chemical plant. The A588 steel was normally superior to carbon steel, yet somewhat inferior to A242 steel, which contains more alloys.

#### **6.4 Knotkova, Vlckova, and Honzak (1982)**

The study of the corrosion behavior of weathering steel conducted by Knotkova, Vlckova, and Honzak (1982) provides the atmospheric corrosion characteristics of weathering steels as a function of the pollution level. Their results contributed to the preparation of a specific standard: “Czechoslovak Directions for the Application of Weathering Steel,” published in December 1978. Fig. 6.2 was plotted with Atmofix weathering steel and low-carbon steel manufactured in Czechoslovakia. The conditions of the atmospheric testing

stations are listed in Table 6.2. Knotkova, et al. (1982) note, " The atmospheres studied in this paper have been limited to test stations with SO<sub>2</sub> contents nearer to the range of Czechoslovakian conditions, and the steels evaluated limited to alloys similar in composition to weathering steels. As a result, this study has been concerned mainly with the effects of pollution by SO<sub>2</sub>, except for some specific microclimates."

SO<sub>2</sub> levels in three atmospheres were as follows:

- Rural: SO<sub>2</sub> content was about 40 mg/m<sup>2</sup>/day or less.
- Urban and industrial: SO<sub>2</sub> content was between about 40 and 90 mg/m<sup>2</sup>/day.
- Heavily industrial: SO<sub>2</sub> content was more than 90 mg/m<sup>2</sup>/day.

Each figure was plotted based on at least 5 years exposure and started at an assumed zero rate for practical purposes.

As seen in Fig. 6.2, the thickness loss per surface of steel corrosion demonstrates an increasing trend in accordance with the content of SO<sub>2</sub>. Especially in a heavy industrial atmosphere, even weathering steel lost a lot of thickness. Sulfur oxide concentration is the main factor affecting the process of steel corrosion.

## **6.5 Results and Discussion**

Schmitt (1967) verified that sulfur dioxide is the most critical pollutant among the various chemical components affecting steel corrosion.

In the next study conducted by Knotkova, et al. (1982), the quantity of SO<sub>2</sub> was highly concentrated in the experiment. They classified the three categories of SO<sub>2</sub> content and figured out that it can be the determining factor of steel corrosion rate.

Weathering steel exposed in heavily industrial areas showed that the range of the thickness loss per surface was quite severe. In other words, weathering steel is not an appropriate material for use in industrial environments contaminated by sulfur dioxide.

## **7 Galvanic Corrosion**

Galvanic corrosion can be defined simply as corrosion that occurs as a result of one metal in electrical contact with another in a conducting, corrosive environment. As Albrecht and Naeemi (1984) stated, “when two dissimilar metals are in contact in a moist or immersed environment, the difference in solution potential between the two induces a current flow through the solution (electrolyte) from the less noble (anodic) to the more noble (cathodic) metal and back through the metallic contact.” In other words, anodic metal chemically reacted more than single exposure, whereas the cathodic metal chemically reacted less than when single exposure.

Cathodic reaction, generally speaking, is found in the majority of practical situations with either oxygen reduction or hydrogen evolution, or a combination of both, while anodic reaction is some form of metal dissolution.

In this chapter, the affecting factors of galvanic corrosion are briefly described. Additionally, a galvanic series of metals, degrees of corrosion, and galvanic corrosion control technology in design are also introduced.

### **7.1 Factors Effecting Galvanic Corrosion**

Many factors, including electrochemical ones, go into determining whether or not galvanic corrosion will occur in a particular instance. These factors are important when considering the theory of galvanizing corrosion.

### **7.1.1 Electrode Potential**

The standard electrode potential of a metal in a solution of its ions gives a rough guide to its position in a galvanic series, but to date, actual measurement of electrode potential is the best method of obtaining a galvanic series.

### **7.1.2 Reaction Kinetics**

The reaction kinetic data indicate how quickly corrosion can take place. The metal dissolution kinetics provides more information on the rate of the anodic reactions in the corrosion cell, and also gives the rate of the cathodic reactions.

### **7.1.3 Composition**

The composition of an alloy affects galvanic corrosion. In addition, the constituents affect the corrosion potential and the kinetics of the cathodic processes involved. In this respect, minor constituents and impurities can play an important role.

### **7.1.4 Protective film characteristics**

The potential dependence, pH dependence, and resistance to various solution constituents can particularly affect the characteristics of the protective film. The protective film characteristics exist on most metals, and are important in determining whether or not galvanic corrosion will occur and what form it will take in a particular environment.

### **7.1.5 Bulk Solution Properties and Environment**

Bulk solution properties consist primarily of the oxygen and pH levels, which determine whether a cathodic reaction is possible for a specific system. The pollutant level can affect all these other factors. Bulk solution environment includes the solution temperature, volume, height above the galvanic couple, and the flow rate across the surface.

### **7.1.6 Galvanic Couple Geometry at Joint**

One of the most important parameters in galvanic corrosion is the area ratio, defined as a high cathode to anode ratio. If the more noble steel is larger in area than the less noble one, this galvanic coupling induces the rapid corrosion from high cathode to anode ratio.

Welding could well give different corrosion properties to a system, as could the use of gaskets and fasteners.

## **7.2 Galvanic Series of Metals**

The use of potential measurements for predicting galvanic corrosion is based on the measurement of the corrosion potential of metals. According to the potential measured in a particular environment, the galvanic series is as shown on Table 7.1

In general, the corrosion rate of the more noble metals in a galvanic couple will be reduced and that of the more active metals will be increased.

### **7.3 Degree of Corrosion**

As Berger (1980) reported, mill scale, which is a brittle highly protective coating and tends to flake off easily, is more noble than steel. Among several factors affecting the degree of corrosion, the area ratio was measured by Phelps (1970), which is mentioned in section 7.1.6.

The two galvanic coupled metals were immersed in standing seawater for 6 months. Under conditions of alternate wetness, the area ratios of the specimens, 1:8, 1:1, and 8:1, effected the corrosion rates of both metals. The resultant measurements are compared in the bar graph shown in Fig. 7.1.

By galvanic coupling the steels, the corrosion thickness loss per surface decreased for the cathodic A242 steel and increased for the anode carbon steel. Most notably, the corrosion of carbon steel tripled when its area was one eighth of that of the A242 steel.

### **7.4 Galvanic Corrosion Control Technology Applied to Design**

Jenkins (1988) investigated the application of galvanic corrosion control technology to engineering design. Jenkins (1988) suggested that it is the professional responsibility of corrosion engineers to insure that corrosion control technology is effectively applied. For instance:

- (1) The painting of the contact areas of both sides of steel.
- (2) The use of applicable plastic material at the contact joint.

(3) The application of galvanic joints to good service conditions to avoid continuous moisture and an attack of deicing salt: such as open exposure far from drainage, or a non-hidden place in the concrete.

For the improvement of communication between design engineers and corrosion engineers, or for direct training of design engineers in corrosion control, corrosion engineers should do what is necessary to insure the application of their technology effectively.

## 8 Deicing Salts

Extensive use of deicing salts for snow removal, such as sodium chloride (NaCl) and calcium chloride (CaCl<sub>2</sub>), began in the early 1960s. Before that time, highway maintenance departments depended primarily on abrasives, such as sand and cinders, combined with plowing, to clear snow and ice from highways; salt was generally added to the abrasives to prevent freezing. However, maintenance departments gradually began to appreciate the salt's accelerated melting effect.

Maintenance engineers directly apply the salts before, during, and after a snowstorm to facilitate snow removal operations. They know that the application of salt for snow and ice removal has been approved after experimentation. The common use of salt has now also been associated with a significant amount of damage to the environment and highway structures (Murray 1977). For example, salt contaminates the steel structure in the following ways according to Albrecht and Naeemi (1984):

- Salt water leaks through the bridge deck, mainly at expansion and construction joints, and drains longitudinally along sloped bottom flanges.
- A mist of salt-water runoff is kicked up in the wake of trucks passing beneath the bridge and settles on the steel structure.
- Dust containing salt particles from dry roadways is blown against the steel structure.

- Salt water lying on the upper surface of the bottom flange wicks up the web by capillary action as much as 10 in. (250 mm)

Corrosion due to deicing salt is very relevant to the previous chapters: angle of exposure (chapter 2), orientation (chapter 3), shelter (chapter 4), continuously moist conditions (chapter 5), and industrial pollutants (chapter 6). The data of two experiments from Cosaboom et al. (1979) and Zoccola (1976) will also be dealt with again in this chapter, and replotted for Fig. 8.1 and Fig. 8.2. Raska (1983) and Hein (1981) also investigated the corrosiveness of several atmospheres.

### 8.1 Cosaboom et al. (1979)

- Environment: Newark, NJ, industrial
- Test sites: Roof of DOT building  
Center-span girder of bridge No. 9 on I-78
- Steels: A242 steel (0.11% P, 0.29% Si, 0.66% Ni, 0.52% Cr, 0.27% Cu)  
Carbon steel (0.007% P, 0.005% Si, 0.01% Ni, 0.02% Cr, 0.024% Cu)
- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical, horizontal, and 30 deg facing south
- Exposure time: 1968 – 1984 (16 years)

The results of the exposure tests in Newark, NJ, as mentioned in Chapter 4, were replotted in Fig. 8.1. The corrosion thickness loss per surface

of the weathering steel specimens mounted on the interior girders of the I-78 bridge was 1.6 times that of their roof counterparts. The increase was caused not by salt but by sheltering because the bridge was not opened to traffic during the first 6.5 years (Cosaboom et al. 1979).

## 8.2 Zoccola (1976)

- Environment: Detroit, MI, industrial
- Test sites: Roof of National Guard Armory  
Interior girder of Eight-Mile Road Bridge next to the wall
- Steels: A242 steel (Test 1: 0.077% P, 0.24% Si, 0.75% Ni, 0.56% Cr, 0.24% Cu)  
(Test 2: 0.08% P, 0.36% Si, 0.72% Ni, 0.64% Cr, 0.34% Cu)  
Carbon steel (Test 2: 0.011% P, 0.05% Si, --% Ni, --% Cr, 0.015% Cu)
- Specimen size: 152 X 102 mm
- Angle of exposure: Vertical and horizontal
- Exposure time: 1966 – 1974 (8 years)

Specimens mounted on the interior girder were 4.4 times more corroded than those mounted on the roof. Additionally, the corrosion rate of the weathering steel specimens was even more like that of the carbon steel at Eight-Mile Road shown in Fig. 8.2. Since the Westbound Service Eight-Mile

Road Bridge passed above the southbound lanes of the expressway, the corrosion rate of the specimens on the interior girder was higher than that of specimens on I-78, shown in Fig. 8.1.

### **8.3 Raska (1983)**

Raska (1983) examined the corrosion of A588 Grade B steel exposed at a bridge on the Texas Gulf Coast located at High Island, Corpus Christi, and Port Isabel. The steel specimens attached to one of the racks at High Island and Port Isabel were placed on the bridge piers for the main span about 80 ft (24 m) above ground. Another rack at Corpus Christi, at the south end of the US 81 Nueces Bay Causeway, was about 8 ft (2.4 m) above the water. Only High Island Bridge is made of weathering steel.

After having corroded, the steel coupons were measured for loss of weight, and this weight was then converted into an equivalent uniform loss per surface. As plotted in Fig. 8.3, the corrosive rate of weathering steel at all three sites was very high even within one year (Albrecht and Naeemi 1984).

### **8.4 Hein (1981)**

Hein (1981) vertically mounted Resista HRL 37 and A588 Grade A weathering steel specimens on guardrails along West-German highways in Rendsburg, Duisburg, Merklingen, and Trockau at reference sites near each bridge. All are located near weather stations. The specimens at the highway sites were easily attacked by deicing salt spray from the roadway contrary to

the reference sites (see Fig. 8.5 to 8.8). Hein (1981) also described weather conditions in order to compare the corrosion of the steels with climate factors. It was mostly cloudy and freezing weather in Rendsburg, sunny and warm in Duisburg, turbulent and freezing in Merklingen, and cloudy and dry in Trockau.

The data are plotted in Fig. 8.4. The corrosion thickness loss per surface of the weathering steel specimens at the four highway sites (curve 1) was, on average, 1.9, 1.3, 2.1, 1.9 times more than that of other counterparts at the reference sites (curve 2) because of the effect of salt spray from the traffic passing the highway. It seems that salt spray easily kicked up in the wake of trucks passing and settled on the steel beams.

## **8.5 Results and Discussion**

The vertical and horizontal specimens at interior girders and fascia girders were more corroded than the specimens on the roof in the first experiment (Cosaboom et al., 1979) because of contamination of salt and water from the bridge deck during the winter season.

The experiments of Cosaboom et al. (1979) and Zoccola (1976) were tested in a similar way; however, the result from Zoccola (1976) demonstrated that A242 weathering steel performed almost the same as carbon steel, at either the vertical or the horizontal position. Since there was a high retaining wall along the shoulder of the highway beneath the low-level service bridges and tunnel-like conditions in the underpass next to the wall, road spray, dirt and salts were carried by the air blast created by the heavy traffic on the

expressway, and easily contaminated the horizontal specimen. The prolonged wet and dry cycle caused by deposits, chlorides, and sulfates in close contact with the steel, tended to accelerate poulitice corrosion.

At the marine site, A588 weathering steel corroded severely within a year or two in the third experiment (Raska, 1983). Raska (1983) concluded, "The weathering steel superstructure of the High Island Bridge is corroding at an excessive rate because the specimens were exposed beneath the bridge, on top of the main span pier."

The last experiment in this chapter, Hein (1981), is not quite comparable with other experiments. Hein (1981) examined the specimens in four different atmospheres. The results showed that more corrosion occurred in freezing weather, especially on the highway. In the turbid and freezing weather of Merklingen, the A588 steel corrosion on the highway showed no difference from HRL 37 steel. On the contrary, the difference in corrosion rates for A588 steel and the HRL 37 steel attached to the guardrail along the highway in Duisburg, where it was sunny and warm, were comparably low.

## **9 Pitting and Crevices**

### **9.1 Pitting**

Wilhelm (1988, pp. 23) described pitting, using a conceptual illustration as shown in Fig 9.1, on an oxide-covered metal surface. Wilhelm (1988) also shows that “iron undergoes pitting, while the majority of the metal surface is covered with oxide, upon which is supported the cathodic reaction.”

Mill scale (ferric oxide,  $\text{Fe}_2\text{O}_3$ ), created by cathodic action, tends to form a large thick covering of pits in the steel. Since it is nobler than base steel, mill scale induces galvanic corrosion along cracks between strong galvanic cells. Removing mill scale before the component is placed in service could prevent continuously damp corrosion. This action does not need to be performed as long as eventual peeling off of the mill scale occurs (Albrecht and Naeemi 1984). The practical experiment will be shown in section 9.3.

### **9.2 Crevices**

Bayliss and Chandler (1991, pp. 279) explain crevices as follows: “a crevice is a very small gap between two steel surfaces that allows access of air and moisture, often through capillary action, but does not provide sufficient space to allow for cleaning and repainting during service.” Typical crevice situations are shown in Fig. 9.2.

Crevice may not be a simple problem of corrosion between two heavy steel plates bolted together, because they are fully loaded even though there is rusting in the small gap. On the other hand, a similar corrosion situation

between thin plates may cause more worrisome structural problems as a result of buckling of the joint and shearing of the bolt. Rust can produce high stresses and the typical buckling within a crevice as shown in Fig. 9.3.

“Crevice are often a more serious problem with alloys, because the passive film may break down at a crevice, particularly if chlorides exist. This can lead to severe pitting and may preclude the use of the alloy for many situations (Bayliss and Chandler, 1991, pp. 280).” The actual situations will be introduced in section 9.4.

### 9.3 Copson (1960)

- Environment:
  - a. Bayonne, NJ, industrial
  - b. Block Island, RI, marine
- Test sites: Low ground, about 800 ft from the ocean
- Steels:
  - A242 steel (0.06% P, 0.18% Si, 0.10% Ni, 0.17% Cr, 0.44% Cu)
  - Copper steel (0.009% P, 0.01% Si, 0.05% Ni, --% Cr, 0.23% Cu)
- Specimen size: 152 X 102 X 0.7 to 2.1 mm
- Angle of exposure: 30 deg facing south <sup>a</sup>  
30 deg facing ocean <sup>b</sup>
- Exposure time: 1941 – 1959 (18.1 years) <sup>a</sup>  
1941 – 1958 (17.1 years) <sup>b</sup>

As part of the pitting corrosion study, Copson (1960) measured the average depth of the four deepest pits on the skyward and groundward surfaces of many steel specimens. The pitting and uniform corrosion of steels with copper bearing and weathering steels are shown in Fig. 9.4.

Pitting and uniform corrosion at the marine site were more severe than at the industrial site. Pitting depths after 17 years were two to three times the average thickness loss per surface. The ratio of pit depths to average corrosion thickness loss is called “the pitting factor” for the low-alloy steel. It also tends to decrease somewhat with time at Bayone, NJ, industrial. From corrosion results at Block Island, RI, the long-time corrosion rates were not favorable in marine atmospheres.

#### **9.4 The Example Case of Crevice Corrosion**

Albrecht and Naeemi (1984) also sampled several actual cases of crevice corrosion. One of the cases was the test of guardrails, among the oldest structures along a highway in Lansing, Michigan. A guardrail showed bulging lapped joints expanding outward by the pressure of corrosion product. There was also a 40 percent section loss of the guardrail in the lapped areas.

After the guardrail bulged at its lapped joints, the state of Michigan banned all use of unpainted weathering steel on the state highway system in 1980. Many other states followed Michigan’s lead.

## 9.5 Results and Discussion

Copson (1960)'s experiment shows that the thickness loss per surface of low-alloy steel was smaller than copper steel due to pitting corrosion. However, the corrosion rate of low-alloy steel was unexpectedly high. This means that the use of weathering steel in a marine atmosphere is not desirable due to pitting corrosion.

In the case of crevices in steel structures, the corrosion may cause the movement of the expansion joint and cause other structural damage to the bridge. Crevices actually facilitate moisture and air entrapment making it impossible to clean and repaint the surfaces. Initial painting of the contacting faces between the connected plates, welding, and filling with mastic of the crevice, is good mitigating precautions to apply in these situations.

## 10. Conclusion

Various service conditions affecting corrosion of steels were reviewed and discussed between chapter 2 and chapter 9. Each chapter finds that the steels have common advantages in corrosion resistance in certain circumstances: the same angle of exposure as the latitude of the test site, skyward exposure facing south, and open exposure with a short period of wetness. As a result, we can conclude as follows:

- Not only does the chemical combination of low-alloy weathering steel have higher amount of phosphorous and silica than ordinary steels, but it also contains small additional amounts of copper, nickel, and chromium. This combination somewhat reduces the corrosion rate of weathering steel compared to carbon or copper steels.
- Under continuous moisture conditions, like a wet tunnel, weathering steel does not exhibit a particularly distinguished corrosion resistance record compared to carbon steel. Sheltered conditions, where evaporates are easily trapped, are the main cause of continuous moisture conditions.
- The thickness loss per surface of weathering steel shows higher resistance than that of carbon steel at the sulfur plants examined by Schmitt (1967). Nevertheless, the corrosion progress of weathering steel was very high in humid, heavily industrial atmospheres. It seems that the combination of sulfur oxides and water significantly effect steel corrosion, more than sulfur or water individually.

- By bimetallic coupling of steels, corrosion is stimulated by the galvanic potential difference. Among the many factors affecting galvanic corrosion, the area ratio is the most important parameter (Oldfield 1967); therefore, the area of the more noble steel should be smaller than that of the less noble steel. Structural or corrosion engineers also have to consider the design of galvanic metal joints and place them far enough from crevices and expansion joints.
- Steel corrosion rates are severely affected in marine atmospheres, for both weathering and carbon steels. It is not reasonable to use exposed weathering steel close to the sea because contamination by salt and water causes severe corrosion the same as carbon steel to weathering steel.
- Crevice corrosion, occurring at the gaps between thin plates, causes very serious structural problems. After the review of experience, many states changed their policy on the use of weathering steel; for example, states do not use uncoated weathering steel for bolted thin plates. Painting may be preferred to the gap between the plates.
- Moisture and road salts seem the most important factor on corrosion because most steel bridge corrosion problems occur near at an expansion joint where the water easily leaks into steel girders. Accordingly, as mentioned in 'Technical advisory Uncoated Weathering Steel in Structures, T 5140.22' (Oct, 1989) released by Federal Highway Administration, implement maintenance and inspection are

needed to detect a deteriorated joint and deck drainage systems to minimize further corrosion.

For the proper application of weathering steel, it is recommended for bridge engineers to better understand corrosion effect under certain microenvironments, detailed design criteria, and maintenance actions in order to prevent unacceptable steel corrosion section loss.

**TABLE 1. 1. Chemical Compositions of Steels (ASTM Standards, 2003)**

Steel Type	Composition, %				
	P	Cu	Ni	Cr	Si
A242	0.15 max	0.20 min	—	—	—
A588 Grade A	0.04 max	0.25 – 0.40	0.40 max	0.40 – 0.65	0.30 – 0.65
A588 Grade B	0.04 max	0.20 – 0.04	0.50 max	0.40 – 0.70	0.15 – 0.50
A599 Grade C	0.04 max	0.20 – 0.50	0.25 – 0.50	0.30 – 0.50	0.15 – 0.40
A588 Grade K	0.04 max	0.30 – 0.50	0.40 max	0.40 – 0.70	0.25 – 0.50
Copper	—	0.02 max	—	—	—
Carbon	0.04 max	0.02 max	—	—	0.40 max

Note: Where " — " appears in this table, there is no requirement.

**TABLE 2.1. Chemical Composition of Steels Exposed to Atmosphere at Worldwide Sites**

Steel Type	Composition (%)				
	P	Si	Ni	Cr	Cu
A588 (Cor-Ten B) pre-78	0.006	0.25	0.015	0.56	0.33
Carbon	0.012	0.016	0.012	0.025	0.014

**TABLE 2.2. Atmospheric Test Sites for Worldwide Data**

Country	Type	Location	Latitude	Longitude
United States	Rural	Potter Co., PA	42° N	78° W
	Industrial	Kearny, NJ	40° 30' N	74° W
	Marine	Kure Beach, NC	35° N	78° W
United Kingdom	Rural	Avon Dam	50° 17' N	2° W
	Industrial	Stratford	52° 12' N	0°
	Marine	Rye	50° 57' N	1° E
Germany	Industrial	Oberhausen	51° 28' N	7° E
	Industrial	Essen Frintrop	51° 28' N	7° E

**TABLE 4.1. Effect of shelter (Larrabee 1966)**

Test Site	Semi Rural	Marine Atmosphere
East	Practically no effect of shelter	The specimen located in position two (next to the top specimen in vertical row) lost from 150 to 250 percent more weight than the specimens in positions four and five. The top specimen, and that in the third position, lost from 50 to 100 percent more weight than those in positions four and five.
North	The two bottom specimens were about 20 percent more corroded than those in the other three positions.	The specimen in position two lost about 75 percent more weight than those in positions four and five.
South	The two bottom specimens were about 20 percent less corroded than those in the other three positions.	
West		All losses were within 30 percent of average for all five vertical positions.

**TABLE 4.2. Environmental conditions during first year of testing (Mckenzie 1978)**

Site	Average atmospheric sulfur compounds mgSO <sub>3</sub> /100cm <sup>2</sup> /day	Average atmospheric chlorides mgCl/100cm <sup>2</sup> /day	Yearly rainfall mm	% year that relative humidity was:		Average temperature °C
				> 70%	> 80%	
Tinsley	2.05	0.07	687	74.6	47.7	10.1
Loudwater	0.48	0.03	575	82.4	64.8	8.8
Eastney	0.49	0.15	481	76.4	53.2	10.5
Iden	0.31	0.08	412	70.7	51.1	10.0

**TABLE 5.1. Effect of sea salt on the corrosion of steel<sup>a</sup> (Chandler 1976)**

Distance from coast (yards)	Salt content of air <sup>b</sup>	Corrosion rate (mm per year)
50	100	0.95
200	27	0.38
400	7	0.06
1300	2	0.04

<sup>a</sup> Based on tests carried out in Nigeria.

<sup>b</sup> Expressed as a percentage of content at 50 yards.

**TABLE 5.2. Water vapor pressure above saturated aqueous of salts at 20°C (68°F) (Tomashov 1966)**

Salt	ZnCl	CaCl	NHNo	NaCl	NHCl	Na SO	(NH) SO	KCl	ZnSO	K SO
Relative Humidity	10	35	67	78	79	81	81	86	91	99

**TABLE 5.3. Composition of steels exposed in railroad tunnels and in industrial atmosphere (%) (Larrabee 1966)**

Steel	C	Mn	P	S	Si	Cu	Ni	Cr
HSLA	0.11	0.39	0.13	0.023	0.66	0.36	0.08	1.0
Copper	0.04	0.31	0.31	0.014	0.002	0.24	0.01	0.03
Carbon	0.03	0.19	0.19	0.003	0.003	0.024	0.03	0.02

**TABLE 6.1. Corrosion penetration of carbon and weathering steels exposed to various chemical plant atmospheres (see FIG. 6.1) (Schmitt 1967)**

Curve No.	Type of Plant	Atmospheric Constituents	Corrosion penetration, mm			Exposure time, years
			Carbon	A242	A588	
1	Sulfur	Chlorides, sulfur and sulfur compounds	1.1	0.518	0.823	2
2	Chlor-alkali	Moisture, chlorides and lime	0.478	0.145	0.188	2
3	Chlorinated hydrocarbons	Chloride compounds	0.272	0.056	0.056	1
4	Chlor-alkali	Moisture, lime and soda ash	0.211	0.053	0.048	2
5	Sulfuric acid	Sulfuric acid fumes	0.114	0.053	0.056	1
6	Petrochemical	Chlorides, hydrogen sulfide and sulfur dioxide	0.086	0.030	0.048	2
7	Petrochemical	Ammonia and ammonium acetate fumes	0.056	0.033	0.048	1

**TABLE 6.2. Characteristics of environment of atmospheric testing stations in which the verification tests of weathering steels were carried out (Knotkova, Vlckova, and Honzak, 1982)**

Data	Atmospheric Station			
	Prague Letnany	Usti nad Labem	Hurbanovo	Kopisty
Geographical position altitude above sea level, m	275	186	115	240
North latitude	58°08'	50°39'	47°52'	50°33'
Type of atmosphere	metropolitan	Heavy polluted industrial, (specific chemical effects)	Rural, changed over to urban	Heavy polluted industrial, decisive effect of SO <sub>2</sub>
Avg annual temperature, °C	8.35	9.8	10.35	9.1
Avg annual relative humidity, %	80.5	78.25	76	73
Avg values of adsorption of SO <sub>2</sub> , mg/m <sup>2</sup> /day	85.75	132.6	40.95	128.95
Avg annual quantity of precipitations, mm	444	376	505	330

**TABLE 7.1. Galvanic series of some metals and alloys in seawater  
(Oldfield 1988)**

Range	Metals
Noble (Cathodic, protected)	Graphite
	Platinum
	Ni-Cr-Mo alloy C
	Titanium
	Alloy 20 stainless steels
	Nickel-copper alloys 400, k-500
	Silver
	Nickel
	Ni Aluminum bronze
	70-30 copper nickel
	Lead
	Type 430 stainless steel
	90-10 copper-nickel
	Type 410 stainless steel
	Manganese bronze
	Admiralty brass, aluminum brass
	Copper
	Naval brass
	Aluminum bronze
	Austenitic nickel cast iron
Low alloy steel	
Mild steel	
Cadmium	
Aluminum alloys	
Zinc	
Active (Anodic, corroded)	Magnesium

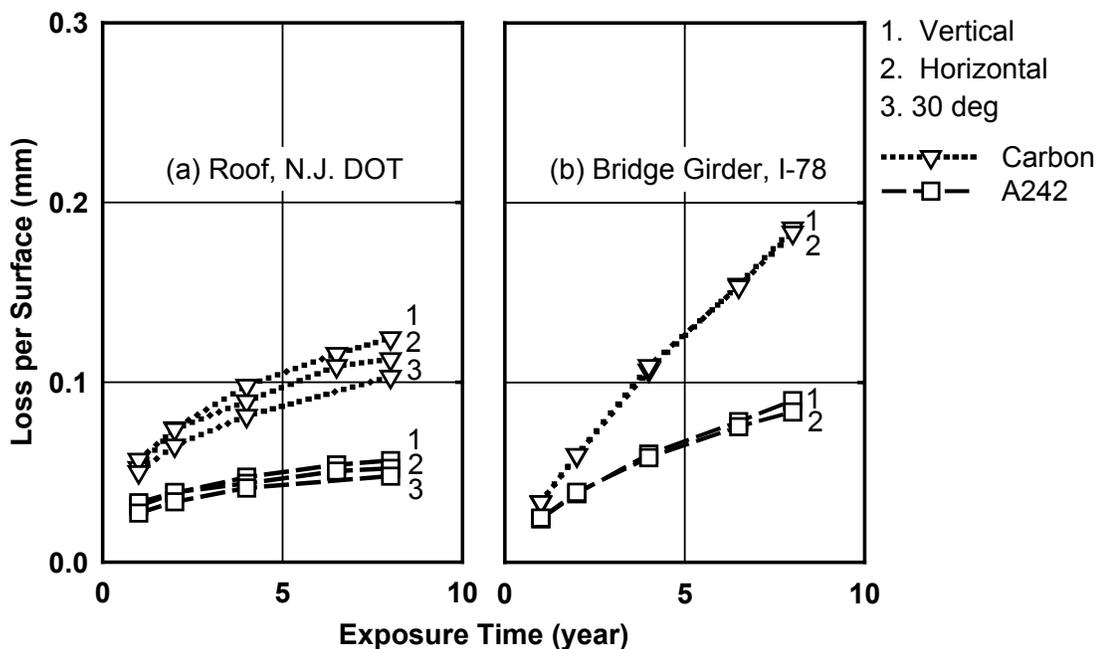


FIG. 2.1. Effect of exposure angle on corrosion of steels in Newark, N.J., industrial atmosphere (Cosaboom 1979)

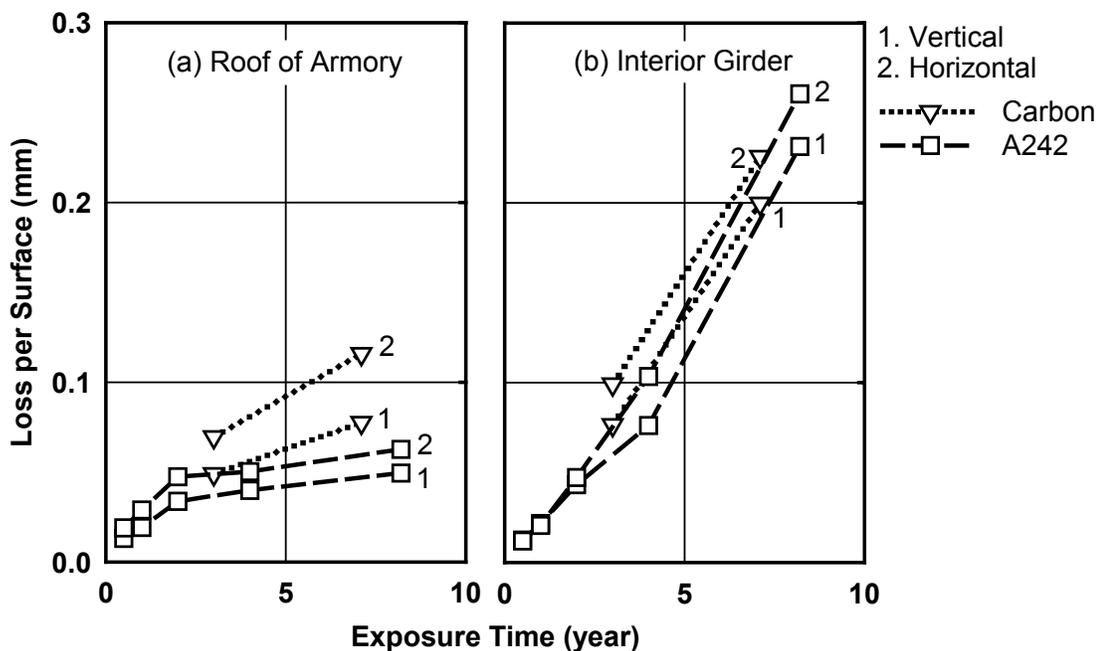


FIG. 2.2. Effect of exposure angle on corrosion of steels in Detroit, Mich. (Zoccola 1976)

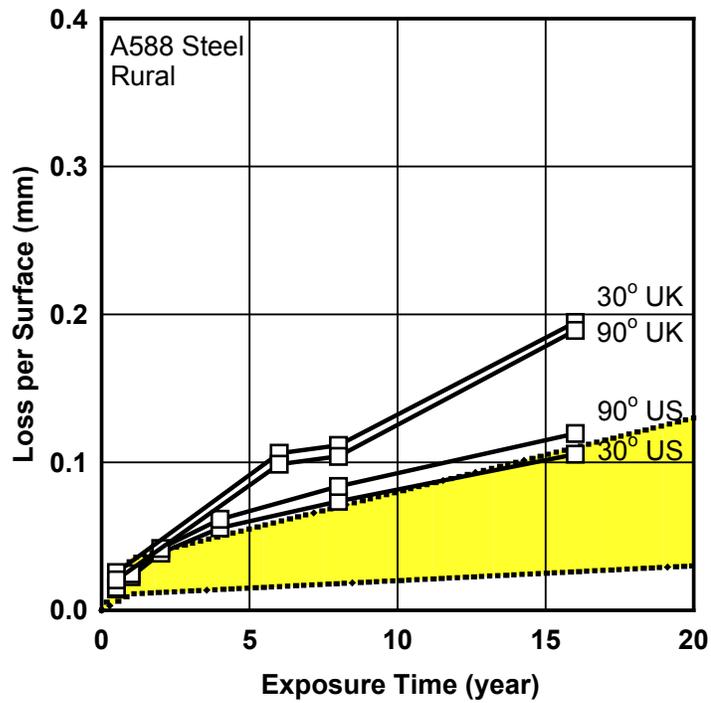


FIG. 2.3. A588 steel in rural environments

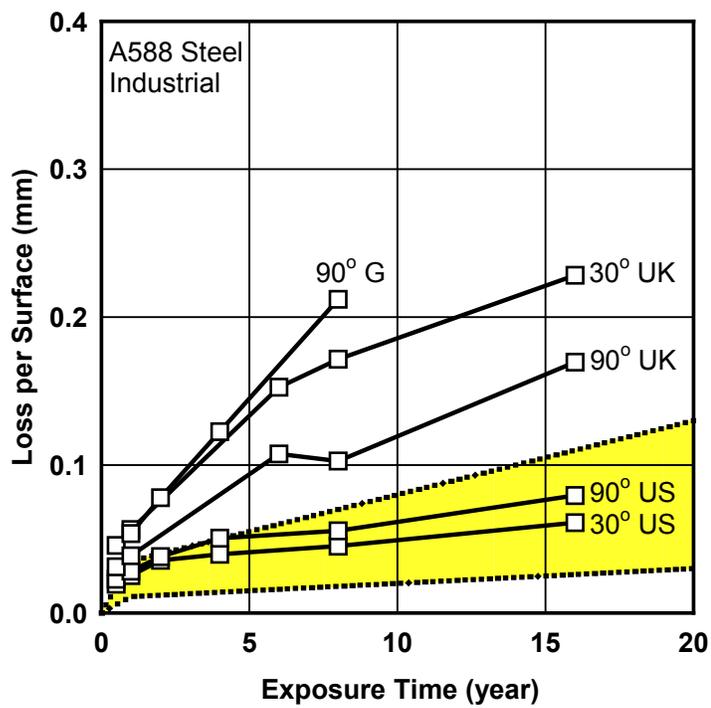


FIG. 2.4. A588 steel in industrial environments

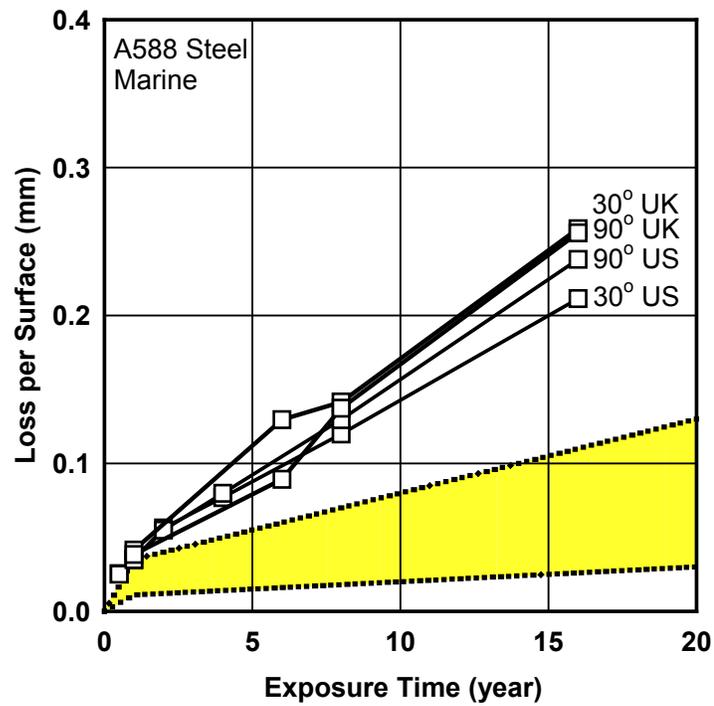


FIG. 2.5. A588 steel in marine environments

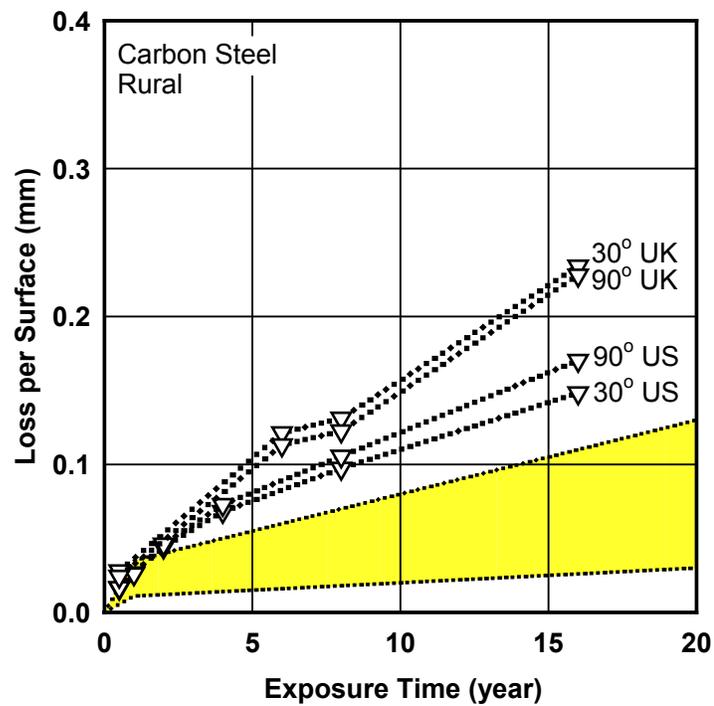


FIG. 2.6. Carbon steel in rural environments

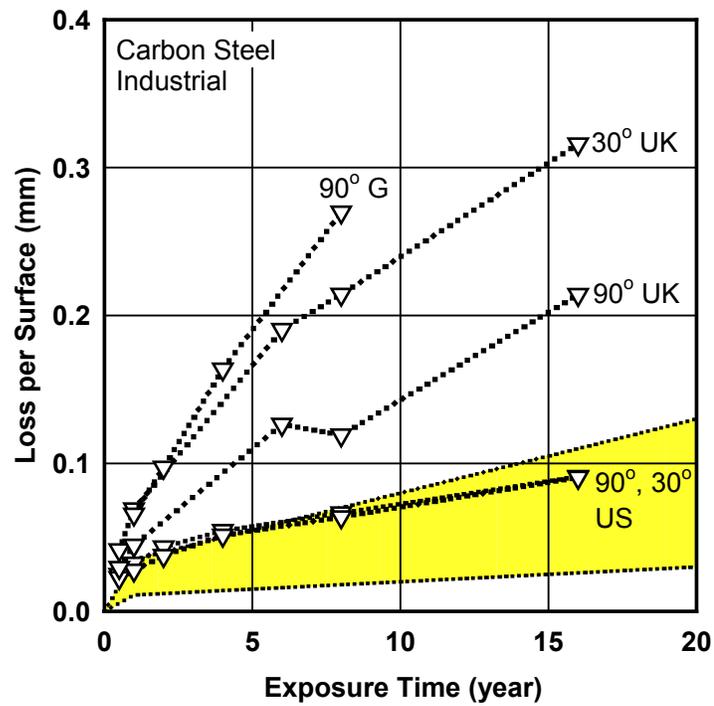


FIG. 2.7. Carbon steel in industrial environments

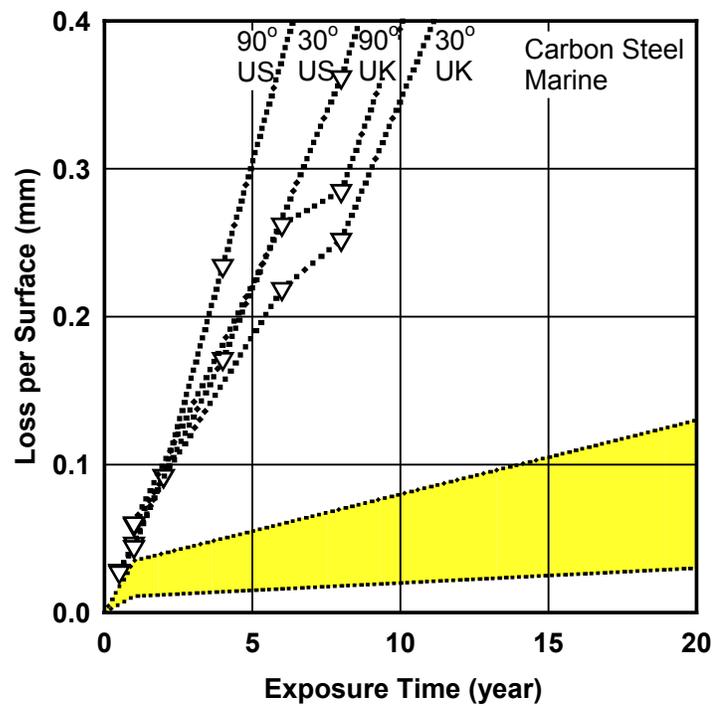
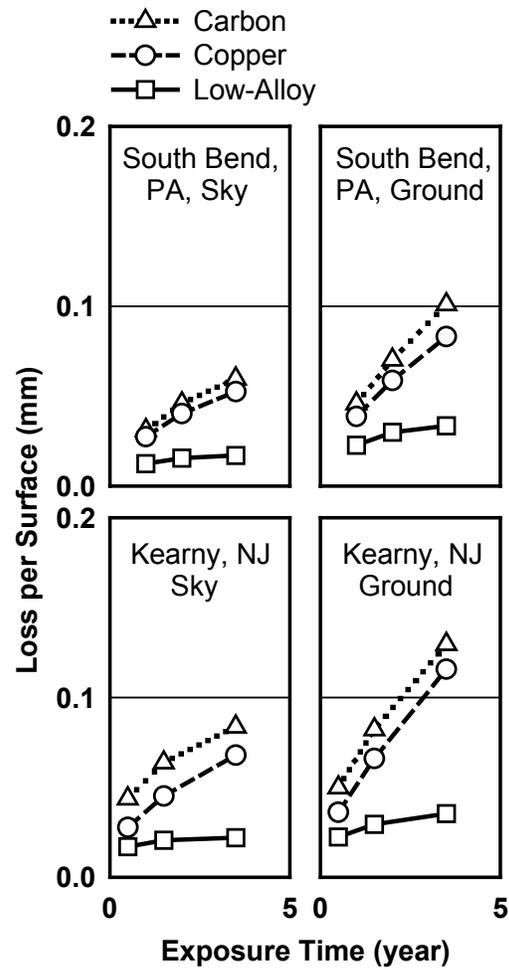


FIG. 2.8. Carbon steel in marine environments



**FIG. 3.1. Effect of skyward versus groundward exposure on corrosion of steels in the rural atmosphere of South Bend, PA, and the industrial atmosphere of Kearny, NJ (Larrabee 1944)**

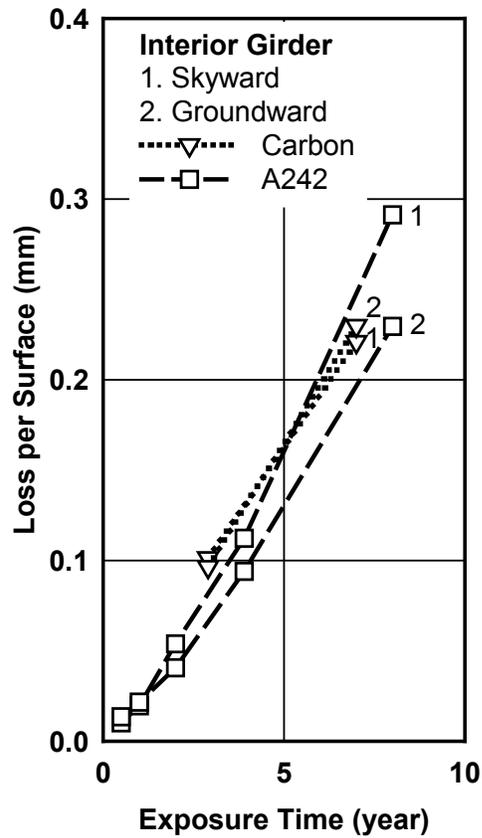
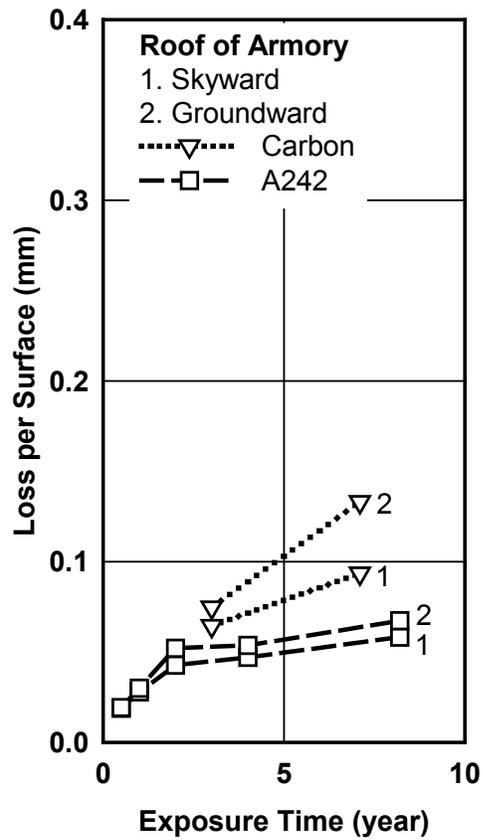


FIG. 3.2(a). Effect of sheltering skyward versus groundward exposure on corrosion of steels horizontally exposed to the Detroit, Mich., industrial atmosphere (Zoccola 1976)



**FIG. 3.2(b). Effect of sheltering skyward versus groundward exposure on corrosion of steels horizontally exposed to the Detroit, Mich., industrial atmosphere (Zoccola 1976)**

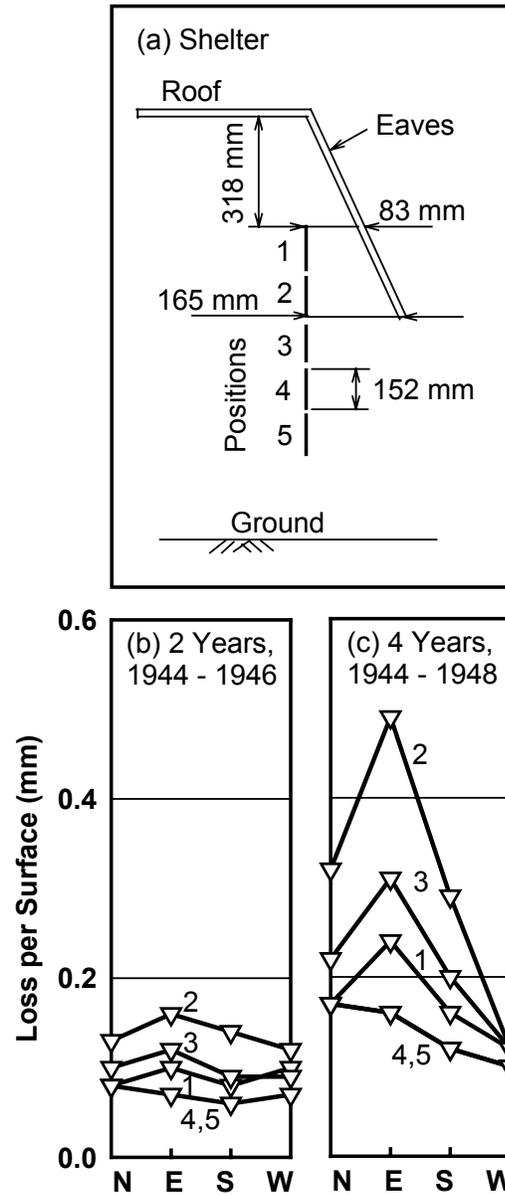


FIG. 4.1. Effect of sheltering on corrosion steel exposed to the Kure Beach, NC, marine atmosphere (Larrabee 1966)

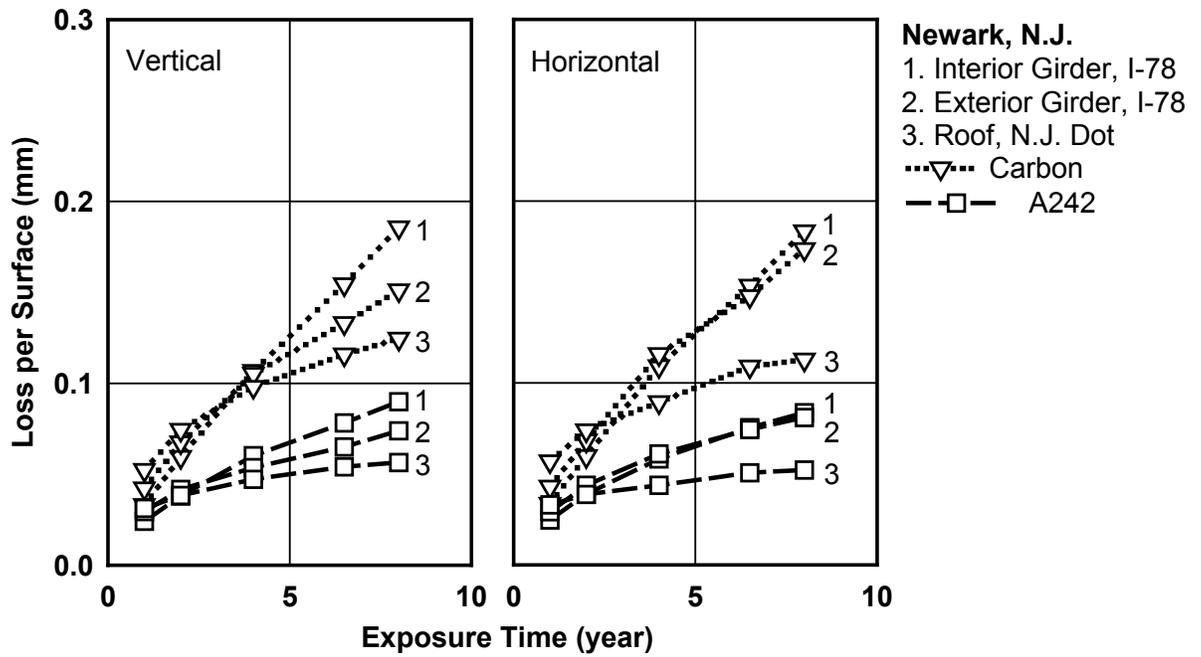


FIG. 4.2. Effect of sheltering on corrosion of steels exposed to the Newark, NJ, industrial atmosphere (Cosaboom 1979)

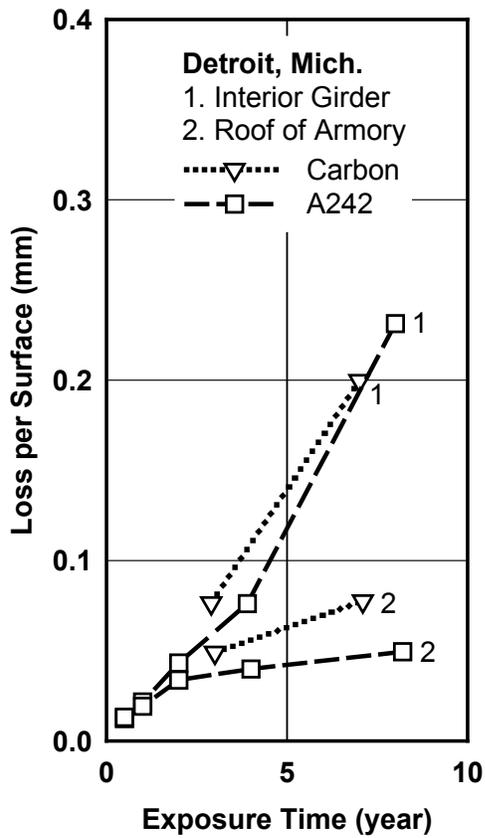


FIG. 4.3. Effect of sheltering on corrosion of steels exposed to the Detroit, Mich, industrial atmosphere (Zoccola 1976)

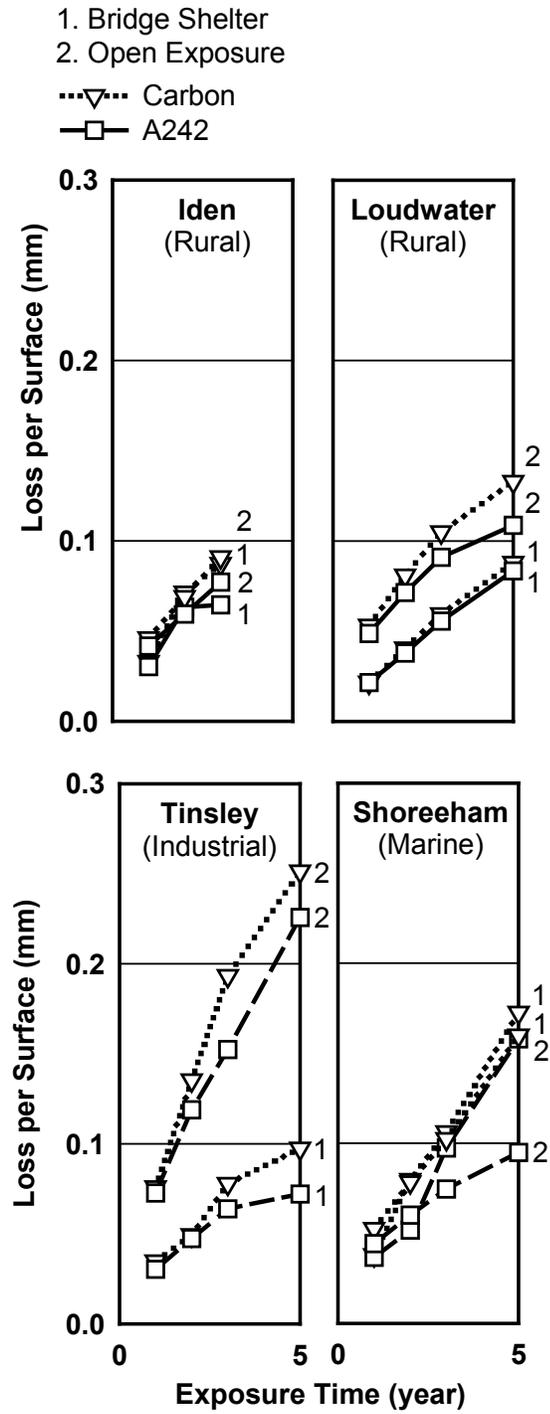
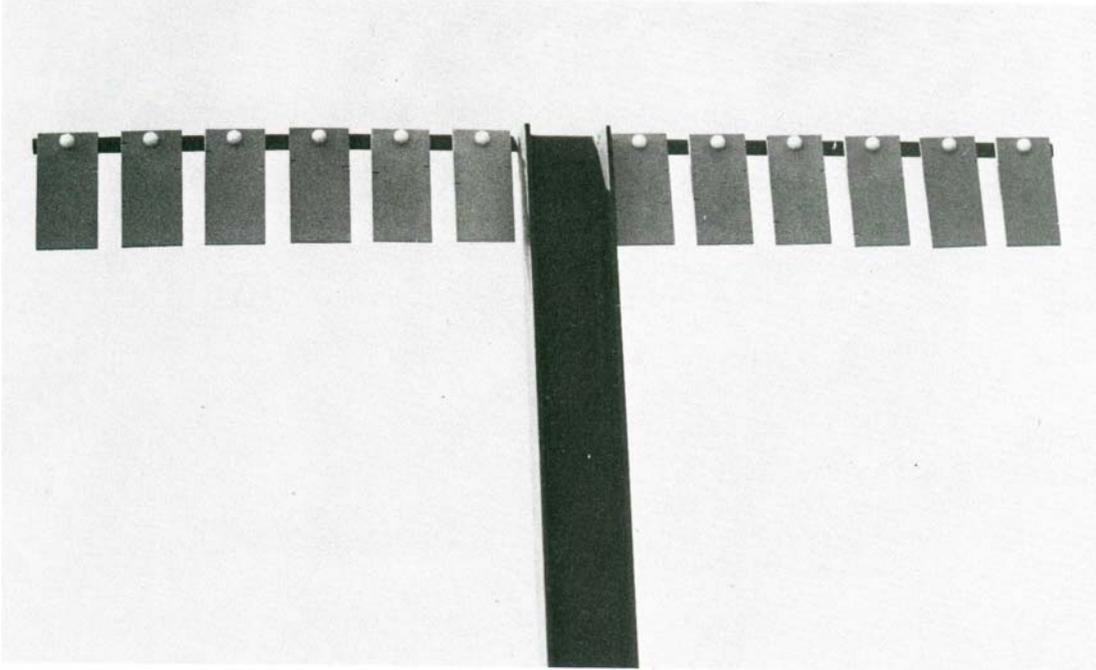
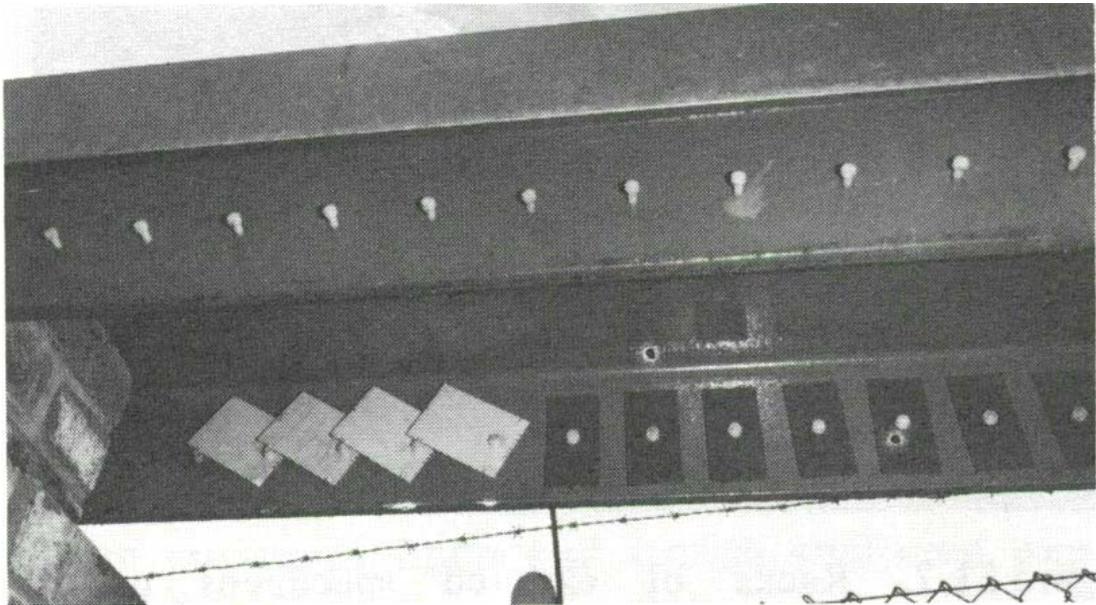


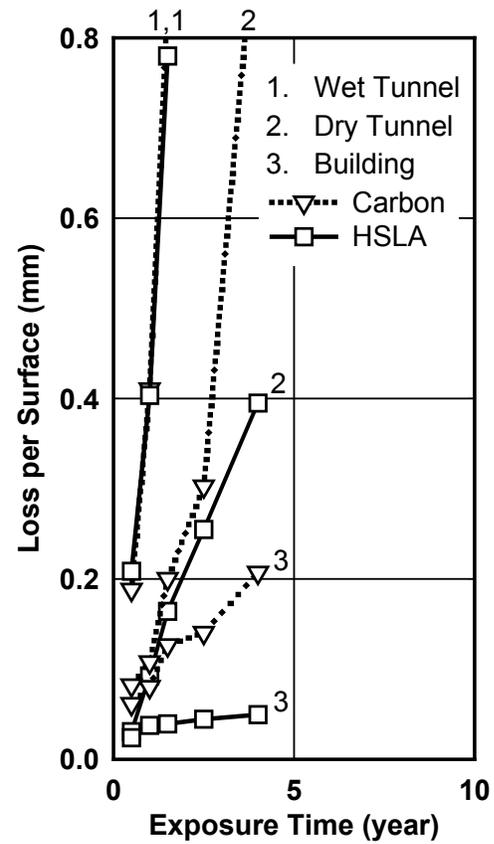
FIG. 4.4. Effect of sheltering corrosion on steels exposed at four British sites (Mckenzie 1978)



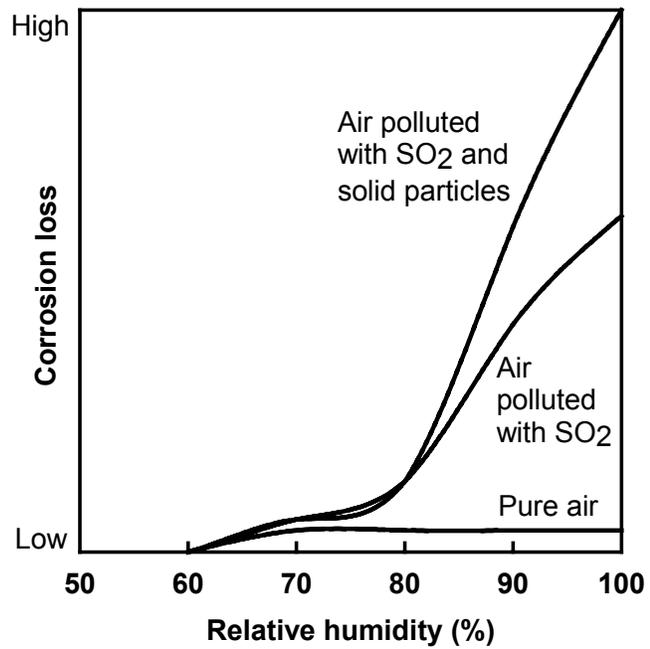
**FIG. 4.5. Open exposure test specimens (McKenzie 1978)**



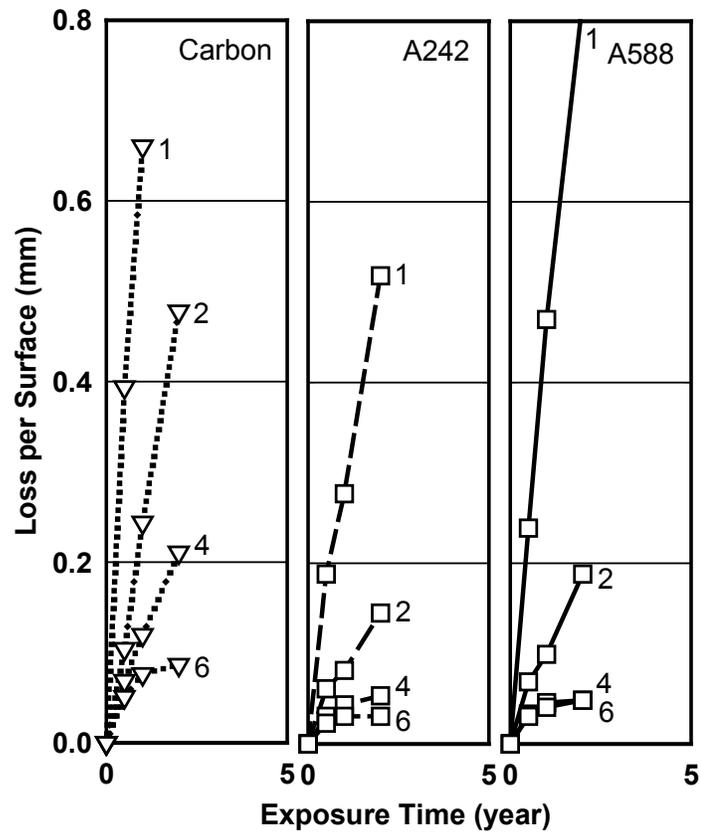
**FIG. 4.6. Girder sheltered test specimens (McKenzie 1978)**



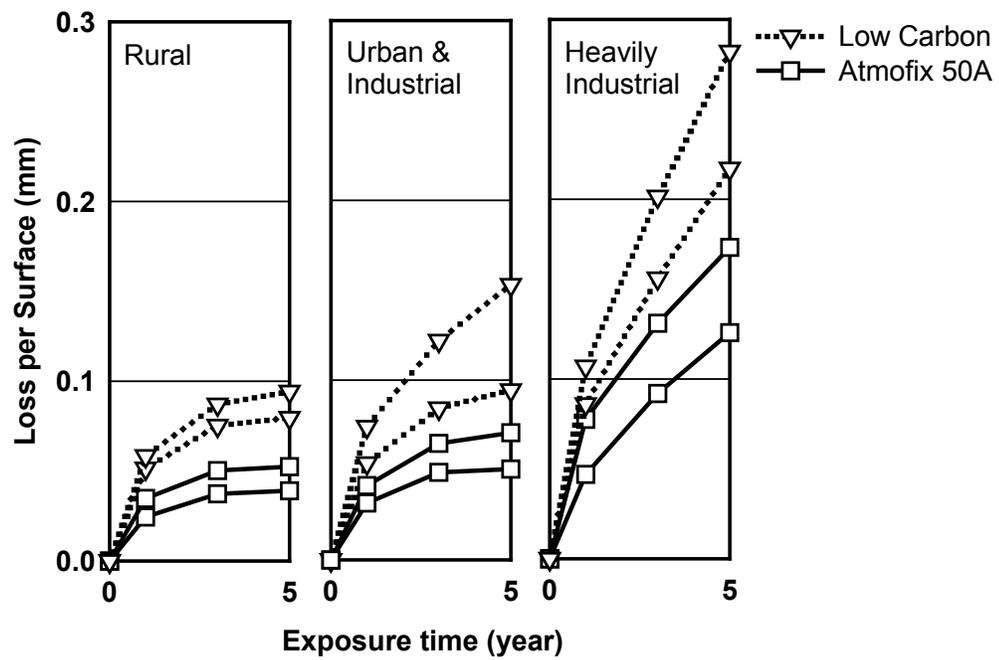
**FIG. 5.1. Effect of continuously moist conditions on corrosion of steels (Larrabee 1966)**



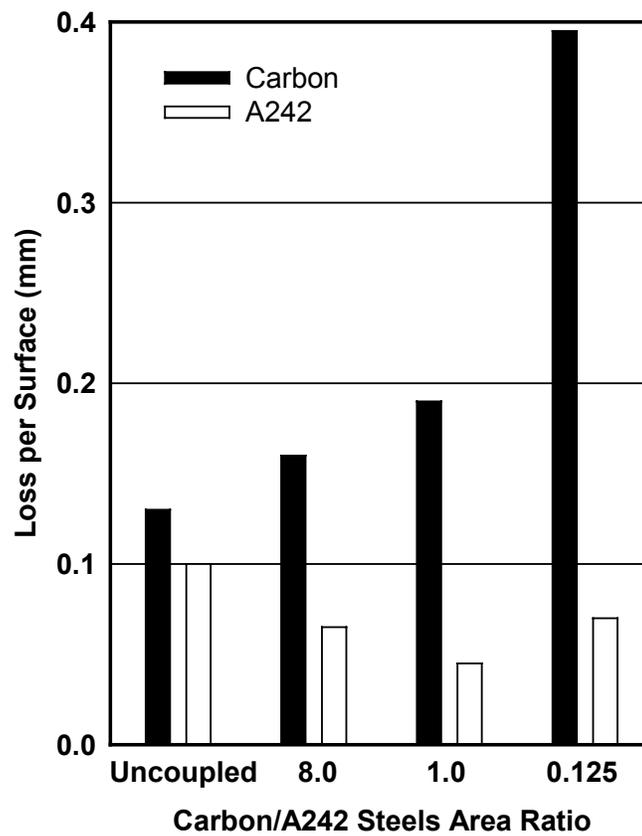
**FIG. 5. 2. Simplified diagram showing the effect of relative humidity and pollution on the corrosion of carbon steel (after Vernon)**



**FIG. 6.1. Corrosion penetration of carbon and weathering steels exposed to various chemical plant atmospheres (see Table 6.1) (Schmitt 1967)**



**FIG. 6.2.** Effect of sulfur dioxide content on corrosion of low carbon and weathering steels exposed to various atmospheres in Czechoslovakia (see Table 6.2) (Knotkova, Vlckova, and Honzak, 1982)



**FIG. 7.1. Corrosion thickness loss per surface of uncoupled and coupled steels after 6 months in seawater (Ellis and LaQue, 1951)**

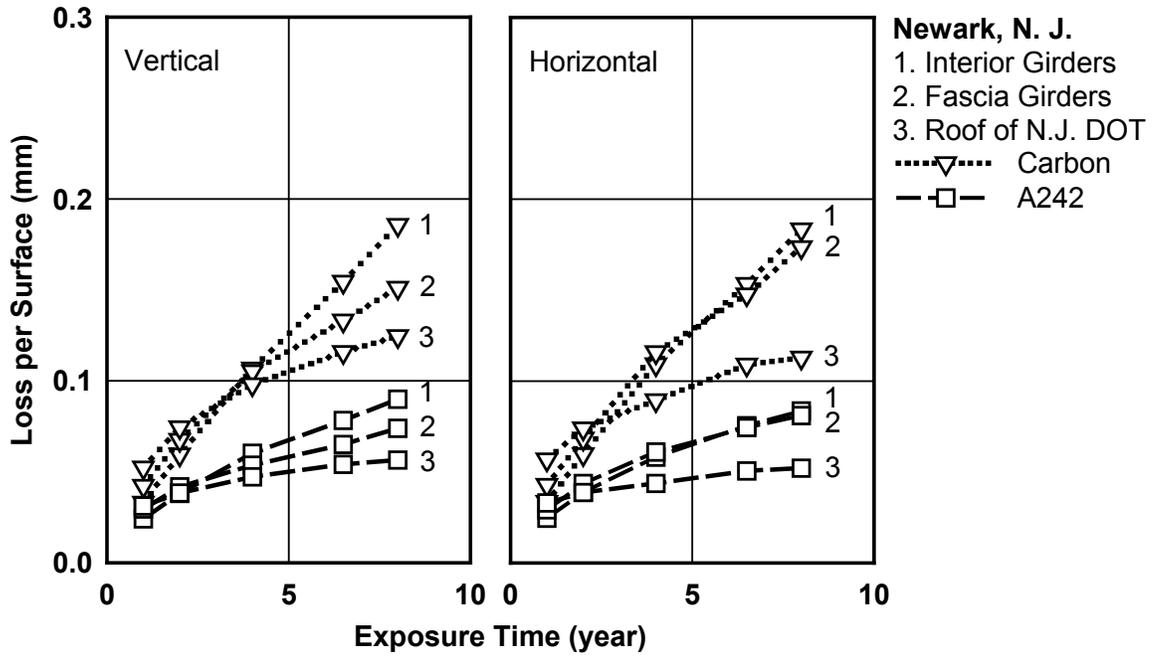


FIG. 8.1. Effect of salt contamination on corrosion (Cosaboom 1979)

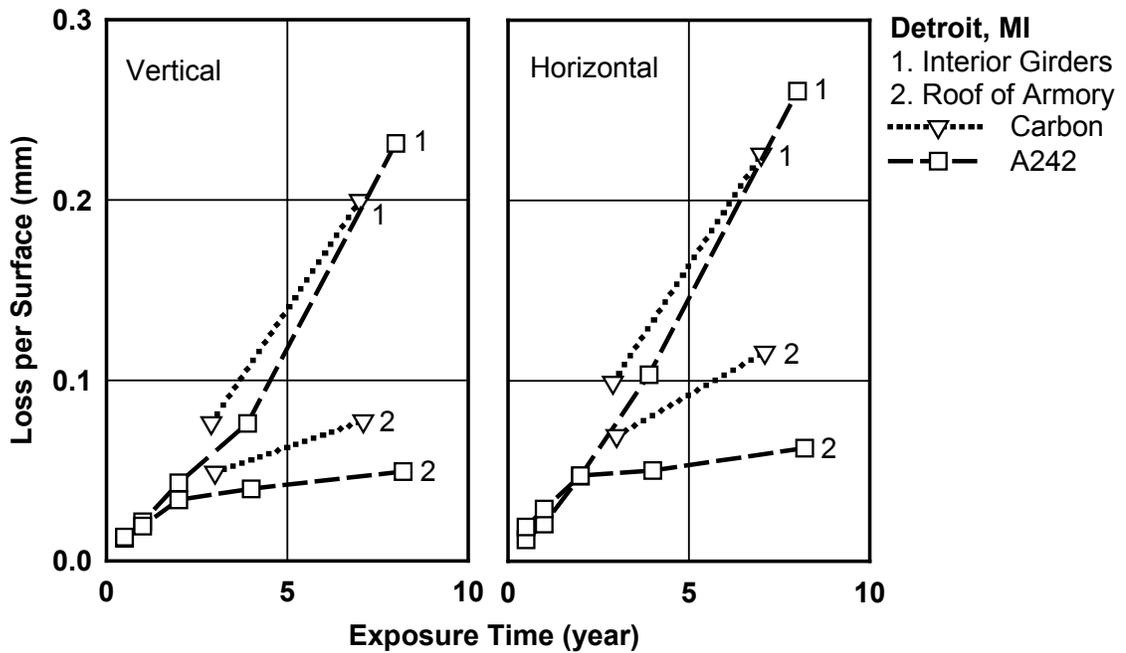
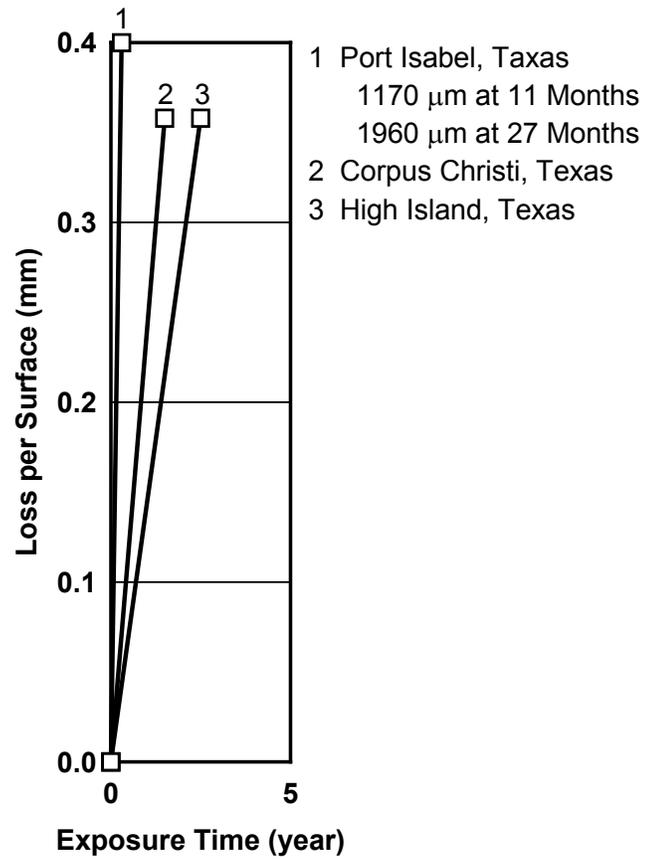
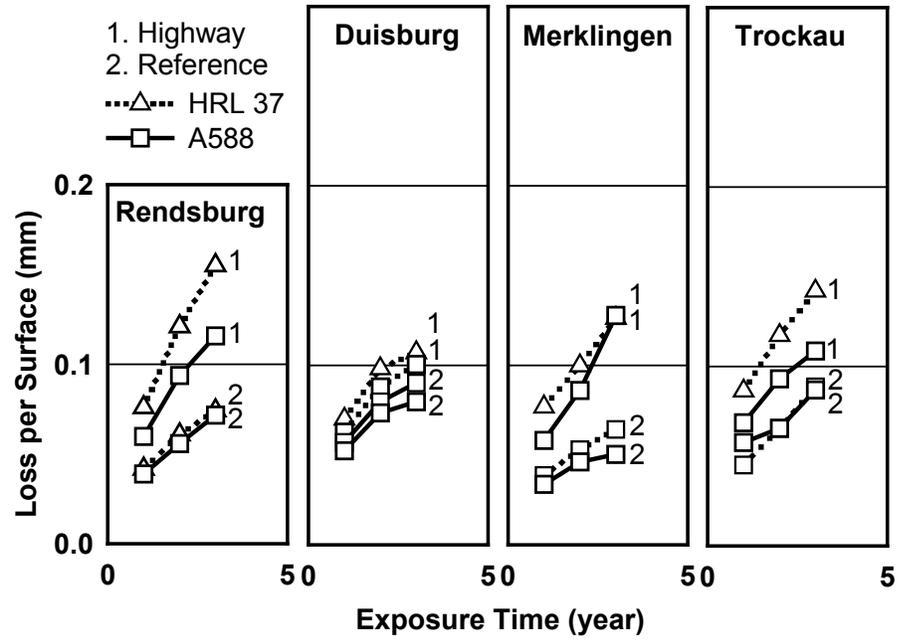


FIG. 8.2. Effect of salt contamination on corrosion (Zoccola 1976)



**FIG. 8.3. Effect of salt contamination on corrosion at Texas Gulf Coast atmosphere (Raska 1983)**



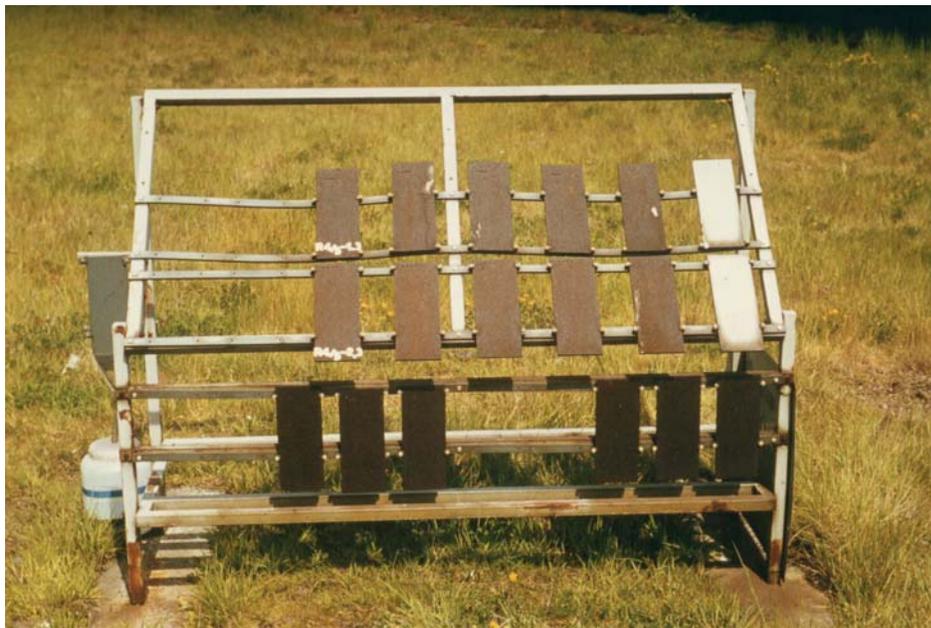
**FIG. 8.4. Effect of salt contamination on corrosion at various atmospheres in FRG (Hein 1981)**



**FIG. 8.5. Reference site in Rendsburg (Hein 1981)**



**FIG. 8.6(a). Highway site in Duisburg (Hein 1981)**



**FIG. 8.6(b). Reference site in Duisburg (Hein 1981)**



**FIG. 8.7(a). Highway site in Merklingen (Hein 1981)**



**FIG. 8.7(b). Reference site in Merklingen (Hein 1981)**



**FIG. 8.8(a). Highway site in Trockau (Hein 1981)**



**FIG. 8.8(b). Reference site in Trockau (Hein 1981)**

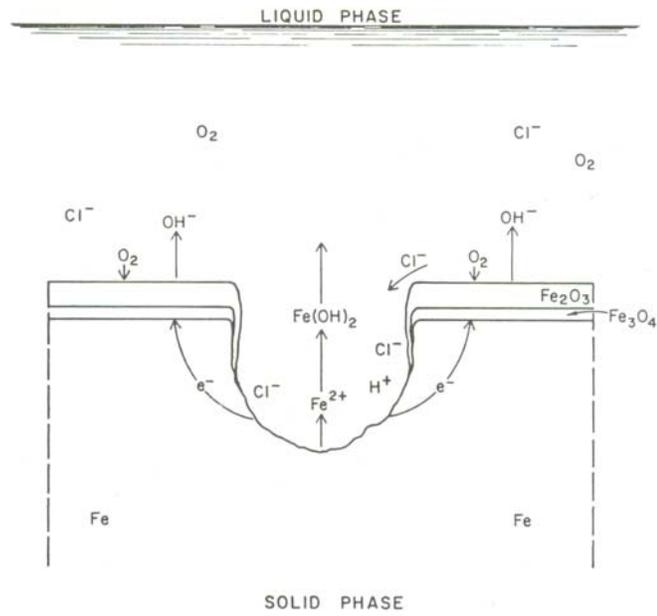


FIG. 9.1. Pitting of oxide covered steel (Wilhelm 1988)

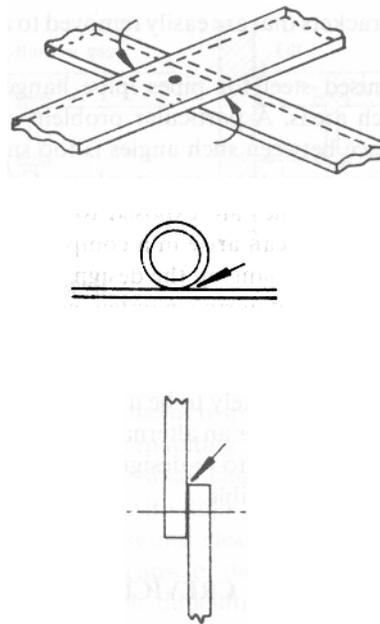
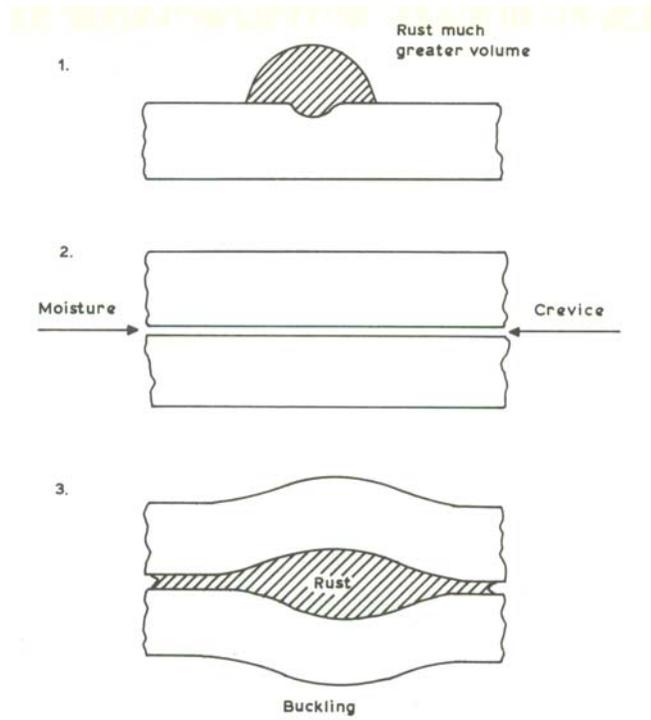
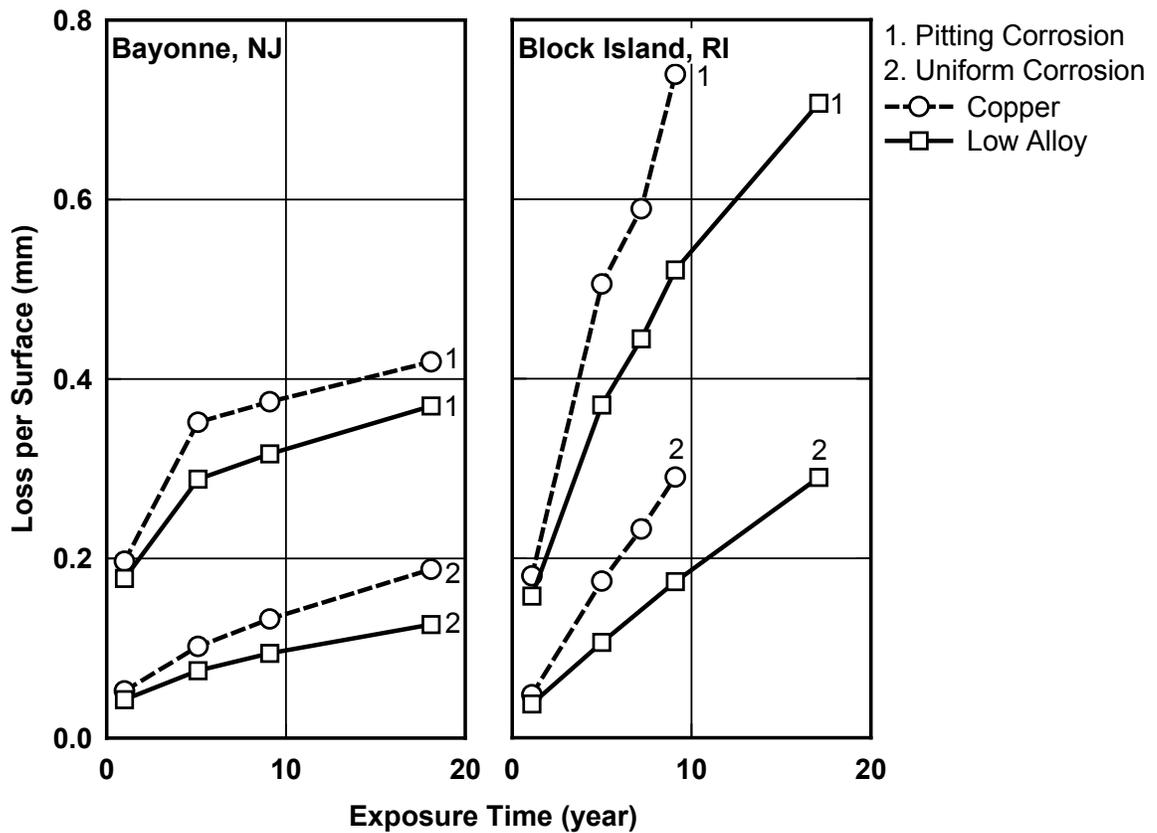


FIG. 9.2. Typical crevices situations (Chandler 1991)



**FIG. 9.3. Rust formation in crevices (Chandler 1991)**



**FIG. 9.4. Comparison of pitting and uniform corrosion of copper steel and low-alloy steel exposed in industrial Bayonne, NJ, and marine Block Island, RI (Copson 1960)**

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