



**American
Iron and Steel
Institute**

American Iron and Steel Institute
1140 Connecticut Ave., NW, Suite 705
Washington, DC 20036
Phone 202.452.7100

www.steel.org

INTERIOR CORROSION OF STRUCTURAL STEEL CLOSED



Bulletin No. 18, February 1970

INTERIOR CORROSION OF STRUCTURAL
STEEL CLOSED SECTIONS

BULLETIN No. 18

FEB 1970

Committee of Steel Plate Producers

american iron and steel institute

ACKNOWLEDGEMENT

This paper is based on researches of C.P. Larrabee, a consultant on corrosion of metals, now deceased. The effort was guided by a Task Group consisting of J.A. Gilligan, A.J. Oudheusden and D.S. Wolford, members of the Engineering Subcommittee of the Committee of Structural Steel Producers and the Committee of Steel Plate Producers of American Iron and Steel Institute and Mr. R.W. Lautensleger who drafted the present text.

Statements attributed to ten observers of closed steel section corrosion behavior in North America and Europe have been authenticated by letters received from most of them.

Use of his file of letters, particularly in reference to Pittsburgh's Glenwood Bridge, permitted by Louis P. Schwendeman of Richardson, Gordon and Associates, is gratefully acknowledged.

ABSTRACT

A survey of light poles, water-tank stanchions, orthotropic deck bridges, marine tubular catwalks, davits and welded steel columns strongly suggests, contrary to some beliefs, that interior surfaces of closed steel sections rust but little in the atmosphere, even when not fully sealed. Only light rusting occurs because amounts of oxygen and water in entrapped air are limited and condensation necessary for rusting is infrequent. Computations based on the oxidation reaction taking into account inside surface, volume of entrapped air, relative humidity and air changes show that the loss of iron thickness due to such rusting is negligible.

Use of closed steel sections for structural members in bridges and buildings is therefore feasible with the knowledge that no strength loss will occur from inside oxidation. The concept applies whether the closed steel section is, for example, of relatively small tubular configuration or of large box shape. The fact that interior surfaces of closed steel sections need not be painted to prevent oxidation will result in substantial reduction of maintenance costs and eliminate the need for man-holes with removable covers where this has been the practice. Schwendeman estimated potential savings in maintenance costs up to 45% where use of closed box sections in bridges eliminate need for painting section interiors.

TABLE OF CONTENTS

	Page
ABSTRACT.....	4
INTRODUCTION.....	7
PART I – Corrosion Survey of Existing Structural Steel Closed Members.....	8
PART II– Theoretical Aspects of Corrosion.....	11
SUMMARY - PART I.....	16
SUMMARY - PART II.....	16
CONCLUSION.....	16
APPENDIX I – Formulas.....	17
APPENDIX II – References.....	18
APPENDIX III – Bibliography.....	18
APPENDIX IV – Notations.....	18

INTRODUCTION

Highway bridge designers in the United States have been concerned about corrosion inside closed box girders, stiffening rib sections of orthotropic steel bridge decks, and similar structural steel closed sections. As a result, expensive protective measures such as painting the interior surfaces and providing sealed access holes for inspection purposes have sometimes been specified. Such measures are unnecessary, as this paper will demonstrate. Painting can frequently be omitted for sections exposed to the atmosphere for certain applications and local atmospheric conditions.

Steel closed sections in the form of pipe and round and square tubing have been widely used in structures for nearly a century. Applications include flag poles, light poles, trolley power line poles, crane booms, davits, bridge railings, water tank supports, and a variety of other specialized structures. Steel pipe and tubing, however, are limited to relatively small cross sections.

Large closed sections fabricated from steel plate can be designed in practically any size and cross section within fabrication, transportation, and erection limits. These sections are commonly used in bridges, buildings, towers, oil drilling platforms, dry docks, and many other structural and architectural applications.

Box sections for bridges and buildings usually are designed with maintenance manholes to provide access for painting because sufficient data on interior corrosion effects has not been available. In some of the newer

applications, box sections are being designed without manholes. Elimination of manholes simplifies the structural design, reduces fabrication costs, and saves on maintenance. For example, Louis P. Schwendeman, Project Engineer for Richardson, Gordon & Associates of Pittsburgh, estimates that maintenance painting of box sections for bridges can be reduced by 45 percent if the sections have no manholes and are sealed.⁽¹⁾ His estimate for a new major highway bridge, Glenwood Bridge, across the Monongahela River near Pittsburgh, also indicates that by the use of closed box sections, the savings in painting represent a 22 percent reduction in overall maintenance cost for this structure.

Part I of the paper cites analogous examples where the interior surfaces of closed sections have been inspected and gives pertinent information gathered from foreign sources.

Part II demonstrates mathematically that, under the worst conditions of temperature and humidity, the corrosion occurring inside box sections would be negligible in normal applications. For instance, for a box girder of an orthotropic steel deck bridge with a ratio of volume (cubic feet) to interior surface area (square feet) equal to one, and the extreme condition of 100 percent relative humidity at 100°F, the calculated maximum corrosion loss would be 0.0009 in. For a wall thickness of 5/16-in., this would be less than 0.3 percent of the thickness. In general, the study indicates that corrosion inside sealed steel sections is structurally insignificant, and that painting of the interior surfaces and maintenance manholes can be eliminated.

PART I – CORROSION SURVEY OF EXISTING STRUCTURAL STEEL CLOSED MEMBERS

Growing use of welded box girders, closed water tank stanchions and other sealed tubular structural members has resulted in an accumulation of corrosion data from field observations. Corrosion experience reported in recent years is summarized below.

Trolley Power Line Poles in Pittsburgh

Through the cooperation of Mr. C.E. Schauck of the Port Authority of Allegheny County, Pennsylvania, samples of steel trolley power line poles from the Pittsburgh area were obtained for examination. The poles, in service 40 to 50 years, consisted of three sections of lap-welded carbon steel pipe with decreasing diameters. The bottom section was 8-inch O.D. pipe, 19-feet long; the center section was 7-inch O.D. and 7-feet long; and the top section was 6-inch O.D. and 7-feet long. All sections had the same nominal wall thickness of one-half inch.

To determine metal loss due to corrosion, the wall thickness of the 8-inch sections was measured by an audigage, a flat crystal ultrasonic testing device. Unfortunately, the audigage was not effective in measuring the wall thickness of the 6-inch and 7-inch sections because of their sharper curvature.

Although the tops of the poles were open to the atmosphere, corrosion in the half-century old 8-inch pipe sections was found to be negligible, as shown in the following table:

WALL THICKNESS OF EIGHT-INCH TROLLEY POWER POLE PIPE

Specimen	Nominal	Measured	% ± Nominal ^a
	Wall Thickness ^a , Inches	Wall Thickness, Inches	
1	0.500	0.493	-1.4%
2	0.500	0.474	-5.2%
3	0.500	0.526	+5.2%
4	0.500	0.498	-0.4%
5	0.500	0.520	+0.4%
6	0.500	0.492	-1.6%

^aOriginal specification allowed ± 12.5 percent variation from 0.500 in. nominal thickness.

A piece of this 8-inch pipe was selected at random, cut lengthwise, and the interior surface was examined. Little or no evidence of corrosion was found. In fact, some mill scale was still present.

The composition of one of the 8-inch pipes, again selected at random, was 0.08% carbon, 0.58% manganese, 0.10% phosphorus, and 0.005% copper. The low copper content would not have increased the steel's corrosion resistance.

The comparative atmospheric corrosion rates of an open hearth steel of similar composition and an open hearth copper-bearing steel have been determined by ASTM's Committee A-5.⁽²⁾ The Committee found that in Pittsburgh the average years to perforation of 22-gage corrugated steel sheets with 0.02% copper content was 1.3 years, whereas the copper-bearing steel with 0.21% copper lasted 4.8 years. The trolley pole sample would probably have about 1/4 to 1/3 the atmospheric corrosion resistance of a copper-bearing steel, yet the pole interior was essentially intact after nearly a half century of service. *A reasonable conclusion is that, even though the top end of the pole was open to the elements, the shielded position of the interior alone was sufficient to prevent corrosion.*

As many as 22,000 of these poles have been used in the Pittsburgh area. After 40 to 50 years of service, with the top of the poles exposed to the atmosphere, about 18,000 are still in good condition and in use today. The other poles have been removed because many of the trolleys have been replaced by buses.

Light Poles in Dayton, Ohio

Mr. I.G. Holmer, Supervisor of the Municipal Affairs Department of the Dayton Power and Light Company, Dayton, Ohio, supplied a sample of a light pole that had been erected in 1905 and removed in 1964. The top of the pole was curved 180 degrees and was closed. No interior surface protection was provided.

The sample was taken immediately above the ground line. Its composition was 0.04% carbon, 0.38% manganese, 0.092% phosphorus with less than 0.0005% copper. The section was halved lengthwise; examination of the interior surface revealed that it retained the original mill scale and had no visible pits to indicate the effects of atmospheric corrosion. The exterior surface of the pole had been painted periodically, but even after 59 years of service, the interior surface was intact. None of the identical poles installed at the same time have failed by corrosion.

Water Tank Stanchions (Water Tank)

Mr. Fred L. Plummer, Executive Director, American Welding Society states that:

"For many years elevated storage tanks in this country have been supported by towers consisting of closed tubular members. Companies such as Chicago Bridge and Iron and the Pittsburgh Des Moines Steel Co. have had extensive experience in the use of such closed sections in which normally the internal surface receives no special treatment of any kind. Some of these have been closed sections and some have been open sections. Service has generally been entirely satisfactory in both cases. In cases where the section has been sealed, I believe no effort has been made to dry the air before sealing."

German Corrosion Protection Study

Welded steel closed sections have been used extensively in Germany, especially in orthotropic deck bridges built in the last 15 to 20 years. Investigations on behalf of the German Federal Railroads are reported by Seils and Kranitzky.⁽³⁾ The study covers six groups of welded structures including four railroad bridges, three highway bridges, hollow supports on a Munich railroad station, a locomotive turntable, a traveling platform on a railroad car and one experimental weldment.

Detailed measurements show that condensation does not occur in steel closed sections if the sections are airtight. Manholes should be sealed with rubber gaskets, according to the report. However, airtight design without manholes is preferred by the authors because it eliminates the need for interior inspection and protection.

If for some reason a steel closed section cannot be completely sealed, the report suggests that adequate draft ventilation be provided by openings on the front and side walls to facilitate evaporation of any water that may accumulate inside. Openings in the floor alone are not suitable for ventilation, particularly when the side walls have no openings, because they tend to increase the relative humidity inside the section.

Water pipes, drain pipes and similar systems should be suspended outside the section whenever possible. If pipes must pass through the closed section, drainage openings should be

provided in case the pipe fails. These openings can be installed with shutters that automatically open under increased pressure from the inside. Areas in the vicinity of shutters and draft openings should be adequately protected against corrosion. The pipe system should be insulated to avoid condensation on their surfaces.

According to the study, simple coatings can be applied to the interior surfaces of an unsealed closed steel section for added corrosion protection. One coating recommended is zinc powder-based paint. It has two important properties: it is unaffected by welding heat and does not lower the quality of the weld bead.

German Experience with Sealed Sections in Orthotropic Bridges

Several multi-span German bridges across the Rhine have welded orthotropic plate decks in which the floor beams and longitudinal U-shaped or trapezoidal box-shaped ribs are shop-welded to the top deck plate. This forms a common top flange for the underlying structure and results in a continuous series of sealed box sections.

These sealed sections are not given any interior corrosion protection. German designers and fabricators confirm that the initial minor corrosion resulting from trapped air will use up available oxygen and the oxidation process will stop. German engineers have noted the loss of section thickness through oxidation to be so small that it can be ignored.

Small Holes Not A Problem

Mr. E. McMinn, retired Director and Chief Engineer of Tubewrights, Ltd., London, a former design and fabricating firm, specializing in tubular sections, states:

"A paper in L'Energia Elettrica (Italy), July, 1953, discusses the mechanics by which water can enter an imperfectly sealed structure, i.e., by condensation, aspiration on heating and cooling, capillary infiltration, etc.⁽⁴⁾ A paragraph from this research study says that 'one essential condition must be fulfilled to produce internal corrosion — an aperture of appreciable size is needed to allow both water and oxygen to enter the system in appreciable quantities. In the case of a closed tube, chemical equilibrium between

water, oxygen and iron oxide is reached as soon as a practically imperceptible layer of oxide is formed.

"Tests we have made indicate that corrosion was unlikely to occur through holes having direct access to the atmosphere, provided they were shielded from actual films of water. Still, we prefer that hollow welded sections be airtight. If this is done, no further precautions are necessary."

Tubing in Marine Atmosphere Shows No Rust

During the Second World War, structures known as Maunsell Forts were constructed in certain British estuaries to protect shipping. In 1943, Tubewrights, Ltd. of London supplied steel for tubular catwalks to connect the forts off the Nore estuary. The catwalks were made from open hearth seamless carbon steel tubes 6-5/8-in. O.D. x 5/16-in. thick and 4-1/2-in. O.D. x 8 gage, as well as from 1-11/16-in. O.D. x 8-gage Bessemer steel continuously welded tubes.

During a fog, late in 1952, the steamship Baalbek collided with a fort and one of the catwalks was wrapped over her bows. The broken catwalk's tubing was examined to determine the condition of its interior surface following its 10-year exposure period to the harsh marine environment. The interior surfaces of the tubes were found to have the original mill finish. In one tube the heat mark from welding was still evident.

Mr. E. McMinn of Tubewrights also cites the excellent condition of two tubular carbon steel davits for hoisting lifeboats that were examined in 1961. The davits, made of 16-in. O.D. x 1-1/2-in. thick tubes tapered at the ends, had been installed on the Aquitania, a vessel built in 1913/14.

After the Aquitania was scrapped, the davits lay in an English shipyard for ten years before they were inspected. Absolutely no evidence of internal corrosion could be found on inspection, although the tubes were 47 years old and had been exposed to severe marine atmospheres for at least 36 years.

Use Soap to Find Leaks

Mr. R.A. McLachlan, formerly Chief Engineer of the Vancouver, B.C. plant of Dominion

Bridge Company, states:

"The practice of hermetically sealing structural members to avoid inside painting and corrosion originated in Europe when closed welded sections were introduced there. No stage of closure short of hermetic sealing is completely dependable, although simple corrosion protection can be provided in case the seal is not complete. In completely sealed structures, no manholes need be provided and no paint is necessary on the inside.

"At onetime I thought that a connection for a pressure line and gage might be necessary to periodically provide slight positive pressure in the member. However, it is quite adequate to initially test the member in the shop under low pressure with a soap solution applied to the welds to detect any leaks, which can then be sealed."

A Welding Engineer's Comments

Mr. G. Zoethout, a consultant welding engineer of Eindhoven, Netherlands, reports:

"All modern fabricators make complete closed sections whenever possible. There are a few fabricators who take some precautions for corrosion protection, but almost always at the customer's insistence. One fabricator uses a normal type of manhole in larger girders. Several field inspections over a period of years have indicated no significant corrosion or condensation. The girders are not painted on the inside.

"Another company is using closed sections as columns. Close to the bottom of each column a hole about 3/4-inch diameter is drilled and then closed with a threaded steel plug. The hole is used in two ways. First, before the column is shipped, pressure is applied to the inside to determine whether welds are airtight. If they are, the plug is reinstalled and the column is erected. After a few years, the column is inspected by removing the plug to see if any water or rust has collected. So far, there has never been any water or corrosion found inside the columns.

"E.D.F. in France has in use a large number of tall welded steel columns, closed at both ends with no access holes. As long as the columns are not filled with

concrete, no problems have ever been recorded. If the columns are filled with concrete, it is a bad practice to close them completely because, in case of fire, water in the concrete will vaporize and exert tremendous internal pressures. This high pressure can rupture a sealed column, but will safely leak out of a column with holes in it."

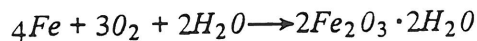
PART II – THEORETICAL ASPECTS OF CORROSION

Calculation of Oxidation Losses

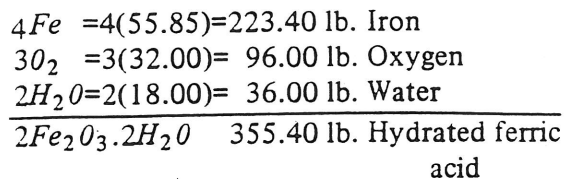
Corrosion within an airtight closed section will occur when water and air are present. Corrosion will cease when either the oxygen or water in the section is consumed in forming rust.

The maximum loss of wall thickness caused by uniform oxidation on the interior surface of the section can be calculated by using a simple corrosion factor. It relates the amount of thickness lost by oxidation to the quantity of water present in the closed section and the inside surface area of the section. The corrosion factor can be used to determine the maximum corrosion loss that would result from oxidation inside any airtight structure.

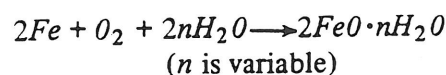
Calculation of the corrosion factor is based on the chemical reaction for the oxidation of iron, assuming that sufficient quantities of oxygen and water are present:



This reaction is valid because most structural steels are at least 98 percent iron by weight. Water is present as moisture in the air. Based on their atomic and molecular weights, the reactants will combine in the following proportions:



Another reaction, forming ferrous rather than ferric oxide, also is possible:



This reaction generally will not occur, unless an excess of water is available.

One cubic foot of dry air at 32°F and one atmosphere pressure contains 0.0187 lb. of oxygen. This amount of oxygen can oxidize 0.0435 lb. of steel, if sufficient moisture is available:

$$\frac{223.4}{96.00} = \frac{Fe}{0.0187}; \quad Fe = 0.0435 \text{ lb. of steel}$$

This is equivalent to 0.00008863 cu. ft. of steel, based on a density of 490.8 lbs. per cu. ft. If the oxidized steel area is one square foot, the thickness lost to oxidation is 0.00008863 ft. or 0.001064 in. The corrosion factor is 0.001064 at 32°F (451.69°R). It is designated as "C" in all subsequent calculations.

At higher temperatures or higher altitudes, the corrosion factor will be smaller. For example, one cubic foot of air at 100°F (559.69°R) and one atmosphere pressure would contain less oxygen because of thermal expansion. Charles' Law relates the absolute temperature and volume of an ideal gas where pressure does not vary:

$$\frac{V}{T} = \frac{V_o}{T_o}; \quad V = \frac{1 \text{ cu. ft. } (559.69)}{(491.69)} = 1.1383 \text{ cu. ft.}$$

Therefore, one cubic foot of dry air at 100°F contains 0.0164 lb. of oxygen, compared to 0.0187 lb. oxygen at 32°F. At 100°F the oxygen in one cubic foot of air can oxidize 0.0382 lb. of steel, if sufficient moisture is available. The loss of thickness for one square foot of steel will be only 0.000934 in. compared to 0.001064 in. for 32°F air.

The maximum depth of corrosion possible in a sealed section is calculated by dividing the volume by the inside surface area and multiplying by the corrosion factor (see chart).

Following is a sample calculation for determining the loss of wall thickness in inches caused by oxidation inside an air-tight steel box section whose inside dimensions are 1 x 2 x 10 ft. This calculation ignores relative humidity but assumes that water is available.

X = Corrosion depth in inches

$$V = 1 \times 2 \times 10 = 20 \text{ cu. ft.}$$

$$C = 0.001064 \text{ in./ft. (at } 32^\circ\text{F)}$$

$$A = 10(1 + 1 + 2 + 2) + 2(1 \times 2) = 64 \text{ sq. ft.}$$

$$X = \frac{V}{A} \cdot C = \frac{20 \text{ cu. ft.}}{64 \text{ sq. ft.}} \cdot 0.001064 \text{ in./ft.} = 0.000332 \text{ in.}$$

CORROSION FACTORS FOR STEEL CLOSED SECTIONS

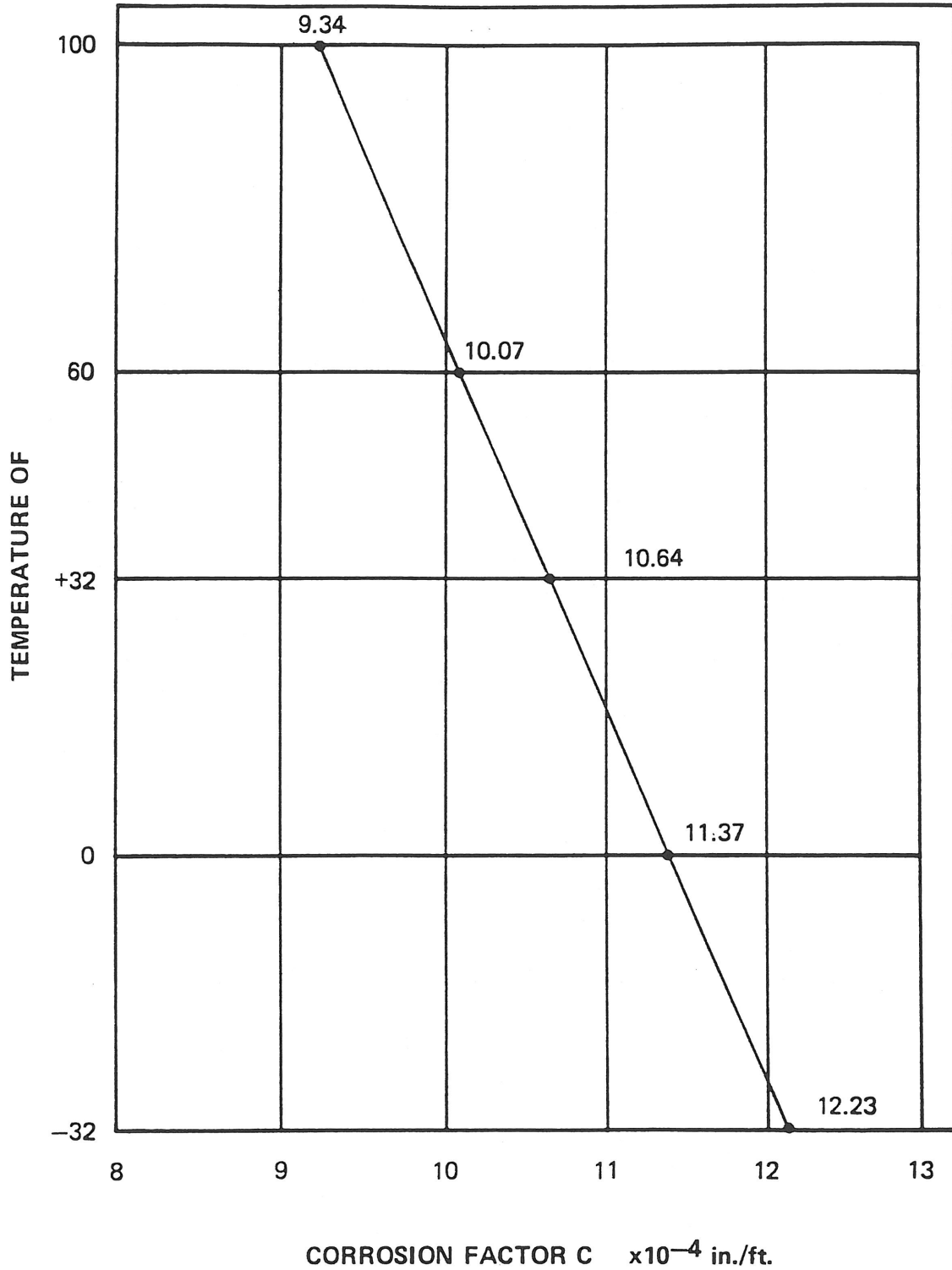


Figure I

If sufficient moisture is present to consume the available oxygen with a closed section, the maximum possible loss of thickness due to oxidation is insignificant. The loss becomes even more insignificant when one realizes it is unlikely that the proper amounts of water and oxygen would be present to permit the reaction to go to completion.

Effect of Water on Corrosion

Because the oxidation of steel is electrochemical in nature, corrosion depends on the amount of water present. A decrease in relative humidity reduces the tendency of a steel to corrode. Corrosion engineers long have known that carbon steels will not rust if exposed to air with less than 30 percent relative humidity. Within the range of 40 to 65 percent relative humidity, the oxidation rate of carbon steel increases markedly.

On a hot day the relative humidity inside a closed section can increase. As the section cools, the moisture condenses over the entire surface, stimulating uniform corrosion. When condensed water runs off to low areas, corrosion damage can become more intense. However, condensation and runoff are so small that their effects on the interior surfaces of sealed box sections are negligible.

From the chemical equation for the oxidation of iron it is possible to calculate the amount of water consumed by complete oxidation and the amount, if any left over. Water is needed to complete the oxidation reaction to form hydrated ferric oxide. Generally, the amount of water in air for any given relative humidity increases with temperature. Assuming a temperature of 100°F, one cubic foot of air can oxidize 0.0382 lb. of steel. The amount of water required is:

$$\frac{223.4}{36.00} = \frac{0.0382}{W}; \quad W = 0.00616 \text{ lb. of water}$$

However, one cubic foot of air at 100°F and 100 percent relative humidity contains 0.0364 lb. of water, or approximately six times the amount of water needed for the reaction to go to completion. In comparison, one cubic foot of air at 60°F and 50 percent relative humidity contains only 0.0061 lb. of water (see Table 1, p. 15). After the oxidation reaction has gone about half way to completion, the relative humidity in the section drops below the

critical humidity (40 to 65 percent) required for corrosion. Under these conditions, the maximum possible corrosion based on available oxygen cannot be reached.

Air Flow in Open Sections

Unsealed manholes in closed sections permit circulation of air and moisture, facilitating oxidation. Air enters a closed section by a process called "breathing". Breathing is a cyclic flow of air into and out of an opening caused by alternate expansion and contraction of the air as a result of daily temperature changes. Breathing effects can be studied by determining the amount of air entering a closed section each day.

A typical air flow determination for a 2 x 4 x 14-ft. box section follows. The section has a volume of 112 cu. ft. and contains an open manhole. Assume that the section is exposed to an average noontime relative humidity of 58 percent and an average daily temperature range from 47°F to 62°F, or 506.69 to 521.69 deg. Rankine, respectively. The average atmospheric pressure is 14.7 psi.

As the air temperature rises from 506.69 deg. to 521.69 deg. Rankine, the air expands and some of it is forced out. The percentage of the volume of air lost, Q , is:

$$Q = (1 - T/T_o) 100 = (1 - 521.69/506.69) 100 \\ Q = 2.96\% \text{ loss} \quad (\text{Appendix I})$$

As the section cools each night, fresh air equal to 2.96 percent of the section's volume is added. Assuming this new air is completely mixed with the original air in the section, the time required to replace one half of the original air in the section can be calculated using the following equation:

$$V_o' = V_o (1 - R)^n \quad (\text{Appendix I})$$

$$n = \frac{\log 56 - \log 112}{\log 0.9704} = 23.92 \text{ days}$$

This means that one half of the air in the box section, containing an open manhole, is exchanged about every 24 days. Complete exchange is not likely because there will always be some original air remaining in the section. Over the course of a year, the inside of the box section will have been exposed to the equivalent of eight fresh volumes of air. This would tend to increase corrosion, therefore, re-

quiring interior painting. In addition, wind-created drafts containing rain water would likewise prolong the corrosion period. Consequently, unsealed manholes are undesirable if corrosion is to be retarded or stopped.

Air Flow in Slowly Leaking Sections

Closed sections that do not have manholes or other large openings can be subject to air exchange. Riveted, bolted, or intermittently welded box sections, not being airtight, will leak slowly as temperature fluctuates. It is possible to measure the rate at which such sections leak by a simple shop test.

The test consists of raising the pressure inside the section to a given gage pressure and measuring the time for the gage pressure to drop to a lower level. From this, a positive "leak constant" for the section can be calculated. Most steel fabricators who test closed sections record the pressure drop over a 30-minute interval.

The gage pressure inside a partially sealed closed section varies in proportion to the pressure differential and the outside atmospheric pressure. When the gage pressure is close to atmospheric pressure, the section leaks much more slowly than when the pressure differential is large because the "driving force" causing the air to leak is much smaller. Because most structural fabrication is performed at atmospheric pressure, the chance of having significant pressure differentials between the inside and outside of a section is small and, therefore, air leaks are small.

The pressure drop inside a hollow structural section caused by a slow leak can be described by the following differential equation, assuming temperature does not vary:

$$\frac{dp}{dt} = -k(p - p_a)$$

The solution for the equation is:

$$(p - p_a) = e^{-kt} (p_o - p_a) \quad (\text{Appendix I})$$

To compare the air exchange for a small leak with the air exchange for an open manhole, the same 2 x 4 x 14-ft. box section previously described is investigated assuming it has a slow leak caused by temperature changes. The leak constant, k , for the section is assumed to be 0.0004 determined by a one hour leak test. The pressure caused by a rise in temperature is found from the following equation:

$$\frac{p_a}{p_o} = \frac{T_a}{T_o}$$

$$p_o = (14.7) \frac{(521.69)}{506.69} = 15.135 \text{ psi}$$

For a 12-hour period (one-half a daily breathing cycle) the general solution to the differential equation for slow leaks is:

$$p = e^{-0.0004(12)}(15.135 - 14.7) = 15.10 \text{ psi}$$

Using the values for the pressure drop caused by the leak, the percent air loss per day is:

$$Q = \left(1 - \frac{P_o}{p}\right) 100 \quad (\text{Appendix I})$$

$$Q = \left(1 - \frac{15.135}{15.100}\right) 100 = 0.232\% \text{ loss}$$

The time needed to replace half the original air in this slowly leaking section is:

$$V_o' = V_o (1 - R)^n$$

$$n = \frac{\log 56 - \log 112}{\log 0.9977} = 301 \text{ days}$$

Air exchange in the slowly leaking section will take almost 13 times as long as in the open section. The corrosion rates will be comparable to those of a tightly sealed section. *In time, small holes tend to plug or rust shut so that slow leaking sections tend to self-seal, eventually becoming airtight.*

TABLE I
MAXIMUM THEORETICAL CORROSION LOSSES
IN STEEL CLOSED SECTIONS

(One Cu. Ft. Sea Level Air Oxidizing One Sq. Ft. Steel)

Relative Humidity, Percent	Temperature, °F	0°	32°	60°	100°
	Other Variables				
0	Oxygen, lb.	0.0200	0.0187	0.0176	0.0164
	Water, lb.	0	0	0	0
	Max. Corrosion Loss, In.	0	0	0	0
50	Oxygen, lb.*	0.0200	0.0187	0.0176	0.0164
	Water, lb.	0.0004	0.0016	0.0061	0.0182
	Max. Corrosion Loss, In.	0.00006	0.00024	0.00092	0.00093**
100	Oxygen, lb.	0.0200	0.0187	0.0176	0.0164
	Water, lb.	0.0007	0.0032	0.0121	0.0364
	Max. Corrosion Loss, In.	0.00011	0.00049	0.00100**	0.00093**

*In humid air, water vapor displaces small amounts of the gases present in air, including oxygen. This table is based on maximum oxygen content in air.

**Available oxygen, rather than water, controls maximum corrosion because sufficient water is available to overcome effect of critical humidity.

SUMMARY – PART I

(1) Studies of light poles, water-tank stanchions, orthotropic deck bridges, marine tubular catwalks, davits and welded steel columns exposed to the atmosphere as long as 60 years by ten observers in North America and Europe strongly suggest that oxidation of inner surfaces of closed steel sections is not a serious problem, even without complete sealing.

(2) Half-century old trolley power line poles fabricated of 6, 7, and 8-inch diameter pipe and open at the upper ends showed little inside rust, according to Schauck and Holmer reporting for Pittsburgh and Dayton areas respectively.

(3) Plummer stated that both Chicago Bridge and Iron Company and the Pittsburgh-Des Moines Steel Company used fully and partly closed steel sections for water-tank stanchions successfully with no special treatment on internal surfaces to prevent oxidation.

(4) A German corrosion protection study involving welded structures such as railroad and highway bridges, railroad station supports, a locomotive turntable and other devices showed no condensation or rust in air-tight sections. They emphasized importance of preventing condensation by various sealing means for closed sections or by draining and ventilating condensed moisture for open sections.

(5) Closed steel sections used in German orthotropic deck bridges during the last 15 or 20 years have proved feasible. Although these sealed sections were not given inside corrosion protection, loss of section thickness assignable to oxidation was negligible.

(6) Tubular catwalks for Maunsel forts in British estuaries showed little inside corrosion after 10 years exposure to severe marine exposure, according to McMinn. He also cited corrosion-free inside surfaces of 47-year old davits from the steamship Aquitania.

(7) Zoethout of the Netherlands told of dry, rust-free interior surfaces of steel columns sealed with screw plugs for inspection which effectively kept moisture out.

SUMMARY – PART II

(8) The oxidation of iron in the presence of oxygen and water can be expressed using two chemical equations for formation of ferric oxide and ferrous oxide. Atomic weights of iron, oxygen, and water provide means of computing volume of moist air to oxidize an area of iron surface to a certain depth.

(9) Oxidation does not occur unless an electrolyte is present at the iron surface. Free water condensed on an iron surface from air will act as an electrolyte and promote chemical combination of iron with oxygen from air to form rust.

(10) The tendency for water to condense depends on the relative humidity of the air and the temperature of the iron surface. Generally, no rusting occurs in air of less than 30% relative humidity, but with 40 to 65% the oxidation rate of carbon steel increases markedly.

(11) Replenishment of oxygen and water in partially sealed sections results from daily temperature changes but proceeds at a very slow rate.

CONCLUSION

Corrosion of inside surfaces of closed steel sections caused by oxygen and water present in entrapped air ordinarily is of little consequence. Free water must condense on the iron surface and act as an electrolyte in the chemical reaction between iron and oxygen from the air for rusting to occur. The possibility of oxidation from this process is greatly reduced by sealing the section. The closed-steel-section concept for controlling corrosion of inner surfaces can be applied to structural members since loss of thickness is negligible and no loss of strength need be anticipated. Savings in maintenance costs up to 45% can result in use of closed box sections for bridges by eliminating need for painting section interiors, according to Schwendeman.

APPENDIX I

Formulas

1. Proof that:

$$Q = \left(1 - \frac{T}{T_o}\right) 100, \text{ in percent:}$$

Charles' Law:

$$\frac{V_o}{V} = \frac{T_o}{T} \text{ (pressure held constant)}$$

$$V = \frac{V_o T}{T_o}$$

$$R = \frac{V_o - V}{V_o} = 1 - \frac{V}{V_o} = 1 - \frac{V_o T}{V_o T_o}$$

$$R = 1 - \frac{T}{T_o}$$

$$Q = \left(1 - \frac{T}{T_o}\right) 100, \text{ in percent}$$

Similarly, Boyle's Law: $p_o V_o = p V$ (temperature held constant)

$$Q = \left(1 - \frac{p_o}{p}\right) 100, \text{ in percent}$$

2. Proof that:

$$V_o' = V_o (1 - R)^n:$$

Breathing
Cycle

0		$V_o' = V_o$	
1		$V_o' = V_o (1 - R)$	
2		$V_o' = V_o (1 - R)$	$(1 - R) = V_o (1 - R)^2$
3		$V_o' = V_o (1 - R)^2$	$(1 - R) = V_o (1 - R)^3$
$n-1$		$V_o' = V_o (1 - R)^{n-2}$	$(1 - R) = V_o (1 - R)^{n-1}$
n		$V_o' = V_o (1 - R)^n$	

In general for n cycles:

$$V_o = V_o (1 - R)^n$$

3. Analysis of Slowly Leaking Sections.

The change in pressure due to a slow leak in a hollow structure can be described by the following differential equation, assuming temperature does not vary:

$$\frac{dp}{dt} = -k(p - p_a) \quad (1)$$

Expanding equation (1):

$$\frac{dp}{dt} = -kp + kp_a \quad (2)$$

$$dp = -kp dt + kp_a dt \quad (3)$$

$$\frac{dp}{p} = -k dt + \frac{kp_a dt}{p} \quad (4)$$

$$\frac{dp}{p} = -k dt \left(1 - \frac{p_a}{p}\right) \quad (5)$$

$$\frac{dp}{p - p_a} = -k dt \quad (6)$$

Integrating:

$$\int \frac{dp}{p - p_a} = -k \int dt \quad (7)$$

$$\ln(p - p_a) = -kt + C, \quad (8)$$

where "C" is a constant and \ln indicates the natural log.

When $t = 0$, $p = p_o$

$$\ln(p_o - p_a) = -k(0) + C \quad (9)$$

$$C = \ln(p_o - p_a) \quad (10)$$

Substituting this value for C in (8):

$$\ln(p - p_a) = -kt + \ln(p_o - p_a) \quad (11)$$

$$k = \frac{\ln(p_o - p_a) - \ln(p - p_a)}{t} \quad (12)$$

$$\text{or: } k = \frac{\ln \left[\frac{p_o - p_a}{p - p_a} \right]}{t} \quad (13)$$

Equation (13) is used in shop testing to evaluate the leak constant, k . When k is known, the equation can be stated in another form for use in calculating Q , the daily percent air loss:

$$kt = \ln \left[\frac{p_o - p_a}{p - p_a} \right] \quad (14)$$

$$ekt = \frac{p_o - p_a}{p - p_a} \quad (15)$$

$$ekt(p - p_a) = (p_o - p_a) \quad (16)$$

$$(p - p_a) = (p_o - p_a) e^{-kt} \quad (17)$$

Equation (17) gives the drop in internal gage pressure, $(p - p_a)$, from an initial gage pressure, $(p_o - p_a)$, with increasing time.

APPENDIX II

References

1. Schwendeman, L.P., "Sealed Box Members in Bridge Trusses Guard Against Weld Corrosion", *Modern Welded Structures*, The James F. Lincoln Arc Welding Foundation, Vol. I, May, 1963, p. 109.
2. American Society for Testing and Materials, Committee A-5 on Corrosion of Iron and Steel, "Report of Subcommittee XIV on Inspection of Black and Galvanized Sheets", *ASTM Proceedings*, Vol. 54, 1954, pp. 110-122.
3. Seils, A. and Kranitzky, W., "Corrosion Protection Inside Closed Hollow-Box Sections", *Der Stahlbau* 28, No. 2, February, 1959, pp. 46-53.
4. Scortecci, M., "I Problemi Connessi Con La Presenza D'Acqua Negli Elementi Delle Strutture Tubolair" (Problems Related to the Presence of Water Within Elements of Tubular Structures), *L'Energia Elettrica*, July, 1953, pp. 459-464.

APPENDIX III

Bibliography

1. Doernen, A. - "Influence of Welding Technique on Methods in Steel Construction", *Schweissen and Schneiden*, Vol. 6, 1957, pp. 235-238.
2. Ernst, E. - "New Methods in Bridge Construction", *Die Bundesbahn* 28, Vol. 19, 1954, pp. 886-897.
3. German Federal Railroads - *Technical Regulations for Rust Prevention on Steel Constructions*, (RoSt), March 15, 1957.
4. German Federal Railroads - *Principles of Structural Design of Steel Railroad Bridges*, December 1, 1955.
5. German Federal Railroads - *Technical Regulations for Steel Constructions*, (TVSt), 11th edition, 1955.
6. German Federal Railroads - *Regulations for Welded Railroad Bridges*, December 1, 1955.
7. Goerg, P. - "Reconstruction of the Kaiser Bridge", from *Kaiser Bridge at Mainz*, festival publication at the reopening of the reconstructed Kaiser Bridge with its interchanges, May, 1955, pp. 23 - 46, Can Roehrig Verlag, Darmstadt.

8. Kloeppe, K. - "Retrospects and Outlooks on the Development of Scientific Fundamentals for Steel Construction", *Der Stahlbau*, Vol. 2, pp. 48 - 72, 1947. Industrie and Handelsverlag, Walter Dorn, Bremen-Horn.

9. Lemmerhold, F. - "Bridges and Building Constructions of the German Federal Railroads in 1956", *Die Bautechnik* 34, 1957, Vol. 11, pp. 405-409 and Vol. 12, pp. 465-471.

10. Nieth, F. - "Conditions of Steel Surfaces in Various Processes for Rust Removing and Descaling", *Metalloberflache* 9, Vol. 10, 1955, Part A, pp. 174-178.

11. Seils, A. - "Explanations to the Technical Regulations for Rust Prevention on Steel Constructions (RoSt) of German Railroads", valid from March 15, 1957. *Der Stahlbau* 27, 1958, Vol. 5, pp. 126-131 and Vol. 6, pp. 165-167.

12. Seils, A. and Kranitzky, W. - "Are the Steel Constructions in Which Closed Hollow Bodies are Universally Applied Endangered by Water Condensation or Internal Corrosion?", *Eisenbahntechnische Rundschau*, Sonderheft 4, (Special Issue - Bridge Construction).

13. Steel Structures Painting Council - "Better Painting of Welds", *Painting Bulletin*, Vol. 4, 1959-1960.

14. "Use of Closed Hollow Profiles and Their Corrosion Protection", *Eisenbahntechnische Rundschau*, Sonderheft 4. (Special Issue - Bridge Construction).

15. Omer W. Blodgett - "The Question of Corrosion in Hollow Steel Sections", Report 1302.163, Lincoln Electric Company, Cleveland, Ohio, 44117.

APPENDIX IV

Notations

Symbols appearing in the text and Appendix I are listed in alphabetical order:

A	Area of inside surface of structural section.
C	Corrosion factor for closed structural sections.
e	Napierian or natural logarithm base, 2.71828. . .
k	Leak constant, characteristic of a given structural section determined by shop testing.

n	Number of complete breathing cycles or days leaking section undergoes repeated heating and cooling.		
p	Absolute pressure in psi.		
p_a	Atmospheric pressure in psi.		
p_o	Initial absolute pressure in psi, at start of leak.	V	Volume of closed box section.
$(p-p_a)$	Final gage pressure in section in psig, after leaking.	V_o	Original volume of air in section before thermal expansion forced some of it out.
(p_o-p_a)	Initial gage pressure in psig, before leaking.	V_o	Remaining volume of original air in section after breathing.
Q	Percentage of air volume lost due to thermal expansion.	W	Amount of water, in pounds, required to complete oxidation of a given amount of steel.
R	Ratio of air volume lost to original air volume.		
t	Time.	X	Section thickness lost due to corrosion inside closed section.
T, T_o, T_a	Temperature of air in section, in		deg Rankine (absolute degrees on Fahrenheit scale). T_o is initial temperature and T is temperature to which air is heated. T_a is used to calculate initial pressure rise required for leaking to begin.