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SOIL-CORROSION STUDIES, 1934. BITUMINOUS COATINGS FOR UNDERGROUND SERVICE

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ABSTRACT

This paper summarizes the results of the studies of bituminous coatings for pipe lines, which were conducted under the auspices of the National Bureau of Standards between 1922 and 1935. Most of the fundamental data in the paper have been published. The paper attempts to interpret those data. Nine types of protective coatings, most of which have been represented by several varieties of coatings, are considered, and the characteristics of each type are discussed. The data indicate that the same degree of protection for a pipe line can be secured in a number of ways. The data show only two outstanding coatings. Neither of these was perfect and neither is in general use. Most coatings, though imperfect, afford sufficient protection to justify their application to pipe lines exposed to corrosive soil. Other important conclusions reached by the author are given in the summary at the close of the paper.

CONTENTS

I. ORIGIN AND SCOPE OF THE INVESTIGATION

As a part of its soil-corrosion investigation, the National Bureau of Standards buried four widely different types of bituminous coatings in 30 soils in 1922. These coatings, together with other types buried in 1924 and 1926, are described in detail in the first report on the soil-corrosion investigation.[1] That paper also describes the soils to which the coatings were exposed and gives some of the early results of the tests. These results are still of some interest because several of the coatings failed within the short period of exposure covered by the report.

The results of the earlier investigations and the corrosion experience of pipe-line operators led to the appointment in 1928, by the American Petroleum Institute, of G. N. Scott as a Research Associate to study the problem of pipe-line protection for oil lines. The American Gas Association in 1929 appointed S. P. Ewing to cooperate in the study of pipe coatings and corrosion.

Although the work of these men was an integral part of the Bureau's soil-corrosion investigation, the results of their investigations have appeared in the publications [2] [3] of the associations named above.

These reports contain practically all of the primary data resulting from the examinations of coatings in the field. Since they were prepared as progress reports, the discussions of the data were brief and, as a result, many pipe-line operators have not derived the benefit from these reports that might be obtained through an intensive study of the data presented. The field work on protective coatings has been supplemented by the determination of some of the physical properties of the coating materials and by other laboratory tests. The results of most of this work have not been published.

Since all experimental work on bituminous pipe coatings has now been suspended, it seems desirable that the net results of all of the investigations should be assembled. This necessitates the reproduction of some data already published, but this duplication will be limited as much as is consistent with the production of an understandable summary.

The purpose of protecting a pipe line is to reduce the total annual charges on the line. Since a discussion of economics is beyond the scope of this paper no attempt will be made to show whether or not a protective coating for any line is desirable. Before this economic problem can be solved the effectiveness of the protective coating must be known. This is the subject of this paper. It will be shown that the effectiveness of a coating depends to a large extent on the soil conditions to which it is subjected. The paper must therefore discuss soil characteristics and correlate them insofar as is possible with the behavior of pipe coatings.

In all of the tests conducted by the National Bureau of Standards the coatings have been applied by or under the direction of the manufacturer of the coating. Although several manufacturers cooperated both in the tests sponsored by the AGA and those of the API, no coatings in the two tests are identical in all particulars. Nor are any of the soils in the two tests identical. In the AGA and the API tests of coatings applied to short lengths of pipe, only one sample of each material was removed from each site at a given inspection.

[1] K. H. Logan, S. P. Ewing, and C. D. Yeomans, *Bureau of Standards soil-corrosion studies; I. Soils, materials, and results of early observations.* Tech. Pap. BS **22**, 447 (1928) T368, 50c.

[2] G. N. Scott. *API pipe-coating tests.* Proc. Am. Petroleum Inst., pt. IV of volumes 11 to 15, incl. (1930 to 1934).

[3] S. P. Ewing. *AGA studies of coatings for pipe lines.* Proc. Am. Gas Assn., p. 774 (1931); p. 741 (1933); p. 627 (1936).

II. COATINGS TESTED

The most commonly used pipe coatings are made from bituminous materials. These materials have two general sources—coal-tar pitch and petroleum asphalt. In the second group have been included for convenience greases having petroleum as a base. As to structure, the bituminous coatings may be classified as dips and cutbacks, the latter class covering all of the very thin coatings except greases, unreinforced coatings, enamels, and fabric reinforced or shielded materials. In each class are several materials which differ rather widely in physical properties and behavior.

The coatings in the National Bureau of Standards' tests were described in Technologic Paper 368,[4] and those in the AGA tests in the 1931 proceedings of the AGA.[5] Scott [6] has described the structure of the coatings in the API test but has given no results of laboratory tests similar to those in the other sets of coatings. On this account, tests of the physical characteristics of many of the materials in the API tests were made by H. S. Christopher. His results are summarized in table 1. The laboratory tests which were applied to the coating materials were not designed to determine the effectiveness of protective coatings, and they are not altogether satisfactory for identifying the materials.

TABLE 1.—*Characteristics of bituminous coating materials in the API tests*

[Determinations by H. S. Christopher]

Designation of material	Specific gravity	Ring and ball softening point	Penetration (Dow) at 115° F in 5 seconds				Ductility (Dow) at 115° F	Consistometer hardness (Abraham) at 115° F.	Insoluble in CS_2	Ash
			50 g	100 g	150 g	200 g				
		°F.					cm		%	%
E	1.028	186	20	----	----	----	14.0	14.7	2.12	0.98
G, N	1.420	202	3	----	----	----	0.7	67.1	42.9	26.5
H, L	1.628	205	2	6	9	12	3.9	54.8	55.4	37.8
K, U	1.266	192	16	24	32	36	16.0	23.5	29.1	18.9
M	1.418	145	83	[a] 11	----	----	60.0	[a] 44.5	37.4	22.9
S	0.996	194	----	[a] 23	----	----	[a] 3.2	10.9	1.0	0.4
T	1.350	191	----	----	----	----	4.1	63.5	34.1	14.4
X, Z	0.997	238	16	----	----	----	2.5	17.1	0.7	0.13
a	1.300	241	----	----	----	7	2.7	34.5	42.8	10.9
d, dd	1.360	190	----	----	----	----	3.6	56.5	32.7	13.2
g, zz, zzz	1.610	205	2	6	11	15	3.8	61.3	55.6	35.3
h	1.685	189	21	----	----	----	10.3	13.0	61.6	61.3
k, kk	1.259	192	27	----	----	----	62.0	9.1	21.9	5.6
n	1.032	190	14	----	----	----	12.6	16.9	4.6	2.4
q, qq	1.006	232	33	[a] 21	----	----	2.5	16.0	0.8	0.4
s, ss	1.421	195	2	----	----	----	2.8	63.0	40.6	26.9
t	1.420	158	25	[a] 5	----	----	58.2	10.0	39.3	21.4
vv	1.050	320+	----	----	----	5	0.0	36.7	17.0	13.4
w, ww	1.470	163	30	----	----	----	7.2	8.8	42.2	39.9
y, yy, yyy	1.011	189	----	[a] 24	----	----	[a] 3.2	10.9	1.1	0.5
z	1.638	222	0	1	2	5	1.7	65.4	57.6	40.2

[a] Temperature of test 77° F instead of 115° F.

[4] K. H. Logan, S. P. Ewing, and C. D. Yeomans, Tech. Pap. BS 22, 447 (1928) T368.
[5] See footnote 3.
[6] See footnote 2.

Since this paper deals with the results of tests by three investigators, some confusion may arise as to the coatings under discussion, especially as both Scott and Ewing designated some coatings by capital letters. To avoid confusion the coatings which Scott designated by capital letters are printed in boldfaced type in this paper to indicate that they were applied to working pipe lines.

Because of uncontrolled variables, the behavior of a single specimen at a given site may be accidental and not reproducible, and since for the short lengths of pipe no two specimens are even nominally similar as to structure and exposure, there is no way to determine the accuracy of the observations. In order to obtain an idea of the behavior of the different types of materials it seems advisable to combine the data for similar materials, even though some manufacturer may feel that his product is superior to another which has been placed in the same group.

III. CONDITIONS UNDER WHICH COATINGS WERE TESTED

The general characteristics of the National Bureau of Standards' test sites are described in Technologic Paper 368.[7] Data on the chemical properties of the soils at these test sites are given in Research Paper 945.[8] Some of the physical and chemical characteristics of the soils in the AGA tests have been given by Ewing,[9] in his 1931 report. Scott [10] has described his test sites very briefly, but he has given none of the characteristics of the soils except their resistivities.

1. PHYSICAL PROPERTIES OF THE SOILS AT THE TEST SITES [11]

The physical properties of soils which might be expected to influence the performance of protective coatings are shown in table 2 for the soils at all the test sites. The aeration of the soils was estimated from careful inspection of the test sites, employing such criteria as the texture of the soil, degree of mottling, average depth of water table, the depth at which mottling appears, and the depth at which the specimens were placed. The terms characterizing the degree of aeration are likewise indicative of drainage conditions except for those soils which, although naturally poorly drained, receive little or no rainfall.

The aeration or drainage of the soils is indicated by the value of the "air pore space," which is the percentage of the total volume of the soil occupied by air under specified conditions. This value is determined in the laboratory from the total volume of previously saturated soil which has been compacted centrifugally by a force of 1,000 times gravity, the volume of the water retained under this force, and the volume of the soil particles. These values naturally are not indicative of the drainage of those soils in which the natural drainage is restricted by the presence of an impermeable layer below the depth at which the specimens were buried.

The moisture equivalent, defined as the percentage of moisture retained by a previously saturated soil under a centrifugal force of

[7] See footnote 4.

[8] K. H. Logan. *Soil-corrosion studies 1934. Rates of loss of weight and penetration of nonferrous materials.* NBS J. Research **17**, 781 (1936) RP945, 10c.

[9] S. P. Ewing, *AGA studies of coatings for pipe lines.* Proc. Am. Gas Assn. p. 774 (1931); p. 741 (1933); p. 627 (1936).

[10] G. N. Scott. *API coating tests.* Proc. Am. Petroleum Inst. **12**, pt. IV, 53 (1931).

[11] Section 1 was prepared by I. A. Denison.

1,000 times gravity, is a measure of the retentiveness of water by the soil and of the texture of the soil. Because of the use of a larger volume of soil, the values shown in table 2 are usually somewhat lower than those obtained by the conventional method.

The specific gravity of the soils in their natural state was determined by measurements made on undisturbed lumps of soil from the test sites. The lumps were immersed in a dish filled with mercury, and the volume of the lump determined by measuring the volume of the mercury displaced. The weight per unit volume was then calculated by dividing the weight of the soil by its volume.

Shrinkage was determined by measuring the volume of the soil at the moisture equivalent and again in the oven-dried condition, the change in volume being expressed as percentage of the volume at the moisture equivalent.

Resistivity was determined by alternating current (60-cycle), the soil samples being saturated with water.

Consideration of all of the data in table 2 for any one soil gives a clear idea of the properties of the soil. From the data given for soil 27, it is seen that the high moisture equivalent, 44.6 percent, the high specific gravity, 2.01, the high shrinkage, 32.5 percent, and the low air pore space, 1.9 percent, are indicative of a heavy, dense, impermeable, and poorly aerated clay. This conclusion is confirmed by the aeration based on field observations. On the other hand, the corresponding values for soil 36 are indicative of a porous, coarse-textured, well-drained, and well-aerated soil.

TABLE 2.—*Properties of soils* [a] *at test sites*

[Aeration of soils: *G*=Good; *F*=Fair; *P*=Poor; *VP*=Very poor]

Soil	Soil type	Location	Moisture equivalent	Aeration	Air pore space	Apparent specific gravity	Volume shrinkage	Resistivity at 60° F (15.6° C)
	NATIONAL BUREAU OF STANDARDS SITES							
			%		%	%	%	Ohm-cm
1	Allis silt loam	Cleveland, Ohio	20.2	*P*	1.1		6.6	1,215
2	Bell clay	Dallas, Tex	35.2	*P*	2.0	1.95	23.0	684
3	Cecil clay loam	Atlanta, Ga	29.9	*G*	18.2	1.60	7.0	30,000
4	Chester loam	Jenkintown, Pa	22.9	*P*	7.0	1.78	2.2	6,670
5	Dublin clay adobe	Oakland, Calif	27.5	*P*	4.9	2.00	22.6	1,346
6	Everett gravelly sandy loam.	Seattle, Wash	9.5	*G*	40.6	1.50	0.1	45,100
7	Silt loam	Cincinnati, Ohio	36.4	*P*	3.7	2.02	34.5	2,120
8	Fargo clay loam	Fargo, N. D	34.8	*P*	8.7	1.56	21.0	350
9	Genesee silt loam	Sidney, Ohio	15.6	*F*	15.8	1.74	5.6	2,820
10	Gloucester sandy loam	Middleboro, Mass	9.0	*F*	27.8	1.58	0.2	7,460
11	Hagerstown loam	Baltimore, Md	31.3	*G*	15.5	1.49	8.6	11,000
12	Hanford fine sandy loam	Los Angeles, Calif	7.5	*G*	33.5	([b])	0	3,190
13	Hanford very fine sandy loam.	Bakersfield, Calif	14.2	*G*	34.5	([b])	0	290
14	Hempstead silt loam	St. Paul, Minn	12.2	*F*	14.4	1.76	1.0	3,520
15	Houston black clay	San Antonio, Tex	50.5	*P*	5.7	2.08	39.8	489
16	Kalmia fine sandy loam	Mobile, Ala	16.5	*F*	12.0	1.65	.6	8,290
17	Keyport loam	Alexandria, Va	27.7	*P*	4.4	1.72	5.4	5,980
18	Knox silt loam	Omaha, Neb	22.0	*G*	16.6	1.26	1.3	1,410
19	Lindley silt loam	Des Moines, Iowa	26.3	*F*	3.9	1.76	11.8	1,970
20	Mahoning silt loam	Cleveland, Ohio	18.6	*P*	3.8	1.90	3.9	2,870
21	Marshall silt loam	Kansas City, Mo	24.8	*P*	10.8	1.66	6.5	2,370
22	Memphis silt loam	Memphis, Tenn	28.4	*G*	9.6	1.67	3.0	5,150

[a] Determinations by I. A. Denison, R. B. Hobbs, and I. C. Frost.
[b] Not determined.

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TABLE 2.—*Properties of soils at test sites*—Continued

Soil	Soil type	Location	Moisture equivalent	Aeration	Air pore space	Apparent specific gravity	Volume shrinkage	Resistivity at 60° F (15.6° C)
	NATIONAL BUREAU OF STANDARDS SITES—Continued							
23	Merced silt loam	Buttonwillow, Calif.	18.4	*F*	6.1	1.69	0.2	278
24	Merrimac gravelly sandy loam.	Norwood, Mass.	9.7	*G*	34.7	1.4	0	11,400
25	Miami clay loam	Milwaukee, Wis.	18.6	*F*	9.5	1.95	7.6	1,780
26	Miami silt loam	Springfield, Ohio	13.3	*F*	20.9	1.95	1.0	2,980
27	Miller clay	Bunkie, La.	44.6	*P*	1.9	2.01	32.5	570
28	Montezuma clay adobe	San Diego, Calif.	19.6	*VP*	2.5	(b)	5.9	408
29	Muck	New Orleans, La.	40.9	*VP*	26.6	(b)	5.8	1,270
30	Muscatine silt loam	Davenport, Ia.	24.0	*P*	7.2	1.81	7.5	1,500
31	Norfolk sand	Jacksonville, Fla.	2.3	*G*	38.1	1.55	0	20,500
32	Ontario loam	Rochester, N. Y.	11.8	*G*	11.7	1.85	0.1	5,700
33	Peat	Milwaukee, Wis.	75.5	*VP*	34.0	(b)	16.9	800
34	Penn silt loam	Norristown, Pa.	22.9	*P*	11.7	1.82	8.4	4,900
35	Ramona loam	Los Angeles, Calif.	15.8	*G*	10.9	1.89	3.1	2,060
36	Ruston sandy loam	Meridian, Miss.	14.9	*G*	16.0	1.62	0	11,200
37	St. Johns fine sand	Jacksonville, Fla.	7.0	*F*	(b)	(b)	0	11,200
38	Sassafras gravelly sandy loam.	Camden, N. J.	5.3	*G*	32.1	1.59	0	38,600
39	Sassafras silt loam	Wilmington, Del.	18.3	*P*	7.5	1.72	3.8	7,440
40	Sharkey clay	New Orleans, La.	31.0	*P*	2.3	1.78	16.4	970
41	Summit silt loam	Kansas City, Mo.	28.1	*F*	6.9	1.61	14.6	1,320
42	Susquehanna clay	Meridian, Miss.	24.8	*F*	14.9	1.79	4.7	13,700
43	Tidal marsh	Elizabeth, N. J.	(b)	*VP*	(b)	(b)	(b)	60
44	Wabash silt loam	Omaha, Neb.	25.3	*G*	7.2	1.55	6.0	1,000
45	Unidentified alkali soil	Casper, Wyo.	10.5	*P*	18.7	(b)	0	263
46	Unidentified sandy loam	Denver, Colo.	7.2	*G*	23.2	(b)	0	1,500
47	Unidentified silt loam	Salt Lake City, Utah	21.1	*P*	2.6	1.72	3.7	1,700
51	Acadia clay	Spindletop, Tex.	39.9	*P*	1.4	2.07	37.9	190
52	Alkali knoll	League City, Tex.	36.6	*P*	3.7	[c] 1.97	33.9	234
53	Cecil clay loam	Atlanta, Ga.	29.9	*G*	18.2	1.60	7.0	30,000
67	Cinders	Milwaukee, Wis.	(b)	*VP*	(b)	(b)	(b)	455
54	Fairmount silt loam	Cincinnati, Ohio	19.8	*P*	4.7	1.96	6.1	886
55	Hagerstown silt loam	Baltimore, Md.	31.3	*G*	15.5	1.49	8.6	11,000
56	Lake Charles clay	El Vista, Tex.	32.2	*P*	5.0	2.03	30.1	406
57	Merced clay adobe	Tranquillity, Calif.	32.3	*P*	5.1	1.89	29.5	128
66	Mohave sandy loam	Phoenix, Ariz.	15.8	*G*	20.1	1.79	2.7	232
58	Muck	New Orleans, La.	56.3	*VP*	22.4	1.43	36.9	712
59	Peat	Kalamazoo, Mich.	(b)	*VP*	(b)	(b)	(b)	(b)
60	do	Plymouth, Ohio	40.2	*VP*	33.2	1.28	9.1	218
61	Sharkey clay	New Orleans, La.	31.0	*P*	2.3	1.78	16.4	970
62	Susquehanna clay	Meridian, Miss.	24.8	*F*	14.9	1.79	4.7	13,700
63	Tidal marsh	Charleston, S. C.	46.4	*VP*	19.5	1.47	18.8	84
64	Docas clay	Chalome Flats, Calif.	32.0	*VP*	4.7	1.88	27.7	62
65		Wilmington, Calif.	27.2	*F*	15.8	1.41	5.7	148
	AMERICAN GAS ASSOCIATION SITES							
1	Cinders	Pittsburgh, Pa.	18.1	*G*	(b)	(b)	(b)	730
2	do	Milwaukee, Wis.	9.5	*VP*	(b)	(b)	(b)	380
3	Tidal marsh	Brockton, Mass.	50.3	*VP*	(b)	(b)	(b)	44
4	do	Atlantic City, N. J.	93.7	*VP*	(b)	(b)	(b)	32
5	Muck	West Palm Beach, Fla.	74.2	*VP*	(b)	(b)	(b)	1,180
6	do	Miami, Fla.	29.1	*VP*	(b)	(b)	(b)	1,650
7	Cecil clay loam	Atlanta, Ga.	29.5	*G*	18.2	1.53	5.7	43,800
8	do	Raleigh, N. C.	32.7	*G*	6.6	1.51	8.0	16,000
9	Susquehanna clay	Shreveport, La.	31.2	*P*	5.3	2.01	18.9	6,843
10	Miller clay	do	28.9	*P*	2.0	2.00	16.5	6,843
11	do	Bryan, Tex.	43.0	*P*	1.5	1.98	36.4	1,000
12	White alkali soil	Los Angeles, Calif.	41.0	*P*	2.2	1.72	30.3	93
13	Black alkali soil	do	14.5	*G*	30.6	1.45	0	1,698
14	Marshall silt loam	Kansas City, Mo.	24.7	*G*	11.5	1.73	12.1	3,150

[a] Determinations by I. A. Denison, R. B. Hobbs, and I. C. Frost.
[b] Not determined.
[c] Measurement made on 20-mesh soil after centrifuging.

TABLE 2.—*Properties of soils at test sites*—Continued

Soil	Soil type	Location	Moisture equivalent	Aeration	Air pore space	Apparent specific gravity	Volume shrinkage	Resistivity at 60° F (15.6° C)
		AMERICAN PETROLEUM INSTITUTE SITES						
1	Bell clay	Temple, Tex	31.6	([b])	5.1	2.00	28.0	947
2	([b])	Arkansas City, Kans	20.7	([b])	19.2	1.76	5.1	1,295
3	Lake Charles clay	Beaumont, Tex	40.7	([b])	2.6	2.00	35.8	495
4	([b])	League City, Tex	21.1	([b])	5.1	1.93	6.7	1,485
5	Miami silt loam	Preble, Ind	21.5	([b])	6.9	1.87	6.4	2,201
6	([b])	Council Hill, Okla	25.4	([b])	5.5	1.78	11.6	5,180
7	([b])	Caney, Kans	20.6	([b])	13.8	2.04	7.2	3,510
8	([b])	Spindle Top Gulley, Tex.	7.6	([b])	2.9	2.04	42.7	259
9	([b])	Long Beach, Calif	9.8	([b])	29.9	1.47	0	353
10	Muscatine silt loam	Mt. Auburn, Ill	([b])	([b])	([b])	([b])	([b])	([b])
11	([b])	Skeatook, Okla	15.7	([b])	16.6	1.65	0	440
12	Merced clay loam	Mendota, Calif	36.8	([b])	7.2	1.84	31.2	61
13	Miller clay	Bunkie, La	38.0	([b])	2.5	2.01	30.2	674
14	Hagerstown silt loam	Chambersburg, Pa	21.3	([b])	8.3	1.46	1.4	5,088
16	([b])	Cholame, Calif	36.8	([b])	3.8	1.88	29.1	155

[b] Not determined.

2. BASIS FOR SELECTION OF TEST SITES

In all the tests of protective coatings the object has been to secure typical rather than destructive soils. It will be shown later that some soils to which certain of the coatings were exposed were neither destructive with respect to coatings nor corrosive with respect to unprotected steel. It is evident that the effectiveness of the coating is indicated by the condition of the protected metal only when the characteristics of the soil involved are known, and it obvious that two coatings cannot be compared unless they were exposed to similar soil conditions. For these reasons it is in many cases impossible to compare the coatings in the three tests.

Since this paper is not a report on the results of tests but is a compilation of information derived from various sources, only such soils and coatings are discussed as are of importance to users of protective coatings. Details of the behavior of coatings in the less-corrosive soils will be found in the reports referred to above.

IV. EFFECT OF SOIL PROPERTIES ON THE BEHAVIOR OF PROTECTIVE COATINGS [12]

It has been generally recognized that coatings applied to pipe lines are not equally effective under all soil conditions. From a number of field inspections Scott [13] and Ewing [14] concluded that the pressure exerted on the coating by the soil, the penetration of stones, clods, etc., and the expansion and contraction of the soil with changes in moisture content, tend to puncture and disrupt protective coatings. This is illustrated by figure 1. Taking the clay or colloidal content of soils as a rough measure of the tendency of soils to form hard clods, Ewing showed that the distortion of coatings is related to the softening

[12] Section IV was prepared by I. A. Denison.
[13] G. N. Scott. *The use and behavior of protective coatings on underground pipes.* Bul. Am. Petroleum Inst. **10**, 78 (1929); Proc. Ninth annual meeting.
[14] S. P. Ewing. *AGA-BS studies of a long gas line.* Am. Gas Assn. Monthly **13**, 70 (Feb. 1931).

point of the coating material and to the clay content of soils. Since the physical properties of soils are determined by the quality or physical behavior of the colloidal material as well as by its amount, it is not to be expected that this relation would apply generally.

In order to relate the distortive power of soils to a definite property of the soil, which is determined by the quality as well as by the quantity of colloidal material, Ewing[15] compared the distortion observed on the first set of coated specimens in the AGA test with the volume shrinkage of soils. Except for two soils, for which the shrinkage was relatively great, although little distortion occurred, the shrinkage values were indicative of degree of distortion. The method used by Ewing for determining shrinkage, although producing precise results, was open to the objection that it required thorough working of the moist soil. The consequent breaking down of the natural structure of the soil might be expected to produce degrees of shrinkage which would not be necessarily comparable to the shrinkage of soil which had not been subjected to mechanical pretreatment, as in nature.

Accordingly, in order to avoid this objection the method described in a previous section was adopted for determining the shrinkage of soil samples from the AGA and API test sites. As will be recalled, the moist soil is compressed by centrifugal force in order to throw out excess water and to produce, so far as possible, a weight per unit volume of soil equal to that of the natural, undisturbed soil.

The measure of distortion adopted was the electrical conductance per square foot of coal-tar enamel coatings, supplemented by visual examination of the coatings. Since conductance due to absorption of water by coal-tar enamels is negligible, at least for the period represented by the tests, the measured conductance of these coatings probably resulted from rupture or puncture of the coating by the soil. Coatings which failed for any other reason, such as cracking or the rupture of air bubbles, were either excluded from this study or the cause of failure was noted.

The conductances of the coal-tar enamel coatings in the AGA test after approximately 5½ years of exposure are shown in table 3 for comparison with the shrinkages of the soils. Values of shrinkage are given only for those soils in which this property may be expected to be a factor in distortion. The values for specific gravity of the soils in the field condition may be regarded as supplementing the shrinkage data. Since the specific gravity is a measure of the denseness of a soil clod, values for this property might be taken to indicate in a general way the relative hardness of clods.

It is apparent from table 3 that the maximum values for conductance occur in the soils having the highest capacity for shrinkage. For a coating of a given hardness and thickness it is generally true that the greater the shrinkage the more severe is the distortion as measured by conductance. High values for specific gravity also are seen to be associated usually with soils in which distortion is severe. In such soils, in addition to the distortion attributable to shrinkage, a distorting effect may result from contact with dense clods under pressure from the weight of the overlying soil.

[15] S. P. Ewing. *AGA studies of coatings for pipe lines, 1931.* Proc. Am. Gas. Assn. p. 774 (1931).

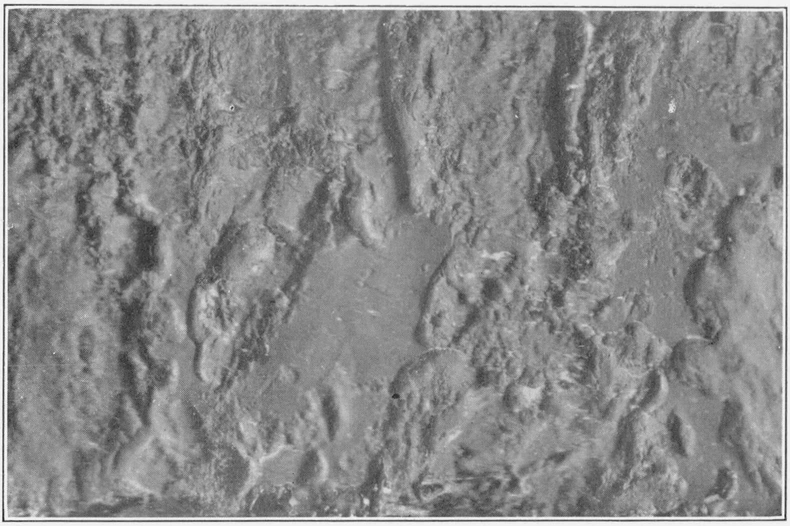

FIGURE 1.—*Distortion of a bituminous coating by clods.*

TABLE 3.—*Conductance of coal-tar enamels in AGA tests (third inspection)*

Coating	Ring and ball soften-ing point	Aver-age thick-ness	Conductance (in micromhos/ft²) at sites—							
			13	7	8	14	10	9	12	11
	° F	in.								
S	162	0.034	200	145	805	2,090	13,700	1,930	32,200	40,300
B	167	.038	564	-------	2,420	1,770	15,300	2,900	9,660	37,000
WR	184	.051	185	1,770	1,610	515	2,090	2,190	22,500	18,500
WL	184	.052	56	80	370	1.53	805	8,050	4,830	4,830
W	208	.058	600	0	12.2	0	805	250	0.056	137
A	232	.070	0	0	-------	25.8	15,300	338	2,900	29,000
Volume shrinkage			0	5.7	8.0	12.1	16.5	18.9	30.3	36.4
Apparent specific gravity			1.45	1.53	1.51	1.73	2.00	2.01	1.72	1.98

The high values for conductance observed in soils 9, 10, 11, 12 indicate that the attempt to protect a pipe line in such soils by most unreinforced coal-tar enamels would result in certain failure. However, the resistance to distortion shown by the thicker enamels of higher softening point in the lighter soils (nos. 7, 8, 13, and 14) raises the question whether such coatings would not provide adequate protection in such soils, provided of course that they could be applied perfectly to a pipe line.

It is not to be inferred from the emphasis which has been placed on shrinkage as a factor in distortion that other factors producing distortion have been overlooked. In fact, severe distortion has been produced in the AGA test in soils in which shrinkage was nonexistent. These soils, which are cinders at Milwaukee (site 2) and the muck soil at Miami (site 6), are continuously wet and therefore not subject to shrinkage. Although distortion is usually severe at these sites, it is sufficient that such conditions can be recognized and appropriate measures of protection taken to prevent distortion.

In order to study further the influence of soil shrinkage on the distortion of protective coatings, the condition of the enamel coatings which were applied to short pipe sections in the API test was compared with the shrinkage values of soils from the corresponding test sites. The periods of exposure for which data are available are approximately 2 and 4 years. Because of the fact that relatively few of the harder enamel coatings showed appreciable conductance, a more sensitive indication of distortion was provided by visual examination of the coatings. In table 4 the results of this examination which pertain to distortion are shown for comparison with the values for shrinkage. The table shows the average condition of the eight coal-tar enamels. In expressing the results of the inspection, three separate classifications of distortion were made, namely, (1) surface distortion to a depth of 10 mils; (2) distortion greater than 10 mils; and (3) number of punctures. To express the extent of surface represented by the first two classes, numbers from 1 to 3 were assigned which have the following meaning: (1) distorted area less than 10 in.² on total area of 1 ft²; (2) distorted area between 10 and 50 in.²; and (3) distorted area greater than 50 in². The number of punctures from one to three are indicated. The number 3, however, may indicate any number of punctures greater than three.

With the exception of the data for sites IV and VI, it is evident that distortion tends to increase with increasing shrinkage. Excepting these two sites, very few punctures of the coating have occurred in any soils having a shrinkage below 10 percent. Much superficial roughening of the surface, as shown for example by the coatings from site IX, may represent merely the roughening attributable to imbedded sand particles and as such may have little significance. It is surprising that such severe distortion should occur at sites IV and VI, and it appears that a factor other than shrinkage is the probable cause of distortion in these soils.

By comparing the condition of the coatings at the end of the 2- and 4-year periods (table 4), it is seen that in those soils in which distortion is marked, the condition of the coatings is generally worse at the later inspection. This evidence of progressive distortion suggests that temporary measures to resist soil stress can be only partly successful.

TABLE 4.—*Average conditions of coal-tar enamels on short pipe sections (1934 inspections API tests)*

Site	Volume shrinkage	Exposure	Distortion [a]		
			Surface	>10 mils	Puncture
	%	yr			
IX	0	2	3.0	0.4	0
		4	2.6	.3	0
XI	0	2	2.9	1.4	.3
		4	1.9	1.3	.4
XIV	1.4	2	3.0	0.5	.4
		4	2.6	.3	.3
II	5.1	2	2.6	.3	.1
		4	2.1	.3	0
V	6.4	2	2.9	0	0
		4	2.9	0	.1
IV	7.2	2	2.3	1.8	.8
		4	3.0	2.8	1.6
VII	7.2	2	2.9	1.4	0
		4	2.9	1.4	.1
X	[b] 7.5	2	3.0	1.3	0
		4	2.6	0.8	0
VI	11.6	2	3.0	2.3	1.1
		4	3.0	2.6	2.1
I	28.0	2	2.1	1.8	1.9
		4	3.0	2.9	1.8
XVI	29.1	2	2.8	1.8	.1
		4	2.1	1.9	1.1
XIII	30.2	2	2.3	1.5	0.5
		4	2.6	1.8	.9
III	35.8	2	1.5	1.6	.5
		4	3.0	2.1	1.3

[a] The values used to indicate surface and subsurface distortion are averages of numerals which have the following meaning:
1. Distorted area less than 10 in.^{2}/ft.^{2}
2. Distorted area between 10 and 50 in.^{2}/ft.^{2}
3. Distorted area greater than 50 in.^{2}/ft.^{2}

As applied to punctures, the numerals give the number of punctures, except that the numeral 3 is also applied to any number greater than 3.

[b] Data from same soil type at National Bureau of Standards test site 30.

Thus far, study of the effect of soil properties on the distortion of protective coatings has been confined to observations made on short lengths of coated pipe. The study was extended to include the effects of soil stress on coatings under actual service conditions by comparing the conductances of the harder coal-tar enamels applied to the operating lines in the API test with the properties of the soils at the test sites.

Comparison between the effects of distortion, as measured by the conductance of the coating and the shrinkage of the soils, is complicated somewhat by the fact that coatings conduct current not only because of ruptures caused by soil stress but also because of a variety of other causes, such as mechanical abrasion, cracking, etc. However, since the coatings were carefully examined at each inspection period, it is possible in the case of each value of conductance to state whether or not the conductance was due chiefly to soil stress. In table 5 the conductances of the three harder coal-tar enamels in the API test are given for each test site for each of the three periods of inspection insofar as data were available. The values for shrinkage and apparent specific gravity of the soil samples are shown for the purpose of comparison.

TABLE 5.—*Comparison of certain soil properties with conductance of coal-tar enamels on operating lines in API tests*

Site	Volume shrinkage	Apparent specific gravity	Exposure	Conductance of coatings [a] (micromhos/ft.^{2})		
				K	*L*	*N*
	%		yr			
IX	0	1.47	1	----------	145	165
			2	----------	[b] 90	[c] 225
			4	----------	19	32
XI	0	1.65	1	300	95	[d] 1,440
			2	[d] 2,900	720	[d] 5,155
			4	[e] 220	280	[e] 1,225
XIV	1.4	1.46	1	[d] 20,000	----------	----------
			2	1,800	----------	----------
			4	780	----------	----------
II	5.1	1.76	1	----------	0.01	0.22
			2	[e] 2,100	190	[b] 60
			4	[e] 23,250	95	2,100
V	6.4	1.87	1	[d] 1,110	----------	----------
			2	[b] 2,750	----------	----------
			4	[b,e] 2,850	----------	----------
VII	7.2	2.04	1	[d] 430	0.07	196
			2	120	0.0	729
			4	205	.05	[b] 55
X	7.5	1.81	1	0	0.1	0
			2	.02	490	[f] 620
			4	36	225	[b] 272
VI	11.6	1.78	1	1.0	14,300	925
			2	450	10,300	700
			4	220	2,400	625
XVI	29.1	1.88	1	----------	44,000	44,000
			2	----------	44,000	44,000
			4	----------	30,000	37,500
XIII	30.2	2.01	1	2,150	----------	----------
			2	[b,c] 1,020	----------	----------
			4	2,000	----------	----------
XII	31.2	1.84	1	----------	21,100	29,500
			2	----------	15,500	34,500
			4	----------	17,500	23,500
III	35.8	2.00	1	22,000	9,295	10,220
			2	5,900	25,900	2,450
			4	1,185	8,300	1,518
VIII	42.7	2.04	1	----------	44,000	9,900
			2	----------	33,500	1,090
			4	----------	16,000	6,400

[a] For characteristics of these coatings see table 1, and for their thickness see table 16.
[b] Ruptured air holes.
[c] Abrasion.
[d] Mechanical injury.
[e] Cracked.
[f] Holidays.

It is evident from table 5 that severe distortion, as indicated by high values of conductance, is confined chiefly to the soils having high shrinkage values. It will be noted that in all of the soils in which the shrinkage is less than 10 percent the conductances are not only usually small but, in most cases, are due to causes other than distortion. The rather marked distortion observed at site VI cannot be accounted for by the rather small shrinkage of 11.6 percent, shown by this soil.

Although the coated sections were inspected carefully at the time the conductance measurements were made in order to determine the cause of the conductance, it was impossible to detect minor defects in the condition of the coating, such as pinholes due to faulty application. Consequently, it cannot be concluded that even the small conductances shown by the specimens in certain soils were actually due to soil stress. In fact, Ewing [16] has concluded that the application of the coatings applied to the line by hand was usually imperfect. It would appear therefore that soil stress is a negligible factor in the behavior of the coal-tar enamels in sites II, V, VII, IX, X, XI, and XIV. The soils at these sites show shrinkages under 10 percent.

In addition to the mechanical action of soils on protective coatings, the drainage or aeration of the soil has an important influence on the performance of coatings. Ewing [17] concluded that the number of coated specimens in the AGA test which were pitted at the end of 5½ years of exposure was lower in the well-drained soils than in the poorly drained soils. Because of the good areation associated with well-drained soils, ferrous ions formed in the process of corrosion are readily oxidized and precipitated in the pinholes in the coating as the difficultly soluble ferric hydroxide. The sealing of these holes by the dense, tightly adherent precipitate results in the cessation of corrosion. On the other hand, because of the deficiency of oxygen in poorly drained soils, ferrous ions remain in the deoxidized condition and diffuse through the ruptures in the coating without being precipitated. Under these conditions the process of corrosion proceeds without interruption.

In a further study of the relation between the areation of the soils at the AGA test sites and the performance of certain classes of coatings, the soils were classified according to degree of aeration. For each of the two classes of coatings studied, the cutbacks and the asphalt emulsions, the deepest pits on the coated specimens at each test site were averaged and the ratios of these pits to the depth of deepest pits on the corresponding bare specimens were calculated. The data were then arranged as shown in table 6.

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[16] S. P. Ewing. *AGA field tests of pipe coatings, 1936.* Proc. Am. Gas Assn. p. 627 (1936).
[17] See footnote 16.

TABLE 6.—*Ratio of depth of deepest pit on coated pipe to pit depth on bare pipe, for soils differing in degree of aeration (AGA tests)*

[Approximate exposure 5.5 years]

Aeration very poor

Soil	Soil type	Pit depth on coated pipe / Pit depth on bare pipe: Average of 4 cutbacks	Pit depth on coated pipe / Pit depth on bare pipe: Average of 5 asphalt emulsions
4	Tidal marsh	2.40	0.96
6	Muck	0.51	.21
3	Tidal marsh	2.60	1.16
5	Muck	0.42	0.47
2	Cinders	.79	.69
	Average	1.34	0.70

Aeration poor

Soil	Soil type	Pit depth on coated pipe / Pit depth on bare pipe: Average of 4 cutbacks	Pit depth on coated pipe / Pit depth on bare pipe: Average of 5 asphalt emulsions
12	White alkali	0.30	0.48
11	Miller clay	.52	.39
10	Miller clay	.29	.60
9	Susquehanna clay	.54	.61
	Average	0.41	0.52

Aeration good

Soil	Soil type	Pit depth on coated pipe / Pit depth on bare pipe: Average of 4 cutbacks	Pit depth on coated pipe / Pit depth on bare pipe: Average of 5 asphalt emulsions
14	Marshall silt loam	0.21	0.24
13	Black alkali	.37	.13
8	Cecil clay loam	.12	.37
7	Cecil clay loam	.18	.18
1	Cinders	.48	.33
	Average	0.27	0.25

It is evident from table 6 that the effectiveness of cutbacks and asphalt emulsions depends largely on the aeration of the soil. Under conditions of good aeration, they are effective in reducing the rate of

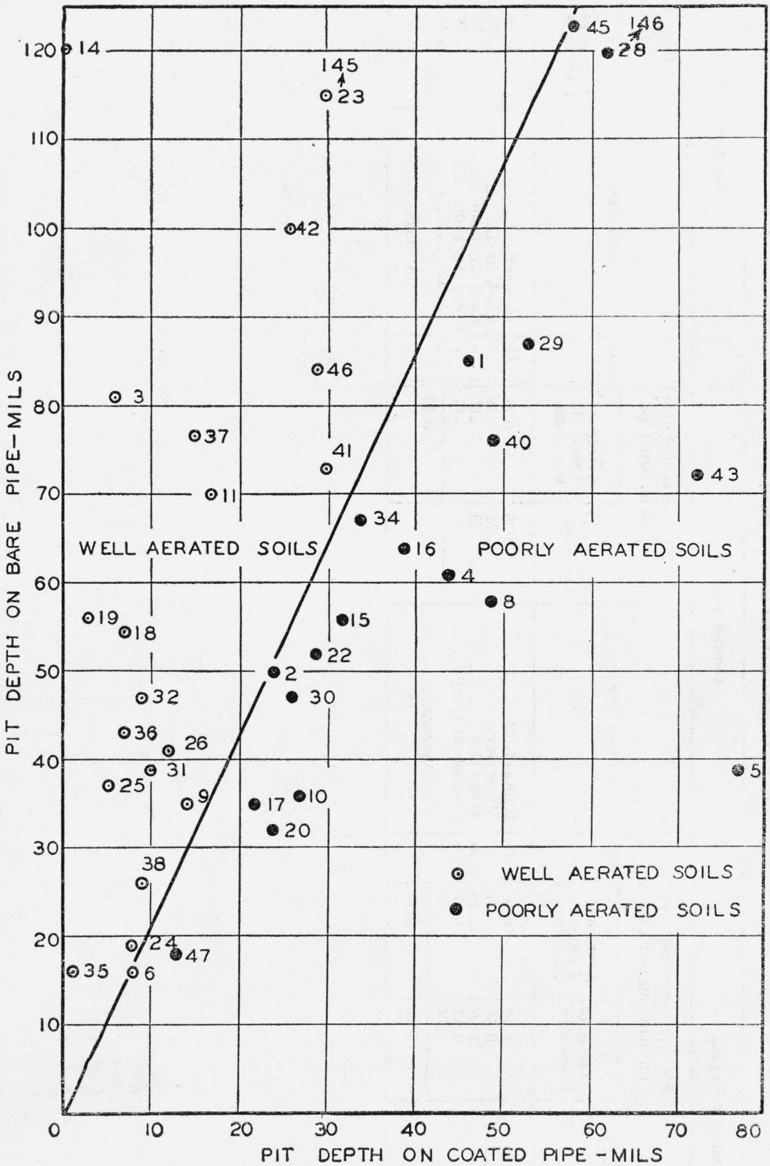

Fig. 2.—Comparison between depths of pits on coated and bare pipe.

pitting, but under conditions of very poor aeration they are usually worthless.

The measurements of depths of pits on sections of coated pipe after burial for 10 years in the Bureau test provide a further opportunity for studying the effect of soil properties on the behavior of thin, porous coatings. The coatings examined are referred to as nos. 4 and 7, in the publication in which they were described.[18] Both coatings were applied by dipping. No. 4 is a Mexican asphalt with an average thickness of 0.011 in. No. 7 is a soft coal-tar pitch with a thickness of about 0.007 in. In addition to these coatings there were buried in six soils an additional group of thin coatings consisting of various types of asphalts and coal tars (nos. 1, 2, 3, 5, 6, 8, 9). All of these coatings were applied to steel pipe 1½ inches in diameter and 17 inches long.

The effect of the soils on the behavior of these coatings was studied by comparing the average depths of the five deepest pits on the specimens with the average depth of the five deepest pits on an equal area of bare steel pipe exposed for the same length of time. The data are expressed as the averages of the five deepest pits on each specimen rather than the maximum pit, in order to represent the average or over-all condition of the coating in the particular soil.

For each of the soils, except nos. 23, 24, 28, 29, 43, and 45, the value for the depth of pit on the coated pipe is obtained by averaging the mean depth of the five deepest pits on specimens 4 and 7. The values for the soils enumerated above are averages of the mean depth of the five deepest pits on specimens 1 to 9, inclusive. This comparison is shown graphically in figure 2.

It is seen from the figure that the soils fall naturally into two groups with respect to their effect on the behavior of thin coatings. For any specified depth of pit on the bare pipe the pit depth on coated pipe is greater in poorly aerated soils than in well aerated soils. In fact, it is only in the latter that these coatings have had any important protective value.

The benefit of thin coatings in the reduction of pitting in well-drained soils is more apparent than real, since in few of the well-drained soils in either the AGA or the Bureau test would a coating of any kind likely be specified. Although the depths of pits in many of these soils would be considered large for the period of exposure, it has been concluded from a study of pit depth-time curves typical of these soils that these pits are not likely to increase to a considerable extent with time.

V. EFFECTIVENESS OF PROTECTIVE COATINGS

1. CRITERION FOR EFFECTIVENESS

The proper criterion from which the effectiveness of a protective coating should be determined has not been established. At one time a number of manufacturers of protective coatings promulgated an elaborate form for the recording of observations when a coating was to be inspected. The form was intended to show how and why the coating changed as well as the extent of its deterioration. Ewing and Scott used three criteria for studying the behavior of coatings: (1) the pattern test which indicates the presence or absence of pinholes and other flaws in the coating; (2) the electrical conductance test which indicates the extent to which moisture has reached the pipe through flaws, pinholes, or absorption; and (3) the condition of the pipe be-

[18] K. H. Logan, S. P. Ewing, and C. D. Yeomans. *Bureau of Standards soil-corrosion studies. I. Soils, materials, and results of early observations.* Tech. Pap. BS 22, 447 (1928) T368, 50¢.

neath the coating. Both Ewing and Scott modified their methods of making pattern and conductance tests in the course of their investigations, and it is for this reason the results of these tests from year to year cannot be compared directly.

If the condition of the pipe is expressed in terms of the depth of the deepest pit, the result depends partly on the corrosiveness of the soil to which the pipe was exposed and the time required for the soil solution to reach the metal beneath the coating. A soil might be destructive to a coating and not be corrosive, or it might be corrosive and not destructive with respect to coatings. Nevertheless, the pipe-line operator is interested chiefly in the extent to which protective coatings will reduce corrosion. From this viewpoint the greatest amount of information can be obtained by an examination of data on the condition of the surface of pipes from which coatings have been removed. This procedure is subject to the serious objection that since the condition of the pipe is determined by the corrosiveness of the soil a comparison of coatings is possible only when they have been exposed to the same soil conditions. Unfortunately, few of the many coatings to be discussed in this paper were so exposed. For this reason the data presented herewith must be used with care if comparisons are made. Because of this peculiarity of the data an attempt has been made in certain parts of the paper to express the effectiveness of the coatings in terms of the leaks to be expected when the coatings are used under certain conditions. Obviously, if the soil were less corrosive or the pipe wall thicker the number of leaks would be reduced.

In weighing the data on protective coatings the question arises as to the relative merits of tests of coatings on working lines and on short lengths of small-diameter pipe. Scott [19] reached the conclusion that tests of coatings which differ greatly in structure on short lengths of pipe do not in general agree closely with line tests when the coatings are arranged in order of their behavior. He regards the tests on short lengths of pipe as useful in eliminating very poor coatings and in the study of the relative merits of coatings belonging to the same class. He also concluded that the tests of coatings on working lines are more severe than on small-pipe sections. Ewing [20] concludes that the two tests give similar results when conditions of application of the coating are the same and that it is impracticable to apply a coating satisfactorily by hand in the field.

It is probable that the apparently poorer performance with respect to corrosion of some coatings when applied to working lines is the result of the inspection of larger pipe areas. These conclusions are of great importance to anyone who is interested in the effectiveness of protective coatings. In this paper data from both types of tests have been used, but greater weight has been given to the line tests because it was felt that these more nearly simulated practical pipe-line conditions.

2. CUTBACKS

Bituminous materials reduced to a paint-like consistency by the addition of a volatile solvent are called cutbacks. They are applied to the pipe by spraying, brushing, or dipping. After exposure to the air for a few hours they form a thin paint-like coating. Their chief

[19] G. N. Scott. *API coating tests.* Proc. Am. Petroleum Inst. **15**, pt. IV, 18 p. (1934).
[20] S. P. Ewing. *AGA field tests of pipe coatings.* Proc. Am. Gas Assn., p. 627 (1936).

virtues are low cost and ease of application. Cutbacks are made from two classes of materials—coal-tar pitches and asphalts. Some also contain finely divided mineral matter. All of the cutback-coated pipes reported on in table 7 were either primed with a bituminous primer or coated with two applications of the cutback. Nevertheless, nearly all of the coatings contained numerous pinholes, as indicated by the electrical tests. Table 7 reveals the fact that on the average the asphalt-base cutbacks were thicker than the coal-tar base materials. It will also be seen that the former type showed slightly less corrosion. Generally speaking, the thicker coatings were superior to the thinner ones.

TABLE 7.—*Performance of cutback coatings*

			Asphalt base					Coal-tar-pitch base				
Average exposure	Sponsor	Number of soils	Identification	Thickness	Pipes corroded	Pipes with pits deeper than 9 mils	Pipes with pits deeper than on bare pipes	Identification	Thickness	Pipes corroded	Pipes with pits deeper than 9 mils	Pipes with pits deeper than on bare pipes
yr				in.	%	%	%		in.	%	%	%
0.78	AGA	11	*M*	0.010	100	18	9	*SS*	0.007	100	18	9
.78	AGA	11	*L*	.024	100	18	9	*K*	.009	100	18	9
.96	API	8						*C*	.020	100	56	44
1.82	API	14	*cc*	.045	79	14	0	*zx*	.012	100	29	7
1.82	API	14	*u*	.047	100	36	7	*b*	.020	86	14	0
1.84	API	8						*C*	.020	100	100	44
2.44	AGA	14	*M*	.010	86	43	14	*SS*	.007	100	71	14
2.44	AGA	14	*L*	.024	71	36	0	*K*	.009	100	71	7
3.78	API	14	*cc*	.045	100	36	7	*zx*	.012	100	50	0
3.78	API	14	*u*	.047	100	43	7	*b*	.020	100	57	14
3.83	API	8						*C*	.020	100	75	36
5.47	AGA	14	*M*	.010	100	71	14	*SS*	.007	100	100	14
5.47	AGA	14	*L*	.024	100	64	14	*K*	.009	100	93	21

A very large percentage of each variety of cutback coating failed to protect completely the pipe to which it was applied for as much as 2 years. After the initial periods of exposure, from 14 to 56 percent of the specimens were definitely pitted. In several instances the maximum pits on the coated specimens were deeper than on the corresponding bare specimens. The performance of the best of these materials is not good enough to justify its use. Since the data cover the performance of nine varieties of cutback coatings furnished by some of the leading manufacturers of this type of material, the conclusion seems justified that it is improbable that any coating of this type will prove satisfactory for the permanent protection of metal placed underground. Cutbacks reduce temporarily the total amount of corrosion and make the pipe easier to clean. They may be used to advantage on temporary lines or lines which are to receive a heavier coating if the soil proves to be corrosive.

3. SHIELDED CUTBACKS

The effect of protecting cutbacks from direct contact with the soil is shown in table 8. In considering this table it should be kept in mind that each coating consisted of a primer and two coats of the cutback in addition to the wrapper.

Coatings *Y* and *x* are quite similar in composition and differ chiefly in thickness. Coating *Y* was applied to working oil lines, while coating *x* was applied to a 2-foot length of 3-inch outside-diameter pipe. Both coatings were covered with aluminum foil. It will be noted from table 8 that although coating *Y* is 50 percent thicker than coating *x*, its record is not nearly so good. This is partly because the successful application of a coating in the field is more difficult than in a shop and partly because the area examined for pits beneath coating *Y* was considerably greater. In addition, the pipe line may have been affected by long-line currents, difference of potential between top and bottom of the pipe, and soil pressure attributable to the weight of the pipe.

TABLE 8.—*Performance of shielded asphalt-base cutbacks*

Exposure	Number of soils	Identification	Thickness (3 coats without shields)	Pipes corroded	Pipes with pits deeper than 9 mils	Pipes with pits deeper than on bare pipe
yr			in.	%	%	%
0.96	10	*Y*	0.029	65	10	10
1.84	10	*Y*	.029	85	40	15
1.82	14	*x*	.018	57	7	0
1.82	14	*l*	.081	85	7	0
3.78	10	*Y*	.029	95	55	10
3.78	14	*x*	.018	86	21	7
3.78	14	*l*	.081	100	43	0

Table 8 shows that under coating *l*, which was four times as thick as coating *x*, the pipe was pitted in a larger percentage of cases. While this result might be attributed to some difference in the coating material, this explanation does not seem adequate since table 7 indicates that the variety of cutback is not very important. A better explanation is that coating *x* was shielded by aluminum foil, which is stiffer and more nearly permanent than the kraft paper which shielded coating *l*. The aluminum may have afforded some cathodic protection also. Comparison of tables 7 and 8 indicates that the application of a shield reduced the pitting of the specimens. It cannot be said, however, that table 8 indicates that a shielded cutback coating gives satisfactory protection against corrosive soils.

4. EMULSIONS

For a proper application of the cutbacks, which have been discussed above, the surface of the metal to be coated must be clean and dry. This is a condition difficult to obtain under field conditions, and it is especially difficult when the pipe has been reconditioned. A satisfactory coating which could be applied to a moist pipe would have an advantage over one that could not, other things being equal. Since asphalt emulsions can be applied to moist pipe, their value as pipe coatings is of particular interest.

Table 9 is a summary of the data on emulsion coatings. These data are derived from two sources, the AGA and the API field exposures, as indicated in the table. Data from the two sources are not comparable because of differences in test sites and periods of exposure. The data in table 9 have been arranged according to the period of exposure of the specimens and secondarily according to the thickness of the coating. The data on the simple and reinforced or shielded specimens have been separated. Those on the same horizontal line are not necessarily for specimens having the same base material.

TABLE 9.—*Performance of emulsion coatings*

Emulsions								Shielded and reinforced emulsions					
Exposure	Sponsor	Number of soils	Identification	Thickness	Pipes corroded	Pipes with pits deeper than 9 mils	Pipes with pits deeper than on bare pipe	Identification	Thickness	Shield	Pipes corroded	Pipes with pits deeper than 9 mils	Pipes with pits deeper than on bare pipe
yr				in.	%	%	%		in.		%	%	%
0.78	AGA	11	*G*	0.016	100	25	25	------	------	------	------	------	------
.78	AGA	11	*E*	.047	91	0	0	*EE*	0.061	Neat cement	100	0	0
.78	AGA	11	*F*[1]	.082	100	0	0	*FF*[1]	.029	Cement added	100	18	9
.96	API	9	*A*[1]	.065	100	50	39	------	------	------	------	------	------
1.82	API	14	*j*	.015	100	64	21	------	------	------	------	------	------
1.82	API	14	*ppp*[2]	.015	100	29	7	------	------	------	------	------	------
1.82	API	14	*fff*[1]	.037	100	64	0	*ff*[1]	.190	Cement mortar	43	0	0
1.82	API	9	*A*[1]	.065	100	67	33	*f*[1]	.149	Asbestos felt	43	0	0
2.44	AGA	14	*G*	.016	100	71	7	------	------	------	------	------	------
2.44	AGA	14	*E*	.047	33	43	7	*EE*	.061	Neat cement	100	7	0
2.44	AGA	14	*F*[1]	.082	64	14	0	*FF*	.029	Cement added	100	70	0
3.78	API	14	*j*	.015	100	79	21	------	------	------	------	------	------
3.78	API	14	*ppp*[2]	.015	100	50	7	------	------	------	------	------	------
3.78	API	14	*fff*[1]	.037	100	93	29	*ff*[1]	.190	Cement mortar	57	0	0
3.78	API	9	*A*[1]	.065	100	89	40	*f*[1]	.149	Asbestos felt	64	0	0
5.47	AGA	14	*G*	.016	100	93	21	------	------	------	------	------	------
5.47	AGA	14	*E*	.047	100	86	14	*EE*	.061	Neat cement	100	36	7
5.47	AGA	14	*F*[1]	.082	100	50	0	*FF*[1]	.029	Cement added	100	72	7

[1] Contains a chromate inhibitor.
[2] Applied over a priming coat of red-lead paint baked on.

Asphalt emulsions are made from several kinds of asphalt and by the use of many emulsifying agents and methods. Several types of emulsions are represented in table 9; but because of other variables mentioned above, it is not possible to determine the effect of the kind of asphalt or the method of emulsification. However, the table gives a general idea as to what may be expected from emulsions as pipe coatings.

Table 9 indicates, as do tables 7 and 8, that very thin coatings are unsatisfactory. The common characteristic of all of the emulsion coatings is the development of corrosion beneath them within a short time after they have been exposed to soil. This is evidence that this type of coating is not impervious to moisture since, in many cases, the corrosion is too severe to be accounted for by the water originally in the coating. This statement is also supported by the fact that for all types of emulsions corrosion is progressive, i. e., the percentage of specimens with measurable pits increases with the period of exposure.

Coating *ppp* differs from coatings *G* and *j* in that a primer of red-lead paint was used beneath the emulsion. This apparently increased the effectiveness of the coating, but none in this group could be considered satisfactory.

Several of the emulsions contained a chromate intended to inhibit corrosion. It is evident from the table that the inhibiting agent was not completely effective.

Although corrosion was observed under most of the coatings, probably because they did not exclude moisture, the specimens protected by the thickest coatings showed less pitting. This is probably because the thickest coatings prevented direct contact between soil particles and the pipe. The improvement in performance because of the use of a shield is quite evident. Although rust was found under the concrete shielded coating, *ff*, no pits developed within approximately 4 years. When the relative thicknesses of the concrete and the emulsion are considered, it is doubtful whether coating *ff* should be classified as an emulsion or as a cement-mortar coating.

The results of the tests of asphalt emulsion coatings may be summarized in the statement that this type of coating is inadequate as a protection against corrosive soils.

5. DIP COATINGS

(a) FOR WROUGHT PIPE

Bituminous coatings are frequently applied to pipe by dipping the latter in a tank of molten coal-tar pitch or asphalt. The process may be repeated after the pipe has cooled in order to reduce the number of pinholes and to produce a thicker coating. The thickness of the coating will depend somewhat on the temperature at which the bitumen is maintained in the dipping vat, but in most cases, the coating is not much thicker than a paint.

In 1924 the National Bureau of Standards buried specimens of coal-tar pitch and asphalt coatings in 47 soils. In seven of these soils nine varieties of coatings were placed. However, as all of the coatings behaved similarly and all proved inadequate, it seems sufficient to present only the data on the coatings which were exposed to all soils. The data for 10-year-old specimens given in table 10 have not been previously published. For this reason more detailed data are presented. The table shows also the condition of bare pipe having approximately the same area exposed to the soil.

While several of the soils listed in table 10 are very corrosive, as indicated by the last column of the table, others are only moderately so. The rates of corrosion in a number of the latter are so low that unprotected pipe would last a long time. The data in table 10 are therefore more favorable to the coatings than they would have been if the tests had been confined to corrosive soils. This is also indicated by the data for the 8-year-old specimens in table 11, which summarizes the data on the dip coatings for all periods of exposure. Eight-year-old specimens were not removed from the less corrosive soils. It will be noted that for this period the average condition of the specimens is much worse than for the 6-year period and almost as bad as for the 10-year period of exposure.

TABLE 10.—*Pit depths on pipes protected by asphalt and coal-tar-pitch dip coatings*

[Exposures of approximately 10 years]

(Pit depth in mils)

Soil type	Asphalt coating	Coal-tar pitch coating	Bare steel
Allis silt loam	99	53	92
Bell clay	32	28	79
Cecil clay loam	14	11	85
Chester loam	63	46	72
Dublin clay loam	37	145+[a]	45
Everett gravelly sandy loam	*M*[b]	22	20
Fairmount silt loam	22	22	39
Fargo clay loam	101	42	62
Genessee silt loam	25	31	54
Gloucester sandy loam	56	22	42
Hagerstown loam	50	29	73
Hanford fine sandy loam	14	*M*[b]	43
Hempstead silt loam	22	*M*[b]	145
Houston black clay	60	36	61
Kalmia fine sandy loam	53	45	74
Keyport loam	29	24	38
Knox silt loam	13	20	61
Lindley silt loam	*M*[b]	14	58
Mahoning silt loam	35	28	36
Memphis silt loam	37	28	64
Merced silt loam	25	35	145+[a]
Merrimac gravelly sandy loam		14	25
Miami clay loam	13	12	42
Miami silt loam	23	22	46
Montezuma clay adobe	54	75	103
Muck	79	52	93
Muscatine silt loam	27	90	53
Norfolk sand	33	13	36
Ontario loam	14	17	50
Peat	46		93
Penn silt loam	48	53	131
Ramona loam	*M*[b]	12	27
Ruston sandy loam	*M*[b]	18	47
St. Johns fine sand	18	17	87
Sassafras gravelly sandy loam	19	*M*[b]	32
Sharkey clay	66	47	92
Summit silt loam	40	33	84
Susquehanna clay	*U*[c]	42	116
Tidal marsh	*M*[b]	145+[a]	82
Alkali soil	70	42	150
Unidentified sandy loam	32	39	98
Unidentified silt loam	*M*[b]	37	28

[a] Pipe wall punctured.
[b] Metal attack.
[c] Unaffected.

TABLE 11.—*Summary of data on dip coatings*

Average approximate exposure	Number of soils	Identification number	Thickness	Pipes corroded	Pipes with pits deeper than 9 mils	Pipes with pits deeper than those on bare pipes
yr			*Mils*	%	%	%
2.4	44	4	0.011	77	34	9
2.4	44	7	.007	82	43	9
6.4	43	4	.011	98	42	16
6.4	43	7	.007	100	42	7
8.4	21	4	.011	100	76	9.5
8.4	22	7	.007	100	86	4.5
10.3	40	4	.011	98	80	7.5
10.3	41	7	.007	100	90	12.2

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There seems to be a slight difference between the asphalt (no. 4) and the coal-tar-pitch (no. 7) coatings in favor of the former. This is probably due to the greater thickness of this coating.

Table 10 and 11 show again that thin bituminous coatings do not afford adequate protection against soils. Three-fourths of the specimens were found to be corroded when they were first removed and a third of them were pitted.

(b) FOR CAST-IRON PIPE

For many years the specifications of the American Water Works Association have included a requirement that the pipe shall be coated inside and out with coal-tar-pitch varnish to be applied by dipping the heated pipe in the heated varnish. In order to obtain some idea of the effectiveness of this coating, sections of 4-inch cast-iron pipe, coated according to these specifications in the ordinary course of pipe manufacture, were cut into 17-inch lengths. Since the coating was injured in places in the course of cutting the pipe, the injured spots were repaired with a solution of the same material applied by a brush. Specimens of this pipe were buried in several corrosive soils in 1926, the pipes being filled with soil from the trench.

When the pipes were returned to the Bureau they were split and both the inside and outside surfaces were examined. Table 12 shows the results of the examination of the specimens removed in 1934. To make the data comparable with data on 6-inch lengths of bare pipes, each 17-inch section was divided into three equal parts. The deepest pit on each part was measured and the average of these pit depths was recorded as the maximum pit. Measurements were made on the outside of the pipe, on the inside, and on the ends which were unprotected. The last-named measurement, together with the maximum pits on the bare specimens of 6-inch cast-iron pipe 6 inches long, indicates the corrosiveness of the soil. The differences between the pit depths on the coated and uncoated sections indicate the effectiveness of the coating.

TABLE 12.—*Pit depths on coated and uncoated cast-iron pipe*

[Approximately 8-years old; pit depth in mils]

Soil	Pit depth			
	Coated pipe		Bare pipe	
	Inside	Outside	End	6-in. cast-iron pipe 6 in. long
3	13	39	75	202
23	19	21	77	230
29	37	60	100	206
40	34	77	50	182
42	11	79	230	117
43	17	42	375	83
45	33	57	95	99
47	9	45	34	23

It is impossible to determine positively why the pit depths on the inside of the pipe were so much shallower than those on the outside of the same pipes. Conditions inside the pipe may have been less corrosive because of different packing of the soil or the coating may have been thicker. It is improbable that the coating on the outside of the pipe was injured before the pipes were buried since they were packed in sawdust for transportation.

It is evident from table 12 that in most cases the coating materially reduced the depths of the maximum pits. It is also evident that, as in the case of other thin coatings, the protection was imperfect. Pattern tests indicated that the coating contained many fine holes, and conductance tests showed that the electrical resistance of the coating was negligible.

6. THICK UNFILLED COATINGS

When the National Bureau of Standards soil-corrosion investigation was started in 1922, specimens of four types of bituminous coatings were included. Two of these were asphalt-base coatings and two coal tar-pitch-base materials. One coating of each material was reinforced by loosely woven cotton fabric somewhat heavier than cheese-cloth.

Specimens of these coatings were removed after 4 and after 12 years of exposure. The pit depths on the pipes to which the coatings were applied are shown in table 13. The unreinforced pitch had so low a softening point, 96° F, that it flowed from the top of the pipe in many soils. For this reason the effect of thickness cannot be determined from the performance of this coating.

TABLE 13.—*Behavior of unfilled thick coatings*

[Pit depth in mils.]

Soil type	4 years' exposure					12 years' exposure				
	Pitch		Asphalt		Steel	Pitch		Asphalt		Steel
	Unreinforced	Reinforced	Unreinforced	Reinforced	Bare	Unreinforced	Reinforced	Unreinforced	Reinforced	Bare
Allis silt loam	62	[a] *U*	*U*	[b] *R*	41	65	20	[c] *M*	55	100
Cecil clay loam	20	*U*	*R*	*R*	63	25	*R*	21	12	78
Chester loam	10	*U*	*U*	*R*	36	67	29	38	23	115
Fairmount silt loam	-----	-----	-----	-----	-----	54	*U*	29	18	59
Fargo clay loam	20	*U*	*R*	*R*	64	70	*M*	72	16	104
Genessee silt loam	23	*U*	*R*	*U*	60	91	*U*	*M*	30	49
Gloucester sandy loam	20	*U*	*R*	*R*	10	42	10	33	16	70
Hagerstown loam	38	*U*	*R*	*R*	70	-----	-----	-----	-----	73
Hemford fine sandy loam	-----	-----	-----	-----	-----	23	*U*	19	*M*	60
Hanford very fine sandy loam	38	*U*	*R*	*R*	73	-----	-----	-----	-----	-----
Hempstead silt loam	*R*	*U*	*R*	*R*	63	53	*U*	*R*	*R*	88
Kalmia fine sandy loam	24	*U*	*R*	*R*	56	101	*U*	21	25	100
Keyport loam	22	*U*	*U*	*R*	30	68	*U*	*M*	12	48
Knox silt loam	32	*U*	*U*	*R*	57	33	*U*	17	39	76
Lindley silt loam	30	*U*	*R*	*R*	54	23	*R*	*R*	25	93
Mahoning silt loam	30	*U*	*R*	*U*	10	101	17	*M*	*M*	81
Marshall silt loam	16	*U*	*R*	*R*	41	-----	-----	-----	-----	-----
Memphis silt loam	*M*	*U*	*R*	*U*	-----	38	26	-----	-----	59
Merced silt loam	84	*U*	*U*	*R*	132	96	*U*	43	30	171
Merrimac gravelly sandy loam	*R*	*U*	*R*	*R*	10	21	*U*	13	34	35
Miami clay loam	12	*U*	*R*	-----	32	19	*U*	*R*	-----	53
Miami silt loam	13	*U*	*R*	*R*	51	23	*M*	*M*	*M*	50
Muck	36	*U*	*R*	*M*	88	[d] 135	21	54	[d] 135+	216

[a] Unaffected. [b] Rusted. [c] Metal attack. [d] Pipe punctured.

TABLE 13.—*Behavior of unfilled thick coatings*—Continued

[Pit depth in mils.]

Soil type	4 years' exposure					12 years' exposure				
	Pitch		Asphalt		Steel	Pitch		Asphalt		Steel
	Unreinforced	Reinforced	Unreinforced	Reinforced	Bare	Unreinforced	Reinforced	Unreinforced	Reinforced	Bare
Muscatine silt loam	40	*U*	*R*	*U*	10	118	*U*	*M*	*M*	57
Ontario loam	------	------	------	------	------	52	*R*	*M*	69	96
Peat	23	*U*	*U*	*U*	33	------	------	------	------	135
Penn silt loam	31	*U*	*R*	*R*	27	42	*U*	*M*	49	42
Ramona loam	20	*U*	*U*	*U*	24	29	*U*	*M*	25	48
Sassafras gravelly sandy loam	------	------	*U*	*R*	------	------	------	------	------	33
Sassafras silt loam	69	*U*	*R*	*R*	31	84	*M*	*M*	74	75
Summit silt loam	------	------	*R*	*R*	------	40	*U*	23	25	74
Tidal marsh	135+	*U*	*M*	*U*	100	[d] 135+	20	*M*	114	160
Alkali soil	------	------	------	*U*	------	68	------	42	------	117
Sandy loam	18	------	*R*	*U*	75	25	*U*	*M*	15	91
Silt loam	26	------	*U*	*U*	------	13	*R*	10	*M*	30
Percentage corroded	100	0	74	65	------	100	48	100	100	------
Percentage pitted (9 mils)	90	0	0	0	------	100	24	48	78	------
Percentage with pits on bare pipe	26	0	0	0	------	27	0	0	0	------

[d] Pipe punctured.

Within 4 years the unreinforced asphalt coating permitted rust to form beneath the coating in 74 percent of the soils to which it was exposed. At the close of the 12-year period of exposure all of the specimens had developed rust beneath the coating and 48 percent of them had developed measurable pits.

The effect of the fabric reinforcement may be seen by comparing the reinforced with the unreinforced asphalt coating. At the close of the shorter test period 65 percent of the specimens of the reinforced, as compared with 74 percent of the unreinforced, coating were rusty. At the close of the longer period of exposure, all pipes beneath the asphalt coatings had rusted. On many specimens the fabric had rotted so badly that only traces of it could be found; and 78 percent of the reinforced asphalt-coated specimens showed measurable pits, as compared with 48 percent of the unreinforced asphalt-coated specimens. In several soils the pits beneath the reinforced asphalt coating were almost as deep as those on a corresponding area of unprotected pipe. Thus in this experiment, in which the coatings had approximately the same thickness, the cotton fabric was a detriment to the asphalt coating. It is probable that the fabric acted as a wick which carried moisture into the material. Nevertheless the table indicates that, on the average, both asphalt coatings reduced corrosion considerably.

Table 13 shows that the reinforced pitch coating was better than the reinforced asphalt, probably because the asphalt absorbed water more readily. More than 50 percent of the reinforced pitch coatings showed no rust and in most cases the fabric was still strong.

The data discussed in the earlier sections of this report show so obviously that the thin coatings are unsatisfactory for severe soil conditions, that no attempt has been made to estimate their performance when applied to pipe lines. Some of the coatings in table 13, although imperfect, are sufficiently good to justify an attempt to interpret the data in terms of the performance to be expected of coatings applied to working lines.

The effectiveness of the coatings in a group of seven soils, which produced pit depth on bare pipes, more than 99 mils in 12 years was estimated by calculating the length of pipe, of a specified material and wall thickness, which is associated with a leak in 12 years. The extension of the length of the pipe from that of the specimens to the length associated with a pit depth equal to the wall thickness was made by means of Scott's pit-depth-area relation. Scott[21] has shown that, as the area from which the deepest pit is selected is increased, the average value of the pit depth increases according to the formula $P_2=P_1(A_2/A_1)^a$, in which A_2 and A_1 are the areas from which the pit depths P_2 and P_1, respectively, are selected, and "a" is a function of soil characteristics. He found that for the data which he examined the value of "a" ranged from 0.376 to 0.150, the average being 0.261. This empirical formula roughly represents the pit-depth–area relation for data upon which it has been tried over a small range, but the extent of its usefulness is uncertain.

The data presented in table 14 are intended only to give a rough idea of the effectiveness of the coatings under discussion. Obviously, if data from other soils were used, or if some other value were taken for "a," the results might have been different.

TABLE 14.—*Effectiveness of the bituminous protective coatings in table 13, as indicated by Scott's pit-depth–area relation*

Coating	Pit depths on specimens			Estimated feet per leak at 12 years					Effectiveness of coatings	
				1½-in. service pipe		8-in. distribution main				
						Steel				
	Average maximum pit depth [1]	Standard deviation	Standard error of the average	Steel [2] $A=71.6$ [3] $t=0.145$	Cast iron $A=79.9$ $t=0.22$ in.	Light $A=325$ $t=0.109$ in.	Heavy $A=325$ $t=0.322$ in.	Class B cast iron $A=341$ $t=0.51$ in.	Ratio of protected to bare length per leak	Percentage increase in thickness of bare pipe wall for equal length per leak
	Mils	*Mils*	*Mils*							
						$a=0.261$				
None	138	42	17	3	12	0.2	13	72	---	---
Unreinforced asphalt	33	24	10	630	2,800	47	2,950	16,300	226	312
Reinforced asphalt	57	45	18	78	347	6	367	2,030	28	139
Unreinforced pitch	96	29	12	11	47	0.8	50	276	4	42
Reinforced pitch	13	11	5	23,000	100,000	1,700	106,000	586,000	8,100	950
						$a=0.150$				
None	---	---	---	---	---	0.1	144	2,940	---	---
Unreinforced asphalt	---	---	---	---	---	1,400	1,860,000	37,900,000	12,900	314
Reinforced asphalt	---	---	---	---	---	38	49,700	1,010,000	345	140
						$a=0.376$				
None	---	---	---	---	---	0.3	5	16	---	---
Unreinforced asphalt	---	---	---	---	---	11	200	691	42	308
Reinforced asphalt	---	---	---	---	---	3	48	164	10	137

[1] Average of data for soils 1, 4, 8, 16, 23, 29, and 43.
[2] A=square inches per foot of length.
[3] t=thickness of pipe wall.

[21] G. N. Scott. *Adjustment of soil-corrosion pit-depth measurements for size of sample.* Proc. Am. Petroleum Inst. 14, pt. IV, 204 (1934).

Columns 2, 3, and 4 illustrate the nature of data on underground corrosion. Taking the data on the pit depths on the unprotected pipe as an example, and assuming that the individual observations from which the average pit depths were obtained are distributed normally, it is to be expected that if other measurements of the maximum pit on a unit area were made, the values would not differ from the average of 138 mils by more than 2.5 times σ_x or 42 mils oftener than 5 times in 100. In other words, the probability is 0.95 that a single value lies between 138+2.5×42 and 138−2.5×42 or between 243 and 33, or, in one case out of 20 the pit depth might be greater than 243 mils or less than 33 mils. Actually, among the seven values used to obtain the average, the maximum was 216 and the minimum 100. Usually, as in the case cited, the difference between the maximum and the average is greater than that between the minimum and the average, i. e., the data do not follow a normal distribution curve.

The values of σ_m indicate the reproducibility of the average in the same way that σ_x shows the reproducibility of a single observation. The values for σ_m indicate that the data for the coated specimens are more erratic than those for the bare pipe. In columns 5 to 9 are shown the lengths of pipe per leak predicted by Scott's formula for pipes having different diameters and wall thicknesses. When the predicted length is not greatly different from the length of the specimen from which the original data were obtained, it is probable that the formula gives reasonably accurate results. When the differences are large, the computed results may be smaller than would actually be found under the assumed soil conditions.

The purpose of the table is not only to compare the effectiveness of four coatings but also to show the effect of different wall thicknesses on the length of pipe per leak. The pipe diameters and thicknesses chosen to illustrate these points are those of pipes in common use. While the thickest pipe of each diameter has been designated as cast iron because, for the diameters assumed, the wall thickness commonly used is greater for this material, the same results would be obtained if any ferrous material of the same wall thickness were used, i. e., the table shows the effect of the thickness of the pipe wall regardless of the ferrous material used to secure that thickness.

The data in columns 5 to 9 for bare pipe indicate that the soils under consideration are very corrosive. In practice, pipes would be replaced before they developed leak frequencies as great as those corresponding to the data shown for any of the unprotected pipes, i. e., none of the pipes would last 12 years.

Following the data for specimens are data on the leak frequencies for pipes protected in four ways, based on Scott's formula, and the assumption of the values for a found by him. If the average value for a is assumed, the reinforced asphalt coating increased the length of pipe per leak to about 28 times that for unprotected pipe, which is more than sufficient to pay for the application of the coatings but not enough to be considered satisfactory protection. If the length of a house service is assumed to be 50 feet and the length of a city block 500 feet, the use of the reinforced asphalt coating on 1½-inch steel service pipe would result in two services out of three leaking within 12 years, while a heavy 8-inch steel main similarly protected would average in the same time one leak per city block.

The reinforced pitch coating was the most effective. It would reduce the leaking steel services to 1 in 460 and the leaks on the thick steel main to about one leak in 21 miles of main.

In considering this coating, it should be remembered that the estimates of effectiveness are based on the performance of the coatings in corrosive soils rather than in those which were destructive to coatings. If the coating had been exposed to soils having large shrinkages the results might have been less favorable.

When pipes are laid in very uniform soils the corrosion is more nearly uniform and the value of the exponent a in Scott's formula is smaller. Conversely, this exponent is larger for soils which are not uniform or for sections of pipe line which traverse more than one soil.

The data in the last column of table 14 indicate that the addition of a protective coating is equivalent to increasing the thickness of the pipe wall by a certain percentage. For example, when $a=0.261$ the application of the reinforced asphalt coating has the same effect on the number of leaks as increasing the thickness of the pipe wall by 139 percent. Under the assumed conditions the light-weight steel pipe protected by reinforced asphalt would not be as effective as the bare heavy steel pipe because the latter is 195 percent thicker. The ratio of the length per leak of protected to unprotected pipe increases with the effectiveness of the coating. The light-weight steel pipe protected by the reinforced pitch coating is shown in the table to be much more effective over the 12-year period of test than any of the bare pipe, because the addition of this coating is equivalent to making the pipe wall 10 times as thick.

It is impossible to determine, from the data presented, how the coatings would be affected by longer periods of exposure, and consequently the relative effectiveness of light-weight coated pipe and heavier uncoated pipe cannot be estimated at this time. However, since many coatings deteriorate within a few years, and since in most soils the rate of corrosion of ferrous materials decreases, it seems probable that the apparent advantage of coated light-weight pipe over unprotected thick-walled pipe will decrease as the period of exposure is increased.

It will be evident from a study of table 14 that a light-weight pipe protected by a very good coating is superior to an unprotected thick-walled pipe during the first 12 years of exposure, and that the thick-walled pipe is superior if the coating does not reduce the leaks to a very small percentage of those on bare pipe. The amount of reduction in leaks equivalent to a given increase in the thickness of the pipe wall can be calculated from Scott's formula by taking P_2 and P_1 equal to the two thicknesses and calculating the reciprocal of the ratio of the corresponding areas per leak. Thus, by means of the formula it can be shown that when a is 0.261, a coating must reduce the leaks on a coated light-weight 8-inch steel pipe to 0.27 percent of those on the bare pipe in order to equal the service of an 8-inch class *B* cast-iron pipe. If the pipe is in a uniform soil, for which the value of a is 0.15, it is necessary to reduce the leaks to 0.004 percent of those on the bare thin pipe, i. e., the coating must prevent practically all leaks.

In concluding this discussion of the effectiveness of protective coatings it should be pointed out that the deductions are only as reliable as the data and the assumptions upon which the calculations are based. The pit depths in the table 14 have large standard errors and the calculations of effectiveness of coatings are based on an empirical formula which has been tested only to a limited extent.

The measure of effectiveness given in table 14 must therefore be regarded as somewhat questionable. Nevertheless, the bases for the table are sufficiently reliable to give the reader a rough idea of the usefulness of certain types of protective coatings. The usefulness of other coatings may be roughly estimated by comparing the conditions of the protected pipes for equal periods of exposure.

7. BITUMINOUS ENAMELS

One of the characteristics of bitumens as protective coatings is their tendency to flow under low pressures. This tendency can be reduced by using a material of higher softening point, but this usually makes a more brittle coating. A reduction in the tendency to flow can also be accomplished by the addition of finely divided inert material commonly known as a filler. A bitumen to which a filler has been added is frequently called an enamel, although the term is also used to designate a bituminous varnish to which a pigment has been added. In this paper the term "enamel" is used to designate a bitumen yielding between 15 and 50 percent of residue on ignition. Ewing and Scott have reported all the data on the performance of enamels tested with the cooperation of the National Bureau of Standards, and the present discussion of the enamels will be limited to a summary of the data of these investigations together with some new data on the properties of these materials.

Because of the limited amount of pipe line available for his tests, Scott was unable to apply all of his coatings to the line at all test sites. Although there are 15 test sites, there are only 6 sites at which all of the 4 unreinforced enamels can be compared. Two or three of these coatings can be compared at two other sites. Data for these latter sites are also presented because the soils at these sites are corrosive and the behavior of coatings in them is therefore of especial interest.

Since the effectiveness of a coating depends to some extent on its thickness, Scott determined the thickness of each coating at each site by four measurements taken 90° apart, 1 foot from each end of each coated section. Table 15 shows the maximum, minimum, and average thicknesses of the four enamel coatings at each site. The maximum and minimum values are averages of 4 measurements, while the average value is the average of 16 measurements.

TABLE 15.—*Thickness of coal-tar-enamel coatings in the API tests*

[Thickness in mils]

Site	Coating *K*			Coating *L*			Coating *M*			Coating *N*		
	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average
II	55	46	52	142	80	100	50	44	47	52	46	49
III	73	59	66	107	63	84	42	39	41	54	44	48
VI	161	48	81	92	66	76	73	58	64	81	58	68
VII	78	62	71	------	------	112	73	64	69	75	69	71
VIII	------	------	------	65	51	56	------	------	------	62	44	53
X	164	67	107	91	86	89	90	68	79	104	64	83
XI	85	48	64	84	64	73	46	39	43	84	53	74
XVI	------	------	------	65	49	55	69	37	56	70	49	60

Obviously, the extreme values would cover a wider range of coating thicknesses. All of the coatings varied considerably in thickness and the average value for the thickness of a given coating was not the same at all of the sites. It seems probable that the variation in the pit depths found on the protected sections is in part the result of variations in the thickness of the coating.

The more important indication of the values for coating thickness is the fact that it is not practicable to apply a coating of uniform thickness by the methods employed in this test. So far as the protective value of the coating is concerned, the value for minimum thickness is the most important since breakdowns of the coating are more likely to recur at this spot.

At each site all of the coatings were inspected on two sections of line on three occasions. Table 15 gives the pit-depth measurements for these examinations. The table also includes data for two sites where not all of the enamels were represented.

Each coated section had adjacent to it an uncoated section for comparison. In table 16 the pit depth on the uncoated section is given as well as the pit depth on the coated section. It will be noted that the corrosiveness of the soil at the test sites, as indicated by the pit depths on the bare sections, varied considerably. It is possible, therefore, that abnormally low or abnormally high rates for pit depths on coated sections are partly the result of variations in the corrosiveness of the soils.

TABLE 16.—*Pit depth on pipe in American Petroleum Institute tests of coal-tar enamels* [a]

[Pit depth in mils]

Site	Section	Coating *K*						Coating *M*					
		1 year		2 years		4 years		1 year		2 years		4 years	
		Bare	Coated	Bare	Coated	Bare	Coated	Bare	Coated	Bare	Coated	Bare	Coated
II	*a*	20	0	43	5	31	5	18	5	44	13	51	16
	b	5	0	39	1	51	17	5	21	27	34	47	18
III	*a*	61	53	77	57	157	94	43	25	113	52	189	117
	b	41	79	114	113	94	40	67	44	114	66	94	119
VI	*a*	5	0	30	0	39	5	23	0	25	22	34	22
	b	29	0	52	36	68	5	29	1	52	73	68	43
VII	*a*	13	5	22	5	50	33	26	17	57	16	63	22
	b	23	1	32	5	50	5	19	33	46	52	45	45
VIII	*a*	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	b	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
X	*a*	52	0	59	0	49	0	54	5	57	28	77	32
	b	40	0	37	0	28	5	25	5	42	5	48	12
XI	*a*	14	43	33	0	46	5	17	32	45	58	45	48
	b	15	0	30	77	33	0	11	19	27	23	47	44
XVI	*a*	-----	-----	-----	-----	-----	-----	5	17	5	33	103	130
	b	-----	-----	-----	-----	-----	-----	1	1	5	5	63	70

[a] Coating *K* is a blend of coal-tar pitch and asphalt.

TABLE 16.—*Pit depth on pipe in American Petroleum Institute tests of coal-tar enamels*—Continued

[Pit depth in mils]

Site	Section	Coating *L*						Coating *N*					
		1 year		2 years		4 years		1 year		2 years		4 years	
		Bare	Coated	Bare	Coated	Bare	Coated	Bare	Coated	Bare	Coated	Bare	Coated
II	a	18	0	44	0	51	0	20	5	43	1	31	5
	b	5	0	27	1	47	1	5	0	39	0	51	0
III	a	61	82	77	78	157	165	61	74	87	5	128	110
	b	41	56	114	134	94	177	53	68	78	5	133	229
VI	a	5	1	30	24	39	42	45	36	49	5	44	38
	b	1	53	26	13	43	39	28	0	54	5	29	19
VII	a	13	0	22	0	50	0	26	22	57	20	63	1
	b	23	0	32	0	50	0	19	1	46	5	45	5
VIII	a	13	5	47	27	54	39	19	15	37	31	63	91
	b	18	34	56	80	101	54	19	5	46	70	85	42
X	a	42	0	47	0	54	1	54	0	57	1	77	5
	b	27	0	41	5	47	16	25	0	42	1	48	1
XI	a	17	0	45	30	45	35	5	13	48	44	54	15
	b	11	5	27	5	47	0	21	5	32	5	37	27
XVI	a	5	5	5	5	66	5	14	27	42	71	90	122
	b	1	1	5	5	63	5	1	1	30	63	17	63

Table 16 shows that, when two sections of the same coating at the same site are compared, the maximum pit depth on one pipe may be more than twice that on the other. This is true for each of the coatings. Out of the 174 cases in which the pit depths on the coated and adjacent uncoated sections can be compared, there are 37 cases or 21.3 percent in which the pit depths were deeper on the coated sections. In eight additional cases the pit depths on the coated and uncoated sections were equal. When it is considered that the data apply to areas of from approximately 5 to 8 square feet and for periods of exposure of 4 years or less, it is evident that the protection afforded by these coatings was far from complete.

There can be no doubt, however, that each coating has materially reduced the number of pits as well as the loss of metal, and consequetly, for the period under consideration, each coating has reduced the cost of reconditioning the pipe, although in some cases the time for the first leak may have been shortened.

The agreement under which the API line tests were conducted prevents the disclosure of the names of the coatings or their makers. It may be said, however, that the coatings represent four of the enamels most commonly used at the time of their application and that they were applied by manufacturers' representatives. It is possible that as a result of the tests, the manufacturers have modified their products or methods of application. While it is hoped that any such changes resulted in improvements of the coatings it must be remembered that this remains to be demonstrated.

Because the differences between the coatings were not sufficient to result in outstanding differences in the data, and because of the erratic nature of the data, the best idea of the effectiveness of enamels as a type of coating can be obtained by combining the data for all four coatings. This has been done in table 17. Columns 3 to 6 show the corrosiveness of the soils as indicated by the pit depths on the bare pipe. The significance of the standard deviation and the standard error of the mean, as well as the method used in determining the length of pipe for a leak, are the same as described in the discussion of table 14, except that because of the smaller number of observations, the accuracy of the results is somewhat less than in table 14. The extrapolation involved in computing the length for a leak in the less corrosive soils is so great that the results are of little value except for showing the general relationship between coated and uncoated pipe in these soils. Since the trend of the errors would be similar for both bare and coated pipe, the indication of their relative performances is probably sufficiently accurate for this purpose.

The table indicates that in the three most corrosive soils, III, VIII, and XVI, the coatings were not very effective. In the less corrosive soils the effectiveness of the enamels was much greater.

The table indicates only the effectiveness of the coatings for an exposure of approximately 4 years. This of course is much too short a period for anything but the elimination of the poorer coatings.

TABLE 17.—*Average effectiveness of coal-tar enamels in API line tests for exposures of approximately 4 years*

[Pit depth in mils.]

Site		Uncoated sections				Enamel-coated sctions			
Designation	Rank as to corrosiveness	Pit depth	Standard deviation	Standard error	Estimated feet per leak on 8-in. pipe, 0.322-in. wall	Pit depth	Standard deviation	Standard error	Estimated feet per leak on 8-in. pipe, 0.322-in. wall
II	9	46	7	2	5, 186	8	7	3	5, 629, 000
III	1	135	32	10	84	131	54	20	125
VI	8	46	12	4	6, 471	27	15	6	66, 480
VII	5	53	19	6	3, 016	14	16	6	659, 500
VIII [a]	2	79	21	6	653	57	21	12	3, 043
X	7	47	13	4	4, 779	9	10	4	3, 586, 000
XI	10	45	10	3	4, 333	22	18	7	89, 730
XVI [b]	3	70	33	9	1, 039	66	50	22	1, 734

[a] Two coatings only.
[b] Three coatings only.

The available data are insufficient for an accurate prediction of the trend of the deterioration. It is evident, however, from table 16, that the condition of the coated sections was somewhat worse at the third examination than at the first. An attempt to show the trend in the performance of the four coatings as a whole has been made in figures 3, 4, and 5. The broken lines show the progress in the pit depths on the unprotected sections while the continuous lines show that for the coated specimens. The curves for the bare sections are based on all pit measurements for those sections rather than for only those sections adjacent to the enameled sections. The values are therefore slightly different from those in table 16, but they are probably more characteristic of the test sites. While in some cases the positions of the curves are defined quite well by the observations, in other cases the locations of the curves are doubtful.

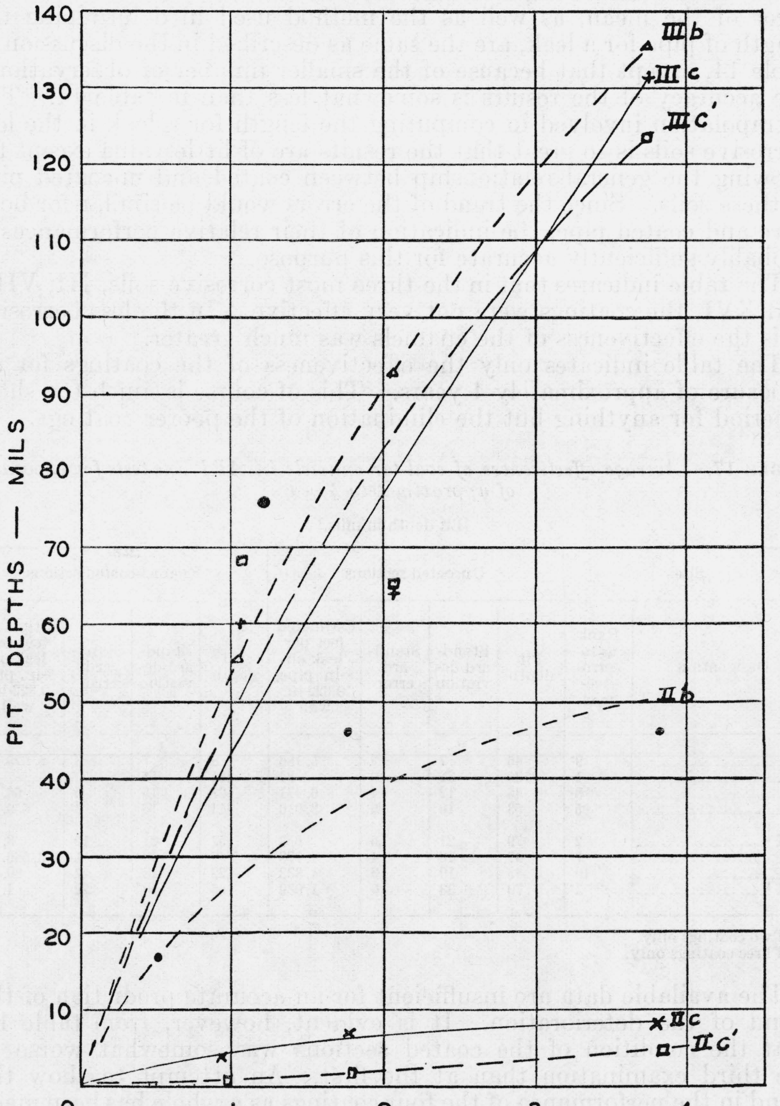

FIGURE 3.—*Effect of time on pit depths on bare and enamel-coated pipe at sites II and III.*

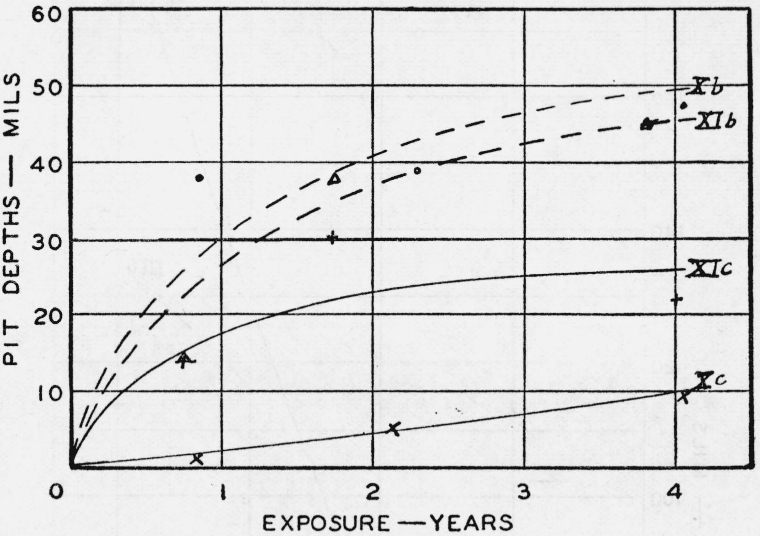

FIGURE 4.—*Effect of time on pit depths on bare and enamel-coated pipe at sites X and XI.*

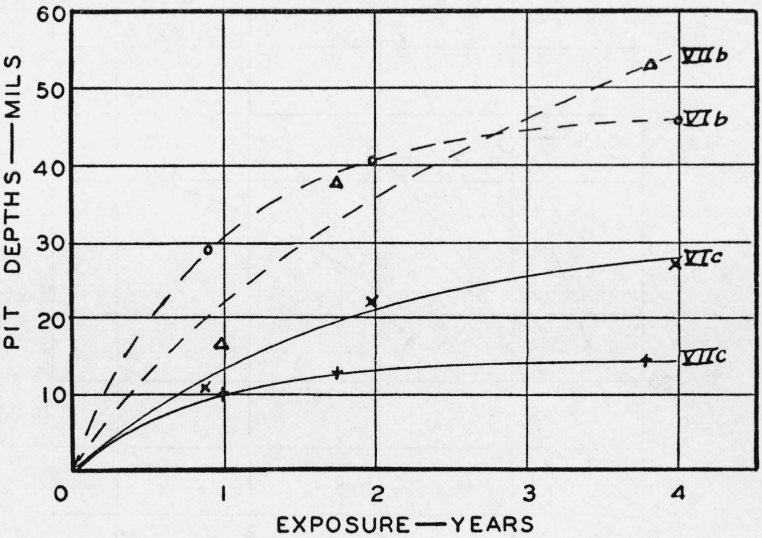

FIGURE 5.—*Effect of time on pit depths on bare and enamel-coated lines at sites VI and VII.*

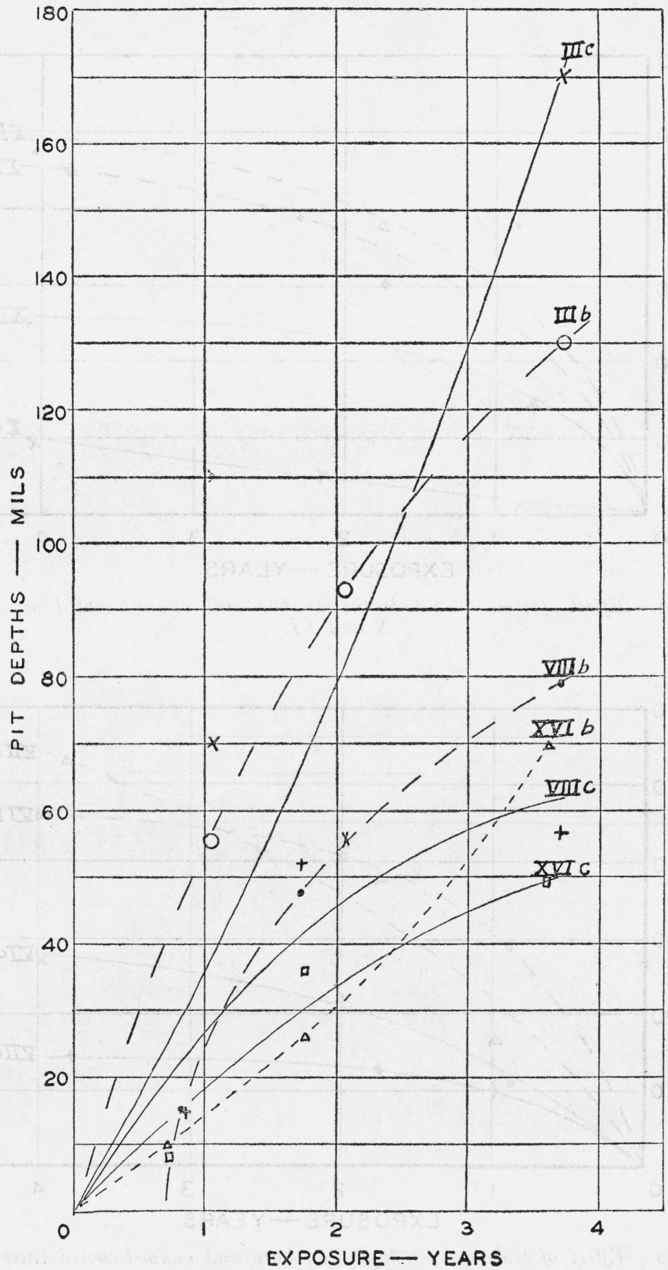

FIGURE 6.—*Effect of time on pit depths on bare and enamel-coated pipes in the three most corrosive soils in the API tests.*

The curves for the coated and uncoated sections in the same site are in most cases similar, with those for the coated pipe lying below the others. In figure 3, curves *IIc'* and *IIIc'* are for the average of coatings *K*, *L*, and *N* only and were drawn to show the effects of disregarding the softest coating. It will be noted that these curves do not differ greatly from the corresponding curves for the averages of all four coatings. This is a partial justification for combining the data for the coatings. Satisfactory curves could not be plotted for individual coatings for some of the test sites.

The curvature of the curves for the bare pipe at sites II, VI, X, and XI indicates that if the pipe wall is fairly thick, few leaks are to be expected on unprotected pipe. In such soils the chief use of a coating is to facilitate the cleaning of the pipe when it is removed for use elsewhere.

Figure 6 shows the trends of the pit depths in the three most corrosive soils in the API tests. Since the coatings *K* and *M* were not tested at site VIII, the data for coatings *L* and *N* only have been used for all sites in order that the curves may be comparable. It will be noted that in these corrosive soils the curves for the coated and uncoated pipe follow each other closely. The shapes of the curves as drawn for the coated pipe suggest that the pit depths on the coated sections are increasing less rapidly than those on the bare pipe, i. e., that, although punctured, the coatings retard the rate of corrosion. It will be noted, however, that in most cases the points which represent the data from which the curves are plotted do not lie close to the curves and there is therefore considerable uncertainty as to the actual trend of the data.

For the less-corrosive soils the curves for the enamel-coated lines lie considerably below those for the unprotected lines. The latter curves seem to be parabolic in form. If they are to be depended upon they indicate that the rate of corrosion decreases rapidly with time, and that after a few years of exposure the pit depths will increase only slightly. Under such soil conditions the pipe-line operator has the choice of using a pipe wall so thick that it will not be penetrated within any desired period, or a lighter-weight pipe protected by a suitable coating. If an enamel is to be used, the performance of the enamels applied to short lengths of pipe in the AGA and API tests affords some data on the characteristics to be desired.

In addition to the four enamels for which data are given in tables 15 and 16, several others have been tested by Scott and Ewing on short lengths of small diameter pipe. The performance of coatings applied in this way was, on the average, considerably better than when the same enamels were applied to pipe lines, as shown by table 18. These coatings were all applied in the field with a sling. This probably accounts for the differences in the results for the line and for the small coated specimens since, with machine-applied coatings, there is no noticeable difference between the two tests which cannot be accounted for by the differences in the areas exposed.

Table 18 indicates that, with the exception of coating 3 in sites II, III, and X, the pit depths were much less on the coated nipples than on the similarly coated line. Either the application of the coatings to the nipples was much better or the nipple test is not as severe as the line test.

TABLE 18.—*Relation between maximum pit depths on enamel-coated line pipe and on similarly coated nipples (API tests)*

[Pit depth in mils]

Site	Bare pipe		Coating 1		Coating 2		Coating 3		Coating 4	
	Line	Nipple	Line	Nipple	Line	Nipple	Line	Nipple	Line	Nipple
II	46	35	11	0	1	26	17	19	3	0
III	135	129	67	0	171	24	118	148	170	16
VI	46	49	5	0	41	13	33	16	29	5
VII	53	37	19	0	0	0	34	15	3	0
X	47	43	3	0	9	0	22	19	3	0
XI	45	46	3	0	18	0	46	19	21	0
Average	62	57	18	0	40	11	45	39	38	4

Table 19 shows the variation in some of the properties of the enamel which is probably the most uniform in the API tests. With the exception of the value of 11.7 for ductility at site VIII, the data appear to be reasonably consistent. The differences in the properties of the coating at different sites must therefore be attributed to real differences in the several lots of the material from which the samples were taken.

Table 19 indicates that the product sold under a single name is not always the same and shows, therefore, the need for specifying such properties as are known to be essential. Unfortunately, there are at this time few data to justify a rigid specification.

Figure 7 shows the conditions of the four coatings applied to 3-inch pipe after 0.83 year exposure at site VIII (Acadia clay). The soil is a heavy clay containing crystals of gypsum. It will be noted that the distortion was greatest for coating *M* and least for coating *N*, as might be expected on account of their softening points.

TABLE 19.—*Physical properties of the same enamel at different test sites*

[Determinations by H. S. Christopher]

Site	Ring and ball softening point	Ductility (Dow) at 115 °F	Consistometer hardness (Abraham) at 115° F	Insoluble in CS_2	Ash
	°F	cm.		%	%
VIII	185	11.7		53.6	36.3
XIII	198	2.8	42.7	51.2	33.2
XI	201	3.4	51.9	56.9	37.4
III	205	5.2	46.4	57.2	40.3
IV	207	4.7	54.3	56.0	38.2
VII	207	4.3	49.3	57.4	37.7
XIV	210	2.2	62.1	56.0	38.3
XII	212	1.5	63.0	53.1	39.1
XVI	212	1.8	61.3	55.2	38.9
1929	208	5.0	51.9	55.7	36.7
1930	205	3.8	61.3	55.6	35.3

The behavior of enamels in heavy clay soils is further illustrated in figure 8, which shows coatings furnished under the same trade designations for the AGA tests after an exposure of 0.77 year to Miller

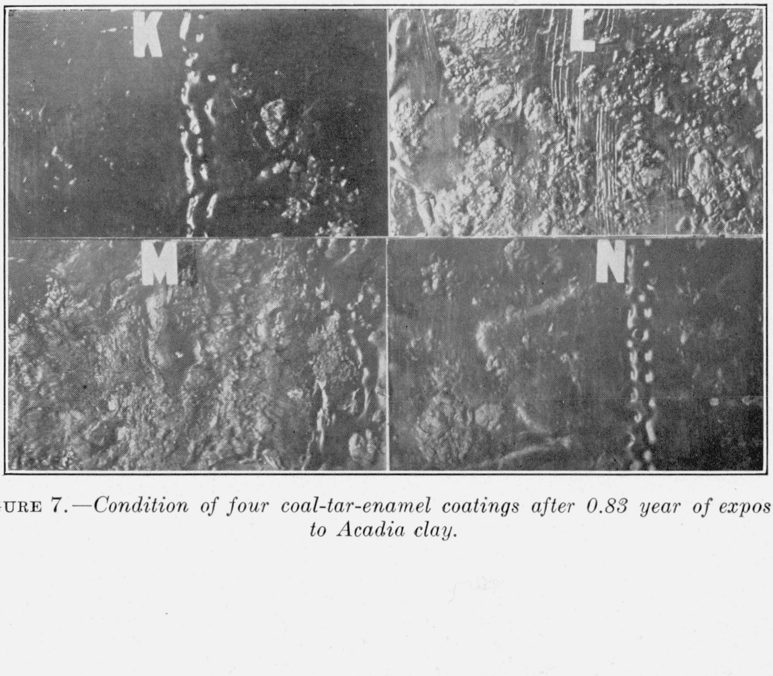

FIGURE 7.—*Condition of four coal-tar-enamel coatings after 0.83 year of exposure to Acadia clay.*

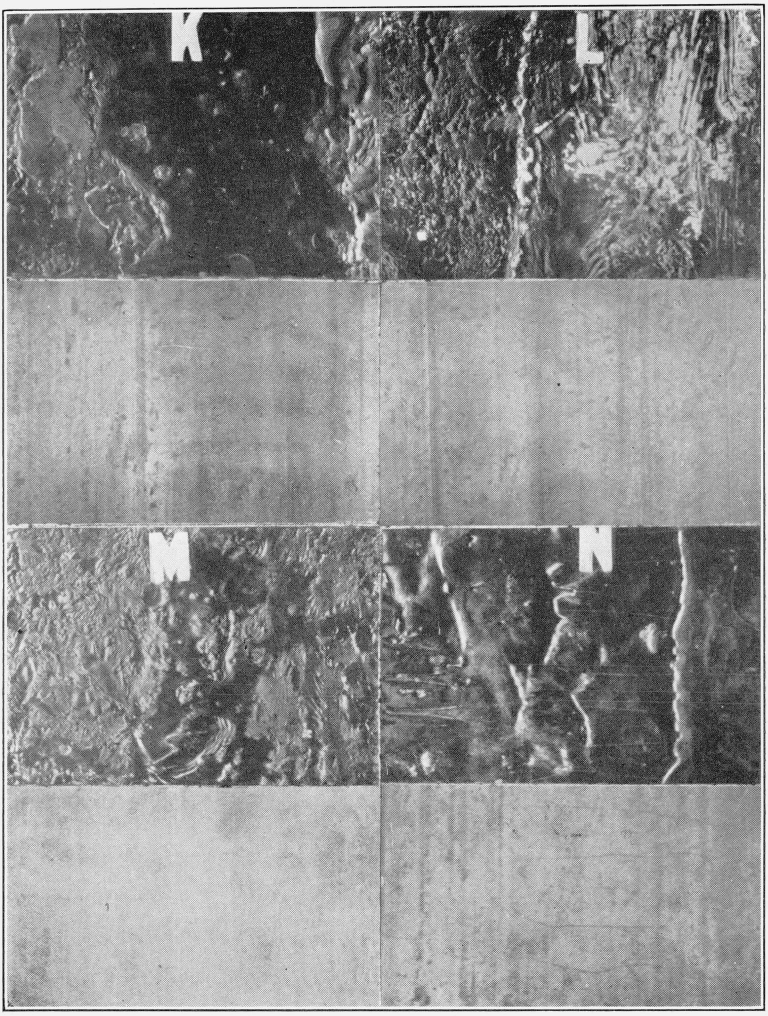

FIGURE 8.—*Condition of four coal-tar-enamel coatings after 0.77 year of exposure to Miller clay.*

[Note rust streaks on pipe of coating *N* corresponding to cracks in the coating (same coatings as in fig. 6).]

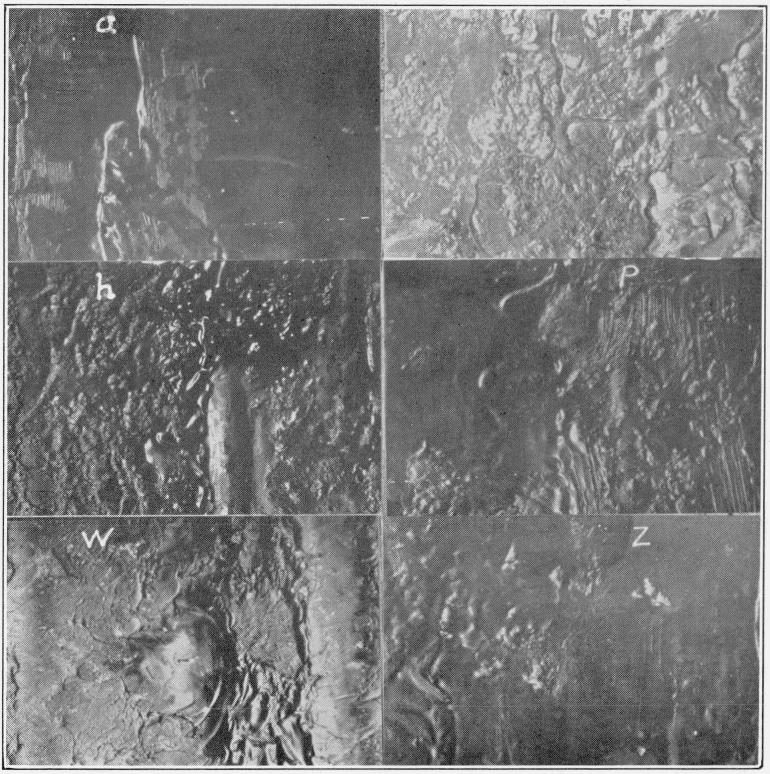

FIGURE 9.—*Condition of six enamel coatings after 0.83 year of exposure to Acadia clay.*

clay at Bryan, Tex. This soil is somewhat heavier than that at API site VIII but the former contains little corrosive material. This is indicated by the lower half of each illustration, which shows the condition of the pipe from which the coating has been removed. Indeed, this soil is one of the least corrosive of the AGA sites.

Figure 8 illustrates several things which may happen to coal-tar enamels under adverse soil conditions. The left side of the illustration for coating *K* shows a spot where the soil has pulled the coating from the pipe. To the right of the bare spot the coating has been distorted by clod pressure, while near the upper right corner the coating has been spalled off, probably because of a blow.

At the left of the illustration of coating *L* distortion is shown together with shallow grooves which may have been made by roots. The white near the center of the picture is whitewash with which the coating was originally covered. Coating *M* shows more serious distortion. The picture of coating *N* shows another type of coating failure—cracking, which was observed at several test sites. That the cracks extended through the coating and remained in this condition for some time is indicated by the rust lines on the section of pipe from which the coating has been removed.

The API tests of enamels applied to short lengths of small-diameter pipe include six enamels in addition to those applied to pipe lines. The appearance of these enamels when removed after 0.83 year exposure to Acadia clay is shown in figure 9, which is comparable with figure 7. The data for the pit depths on all of the enamels after 4 years of exposure in the API tests are shown in table 20. The table also shows the thickness and the ring and ball softening points of those enamels. The first four of these coatings are duplicates of coatings in table 16, which is a better indicator of the performance of the coatings under working conditions. Coating *k* is a blend of coal tar and asphalt. Coatings *h* and *w* are asphalt enamels; the others are coal-tar-pitch enamels. Since there was only a single specimen of each coating it is possible that the apparent relative merits of the coatings are in part accidental, and conclusions as to the relative merits are subject to revision when more data become available.

The table indicates that the thickness and softening points are important factors in the performance of the enamels.

Coatings *p* and *zzz* were identical except that coating *p* was applied over a priming coat of red lead. The asphalt enamels were apparently slightly inferior to the others, possibly because of a greater tendency to absorb water, since at most sites their conductance was relatively high.

The enamels in table 20 are all proprietary materials and are identified in Scott's report[22] on the installations of his specimens. However, since most coating manufacturers modify their products from time to time it seems best to treat each material on the basis of its properties rather than as a product having a certain name. It is quite possible that the product sold later under the same name has been modified to overcome the defects described by Scott. Only tests or experience will tell whether the modifications are effective.

[22] G. N. Scott. *API coating tests.* Proc. Am. Petroleum Inst. **12**, **pt. IV**, 55 (1931).

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TABLE 20.—*Pit depths on 4-year-old enamel coated small-diameter pipe in the API tests*

(Pit depth in mils)

Site	Coatings—										Bare
	t	*s*	*zzz*	*k*	*dd*	*a*	*h*	*p* [1]	*z*	*w*	
II	19	0	26	0	18	5	5	0	0	21	35
III	15	16	24	0	136	19	85	0	52	110	129
VI	16	5	13	0	19	1	14	15	22	30	49
VII	15	0	0	0	5	0	17	0	0	17	37
X	19	0	0	0	0	5	5	0	0	5	43
XI	19	0	0	0	20	0	5	0	0	1	46
Thickness (mils)	52	41	77	75	50	54	69	71	72	92	None
Softening point (°F)	158	195	205	192	190	241	189	205	222	163	------

[1] Applied over a red-lead paint, baked on.

In Ewing's [23] tests there are four soils which are corrosive but in which little soil stress would be expected because they are wet much of the time. Soils 3 and 4 are tidal marshes. Soils 5 and 6 are mucks. All of these soils are corrosive, as indicated in the last column of table 21. This column shows that for these soils the maximum pit depth is roughly proportional to the period of exposure. With the exceptions of coatings *WL* and *WR*, which differ only in the primer used, the enamels listed in table 21 are nominally the same as those buried by Scott a year later. In most cases, however, Scott's coatings were considerably thicker.

It will be noted that the deterioration of the coatings was progressive not only as to pit depths, but also as to the number of failures. None of these enamels has a perfect record in all four soils throughout the test. No soil is outstanding in its corrosiveness with respect to the enameled specimens. The data are insufficient and too erratic to justify the plotting of curves to show the progress of the corrosion. It can be seen that the thinner coatings had the most failures and that the coatings with the lower softening points were in general thinner than those having higher softening points. The latter contained larger amounts of inert material. The points of difference between the coatings are, however, too many to permit the determination of the characteristics which control their performance. It seems advisable, therefore, that any specification for an enamel should be based on its reaction to forces representing the soil characteristics and operating conditions which tend to destroy coatings rather than on the composition and physical characteristics of the coating as conventionally determined.

Among the important influences on coating behavior to be considered in the writing of specifications are soil pressure, adhesion of the coating to the soil and to the pipe, temperature changes, shocks, and moisture.

In view of the performance of the enamels in the wet soils it seems doubtful whether they should be recommended for such conditions in cases where superior coatings can be secured at but slightly greater costs. There can be no doubt, however, that the better enamels

[23] S. Ewing. *AGA studies of pipe-line coatings.* Proc. Am. Gas Assn., p. 774 (1931), p. 741 (1933), p. 627 (1936).

will materially reduce corrosion in wet soils for at least five years and probably for a considerably longer period.

TABLE 21.—*Performance of AGA enamels in poorly drained organic soils*

(Pit depth in mils)

Exposure	Soil	Coatings									Bare
		C	*S*	*H*	*B*	*WR*	*WL*[1]	*W*	*R*	*A*	
yr											
0.86	3	0	0	0	0	0	0	0	0	0	0
.86	4	0	0	0	0	0	0	0	0	0	0
.75	5	0	0	0	0	0	0	0	0	0	26
.74	6	0	0	0	0	0	0	0	0	0	0
2.49	3	0	44	0	0	0	0	0	0	0	15
2.49	4	38	0	27	0	0	0	0	0	0	24
2.52	5	0	12	0	30	0	0	0	0	0	45
2.51	6	0	0	0	40	20	0	0	0	0	51
5.80	3	70	38	0	135+	0	13	16	5	0	43
5.75	4	5	122	135+	5	0	0	0	0	0	42
5.46	5	20	23	5	30	33	37	35	0	5	63
5.46	6	47	37	5	50	42	0	25	0	0	115
Thickness (mils)	------	14	34	34	38	50	52	58	61	70	0
Softening point (°F)	------	156	162	187	167	184	184	208	201	232	------

[1] Coating applied over red-lead paint.

8. REINFORCED BITUMINOUS COATINGS

It has been shown that asphalts and coal-tar pitches may have in varying degree four faults which detract from their value as protective-coating materials: absorption of water, low resistance to shock, susceptibility to changes in temperature, and cold flow under stress. The addition of finely divided inert materials improves the bitumens as coating materials but does not result in products which are entirely satisfactory for use under severe soil conditions. Further improvements have been attempted through the use of reinforcing fabrics, either imbedded in the coating or placed over the coating as a shield. At first, various organic fabrics such as burlap and coarse cotton cloth were used as reinforcements. Later, bitumen-impregnated organic and asbestos felts similar to roofing felts were used extensively. The use of these materials not only results in coatings which are more resistant to shock and to soil stress but usually involves the application of more bitumen. It is generally agreed that the protection of the pipe against moisture depends upon the kind and amount of bitumen present. Most fabrics, even though impregnated with bitumen, absorb some moisture. In this respect their incorporation in a coating may be a source of weakness, although the net result may be favorable because of the improvement in the mechanical properties of the coating.

Because the incorporation of the fabric in the body of the coating may introduce moisture, some coating manufacturers and users have thought it better to place the fabric on the outside of the coating as a shield. The chief objection to this method is that frequently less bitumen is applied to the pipe. The idea of shielding the bituminous coating resulted in the development of new types of shields, such as thin sheet metal.

The general effect of using a fabric reinforcement with unfilled bitumen has been shown in tables 13 and 14. The effect of the fabric on enamels and on some other coatings is shown in table 22, which is a rearrangement of data reported by Scott.[24]

In the third and fifth columns of table 22 the standard deviations of the data in the second and fourth columns have been given in order that the reader may realize more clearly the uncertainties of the data. Since there were but two specimens of most of the materials at each site, the reproducibility of the data is less definitely known than is the reproducibility of the data for bare pipe or for the enamels. Because not all materials could be tested at each site on account of lack of space, it is not possible to compare the performances of all of the coatings in all soils. However, the table furnishes a sufficient number of comparisons to indicate in a general way the relative merits of several coatings. In making comparisons one should keep in mind the fact that the thickness of the asbestos felt was about 25 mils and that of the rag felt about 50 mils. The thickness of the concrete was about 350 mils, but it varied considerably at different sites. The thickness of the cotton fabrics was about 15 mils, but the weave was so open that a considerable amount of bitumen was included with the fabric.

A comparison of the data for the unreinforced enamels with those for the shielded enamel *G* indicates that the shield materially reduced the pit depths at all sites, although the shielded enamel was not as thick as the average of the unshielded enamels. All of the other coatings, with the exception of the unreinforced emulsion, were so much thicker than the enamels that it is impossible to determine from the data whether the superiority of the reinforced coatings was the result of the reinforcement or of the added bitumen. Likewise, it is difficult to determine whether the asbestos felt was more serviceable than the rag felt.

Coating *T*, which contained two layers of rag felt with intervening layers of enamel, appeared to be slightly superior to coating *U*, which is less than half as thick, and contained a single layer of asbestos felt. The unfilled asphalt reinforced with rag felt, *S*, appears to be slightly superior to the asphalt enamel reinforced with asbestos felt, *R*, possibly because the latter coating was not as thick, although this difference may be accounted for by the difference in thickness of the felts. In most soils, where comparisons can be made, the coatings reinforced with cotton fabric appear to have been slightly inferior to the coatings reinforced with felt, although the former were thicker and contained more mopped asphalt per unit area.

The investigation conducted by Ewing[25] throws additional light on the relative merits of reinforcing materials. This investigator has found that the organic materials, even when impregnated with grease or bitumen, absorb moisture, and decay. The absorption of moisture increases the conductivity of the coating and decreases its value if used in connection with cathodic protection.

The use of burlap is extensive in some countries but has largely been discontinued in the United States because of the tendency of the fibers to protrude through the coating and to act as small capillaries which conduct water into the coating.

[24] G. N. Scott. *API coating tests, IV.* Proc. Am. Petroleum Inst., **15**, pt. IV 18 (1934).
[25] S. Ewing. *AGA field tests of pipe coatings.* Proc. Am. Gas Assn. p. 627 (1936).

In a laboratory test of materials available for the reinforcement of bituminous coatings, Scott and Ewing[26] tested 26 materials by exposing them to moist soil. All of the fabrics decreased in strength within 1 year. The decrease was much greater for the organic fabrics. Rot inhibitors delayed but did not prevent rotting.

Table 22 indicates that for the period of the test, the emulsion protected by the heavy layer of sand and cement mortar appears to have been somewhat more effective than the other coatings in table 22 with which it can be compared.

Three facts regarding the data in table 22 are outstanding. One is that although the exposures of the coatings are only 4 years, measurable pits developed beneath all of these coatings in most of the soils to which they were exposed. Another is the relatively great thickness and the large number of parts of the more effective coatings. A third fact of importance is that the same degree of effectiveness can be secured in several ways. None of the coatings in table 22 is outstanding in its performance though, in general, the effectiveness of the coating appears to be roughly proportional to its thickness and nearly independent of its structure. More data will be needed to define the engineering principles upon which a coating should be designed. To obtain such data was the purpose of the API coating tests.

Table 22.—*Effect of reinforcement on bituminous coatings on working lines*

[Average depth of maximum pits, in mils, after 4 years]

Site	Bare pipe		Coal-tar-enamel coatings					Reinforced-asphalt coatings [1]					
			Not reinforced [2]		Reinforced or shielded			Unfilled				Emulsions	
	Average of 12 specimens	Standard deviation	*K, L, N*	Standard deviation	*G*, asbestos-felt shield	*U*, asbestos felt, reinforced	*T*, double rag felt, reinforced	*R*, enamel and asbestos felt	*S*, rag felt, reinforced	*E*, single cotton fabric, reinforced	*Z*, double cotton fabric, reinforced	*A*, inhibitor only	*F*, inhibitor and sand, and cement shield
II	46	7	5	6	1	3	------	24	8	8	9	63	------
III	135	32	136	61	3	1	------	12		------	10	140	------
VI	46	12	25	16	17	------	1	------	------	26		41	5
VII	53	19	7	12	28	5	16	14	5	------	33	------	------
VIII	79	21	[3] 57	21	40	31	5	40	46	------	20	------	28
IX	65	27	3	2	11	0	1	3	------	------	19	------	1
X	47	13	5	5	0	------	3	------	------	1	------	33	1
XI	45	10	14	13	------	3	1	9	------	27	19	------	------
XIII	50	16	[1] 54	4	1	9	------	------	72	58	36	67	6
XIV	18	8	[1] 8	3	------	3	------	5	3	3	------	10	3
XVI	70	33	49	48	23	8	7	------	------	25	37	------	61
Thickness (mils)	------	------	70	------	63	171	351	143	150	151	206	65	419

[1] Average of 2 specimens.
[2] Average of 6 specimens.
[3] Average of 4 specimens.

[26] G. N. Scott and S. Ewing. *Deterioration of pipe-line fabrics.* Oil and Gas J. **34**, 112 (Oct. 24, 1933).

9. GREASE COATINGS

Several manufacturers and pipe-line operators have suggested greases as a means of retarding the corrosion of pipe lines. The API line tests of protective coatings included one grease coating reinforced by cotton fabric. The grease contained a material intended to inhibit corrosion and the fabric was treated to retard decay. The outer layer was a heavy grease. The average thickness of the coating was 107 mils. No section of the line protected by grease was free from corrosion at the close of the 2-year test period and only 4 of the 20 sections were free from rust at the end of the 1-year period.

Evidently the rust inhibitor contained in the grease was only partially effective even for a period of less than 1 year. Nevertheless, at the close of the 4-year period the fabric-reinforced grease appeared to be as effective in reducing pit depths as any coating of its thickness and more effective than several thicker coatings. The coating was not exposed to the three most corrosive soils. The effectiveness of the coating after 4 years is indicated by table 23.

TABLE 23.—*Maximum pit depths on pipe protected by reinforced grease and other coatings (API tests)*

[Average depth of maximum pit after 4 years]

[Pit depth in mils]

Site	Bare pipe	*B*, cotton fabric-reinforced grease	*E*, cotton fabric-reinforced asphalt	*K*, coal-tar enamel, unreinforced	*U*, coal-tar enamel, reinforced with asbestos felt
I	20	5	3	----------	1
II	46	11	8	11	3
IV	38	1	3	----------	0
V	38	3	3	23	----------
VI	46	19	26	5	----------
VII	53	5	----------	19	5
IX	65	5	----------	----------	0
X	47	3	1	3	----------
XI	45	14	27	3	3
XIV	18	9	3	8	3

Unreinforced grease coatings have been used to a considerable extent but few definite data are available on their performance. They seem to render the best service when applied in soils which are continuously wet and to fail soonest in soils that frequently become very dry.

One pipe line company has tried grease shielded by a wrapper of copper foil. The writer has seen no data on the performance of this coating but there appears to be a possibility of galvanic action between the copper shield and the steel pipe if pressure forces the shield into metallic contact with the pipe at any point. Possibly a copper foil backed by organic or inorganic fabric would prove more satisfactory.

10. MASTIC COATINGS

Of all the coatings in the API tests the mastic coating was the best for the first 4 years of the test. This coating was made of a mixture of asphalt and graded mineral matter applied by machine to a thickness of 0.519 inch. Even this coating showed rust spots on two sections at the 4-year inspection. Whether this rusting was the result of imperfections in the coating or of deterioration cannot be determined until additional inspections have been made.

VI. APPLICATION OF DATA TO PIPE LINES

Since readers may wish to apply the data in this report to the solution of the problem of protecting a pipe line or service pipe, the relation of the data to pipe-line protection will be considered briefly.

Those who wish to estimate the pit depth on any chosen area of protected pipe from the performance of a similarly coated specimen may do so by the application of Scott's pit-depth-area relation which has been discussed on page 719. If this formula is used it should be remembered that the results become less reliable as the extrapolation is extended and that the values for the exponent a in Scott's equation differ for different soil conditions.

Few if any experiments completely duplicate the service conditions upon which they are supposed to throw light. This is especially true of experiments with protective coatings even when the coatings are applied to working lines. In the first place, the serviceability of a pipe line or service pipe is governed largely by its worst condition, since a single leak may involve a temporary shut-down of the line and possibly large expenses because of damages to pavements or because of the escape of the transported fluid. On this account the worst performance of a coating is of more importance than its average performance. On the other hand, an imperfect coating may be greatly preferable to none at all. The danger lies in expecting greater protection from a coating than is justified by the character of the coating.

In this connection a phenomenon common to all problems involving maxima must be kept in mind. The larger the sample from which the maximum is chosen, the larger will be that maximum. In other words, the first leak will probably occur on a long line before it appears on a short one exposed to the same conditions. It is to be expected then that even if the average performance of a coating on the short length of pipe is representative of the average performance of the coating on a working pipe line, the first failure of the coating on the line will occur in a shorter time than it occurred in the experiment. How serious this is in a particular case depends upon the amount of trouble caused by a single leak. On lines which are easily accessible the average condition of the line is much more important than the worst condition. On lines under pavement and on lines on which a single leak may result in an explosion the worst condition is the controlling factor.

It may be assumed that the coatings used in the experiments were applied to the pipes with greater care than they would have been applied under average pipe line conditions. However, the results of the tests have shown the necessity for care and have probably caused improvements in materials and in operating practice.

Most bituminous coatings cannot be successfully applied to damp or dirty pipe. It is very difficult to avoid these conditions when coatings are applied in the field.

The resistance of most bituminous coatings to shock and abrasion is much less than that of the pipe to which the coating is applied. It follows that if a coating is to start its service uninjured the coated line must be handled with greater care than would be required for an uncoated pipe.

While it is customary to test a pipe line to determine whether it is free from flaws and imperfections, there is no satisfactory way of making similar tests of a protective coating after it has been placed in the trench. The best that can be done is to test the coating by means of an electrical fault finder [27] at the latest practicable point in the laying of the line. Obviously, because of the ease with which a coating may be injured as the coated pipe is handled and as the trench is backfilled, and because of the difficulty in making satisfactory field joints for the coating, the probability that the line will be completely protected is small. With respect to pipe lines this difficulty may be overcome by the application of cathodic protection.[28]

If cathodic protection is to be applied to a coated line the current required will depend on the electrical resistance of the coating and upon its freedom from flaws and pinholes. The resistance of the coating is largely affected by the amount of moisture which it will absorb. From this standpoint coal-tar-pitch coatings appear to be superior to asphalt-base materials, but either material if of sufficient thickness will have a sufficiently high specific resistance.

It is not possible to say that one material should be generally used in preference to any other. The selection of the coating material should be governed by such data as have been presented, supplemented by equally important data as to availability, ease of application, suitability of the material for local field and labor conditions, and the estimated cost of the coating throughout the life of the line. It follows that whenever possible the choice of the protective coating should be made by some one thoroughly familiar with the characteristics and uses of pipe coatings.

VII. SUMMARY

Although protective coatings have been applied to pipe lines for half a century or more and many tests of protective coatings have been made, few data are available upon which an engineer can base a reliable estimate of the saving which can be expected through the use of a protective coating.

There are several methods by which certain characteristics of coatings can be indicated, but there is no recognized way of expressing the serviceability of a coating. Because of this, ideas as to the protective value of coatings are vague and lead to uncertain results when applied to the design of a pipe line.

The experiments upon which this report is based were started between 1922 and 1930 and represent pipe-coating practice at that period. They have resulted in the modification of pipe-coating practice and in the development of better coatings. Unfortunately, the testing of

[27] C. W. Clarvoe. *The detection of flaws in pipe-line coatings before burial.* Pipe Line News **5**, 13 (July 1933).

[28] S. P. Ewing. *Cathodic protection of pipe lines from soil corrosion.* Natural Gas **16** (March and April 1935).

new coatings in the field by national organizations has been discontinued. The effectiveness of the newer coatings must be determined largely by the experiences of users of the coatings. Data obtained in this way are accumulated but slowly. They are usually lacking in essential details of the conditions which determine the success or failure of the coating and are sometimes influenced by the interests of those who report the data. The reader of this report should neither assume that the results presented are the best that can be obtained with protective coatings nor that the causes of failures of coatings have been overcome completely.

The results of the tests under the general supervision of the National Bureau of Standards seem to warrant the following generalizations.

The performance of a protective coating is controlled by the soil conditions to which it is subjected. The shrinkage and the relative density of the soils are important factors in the distortion of coatings. Distortion is especially severe in dense soils which undergo marked changes in volume with change in moisture content. Because of the effect of soil characteristics on coating behavior, when practicable, coatings should be selected with reference to the soil conditions to which they are to be exposed.

Although no coating tested completely prevented corrosion under all soil conditions for as long as 4 years, almost all of them materially reduced the loss of metal during the period of test.

Coatings which are somewhat porous, such as cut-backs and asphalt emulsions, are effective in preventing pitting in well aerated soils.

The thickness of the bitumen is an important factor in the effectiveness of a coating. Very thin bituminous coatings are unsuitable for severe soil conditions.

Thickness for thickness, coal-tar-base coatings absorb less water and have better insulating qualities than coatings having asphalt as a base.

The coal-tar-base coatings are, in general, more severely affected by soil stresses, sudden changes in temperature, and shocks.

The application of coatings by means of a sling as used in the API tests results in imperfect coatings.

Shields and reinforcements reduce the depth of the deepest pit to a great extent during the first few years of exposure, probably because of their resistance to soil stress, although the relatively great thickness of reinforced and shielded coatings may be a factor.

Asbestos felt offers more permanent reinforcement to bituminous materials than rag felt.

No bituminous coating or coating material is inherently greatly superior to all others. It is possible to secure similar results by several methods.

Although protective coatings have been in use many years there are few detailed records of the performance of coatings covering periods of more than 5 years. The life of protective coatings is therefore somewhat uncertain.

Bituminous coating materials suitable for the service required of them materially reduce corrosion losses. However, because of the nature of the materials used and the conditions under which pipe lines are usually laid, a pipe coating free from imperfections and injuries is scarcely to be expected.

The conclusions drawn above are based on the performance of types of coatings. The best coating in each type was somewhat more effective than the average upon which the conclusions are based. It is probable that the tests have resulted in the production of coatings that are better than any in the tests which form the basis for these conclusions.

WASHINGTON, August 21, 1937.