

HIGHWAY RESEARCH RECORD

Number 140

Corrosion and
Protection of
Metals

4 Reports

Subject Classification

34 General Materials

HIGHWAY RESEARCH BOARD

DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

Washington, D. C., 1966

Publication 1384

Department of Materials and Construction

R. L. Peyton, Chairman
Assistant State Highway Engineer
State Highway Commission of Kansas, Topeka

HIGHWAY RESEARCH BOARD STAFF

R. E. Bollen, Engineer of Materials and Construction
W. G. Gunderman, Assistant Engineer of Materials and Construction

GENERAL MATERIALS DIVISION

John L. Beaton, Chairman
Materials and Research Engineer, Materials and Research Department
California Division of Highways, Sacramento

COMMITTEE ON METALS IN HIGHWAY STRUCTURES

(As of December 31, 1965)

LaMotte Grover, Chairman
Welding Engineer, Air Reduction Sales Company
New York, New York

- W. C. Anderson, Chief Research and Development Engineer, The Union Metal Manufacturing Company, Canton, Ohio
John L. Beaton, Materials and Research Engineer, Materials and Research Department, California Division of Highways, Sacramento
Gordon Cape, Manager of Technical Research, Dominion Bridge Company, Ltd., Montreal, Canada
S. K. Coburn, Research Technologist, Applied Research Laboratory, U. S. Steel Corporation, Monroeville, Pennsylvania
Frank Couch, Welding Engineer, Bethlehem Steel Company, Bethlehem, Pennsylvania
John R. Daesen, Director, The Galvanizing Institute, Protomatic, Inc., Park Ridge, Illinois
T. D. Dismuke, Product Engineering Group, Homer Research Laboratories, Bethlehem Steel Company, Bethlehem, Pennsylvania
E. S. Elcock, Wichita, Kansas
Eric L. Erickson, Chief, Bridge Division, Office of Engineering, U. S. Bureau of Public Roads, Washington, D. C.
Edward A. Fenton, Technical Director, American Welding Society, New York, N. Y.
James H. Havens, Director of Research, Kentucky Department of Highways, Lexington
H. H. Hawley, First Assistant Engineer of Bridges, Ohio Department of Highways, Bureau of Bridges, Columbus
G. O. Hoglund, Alcoa Process Development Laboratories, Alcoa Technical Center, Pittsburgh, Pennsylvania
Ray I. Lindberg, Research Scientist, Metallurgical Research Division, Reynolds Metals Company, Richmond, Virginia
Thomas A. Lowe, Research Engineer, Department of Metallurgical Research, Kaiser Aluminum & Chemical Corporation, Spokane, Washington
Robert A. Manson, Metallurgist, Bridge Section, Minnesota Department of Highways, St. Paul
Arthur W. Moon, Office of Deputy Chief Engineer, Structures, New York State Department of Public Works, Albany
Robert A. Norton, Engineer of Hydraulics & Bridge Maintenance, Connecticut State Highway Department, Wethersfield
J. C. Oliver, Testing Engineer, Alabama State Highway Department, Montgomery
Robert A. Pege, Supervising Engineer, Bureau of Structures and Materials, Division of Research and Evaluation, New Jersey State Highway Department, Trenton

Robert G. Pike, Physical Chemist, U. S. Bureau of Public Roads, Washington, D. C.
Joseph W. Pitts, Metallurgist, National Bureau of Standards, Washington, D. C.
Harry D. Richardson, Director, Nuclear Science Center, Louisiana State University,
Baton Rouge
Melvin Romanoff, Chemist, Metal Reactions Section, Metallurgy Division, National
Bureau of Standards, Washington, D. C.
W. W. Sanders, Jr., Department of Civil Engineering, Iowa State University, Ames
Clyde F. Silvus, Bridge Engineer, Texas Highway Department, Austin
Oscar Teitel, Product Engineer, International Pipe and Ceramics Corporation,
East Orange, New Jersey
Lewis A. Tomes, Research Associate, Calcium Chloride Institute, Washington, D. C.
George J. Verbeck, Director of Research, Portland Cement Association, Skokie,
Illinois
L. E. Wood, Department of Civil Engineering, Purdue University, Lafayette, Indiana

Foreword

The problem of corrosion control in the highway field had for many years been confined to determining, usually by experience, how many coats of which paint to apply to a given item. As illustrated by this and other recent publications including Highway Research Records No. 56 and No. 95, corrosion resistance is rapidly becoming the speciality in the highway field that it has been for years in pipelines and the chemical industry.

This publication should be of primary interest to materials engineers, but also contains information which should be made available to maintenance engineers and design engineers.

Bauman and Lewis cite references of previous researchers which indicated that blast furnace slag does not cause corrosion when used in cement and concrete. They then describe 5-year tests of pipe buried in backfills consisting of limestone, natural sand, gravel, native soil, coal cinders, and several types and sizes of slags. They concluded that only the cinders were seriously corrosive in effect and corrosion of black pipe was appreciably greater than that of galvanized pipe in all backfill materials.

Pennington worked with steel, gray cast-iron, and ductile cast-iron. He concludes "steel is the best for a given thickness where buried bare in soil, although gray cast-iron in larger commercial sizes is the only one not requiring an external coating for a service life of 50 years." He also applies a new interpretive technique developed at the U.S. Bureau of Reclamation to data from underground pitting corrosion studies of the National Bureau of Standards.

Britton reviews the experience of the New York State Department of Public Works in painting of structural steel from 1926 to the present and relates it to material specifications.

Daesen illustrates the mechanism of protective action against corrosion by examples and suggests simple tools for the engineer to help evaluate general information on materials offered for corrosion control. Greenberg's discussion of the Daesen paper points out some design modifications which might be made.

Contents

FIVE-YEAR FIELD CORROSION STUDY OF STEEL PIPE TO DETERMINE EFFECTS OF BACKFILL MATERIALS

E. W. Bauman and D. W. Lewis 1

CORROSION OF STEEL AND TWO TYPES OF CAST IRON IN SOIL

William A. Pennington 9

Discussion: Melvin Romanoff; William A. Pennington 21

AN ENGINEERING APPROACH TO IMPROVED PROTECTION OF STRUCTURAL STEEL

H. B. Britton 23

CORROSION CONTROL—A DESIGN FUNCTION

John R. Daesen 39

Discussion: Simon A. Greenberg; John R. Daesen 49

Five-Year Field Corrosion Study of Steel Pipe To Determine Effects of Backfill Materials

E. W. BAUMAN and D. W. LEWIS, National Slag Association

Results of a corrosion study involving exposure of galvanized and black pipe specimens for five years in various backfill materials are reported. Backfill materials used included slags, limestone and gravels, native soil and coal cinders. Corrosion of the pipe, considering the variability inherent in tests of this type, was similar in all backfill materials except coal cinders. Only the cinders were seriously corrosive in effect, and no other backfill used reacted in this manner. Corrosion of black pipe was appreciably greater than that of galvanized pipe in all backfill materials.

•BLAST furnace slag has been extensively employed as a mineral aggregate for more than half a century in all types of construction and as a raw material in the manufacture of cement, mineral wool and glass. The service record in all uses has been excellent.

Nevertheless, since blast furnace slag contains small amounts of sulfur compounds—chiefly present as calcium sulfide or sulfate—there have been occasional fears that corrosion of metals might result from use as aggregate or as a cement ingredient in reinforced concrete, or as a fill material in contact with metal. The reported effects of the sulfur compounds in cinders have no doubt contributed to the questions regarding possible corrosive effects of slag, despite the fact that slag is completely different in composition from cinders.

USE IN CONCRETE AND AS BACKFILL

Performance of Slag Aggregate in Concrete

There have been many laboratory and field investigations in the United States and abroad, demonstrating that blast furnace slag has no corrosive effects when used either as aggregate or as a cement ingredient in reinforced concrete. These date back at least to the research of J. R. Stead in England prior to 1920 (1) who concluded that "slag does not attack or corrode the iron or steel bars bedded in the concrete but is itself protective against corrosion."

Among the many other investigations and published reports relating to use of slag aggregate in reinforced concrete, the performance surveys made by Committee C-9 of the American Society for Testing Materials (2) merit mention. No restrictions were placed on sulfur content of slag concrete aggregate "for the reason that inspections made by members of the Committee of reinforced slag concrete structures in the course of demolition showed no corrosion of reinforcement that could be attributed to the slag, nor is there any published evidence that such corrosion has been observed so far as the Committee is aware." Thirty-eight years later Larrabee and Coburn (3) reported similar findings: no evidence of any corrosion resulting from use of slag aggregate existed.

Bogue (4) stated that any effect of slag would be accentuated in portland blast furnace slag cements where large amounts of slag are intimately interground with the cement

Paper sponsored by Committee on Metals in Highway Structures and presented at the 45th Annual Meeting.

clinker, and pointed out that no discrediting effects had been established in over 60 years of such use. Further evidence of lack of any corrosive tendencies of slag cements is found in the research of the Corps of Engineers (5) where tests indicated that portland blast furnace slag cements resulted in less corrosion of reinforcing bars than did Type II portland cement. Still later, studies were conducted by the Portland Cement Association (6) to evaluate effects on prestressing wire: "It has been found that the presence of sulfides in concrete made with cinders may occasionally cause corrosion of embedded steel. The question arises as to whether the sulfide content in portland blast furnace slag cements would have similar effects." After tests with five Type IS and three Type I cements, the authors concluded: ". . . the corrodibility of prestressing wire in concrete made with Type IS cements was the same as that in concrete made with Type I cements."

Many other studies and investigations similar to the few referred to above have been made, and reported in the literature. Complete summaries of early work in this field are contained in Symposium No. 10 of the National Slag Association (7). These studies have served to disprove definitely any association of slag with corrosion of steel in concrete, whether used as aggregate or as part of the cement.

Slag as Backfill

Although slag has been used as a fill and backfill material for many years in contact with metals of various kinds without any evidence of causing corrosion, far less information is available in the literature than in the case of use in concrete. Many large cities, such as Youngstown, Pittsburgh and Cleveland, have used slag as backfill around utility lines since the early 1900's. Hudson (8), based on a review of available laboratory and field data, concluded that it was unlikely that blast furnace slag backfills would be seriously corrosive and noted the desirability of additional investigations. At a recent conference in Youngstown, Ohio, on corrosion of piping for radiant heat installations (9), the fact that slag is noncorrosive and totally different in reaction from cinders was again demonstrated. Nevertheless, in some areas questions regarding use of slag still arise occasionally, based on the erroneous idea that blast furnace slag and cinders might be similar in their reactions.

In view of such unwarranted concern, it was decided several years ago that additional information was desirable on the use of blast furnace slag as backfill materials around pipe. Accordingly, the National Slag Association started to obtain service record information that would include both backfill and concrete aggregate use. A tabulation of recorded installations of pipe in slag, dating as far back as 1911, was released in 1960 (10). In no case were any corrosion problems encountered. The Association's Technical Committee, under the chairmanship of Fred Hubbard at that time, also recommended that actual field tests of pipe embedded in various backfill media be conducted. As a result, the study described in this report was started in the fall of 1958 on the grounds of the NSA Laboratory site at Canfield, Ohio.

PURPOSE AND SCOPE OF TESTS

The tests were designed to furnish information on the corrosivity of various backfill materials toward both black (uncoated carbon-steel) and galvanized steel pipe during a five-year exposure period. Blast furnace slag, both granulated and air-cooled, was used, along with coal cinders, natural aggregates and the native soil; and, since steel slags were coming into use as backfill materials, they were also included in the study. In the case of the air-cooled blast furnace slag, the steel slag and the natural aggregates several sizes of each were employed since it was thought size of backfill materials might influence corrosion rates.

In all, 16 backfill materials (Table 1) were used, with both black and galvanized pipe specimens buried in each. After five years, the pipe specimens were removed, cleaned, and the extent of corrosion evaluated. Details of the procedures, materials and results of the study are covered in the following sections of this report.

TABLE 1
BACKFILL MATERIALS USED IN PIPE CORROSION TESTS

Trench No.	Type of Material	Source	Size	Magnetic Particles (% by wt)
1	Granulated blast furnace slag	A	No. 4 - 0	4.1
2	Granulated blast furnace slag	B	$\frac{3}{4}$ in. - 0	20.9
3	Air-cooled blast furnace slag	C	No. 4 - 0	3.6
4	Air-cooled blast furnace slag	C	$1\frac{1}{2}$ in. - $\frac{3}{4}$ in.	
5	Air-cooled blast furnace slag	C	$\frac{3}{4}$ in. - No. 4	
6	Limestone	D	No. 4 - 0	
7	Limestone	D	$1\frac{1}{2}$ in. - $\frac{3}{4}$ in.	
8	Limestone	D	$\frac{3}{4}$ in. - No. 4	
9	Natural sand	E	No. 4 - 0	
10	Gravel	E	$1\frac{1}{2}$ in. - $\frac{3}{4}$ in.	
11	Gravel	E	$\frac{3}{4}$ in. - No. 4	
12	Native soil			
13	Coal cinders	F	$\frac{3}{4}$ in. - 0	
14	Steel slag	G	No. 4 - 0	34.0
15	Steel slag	G	$\frac{3}{4}$ in. - No. 4	39.5
16	Granulated blast furnace slag	B	$\frac{3}{4}$ in. - 0	0.5

MATERIALS AND TEST PROCEDURES

Test Site

The test site was near the back property line of the laboratory grounds, located on a large area of level land. The soil tests were conducted at the end of the study, to permit a comparison of results with the extensive underground corrosion work of the National Bureau of Standards (NBS), as reported in NBS Circular 579 (11). Resistivity and pH tests, using recommended procedures of NBS, showed the following values:

Depth	Resistivity (ohm-cm)	pH
0-11 in. from surface	4780	6.1
11-22 in.	5310	4.3

These results indicate the native soil to be quite similar, on the average, to Hagerstown loam at the NBS corrosion Test Site No. 55. The Hagerstown loam is considered to be a moderately corrosive soil, typical of well-drained, high-resistivity soils found in the eastern part of the United States (11).

Pipe

Standard $\frac{3}{4}$ -inch black and galvanized (2 oz zinc/sq ft) steel pipe stock purchased from a local hardware dealer was used. Compositions of the base steels in these pipe samples are unknown. The pipe was cut into 15-in. lengths, and the ends sealed with cork plugs followed by dipping the ends in hot asphalt (85-100 penetration). Exposed external surfaces of the pipe were as obtained from the dealer.

Backfill Materials

The backfill materials included three granulated blast furnace slags, three sizes of air-cooled blast furnace slag, two sizes of open hearth steel slag, three sizes of crushed limestone, two sizes of gravel, natural sand, coal cinders and the native soil,

Each material was used in a single trench, which contained one specimen of each type of pipe.

Characteristics of each of these materials and the trench numbers in which they were used are given in Table 1. The granulated slags were processed to provide a wide range in percentage of magnetic particles, in an effort to determine whether this would affect corrosion. The steel slag samples had not been processed for removal of metallics and, consequently, contained high percentages of magnetic particles.

Field Burial Procedure

Each backfill material was used in an individual trench, all 16 of which were located in a row. Each trench was 4 ft 0 in. long, 1 ft 6 in. deep and 1 ft 0 in. wide, with a 1 ft 0 in. wall of undisturbed soil separating the ends of adjacent excavations.

In each trench a 6-in. layer of the backfill (or bedding) material was tamped into the bottom. One piece of each type of pipe was then placed horizontally in the bed, with the pipe ends 6 in. apart and 6 in. from the ends of the trench. Another 6-in. layer of the backfill material was then tamped over and around the pipe specimens. The remaining 6 in. of the depth was filled with the native soil, tamped and seeded to grass.

This procedure resulted in each test specimen being enveloped, in all directions, by approximately 6 in. of the selected backfill material. Minimum distance between pipe specimens was 6 in. within a given trench and 2 ft 0 in. between trenches. In trenches 1 and 16, an iron peg was driven 3 in. from the ends of the pipe and referenced to property markers to facilitate later location of the specimens.

Specimen Cleaning

After five years under ground, the specimens were carefully removed. One-half of each specimen was wire-brushed by hand to remove loose scale, corrosion products and adhering aggregates or soil, while the other half was left in its "as removed" condition.

Visual examination at this point indicated that additional cleaning would be essential if reliable evaluation of results was to be obtained. Many of the black pipe specimens were quite similar in appearance, with a high percentage of the total area covered by rust stains, scale and/or adhering aggregate, not all of which could be readily removed by brushing. Galvanized specimens were sufficiently stained and discolored as to render estimates of area of zinc removal, etc., difficult.

Accordingly, all specimens were completely cleaned in conformance with the methods used by NBS in their extensive studies of corrosion (11).

Measurement of Relative Corrosivity of Backfill Materials

The relative corrosivity of the backfill materials toward the black (bare carbon-steel) pipe was evaluated on the basis of measurement of the depth of corrosion pits in the pipe surface. These measurements were made with a dial pit-depth gage as shown in Appendix 3 of the NBS report (11).

Galvanized pipe specimens were carefully examined visually, and estimates made of the surface condition (area of bare steel exposed and area still covered by zinc or zinc-iron alloy). The original thickness of zinc coating was measured (on ends of the pipe protected by dipping in asphalt before burial), establishing the zinc application rate as 2 oz/sq ft.

TEST RESULTS

The test results are presented and discussed separately for the black (bare carbon-steel) and galvanized pipe in the following sections.

Corrosivity Toward Bare Carbon-Steel

The backfill materials were divided into three general groups, based on the average depth of the five deepest corrosion pits on the pipe specimens: the first group included

coal cinders only, with an average pit depth of 52 mils; the second included some of the slags, gravel and native soil, with pit depths ranging from 22 to 30 mils; and the third, with pit depths of 11 to 18 mils, included some slags, gravel, limestone and sand.

Figure 1 shows the black pipe specimens with a graph of the average depth of the five deepest corrosion pits on each. The areas affected by corrosion varied widely, as did the "fineness" or "coarseness" of the corrosion pattern. No weight loss data are available to determine any correlation with affected areas.

However, depth of pitting is of greater potential importance than weight loss in pipe corrosion, since it may result in perforation and leakage, and, therefore controls pipe life. The cinders are far more corrosive than any of the other backfill materials, with the entire exposed area of the pipe severely pitted. Only the cinders produced greater corrosion than would be expected in any moderately corrosive soil.

For the other backfill materials used, variations between materials, within either of the two groups into which they are divided in Figure 1, are minor and of no significance in view of the variability in such exposure tests. Similarly, the data fail to show any significant effects caused by different sizes of a given material or by variations in percentages of magnetic particles in the slags.

In fact, it seems probable that all backfill materials, except cinders, should be considered as falling in the same range, without significant differences among them. The average depth of pitting for all materials is 22.4 mils, with individual deviations from this value of -51 percent and +132 percent (cinders). Excluding the cinders, the average for the others is 20.4 mils with maximum individual variations of -46 percent and +47 percent. In NBS studies (11), depths of corrosion pitting on pipe specimens sometimes varied more than 50 percent from the average for two such specimens exposed to presumably identical conditions. In view of the extreme variability encountered in other studies of this type, even between duplicate specimens, significance of the groupings used for the results (with one exception) cannot be established. Only the difference between cinders and the other materials seems to be sufficiently large to be considered significant.

Since the native soil at the test site appears to resemble the Hagerstown loam at the NBS Test Site No. 55, a comparison of test results with their work (11) is of interest. Table 2 gives weight loss and maximum pit depths for plain steel pipe from NBS tests.

Comparing their results with those from the current study, pitting of bare steel tended to be more severe in the NBS tests for a 5-yr exposure than for the black pipe

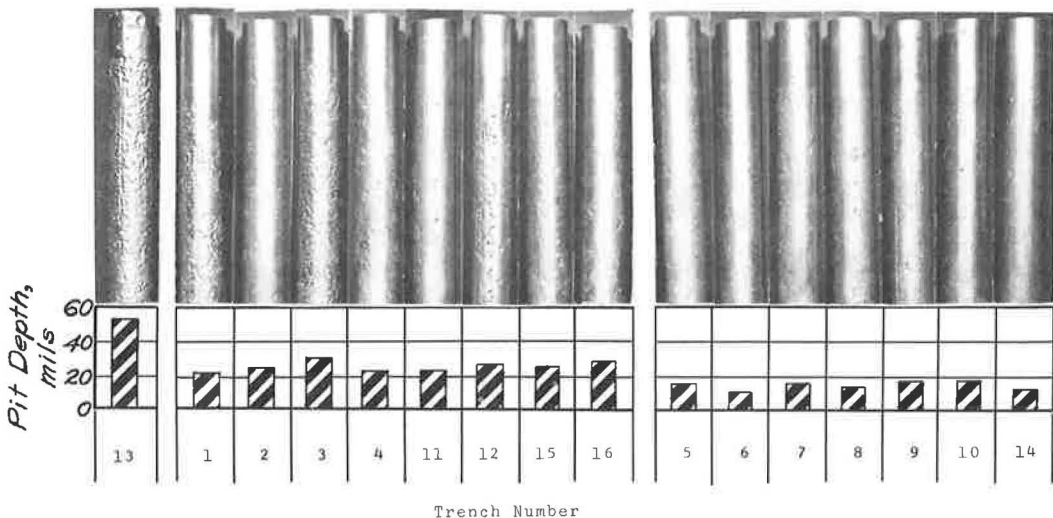


Figure 1. Corrosion of black pipe specimens after 5 years of exposure.

TABLE 2
WEIGHT LOSS AND PIT DEPTH OF
BARE STEEL PIPE BURIED IN 1937
AT NBS TEST SITE NO. 55^a

Exposure (yr)	Bare Steel ^b	
	Weight Loss (oz/ft ²)	Max. Pit Depth (mils)
1.9	1.8	33
3.9	2.6	50
9.0	4.1	92
11.0	3.9	84
12.6	3.4	73

^aData from Table 66 (11).

^bAverage of two specimens.

used in this study. Although NBS used larger pipe (therefore, greater exposed areas), it is believed reasonable to conclude that corrosion was less severe in our study than at NBS Site No. 55. Since the soil at Site No. 55 was not unusually corrosive, it seems that all backfill materials used in this study, except cinders, developed somewhat less corrosion than might be expected from an average natural soil. The NBS tests show a leveling off of corrosion with time, typical of results in this type of material. Other materials, such as poorly aerated soils and cinders, maintain a high rate of corrosion over long periods of time. The limited scope of our investigation did not include provision for specimen removal at varying times to establish such a corrosion-time correlation. However, it seems probable that little additional corrosion should be expected from longer exposure times with

the slags and natural aggregates used in this study.

Corrosivity Toward Galvanized Steel Pipe

Figure 2 shows the galvanized pipe specimens with a graph indicating the area of bare steel exposed (from which all zinc and zinc-iron alloy had been removed by corrosion). For convenience, results are shown in the same order (by trench numbers) as those previously mentioned. Discoloration of the remaining zinc and zinc-iron alloy coatings on these specimens (especially in the case of the one in native soil—Trench 12) makes photographic presentation of the corrosion effects difficult. However, corrosion pitting and exposure of bare steel were extremely minor or nonexistent on all specimens except that from the coal cinder backfill (Trench 13). In the case of the

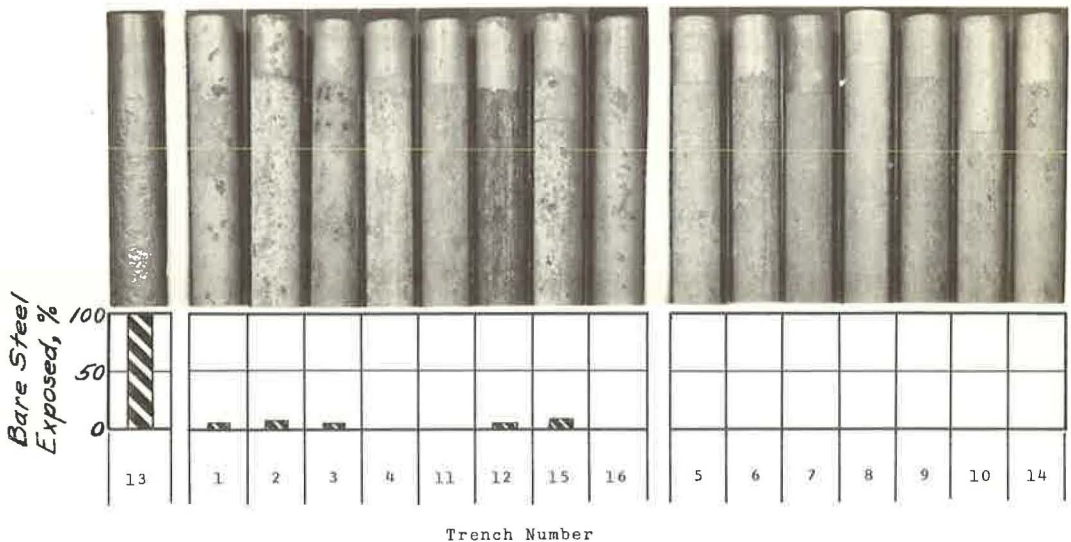


Figure 2. Corrosion of galvanized pipe specimens after 5 years of exposure.

cinders, all of the zinc had been removed by corrosion exposing the base steel over the entire pipe, and extensive pitting had begun indicating very corrosive conditions.

The results point to several definite trends. Coal cinders are far more corrosive than any of the other backfill materials used. Differences between the other materials are minor and, in view of the variability inherent in tests of this kind, probably have no significance.

For all materials except cinders, either zinc or zinc-iron alloys were intact over the entire pipe specimens, or had been removed over only a small percentage of the total area. NBS tests (11) have shown that both the zinc and zinc-iron alloy layers can furnish protection to the underlying steel mechanically when the coating is continuous. When the coating continuity has been destroyed, protection may be provided either galvanically or by the formation of a whitish protective film that appears to be composed chiefly of a zinc silicate. (Such films appear on a number of the pipe specimens in Figure 2.) Additional long-time protection of those specimens having only minor spots of bare steel would, therefore, be expected in any of the backfill materials other than cinders.

Complete removal of all zinc and zinc-iron alloy and absence of any other protective film on the specimen exposed to coal cinders shows that no protection from further corrosion could be expected from the galvanizing. The extensive pitting already begun would be continued with additional exposure time.

CONCLUSIONS

The data obtained on the relative corrosivity of 16 backfill materials on uncoated carbon and galvanized steel pipe specimens during a 5-yr exposure period are believed to justify the following general conclusions:

1. The slag, natural aggregate and native soil backfill materials used in this study were all somewhat similar in corrosivity characteristics.
2. There was no evidence that the gradation or magnetic particle content of the backfill materials had any significant influence on the degree of attack on the test metals.
3. The coal cinder backfill was the only one of the variety of backfill materials used that was extremely aggressive toward uncoated carbon and galvanized steel pipe specimens.
4. The backfill materials used were all more corrosive toward the uncoated carbon-steel than toward the galvanized steel.

ACKNOWLEDGMENTS

The tests and evaluations included in this report were materially assisted by the efforts of many persons, including the laboratory personnel who prepared the test site, excavated and cleaned the specimens, under the supervision of H. T. Williams. Special thanks are due Melvin Romanoff, Corrosion Section, Metallurgy Division, National Bureau of Standards, for his advice and counsel on cleaning the specimens, measurement of corrosion and evaluation of the data; and to S. K. Coburn, Corrosion Engineer, United States Steel Corporation, for obtaining photographs of the specimens.

REFERENCES

1. Stead, J. E. Blast Furnace Slag in Concrete and Reinforced Concrete. Engineering World, Feb. -March 1919.
2. Report of Committee C-9. Proc. ASTM, Vol. 23, p. 221, 1923.
3. Larrabee, C. P., and Coburn, S. K. Experience with Blast-Furnace Slag as an Aggregate in Reinforced Concrete. Corrosion, Vol. 17, pp. 155-156, April 1961.
4. Bogue, R. H. Blast Furnace Slag in Concrete. Jour. ACI, pp. 227-230, Oct. 1955.
5. Mather, Bryant. Laboratory Tests of Portland Blast-Furnace Slag Cement. Jour. ACI, pp. 205-232, Sept. 1957.

6. Ost, B., and Monfore, G. E. Corrodibility of Prestressing Wire in Concrete Made with Type I and Type IS Cements. Research Dept. Bull. 159, Portland Cement Assoc., 1963.
7. Is There Any Corrosive Quality in Slag? Symp. No. 10, Nat. Slag Assoc., Nov. 1928.
8. Hudson, J. C. Does the Sulfur Content of Blast Furnace Slag Backfills Render Them Corrosive? Jour. of the Iron and Steel Inst., pp. 702-704, Aug. 1963.
9. Non-Corrosive Properties of Blast Furnace Slag Revealed in Special Conference on Corrosion of Metal Pipe. Nat. Slag Assoc. Rept. NSA 164-1, Jan. 1964.
10. Several Recorded Installations of Metal Pipe Encased in Slag Concrete or Embedded in Slag Aggregate. Nat. Slag Assoc. Circular Letter 28-60, Sept. 9, 1960.
11. Romanoff, Melvin. Underground Corrosion. Nat. Bur. Stds. Circular 579, April 1, 1957.

Corrosion of Steel and Two Types of Cast Iron in Soil

WILLIAM A. PENNINGTON

Physical Scientist, Division of Research, Bureau of Reclamation, Denver, Colorado

Of the three pipe materials, steel and gray and ductile cast irons, steel is the best for a given thickness where buried bare in soil, although gray cast iron in larger commercial sizes is the only one not requiring an external coating for a service life of 50 years. The underground pitting corrosion study subjected National Bureau of Standards data to an interpretive technique developed at the U. S. Bureau of Reclamation. Pit depth relations given as two types of equations have been established for the three materials. Ductile cast iron, made according to manufacturer's schedule, has about the same service life as steel in "severely corrosive" soil, even though its pitting rate is greater than either steel or gray cast iron.

•THROUGH years of experience in installing water-conveying metal pipes in soil, the Bureau of Reclamation has learned that plain carbon steel, properly coated externally, is the most economical of the wrought metals. Consequently, a very high percentage of such installations are steel. One of the main objectives in this study has been to examine the experimental soil corrosion data of the National Bureau of Standards (NBS) for wrought metals to ascertain whether these data can be employed to reach the same conclusion. Having demonstrated that reliable experimental data can be so used, similar data for gray and ductile cast irons have been compared with those for steel to predict the relative performance of these three materials. The interpretive technique developed in this study is particularly apropos in evaluating new materials or others not yet tested in the field.

CRITERION FOR FAILURE

One of the first responsibilities in facing a problem of this kind is to determine the kind of information needed to arrive at justifiable conclusions as to the longevity of various pipe materials. Inasmuch as the interior of the pipe must be coated to assure the retention of the designed water-carrying capacity, it is reasonable to dispense with failure from the inside. Where phenomena that interfere with water-carrying capacity do not prevail, there can, in general, be no failure from corrosion on the inside of the pipe. For the solution of the problem, attention should be focused on external corrosion.

Pit depth has been selected as the criterion in this study because it is directly related to the service life of a metal pipe. Weight loss data, on the other hand, make virtually no contribution to an understanding of pipe failure caused by external corrosion and therefore such data have not been studied in this investigation. The Bureau of Reclamation considers a length of pipe to have failed from corrosion when the wall is completely penetrated by a corrosion pit. Because of the long service planned for and expected of Reclamation structures, no credit will be given to corrosion products fulfilling the function of the metal that has been corroded away. "Graphitized" corrosion

products on gray cast iron will often plug a hole. Even so, conservative design can make no allowance for such possible beneficial effect.

Experimental data obtained through the years by NBS have served as a basis for this study. The first test was started in 1922; some tests are still in progress, though on a reduced scale. The longest test ran for about 17 years. In 1957, NBS Circular No. 579 by Romanoff (1) was issued reporting results from the inception of the program up to that time.

In 1958, a test was started to evaluate ductile cast iron. The results covering three inspection periods, the longest being 4 years, were reported by Romanoff (2) in 1964 in the Journal of the American Water Works Association.

The work done by NBS is the most renowned, most extensive, thorough, and complete to be found in the field of underground corrosion. This work well deserves the international recognition accorded it.

One of the greatest deterrents to the proper interpretation of experimental pit depth data is the tremendous scatter inherent in the measurements. Although the individual values for a single measurement do not merit much confidence, an average of a large number of such measurements can be highly reproducible. Suppose a group of specimens for 1 year has an average maximum pit depth greater than the average of another group exposed for 2 years. This sometimes happens, but does not mean that a material does not corrode more and more as time goes on. The "apparent reversal of corrosion" is not statistically real. It results from the great scatter inherent in the experimental data. One of the fundamental developments in this study is the evolution of a reliable method of averaging even where the inspection time periods are different. The evolution of this method is described in the laboratory report (3) which serves as a basis for this paper. Even though this averaging technique can be employed to determine the relative corrosivity of various soils, it has not been used for this purpose. It has been employed exclusively to determine the relative merits of various ferrous metals. The method developed dampens the data-oscillations characteristics of pitting-type corrosion in soils. This interpretive technique results in "a running average"; and, though the time periods are different, it is just as reliable as the arithmetic average for constant time.

Both wrought and cast materials have been studied. Among the former were mild steel, wrought iron, ingot iron, copper-bearing steel, nickel-copper low-alloy high-tensile steel, and a steel containing about 5 percent chromium; among the latter were gray cast iron and ductile cast iron. Mild steel is the cheapest of the wrought materials studied, and it also excels all other wrought materials from the viewpoint of life of pipe for a given thickness, except wrought iron which will give a 5 percent greater life than mild steel, but the present cost is so much higher that it cannot compete. Therefore, mild steel is the present economic choice of the wrought products. Throughout this paper, it has been compared with the two cast products as to its corrosion behavior without reference to cost. The cost comparisons have not been made because of the many factors involved—there is likelihood of price changes; also some sizes of a given metal pipe may not require an external coating, whereas the same size in another metal would require coating.

CORROSION RATE EQUATIONS

Before attempting to understand the pit depth-time curve itself, the nature of the data to be analyzed should be discussed. For this purpose, data for gray cast iron and steel are used. Up to the present time, a technique of soil corrosion testing has never been developed which will give low scatter of the data obtained. This does not mean that available data cannot be interpreted. It does mean, however, that it is difficult to make the interpretation, especially if one depends on one of the stereotype statistical methods generally employed. There is ample opportunity with high-scatter data using conventional techniques for the interpreter to reach the erroneous conclusion that all low-alloy ferrous materials corrode alike.

Often one can get a fairly clear picture of a group of data by making a composite. By so doing, each point will be an average of many points and hence, the scatter will

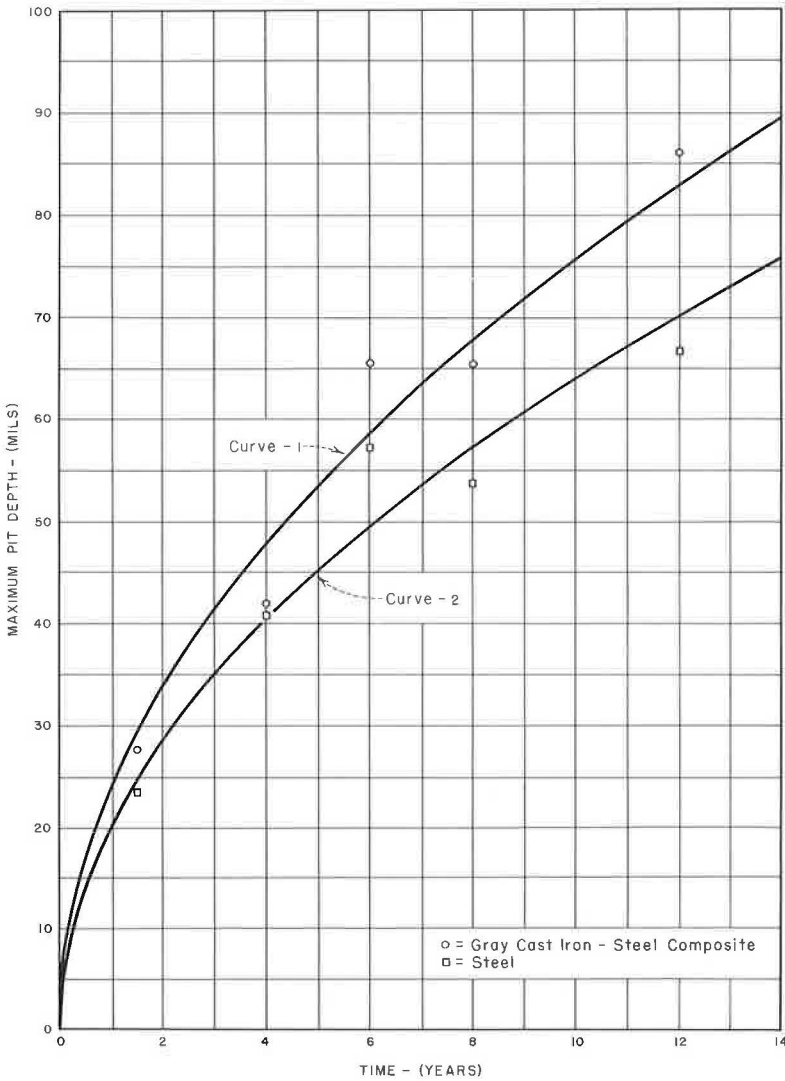


Figure 1. Pit depth-time curves.

be much lower. Some of the data plotted in Figure 1 are a composite for gray cast iron and steel and have been taken from Circular No. 579, Tables 13 and 27. These data are for Material K, open hearth steel, and for Material L, gray cast iron, in Soils 1 to 19 with the exception of Soil 13 where the exposure period was shorter than for the others. In making up the composite, the data for the two metals have been accepted as though they were one and the same metal. This expediency doubles the number of measurements included in a plotted point.

It is obvious that the data cannot be represented by a linear relation. It has been shown (3) that the relation can be given by

$$D = g\sqrt{t} \quad (1)$$

where D , g , and t are maximum pit depth, corrosivity constant, and time. Other pit depth time equations can be found in the technical literature, but none are as suitable

as Eq. 1. Cikerman's (4) $D = A(1 - e^{-Bt})$, where D and t are maximum pit depth and time, respectively, and A and B are constants, appears to be about as inappropriate as can be found. His equation requires that the maximum pit depth approach the value A asymptotically with time, but ordinary ferrous materials do not attain a state of passivity in soil as would be required by the equation.

The corrosivity constant in Eq. 1 can best be evaluated as a weighted average. For example, for five data points,

$$g = \frac{g_A \sqrt{t_A} + g_B \sqrt{t_B} + g_C \sqrt{t_C} + g_D \sqrt{t_D} + g_E \sqrt{t_E}}{\sqrt{t_A} + \sqrt{t_B} + \sqrt{t_C} + \sqrt{t_D} + \sqrt{t_E}} \quad (2)$$

Eq. 2 can be simplified:

$$g = \frac{\Sigma D}{\Sigma \sqrt{t}} \quad (3)$$

where Σ denotes a summation.

The pit depth-time data for the two materials for Soil 1, Allis Silt Loam, are given in Table 1 and are employed to illustrate the use of Eq. 3. Substitutions in Eq. 3 give $g_L = 55.57$ and $g_K = 23.62$.

Because one year is not necessarily the same as another, it is desirable to eliminate \sqrt{t} by dividing the equation for one material by the equation for a second material. Not only is it essential that the two t 's be the same value, but they must also be for precisely the same period. Division gives

$$D_L/D_K = g_L/g_K \quad (4)$$

It has been found that either of these ratios can be given as functions of g_L or g_K , either as

$$D_L/D_K - 1 = m\sqrt{g_L} \quad (5)$$

or

$$(D_L/D_K - 1)^2 = m^2 g_K (D_L/D_K) \quad (6)$$

Eq. 6 can be solved for D_L/D_K :

$$D_L/D_K = \frac{2 + m^2 g_K + \sqrt{m^2 g_K (4 + m^2 g_K)}}{2} \quad (7)$$

Since the pitting ratio (Eq. 5) is a linear function of \sqrt{g} , the average constant m should be obtained by weighting the individual values m_A , m_B , etc., with \sqrt{g} , precisely as the weighting was done in the development of Eq. 3. Not only should there be a weighting with \sqrt{g} but certainly a value of m_A is more reliable if the time period is long; hence, there should be a weighting with some function of time. Because g_L and g_K are obtained statistically by weighting g_{LA} , g_{LB} , g_A , g_B , etc., with \sqrt{t} , then m_A , m_B , etc., should be weighted with \sqrt{t} , as well as with \sqrt{g} . It follows that

$$m = \frac{\Sigma [\sqrt{t} (D_L/D_K - 1)]}{\Sigma [\sqrt{t} \sqrt{g_L}]} \quad (8)$$

TABLE 1

PIT DEPTH-TIME DATA FOR MATERIALS
L AND K IN ALLIS SILT LOAM^a

Time (yr)	\sqrt{t}	Max. Pit Depth (mils)	
		D_L	D_K
1.0	1.000	44	10
3.6	1.897	72	36
5.5	2.345	84	55
7.7	2.775	221	54
9.6	3.098	234	94
11.6	3.406	152	94
Totals	14.521	807	343

^aData available in Ref. (1).

Eqs. 5, 6, and 7 have been called "pitting ratio equations," where substance K serves as the reference material; m is the pitting ratio constant.

At first, open hearth steel was selected as the standard reference material, but later it was shown in the laboratory report that there is no appreciable difference in its corrosion behavior and that of Bessemer steel. Both materials can be considered alike, and either one can be used as the standard.

Inasmuch as the pitting-ratio equations involve two pipe materials at the same time, it is certainly implied that the pipe conditions should be the same. Not only should the soils be the same, but the time should be the same and, in general, the size of the pipe and surface condition

should be the same. From time to time, however, one may wish to compare different size pipe of the same and different materials, and also different surface conditions.

EFFECT OF PIPE DIAMETER

The following equation has been developed (3) for the relation of pipe size and maximum pit depth:

$$D = a(1 - e^{-bd}) \quad (9)$$

where D is the maximum pit depth in a given time in a given soil or group of soils, d is the outside diameter, and a, b, and e are constants, the last being the base for natural logarithms.

Materials M and e of the 1922 NBS test have been selected to evaluate the constants. They are both Bessemer steel pipe, M having an outside diameter of 3.50 in. and e, 1.90 in. These dimensions correspond to nominal 3-in. and 1.5-in. pipe, respectively.

Eq. 8 can be used to evaluate m which can be substituted in Eq. 5 (along with a given value of g_M) to evaluate D_M/D_e . This ratio, in terms of b, can be obtained by dividing Eq. 9 for M by Eq. 9 for e. Thus b can be determined. If unity is substituted for D, along with this value of b in Eq. 9 for e, then a can be evaluated. Where g_M is 40,

$$D_r = D_M/D_e = 1.268 (1 - e^{-0.8174d}) \quad (10)$$

where D_r is the pitting ratio when the 1.5-in. steel pipe is the standard reference.

Eq. 10 has been plotted as Figure 2, using D_r as the ordinate.

Similar calculations have been made with additional values of g_M (Table 2). The first three columns pertain to 3-, 1.5-, and 6-in. pipe, respectively.

EFFECT OF MILL SCALE

A study has been made to determine the effect of scale on Bessemer steel in the NBS 1922 test. The scaled steel was designated e, the cleaned steel y. Both were nominally 1.5-in. pipe with a wall thickness of 0.145 inch. The supplementary data developed yield

$$D_e/D_y - 1 = 0.0066728 \sqrt{g_e} \quad (11)$$

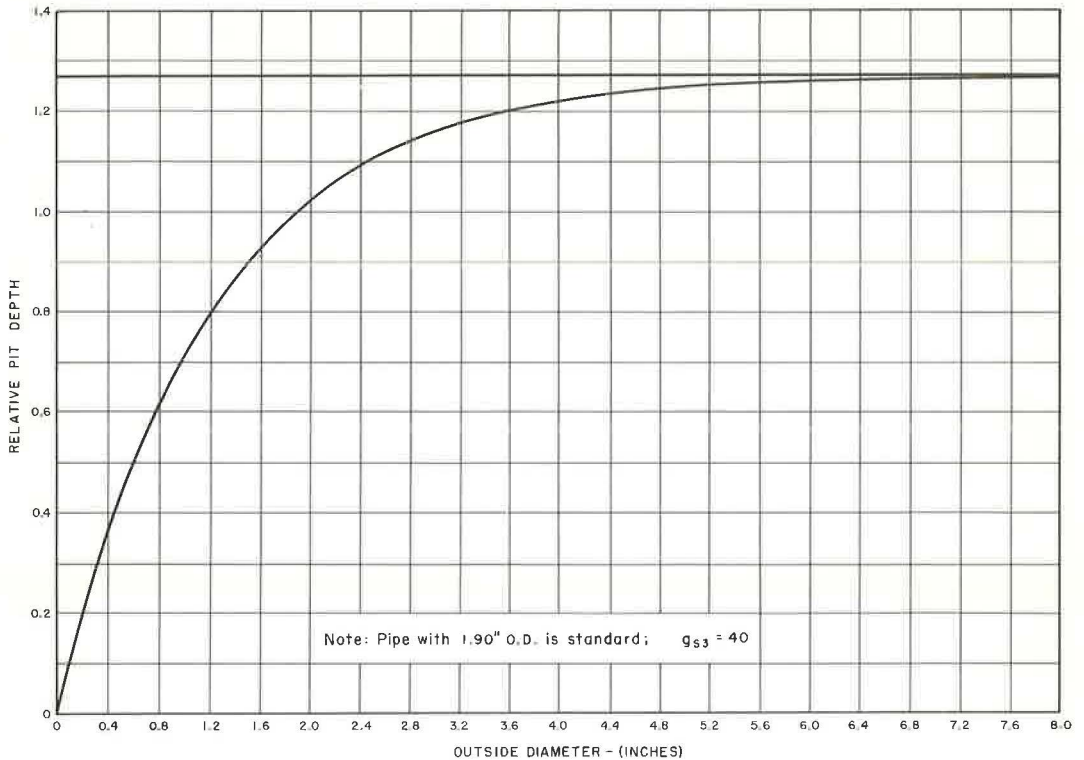


Figure 2. Effect of pipe size on the relative maximum pit depth of Bessemer steel.

TABLE 2
CONSTANTS FOR EQ. 9 AT FIVE
LEVELS OF CORROSION

g_M	g_e	g_{S_s}	a	b
10	9.1083	10.120	1.1112	1.2651
20	17.568	20.587	1.1730	1.0075
30	25.655	31.301	1.2226	0.8965
40	33.450	42.277	1.2684	0.8174
50	41.020	53.526	1.3120	0.7559

If one selects a soil of such corrosivity that g_M (3-in. pipe) is 40, g_e (Table 2) will be 33.450. Substituting this value in Eq. 11, $D_e/D_y = 1.039$, which signifies that the scaled steel pits a little less than 4 percent more than the descaled steel. This indicates that the effect of scale as it appears on normally manufactured steel pipe can be ignored in most cases.

CAST IRONS

Cast irons are subject to greater changes in physical composition than wrought materials and to greater fluctuations in corrosion rates. Both gray and ductile cast irons consist of graphite precipitated in a steel matrix—whether the matrix is ferrite, pearlite, or a mixture of the two. The nature of the graphite is entirely different in the two kinds of iron. In gray cast iron, graphite is in the form of long stringers (sometimes called plates) that break up the continuity of the matrix and cause the product to be brittle. On the other hand, graphite in ductile cast iron is in the form of well-rounded spheroids which do not interfere with the continuity of the matrix; hence ductile cast iron is more like malleable cast iron, or even steel, in mechanical properties.

As far as corrosion is concerned, both of these products are two-phase materials. The inherent steel-graphite cells have, if an electrolyte is present, a fairly high electrical potential which would speed up the dissolution of the steel matrix, the anodic

material. From a strictly theoretical viewpoint involving microstructure, ductile cast iron because of these cells should pit considerably faster than steel. Gray cast iron has the same kind of cells, but the nature of the graphite's physical form offers a physical barrier to the progress of corrosion. The steel-graphite cells tend to enhance the rate of pitting, but the "barrier effect" of the graphite tends to interfere. One cannot judge from theory based on microstructure which will prevail, and therefore cannot say whether gray cast iron will pit more or less than steel. It can be concluded from microstructure that gray cast iron is superior to ductile cast iron because the latter does not have graphite barriers to interfere with the progress of corrosion. Strictly from this theoretical viewpoint, steel is superior to ductile cast iron, because steel does not have steel-graphite cells.

Gray Cast Iron

NBS data for all the gray cast irons (Table 3) have been examined for the development of equations of the type of Eq. 6. Each of these equations has been used to get the pitting ratio (Table 3) where $g_M = 40$, an average of the six values was accepted as representing gray cast iron. From Eq. 6, m^2 can be evaluated by substituting 1.848 for the ratio and 40 for g_{M_3} . Thus,

$$(D_{G_6}/D_{M_3} - 1)^2 = 0.0097281 g_{M_3} (D_{G_6}/D_{M_3}) \quad (12)$$

which gives $g_{G_6} = 73.92$. While m^2 has been evaluated for a specific value of g_{M_3} , Eq. 12 holds for other values of g_{M_3} .

The data in Table 4 pertain to steel and gray cast iron, but not to a specific sample; therefore, g_S has been substituted for g_M . Column 2 was calculated by Eq. 10. The first value in Column 3 was calculated by Eq. 12 using $g_{S_3} = g_{M_3} = 40$. The other (identical) values in Column 3, occur because g_G/g_S is constant for a given size pipe.

Ductile Cast Iron

Inasmuch as ductile cast iron is a relatively new commercial product, it was not included among the materials tested and reported in NBS Circular No. 579. In 1958, NBS began to evaluate this material testing six soils, and the test is continuing. The results so far are nominally for 1-, 2-, and 4-yr test periods. Another lot of samples will probably be inspected at the end of 8 years; a fifth lot will be removed later.

TABLE 3
PITTING RATIO, GRAY CAST IRON TO STEEL^a

Designation	Test	Description	Pitting Ratio
L	1922	Sand cast (northern ore)	1.789
Z	1922	Sand cast (southern ore)	2.074
L	1928	Sand cast (northern ore)	1.809
A	1928	Southern cast iron	1.770
I	1928	Monocast (centrifugal)	1.624
A	1941	Plain cast iron	2.020
			1.848

^a6-in. cast iron; 3-in. steel; $g_M = 40$.

TABLE 4
CORROSION CONSTANTS FOR
VARIOUS PIPE SIZES ($g_{S_3} = 40$)

Pipe Size (in.)	g_S	g_G
6	42.28	73.91
24	42.43	74.17
48	42.43	74.17

supplementary data used in the calculations lead to

$$(D_D/D_S - 1)^2 = 0.041951 g_S (D_D/D_S) \quad (13)$$

which is a comparison of ductile cast iron with 2.50-in. OD to steel with 1.90-in. OD.

Eq. 10 was used to obtain the data in Table 5 for the calculations in this section. A pitting value of 40 mils for the first year for a 3-in. steel pipe was again chosen as a standard. It should be recalled that D_r in Column 2 is not absolute pit depth but rather the relative pit depth with 1.5-in. pipe as a standard.

Substituting $g_S = 33.45$ in Eq. 13, $D_D/D_S = 3.078$, but g_D/g_S is the same, hence $g_D = 102.96$ for a ductile cast iron pipe with 2.50-in. OD. In Table 5, g_S for 2.50-in. OD pipe is 36.93; therefore, $g_D/g_S = D_D/D_S = 2.788$, where the pipe size is the same and g_S for a 3-in. pipe is 40.

It now remains to obtain the ratio and the equation where ductile cast iron is 6-in. pipe and steel is nominal 3-in. (our standard). The pitting ratio given immediately above is for the same size pipe. Steel, the same size as 6-in. ductile cast iron pipe (6.90-in. OD), has a g_S value of 42.28 where the 3-in. pipe has a value of $g_S = 40$;

therefore, $g_D/42.28 = 2.788$ or $g_D = 117.88$ (for 6-in. pipe), but g_S for 3-in., is 40, hence, $g_D/g_S = D_D/D_S = 2.947$, which is the pitting ratio of 6-in. ductile cast iron to 3-in. steel where g_S for the latter is 40.

Table 3 indicates that some of the gray cast irons differed from the average by 12 percent. Because of this observation, D_D/D_S is adjusted downward in case that the sample of ductile cast iron being tested might be the worst one that could be obtained. The adjusted ratio with this conservative approach is $D_D/D_S = 2.631$, where g_{S_3} is 40.

If on using this lower value to find equations for calculations to get service lives,

TABLE 5
CORROSION CONSTANTS FOR
STEEL WITH VARYING PIPE
DIAMETERS

OD (in.)	D_r	g_S
1.90	1.0000	33.45
2.50	1.1040	36.93
3.50	1.1958	40.00
6.90	1.2638	42.28
24.00 and above	1.2684	42.43

*Romanoff later furnished tabular data for steel which were used in Appendix XVIII of the laboratory report (3) for a comparison of ductile cast iron and steel. This comparison is less favorable than that presented here. Figure 9 refers to the original manuscript.

it is found that ductile cast iron should have an exterior coating for underground service, then one can say with even more certainty that it should be coated if the ratio ranges higher to a possible 3.301.

Through the use of 2.631 it will be found that $(2.631 - 1)^2 = m^2(40)(2.631)$, or $m^2 = 0.025277$, and

$$\left(\frac{D_{D_6}}{D_{S_3}} - 1\right)^2 = 0.025277 g_{S_3} \left(\frac{D_{D_6}}{D_{S_3}}\right) \quad (14)$$

This equation compares ductile cast iron (6-in. pipe) to 3-in. steel pipe. Similar equations have been given (3) for 24- and 48-in. pipe.

EXPECTED SERVICE LIFE OF STEEL AND GRAY AND DUCTILE CAST IRONS

One of the first things to decide in connection with the service life of these three materials is the types of soils to be considered. As the standard reference, 3-in. steel pipe was chosen primarily because of its structural uniformity and its repetitious and reliable performance in underground corrosion. It was also exposed in nearly every test considered. The average corrosivity constant for steel in 37 soils in the 1922 test is $g_M = 22.80$; for 16 soils in the 1928 test $g_M = 44.57$. The selected value of $g_M = 40$, as a design level, is actually below the average corrosivity in the 1928 test.

The data will be set up for five corrosivities in steps of 10 going from $g_M = 10$ to $g_M = 50$ with special emphasis at the level $g_M = 40$.

Table 6 gives the wall thickness of the three materials in the three sizes that are being or would be used. In general, these values have been chosen to carry the design pressure within the pipe. In the case of ductile cast iron, it is overdesigned because thinner metal is not made by the commercial schedule. In general, there is a mortar lining so that the pipe would have to be large enough to accommodate the lining and still have the 6-, 24-, or 48-in. inside diameter. The effect of the mortar lining is not considered in this paper; therefore, discussion is restricted to exterior corrosion of bare metal.

The same outside diameter (6.90-in. OD for the 6-in. pipe) is selected regardless of whether it is steel, gray cast iron or ductile cast iron. It is not necessary to select any specific outside diameter for either the 24- or the 48-in. pipe; Eq. 10 gives the same answer, for all practical purposes, regardless of what the diameter is, provided it is as large as 12 in.

One can select g_S values from Table 5 to give the ratios g_{S_6}/g_{S_3} and D_{S_6}/D_{S_3} and then evaluate m from Eq. 6 using $g_{S_3} = 40$. A resubstitution in Eq. 6 gives

$$\left(\frac{D_{S_6}}{D_{S_3}} - 1\right)^2 = 0.000076845 g_{S_3} \left(\frac{D_{S_6}}{D_{S_3}}\right) \quad (15)$$

TABLE 6

DIMENSIONS OF COMMERCIAL PIPE FOR CARRYING WATER

Nominal Diam. (inside)	Wall Thickness (in.)		
	Steel	Gray Cast Iron	Ductile Cast Iron
6	0.0747	0.38	0.31
24	0.1345	0.73	0.41
48	0.2500	1.14	0.59

Eqs. 15, 12, and 14 have been used to get the data in Columns 2, 3, and 4, respectively, of Table 7. Other equations (3) were used to obtain similar values given in Table 8 for larger pipe. From Table 7, it is found, where $g_{S_3} = 40$, that $D_{S_6} = 42.28\sqrt{t}$, from which service life can be calculated for a given thickness or the thickness can be calculated to give a chosen service life. The life of three materials having a thickness of 250 mils has been calculated for varying levels of corrosivity (Table 9).

TABLE 7
g-VALUES FOR 6-IN. PIPE

g_{S_3}	Steel g_{S_6}	Iron	
		Gray Cast g_{G_6}	Ductile Cast g_{D_6}
10	10.28	13.64	16.45
20	20.80	30.98	40.15
30	31.48	51.16	69.87
40	42.28	73.91	105.24
50	53.20	99.08	146.08

TABLE 8
g-VALUES FOR 24-IN. AND LARGER
PIPE

g_{S_3}	Steel g_S	Iron	
		Gray Cast g_g	Ductile Cast g_D
10	10.30	13.66	16.48
20	20.85	31.06	40.25
30	31.57	51.32	70.08
40	42.43	74.20	105.60
50	53.41	99.47	146.63

TABLE 9
LIFE OF 6-IN. PIPE MATERIALS
250 MILS THICK

g_{S_3}	Life (yr)		
	Steel	Gray Cast Iron	Ductile Cast Iron
10	590	340	230
20	140	65	39
30	63	24	13
40	35	11	5.6
50	22	6.4	2.9

Romanoff (2) found one piece of ductile cast iron 250 mils thick had pitted through in less than 4 years where g_S was 38.6 and in another soil in less than 5 years where g_S was 12.3. These g_S values have wide scatter and are probably not accurate. On the contrary, the findings of a hole completely through the wall is a reliable observation. None of the steel pieces 0.145 in. thick had perforated.

Table 10 gives the thickness of the three materials necessary for a life of 50 years for 6-in. pipe. The soils have been classified as to corrosivity in Column 5, ranging from very mildly corrosive at $g_S = 10$ to very severely corrosive at $g_S = 50$. Again the equations were taken from Table 7. The life of pipe made to commercial schedule is given in Table 11. The equations employed were taken from Tables 7 and 8; the thicknesses are given in Table 6.

None of the materials can be used in 6-in. pipe, where $g_{S_3} = 40$, without an exterior coating if a 50-yr life is expected (Table 11). Gray cast iron can be used in 24- and 48-in. pipe without an exterior coating. Both steel and ductile cast iron require an exterior coating in all three sizes studied.

In a soil where steel will pit 40 mils the first year, the relative thickness required for 50-yr life is about 1:1.75:2.5 for steel, gray cast iron, and ductile cast iron, respectively. These ratios can be obtained by dividing Eqs. 16, 17, and 18 by Eq. 16.

It should be recalled that a 12 percent allowance favoring ductile cast iron has been made. Even so, the conclusion is reached that the product should have an exterior coating for 50-yr life. If the 12 percent allowance had not been made for ductile cast iron, the necessity for coating would appear to be all the stronger.

TABLE 10
THICKNESS REQUIRED FOR 50-YEAR LIFE

g_s	Thickness (mils)			Nature of Soil
	Steel	Gray Cast Iron	Ductile Cast Iron	
10	73	96	120	Very mildly corrosive
20	150	220	280	Mildly corrosive
30	220	360	490	Corrosive
40	300	520	740	Severely corrosive
50	380	700	1,000	Very severely corrosive

TABLE 11
LIFE OF PIPE MADE TO COMMERCIAL SCHEDULE*

Nom. Diameter (in.)	g_{S_3}	Life (yr)		
		Steel	Gray Cast	Ductile Cast
6	10	53	780	360
	20	13	150	60
	30	5.6	55	20
	40	3.1	26	8.7
	50	2	15	4.5
24	10	170	2,900	620
	20	42	550	104
	30	18	200	34
	40	10	97	15
	50	6.3	54	7.8
48	10	590	7,000	1,300
	20	144	1,310	220
	30	63	490	71
	40	35	240	31
	50	22	130	16

*See Table 6 for thickness.

The expected relative behavior of the three materials is illustrated. Figure 3 shows the pitting ratios of 6-in. pipe for various levels of corrosivity where 3-in. steel pipe is taken as a standard. Actually, this is a plot of Eqs. 15, 12, and 14. Figure 4 shows the relation of maximum pit depth with time where $g_s = 40$. This figure is a plot of

$$D_{S_6} = 42.28\sqrt{t} \quad (16)$$

$$D_{G_6} = 73.91\sqrt{t} \quad (17)$$

and

$$D_{D_6} = 105.24\sqrt{t} \quad (18)$$

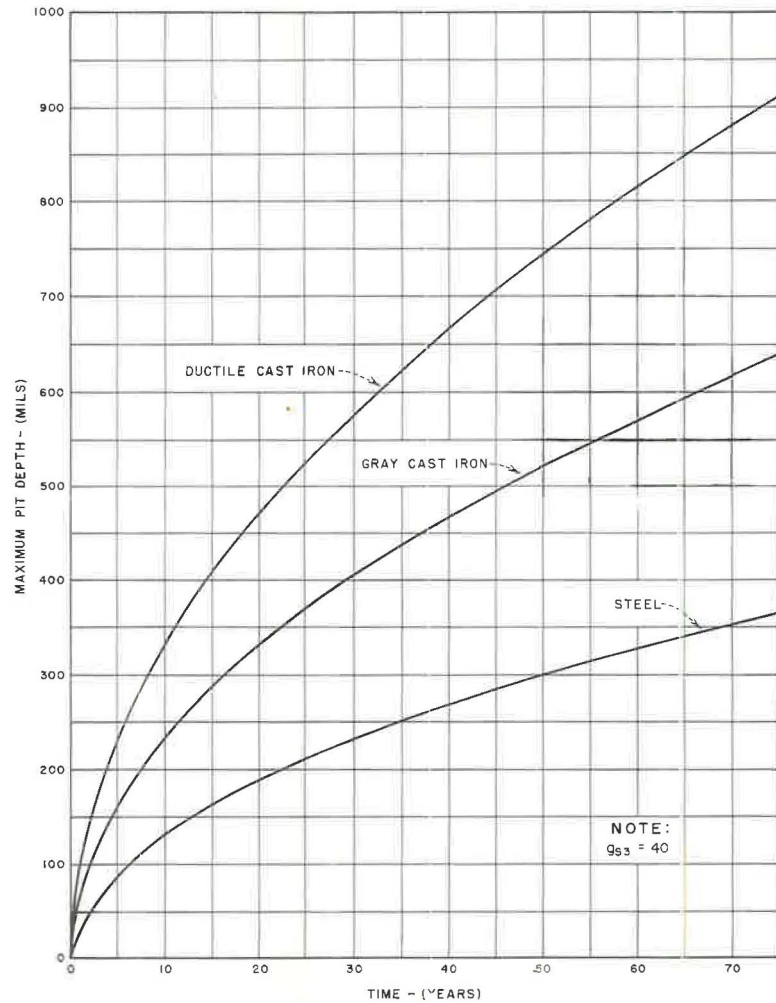


Figure 3. Pitting ratios for 6-in. pipe.

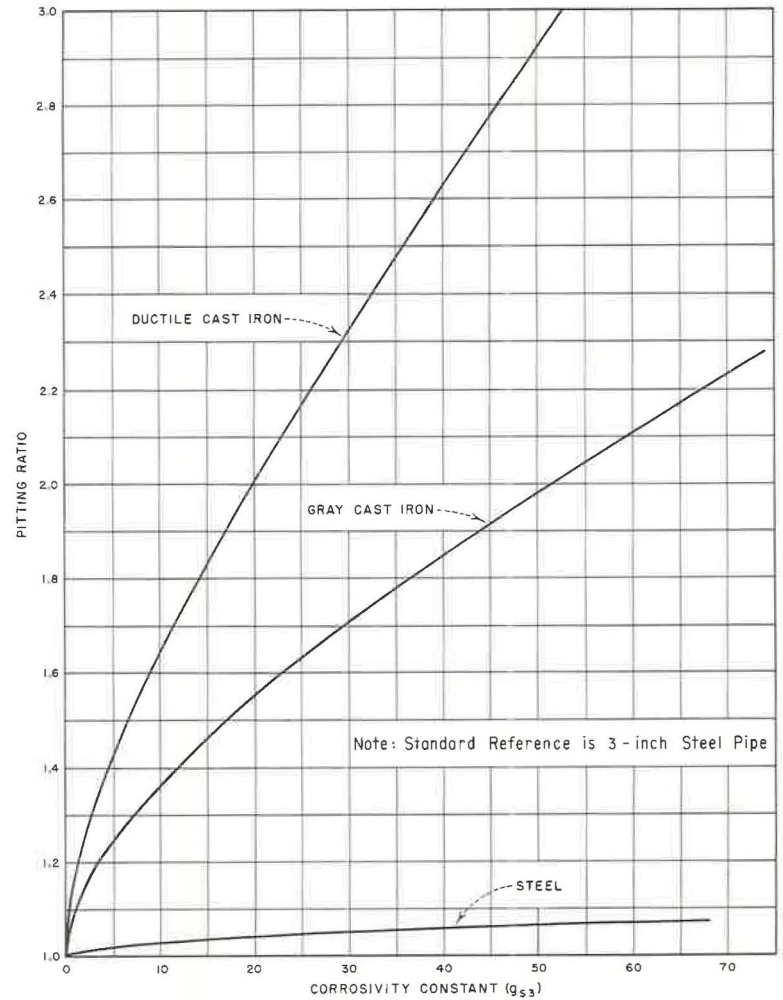


Figure 4. Maximum pit depth-time relations for 6-in. pipe.

Romanoff found two specimens of ductile cast iron perforated in less than 4 years where the wall thickness was 0.250 in.; therefore, the value of 5.6 at $g_S = 40$ in Table 9 appears quite reliable. Field experience supports the value of 3.1 and 5.6 for 6-in. steel pipe in Table 11. Gray cast irons have been known to have very long lives where they were exceptionally thick and where they were buried in low and even medium corrosive soils. It is not surprising to find a value of 7,000 years for 48-in. pipe where $g_S = 10$. Steel of the same thickness would last nearly twice as long.

These predicted values of long lives depend on the validity of Eq. 1 which is a diffusion-type equation. Whether it holds for the very long times predicted depends on whether the corrosion products stay in place throughout the life of the pipe.

SUMMARY AND CONCLUSIONS

1. Experimental data can be employed to predict the field performance of wrought ferrous pipe buried in soil.

2. NBS data reveal that the pitting ratios of steel to gray cast iron to ductile cast iron are about 1:1.75:2.5 where $g_{S_3} = 40$.

3. All three metals require an external coating on 6-in. pipe to give 50-yr life where $g_{S_3} = 40$.

4. Both steel and ductile cast iron require an external coating on 24- and 48-in. commercial pipe for 50-yr life where $g_{S_3} = 40$. Gray cast iron, in these sizes, does not require an external coating.

REFERENCES

1. Romanoff, Melvin. *Underground Corrosion*. National Bureau of Standards Circular No. 579, U.S. Government Printing Office, Washington, D.C., 1957.
2. Romanoff, Melvin. *Exterior Corrosion of Cast-Iron Pipe*. J. AWWA. 56, No. 9, pp. 1129-43, 1964.
3. Pennington, William A. *Corrosion of Some Ferrous Metals in Soil with Emphasis on Mild Steel and on Gray and Ductile Cast Irons*. U.S. Bureau of Reclamation Laboratory Report No. ChE 26, 1965.
4. Cikerman, L. J. *Method of Predicting Long Term Corrosion Damage of Underground Metal Pipes*. Gazavoe Delco, No. 4, pp. 30-32, 1963.

Discussion

MELVIN ROMANOFF, Chemist, Metal Reactions Section, Metallurgy Division, National Bureau of Standards—These few moments related to Dr. Pennington's presentation seem the appropriate time to extend congratulations to the author and his associates at the Bureau of Reclamation on their unbiased study in applying the fundamental soil corrosion data which were obtained by the National Bureau of Standards toward the solution of a practical corrosion problem.

In compiling NBS Circular 579 it was intended to provide a useful reference for both the technician who is interested in the theoretical aspects of underground corrosion and the engineer who is interested in the practical aspects of the methods commonly used for the prevention of corrosion.

Because of the many diverse factors that affect the corrosion of underground structures, interpretations of test results for application to actual service installations are often matters of considerable difficulty. For this reason, engineers may have different interpretations from similar corrosion data.

Hence, it was also intended that the extensive data on the many different metals and alloys in the wide variety of soil environments, contained in Circular 579 would be

utilized by engineers toward the solution of their specific problems in underground structures.

Toward this purpose, Dr. Pennington has used the experimental pit-depth data obtained through the years by the National Bureau of Standards to determine quantitatively the relative merits of different ferrous materials with which the Bureau of Reclamation is concerned for use in pipeline systems. In other words, the author's contribution is in the interpretation of the Bureau of Standards corrosion data to a Bureau of Reclamation service problem.

The Bureau of Reclamation is justified in its concern about pitting attack because in pipe designed to carry fluids, the time to perforation is of greatest importance.

Although Dr. Pennington does not use his technique for the following purposes, his method could also be used for the interpretation of corrosion data to evaluate the relative merits of ferrous metals with respect to weight loss, and to determine the relative corrosivity of the same metal in different soils.

Those of us who have devoted continuing effort in obtaining the original data can be hopeful that more and more use will be made of the data in the solution of other practical problems involving underground corrosion. The author's method can well set a pattern to be used by others toward this end.

WILLIAM A. PENNINGTON, Closure—The author and the Bureau of Reclamation are grateful for Mr. Romanoff's discussion. We agree that NBS Circular 579 has served its purpose well in providing reliable test data for the practical engineer's use in evaluating the merits of various pipe materials embedded in soils in a given application.

We are glad that we could find information already available for our purpose. Otherwise we either could not have made the study at all or else great additional expense in money and time would have been involved to arrive at the conclusions formulated. There certainly would not be any justification for a duplication in testing effort when the National Bureau of Standards had already obtained the test information needed to determine the relative merits of various ferrous pipe materials.

Mr. Romanoff suggests that the technique could be used to determine the corrosivity of soils by using the same metal in different soils. This is quite true; however, a great many tests would be involved—more than when evaluating the relative merits of the various metals. The reason for this is the difficulty of having uniformity in a soil. There can be little question about the uniformity of metal composition for a given type of metal.

We shall derive great satisfaction from our study if the interpretive technique will be employed by other engineers in adapting the NBS data to a solution of other practical problems in soil corrosion.

An Engineering Approach to Improved Protection of Structural Steel

H. B. BRITTON, New York State Department of Public Works

•THE problems relating to the successful painting of structural steel have been considered in many papers presented by technical paint people for consumption within their own industry. However, the subject has not, by any means, received sufficient consideration in the forum of the ultimate user—in this case, the bridge engineer who is charged with the responsibility of providing a durable bridge structure as free of maintenance as possible and yet aesthetically acceptable.

To contribute to the general knowledge and to offer some ideas which might be useful to others concerned with the problem of protecting their bridges, we have prepared information based on the experience of the New York State Department of Public Works, Division of Construction, over the past few years.

BACKGROUND

From the organization in 1926 of the New York State Department of Public Works, Division of Construction through 1957, there were few changes in the paint formulations designed for the protection of bridge structures.

Primer

During this period, the requirements for a shop primer changed only slightly. The paint specified in 1926 had the following composition:

One grade of pigment known as ninety-five (95) percent is required.

Dry Pigment. The pigment shall consist entirely of oxides of lead free from all adulterants and shall meet the following requirements:

	Percent
True red lead (Pb_3O_4), not less than	95
Total impurities, including moisture, soluble matter in water, and matter insoluble in a mixture of nitric acid and hydrogen peroxide, not more than	1
Coarse particles retained on a standard 325-mesh sieve, not more than	1
The red lead, ready mixed paint, shall consist of:	
Red Lead	74 to 76
Vehicle	24 to 26

The vehicle shall consist of a mixture of raw and boiled linseed oil in the proportion of one-third ($\frac{1}{3}$) to one-half ($\frac{1}{2}$) boiled oil, the balance being raw oil.

In 1929 the specification was modified as follows:

One grade of pigment known as ninety-five (95) percent is required.

Dry Pigment. The pigment shall consist entirely of oxides of lead free from all adulterants and shall meet the following requirements:

	Percent
True red lead (Pb_3O_4), not less than	95
Total impurities, including moisture, soluble matter in water, and matter insoluble in a mixture of nitric acid and hydrogen peroxide, not more than	1
Coarse particles retained on a standard 325-mesh sieve, not more than	1
The red lead, ready mixed paint, shall consist of:	
Red Lead	78 to 81
Vehicle	19 to 22

The vehicle shall consist of a mixture of raw and boiled linseed oil in the proportion of one-third to one-half boiled oil, the balance being raw oil.

This specification for red lead primer was continued through 1958. In other words, no improvement was made in the red lead primer through this period when to overcome some of the disadvantages complained about by steel fabricators as well as shop and field painters, these paints were up-graded through research in the industry to reduce gloss and improve drying characteristics.

First and Second Field Coats. —In 1926 the specification for intermediate and finish coats was based upon a pigmentation of the Department standard white paint. The specification reads as follows:

Gray Paints

The gray paints will be ordered in the form of ready mixed paint and they shall meet the requirements as to composition as called for under White Paint but having substituted for the extending pigments sufficient suitable pigment color in order to furnish the required color and hiding power.

The Department specification for White Paint was as follows:

White Paint

The paint shall be well ground, shall not settle badly or cake in the container, shall be readily broken up with a paddle to a smooth, uniform paint of good brushing consistency, and shall dry within eighteen (18) hours to a full oil gloss without streaking, running or sagging. The color and hiding power shall be equal to that which may be specified.

Pigment. The pigment shall be composed of:

	Min. Percent	Max. Percent
White lead (Basic carbonate, basic sulphate, or a mixture thereof)	45	70
Zinc oxide (ZnO)	30	55
Silica, magnesium silicate, aluminum silicate, barium sulphate, or any mixture thereof	0	15

In no case shall the sum of the basic lead carbonate, basic lead sulphate, and zinc oxide be less than eighty-five (85) percent. The lead and zinc pigments may be introduced in the form of any mixture preferred of basic carbonate white lead, basic sulphate white lead, zinc oxide, or leaded zinc, provided the above requirements as to composition are met.

Liquid. The liquid in the paint shall consist of not less than ninety (90) percent of pure raw linseed oil previously specified, the balance to be combined drier and thinner.

The paint shall consist of:

	Min. Percent	Max. Percent
Pigment	62	66
Liquid (containing at least 90 percent linseed oil)	34	38
Water	—	0.5
Coarse particles and "skins" (total residue retained on No. 200 sieve based on pigment)	—	0.5

From 1929 to 1935 the specification for intermediate and finish coats was modified to read as follows:

Gray Paints

The gray paints will be ordered in the form of ready mixed paint and they shall meet the requirements as to composition as called for under White Paint but having substituted for the extending pigments sufficient suitable pigment color in order to furnish the required color and hiding power. The color of the gray paint shall be what is known as Battleship Gray. The paint for the first coat shall be lighter in color than the second coat.

White Paint

The paint shall be well ground, shall not settle badly or cake in the container, shall be readily broken up with a paddle to a smooth, uniform paint of good brushing consistency, and shall dry within eighteen hours to a full oil gloss without streaking, running or sagging. The color and hiding power shall be equal to that which may be specified.

Pigment. The pigment shall be composed of:

	Min. Percent	Max. Percent
White lead (Basic carbonate)	45	70
Zinc oxide (ZnO)	30	55
Silica, magnesium silicate, aluminum silicate, barium sulphate or any mixture thereof	0	15

In no case shall the sum of the basic lead carbonate and zinc oxide be less than eighty-five percent.

Liquid. The liquid in the paint shall consist of not less than ninety percent of pure raw linseed oil previously specified. The balance to be combined drier and thinner.

The paint shall consist of:

	Min. Percent	Max. Percent
Pigment	62	66
Liquid (containing at least 90 percent linseed oil)	34	38
Water	—	0.5
Coarse particles and "skins" (total residue retained on No. 200 sieve based on pigments)	—	0.5

From 1935 to 1957 minor modifications in the standard white paint specification consisted of the following:

	Min. Percent	Max. Percent
1935—White lead (Basic carbonate)	50	70
Zinc oxide (ZnO)	30	40
Silica, magnesium silicate, aluminum silicate, barium sulphate or any mixture thereof	0	10
1939—Sum of basic lead (carbonate) and zinc oxide was increased from a minimum of 88% to a minimum of 90%.		
1942—The second field coat was designated as Gray-Green Paint and specification follows:		

Gray-Green Paint

The gray-green paint shall be ordered in the form of ready mixed paint. It shall meet the requirements as to composition as called for under White Paint, except that the color of the paint shall be the same as indicated in a panel on file in the Assistant Chief Engineer's office. The color shall be obtained by substituting for the inert pigments and a portion of the zinc oxide, if necessary, chromium oxide or pure chrome green and other suitable pigments necessary to procure the desired color.

The chromium oxide shall conform to the A.S.T.M. specifications D-263-40 for chrome oxide green. The pure chrome green shall conform to the A.S.T.M. specifications D-212-40 for pure chrome green.

1957—The gray-green paint specification was modified to require the use of chromium oxide and other suitable pigments necessary to procure the desired color, eliminating the permissive use of pure chrome green as a tinting pigment.

The selection of a gray-green paint to blend in with the landscape was an innovation that a number of States adopted about 1942. Due to the war it was impossible to procure chrome oxide green for civilian purposes which resulted in the use of pure chrome green for tinting. As with the primer there had been no basic changes in the composition requirements from those existing in 1926. None of the newer technology of the paint industry had been adopted thus by comparison with the more modern formulations of the period the gray-green paint faded rapidly and ununiformly. This resulted, in many instances, in unattractive structures in as short a time as five years.

In 1926 specifications for linseed oil, thinner and drier were as follows:

Linseed Oil

The raw linseed oil must be strictly pure, well settled linseed oil, perfectly clear, and not show any sediment or loss of more than two-tenths (0.2) percent when heated for one-half ($\frac{1}{2}$) hour at a temperature between 105° and 110° C. (221° and 230° F.) Raw and boiled linseed oil shall conform to the requirements of U.S. Bureau of Standards Circular No. 82 as adopted by the Federal Specifications Board. These are as follows:

	Raw Oil		Boiled Oil	
	Max.	Min.	Max.	Min.
Loss on heating at 105° -110° C. (221° to 230° F.) (percent)	0.2	—	0.2	—
Foots by volume (percent)	2.0	—	—	—
Specific Gravity, 15.5°/15.5° C. (60°/60° F.)	0.936	0.932	0.945	0.937
Acid number	6.0	—	8.0	—
Saponification number	195.0	189.0	195.0	189.0
Unsaponifiable matter (percent)	1.5	—	1.50	—
Iodine number (Hanus)*	—	170.0	—	168.0
Ash (percent)	—	—	0.7	0.2
Manganese (percent)	—	—	—	0.03
Lead (percent)	—	—	—	0.1
Time of drying on glass (hours)	—	—	20.0	—
Color	Not darker than a freshly prepared solution of 1.0 gm. potassium bichromate in 100 cc. pure strong (1.84 sp. gr.) sulphuric acid.			

*When oil from North American seed is specified by the purchaser, the iodine number must be not less than 180 in the case of raw oil and 178 in the case of boiled oil and the oil shall conform to all the other requirements as above.

Thinner

a. Turpentine. The turpentine used shall either be the distillate commonly known as "Gum Turpentine" or "Spirits Turpentine" which is distilled from pine oleoresins or the product secured from resinous wood by extraction with volatile solvents, by steam, or by destructive distillation, and shall meet the following requirements:

The turpentine shall be clear and free from suspended matter and water.

The color shall be "standard" or better.

The specific gravity shall be not less than 0.862 nor more than 0.875 at 15.5°/15.5° C. (60°/60° F.).

The refractive index at 20° C. (68° F.) shall be not less than 1.465 nor more than 1.478.

The initial boiling point shall be not less than 150° C. (302° F.) nor more than 160° C. (320° F.) at 760 mm. pressure.

Ninety (90) percent of the turpentine shall distill below 170° C. (338 F.) at 760 mm. pressure.

The polymerization residue shall not exceed two (2) percent, and its refractive index at 20° C. (68 F.) shall not be less than 1.500.

b. Mineral Spirits. The mineral spirits shall be clear and free from suspended matter and water. The color shall be "water white".

Spot Test: The mineral spirits shall evaporate completely from filter paper.

The flash point shall be not lower than 30° C. (86° F.) when tested in a closed cup tester.

Sulphur shall be absent as determined by the white lead test.

The distillate below 130° C. (266° F.) shall not exceed five (5) percent.

Drier

The drier shall be composed of lead, manganese, or cobalt, or a mixture of any of these elements combined with a suitable fatty oil, with or without resins or "gums" and mineral spirits or turpentine, or a mixture of these solvents. It shall be free from sediment and suspended matter. The drier when flowed on metal and baked for two (2) hours at 100° C. (212° F.) shall leave an elastic film. The flash point shall be not lower than 30° C. (86° F.) when tested in a closed cup tester. It shall mix with pure raw linseed oil in the proportion of one (1) volume of drier to nineteen (19) volumes of oil without curdling, and the resulting mixture when flowed on glass shall dry in not more than eighteen (18) hours. When mixed with pure raw linseed oil in the proportion of one volume of drier to eight (8) of oil, the resulting mixture shall be no darker than a solution of 6 g. of potassium dichromate in 100 c.c. of pure sulphuric acid of specific gravity 1.84.

From 1935 to 1947 the specifications for linseed oil and thinner required compliance with ASTM Standards. There was no change in the drier requirements. From 1947 to 1957 no requirements for the vehicle were indicated in the specifications.

Throughout the period from 1926 to 1957 the specifications contained no indication of a desired minimum film thickness for the three coats of paint required. This resulted in a variable performance of the system depending on the care in application exhibited on a particular job. This was magnified further by the environment a particular structure was subjected to; in New York State this ranges from rural to marine as well as industrial both heavy and chemical.

INVESTIGATION

In 1954, Deputy Chief Engineer (Bridges) E. W. Wendell initiated an investigation which culminated in the adoption of our current paint systems. This preliminary investigation included extensive studies by department personnel with regard to the problems involved. These studies were followed by consultations with personnel of the technical departments of raw material suppliers to obtain all available information relative to the substantiation of our findings and to lay the groundwork for upgrading our paint systems. The result of this preliminary work indicated the reason for unsatisfactory performance of existing paint systems.

Primer

Because of its excellent hiding power there was a tendency to spread the primer too far, thus insufficient dry films were obtained to protect the steel from its environment. In addition red lead paint possessed the inherent characteristic of settling heavy which often made it impossible to remix the paint properly. This resulted in the application of a paint low in pigment content. The oily gloss of the full oil type red lead paint made it difficult for painters to obtain adequate adhesion when applying overcoats. In addition, slow drying created a hardship in scheduling movement of the steel and repainting.

Another practical problem with the primer was that it did not weather well. Often with large structures many months elapse between shop priming and the application of the field coats. Carbonation of the red lead with its known tendency to chalk and erode left insufficient film thickness of the paint to protect the steel.

First and Second Field Coats

Intermediate and finish coats provided little, if any, anti-corrosive properties and also presented problems with regard to the general appearance of the finished structure. While color was good initially, appearance fell off rapidly. This was particularly true during that period when pure chrome green was used as a tinting pigment in the finish coat. When the color stable green pigment (chromium oxide) was required, conditions of the finish coat improved but it was noted that these finishes acquired an irregular washed-out, unpleasant yellow cast after five or six years. This could have been due, for one thing, to the unauthorized use of some pure chrome green in order to match the required color. Another reason could be the high white lead content. White lead coatings, while producing durable films, are inclined to fade ununiformly giving a mottled appearance. The straight oil vehicle with its rather limited durability also contributed to the failure.

It became evident that by modernizing our paint requirements that savings in initial cost could be realized, but more important the life expectancy of the paint systems could be extended resulting in the ever important maintenance cost savings to be gained, that is, cost per square foot per year.

With these points in mind, in 1956 the Division of Construction in cooperation with a major pigment supplier began an investigation in an effort to solve our problems. The pigment company had a relatively new anti-corrosive pigment, basic lead silico chromate, which had been evaluated at their test stations for seven years as well as on several small structures throughout the country. It had been demonstrated through these tests that in addition to providing anti-corrosive properties at least as good as red lead, it weathered far better and because of its unique low tinting strength could be incorporated into finishes to enhance color retention.

Over the years the original test panels protected with coatings containing basic lead silico chromate as well as control red lead films, were observed and pictures taken at intervals for the record. In one set, on sandblasted steel, comparing the two pigments as single pigments formulated into linseed oil primers at 31 PVC (90% oil - 10% volatile) and exposed at 45° South on Long Island, it became apparent within 16 months that basic lead silico chromate imparted superior weathering characteristics. In addition, where multi-coats were used forming a typical paint system, improved corrosion protection became evident with time. It should be noted that all paint films were applied by brush at a spreading rate calculated to give dried film thicknesses of 1.5 mils. Table 1 (1) gives corrosion ratings for the different test areas of the specimens.

TABLE 1
CORROSION^a

Months Exposure	9	16	21	28	36	49	58	65	75	86	96	101
(a) Basic Lead Silico Chromate in Linseed Oil												
One coat primer	10	10	8	6	4	2	1					
Two coats primer							10	9	9	7	7	7
One primer and 1 topcoat									10	10	10	10
(b) 97% Grade Red Lead in Linseed Oil												
One coat primer	10	6	3	1								
Two coats primer					10	9	3	1				
One primer and 1 topcoat						10	9	9	8	7	7	7

^aCorrosion ratings are based on "10" as perfect, down to "1", which represents total failure.

Another series exposed under the same conditions using the single pigments in paints formulated with a long oil alkyd resin vehicle at 30 PVC but applied to cold-rolled steel gave similar results. The corrosion ratings are presented in Table 2 (1). In addition to improved protection, it was noted here that the exposed basic lead silico chromate primer retained its color with little drift from what it was originally. It was this that indicated the potential use of the pigment for color stable, anti-corrosive finishes.

Figure 1 shows the comparison of the basic lead silico chromate and red lead alkyd resin paints described in Table 2. On each panel, one coat of primer was applied over-all, a second coat over the upper half, and a finish coat over the mid-section.

TABLE 2
CORROSION

Months Exposure	34	40	54	62	74	80	90	99	105
(a) Basic Lead Silico Chromate with Alkyd Resin									
One coat primer					10	9	9	8	7
Two coats primer					10	10	10	10	10
One primer and 1 topcoat					10	10	10	10	10
(b) 97% Grade Red Lead with Alkyd Resin									
One coat primer	10	9	5	3	1				
Two coats primer					10	10	10	9	9
One primer and 1 topcoat					10	9	9	8	6

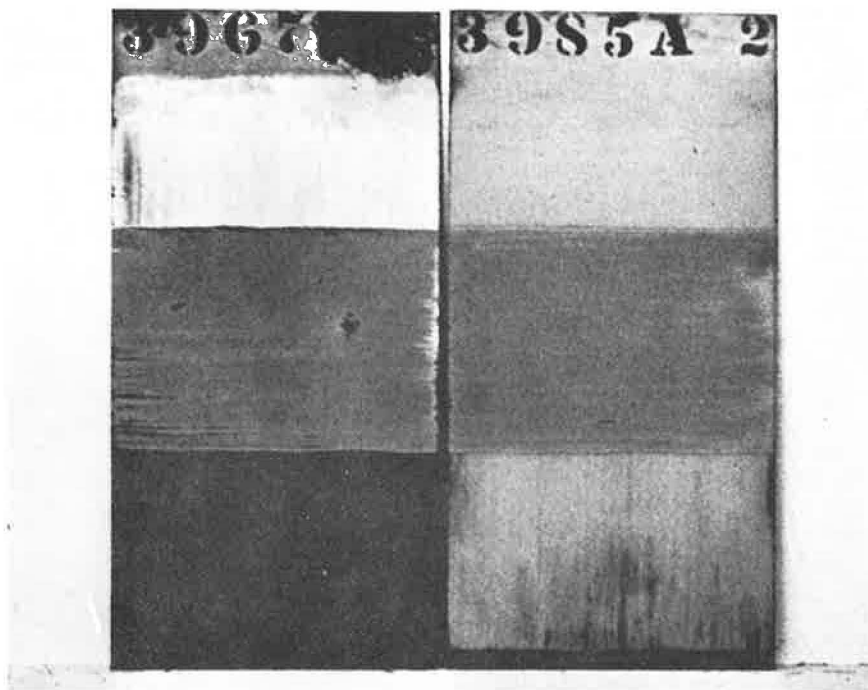


Figure 1. Comparison of red lead (left) and basic lead silico chromate (right) in a long oil alkyd after 110 months exposure at 45° South on Long Island.

The first cooperative test started with the exposure at 45° South on Long Island, using small angle specimens. New York's standard three coat system, previously described, and one based on this new pigment formulated to be present in all coats of paint were selected and laboratory batches prepared. To derive specific information uncluttered by many variables, all coatings were applied to similar surfaces (both sand-blasted and lightly rusted mill scale carrying angles) at rates designed to give equal dried film thicknesses (1.5 mils).

The basic lead silico chromate experimental system was composed of:

1. Primer—Basic lead silico chromate in 80/20 raw linseed oil/long oil alkyd (current TT-P-61 5b, Type I).
2. Gray intermediate—Basic lead silico chromate, titanium dioxide, zinc oxide, extender and tinting pigments in 2/1 raw linseed oil/long oil alkyd.
3. Gray-green finish—Basic lead silico chromate, titanium dioxide, chromium oxide, toning colors in 5/3 raw linseed oil/long oil alkyd.

The test angle specimens were painted in the following manner. One coat of primer was applied overall. The intermediate was applied over the upper half (both faces). The finish coat was applied to one face—the right side. This then gave an angle having exposed primer on the lower left segment, primer and intermediate coat applied to the upper left segment, primer and finish coat applied to the lower right segment, and the complete three coat system applied to the upper right segment.

Because of adequate controlled thicknesses, corrosion did not develop with the comparative primers for several years. However, to make a point, when failure had developed just shy of requiring touch-up, the control was three years old. The modification required five years to reach that point. Of more significance, the control primer started chalking or wearing away within 12 months, while the modified primer showed no indication of chalking after 25 months. This point would be of still more significance to an engineer charged with the responsibility of protecting steel at the site in southern climates.

This was substantiated by a subsequent exposure designed to demonstrate erosion characteristics. A basic lead silico chromate primer containing a vehicle composed of 80 percent linseed oil and 20 percent alkyd resin was compared with New York State's existing M20 red lead-linseed oil paint and also Federal Specification TT-P-86c, Type I. The red lead primers lost 15 percent of their film in 15 months and 20 percent within 22 months, while the basic lead silico chromate primer lost only 4 percent over a 32-month period.

The difference in general appearance of the comparative finish coats was most striking. Within 18 months the control New York State gray-green had faded badly and non-uniformly. The basic lead silico chromate gray-green by comparison, still maintained an appearance rated as good after 8 years.

Pictures were taken of this series at intervals, which demonstrated the weathering characteristics experienced.

Figure 2 shows the condition of the control and experimental systems after 19 months exposure. The development of chalking as well as severe fading of the control finish is apparent. The typical carbonation of red lead after extended exposure is evident.

Figure 3 taken after 66 months shows the same paint systems. It is apparent that the control finish (right side of left angle) has completely weathered away. In addition, the excellent weather and corrosion resistance of the basic lead silico chromate experimental primer as compared with the red lead primer should be noted (comparing films on lower left quarters of the two angles).

Thus within two years it became evident that the experimental system had potential advantages. To coincide with this laboratory work, it was decided early in 1957 to give this same system a practical trial on a large structure. A bridge on the outskirts of Albany (Southern Boulevard Bridge) was selected to evaluate the system. It was considered a typical condition to which bridge coatings would be subjected in New York State. Considerable repair and widening, using freshly fabricated steel, was scheduled along with touching up and refinishing of the existing steel.



Figure 2. Comparison of control New York State system (left) and experimental basic lead silico chromate system (right) after 19 months exposure at 45° South on Long Island.

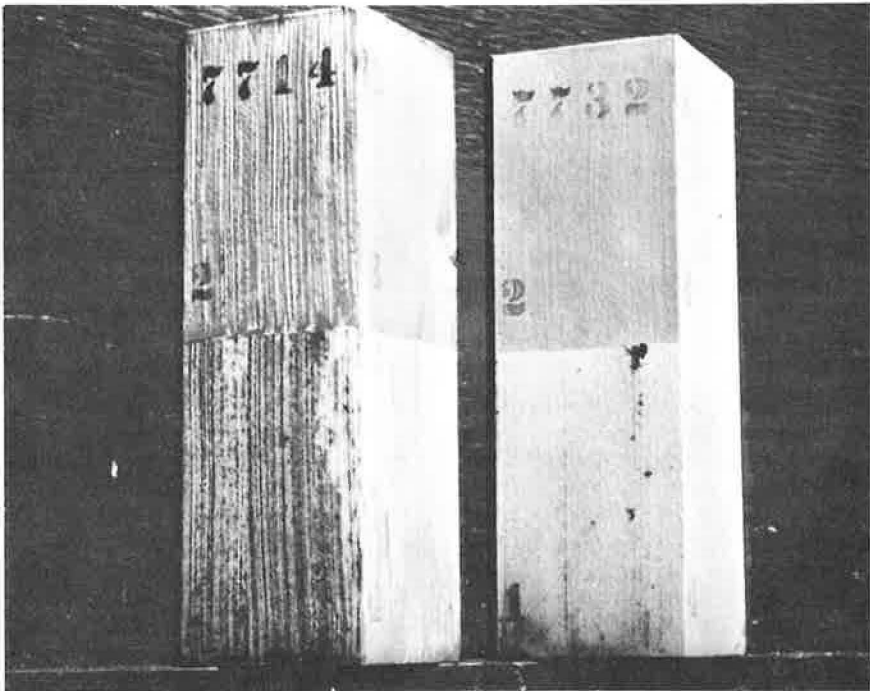


Figure 3. Comparison of control New York State system (left) and experimental basic lead silico chromate system (right) after 66 months exposure at 45° South on Long Island.

The environment at Albany is that expected over much of the state. Cold winters prevail with much snow and, accordingly, any number of corrosive de-icing applications. The summers are hot with ample humidity, aided by a river running through the ravine which the bridge spans.

Special specifications were written and commercial quantities of paints were prepared and applied following normal practices required by the Department.

This work was completed in 1957. Since that time, or 8 years, no maintenance repainting has been found necessary. The pleasing initial appearance of the gray-green finish has held throughout the exposure. It is our opinion that this system, with the possible exception of localized spots, will not require refinishing for at least another four years. It is interesting how well this large test run under normal field conditions has correlated with the laboratory test put out under controlled conditions.

IMPLEMENTATION

Based on the performance of the system on the Southern Boulevard Bridge as well as the continued high ratings of the laboratory field tests, an interim specification following the original experimental composition was adopted by the Department in the fall of 1958, which made the new system mandatory for new construction. In 1962, when the Division of Construction specifications were revised, these paint formulations were included.*

Since there was a requirement in our specifications which called for three coats of primer for surfaces not in contact, which after fabrication, would be inaccessible, a maroon primer was added to the list of paints.

In addition to this basic bridge painting system, other modifications were made in the specifications. The black finish, available for use on structures maintained by railroads, was changed from a simple decorative black pigmented linseed oil paint to one containing some basic lead silico chromate in the pigmentation and alkyd resin to reinforce the oil vehicle. Thus this coating has been upgraded to provide positive anti-corrosive properties, augmenting those of the undercoats.

The white paint for use on curb protection plates and guide railing was upgraded to provide a stain resisting system. This paint calls for the use of fungicides and was formulated so that it could be used on steel, concrete or wood surfaces.

The Department modernized its infrequently used aluminum paint specification. To get away from the practice of tinting the aluminum finish with blue, to provide a contrasting undercoat for the finish, non-leaving aluminum was adopted. Adequate contrast

*The original paper contained the following sections of documents from the State of New York Department of Public Works which are not reproduced here:

Public Works Specifications of January 2, 1962
 Section M 18 A Paints and Painting Materials
 Section M 18 B Maroon Primer
 Section M 18 D Black Paint
 Section M 18 E Stain Resistant White Paint
 Section M 18 G Gray Paint
 Section M 18 J Ready-Mixed Aluminum Paint
 Section M 18 K Zinc Chromate Primer

Part II Section 8a—Painting—General Specifications Painting of Metal Structures
 Addenda No. 19 to Public Works Specifications of January 2, 1962
 Section M 18 C A Dull Orange Primer
 Section M 18 H A Gray-Green Paint

Materials Method N.Y. 6. June 25, 1962 "Sampling of Paint for Field Application"
 Materials Method N.Y. 6.1.—November 1, 1962 "Sampling and Control of Paints for Shop Application"
 Materials Method N.Y. 6.11.—"Shop Paint Application Samples"

to the leafing aluminum finish was obtained. Perhaps more importantly with this new undercoat-finish system, the unsightly appearance of a structure when the finish erodes away, exposing an irregular blue color, now becomes a thing of the past.

For the protection on the bottom areas of aluminum railing posts which would come in contact with freshly placed concrete, a zinc chromate primer was added to the specifications.

To substantiate the validity of this approach for providing paint systems to improve protection of structural steel, due consideration should be given to the facilities placed at one's disposal and the intimate contact with eminently qualified technical personnel, together with the results obtained.

From the beginning a program of investigation and research was developed whereby we could take advantage of any advances made in the paint industry.

As an illustration, tests were run on the Skyway Bridge in Buffalo. This is an elevated structure providing 135 ft of under-clearance for the Buffalo Ship Canal. It is located at the eastern-most end of Lake Erie and is subjected to abnormally high winds as well as a full range of climatic conditions. Its industrial environment is made up of steel mills, cement mills, flour mills and a variety of chemical plants.

In September 1958, nine complete and different paint systems were applied to a portion of the railing of the Skyway Bridge. In October 1959, ten complete and different paint systems were applied to another portion of the railing of this same structure, and three complete and different paint systems were applied to the beam-type guide railing fastened to the metal protection plate for curbs.

The September 1958 series consisted of the following:

<u>Area</u>	<u>Composition</u>
1	M20A—M23A—M22A
2	M20A—M19A—M23A—M22A
3	M20A—M23A—Epitex T. C.
4	M20A—M19A—M23A—Epitex T. C.
5	M20A—M23A in alkyd—Parlon T. C.
6	M20A—M19A—M23A in alkyd—Parlon T. C.
7A	M20—M23—M24
7B	M20—M23—M24A
8	M20—M23—M23—M22
	Old paint removed essentially to metal.

Paint Description

M19A—Basic lead silico chromate maroon intermediate

M20A—Basic lead silico chromate orange primer

M22A—Basic silicate white lead—basic carbonate white lead—TiO₂—oil—alkyd white top coat

M23A—Basic lead silico chromate—TiO₂—gray—oil—alkyd undercoat

M24A—Basic lead silico chromate—gray green top coat

M20—Red lead primer

M22—White lead—zinc oxide white top coat

M23—White lead—zinc oxide gray undercoat

M24—White lead—zinc oxide gray green top coat

Epitex T. C. —T-8397 M22A with epoxy ester vehicle

M23A in alkyd—T-9044 M23A pigmentation—untinted in straight alkyd vehicle

Parlon T. C. —T-9904—TiO₂—dyphos—oil—alkyd—Parlon

The October 1959 series consisted of the following:

<u>Area</u>	<u>Composition</u>
1	M19A—M23A—M22A
2	M19A—M23A—MIL-P-1264
3	M19A—M23A—M24A in alkyd

<u>Area</u>	<u>Composition</u>
4	M19A-M23A-Lt. green in alkyd
5	M19A-M23A-Lt. green in epoxy ester
6	M19A-M23A-M25A + M-50
7	M19A-M23A-M25A
8	M19A-M22A-M22A
9	M19A-MIL-P-1264-MIL-P-1264
10	M20A-M23A-Acrylic (double coat)

Guide Rail Test

1. M19A-M22A-M22A
 2. M19A-M22A + sand-M22A
 3. M19A-M22A + pumice-M22A + pumice
- Old paint removed essentially to metal

Paint Description

M19A-Basic lead silico chromate maroon intermediate
M20A-Basic lead silico chromate orange primer
M22A-Basic silicate white lead-basic carbonate white lead-TiO₂ oil-alkyd
M23A-Basic lead silico chromate-TiO₂-gray-oil-alkyd undercoat
MIL-P-1264-T-9720-TiO₂-ZnO-alkyd
M24A in alkyd-T-8356-M24A in straight alkyd vehicle
Lt. green in alkyd-T-9729-basic lead silico chromate-TiO₂-epoxy ester
M25A N. Y. S. aluminum top coat
M25A + M50-1 lb basic lead silico chromate paste (75% pigment in oil) mixed into 1 gallon M25A
Acrylic-T-9808-TiO₂-inert in acrylic emulsion
M22A + sand-sand thrown onto wet film of M22A before it sets
M22A + pumice-1/2 lb pumice mixed into 1 gallon M22A

For the purpose of correlating the results of this test, these same series of paint systems were also applied to prepared structural angles and steel plates, and exposed at the pigment supplier's test stands, under rural, marine (salt and fresh water) and industrial environments.

These test areas were inspected at regular intervals but tests had to be concluded in July 1962 since a contract was being prepared to repaint this structure in the Fall.

The following is a summation of the observations made at the time of inspection:

1958 Test

Overall, all systems are giving good protection, due in part to the reasonably careful paint application. The best systems, from the standpoint of protection, appearance and visibility are:

- 1-M20A-M23A-M22A
- 2-M20A-M19A-M23A-M22A
- 6-M20A-M19A-M23A in alkyd-Parlon T. C.
- 7A-(except visibility) M20-M23-M24

1959 Test

All systems are giving good protection, visibility is best with M22A or MIL-P-1264 as a finish. Except for high visibility requirements, Test 4 with a light green alkyd finish is very satisfactory. Acrylic finish did not cure properly under cool weather conditions prevailing during painting, therefore, is not considered practical for all-purpose use.

1959 Guide Rail Test

Visibility of these systems is excellent considering their location on the structure. Those systems containing sand or pumice exhibited remarkable resistance to removal by scraping when compared with the conventional paint system used on the rest of the structure.

The late Elmer G. H. Youngmann, District Engineer with headquarters in Buffalo, New York, requested a design of a white paint system for use on railings, guide rails and the metal protection plate for curbs on this structure, for the purpose of providing better visibility, thereby reducing the potential mental hazard. Sand was applied to the intermediate coat of paint used on guide rails and the metal protection plate for curbs. At the same time the wet film thickness was increased on intermediate and finish coat from 3.2-4 to 5.3 mils.

In 1959 drying difficulties were encountered with the gray-green finish. Without a careful selection of drier catalysts the paint skin-dried, producing wrinkling. It was found necessary to modify the specification to require the use of a particular drier combination which would insure relative freedom from this defect.

In 1960 it was observed that the new gray-green finish had a tendency to dry with an irregular gloss and have poor color uniformity under unfavorable, drying conditions (hot humid air). While initially this was objectionable, the weathered film fortunately dulled down uniformly to produce a lasting attractive finish.

Figure 4 shows the flashing or irregular gloss defect on certain structures. This effect usually developed at laps or where the coating had been applied unevenly.

To overcome this defect the alkyd resin was increased considerably while retaining some linseed oil for ease of applying the paint. The pigmentation, containing basic lead silico chromate, was maintained essentially the same. Two independent investigations were made in order to arrive at the proper ratio of alkyd to oil. This work was undertaken in 1961.



Figure 4. A demonstration of irregular gloss experienced with gray-green finish coat paint.

The first, which involved application of test paints to small specimens exposed to 45° South weathering, comprised a vehicle ladder wherein the percentage of resin (long oil alkyd) in the vehicle ranged from 35 percent (as specified) up to 100 percent at the expense of raw linseed oil. It was obvious from the beginning that high concentrations of alkyd resin (80% to 100%) offered problems in practical application. Inspection within two years showed a definite break in gloss retention and uniformity where the ratio of resin to oil was 65 to 35. Here and above, appearance was better.

To check this out practically, field tests were made on State structures on Long Island and upstate in the Rochester area in 1962, using four vehicle compositions: 35:65 long oil alkyd resin to raw linseed oil, 65:35, 80:20, and finally 100 percent resin. The paints were applied by State maintenance crews directly to scraped, wirebrushed and dusted surfaces at normal spreading rates under the following preselected environmental conditions.

<u>Application*</u>	<u>Temp. Limits Steel Surface</u>	<u>Humidity Limits</u>
Brush	40- 48 F	80-90
Brush	40- 48 F	25-40
Brush	110-125 F	80-90
Brush	110-125 F	25-40

*Paints are to be applied over a solid intact previously painted surface or a properly undercoated surface.

Thus four extreme conditions, which could be met in practice, were used to evaluate paint modifications. The observations of the painters were noted and, in addition, the weathering characteristics were recorded at frequent intervals thereafter.

The standard formulation initially showed, as it had in field use, the flashing phenomenon. The 65:35 resin:oil combination showed excellent uniformity regardless of the environmental conditions. The higher resin content coatings (80% and 100%) were inclined to retain high gloss points where overlapped, although were satisfactory when properly spread out. The disadvantage of these latter paints, particularly the 100 percent resin, was difficulty in handling. This is of particular importance from a practical point of view. In the protection of steel, the development of an anti-corrosive system using coatings of highest durability is essential. Unfortunately in field practice such coatings often are difficult to apply properly by brush, as required by the State. Therefore, some compromise must be made to ease the handling characteristics so that useful films can be uniformly applied. This is best accomplished by the inclusion of some linseed oil rather than permitting the use of high solvent additives. Another result of this compromise is to obtain a higher vehicle solids content which will, in turn, result in a higher paint film build. With these points in mind, a new specification for the gray-green using 65:35 long oil alkyd:raw linseed oil was adopted in 1964.

The fabricators experienced difficulty in handling the orange primer since they were not familiar with its lean hiding compared with the previously used red lead. Their painters had the tendency to over-apply un-uniformly to obtain hiding, which resulted in excessively thick films. Being high in linseed oil these films skin dried and wrinkled and in cold weather dried slowly, making them susceptible to damage in the course of handling the structural members.

With the aid of interested fabricators and the research laboratory staff of the co-operating pigment company, modifications in the primer specification were fully investigated. As a result of this work, a revision was made and adopted in 1964. Specifically, the drier catalyst requirements were changed, the alkyd resin content was raised to improve winter drying without adversely affecting steel surface wetting characteristics, and a small amount of pure iron oxide tinting pigment was included to upgrade the hiding. The hiding was increased just enough so that the applicator would not tend to load on the paint excessively, would be satisfied in his own mind that he was hiding well, and at the same time would not spread it too far to obtain inadequate film thickness. For reference, this paint coincides with Federal Specification TT-P-0061 5c, Type V, except for the requirement that pure iron oxide be used.

QUALITY CONTROL OF PAINT

With the adoption of our new paint systems we introduced a new method of control in order to assure delivery of material conforming to the required specifications. This consisted of requiring the use of an approved lever-type ring seal on the containers and the employment of tamper-proof tags installed on the ring seal. Paint manufacturers installed the tamper-proof tags which were furnished by the office of the Deputy Chief Engineer (Bridges).

The paint manufacturer's request for the tamper-proof tags indicated the project for which the paint was made, together with the gallonage of each type and the size of container. Based upon this information the required number of tamper-proof tags would be supplied the manufacturer.

Tags broken by the Department inspectors for purpose of sampling paint for submission to the Department laboratory for analysis were replaced by him with a tag of the same type but a different color. By this method of control we were able to compile a record of the amount of paint supplied to any given contract. Any unauthorized tampering with, or breaking of the tags would be cause for rejection of the paint at the Contractor's expense.

As a result of the experience gained by this method of control, a far more comprehensive and orderly program was developed by the personnel of the Bureau of Materials in the office of George W. McAlpin, Deputy Chief Engineer (Research).*

PRACTICES AND INSPECTION

While paint compositions, as the example, have been changed to keep abreast of progress—and will continue to be—painting practices in the main have remained static. Fabricators are required to clean the steel of foreign matter and to remove by mechanical or manual means loose scale and rust. Removal of rust and scale can at times be rather haphazard, depending on the size of the project and the number of inspectors available. The inspectors may be from outside testing laboratories or Department employees.

Two other causes of potential paint failure are poor caulking of lap joints and insufficient film thickness of paint applied to sharp edges (bolt and rivet heads, edges of flanges, welds, etc.). The shop inspectors watch these carefully because our specifications are explicit in spelling out preventive procedures. For example, with sharp edges these critical points must be striped with the shop primer prior to general application of the prime coat to the steel when those areas are again coated to build film thickness. There would be a definite advantage to continuing that practice with each succeeding paint coat, and in fact, such an interpretation can be made from the wording of our specification, but unfortunately it is not required.

In order to obtain adequate film thickness for the bridge paint system, the inspectors—from fabrication to completion—must now insure that certain prescribed wet film thicknesses of each coat be applied. It is the intent of the Department that a minimum of 7 mils dry of the three coat paint system be obtained. There are several wet paint film thickness gages to utilize during application as well as two or three acceptable dried film gages to check the finished job. The inspectors are expected to use these frequently.

We are conscious of the fact that our surface preparation requirements for new construction have not kept abreast of the times as they have in some States. We still require only mechanical and hand scraping and wirebrushing to remove loose rust and scale. Blasting methods are now available which would make complete stripping of the steel to virgin metal economically feasible. The problem is that few fabricators in the Northeast have been equipped to undertake this work. When they become so, the Department will likely upgrade its requirements. This, it is recognized, will noticeably lengthen paint film life and result in further maintenance cost savings—particularly in the more severe environmental areas of the State.

*See footnote p. 32.

SUMMARY

From the foregoing it can be concluded that our approach to improve protection of structural steel was valid and that we have benefited through a liaison that has accorded us the results of the continuing experience and research of technically qualified personnel in the paint industry.

With our improved paints, and in spite of our limited requirements for surface preparation, we anticipate:

1. Twelve years attractive, protective performance from the three coat system.
2. Minor amount of required scraping and spot priming followed by a full coat of finish on the 12-year cycle.

For the future, it is to be expected that the protection of our structures could be further enhanced by:

1. Adoption of improved cleaning methods.
2. Improved control of paint application through more stringent inspection.
3. The testing and possible adoption of coatings containing still more durable vehicles—a goal not now possible with limited surface preparation and the lack of practical knowledge in our field to properly apply these more difficult to handle materials.

ACKNOWLEDGMENTS

The author wishes to thank the management as well as the research and technical personnel of the National Lead Company for their assistance and cooperation extending over the period of the last nine years. Special thanks are extended to George Diehlman, E. K. Zimmerman, R. P. Bates and William Klein of National Lead Company; S. C. Frye of Bethlehem Steel Corporation; the construction and maintenance personnel of the New York State Department of Public Works; and Vernon J. Burns, Deputy Chief Engineer (Design).

REFERENCES

1. Basic Lead Silico Chromate, an Anti-Corrosive Pigment. Official Digest, January 1961.
2. Keane, J. D. Highway Bridge Painting. HRB Bull. 243, 1960.

Corrosion Control—A Design Function

JOHN R. DAESEN, Director, The Galvanizing Institute

Considerations of the mechanism of the protective action against corrosion are illustrated by examples, and simple investigative tools are suggested to provide the design and maintenance engineer with help in evaluating and particularizing general information on materials offered for corrosion control. The need for more specific disclosure in specifications for materials offered for corrosion control is also brought out.

•THE grave results of interruption of service for maintenance, as well as unsupportable cost, demand that protection against corrosion be designed into highway structures, instead of merely being added to them. Such operations as surface preparation of structures and painting should only be performed at the longest possible intervals.

CORROSION CONTROL IN DESIGN AND PURCHASE

Because the financing of Interstate highways leaves the burden of maintenance to local bodies, it is not only a hardship to some of these communities when structures requiring excessive maintenance are built, but it is also a serious lack of protection of investment.

In securing bids on alternate construction materials, a policy which makes no cost allowance for materials which minimize maintenance costs is unrealistic. In spite of the demonstrated great advantage in maintenance of hot dip galvanized guardrail, painted steel guardrail, otherwise unprotected, has been installed on some Interstate highways in the last year. This suggests that corrective action in contract specification may be indicated. Design engineers should add to their calculations, in addition to "cost per thousand psi yield strength," the figure "maintenance cost per unit of structure per year."

Effective judgment of the problem requires an orderly appraisal of the specific causes and extent of corrosion in the particular case and a competent understanding of the mechanism by which the proposed protective means is to do its work.

Moist air is a slow corrodent of metal structures, but persistent wetness, uneven aeration, or the presence of active dissolved ions can accelerate corrosion greatly. Discharge of active gaseous waste by industry or transportation vehicles may so greatly accelerate attack that certain areas should be given preferential treatment in the design of corrosion protection. In providing such special improved resistance, the design engineer needs to know not merely the general order of excellence in corrosion resistance of the available materials, but also the specific performance of each in the corrosion hazard of the particular locality and structure.

MULTIPLICITY OF MATERIALS

For the designer of structures or of maintenance programs who is not a specialist in corrosion control, this orderly appraisal is made difficult by the limited availability of data on corrosive conditions, and particularly, by the great number of new products of merit (some tested in only limited areas or incompletely identified by composition).

The great variety of new synthetic paints calls to mind the fact that each was found to have its own particular limitations after expensive field testing.

Metal Progress (August 1965) lists some 250 grades of high strength and extra high strength steels, many of which make claims for improved corrosion resistance. One steel is listed as having twice the corrosion resistance of carbon steel, another 4 to 6 times, and another 5 to 8 times. It must be apparent that the ratio of improvement over this standard can hardly be the same in all atmospheres. The wide ranges of composition indicated for many of these steels, overlapping those given for other steels, make it extremely difficult for a user to judge which are similar in composition and approximately equivalent in performance.

NEED FOR SELECTIVE STANDARDS

Evaluation of these products is made difficult by loosely drawn standard specifications, which are too broad to define a class of material except for very limited performance requirements. A notable example of such a standard specification is ASTM Specification A 242-64T for High Strength Low Alloy Structural Steel. This is also approved as an American Standard Association standard.

Its shortcoming lies not in provisions for physical properties, which are complete, but in its breadth of chemical requirements: carbon, manganese and sulfur only being specified. "Choice and use of alloying elements... shall be made by the manufacturer and included and reported... for information purposes only to identify the type of steel applied."

As for corrosion resistance, provision 4(c)* does not justify expectation of improved corrosion resistance by merely specifying that the steel shall conform to ASTM Specification A 242.

EFFECT OF COPPER AND PHOSPHORUS

Today's engineering journals tend to seek a wide range of readership and feature articles in very general terms. As a result, certain generalities are widely circulated. One of these is the great improvement in corrosion resistance offered by a 0.20 percent copper content in steel. This was strongly documented by the test of ASTM Committee A-5 on Corrugated Steel Sheets, exposed in a number of sites in 1917, and inspected semiannually to 1951.

As a result of far more complete documentation of chemical analyses of the material of this test than is current in recent field tests of this committee, we are able to show in Figure 1, from data of the Report of Committee A-5, 1954, not only the effect of copper which has been widely reiterated, but also the very positive effect of phosphorus in improving corrosion resistance, as shown by the average life to perforation of groups of sheets of from 3 to 14 of specific chemistry.

Because of the very great hardening effect of phosphorus, large amounts of this element are not used with carbon contents of over about 0.12 percent. Users should note that phosphorus over 0.05 percent in a steel may be expected to add to the steel's corrosion resistance, especially if copper is present. They will not find it present as an aid to corrosion resistance in steels of 0.20 carbon or higher.

The dotted portion of the curves of Figure 1 are not from data of the above test, but reflect the results reported in "Corrosion Testing," the 1951 Edgar Marburg Lecture by F. L. LaQue, on openhearth irons in marine atmosphere: "There can be as much as a ten-fold difference in corrosion between irons carrying 0.005 percent and 0.05 percent copper." He stated in Metals Review (June 1965): "... the resistance to atmospheric corrosion is improved more than five-fold by elevating copper from 0.005 to 0.03 percent."

*"If the steel is specified for materially greater atmospheric corrosion resistance than structural carbon steel containing copper, the purchaser should so indicate and consult with the manufacturer."

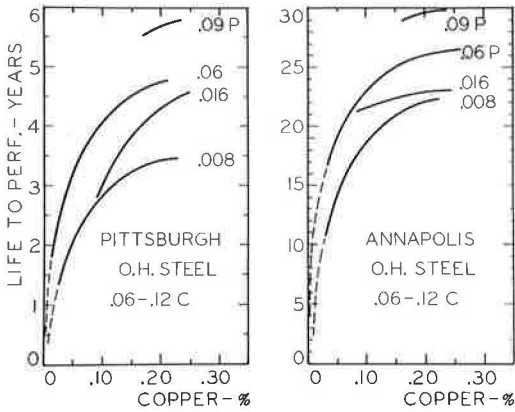


Figure 1. Average life of corrugated black sheets to perforation: 26 x 30 in., 22 gage, 3 to 14 sheets per lot.

Since most carbon steel contains about 0.03 percent copper as a residual element, it is apparent that the general claim for improved corrosion resistance should indicate the copper content of the standard of comparison.

The difference in actual resistance between the industrial atmosphere of Pittsburgh and the mild marine atmosphere of Annapolis is not the most interesting feature of the data. Note that proportionally, increased phosphorus is far more effective in the sulfur containing atmosphere, where the ten-fold increase from 0.008 to 0.09 phosphorus yielded a 66 percent improvement at 0.20 percent copper. In the purer atmosphere of Annapolis, this ten-fold increase in phosphorus caused only a 33 percent improvement, only half that obtained in the more rigorous atmosphere. This effect could profitably be more widely recognized.

EFFECT OF ATMOSPHERE ON RELATIVE PERFORMANCE

The well-publicized characteristic of corrosion-resisting low alloy steels of developing increased resistance during exposure (Fig. 2) is also a characteristic of plain carbon steel and malleable iron, except in a very aggressive seashore application. These data are calculated from the recently reported results (Subcommittee Reports of Committee A-5, ASTM, 1965) of weighing of bare 4- x 6- x 1/4-in. sheet samples exposed with other panels of the same material coated with zinc and aluminum. These sheets had been exposed at several locations for 6 years. Previously, similar samples were weighed after cleaning, after a 2-yr exposure period.

The 4 to 1 increase in corrosion resistance claimed for some low alloy steel is almost met at the unusual seashore exposure, but falls to about 3 to 1 in the industrial exposure of Newark, N. J., and to 2 to 1 in the milder marine exposure of the 800-ft lot at Kure Beach, N. C., for the 6-yr period. The great difference in behavior of

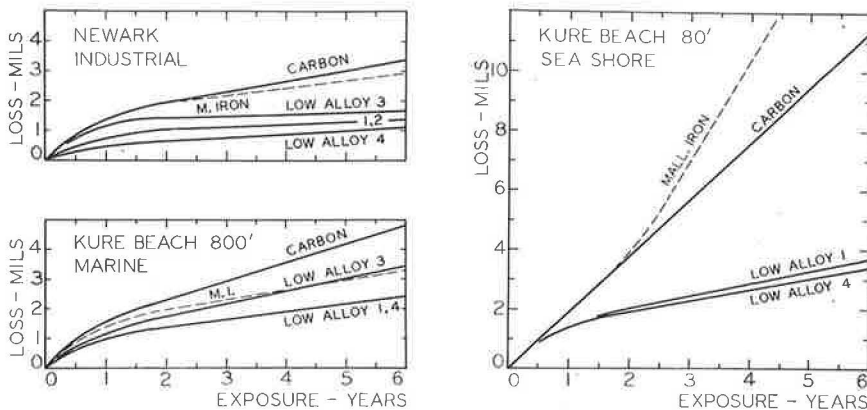


Figure 2. Calculated average loss from each surface determined by weighing at 2 and 6 years: 4- x 6- x 1/4-in. panels.

malleable iron, rapidly attacked at the seashore, but equally resistant with low alloy 3 at only 800 ft from the same location, is notable.

The low alloy steels are very poorly identified in this test (principally designed to test coatings) by wide ranges of alloy elements. Specific analyses for certain elements have been listed as follows:

Steel Type	Carbon	Copper	Nickel	Chromium	Zirconium
LA I	0.10	0.50	0.62	0.47	—
LA II	0.17	0.06	0.02	0.64	0.03
LA III	0.14	0.37	0.54	—	—
LA IV	0.10	0.24	0.30	1.10	—

The carbon steel selected to "serve as a standard of comparison" is not identified by carbon, copper or phosphorus content. Users will be best served by prompt, complete disclosure by this committee of the balance of the chemical composition of these very interesting samples. Highway engineers can effect this by indicating their interest to the committee.

MECHANISM OF CORROSION PROTECTION

This discussion of the basic mechanisms of protection is illustrated by examples to indicate the general nature of the effects and suggest simple nonspecialized tests for observation of the progress of corrosion. A low power stereo microscope, with ample auxiliary illumination is ideal for disclosing far more detail in weathered specimens than can be observed without visual aid.

In actual fact, the protection of outdoor structures against atmospheric corrosion is provided by some form of barrier film. Complete isolation of the structure from corrosive elements by barrier film action alone is unattainable because of: damage to the barrier film in shipping and erecting; holidays in application of paint coatings on structures in place; permeability of paint or porosity of metal films, allowing access of air and moisture; and mechanical damage or corrosive depletion of the film in use.

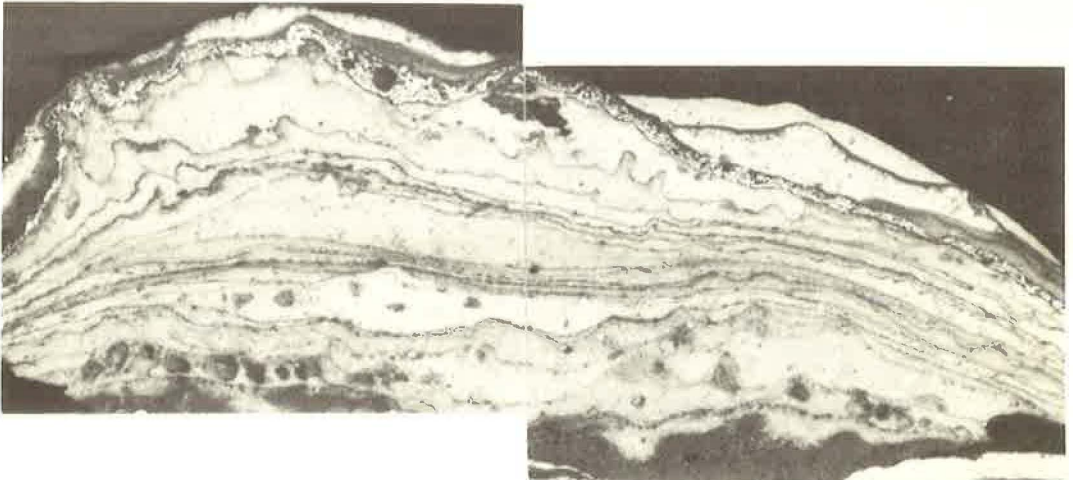


Figure 3. Section of multi-coat paint flake from corroded steel structure.

Inert Barrier Films

Figure 3 shows a section at low magnification of a heavy flake of multiple paint coats, picked off of a badly rusted steel bridge over a small gully in a public park. The 20 or more layers of paint, of uneven thickness near the edge of the steel member, have been totally inadequate to prevent destruction of the underlying steel, to the point of its partial disappearance. While the variation in color of the different films may reflect changes for aesthetic considerations, we may safely assume that many new hopeful solutions were offered for this problem, one of the most recent being obviously a 4-mil layer of aluminum paint. A similar investigation of larger painted outdoor structures would reveal an equally interesting stratified record in many cases.

The nonuniformity of micro-structure of all commercial metals of construction, which permits local cells of corrosive attack, dictates a dynamic defense against localized attack, and a reduction, if inhibition is impossible, of corrosive action. Inert barrier films with many imperfections distributed uniformly on a micro-scale provide such a defense, and permeable paint coatings applied to grit blasted steel may be taken for an example.

Figure 4 shows the surfaces of two test pieces of structural steel with a prime coat and a top coat totaling only 3 mils dry film thickness, after about 2 years exposure in a

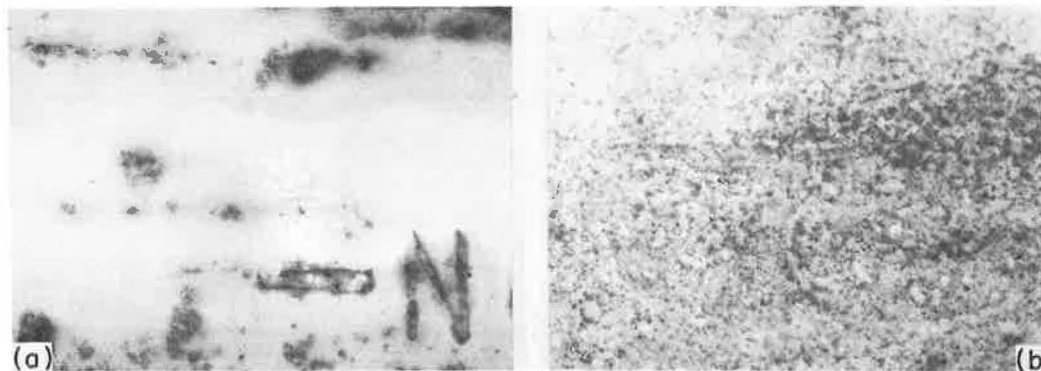


Figure 4. Surface of 3-mil paint system on structural steel after 2 years marine exposure: (a) over intact mill scale; (b) over grit blasted surface.

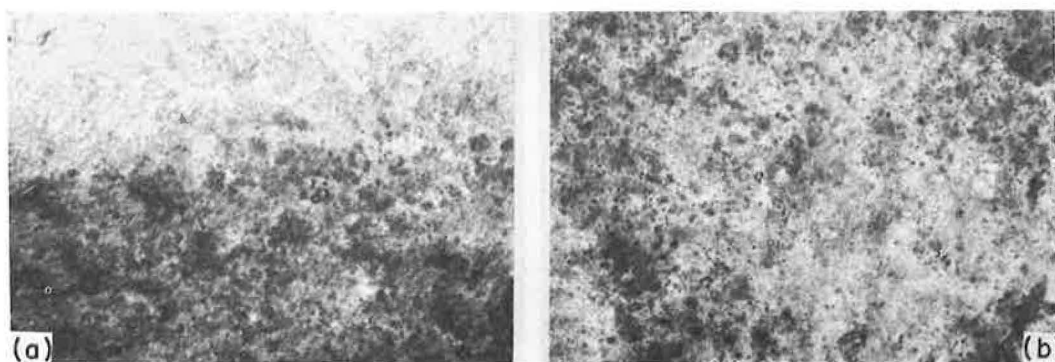


Figure 5. Surface of hot dip aluminum coated low alloy steel panel: (a) pitted and rust stained after 4 years marine exposure; (b) pitted and reported yellow stained after 4 years marine exposure.

marine atmosphere. Figure 4a is of a sample with the paint system applied directly over a fairly intact coating of mill scale. The coat is in good shape except for areas where the mill scale layer was broken, giving fine opportunity for local cell action and rusting. Figure 4b is of a specimen grit blasted before painting. Here there is more uniformity of the base, and the moisture and air that permeated the paint film have caused no massive rust, but pinpoints of reaction have formed over the entire surface.

In a program of continuous maintenance by repainting, the shallow depth of the many tiny pits formed in the base of the grit blasted steel will cause less trouble with failure of subsequent paint coats than will be the case with the deeper rust pits at breaks in the mill scale of the unprepared steel.

Micro-cracked chromium on nickel plate is another example of an inert barrier film with many imperfections distributed uniformly on a micro-scale. A similar reduction of local intensity of attack is secured.

Self-Replacing Barrier Films—Non-Anodic

Figure 5a shows the surface of aluminum coated low alloy steel exposed to a marine atmosphere for several years. While aluminum has a potential anodic to steel when a fresh surface is exposed, the oxidized barrier film formed by exposure in many areas does not permit anodic protection, and if pores are present or develop, as in the case of this 5-mil thick coating, corrosive action penetrates the pores and causes rust staining.

Fine pitting of aluminum coatings is sometimes associated with first a yellow stain, which later becomes black and remains without further change in appearance (Fig. 5b). This may originate from the combined iron of the alloy layer, or may reflect attack of the base. Micro-sections of such coatings are required to establish the presence or absence of attack of the steel base.

Self-Replacing Barrier Films—Anodic

The most effective barrier film is provided by an applied metallic coating such as hot dip galvanizing, of such potential with reference to steel that it will remain anodic even in mild atmospheric exposure, but which forms its own barrier film by oxidation during exposure. Small openings, accidental or otherwise, in the coating do not permit rusting of the exposed steel because of the anodic action of the coating.

As the oxidized barrier film is worn or dissolved off, fresh barrier material is formed. When the metallic zinc coating is applied in substantial thickness (2 oz/sq ft of surface, equivalent to 3.4 mils), this action yields long life in all but the most aggressive exposures. For the latter, the galvanized coating is effectively complemented by a paint system chosen for its resistance to the particular corrodent. Then, replacement of the paint film on a regular maintenance basis does not necessitate costly grit blasting of the base to give the new paint film a chance for reasonable life.

An essential characteristic of these anodic self-replacing films may be the presence of unreacted metal ions in the forming oxidized layer, or an action of alloy elements in maintaining a lower state of oxidation of some of the atoms of the base or coating metal.

Sprayed coatings of aluminum or zinc may not be equated directly with coatings of these metals applied by hot dipping, because of their greater porosity. The degree of anodic action must be determined for the particular coating in the exposure medium selected. Their high cost of application usually dictates thin coatings. Sealing plastic coatings are generally used with these, and the protection afforded has been shown to vary considerably with different sealants.

Self-Replacing Barrier Films—Rust Coating Formed on Base

Statuary bronze is the oldest example of an effective, self-replacing film formed on the base itself. The rust film on steel, usually too porous to provide much protection, is considerably more resistant with small amounts of copper and phosphorus added to the steel (Fig. 1). In some low alloy steels, the resistance is further increased by additions of silicon, chromium and nickel.

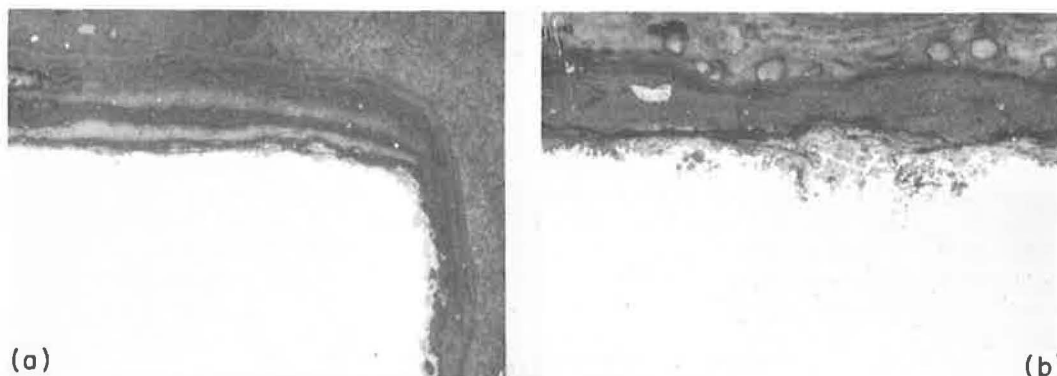


Figure 6. Section of painted cast iron destroyed by atmospheric corrosion, unetched: (a) corrosion (light gray) under multiple paint films, exposed face; (b) corrosion (light gray) under heavy prime coat (dark gray) on mating surface which trapped water.

The highway structure must not have its surface so damaged during use, as a result of corrosion penetrating the guard, that it makes re-application of protective coatings too costly or impossible. Far more important, in these days of high design stresses and lightweight sections, the metal must not be weakened against shock or fatigue by corrosion pits which could act as stress raisers.

Figure 6 shows the rusting of the cast iron base under (a) a number of paint films applied over a period of time, and (b) under a heavy prime coat applied between mating metallic surfaces capable of holding moisture. The continued presence of paint did not prevent such severe rusting that portions of the decorative cast iron trim had been completely destroyed.

Use of low power stereo examination of surfaces or of oblique sections or grooves (applicable to structures in use) is a means of estimating implication of the base by corrosive action. This can, and should, be done far more frequently than is possible for a more formal examination of dismantled sections.

As an example, Figure 7 shows the end of a 2- x 2- x 1/4-in. angle of low alloy steel which had been exposed for some years in an industrial atmosphere without protective

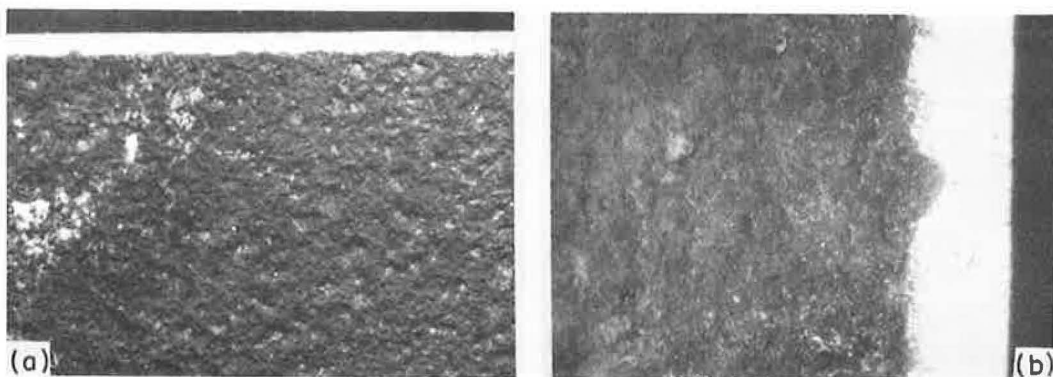


Figure 7. Low alloy steel unprotected 10 years in industrial atmosphere, edge beveled at 30-deg angle [right photo (b) is 5 X left (a)].

coating of any kind, except its own rust film. In Figure 7a, a part of the outer face of one leg is sawed off and then beveled at an angle of 30 deg with the surface. The deep pitting, evident on the surface, is given rough quantitative measure by the trace of the intersection of the bevel plane with the irregular surface.

At this angle, horizontal distances are equivalent to half their amount in a vertical plane, normal to the surface. The deepest pit is shown at greater magnification in Figure 7b, and there is a fine encroachment into the steel by dark markings which suggests general attack on a much finer scale than is apparent on the surface. Micro examination of sections at a higher magnification is indicated to assess the possibility of formation of stress raisers that could adversely affect fatigue or shock resistance of structures in this condition, even though weight loss tests should indicate a practical cessation of rusting.

FALSE ALARMS FROM DISCOLORATION

The color of rust, which has been an indicator of attack on steel for so long, is still an aid to evaluation of corrosion protection that cannot lightly be abandoned. Our deeply ingrained satisfaction with conditions that appear orderly and ship-shape arises from a perhaps unrecognized conviction that such things will perform their function.

A red or brown discoloration is not always a sign of attack on the base steel. Hot dip coatings which are bonded to the steel base by a diffusion layer of the base into the coating metal, as with zinc and aluminum, may show a red or brown deposit when this alloy layer is exposed in weathering. The color then is due to iron from this layer, redeposited on the weathered surface.

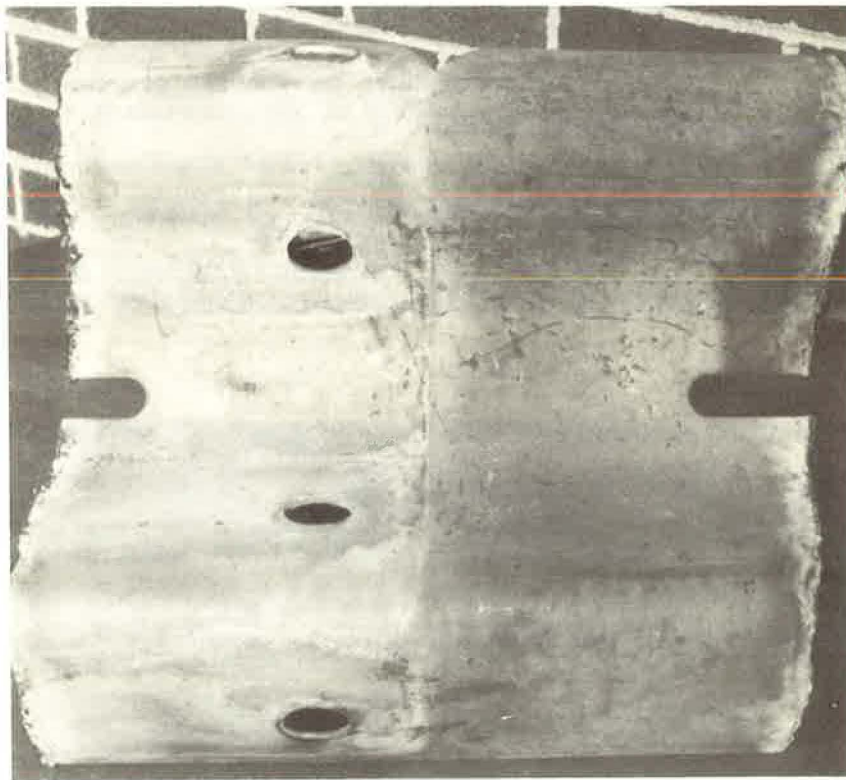


Figure 8. Galvanized guardrail stained by refinery fumes—light gray area covered by lap of adjoining rail; "red brown" stain from precipitated iron from zinc-iron alloy layer of coating ($\frac{1}{8}$ natural size).

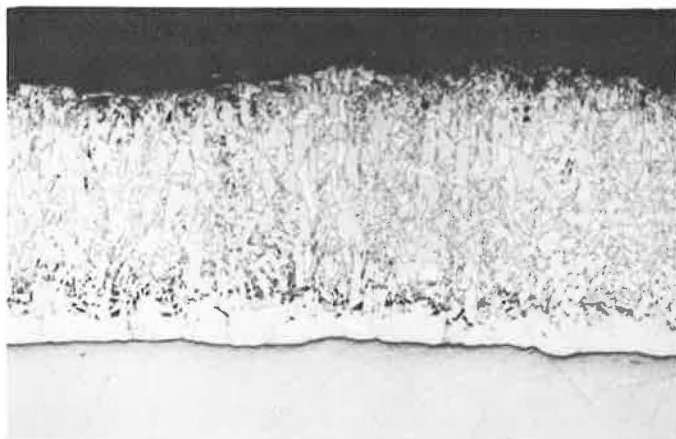


Figure 9. Galvanized guardrail stained by refinery fumes—section of 7-mil coating at covered area, diffuse alloy throughout, nitramyl etch, 200 X.

Such a condition is seen in the section of galvanized guardrail (Fig. 8) which is stained "dark brown" on the exposed face area, while the part covered by the lap of the adjoining rail is still gray. The micro-section (Fig. 9) of the coating shows that the alloy of zinc and iron, in this case, extends through the entire 7-mil thickness of the galvanized coating. Far from being ready to rust, this structure has twice the specified coating of 2 oz/sq ft of surface (3.4 mil). Yet in this case, authorities elected to paint this surface, stained by close proximity to an oil refinery, because of public reaction to a surface which suggested possible early failure.

While the appearance of a rust color may occur on the surface of protective coatings which still have many years of protective life, with no involvement of the base, absence of such staining would be far more desirable, for the peace of mind of the public and the highway and utility engineer.

ADAPTABILITY OF STEEL TO GALVANIZING

In the case of galvanized coatings, selection of the steel base composition can play a profound role in avoiding early discoloration of this type, or unattractive roughness. This selection need impose no limitation on the physical characteristics of the steel.

Figure 10 shows sections of galvanized coatings secured in tests under the same commercial conditions on three different pieces of steel supplied for the same purpose (welded steel poles). All were called extra strength steel with a 60,000-psi minimum yield strength. Each developed its own characteristic galvanized coating, which reflects the difference in silicon content of the steel:

	Surface Appearance	Thickness of Coating (mil)	Micro-structure	Silicon (%)
A	Smooth	4.4	Dense alloy and zinc	0.02
B	Rough	8.75	Diffuse alloy only	0.05
C	Gray, matte in some areas	5.0	Dense alloy to surface	0.25

The coating on A is well over the 3.4-mil equivalent to the 2 oz usually specified. While the B and C coatings are heavier than A, they are too unattractive in appearance to be salable.

Silicon is one of the cheapest means of increasing tensile strength of steel. Use of somewhat more expensive alloy elements in small amounts, and a lower silicon content was the commercial solution to this problem.

Generally speaking, the type of low alloy steel with 0.12 to 0.15 percent maximum carbon, containing silicon and phosphorus over 0.30 and 0.04 percent, respectively, may be expected to develop in massive sections a gray, matte surface in galvanizing (sometimes avoidable by taking unusual precautions). In steels over 0.20 percent carbon, as the strength increases, silicon contents over about 0.03 percent have a significant effect in causing rapid alloy growth, thick coatings and roughness. The presence of other hardening elements and the degree and kind of stress in the member modify

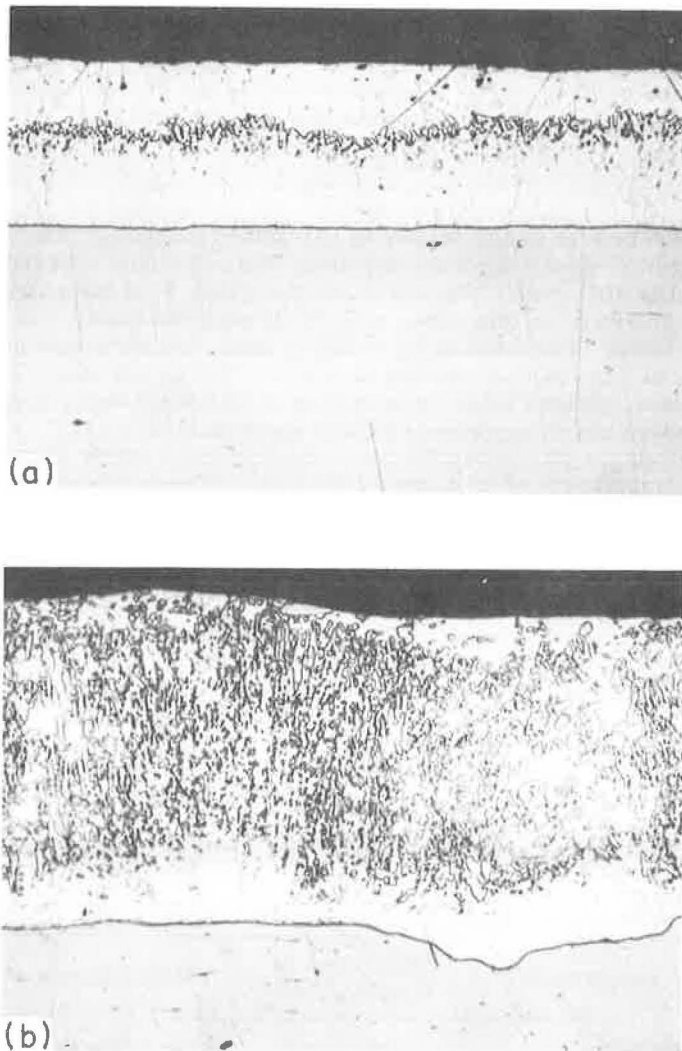


Figure 10. Sections of galvanized coating on 60,000 Y S steel—nitramyl etch, 200 X: (a) smooth, 4.4 mil with 0.02% silicon, dense alloy and zinc; (b) rough, 8.75 mil with 0.05% silicon, diffuse alloy.

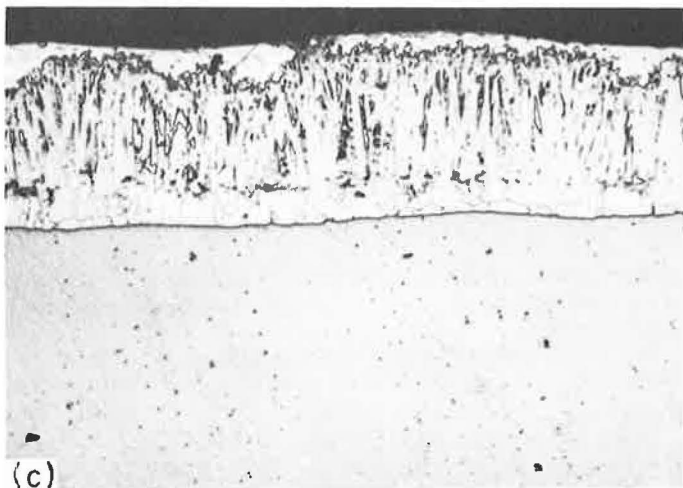


Figure 10 (continued). (c) Gray, 5.0 mil with 0.25% silicon, alloy to surface.

this action. Here, the adaptability for galvanizing should be determined by discussion or test.

The presumption that the most complete protection can be had by applying hot dip galvanized coatings to a corrosion resisting steel is faulty, in that many of these corrosion resisting steels (but by no means all) do not form the attractive, long wearing, dense structure of alloy with a zinc outer layer (Fig. 10a), but may develop coatings (Fig. 10b and c). When, after many years, magnetic tests indicate loss by corrosion of a major part of the galvanized coating, the structure will be well protected by suitable paint coatings applied on a regular maintenance schedule to a base not subject to pitting and rusting. In any event, suitability of the steel for galvanizing should be established as a part of design, particularly when higher strength or corrosion resistant steels are used.

SUMMARY

Highway and utility engineers have a pressing need for effective information on the capabilities of materials and systems to control corrosion. They also have a unique opportunity, and indeed an obligation, to aid in adoption of standard specifications which are truly informative and selective. The direction for improvement in these areas is suggested by examples.

By participation in the work of technical committees, engineers of highway and utility organizations can insure not only effective standards, but also the informative test programs and factual reports of materials in use that are needed to develop adequate standard specifications.

Discussion

SIMON A. GREENBERG, Industrial Consultant, Flushing, New York—The author of this paper is to be complimented for his precise, simplified and interesting description of the corrosion phenomenon, especially as it occurs in the atmospheres to which bridge structures are normally exposed. This paper should help the bridge engineer understand better how corrosion occurs and how to prevent it.

There are two separate subjects of the paper I should like to discuss. First is the matter of providing for corrosion control as a design function.

There are a number of design details which can contribute to the occurrence of localized corrosion on a bridge structure, regardless of the means of corrosion protection used. The following few examples by no means include all the details which can contribute to corrosion protection or failure; they are only given as typical.

In plate girders, it should be required that all stiffeners be coped to a size which is at least $\frac{1}{4}$ in. greater than the size of the flange-to-web weld. This will prevent the accumulation of rain water and dirt in the corners formed by the stiffeners and the web. (There is some evidence that coping of the stiffeners reduces the fatigue strength of a girder; this reduction is very small and is offset by quality advantages for such copings so that it is common practice to cope stiffeners.) I have found that copes are generally used but too often their sizes are too small to permit effective drainage.

Flanges of girders should not be permitted to have their edges curl upwards since this creates a natural trough for water to settle in. In fact, it would be desirable to have the flanges on the bottom slope downward ever so slightly to assure drainage.

On trusses, use of access holes in the bottom chord sections is not necessary with welded construction. I encountered some difficulty in convincing a highway department of this recently.

If the bottom chord is a welded box section, the inside faces of the plates can be painted to within two or three inches of the edges to be welded. The heat of welding will usually be enough to drive off any moisture. When the ends are sealed, the member is as corrosion resistant on the inside as it need be for the life of the structure. Adding access holes only provides openings for moisture to enter.

Connections of diagonals or ties to the bottom chord should be so designed and executed that troughs are not formed to trap rain water and dirt.

More examples could be cited, but the foregoing should suffice to suggest the considerations which should be given in the design and construction of bridges to prevent "built in" water pockets.

Another subject concerns one method of corrosion protection which the author has not touched on in his paper. It is metallizing or metal spraying.

In this process the surface to be coated is sand or grit blasted to produce a roughened surface to which the protective metal will bond when it is sprayed onto the base metal.

Metallizing for corrosion protection has found limited interest for large structures until recently. This has been due to a lack of information on the life expectancy of such coatings under actual exposures. Now, with ten years of experience under a test program conducted by the American Welding Society Committee on Metallizing, it is possible to predict the type of coating and thickness of coating which is needed for protection for a given period of time in a given atmosphere.

In 1953, about 2,000 test specimens coated with aluminum and a like amount coated with zinc were prepared and exposed in standard ASTM and other established locations in rural, urban, industrial, salt air and severe marine atmospheres, as well as sea water immersion.

The specimens were sprayed in a series of five thicknesses from 0.003 to 0.015 in. In addition, for each coating thickness of zinc some specimens were exposed without any seal coating; some were sprayed with a wash primer and one coat of aluminum vinyl; a third series was sealed with two coats of chlorinated rubber. The aluminum sprayed specimens were exposed with no sealant, with a wash primer and one coat of aluminum vinyl, and with a wash primer and two coats of aluminum vinyl.

The 10-yr inspection of the specimens last spring at all test sites showed that no rusting of the base metal has occurred on any of the aluminum specimens at any of the atmospheric locations. The panels without sealers have acquired nodes of corrosion product and do show some discoloration. Panels which had been given two seal coats of aluminum vinyl were brightest and cleanest of all.

Unsealed zinc coated panels which have 0.003-in. thick coatings and no seal coating have shown red rust at sites in industrial atmospheres. The unsealed panels which have thicker coatings have some accumulation of corrosion product which varies from light to dark gray in the different atmospheres.

The sealants used with zinc both leave something to be desired. Chlorinated rubber has not been effective at all. Aluminum vinyl is better but not as good as with aluminum; in some instances blistering of the vinyl sealant has occurred.

For bridges serving in rural atmospheres, a coating of 0.003 to 0.006 in. of zinc with a sealer should provide long time protection. For more severe atmospheres aluminum coatings should be used with aluminum vinyl as the sealer.

The initial cost of metallizing should be expected to be significantly higher than for painting or galvanizing. The cost and frequency of maintenance should be lower. In any case, this is a method of corrosion protection which should be considered along with the more established methods for providing corrosion protection to bridge structures.

JOHN R. DAESSEN, Closure—We are grateful to Mr. Greenberg for expanding the utility of the paper by his very specific suggestions of design details that avoid the trapping of water. This has an important effect on the life of galvanized coatings, as it has on most materials. Figure 11 shows how ineffective maintenance by painting can be when water is trapped in the overlap joint of painted but not galvanized guardrail.

We do not, however, approve his summary of the results of the test of the American Welding Society Committee on Metallizing, on sprayed aluminum and zinc coatings. He states "The 10-yr inspection. . . showed that no rusting of the base metal has occurred on any of the aluminum specimens at any of the atmospheric locations." But the Six Year Report states, page 4, "Some unsealed 0.003-in. thick aluminum coated panels have evidence of red rust staining on the surface of the aluminum. No particular significance is associated with this condition since it is a common occurrence on thin metallized aluminum coatings in some environments, and has existed since the initiation of this program."

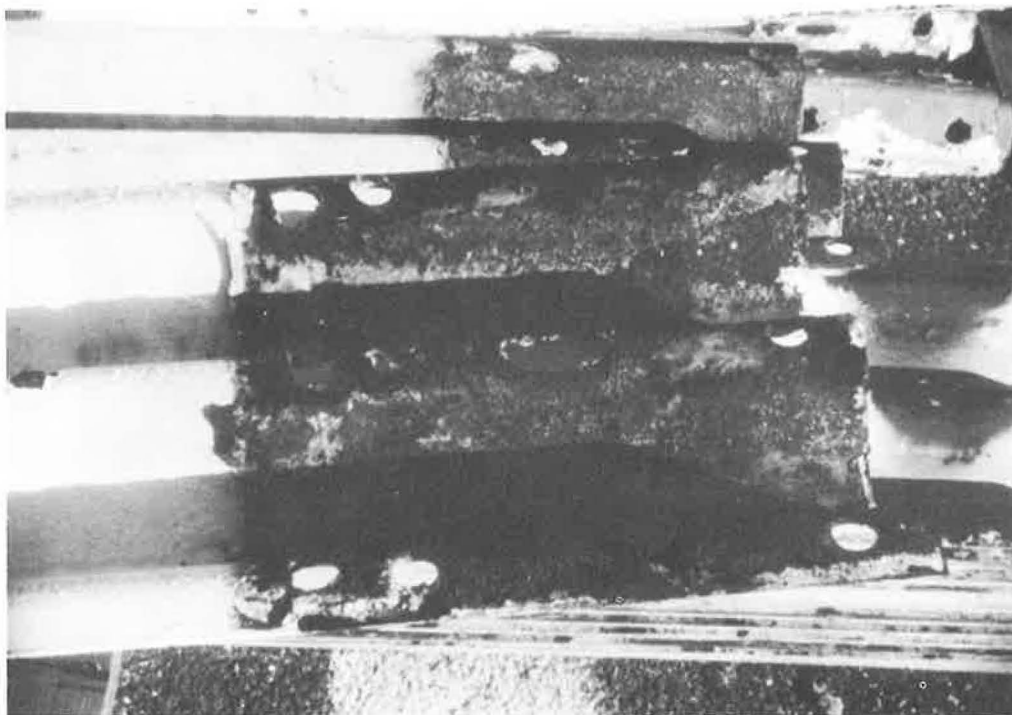


Figure 11. Dismantled, painted (but not galvanized) guardrail, rusted at overlap by entrapped moisture.

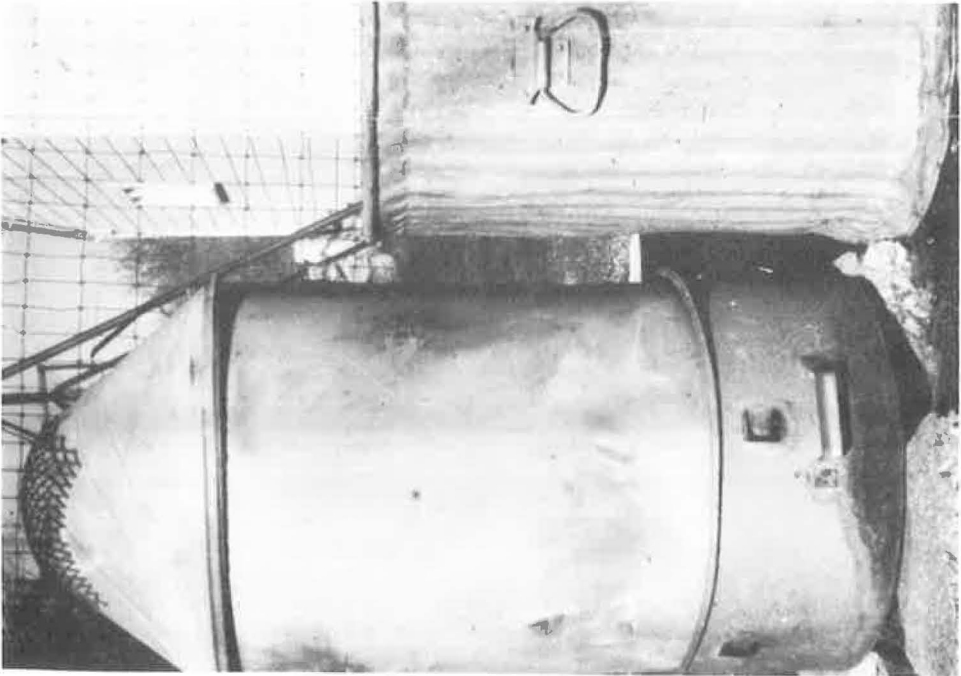


Figure 12. Three-year-old rusted hot dip aluminum-coated burner and 20-year-old hot dip galvanized trash can, unrusted.



Figure 13. Gray transition zone adjoining rusted area in Figure 12, pits, blisters and rust nodules in aluminum coating (surface 2 X).

Table 7 of the Six Year Report shows that all unsealed aluminum coatings up to 12-mil thickness exposed in the industrial exposures have "some blisters." And the photomicrograph of a tiny (0.02-in. diameter) blister filled with a dark corrosion product is described on page 6: "Figure 4 is a photomicrograph showing a blister in an aluminum

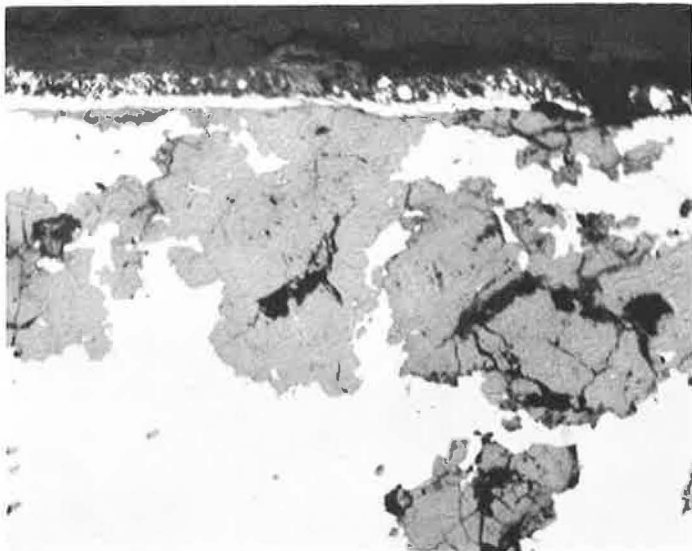


Figure 14. Deep rust penetration at pitted area in aluminum coating of Figures 12 and 13—adherent oxide (gray) and void left by loose oxide (black) above aluminum coating (section 125 X; unetched).

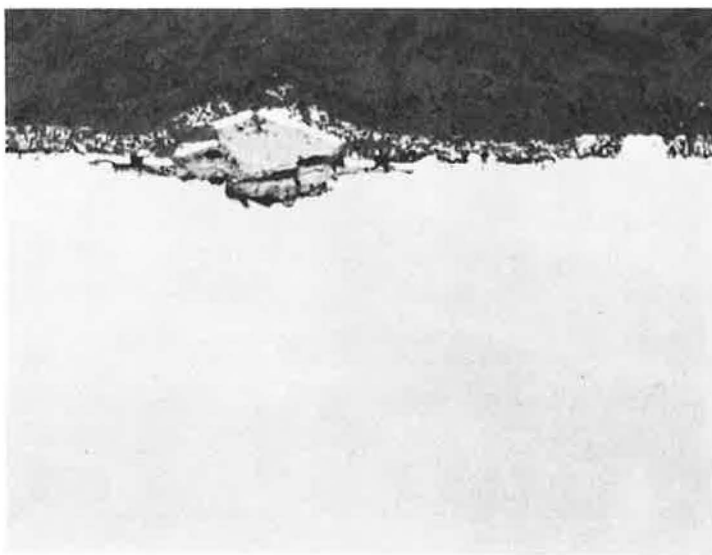


Figure 15. Small blister at gray area in aluminum coating—structureless gray, adherent oxide under textured bakelite mount material and over aluminum coating (section 125 X; unetched).

coated panel. This blistering is not fully understood. Apparently, local cell action promotes focal points of attack either within the coating or at the interface between the coating and the steel base metal. . . . After the corrosion products have been dispersed, a small pit exists."

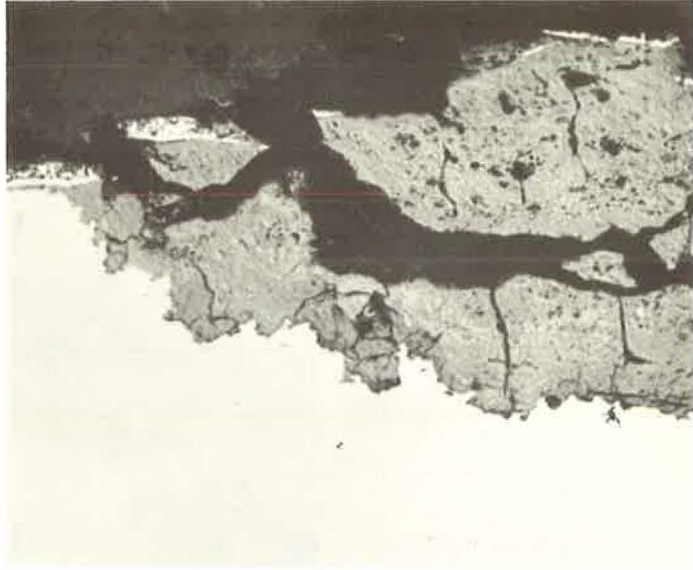


Figure 16. Larger blister at gray area in aluminum coating—fragments of metallic aluminum coating lifted on massive rust from steel base (section 125 X; unetched).



Figure 17. Rusting of base steel under intact aluminum coating at pitted area of Figures 12 and 13—some of the fractures in the aluminum-iron alloy layer of coating have become channels for oxidation process (section 625 X, after 25% reduction in reproduction; unetched after high pressure lapping on paper over plate glass).

These nodes, blisters and pits do not support the statement on page 9 of the Six Year Report, "In the heavily industrial environment (East Chicago) the aluminum coated panels exhibit no evidence of base metal corrosion."

On the zinc coatings, Mr. Greenberg states, "Unsealed zinc coated panels which have 0.003-in. thick coatings and no seal coating have shown red rust at sites in industrial atmospheres." The Six Year Report states, "In one industrial environment the sealed and unsealed zinc coated panels with a coating thickness of 0.003 in. exhibit evidence of base metal corrosion over a small percentage of their surface areas." But the detail report in Table 8 has no reference to this except the statement under 0.003-in. coating at East Chicago "some pinpoints of base metal corrosion on surfaces." Not even pinpoints of base metal corrosion are reported for any other zinc coatings, sealed or unsealed.

In the absence of proof that the blistering and pitting noted for the aluminum unsealed coatings involves no base metal corrosion, we must conclude that unsealed aluminum has shown no superiority in atmospheric corrosion over unsealed zinc in this test.

As far as integrity of the base is concerned, we have seen deep penetration of the base steel under thin hot dip aluminum coatings in atmospheric exposure (Figs. 12 through 17). Here, the characteristic failure of aluminum to maintain an anodic potential to steel has permitted serious attack of the steel through pores in an otherwise intact aluminum coating.

It is obvious that more positive evidence is needed to demonstrate that blisters in these unsealed aluminum coatings on steel contain no base metal corrosion product, and that there has been no irregular penetration of the base by corrosion at these points.

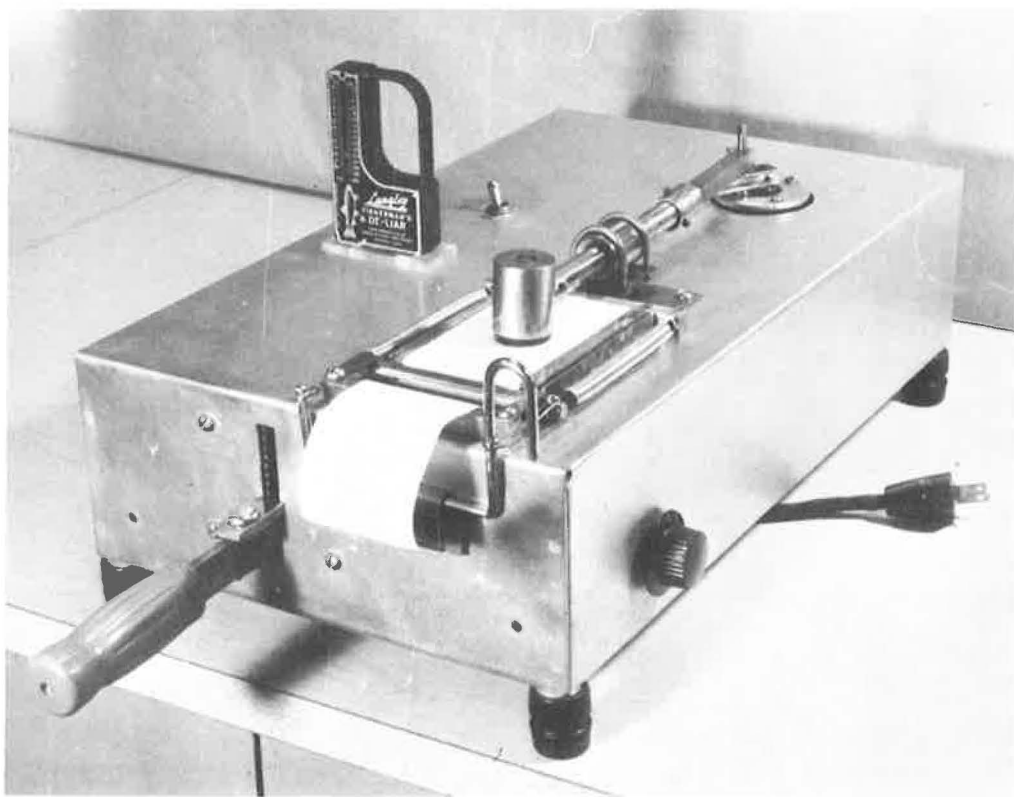


Figure 18. High pressure lap for oxidized micro-sections, or those with wide hardness and electro-potential ranges.

Obviously such penetration of the steel base can seriously impair shock and fatigue resistance.

We agree that the sprayed zinc coatings were improperly sealed, and we urge serious work on this problem. The combination of an effective sealer with a porous metal coating is seen to be of value with aluminum, and would prove equally useful with sprayed zinc.

The "significantly" higher initial cost of metallizing mentioned by Mr. Greenberg may be more readily visualized when it is realized that the cost of grit blasting, in preparation for metal spraying, is usually more than the entire cost of galvanizing, except on very heavy members or structures already in place.

Because the preparation of micro-sections of partially corroded materials of different hardness is so difficult as to restrict considerably the use of this method of study, Figure 18 shows the method devised for lapping these specimens, mounted in bakelite, at a total load of 20-lb pressure, on a paper strip over plate glass, using a thin paste of 0.1-micron alumina, Type B, in surgeons' green soap (not a water solution). The specimen is first flattened with 180, 400 and 600 grit silicon carbide paper. Use of paper over plate glass permits periodic replacement of lap surface as it becomes charged with abraded material. At the 60 oscillations per minute, there is no smearing of soft components, and hard inclusions are flattened rather than being torn out. Usually the fine micro-structure of coatings is faintly apparent on the unetched polished surface. The absence of water avoids electrolytic attack during surfacing.