Underground Corrosion

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TABLE 11. *Composition of cast ferrous materials*

Material	Identification		Number of speci-mens buried	Form	Nominal width or dia-meter	Length	Thick-ness	C			Si	Mn	S	P	Cr	Ni	Cu
	Symbol	Year buried						Free	Com-bined	Total							
					Inches	*Inches*	*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
deLavaud cast iron	C	1922–24	639	Pipe	6.0	6.0	0.44			3.56	2.34	0.73	0.083	0.77			
Sand mold cast iron (northern ore)	L	1922	370	do	6.0	6.0	.44			3.45	1.55	.56	.075	.55			
Sand mold cast iron (southern ore)	Z	1922	280	do	6.0	6.0	.44			3.40	1.61	.43	.083	.84			
Southern cast iron	A	1928	140	do	6.0	6.0	.44	2.90	0.70	3.60	1.70	.40		.80			
Monocast iron	I	1928	160	do	6.0	6.0	.25	2.65	.75	3.40	1.50	.50		.70			
Charcoal cast iron [a]	CB	1939	150	Plate	3.5	12.0	.375			2.40	0.95	.95	.065	.17			1.00
deLavaud cast iron [a b]	CC	1939	150	do	3.5	12.0	.50		3.70		1.51	.38	.071	.78			
Rattled cast iron [c]	G	1932	150	Pipe	1.25	13.5	.250	2.94	0.64	3.58	1.64	.48	.074	.79			
Sand-coated cast iron	F	1932	150	do	1.25	13.5	.250	2.94	.64	3.58	1.64	.48	.074	.70			
Plain cast iron	A	1941	150	do	1.5	13.0	.250			3.22	2.19	.91	.12				
High-silicon cast iron	D	1922	568	do	3.0	6.0				0.72	13.44	.26	.123	.11			
Low-alloy cast iron	I	1932	150	do	1.25	12.0	.350			2.53	1.43	.28	.077	.128			.51
Do	J	1932	150	do	1.25	12.0	.350			2.90	2.04	.83	.060	.248			.62
Do	C	1932	150	do	1.5	12.0	.250	3.00	.50	3.50	2.50	.70	.050	.400	0.30	0.15	
Do	B	1941	150	do	1.5	13.0	.250			3.28	2.09	.83	.12			1.27	.32
Do	C	1941	150	do	1.5	13.0	.250			3.24	2.08	.80	.12			1.71	.98
Do	NC	1941	150	Plate	2.5	14.0	.5			2.80	2.03					2.08	1.10
Do	N	1941	150	do	2.5	14.0	.5			2.75	2.00					3.10	
Do	D	1941	150	Pipe	1.5	13.0	.250			3.21	2.11	.72	12			3.32	
High-alloy cast iron	E	1932	150	do	1.5	10.0	.250			2.98	2.13	1.00			2.61	15.00	6.58

[a] The deLavaud and charcoal cast-iron plates were connected together by means of a charcoal cast-iron bolt and a steel bolt.
[b] Curved plate cut from 12-in. class 150 super deLavaud pipe.
[c] Ordinary iron horizontally cast in green-sand molds and rattled to remove sand.

b. Cast Materials

The original field tests included sand cast-iron pipe, (materials L and Z, 1922, table 11) de Lavaud centrifugal cast pipe, (material C, 1922) and high-silicon cast-iron pipe (material D, 1922). Subsequent exposures included some alloy cast irons, which had become available. Improvement in the structure of cast iron brought about by alloy additions or by modifications in the manufacturing process apparently has the effect of reducing graphitic corrosion, which results from electrolytic action between ferrite and graphite, the former constituting the anode and the latter the cathode of galvanic cells within the corroding iron. Graphitization may decrease or accelerate the normal rate of corrosion depending upon the tendency of corrosion products to deposit within the pores of the castings as determined by the nature of the environment [145].

Although a large variety of special cast irons are now available, relatively few were available for inclusion in the field tests. Cast irons of compositions other than those given in table 11 are now in use for types of service that suggest that these irons might be successfully employed for underground service. For example, Dieffenbach [146] reported that a copper-molybdenum cast iron showed no noticeable corrosion in more than 2 years of service as lock gate valves under conditions where protective coatings could not be used. Cast irons containing small percentages of nickel, chromium, and molybdenum also are understood to be used for similar purposes.

c. Miscellaneous Ferrous Materials

Miscellaneous ferrous materials buried at the test sites include nuts, bolts, elbows, nipples, and similar fittings listed in table 12.

TABLE 12. *Miscellaneous ferrous specimens included in the NBS tests*

Symbol	Material	Year buried	Number of specimens buried
A	Malleable-iron nuts and bolts, decarburized	1932	48
B	Malleable-iron nuts and bolts, not decarburized	1932	48
C	Malleable-iron nuts and bolts, high strength	1932	48
D	Steel nuts and bolts	1932	48
CD	Charcoal cast-iron nuts and bolts	1939	150
CE	Steel nuts and bolts	1939	150
E	Sheradized nuts and bolts	1924	100
—	Lead-coated nuts and bolts	1924	96
—	Black wrought iron nuts and bolts	1924	100
E	2-in. cast steel elbows	1924	56
I	4-in. machined cast iron nipple	1924	24
V	2-in. semisteel nipples	1924	48
S	2-in. malleable-iron bends	1924	48
—	1½-in. coupling attached to threaded pipe	1922	192

8.2. Results on Wrought Materials

a. Plain Irons and Steels

The loss in weight and the maximum penetration of the 1½-in. and 3-in. wrought black pipe for all removals of the specimens buried in 1922 in the original 47 NBS test sites are given in table 13. In some of the soils it was necessary to discontinue the

tests in less than 12 years because the sites were no longer available. However, approximately half of the exposures were continued for 12 years and in 19 of the less corrosive soils, exposure was continued for approximately 17 years. In 1928, samples of some of the 3-in. pipes were exposed to 28 additional soils, and in later years (1932 and 1937) samples of 1½-in. pipes and a plate were exposed to 15 soils. These results are given in tables 14 and 15.

For similar periods of exposure the relative corrosion rate of a material in two soils may not be the same, as the initial rate of loss in weight or pitting may be maintained in one soil, whereas in another the rates may decrease because of the effect of the corrosion products and properties of the soil. Differences of this nature are illustrated in figure 11, which shows the relation of maximum pit depth of wrought iron and steel to the length of exposure in five different soils. Because of these changes in the rates of corrosion with time, the data for all periods of exposure should be taken into account before attempting to estimate the behavior of a material in a soil or the corrosiveness of that soil.

The depth of the deepest pit is a function of the area from which it is chosen. For a given material, the maximum pit depth resulting from a particular exposure has been found to vary with the exposed area, i.e., the greater the exposed area the greater the chance of finding one or more unusually deep pits [110]. Table 16 presents the maximum and weighted maximum pit depths of the wrought pipe specimens during the maximum exposure period. The weighted values have been adjusted to give comparable data based on their area for the specimens of different sizes, that is, the single deepest pit on each 1½-in. pipe and the two deepest pits on each of the two 3-in. pipes. Therefore, the data in the last 4 columns for the 3-in. pipe may be compared with data for similar materials of the 1½-in. pipe in columns 3 to 6. As a check on this procedure, the pit depths of the corresponding 1½-in. and 3-in. wrought iron and Bessemer steel specimens (table 16) may be compared. In each case the same manufacturer furnished both sizes of the same materials. There are 19 soils in which the weighted pit depths are of the same magnitude and 16 soils in which the weighted pit depths are greater for the larger specimens compared with 12 soils in which the pit depths are less.

Effect of Composition. Although the principal purpose of the original soil-corrosion investigation was to determine the effect of soils, a comparison of the different materials could not be avoided because of their varying compositions.

A comparison of the behavior of the more commonly used irons and steels was made in Research Paper 883 [113], which reported the average depths of the deepest pits, over an interval of 12 years, of all the ferrous specimens buried in 1922. The difference in the soils was so great that average rates for all soils had little value, except that they permitted a comparison of different materials exposed to the same conditions. The pit depths were adjusted to take into account the areas of the specimens.

Although table 16 indicates that there may be a small difference between open-hearth iron specimens and the other 1½-in. wrought specimens, this difference is not considered to be significant. Similarly, the 3-in. open-hearth steel, containing 0.2 percent of copper, may corrode at a greater rate than copper-free steel. In both cases the reason for the differences may be due to the character of the surfaces or the different surface finishes of the specimens employed. In the case of the open-hearth iron, the surfaces of the specimens may have been covered by an almost continuous thin oxide film that broke down in a relatively few places, thus concentrating the galvanic action. A basis for this suggestion is the low loss in weight of the specimens of this material (table 13).

The copper-bearing steel specimens, on the other hand, carried heavy local patches of mill scale that had not been removed after fabrication. It is possible that galvanic action between this mill scale and the remainder of the surface of the pipe accelerated the corrosion, or that after a period of exposure the mill scale became loosened and galvanic action between the unprotected spots and the oxidized areas caused additional corrosion.

The loss in weight is smallest for the wrought-iron specimens, but the difference between the average maximum rates of penetration for wrought-iron and Bessemer steel is not sufficient to show positively a difference in the rates of corrosion of these materials for either the 1½-in. or the 3-in. specimens.

The averages of the data for all soils for any material in table 16 indicate that the maximum pit depth is generally greater on the 3-in. than on the 1½-in. specimens. However, the data for individual soils show that this is not always the case. This is the "area effect" previously mentioned in the description of the weighting procedure.

Because each of these test sites was examined carefully and no location accepted where there was a possibility of stray currents in the earth, the corrosion observed in the specimens could not have been caused by stray currents. Moreover, an examination of the distribution of the corrosion with respect to the position of the specimens in the trench confirmed this statement. It is evident in tables 13 through 15 for the wrought ferrous materials, that as a rule all the specimens in the same trench corroded similarly with respect to losses in weight and depths of deepest pits. Further examination of the specimens showed that the distribution of the corroded areas of individual specimens in the same trench was also similar. From this it follows that the cause of corrosion did not lie within the specimens because they differed in composition and were furnished by several independent pipe mills. Differences in composition of the plain irons and steels were thus eliminated as primary causes of underground

TABLE 14. *Loss in weight and maximum penetration of 3-inch wrought black ferrous pipe buried in 1928*

(Average of two specimens)

Soil		Duration of exposure	Loss in weight			Maximum penetration		
No.	Type		Open-hearth iron	Wrought iron	Bessemer steel	Open-hearth iron	Wrought iron	Bessemer steel
	Material		A	B	M	A	B	M
		Years	oz/ft^2	oz/ft^2	oz/ft^2	*Mils*	*Mils*	*Mils*
52	Lake Charles clay loam	2.0	3.1	3.4	2.7	66	62	40
		5.4	14.7	14.6	13.5	116	123	118
		7.5	19.0	19.0	16.9	116	176	163
54	Fairmount silt loam	1.9	1.0	1.0	0.7	14	16	6
		5.2	1.5	1.3	1.2	14	21	11
		7.3	3.4	2.5	3.5	54	36	40
68	Gila clay	1.7	3.2	3.6	2.9	42	50	37
		5.1	3.7	4.3	3.7	43	43	38
		7.2	4.8	4.9	4.4	48	48	45
101	Billings silt loam (low alkali)	1.9	3.9	5.2	3.9	70	66	60
		4.1	7.5	8.8	7.2	116	94	94
		9.3	10.5	9.4	9.1	131	95	86
102	Billings silt loam (moderate alkali)	1.9	3.9	5.1	4.3	42	37	26
		4.1	9.4	10.2	9.3	102	80	72
		9.3	18.3	16.1	17.6	124	93	95
103	Billings silt loam (high alkali)	1.9	3.7	5.0	3.6	63	48	37
		4.1	11.2	10.4	10.1	88	86	66
		9.3	18.8	21.3	17.8	190	136	192
104	Cecil clay	1.9	2.9	3.0	2.5	71	70	88
		4.1	4.8	4.3	3.7	84	86	93
		11.7	7.1	7.2	7.6	88	94	114
105	Cecil clay loam	2.0	3.2	3.6	3.4	50	45	58
		4.0	3.6	3.8	4.2	48	48	46
		11.7	4.8	3.7	4.9	58	51	54
106	do	1.9	2.6	2.5	2.0	62	46	48
		4.1	3.4	4.0	3.6	64	64	56
		11.7	7.3	8.6	9.0	93	70	75
107	Cecil fine sandy loam	1.9	2.0	2.3	2.4	57	66	64
		4.1	2.9	3.2	3.1	73	72	66
		11.7	5.4	5.5	5.6	97	90	129
108	Cecil gravelly loam	1.9	2.8	3.3	3.4	67	38	53
		4.0	3.1	3.6	3.4	86	50	62
		11.7	4.7	4.5	5.9	85	70	95
109	Fresno fine sandy loam (low alkali)	1.9	4.7	5.9	5.2	70	70	74
		4.0	7.9	7.6	6.3	74	82	63
		9.2	11.6	11.8	11.3	121	100	108
110	Fresno fine sandy loam (moderate alkali)	1.9	3.9	4.5	4.1	74	60	42
		4.0	7.6	7.1	7.4	84	85	73
		9.2	18.6	15.8	20.2	155	126	155
111	Fresno fine sandy loam (high alkali)	1.6	4.4	4.5	5.2	54	48	38
		3.7	8.7	7.8	8.7	104	78	80
		8.9	17.6	18.8	19.4	162+	165	119
112	Imperial clay (moderate alkali)	1.9	7.1	7.3	7.3	76	58	68
		4.0	14.5	13.6	14.0	188+	128	132
		5.9	19.8	16.9	18.8	250+	177+	232+
113	Imperial clay (high alkali)	1.9	8.2	8.1	8.2	92	54	54
		4.0	19.0	16.0	18.5	216+	157+	216+
		5.9	25.8	21.8	23.6	224+	178+	231+
114	Lake Charles clay	0.9	1.5	1.3	1.3	32	15	14
		3.0	4.8	6.0	5.0	99	72	67
		10.5	14.3	14.6	14.1	159	90	106
115	Memphis silt loam	2.0	1.8	1.9	1.7	32	34	32
		4.1	2.4	2.8	2.7	75	64	64
		11.7	3.3	3.5	3.9	89	48	64
116	Merced clay	1.9	6.1	6.6	5.8	46	51	36
		4.0	13.0	11.8	11.5	96	97	90
		9.3	21.6	19.1	19.4	121	173	88
117	Merced clay loam adobe	1.9	7.6	7.9	8.0	118	92	86
		4.0	9.6	9.9	9.4	135	112	101
		9.3	21.0	19.8	20.5	185	127	141
118	Niland gravelly sand (low alkali)	1.9	5.4	5.0	5.5	108	72	60
		4.0	12.2	10.9	13.1	151+	124	122+
		5.9	16.0	15.4	14.9	240+	153	158
119	Norfolk sandy loam	2.0	0.7	0.6	0.5	<10	<10	<10
		4.0	3.9	4.3	4.6	86	52	68
		11.7	8.2	8.7	8.9	98	67	77

TABLE 14. *Loss in weight and maximum penetration of 3-inch wrought black ferrous pipe buried in 1928*—Continued

(Average of two specimens)

Soil No.	Soil Type (Material)	Duration of exposure	Loss in weight: Open-hearth iron A	Loss in weight: Wrought iron B	Loss in weight: Bessemer steel M	Maximum penetration: Open-hearth iron A	Maximum penetration: Wrought iron B	Maximum penetration: Bessemer steel M
		Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*
120	Norfolk sand	2.0	2.4	2.6	2.6	72	46	49
		4.0	0.9	0.9	0.8	22	20	20
		11.6	1.8	1.8	2.1	36	28	26
121	do	2.0	1.1	0.9	0.8	22	19	20
		4.0	1.0	.9	.7	26	20	20
		11.7	1.4	1.4	1.5	28	25	21
122	Panoche clay loam	1.9	1.9	2.2	1.9	46	32	25
		4.0	2.8	3.2	3.6	48	60	38
		9.3	5.0	4.5	7.1	58	49	48
123	Susquehanna clay	2.0	3.0	3.2	3.2	32	30	32
		4.1	5.5	6.4	5.4	46	38	44
		11.7	10.4	10.9	10.9	44	60	62
124	Susquehanna silt loam	0.9	2.4	2.6	2.7	47	48	47
		2.7	4.5	5.0	5.2	54	54	55
		10.5	8.1	8.5	8.5	84	80	80
125	Susquehanna fine sandy loam	2.0	3.4	3.9	3.6	42	46	40
		4.1	4.9	4.5	4.6	56	44	47
		11.8	7.0	7.9	8.5	68	74	78

TABLE 15. *Loss in weight and maximum penetration of wrought black ferrous pipe (1½ inch) and plate buried in 1932 and 1937*

(Average of two specimens)

Soil No.	Soil Type (Material)	Exposure: For pipe A, B, and N	Exposure: For pipe S and plate A	Loss in weight: Wrought iron pipe, hand puddled A	Loss in weight: Wrought iron pipe, mechanically puddled B	Loss in weight: Carbon steel pipe N	Loss in weight: Carbon steel pipe S	Loss in weight: Open-hearth steel plate A	Max. penetration: Wrought iron pipe, hand puddled A	Max. penetration: Wrought iron pipe, mechanically puddled B	Max. penetration: Carbon steel pipe N	Max. penetration: Carbon steel pipe S	Max. penetration: Open-hearth steel plate A
		Years	*Years*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
51	Acadia clay	2.0	2.1	11.7	8.2	7.4	7.5	11.6	50	60	82	52	54
		5.4	......	12.6	13.6	12.7	......	......	144	[a]129+	154+	......	......
		7.5	[b]9.0	15.1	15.3	11.5	17.4	19.1	122+	145+	135+	128+	138+
		[c]14.3	......	23.9	26.7	21.0	......	......	135+	131+	146+	......	......
53	Cecil clay loam	2.0	2.1	3.5	3.4	2.7	1.8	1.8	34	30	37	42	40
		5.5	4.0	2.6	3.0	3.0	2.9	3.2	64	71	50	98	76
		7.6	8.9	3.3	3.4	4.2	3.4	3.9	77	76	54	74	57
		9.5	11.2	3.7	3.7	4.1	3.4	3.4	50	73	59	78	72
		14.3	12.7	4.9	4.8	4.4	3.9	4.0	72	66	84	68	78
55	Hagerstown loam	1.9	1.9	2.8	2.9	2.4	1.8	2.0	40	42	41	33	42
		5.2	3.9	2.3	2.4	2.2	2.6	2.6	79	84	57	50	54
		7.1	9.0	3.5	3.4	3.2	4.1	3.8	70	60	57	92	90
		9.1	11.0	3.7	3.8	3.8	3.9	3.3	60	84	59	84	77
		14.2	12.6	3.4	3.7	3.1	3.4	4.0	76	88	65	73	66
56	Lake Charles clay	2.0	2.1	3.5	4.4	4.0	13.8	14.4	22	24	20	77	80
		5.4	4.0	10.8	7.6	13.9	16.0	18.3	66	65	71	104	100
		7.5	8.9	17.2	14.7	21.0	27.8	28.0	90	106+	125+	145+	126+
		9.4	11.1	[d]22.8	19.5	28.8	[e]D	48.1	[d]96	106	154+	145+	188+
		14.4	12.7	26.6	26.5	35.2	D	D	145+	145+	135+	145+	188+
58	Muck	2.0	2.1	3.5	3.2	3.2	5.1	5.7	20	18	18	29	31
		5.5	4.0	9.8	10.4	11.2	8.8	9.9	68	64	103	46	61
		7.6	8.9	11.9	11.6	14.1	17.3	16.9	84	110	110	98	89
		9.5	11.2	12.6	12.7	16.2	16.3	17.2	118	116	110	110	161+
		14.4	12.7	19.6	17.4	25.5	17.6	18.1	96	78	154+	124	188+
59	Carlisle muck	......	2.1	......	......	......	1.5	1.5	......	......	......	12	6
		5.1	4.0	1.8	1.6	2.4	3.3	4.2	25	18	20	20	22
		7.2	9.1	2.0	1.8	3.0	7.5	9.9	18	15	30	101	98
		9.1	11.1	2.4	2.3	4.7	9.6	9.5	32	28	40	76	96
		[c]14.2	12.7	4.3	4.2	3.9	9.6	11.1	37	32	34	72	90
60	Rifle peat	1.9	2.1	5.7	5.0	6.2	4.0	6.3	24	24	37	15	30
		5.2	4.0	6.3	6.8	11.0	8.1	9.5	38	37	24	38	40
		7.3	9.1	5.1	5.4	7.6	17.6	22.0	30	34	17	58	56
		9.2	11.1	14.3	[f]16.5	16.7	19.6	15.8	[f]55	[f]64	[f]27	89	63
		14.3	12.7	25.1	28.8	28.8	21.0	21.7	78	78	82	118	60

See footnotes at end of table.

TABLE 15. *Loss in weight and maximum penetration of wrought black ferrous pipe (1½ inch) and plate buried in 1932 and 1937*—Continued

(Average of two specimens)

Soil		Exposure		Loss in weight					Maximum penetration				
No.	Type / Material	For pipe A, B, and N	For pipe S and plate A	Wrought iron pipe, hand puddled A	Wrought iron pipe, mechanically puddled B	Carbon steel pipe N	Carbon steel pipe S	Open-hearth steel plate A	Wrought iron pipe, hand puddled A	Wrought iron pipe, mechanically puddled B	Carbon steel pipe N	Carbon steel pipe S	Open-hearth steel plate A
		Years	*Years*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
61	Sharkey clay	1.0	2.1	1.3	1.2	0.8	2.2	2.6	17	10	10	40	34
		5.5	4.0	5.6	4.9	4.0	5.0	5.4	41	37	[f]54	45	50
		7.6	8.9	6.3	6.4	5.6	4.2	4.3	44	50	63	48	90
		9.5	11.2	6.4	5.7	5.8	6.9	7.3	61	[f]86	[f]96	58	103
		14.4	12.7	10.2	11.9	10.0	7.5	8.1	84	82	88	64	85
62	Susquehanna clay	1.9	2.1	3.0	4.0	4.1	3.2	2.8	49	70	62	40	34
		5.5	4.0	4.0	4.0	4.7	4.3	3.7	54	56	66	56	47
		7.6	8.9	6.0	6.0	5.3	5.3	4.2	69	78	71	68	59
		9.5	11.2	7.8	9.4	6.6	6.0	5.0	[f]72	[f]101	[f]87	72	77
		14.3	12.7	8.3	7.1	7.9	6.8	5.9	74	65	101	79	84
63	Tidal marsh	2.0	2.1	3.0	2.6	3.8	2.7	3.6	28	16	15	24	18
		5.6	4.0	3.1	2.4	4.5	9.2	[d]6.2	22	37	36	38	[d]26
		7.7	8.9	3.4	3.5	7.1	10.7	[d]8.9	64	39	70	80	[d]36
		9.6	11.2	8.5	4.2	[f]9.0	12.2	16.9	100	[f]55	54	94	48
		14.4	12.6	[f]10.1	[f]6.8	9.6	18.5	16.5	74	80	61	126	44
64	Docas clay	1.9	2.1	11.4	13.3	12.6	8.7	7.1	102	118	130	80	44
		5.2	4.0	22.1	23.1	25.3	6.0	7.4	129	110	154+	67	78
		7.3	9.0	34.4	35.4	35.6	4.7	7.5	144+	145+	154+	80	87
		9.2	11.2	[g]16.0+	[g]18.4+	D	12.4	[f]19.0	120+	145+	154+	118	156+
		14.2	12.8	[g]38.3+	[g]18.4+	D	[f]17.2	18.6	145+	145+	154+	122	188+
65	Chino silt loam	1.9	2.1	8.0	6.2	7.4	4.3	4.6	54	66	40	50	47
		5.3	4.0	7.4	7.2	10.3	4.6	5.3	91	87	74	59	51
		7.3	9.0	9.0	8.8	13.7	7.0	7.2	110+	106	83	65	75
		9.2	11.2	13.6	11.4	12.9	6.2	6.1	102	110	112	84	79
		14.2	12.7	10.4	9.2	13.0	7.2	8.2	98	98	86	98	91
66	Mohave fine gravelly loam	1.9	2.1	8.6	7.8	7.7	9.2	8.3	88	82	66	145+	86
		5.3	4.0	10.2	11.3	15.1	12.3	16.8	85	106	154+	145+	188+
		7.4	9.0	11.6	11.1	14.3	[f]8.1	4.6	110	140+	154+	78	66
		9.2	11.2	[d]5.8	10.0	18.6	16.3	[f]17.7	[d]88	130+	154+	145+	188+
		14.2	12.7	20.3	[g]17.2+	D	[f]20.3	19.9	142+	145+	154+	145+	188+
67	Cinders	2.0	2.1	8.6	11.4	21.5	40.0	12.0	100	98	154+	145+	46
		5.3	4.0	31.8	24.9	34.6	37.0	34.3	145+	145+	119+	145+	132+
		7.3	9.0	29.7	27.0	23.5	31.7	D	145+	145+	127+	145+	188+
		9.2	11.1	[g]15.2+	D	[g]58.4+	D	37.8	145+	145+	154+	145+	188+
		14.3	12.7	D	D	D	D	D	145+	145+	154+	145+	188+
70	Merced silt loam	...	2.1	...	...	...	4.9	5.0	...	...	...	50	86
		...	4.0	...	...	...	[f]9.7	10.6	...	...	...	118+	188+
		...	9.0	...	...	...	13.4	17.9	...	...	...	122	66
		...	11.2	...	...	...	24.5	24.0	...	...	...	145+	188+
		...	12.8	...	...	...	21.3	25.7	...	...	...	145+	188+

[a] +, one or more specimens contained holes because of corrosion.
[b] Data for 8 specimens.
[c] Data for 4 specimens.
[d] Data for 1 specimen. The other specimen was missing.
[e] D, both specimens destroyed by corrosion.
[f] Data for the individual specimens differed from the average by more than 50 percent.
[g] Data for 1 specimen. The other specimen was destroyed by corrosion.

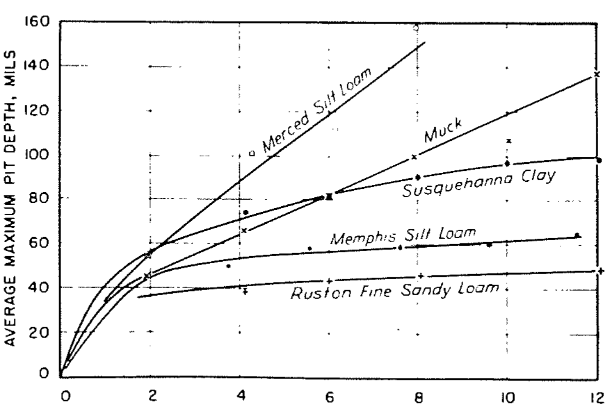

FIGURE 11. *Pit-depth-time curves for wrought ferrous pipe.*

TABLE 16. *Maximum pit depth and weighted maximum penetration of 1½-inch and 3-inch wrought black pipe specimens (buried in 1922) during the maximum exposure period*

(Average of two specimens, in mils)

Soil	Maximum exposure	Maximum penetration								Weighted maximum penetration [a]			
		1½-inch pipe				3-inch pipe				3-inch pipe			
		Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with Cu	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with Cu
	Material	a	b	e	y	B	K	M	Y	B	K	M	Y
	Years												
1	11.6	92	74	86	91	96	94	101	125	90	91	95	120
2	17.6	71	60	56	80	56	70	58	67	54	62	56	64
3	12.1	[b]118+	80	78	75	76	82	84	90	64	74	79	77
4	12.0	145+	78	79	82	87	108	84	152	74	103	71	146
5	17.5	76	54	51	42	66	91	62	71	62	82	58	68
6	17.5	27	30	26	21	32	30	23	32	30	27	20	29
7	16.9	52	40	50	61	74	67	48	56	57	55	47	51
8	11.8	100	76	74	67	83	93	110	127	80	86	68	109
9	16.9	69	51	64	65	68	58	68	109	58	52	66	95
10	12.0	50	52	40	42	48	56	54	66	45	47	48	53
11	11.9	99	75	76	70	90	70	92	88	84	66	80	74
12	17.5	70	60	72	64	76	56	86	85	70	54	83	81
13	5.9	49	97	67	85	59	67	75	71	56	70	70	64
14	11.8	120	109	130	131	127	97	135	161	117	90	129	154
15	17.6	78	66	62	58	65	82	72	62	60	69	66	60
16	12.0	92	84	94	120	84	86	96	90	80	76	94	88
17	17.0	42	38	42	39	43	50	48	57	41	46	44	51
18	11.7	71	72	71	67	64	70	62	80	60	61	60	76
19	11.6	62	71	71	66	66	85	65	68	62	78	64	68
20	11.6	67	52	72	64	45	80	56	65	44	72	55	57
21	6.0	71	52	60	63	60	59	66	60	56	54	60	55
22	11.6	72	66	66	78	68	65	66	71	66	63	63	65
23	12.1	145+	145+	145+	145+	158	159	163	216+	157	158	145	216+
24	17.2	28	24	21	26	30	28	36	28	31	26	30	30
25	17.0	75	50	48	42	54	62	57	57	51	54	53	54
26	16.9	70	66	67	64	72	66	78	80	69	64	77	75
27	17.6	42	58	69	60	74	92	84	78	68	84	78	59
28	9.6	145+	132+	137+	145+	167	183+	152	216+	160	180	142	216+
29	12.0	145+	97	136+	145+	134	216+	128	216+	117	194+	101	171+
30	17.0	54	51	58	51	62	64	76	66	60	63	72	63
31	17.7	50	44	43	53	42	90	66	49	40	83	64	47
32	11.7	58	55	46	50	59	86	62	94	58	81	58	90
33	11.7	130+	98	92	104	112	117	115	111	103	113	102	106
34	12.0	82	48	84	94	71	73	77	104	66	68	73	101
35	17.5	32	54	40	17	36	38	69	97	31	24	57	54
36	17.7	56	54	55	48	50	60	50	57	50	59	48	53
37	12.0	76	71	89	74	80	72	95	127	73	69	91	120
38	17.2	52	34	28	36	37	38	42	35	34	33	36	31
39	12.0	77	56	50	60	69	72	94	106	60	67	81	98
40	12.0	139	101	87	82	70	99	96	92	67	95	87	88
41	17.4	122	94	92	101	86	72	101	80	81	71	94	77
42	12.0	94	92	113+	111+	96	129	103	116	94	122	98	106
43	12.0	94	102+	100	105	138	136	119	155+	131	126	102	135+
44	11.6	87	56	63	69	65	72	82	88	62	54	77	79
45	11.7	143	114	138	117	118	138	128	158	111	135	126	150
46	12.0	80	95	108+	118+	82	68	136	134	77	60	115	127
47	17.4	42	53	37	57	51	40	48	46	48	38	47	44
	Average	81	70	73	75	75	83	82	95	70	78	75	87

[a] The maximum penetration and the weighted maximum penetration for the 1½-inch pipe have the same value.

[b] A plus (+) indicates that 1 or both specimens were punctured by corrosion.

corrosion. Furthermore, it is observed (tables 13, 14, and 15) that in some soils all materials corroded much more seriously than in other soils. It is evident, therefore, that the chief causes of corrosion of the commonly used wrought materials are associated with soils or soil conditions. The similar corrosion of specimens of different wrought materials exposed to the same soil is shown in figure 12, and figure 13 illustrates the variation in the corrosiveness of different soils with respect to the same material.

Effect of Environment. It was observed in inspecting underground pipelines and specimens from the NBS tests, that corrosion may take widely different forms, from the production of sharp isolated pits to a uniform attack of the metal surface as illustrated in figure 13. It will be observed that in specimen 1 there is very little pitting, although practically the entire surface has been attacked, whereas in the specimens in the lower row, pitting is especially pronounced and the corroded areas are relatively small.

The variation in the type of corrosion on the same steel that may occur in soils is exhibited in figure 14, which illustrates corrosion patterns on Bessemer steel specimens, ranging from a uniform attack of the metal surface without pitting (14–1) to a highly localized attack in the form of deep,