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SOIL-CORROSION STUDIES, 1939: FERROUS AND NONFERROUS CORROSION-RESISTANT MATERIALS

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ABSTRACT

Since the beginning of the Bureau's soil-corrosion investigation in 1922, specimens of a wide variety of materials suggested for service underground have been exposed to various soil conditions and inspected at regular intervals. In this paper is reported the condition of the specimens of ferrous and nonferrous metals after underground exposures of from 2 to 17 years. Because of the variety of environmental conditions represented at the test sites, some idea of the corrosion resistance of the materials in most of the corrosive environments commonly encountered in soils can be obtained. Relations between corrodibility and chemical composition are indicated for certain classes of materials.

CONTENTS

I. INTRODUCTION

The investigation of corrosion-resistant materials by the National Bureau of Standards is an outgrowth of the original investigation of soil corrosion begun by the Bureau in 1922. The first sets of the specimens of corrosion-resistant materials and nonbituminous protective coatings were buried at 15 test sites in 1932, and sets of additional materials were buried in 1937, 1939, and 1941. In this paper are presented the results of the inspection of ferrous and nonferrous specimens after exposures of 7 years and 2 years, respectively. The condition of the specimens of protective coatings is reported elsewhere.[1] As this report will be succeeded by others when the specimens have been ex-

[1] Kirk H. Logan, Soil-corrosion studies 1939, coatings for the protection of metals underground. J. Research NBS 28, 57 (1942) RP1446.

posed for longer periods, detailed comparisons of the materials for the purpose of evaluating their relative resistance to corrosion will be deferred until later inspections have been made. This report is presented at this time in order that the trends shown by the data may be considered in the selection and development of materials for underground service.

As the field tests have been previously described in detail,[2] it is sufficient to state that the corrosion data presented here are chiefly for the third of a series of five inspections which are made at approximately 2-year intervals. Data for certain materials buried for longer and shorter periods are also included. With some modification, this paper will follow the form of previous papers in order that the data from successive inspections may be readily compared and the progress of the corrosion noted. The chief departure from the earlier reports consists in the presentation of the data for loss of weight as well as for maximum penetration as total loss per unit area and total pit depth rather than as rates. The reason for this change is that presentation of the data as rates implies that the progress of corrosion is proportional to the duration of exposure, or at least that the corrosion-time relation is the same for comparable materials. This is not generally true. For the benefit of those who desire the corrosion data expressed also as rates, the exact duration of exposure for each material at each test site will be given.

Since the primary purpose of this investigation is to determine what metals and alloys are most corrosion resistant in different corrosive environments, it is natural that the corrosiveness of the soils was an important consideration in the selection of the sites for the field tests. Although several of the soils would be considered only mildly corrosive, the corrosion rate in the soils as a group is considerably higher than it would be in a group selected to represent the most typical or extensive soils in the various localities. Failure of a material in a number of the soils under consideration does not necessarily reflect on the usefulness of that material for a wide variety of moderately corrosive soil conditions.

II. PROPERTIES OF THE SOILS AT THE TEST SITES

The nature of the soils at the test sites is indicated by the physical and chemical properties shown in table 1. The texture of the soils and their retentiveness of water is indicated relatively by values for the moisture equivalent, the quantity of water retained by a previously saturated soil against a centrifugal force of 1,000 times gravity. Since the true specific gravity of the mineral portion of soils varies within narrow limits, the apparent specific gravity, except in the case of organic soils, can be taken as a measure of their compactness and hence as a relative measure of their porosity. A soil having a very high moisture equivalent and a high apparent specific gravity, such as Acadia clay, soil 51, may be considered to be very fine in texture, highly retentive of water, very dense, and impermeable to the flow of air and water, and this is confirmed by the aeration or drainage of the soil, which is poor. On the other hand, the fairly large value for the moisture equivalent (32 percent) of Hagerstown loam, soil 55, indicates this soil to be fairly heavy in texture and retentive of water. However,

[2] Kirk H. Logan, *Soil-corrosion studies, 1937: Corrosion-resistant materials and special tests*, J. Research NBS **23**, 515 (1939) RP1250.

TABLE 1.—*Properties of soils at the test sites*

Soil		Location	Aeration [1]	Moisture equivalent	Apparent specific gravity	Resistivity at 60° F (15.6° C)	pH	Total acidity, milligram equivalent per 100 g of soil	Composition of water extract—milligram equivalent per 100 g of soil						
No.	Type								Na + K As Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4
				Percent		*Ohm-cm*									
51	Acadia clay	Spindletop, Tex	*P*	47.1	2.07	190	6.2	13.2	10.27	15.55	5.03	0.00	0.56	5.75	22.00
53	Cecil clay loam	Atlanta, Ga	*G*	33.7	1.60	17,794	4.6	9.6	------	------	------	------	------	------	------
55	Hagerstown loam	Baltimore, Md	*G*	32.0	1.49	5,213	5.8	10.9	------	------	------	------	------	------	------
56	Lake Charles clay	El Vista, Tex	*P*	28.7	2.03	406	7.1	4.5	3.12	0.69	0.47	.00	.80	1.59	3.04
58	Muck	New Orleans, La	*VP*	57.8	1.43	712	4.0	79.3	2.03	2.23	1.29	.00	.00	0.47	2.54
59	Carlisle muck	Kalamazoo, Mich	*VP*	43.6	------	1,659	5.5	33.3	1.03	3.08	2.70	.00	.00	3.47	1.04
60	Rifle peat	Plymouth, Ohio	*VP*	43.4	1.28	218	2.6	297.4	2.91	10.95	2.86	.00	.00	0.00	56.70
61	Sharkey clay	New Orleans, La	*P*	30.8	1.78	943	5.9	8.6	0.73	0.68	0.33	.00	.71	.10	0.91
62	Susquehanna clay	Meridian, Miss	*F*	34.6	1.79	6,922	4.1	24.2	------	------	------	------	------	------	------
63	Tidal marsh	Charleston, S. C	*VP*	46.7	1.47	84	2.9	100.2	33.60	6.85	4.00	.00	.00	12.70	36.60
64	Docas Clay	Cholame, Calif	*P*	41.1	1.88	62	8.3	[2] *A*	28.10	2.29	0.76	.00	.89	28.80	0.26
65	Chino silt loam	Wilmington, Calif	*F*	26.4	1.41	148	7.2	*A*	7.65	12.40	2.20	.00	1.30	6.05	16.90
66	Mohave fine gravelly loam	Phoenix, Ariz	*G*	16.5	1.79	232	8.7	*A*	6.55	0.51	0.18	.00	0.73	2.77	2.97
67	Cinders	Milwaukee, Wis	*VP*	11.1	------	455	8.0	*A*	0.77	3.03	.53	.00	.55	0.08	2.89
69	Houghton muck	Kalamazoo, Mich	*VP*	------	------	------	------	------	------	------	------	------	------	------	------
70	Merced silt loam	Buttonwillow, Calif	*F*	24.7	1.69	278	9.4	*A*	8.38	0.38	.22	.02	1.87	1.12	5.57

[1] Aeration of soils: *G*, good; *F*, fair; *P*, poor; *VP*, very poo

[2] Alkaline.

it is also very porous and well aerated, and this is indicated by the low value for the apparent specific gravity, 1.49.

Consideration of the chemical properties given in table 1 shows that the test sites represent a wide range of soil conditions. The range in pH is from 2.6 to 9.4, which are approximately the extreme limits shown by soils. The resistivity ranges from 62 to approximately 18,000 ohm-cm, corresponding to the concentration of sea water, on the one hand, to the concentration of salts in a highly weathered soil, on the other. The soluble material in Merced clay adobe, soil 57, and in Rifle peat, soil 60, is seen to be almost exclusively in the form of sulfates. Soil 57 is alkaline in reaction, while soil 60 is extremely acid, so much so that the soil actually contains sulfuric acid. In Docas clay, soil 64, the soluble material is almost entirely sodium chloride.

The names of the soils given in table 1 were assigned by the Soil Survey of the Bureau of Chemistry and Soils of the United States Department of Agriculture. That part of the name which describes the texture of the soil refers to the texture of the uppermost, or *A* horizon. As the specimens were buried at depths from 18 inches to 4 feet, they usually lie in the *B* or *C* horizons. Since these horizons are frequently heavier in texture than the *A* horizon, the aeration of the soil in which the specimen lies may be poorer than the name of the soil suggests.

III. FERROUS MATERIALS

1. SPECIMENS EXPOSED FOR 7 YEARS

(a) CAST MATERIALS

The composition and dimensions of the specimens of cast iron are given in table 2. The significant features of these and other materials, both ferrous and nonferrous, with respect to corrosion in various environments have been summarized elsewhere.[3]

The measurements of corrosion losses and depths of pits shown in tables 3 and 4, respectively, were made on 1-foot lengths of 1½-inch cast-iron pipe protected from internal corrosion by caps at both ends. The period of exposure was approximately 7 years. The values reported in these and other tables are the averages of measurements made on two specimens, except as otherwise noted. Usually the two specimens of the same material in the same soil yielded results which

TABLE 2.—*Composition of cast-iron pipes* [1]

Material	Identification	Thickness	C			Si	Mn	S	P	Cr	Ni	Cu
			Free	Combined	Total							
		in.	%	%	%	%	%	%	%	%	%	%
Rattled [2] cast iron	*G*	0.250	2.94	0.64	3.58	1.64	0.48	0.074	0.79	-----	-----	-----
Sand-coated cast iron	*F*	.250	2.94	.64	3.58	1.64	.48	.074	.79	-----	-----	-----
Special process cast iron	*I*	.350	-----	-----	2.53	1.43	.28	.077	.128	-----	-----	0.51
Do	*J*	.350	-----	-----	2.90	2.04	.83	.060	.248	-----	-----	.62
Low-alloy cast iron	*C*	.250	3.00	.50	3.50	2.50	.70	.050	.400	0.30	0.15	-----
High-alloy cast iron	*E*	.250	-----	-----	2.98	2.13	1.00	-----	-----	2.61	15.00	6.58

[1] These pipes were 12 inches long and approximately ¼ inch in internal diameter. They were buried in 1932.
[2] Ordinary iron horizontally cast in green-sand molds and rattled to remove sand.

[3] Materials in the National Bureau of Standards Soil-Corrosion Tests, NBS Letter Circular LC646 (1941).

agreed closely. Occasionally, however, they differed widely. Those cases in which the losses in weight or pit depths of the individual specimens differed from the average by more than 50 percent are indicated in table 3 and in succeeding tables. Whenever possible,

TABLE 3.—*Loss of weight of cast-iron pipe exposed for 7 years*

[In ounces per square foot [a]]

Soil		Exposure	Horizontally cast in sand mold,	Special process				Low-Alloy,	High-alloy,
						I+J			
No.	Type		*G*	*I*	*J*	Average	Standard error	*C*	*E*
		Years							
51	Acadia clay	7.53	20.86	21.08	21.03	21.05	0.5	23.73	3.88
53	Cecil clay loam	7.56	2.56	1.69	1.75	1.72	.1	1.64	0.66
55	Hagerstown loam	7.08	3.08	2.35	2.43	2.39	.1	2.02	.73
56	Lake Charles clay	7.52	21.97	24.70	22.67	23.69	2.2	19.59	9.39
58	Muck	7.60	18.96	20.57	20.00	20.28	0.6	18.01	8.62
59	Carlisle muck	7.22	[b] 3.88	[b] 2.97	3.19	3.08	.9	2.21	[b] 0.59
60	Rifle peat	7.33	4.92	7.23	5.67	6.45	.9	4.28	[c] 1.30
61	Sharkey clay	7.59	4.53	5.30	5.34	5.32	.2	4.99	1.68
62	Susquehanna clay	7.57	5.02	4.25	4.84	4.54	.4	2.46	0.98
63	Tidal marsh	7.67	1.44	3.46	3.01	3.23	.7	[c] 2.07	.68
64	Docas clay	7.30	35.46	39.41	44.12	41.76	2.6	44.69	5.78
65	Chino silt loam	7.34	7.14	8.01	9.01	8.51	0.4	11.10	2.04
66	Mohave fine gravelly loam	7.37	5.56	4.73	7.57	6.15	1.5	5.99	3.54
67	Cinders	7.34	22.96	29.75	36.47	33.11	6.8	26.67	24.30

[a] Each ounce per square foot corresponds to an average penetration of 0.0017 inch.
[b] Loss of weight of individual specimens differed from the average by more than 50 percent.
[c] Data for only 1 specimen.

TABLE 4.—*Depths of maximum pits on cast-iron pipe exposed for 7 years*

[In mils]

Soil		Horizontally cast in sand mold					Special process					Low-alloy,	High-alloy,
				F+G					I+J				
No.	Type	*F*	*G*	Average	Standard deviation	Standard error	*I*	*J*	Average	Standard deviation	Standard error	*C*	*E*
51	Acadia clay	[a]250+	250+	250+			304+	[b]260	282+	40	23	250+	[b]35
53	Cecil clay loam	102	71	86	26	15	50	60	55	13	7	88	51
55	Hagerstown loam	126	126	126	10	6	90	97	94	9	5	95	41
56	Lake Charles clay	250+	250+	250+			191	184	188	19	11	150	53
58	Muck	200+	250+	225+			192	179	186	26	15	176	[c]58
59	Carlisle muck	46	52	49	16	9	44	57	50	8	5	[c]20	28
60	Rifle peat	[b]35	[b]26	30	7	4	80	[b]25	52	31	18	[b]18	[bc]22
61	Sharkey clay	56	76	66	13	7	90	78	84	11	6	53	[b]30
62	Susquehanna clay	106	118	112	14	8	94	84	89	12	7	83	[b]37
63	Tidal marsh	52	[b]61	56	8	5	[c]90	[b]72	81	36	21	[d]132	55
64	Docas clay	150	[b]122	136	15	9	[e]146	[e]156	151	21	12	[b]143	40
65	Chino silt loam	86	112	99	31	18	110	118	114	10	6	128	42
66	Mohave fine gravelly loam	122	181+	152	57	33	149	200	174	69	40	161	38
67	Cinders	250+	[b]210+	230+	35	20	[e]240	276+	258	55	32	250+	[b]208+

[a] The plus sign in all cases indicates that 1 or both specimens were punctured.
[b] Average pit depths of the 1937 removal are greater.
[c] Individual specimens differed from the average by more than 50 percent.
[d] Data for only 1 specimen.
[e] Uniform corrosion—no reference surface.

the data for specimens of materials of the same general class, which corrode alike, as for example, the specimens designated by *I* and *J* in table 3 have been combined, and the average and the standard errors have been calculated. This provides a rough measure of the range of variation of the mean values which might be due to chance.[4]

None of the alloy cast irons except the high-alloy, *E*, showed definite superiority over ordinary cast iron in the various soils with respect to loss of weight or with respect to maximum penetration. However, in attempting to evaluate the behavior of different materials and the influence of various alloying elements on corrosion, it is important to determine whether the observed effects also apply to previous periods of inspection. The consistency of the data for the three periods of inspection was studied by first reducing the corrosion losses and pit depths for the cast-iron specimens to a scale of relative values, taking the loss of weight or depth of pit of material *G* in each soil as 100. Values for the other materials in each soil were then calculated on this basis and the relative values averaged for each material.

These data indicate that at the times of this and the two previous inspections the only material which was definitely superior to the ordinary cast iron, *G*, both with respect to loss in weight and depth of pits, was the high-alloy cast iron, *E*.

In table 4 several pit depths are not so great as those found on corresponding specimens removed 2 years previously. This effect is probably ascribable to differences in soil conditions in the trench, although great care was exercised in the selection of the test sites. That differences in soil conditions are sometimes confined to small sections of the trench is indicated by the fact that although the average of the maximum pits for the *J* specimens removed from soils 60 and 63 in 1939 was less than the average value for the same kind of specimens removed in 1937, the *I* specimens removed in 1939, which were only 6 inches from the *J* specimens, developed deeper pits than the *I* specimens removed in 1937. Soils 60 and 63 are composed largely of several varieties of vegetation in various stages of decay. The occasionally poor reproducibility of the data is mentioned in order to call attention to the variability in local soil conditions to which pipe in service may be exposed and to show that comparisons based on the behavior of single specimens may be misleading.

(b) WROUGHT IRON, CARBON STEEL, AND ALLOY IRONS AND STEELS

The compositions and dimensions of the specimens of wrought iron, low-carbon steel, and alloy irons and steels buried in 1932 and in 1937 are given in table 5.

In tables 6 and 7 are shown the losses in weight and depths of the deepest pits on pipe specimens of mechanically puddled and hand-puddled wrought iron, low-carbon steel, and alloy open-hearth iron, and several alloy steels, all exposed for 7 years. For the purpose of comparison,

[4] The standard deviation has been computed by means of the equation

$$\sigma=\sqrt{\frac{\Sigma X^2}{N}-\left(\frac{\Sigma X}{N}\right)^2},$$

where X is the loss of weight or the pit depth, and N is the number of specimens. If the standard deviation is divided by $\sqrt{N-1}$, the standard error of the average is obtained. The standard deviation is a measure of the dispersion of the data. When the data are sufficiently numerous and distributed normally with respect to their mean, the probability of an observation differing from the mean by more than twice the standard deviation is about 0.0455. The standard error of the mean is similarly interpreted with respect to the mean which would be obtained through an indefinite number of observations. Unfortunately the data under consideration are few in number and are not distributed normally. On this account, the probability of a deviation larger than 2σ is greater than that indicated above, and the precision of the average is less.

TABLE 5.—*Composition of wrought ferrous materials*

Material	Identification	Year buried	Form	Nominal width or diameter	Length	Thickness	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	Other elements
WROUGHT IRON																
				in.	*in.*	*in.*	%	%	%	%	%	%	%	%	%	%
Hand-puddled	*A*	1932	Pipe	1.5	12	0.145	0.016	0.10	0.029	0.018	0.160					Oxide+ slag, 2.56.
Roe process	*B*	1932	do	1.5	12	.145	.017	.125	.041	.018	.106					Oxide + slag, 2.681
CARBON STEELS																
Low-carbon steel	*N*	1932	Pipe	2.4	10	0.145	0.15		0.49	0.030	0.013					
LOW-ALLOY IRONS AND STEELS																
Special open-hearth steel	*A*	1937	Plate	2.5	12	0.250	0.033	0.002	0.029	0.017	0.006	0.049	0.034	0.052		
Copper-molybdenum–open-hearth iron.	*O*	1937	do	2.5	12	.25	.03	.003	.16	.032	.007	.02	.15	.45	0.07	
Do	*N*	1937	do	2.5	12	.25	.06	.001	.098	.029	.069	.02	.14	.54	.13	
Do	*H*	1932	Pipe	1.5	12	.145	.04	.05	.32	.027	.016			.52	.15	
Copper-nickel steel	*J*	1937	Plate	2.5	12	.25	.06	.047	.49	.025	.095		.52	.95		
Do	*B*	1937	do	2.5	12	.25	.07	.14	.44	.022	.010		1.96	1.01		
Do	*D*	1932	Pipe	1.5	12	.145	.14	.19	.21				2.47	1.08		
Chromium-silicon-copper-phosphoros steel.	*C*	1937	Plate	2.5	12	.25	.075	.84	.20	.018	.124	1.02	0.022	0.428		
2% chromium steel with molybdenum.	*KK*	1937	do	2.5	12	.25	.082	.51	.46	.015	.017	2.01	.07	.004	.57	
CHROMIUM STEELS																
4 to 6% chromium steel	*P*	1932	Pipe	2.3	10	0.154	0.13		0.46	0.025	0.012	5.05				
Do	*D*	1937	Plate	2.5	12	.25	.077	0.43	.37	.005	.015	5.02	0.09	0.008		
4 to 6% chromium steel with molybdenum.	*E*	1937	do	2.5	12	.25	.074	.41	.32	.006	.013	4.67	.09	.004	0.51	(Al, 0.030; Ti, 0.022.
Do	*H*	1937	do	2.5	12	.25	.060	.39	.40	.014	.021	5.76	.17	.004	.43	Al, 0.27.
12% chromium steel	*U*	1932	do	4	6	.063	.065	.28	.38	.017	.011	11.95	.482	.025		
18% chromium steel	*V*	1932	do	4	6	.063	.070	.34	.36	.015	.014	17.08	.092	.021		
Do	*X*	1932	Pipe	1.5	12	.145	.12	.277	.42	.017	.016	17.72	.287			
HIGH-CHROMIUM NICKEL AND MANGANESE STEELS																
18% chromium steel with nickel	*K*	1932	Plate	3	11	0.025	0.08	0.33	0.44	0.022	0.015	17.20	8.95			
Do	*R*	1932	Pipe	1.5	12	.145	.05	.28	.46	.011	.015	17.52	8.85			
Do	*W*	1932	Plate	4	6	.063	.093	.42	.36	.017	.008	18.69	9.18	0.016		
18% chromium steel with nickel and manganese.	*T*	1932	do	6	10	.063	.06	.40	6.09			17.76	3.83	.95		
Do	*S*	1932	do	6	10	.063	.07	.48	9.44			17.78		.74		
22% chromium steel with nickel and manganese.	*Y*	1932	do	4	6	.063	.144	.59	1.80	.011	.015	22.68	12.94	.021		

TABLE 6.—*Loss of weight of specimens of wrought iron, low-carbon steel, and alloy irons and steels exposed for 7 years*

[In ounces per square foot [a]]

Soil		Wrought iron				Cu-Mo open-hearth iron	Low-carbon steel	Alloy steel			
No.	Type	Hand-puddled	Mechanically puddled	A+B Average	A+B Standard error			2.5% Ni 1.1% Cr	5% Cr	18% Cr	18% Cr 8% Ni
		A	B			H	N	D	P	X	R
51	Acadia clay	15.09	15.28	15.18	0.1	11.61	11.50	9.58	10.73	------	------
53	Cecil clay loam	3.31	3.38	3.34	.2	3.87	4.18	2.59	2.37	------	------
55	Hagerstown loam	3.48	3.36	3.42	.2	3.38	3.21	2.15	1.65	------	------
56	Lake Charles clay	17.16	14.70	15.93	1.7	13.04	20.97	9.74	17.98	------	------
58	Muck	11.94	11.62	11.78	.3	12.24	14.08	9.73	11.73	([b])	0.0014
59	Carlisle muck	2.05	1.83	1.94	.2	2.60	3.00	2.91	2.28	------	------
60	Rifle peat	5.13	5.38	5.26	.1	4.50	7.63	3.79	[c] 2.90	------	------
61	Sharkey clay	6.26	6.43	6.34	.3	4.87	5.65	3.80	5.04	------	------
62	Susquehanna clay	5.97	5.97	5.97	.3	5.05	5.32	3.66	3.46	0.0040	.00060
63	Tidal marsh	3.41	3.48	3.44	.2	4.82	7.07	4.14	4.16	([b])	([b])
64	Docas clay	34.40	35.37	34.88	1.6	34.64	35.58	37.65	29.59	([b])	.016
65	Chino silt loam	9.05	8.83	8.94	.6	14.72	13.73	6.09	13.39	------	------
66	Mohave fine gravelly loam	11.57	11.14	11.36	1.1	14.31	14.34	9.23	13.00	------	------
67	Cinders	29.72	26.97	28.34	2.2	13.75	23.54	27.48	7.54	[d] .027	.0

[a] Each ounce per square foot corresponds to an average penetration of 0.0015 inch.
[b] Data not used because of abnormal corrosion due to the presence of asphalt at the ends of the pipe.
[c] Loss of weight of individual specimens differed from the average by more than 50 percent.
[d] Data on 1 specimen only.

TABLE 7.—*Depths of maximum pits on specimens of wrought iron, low-carbon steel, and alloy irons and steels exposed for 7 years*

[In mils]

Soil		Wrought iron				Cu-Mo open-hearth iron	Low-carbon steel	Alloy steel			
No.	Type	Hand-puddled	Mechanically puddled	A+B Average	A+B Standard error			2.5% Ni 1.1% Cr	5% Cr	18% Cr	18% Cr 8% Ni
		A	B			H	N	D	P	X	R
51	Acadia clay	[a] 122+	145+	134+	11	97	135+	70	106	------	------
53	Cecil clay loam	77	76	76	2	92	54	44	57	------	------
55	Hagerstown loam	[e] 70	[e] 60	65	5	[e] 68	57	51	88	------	------
56	Lake Charles clay	90	106+	98+	18	112+	125+	145+	154+	------	------
58	Muck	84	110	97	8	145+	110	110+	70	[b] 36	[c] *U*
59	Carlisle muck	[e] 18	[e] 15	16	2	[b] 10	30	14	[b] [e] 20	------	------
60	Rifle peat	[e] 30	[e] 34	32	3	[e] 16	[e] 17	[e] 14	[e] 62	------	------
61	Sharkey clay	44	50	47	3	65	63	51	38	------	------
62	Susquehanna clay	69	78	74	4	[e] 78	71	72	125+	*U*	*U*
63	Tidal marsh	64	39	52	7	103	70	41	89	([d])	21
64	Docas clay	144+	145+	144+	2	145+	154+	145+	154+	21	*U*
65	Chino silt loam	110+	106	108+	15	117	83	68	138+	------	------
66	Mohave fine gravelly loam	110	140+	125+	11	145+	154+	141+	154+	------	------
67	Cinders	145+	145+	145+	------	[c] 80	127+	145+	65	*U*	*U*

[a] The plus marks indicate that 1 or more specimens were punctured.
[b] Pit depths on individual specimens differed from the average by more than 50 percent.
[c] *U*, unaffected by corrosion.
[d] Data can not be used because of corrosion due to asphalt on the specimen.
[e] Corresponding 1937 pit depths were greater.

the low-carbon steel, *N*, will be considered the reference material. In all but two of the soils the sum of the losses of weight of the two specimens of either low-alloy steel, *D* or *P*, is less than the sum of the losses of weight of the two specimens of low-carbon steel, *N*, but in several cases one of the low-carbon steel specimens lost less weight than one of the low-alloy steel specimens. The losses for the stainless steels, *X* and *R*, were negligible. With respect to pitting, however, the differences in the behavior of the alloy steels containing less than 18 percent of chromium are not so marked. In fact, the addition of 5 percent of chromium to steel apparently did not reduce the depths of the deepest pits. The pits of the stainless steels are very shallow even in extremely corrosive soils.

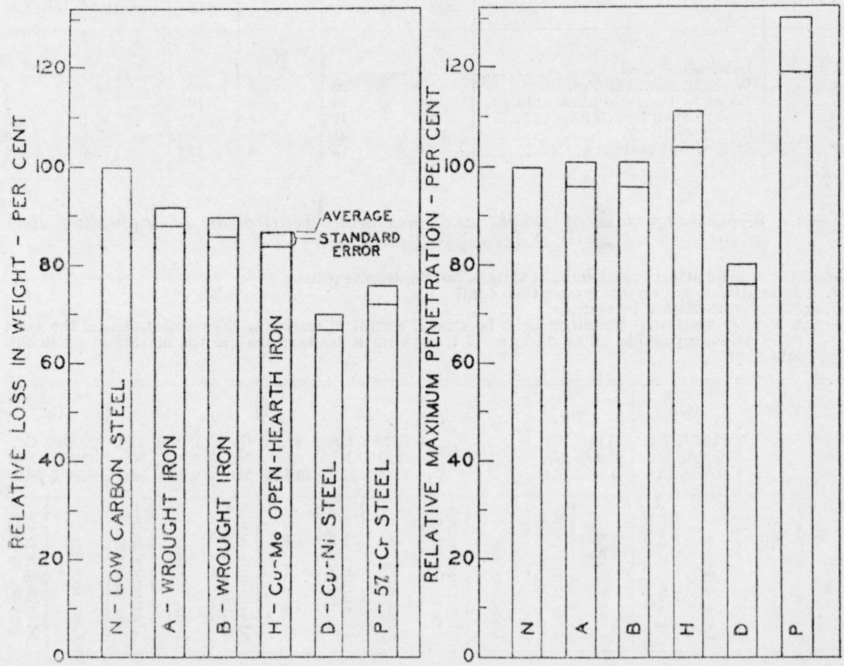

FIGURE 1.—*Relative loss of weight and penetration of wrought ferrous materials.*

Low-carbon steel = 100 percent.

The differences in the corrosion of the other materials, namely, wrought iron and copper-molybdenum open-hearth iron, with respect to low-carbon steel are probably not significant for the group of soils considered as a whole.

In table 8 the corrosion data for the wrought specimens are shown relatively on the basis of the three periods of exposure (2, 5, and 7 years), low-carbon steel being taken as the reference material. In comparisons of the materials, the standard errors of the averages should be kept in mind. The standard deviations indicate that the material which showed the lowest average loss of weight or pit depth for the 15 soils of the test might not be the most suitable material for some one of the soils. Insofar as practicable, a material should be selected on the basis of its suitability for the condition to which it is to be exposed rather than on account of its average performance. The data are shown graphically in figure 1. It is of interest to note that although steel with 5 percent of chromium, material *P*, is superior to ordinary steel with respect to loss of weight, the alloy steel is inferior with respect to pitting.

TABLE 8.—*Loss of weight and maximum penetration of wrought ferrous specimens on a relative basis*

[Average of three periods of exposure]

Material		Loss of weight			Maximum penetration		
Symbol	Type	Average	Standard deviation	Standard error	Average	Standard deviation	Standard error
		%	%	%	%	%	%
N	Low-carbon steel	100	------	------	100	------	------
A	Wrought iron, hand-puddled	92	26	4	101	34	5
B	Wrought iron, machine puddled	90	24	4	101	31	5
H	Cu-Mo open-hearth iron	87	19	3	111	46	7
D	Cu-Ni steel	70	21	3	80	27	4
P	Steel with 5 percent of Cr	76	23	4	130	72	11

TABLE 9.—*Average loss of weight and maximum penetration of high-alloy steel sheets exposed for 7 years*

M, shallow metal attack, roughening of surface, but no definite pitting.
P, definite pitting, but no pits greater than 6 mils.
U, apparently unaffected by corrosion.
+, one or more specimens contained holes because of corrosion, rendering the computation of the exact penetration impossible. The thickness of the specimen has been used as the maximum pit in this case.

Soil No.	(5) [a] 11.95% Cr, 0.48% Ni, 0.38% Mn		(5) 17.08% Cr, 0.09% Ni, 0.36% Mn		(2) 17.72% Cr, 9.44% Mn		(1) 17.76% Cr, 3.83% Ni, 6.09% Mn		(2) 17.2% Cr, 8.95% Ni, 0.44% Mn		(5) 18.69% Cr, 9.18% Ni, 0.36% Mn		(5) 22.68% Cr, 12.94% Ni, 1.80% Mn	
	Loss, average	Maximum, penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average
	U		*V*		*S*		*T*		*K* [c]		*W*		*Y*	
	oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
51	------	------	------	------	------	------	------	------	0.0047	10	------	------	------	------
53	------	------	------	------	------	------	------	------	.0015	P	------	------	------	------
55	0.00059	*U*	0.0023	*M*	------	------	------	------	------	------	0.00086	*U*	0.0014	*U*
56	------	------	------	------	------	------	------	------	.038	25+	------	------	------	------
58	------	------	------	------	------	------	------	------	.0014	*U*	------	------	------	------
59	.00078	*U*	.0016	*M*	------	------	------	------	.00091	*U*	.0011	*U*	.0015	*M*
60	[b] 4.0	[b] 48+	[b] .33	[b] 8	------	------	------	------	.0015	*U*	.0021	*P*	[b] .16	[b] 4
61	------	------	------	------	------	------	------	------	.0011	*U*	------	------	------	------
62	------	------	------	------	------	------	------	------	.00068	*U*	------	------	------	------
63	------	------	------	------	------	------	------	------	.0023	*P*	------	------	------	------
64	1.7	63+	.44	63+	0.34	63+	0.64	63+	.0026	[b] 8	.0025	*M*	.0055	*P*
65	0.33	62+	[b] .38	59+	------	------	------	------	[b] .019	[b] 12+	.0017	*P*	.0036	*P*
66	.73	63+	[b] .41	[b] 44+	------	------	------	------	[b] .13	[b] 12+	.0016	*M*	.0041	*P*
67	------	------	------	------	[b] .55	[b] 32+	.0021	*M*	.0014	*P*	------	------	------	------

[a] The number in parentheses indicates the number of specimens removed from each test site.
[b] Loss or maximum pit for 1 or more specimens was greater than the average by more than 50 percent.
[c] Polished surface.

(c) HIGH-ALLOY STEEL SHEET

In 1932, specimens of high-chromium steels, including steels with nickel and manganese, were buried at certain of the test sites. The environments chosen were chiefly those in which stainless steels would be most susceptible to corrosive attack, namely, those having reducing conditions such as would be found in organic soils and in poorly aerated alkali soils high in chlorides and sulfates. The data shown in table 9 indicate that stainless steels must contain at least 8 percent of nickel to withstand corrosion under such conditions. In soils free of soluble salts, 55 and 59, all the steels containing 12 or more percent of chromium remain practically uncorroded. The marked localization of attack on many of the specimens is brought out by comparison of the loss in weight with the maximum penetration.

2. ALLOY IRONS AND STEELS EXPOSED FOR 2 YEARS

In tables 10 and 11 are shown data on loss of weight and maximum penetration for a variety of the alloy irons and steels exposed to corrosion for 2 years. The losses in weight of the various materials show no consistent differences except for the specimens containing 4 to 6 percent of chromium, for which the losses in weight are generally less. The values for maximum penetration, however, do not indicate a definite trend for any of the materials, the steel containing 18 percent of chromium being excluded from consideration. The failure of the copper-nickel steel, *B*, to show somewhat superior corrosion resistance, as would have been predicted from the behavior of specimens of approx-

TABLE 10.—*Loss of weight of alloy irons and steels exposed for 2 years*

[In ounces per square foot]

Soil		Exposure	Open-hearth steel	Open-hearth iron		Low-alloy				4 to 6% chromium steel			High-alloy steel
No.	Type			0.45% Cu .07% Mo	0.54% Cu .13% Mo	0.95% Cu .52% Ni	1.01% Cu 1.96% Ni	Cr-Si-Cu-P-steel 1.02% Cr	2.01% Cr 0.57% Mo	5.02% Cr	4.67% Cr 0.51% Mo .030% Al .022% Ti	5.76% Cr 0.43% Mo .027% Al	18% Cr
			A	*O*	*N*	*J*	*B*	*C*	*KK*	*D*	*E*	H_1	H_2
		Years											
51	Acadia clay	2.08	11.6	7.5	7.2	7.0	7.4	9.2	7.9	6.6	7.1	[a]8.3	[a]2.8
53	Cecil clay loam	2.10	1.8	2.1	2.0	0.81	0.65	1.5	1.6	0.87	0.91	[a]0.78	[a]0.045
55	Hagerstown loam	1.88	2.0	2.0	1.9	1.2	.75	1.3	1.6	.70	.62	.69	------
56	Lake Charles clay	2.08	14.4	12.4	13.0	14.0	13.0	12.5	9.0	9.4	9.6	[a]11.4	[a]4.0
58	Muck	2.09	5.7	5.8	5.5	5.2	6.2	4.4	3.3	4.1	3.9	3.5	------
60	Rifle peat	2.07	6.3	4.1	4.8	5.3	6.4	5.8	3.8	4.5	4.1	4.6	------
61	Sharkey clay	2.08	2.6	3.0	2.7	2.3	2.0	2.4	2.4	0.65	0.86	0.75	------
62	Susquehanna clay	2.10	2.8	3.0	3.0	2.4	2.1	1.9	2.4	.69	.69	.71	------
63	Tidal marsh	2.12	3.6	[a]2.5	3.0	2.5	2.3	2.4	1.8	1.8	1.7	[a]1.7	[a]1.6
64	Docas clay	2.08	7.1	8.0	8.0	9.0	6.6	4.9	4.9	4.5	4.2	5.9	------
65	Chino silt loam	2.08	4.6	5.0	4.6	3.4	4.9	4.4	4.2	2.3	2.5	2.5	------
66	Mohave fine gravelly loam	2.08	8.3	9.1	7.4	7.3	8.9	6.9	7.2	5.8	7.9	8.4	------
67	Cinders	2.08	12.0	33.8	20.9	20.3	23.0	17.7	18.1	17.1	12.2	12.6	------
69	Houghton muck	2.08	1.5	1.3	1.4	1.6	1.4	1.1	1.2	0.36	0.41	0.24	------
70	Merced silt loam	2.08	5.0	5.4	4.8	4.2	3.9	5.4	5.4	4.9	5.2	5.0	------

[a] Loss of weight of 1 specimen.

imately the same composition (*D*) in the 7-year test, may be attributed to the fact that the mill scale had been removed from the older specimens, whereas the 2-year-old specimens were covered with an unusually uniform and adherent oxide coating. Failure of this coating locally might be expected to result in accelerated pitting because of the difference of potential between the oxide and the metal beneath it. Tests [5] of materials with and without mill scale have indicated that the effect of the mill scale is temporary.

TABLE 11.—*Maximum penetration of alloy irons and steels exposed for 2 years*

[In mils]

Soil		Open-hearth iron	Low-alloy steel						4 to 6% chromium steel			High-alloy steel
No.	Type	Open-hearth steel	0.45% Cu .07% Mo	0.54% Cu .13% Mo	0.95% Cu .52% Ni	1.01% Cu 1.96% Ni	Cr-Si-Cu-P-steel 1.01% Cr	2.01% Cr 0.57% Mo	5.02% Cr	4.67% Cr 0.51% Mo .030% Al .022% Ti	5.76% Cr 0.43% Mo .027% Al	18%Cr
		A	*O*	*N*	*J*	*B*	*C*	*KK*	*D*	*E*	H_1	H_2
51	Acadia clay	54	54	66	63	54	58	35	62	50	[a]64	[a]70
53	Cecil clay loam	40	38	38	38	26	40	40	43	36	[a]32	[a]11
55	Hagerstown loam	42	31	29	34	34	40	26	34	34	30	------
56	Lake Charles clay	80	100	77	82	100	52	38	66	62	[a]60	[a]57
58	Muck	36	30	32	26	36	71	29	48	39	48	------
60	Rifle peat	30	21	20	25	20	23	19	32	26	26	------
61	Sharkey clay	34	33	32	53	62	30	31	30	26	24	------
62	Susquehanna clay	34	36	36	38	51	36	26	32	26	32	------
63	Tidal marsh	18	[a]20	33	14	22	31	20	62	46	[a]42	[ab]*P*
64	Docas clay	44	70	72	60	66	42	56	48	46	46	------
65	Chino silt loam	47	44	32	49	45	50	56	37	39	50	------
66	Mohave fine gravelly loam.	86	105	132	108	38	56	78	59	81	72	------
67	Cinders	[c]46	[c]70	[c]50	[c]58	[c]64	[c]58	[c]53	[c]46	[c]56	[c]41	------
69	Houghton muck	6	5	6	6	6	14	22	18	20	18	------
70	Merced silt loam	56	48	51	48	50	66	102	87	79	88	------

[a] Deepest pit on only 1 specimen.
[b] *P*, no pits greater than 6 mils.
Uniform corrosion—impossible to measure true penetration.

IV. COPPER AND COPPER ALLOYS

In table 12 are shown the compositions of the specimens of copper and copper alloys buried in 1926 and in 1932.

1. SPECIMENS EXPOSED FOR 13 YEARS

Six specimens of two varieties of copper and of four copper alloys were buried at 47 test sites in 1926. The last two specimens of each of these materials were removed from the more corrosive soils in 1934, but in the less corrosive soils the last specimens were allowed to remain until 1939. In tables 13 and 14 are included the losses in weight and the condition of the surfaces of this latter group of specimens. As the properties of the soils, the location of the test sites, as well as the condition of the specimens at the time of the previous inspections

[5] K. H. Logan, *Soil Corrosion Studies, 1934*. J. Research NBS **16**, 432 (1936) RP883.

TABLE 12.—*Composition of copper and copper alloys*

Material	Identification	Year buried	Form	Width or diam.	Length	Wall thickness	Cu	Zn	Sn	Pb	Ni	Fe	Si	Mn	P	Al
				in.	*in.*	*in.*	%	%	%	%	%	%	%	%	%	%
Copper:																
Tough pitch copper	*C*	1932	Pipe	1.7	12	0.145	99.97									
Deoxidized copper	*A*	1932	do	1.7	13	.144	99.94								0.018	
Do	*P*	1926	do	0.9	12	.06	99.94								.015	
Copper	*M*	1926	do	.9	12	.06	99.93									
Copper with soldered fittings	*M*	1932	do	1.5	12	.062										
Brass:																
Red brass	*F*	1932	do	1.7	12	.143	85.18	14.80				0.01				
Admiralty metal	*H*	1932	do	1.7	12	.143	71.28	27.39	1.30	0.01		.02				
Two and one leaded brass	*K*	1932	do	1.7	12	.08	67.08	31.07		.84		(a)	1.01			
Brass	*J*	1932	do	1.7	13	.145	66.50	33.06		.42		0.02				
Muntz metal	*L*	1932	do	1.7	12	.08	60.06	39.58		.36		(a)				
Do	*B*	1926	do	0.8	12	.103	60	40								
Do	*Me*	1926	Ell	.7	2	.16	59.00	38.50		2.50						
Bronze:																
Bronze	*E*	1932	Pipe	1.7	12	.141	97.15		1.80			0.01	1.04			
Aluminum bronze	*N*	1926	Rod	0.4	12		87.00					3.50				9.50
Copper-silicon alloy:																
Copper-silicon alloy	*N*	1932	Pipe	1.7	12	.145	98.11		0.14		0.01	0.11	1.49	0.18		
Do	*D*	1932	do	1.7	12	.143	95.46				.08	.21	3.19	1.06		
Copper-nickel alloy	*G*	1932	do	1.7	12	.145	74.45	4.99			20.04			0.52		
Copper-zinc-nickel alloy	*A*	1926	Rod	0.4	12		47.00	40.50		2.50	10.00					

[a] Trace.

have been previously given,[6] they will not be included in this report. If allowance is made for the effects of accidental variations in the materials and in soil conditions, it may be concluded that the two varieties of copper, specimens *M* and *P*, behave alike. At all of the

TABLE 13.—*Loss of weight of specimens of copper and copper alloys*

[In ounces per square foot]

Soil		Exposure	Copper		Brass		Copper-zinc-nickel alloy. 47 Cu 40 Zn 10 Ni	Aluminum bronze. 87 Cu 9.5 Al 3.5 Fe
No.	Type		*M*	Deoxidized	60 Cu 40 Zn	59 Cu 38 Zn 2.5 Pb		
				P	*B*	*Me*	*A*	*N*
		Years						
2	Bell clay	13.54	0.31	0.22	0.88	1.21	1.36	0.26
5	Dublin clay adobe	13.36	.40	[a].43	.78	4.24	1.58	.60
6	Everett gravelly sandy loam	13.33	.14	.12	.23	0.33	[a]0.74	[a].031
7	Maddox silt loam	13.44	[a].48	[a].34	[a]2.53	--------	[a]2.08	[a].43
9	Genessee silt loam	13.44	.41	.48	2.34	1.24	2.22	.15
10	Gloucester sandy loam	13.18	[a]1.01	[a]1.24	[a]3.10	--------	2.73	.49
24	Merrimac gravelly sandy loam	13.18	0.25	0.24	0.34	--------	0.40	.23
26	Miami silt loam	13.44	.18	.16	.97	0.78	1.58	.46
27	Miller clay	13.58	.16	.16	.62	1.08	0.85	.31
30	Muscatine silt loam	13.39	[b].10	[b].13	[b].19	[b]0.64	[b].43	[b].094
31	Norfolk sand	13.66	[a].11	[a].12	[a].26	[a].36	.30	.36
36	Ruston sandy loam	13.61	.26	.26	.67	.53	1.18	.20
41	Summit silt loam	13.38	.36	.40	1.12	.83	1.69	.47
47	Unidentified silt loam	13.36	.42	.47	0.50	4.02	1.36	.75
54	Fairmount silt loam	7.33	.11	.048	.20	--------	0.46	.054

[a] Data for only 1 specimen. [b] Average of 4 specimens.

TABLE 14.—*Condition of copper and copper alloys*

[Figures are pit depths in mils]

The following letters indicate the condition of the worse of 2 specimens, except as otherwise noted:
M, shallow metal attack, roughening of surface but no definite pitting.
P, definite pitting, no pits greater than 6 mils.
S, uniform corrosion.
D, selective corrosion, such as dezincification over large areas.
d, selective corrosion over small areas.

Soil		Exposure	Copper	Copper (deoxidized)	Brass	Copper-zinc-nickel alloy	Aluminum bronze
No.	Type		*M*	*P*	*B*	*A*	*N*
		Years					
2	Bell clay	13.54	*P*	*P*	*PDS*	*PD*	*M*
5	Dublin clay adobe	13.36	8	[a] *P*	*PD*	7*D*	*P*
6	Everett gravelly sandy loam	13.33	*P*	*P*	*Pd*	[a] *PD*	[a] *P*
7	Maddox silt loam	13.44	[a] *P*	[a] *P*	[a] *PDS*	[a] 9	[a] *P*
9	Genessee silt loam	13.44	*PS*	*PS*	7*D*	12*D*	*P*
10	Gloucester sandy loam	13.18	[a] 11*S*	[a] 7*S*	[a] 8*DS*	11*D*	*P*
24	Merrimac gravelly sandy loam	13.18	*P*	*P*	*Pd*	*PD*	*P*
26	Miami silt loam	13.44	*P*	*P*	*PD*	*PD*	*P*
27	Miller clay	13.58	*P*	*P*	*PD*	*PD*	*P*
30	Muscatine silt loam	13.39	[b] *P*	[b] *P*	[b] *PD*	[b] *PD*	[b] *P*
31	Norfolk sand	13.66	[a] *P*	[a] *P*	[a] *Pd*	[a] *PD*	*M*
36	Ruston sandy loam	13.61	*P*	*P*	10*D*	10*D*	*P*
41	Summit silt loam	13.38	*P*	*P*	*PD*	7*D*	*P*
47	Unidentified silt loam	13.36	16	10	*PD*	*PD*	*P*
54	Fairmount silt loam	7.33	*P*	*M*	*Pd*	*PD*	*P*

[a] Only 1 specimen removed. [b] 4 specimens removed.

[6] Kirk H. Logan, *Soil-corrosion studies, 1934: Rates of loss of weight and penetration of nonferrous materials,* J. Research NBS **17**, 782 (1936) RP945.

test sites, with probably one exception, the corrosion rate of copper was low.

Low-copper alloys, specimens *B*, *Me*, and *A*, corroded at considerably higher rates than copper or the aluminum bronze, *N*. The presence of 2.5 percent of lead in specimen *Me*, which was in the form of a small forged ell, apparently had a somewhat detrimental effect on the corrosion of nominally 60:40 brass. This result is not consistent with the effect of lead in the brasses in the 1932 series discussed below, perhaps owing to the mechanical treatment of the ells.

2. SPECIMENS EXPOSED FOR 7 YEARS

Tables 15 and 16 show the losses in weight and maximum penetration of the two varieties of copper, a series of brasses ranging in zinc content from 15 to 40 percent, and of several of the other copper alloys. Corresponding values for the open-hearth steel are included for comparison. It will be noted that in several soils the deoxidized copper, *A*, lost considerably more weight and pitted more deeply than did the tough-pitch copper. The deoxidized specimens that showed high rates of corrosion had spiral lines of corrosion, which may indicate an effect of the straightening rolls. The apparent inferiority of the deoxidized copper in certain soils may therefore be accidental. Because of this possibility, the data for this material have been omitted from table 17.

The high degree of consistency shown by the loss-of-weight data for the tough-pitch copper, *C*, and the brass specimens is striking. If the data for the tidal marsh, soil 63, is excluded from consideration, a definite increase in loss in weight with increase in zinc content is to be observed. With a few exceptions to be mentioned, this continuity is interrupted only by the occasional superior performance of the red brass, *F*, over copper and the slight but definite superiority of the leaded brass, *K*, over the brass, *J*. The data for the tidal marsh are unique in that the corrosion rate decreases with increase in zinc content. This behavior, which is exactly opposite to that shown by the other soils, is to be explained by the resistance shown by low-copper alloys to hydrogen sulfide and other sulfur compounds.[7] The resistance to corrosion shown by the Admiralty metal, *H*, and the copper-nickel alloy, *G*, toward a soil containing sodium and potassium chlorides almost exclusively, soil 64, is to be expected from the known resistance of these materials to salt water. Soils containing chlorides are particularly corrosive to copper.

Since materials *K* and *J* contained approximately the same amounts of copper and zinc, the superiority shown by the leaded brass, *K*, would seem to be due to its slightly higher lead content, namely, 0.84 percent, as compared with 0.42 percent in material *J*. However, it should be recalled that material *Me*, which was inferior to material *B* (table 13), differed from the latter in that it contained 2.5 percent of lead. Also material *K* differed from material *J* in that material *K* contained 1 percent of silicon. The effect of the silicon cannot be determined from the data.

The materials listed in table 17 maintained approximately the same order of corrodibility for the three periods of exposure. Because of the degree of consistency shown, it might seem logical that the relative order indicated in the table could be accepted tentatively as the order

[7] Metals Handbook (Am. Soc. Metals, Cleveland, Ohio, 1939).

TABLE 15.—*Loss of weight of specimens of copper and copper alloys*

[In ounces per square foot]

Soil		Exposure	Tough-pitch copper	Deoxidized copper	Red brass	Admiralty metal	Two-and-one leaded brass	Brass, 66% Cu 33% Zn	Muntz metal	Bronze, 97% Cu 1% Si 1.8% Sn	Alloy				Open-hearth steel
No.	Type										98% Cu 1.5% Si	95% Cu 1.5% Si	95% Cu 3% Si	75% Cu 20% Ni 5% Zn	
			C	*A*	*F*	*H*	*K*	*J*	*L*	*E*	*N*	*N*[d]	*D*	*G*	*N*
		Years													
51	Acadia clay	7.53	0.35	0.40	0.45	0.57	0.50	0.79	1.04	0.97	0.48	-------	0.41	0.44	11.50
53	Cecil clay loam	7.56	.23	.20	.25	.29	.48	.42	0.61	.38	.33	[b] 0.25	.39	.29	4.18
55	Hagerstown loam	7.08	.17	.15	.16	.23	.27	.37	.66	.24	.23	-------	.28	.15	3.21
56	Lake Charles clay	7.52	.60	.80	.64	.46	.48	.74	.71	.60	.40	-------	.52	.56	20.97
58	Muck	7.60	1.66	1.72	1.43	1.87	1.59	2.20	4.61	1.67	1.70	[b] 1.56	1.75	1.22	14.08
59	Carlisle muck	7.22	[a] 0.089	[a] 0.11	[a] 0.12	[b] 0.10	[a] 0.10	0.0097	0.02	[a] 0.23	[a] 0.14	-------	[a] 0.18	[a] 0.081	3.00
60	Rifle peat	7.33	1.03	1.10	.80	1.16	.84	1.52	1.43	1.03	1.06	-------	.72	.92	7.63
61	Sharkey clay	7.59	0.37	0.38	.49	0.77	.61	1.35	2.97	0.65	0.38	-------	.61	.69	5.65
62	Susquehanna clay	7.57	.33	.38	.39	.43	.55	0.51	1.08	.52	.42	-------	.50	.44	5.32
63	Tidal marsh	7.67	4.34	4.24	1.10	.18	.34	.071	0.093	3.53	4.58	-------	4.86	2.84	7.07
64	Docas clay	7.30	1.56	3.00	0.52	.40	.80	2.11	9.79	1.44	1.74	-------	1.43	0.27	35.58
65	Chino silt loam	7.34	0.55	[a] 2.37	.58	.87	1.03	3.10	3.38	1.17	2.42	[a] 2.74	[a] 1.28	.43	13.73
66	Mohave fine gravelly loam	7.37	.32	[a] 1.32	.48	.44	[a] 1.24	0.88	1.50	1.22	0.54	-------	0.40	.38	14.35
67	Cinders	7.34	1.42	4.89	2.37	2.96	[c] *z*	*z*	*z*	1.47	1.99	-------	2.69	1.25	23.55

[a] Individual specimens differed from the average by more than 50 percent.
[b] Data for only specimen.
[c] *z*, destroyed by corrosion-dezincification.
[d] Contains brazed joint.

TABLE 16.—*Depths of maximum pits on specimens of copper and copper alloys.*

P, definite pitting—no pits on both specimens greater than 6 mils.
d, selective corrosion over small areas.
D, selective corrosion over large areas (several square inches per square foot).
s, uniform corrosion—impossible to measure true penetration.
z, specimens destroyed by corrosion (dezincification).

Soil No.	Tough-pitch copper	Deoxidized copper	Copper with soldered joints	Red brass	Admiralty metal	Two-and-one leaded brass	Brass, 66% Cu 33% Zn	Muntz metal	Bronze, 97% Cu 1% Si 1.8% Sn	Alloy				Open-hearth steel
										95 %Cu 1.5% Si	95% Cu 1.5% Si	95% Cu 3% Si	75% Cu 20% Ni 5% Zn	
	C	*A*	*M*[a]	*F*	*H*	*K*	*J*	*L*	*E*	*N*	*N*[b]	*D*	*G*	*N*
51	*P*	*P*	*P*	*PD*	*8D*	*PD*	*9D*	*PD*	6	*P*	----------	*P*	*PD*	135+
53	11	10	9	12	21	*Pd*	*9D*	*6D*	14	*P*	9	*P*	*5d*	54
55	7	5	5	*11D*	*20d*	*6D*	*8D*	*6D*	15	6	----------	10	*PD*	57
56	8	*P*	*P*[c]	*PD*	*PD*	*6D*	*PD*	*PD*	12	*P*	----------	7	*5D*	125+
58	14	10	12	*PsD*	37	*12D*	*13D*	*8D*	33	9	16	12	*8sD*	110
59	*P*	*P*	*P*	8	[d]8	6	*P*	*P*	6	*P*	----------	*P*	*P*	30
60	9	8	*P*	*6sD*	*14D*	*5D*	*14D*	*8D*	12	*P*	----------	*P*	*11D*	17
61	16	8	12	*20D*	36	*PD*	*9D*	*20d*	35	11	----------	5	*21D*	63
62	6	14	12	*12d*	*26d*	*12D*	*14D*	*6D*	*P*	6	----------	12	*12d*	71
63	*7s*	*8s*	*Ps*	*10s*	*P*	*P*	*P*	*P*	14	*6s*	----------	*13s*	*P*	70
64	*14s*	*P*	10	*8D*	*5D*	10	*24D*	*6D*	12	12	----------	*12s*	13	154+
65	20	18	24	*12D*	*31D*	*6D*	*20D*	*12D*	33	20	24	14	*10D*	83
66	*P*	8	[d]26	*14D*	*56D*[e]	*7D*	*18D*	*6D*	15	14	----------	16	*PD*	154+
67	24	44	30	*32D*	*47d*	*z*	*z*	*z*	33	31	----------	28	*26d*	127+

[a] These specimens had streamlined caps and couplings soldered in place.
[b] These specimens had brazed joints—data for only 1 specimen.
[c] The only case in which the corrosion of the solder is worse than that on the copper. The solder between the joints crumbled when scratched with an instrument.
[d] Data for only 1 specimen.
[e] Individual pit depths differed from the average by more than 50 percent.

of merit of the materials for soil conditions generally. However, as loss in weight is only one criterion of behavior, consideration would also have to be given to the depth of pitting and the tendency of the material to dezincify.

The values for maximum penetration shown in table 16 call for no special comment other than to point out that for the materials subject to selective corrosion or dezincification, the data on maximum pits do not indicate the degree of deterioration of the specimens.

TABLE 17.—*Relative average loss of weight of copper and copper alloys*

Material: Symbol	Material: Type	Composition			Average	Standard deviation	Standard error
		Cu	Zn	Pb			
		%	%	%	%	%	%
C	Tough-pitch copper	99.97			100		
F	Red brass	85.2	14.8		105	32	5
H	Admiralty metal	71.3	27.4		122	53	9
K	Two-and-one leaded brass	67.1	31.1	0.8	173	188	31
J	Brass	66.5	33.1	.4	231	245	40
L	Muntz metal	60.1	39.6	.4	538	1,062	174
		Cu	Si	Sn			
E	Bronze	97.2	1.0	1.8	199	154	25
N	Copper-silicon alloy	98.1	1.0		158	85	14
D	do	95.5	3.2		147	68	11
		Cu	Zn	Ni			
G	Copper-nickel alloy	74.5	5.0	20.0	104	57	9

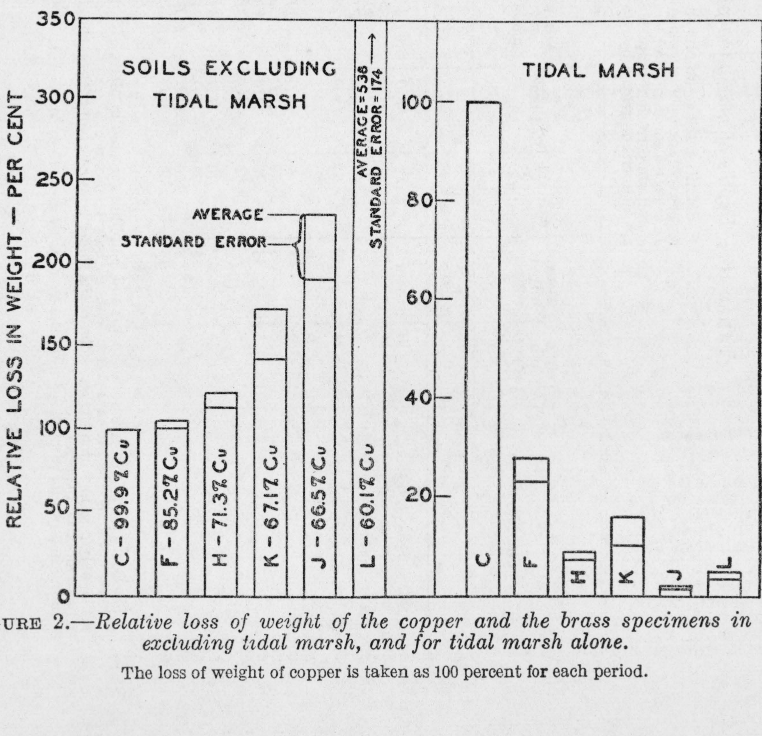

FIGURE 2.—*Relative loss of weight of the copper and the brass specimens in soils excluding tidal marsh, and for tidal marsh alone.*

The loss of weight of copper is taken as 100 percent for each period.

In table 17 are shown the average losses in weight calculated on a relative basis for the specimens of copper and copper alloys exposed for 2, 5, and 7 years. In calculating these averages, the data for soils 63 and 67 were omitted, the former because the loss of weight of the specimens followed a different trend from that shown by the other soils, the latter because of the complete destruction of the low-copper specimens.

In figure 2 the relative weight losses of the copper and brass specimens are shown graphically for the soils, excluding tidal marsh, and for tidal marsh alone, for the average of the three periods of exposure. The loss of weight of copper, material C, is taken as 100 for each period of exposure.

V. ZINC

The corrosion of zinc in soils is of importance in connection with the protection of iron and steel by zinc applied as a coating or used as an anode in a cathodic protection circuit. If there are soil conditions which are corrosive to ferrous metals but not to zinc, the latter metal could not be depended on for the protection of steel cathodically. The composition of the two varieties of zinc for which corrosion data are available is shown in table 18. In table 19, values are given for the corrosion losses and maximum penetration after exposure for 2 years.

TABLE 18.—*Composition of zinc plates*

Material	Identification	Length	Width or diameter	Thickness of plate	Al	Cu	Fe	Mg	Pb	Cd	Sn
		in.	*in.*	*in.*							
Rolled zinc	*Z*	12	2.3	0.15	------	------	0.009	------	0.095	0.0038	------
Die-casting zinc	*CZ*	6.81	4.44	.125	4.00	1.05	.018	0.02 to 0.05	<.003	<.003	<0.001

TABLE 19.—*Loss of weight and maximum penetration of zinc plates exposed for 2 years*

Soil		Rolled zinc		Die-cast zinc	
No.	Type	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		oz/ft²	*Mils*	*oz/ft²*	*Mils*
51	Acadia clay	1.97	30	2.61	33
53	Cecil clay loam	0.24	10	0.27	15
55	Hagerstown loam	.39	13	.40	21
56	Lake Charles clay	1.09	10	2.25	25
58	Muck	3.30	38	3.67	[a] 108+
60	Rifle peat	4.62	53	7.50	[b] 74
61	Sharkey clay	0.49	12	[c] 0.47	[c] 14
62	Susquehanna clay	.56	9	.43	[c] 12
63	Tidal marsh	1.15	26	.90	12
64	Docas clay	0.70	16	1.34	18
65	Chino silt loam	.54	30	1.24	22
66	Mohave fine gravelly loam	1.69	25	3.63	95
67	Cinders	[d] 4.59	[d] 64	10.6	[b] 57
69	Houghton muck	0.69	([e])	0.91	12
70	Merced silt loam	1.71	56	2.05	34

[a] The plus signs indicate that 1 specimen contained holes because of corrosion.
[b] Severe uniform corrosion. Impossible to measure the true penetration.
[c] Individual specimens differed from the average by more than 50 percent.
[d] Data on only 1 specimen. The other specimen has been almost entirely destroyed.
[e] No pits greater than 6 mils.

The effect of purity on the corrosion rate of zinc in soils is indicated by the data. In every case that can not be attributed to chance, the corrosion rate is lower for the rolled zinc. The rate of maximum penetration is also lower for the purer material.

The zinc specimens corroded under the same conditions which corrode iron and steel, namely, in soils high in soluble salts and in poorly aerated organic soils.

VI. LEAD

The composition of the leads used for the soil-corrosion tests is shown in table 20.

TABLE 20.—*Composition of the lead specimens*

Material	Identification	Year buried	Form	Width or diameter	Length	Thickness	Cu	Bi	Sb	Sn	Te
				in.	*in.*	*in.*	%	%	%	%	%
Chemical lead	*O*	1937	Pipe	1.5	12	0.177	0.056	0.002	0.0011	None	
Tellurium lead	*T*	1937	do	1.5	12	.177	.082	None	.0011	do	0.043
Antimonial lead	*A*	1922	Sheet	8.5	22	.12	.062	do	.82	do	
Do	*B*	1937	Pipe	1.5	12	.177	.036	.016	5.31	do	
Commercial lead	*H*	1922	Sheet	3.5	22	.11	.013	.037			

1. SPECIMENS EXPOSED FOR 16 TO 17 YEARS

The condition of the commercially pure lead and of the lead containing 0.82 percent of antimony after exposures of from 16 to 17 years in 12 of the original 47 test sites is shown in table 21. If there is any real difference in the behavior of these varieties of lead in this group of soils, it is probably too small to be important practically.

2. SPECIMENS EXPOSED FOR 2 YEARS

Data on the corrosion of three varieties of lead exposed to the more corrosive group of soils for 2 years are shown in table 22. The data for the antimonial lead indicate that the addition of 5 percent of

TABLE 21.—*Loss of weight and maximum penetration of lead cable sheath* [a]

H, hole due to corrosion from one side of the specimen.
P, definite pitting, but no pits greater than 6 mils.

Soil No.	Soil Type	Exposure	Antimony lead, *A*: Weight loss	Antimony lead, *A*: Maximum penetration	Commercially pure lead, *H*: Weight loss	Commercially pure lead, *H*: Maximum penetration
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
2	Bell clay	15.48	1.56	45	1.20	30
5	Dublin clay adobe	15.56	3.51	*H*	6.66	*H*
6	Everett gravelly sandy loam	15.53	0.37	22	0.26	28
7	Maddox silt loam	16.94	1.47	39	1.60	32
12	Hanford fine sandy loam	15.59	1.88	30	1.85	43
27	Miller clay	15.69	1.37	39	0.67	31
30	Muscatine silt loam	17.04	2.28	56	1.04	51
31	Norfolk sand	15.73	0.37	*P*	0.28	15
35	Ramona loam	15.59	.19	12	.31	37
36	Ruston sandy loam	15.69	.69	17	.48	22
41	Summit silt loam	17.41	.77	41	.50	27
47	Unidentified silt loam	17.43	1.12	32	.79	30

[a] Data on 1 specimen except for soil 7, for which the average of 2 specimens has been taken.

antimony, made for the purpose of improving the mechanical properties of the lead, has increased its resistance to corrosion. The improvement in the corrosion resistance of lead to sulfuric acid and some other chemicals produced by the addition of alloying elements has been previously reported by Hiers.[8] [9] There is no evident benefit from adding 0.04 percent of tellurium, at least for the initial period of exposure to soils.

TABLE 22.—*Loss of weight and maximum penetration of lead pipe exposed 2 years*

Soil No.	Soil Type	Chemical lead [a] Loss of weight	Chemical lead [a] Maximum penetration	Tellurium lead [b] Loss of weight	Tellurium lead [b] Maximum penetration	Antimonial lead [c] Loss of weight	Antimonial lead [c] Maximum penetration
		oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
51	Acadia clay	0.62	40	1.21	54	1.05	56
53	Cecil clay loam	.22	24	0.25	16	0.25	12
55	Hagerstown loam	.37	24	.34	32	.19	28
56	Lake Charles clay	.21	38	.38	68	.31	42
58	Muck	1.56	62	1.68	55	1.45	52
60	Rifle peat	0.18	21	0.15	33	0.10	10
61	Sharkey clay	[d] 1.46	41	[d] 1.21	35	[d] .94	44
62	Susquehanna clay	0.30	38	0.36	28	0.27	20
63	Tidal marsh	.054	15	.056	15	.038	8
64	Docas clay	.20	32	.25	38	.12	25
65	Chino silt loam	.14	46	.17	41	.17	8
66	Mohave fine gravelly loam	.10	44	.25	35	.063	19
67	Cinders	[d] 3.67	84	[d] 3.35	74	[d] 3.14	58
69	Houghton muck	0.36	28	0.23	18	0.20	10
70	Merced silt loam	.034	54	.094	22	.10	16

[a] Cu, 0.056%; Bi, 0.002%; Sb, 0.0011%.
[b] Cu, 0.082%; Sb, 0.0011%; Te, 0.043%.
[c] Cu, 0.036%; Bi, 0.016%; Sb, 5.31%.
[d] Individual specimens differ from the average by more than 50%.

In general, the lead was only slightly corroded under a variety of soil conditions that were corrosive to ferrous metals, copper, and zinc. For example, the lead was only slightly corroded by Rifle peat, soil 60; by tidal marsh, soil 63; and by the alkali soils, 64, 65, and 66. The explanation for the resistance to corrosion shown by the lead in these environments is, of course, the polarizing effects of sulfates and chlorides on the local-action cells responsible for corrosion. Acadia clay, soil 51, is an apparent rather than a real exception to this rule. Although this soil is corrosive to lead, the analysis in table 1 shows the soil to be high in sulfates. The sulfates are present, however, as difficultly soluble gypsum crystals, which are brought into solution only with continuous agitation over a long period.

VII. SUMMARY

In this paper is reported the condition of the specimens of a variety of ferrous metals and alloys, and copper and copper alloys, exposed to various soils for 7 years. The results of inspections of nine alloy irons and steels and of several varieties of zinc and lead exposed for 2 years are also given, together with data on other materials buried for longer periods.

After exposure of the specimens to a specially selected group of soils

[8] George O. Hiers, Mech. Eng. 58, 793 (1936).
[9] George O. Hiers, Ind. Eng. Chem. 28, 1406 (1936).

for 7 years, little difference was observed in the corrosion resistance of the wrought iron, low-carbon steel, copper-molybdenum open-hearth iron, or steel containing between 4 and 6 percent of chromium. A copper-nickel steel from which the mill scale had been removed showed somewhat greater resistance to corrosion.

By increasing the chromium and nickel contents, ferrous metals may be made highly resistant to soil corrosion. In fact, corrosion of a certain alloy of the 18:8 variety was practically negligible.

Except in a tidal marsh soil, the corrosion rate of the copper-zinc alloys increased generally with the zinc content. The copper, however, corroded in a soil high in chlorides, but this soil had relatively little effect on the Admiralty metal and the 70:30 copper-nickel alloy, as would have been predicted from the resistance of these materials to corrosion by sea water. The behavior of the brasses in the tidal marsh containing sulfides was unique in that the corrosion rate decreased with increasing zinc content, the reverse of the normal order.

Data are presented on the corrosion of several zinc and lead-alloy specimens. The zinc specimens corroded under much the same conditions which were corrosive to ferrous metals. The lead underwent corrosive attack in acid organic soils, in cinders and in heavy, poorly aerated soils low in chlorides and sulfates. In the presence of these radicles the corrosion rate of the lead was comparatively low.

Since a large proportion of the soils to which the specimens were exposed is very corrosive, the failure of certain materials in these environments does not necessarily reflect on the usefulness of these materials for a wide variety of moderately corrosive soil conditions.

The author acknowledges the assistance of I. A. Denison, who made helpful suggestions regarding the effects of alloying elements, and of Melvin Romanoff, who supervised the preparation of the specimens, the measurements of corrosion, and the calculation of the data reported in the tables. The assistance of David Fickle and Richard F. Thomas in these various operations is also acknowledged.

WASHINGTON, December 2, 1941.

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