

# Polarization Measurements as Related to Corrosion of Underground Steel Piling

W. J. Schwerdtfeger

Institute for Materials Research, National Bureau of Standards, Washington, D.C. 20234

(April 14, 1971)

Most of this paper is devoted to the author's evaluation of polarization measurements made by the Corps of Engineers (Lower Mississippi Valley Division) on steel pipe specimens exposed to the soil at four dam sites as related to the corrosion of steel piling (underground) observed at the sites. As the polarization measurements were made periodically on weighed specimens for periods as long as seven years, the Corps' data offered an excellent opportunity for evaluating the accuracy and practicability of a polarization technique for measuring corrosion rates. Reasonable agreement between calculated and actual corrosion on the specimens made it possible to estimate maximum anticipated corrosion on the piling after 50 years of exposure.

Confidence gained in the value of polarization measurements made on short length pipe specimens led the author to make measurements on actual piling. Instantaneous corrosion rates were measured on two driven pipe piles, 72 ft (22 m) and 19 ft (5.8 m) in length, both of which had been exposed for 12 years. One month later, the short pile was extracted and examined. Relatively low corrosion rates calculated from the polarization data were verified by the appearance of the pile and by the limited extent of the pitting.

Key words: Corrosion; corrosion rate; disturbed soil; instantaneous rate; pit depth; pitting factor; polarization; steel piling; undisturbed soil; weight loss.

## 1. Introduction

Corrosion observed on structural steel piling exposed to underground environments based on visual inspection and measurements of pit depth has been described by Romanoff [1].<sup>1</sup> His inspections were made in cooperation with the Corps of Engineers (Lower Mississippi Valley Division) and the American Iron and Steel Institute. During the course of an investigation at four dam sites, where piling had been examined, Romanoff decided to expose steel pipe specimens, arranged in groups of four, to the same underground environments nearby. One specimen of each group was wired to enable periodic monitoring of instantaneous rates of corrosion by polarization measurements. The groups of specimens were removed from each site at intervals of 1, 2, 4, and 7 years.

The buried specimens, exposed to back-filled trenches, served a two-fold purpose. Romanoff [1] reported that steel exposed to excavated soils was subject to more severe corrosion than that which he observed on driven piling for a given environment. Thus, the steel specimens would provide the opportunity for comparing corrosion under the two conditions of exposure (driven or buried). Secondly, they offered an excellent chance for evaluating the accuracy and practicability of a polarization technique for measuring corrosion. The method was evaluated by comparing the cumulative metal losses (based on Faraday's law) of the wired specimens with their actual weight losses.

Past work has demonstrated that instantaneous rates of corrosion on pipe specimens in situ can be measured by a polarization technique and averaged for periodic intervals in calculating metal losses resulting from corrosion for a given period of exposure [2]. As exposure time for some of the Corps of Engineers' specimens extended over a period of 7 years, an excellent opportunity prevailed for a further evaluation of the technique as applied to underground corrosion. Furthermore, it became possible to monitor corrosion rates at each of the four sites over a period of 7 years. By thus monitoring corrosion rates, the length of exposure time required to obtain reliable performance data of metals exposed to a given environment can be estimated.

Romanoff [1] concluded, based primarily on visual observation and experience, that iron exposed to soil in backfilled trenches is more severely corroded than when exposed to the same soil (undisturbed). Romanoff referred to undisturbed soil as that soil adjacent to driven piling below the backfilled soil. In order to further substantiate this conclusion, Romanoff exposed iron pipe specimens to excavated trenches in the same areas where driven piling had previously been visually examined. The Corps of Engineers, responsible for making the polarization measurements, also exposed iron rods, limited in number, by driving some of them into the soil and by exposing other identical rods to excavated soil nearby. The National Bureau of Standards prepared weighed pipe specimens for the burial program. The rod specimens were

<sup>1</sup> Figures in brackets indicate the literature references at the end of this paper.

prepared by the Corps of Engineers. The Corps furnished the Bureau with copies of the polarization curves obtained at the periodic intervals. During the period of 7 years, all specimens involved in four removals were sent to the Bureau for cleaning and determination of metal losses.

In a recent report [3] by the Corps of Engineers on the corrosion of underground steel piling, the results of measurements made on the pipe and rod specimens are included. Included in that report are the weight losses and maximum pit depths on all specimens, pipe and rod, unwired and wired. Estimated weight losses based on electrical measurements are summarized and discussed in relation to what was observed on nearby piling.

In this paper, the polarization curves submitted to NBS by the Corps of Engineers are evaluated by the Bureau. This accounts for any differences (averaging 9%) between the Corps estimated weight losses and the calculated weight losses tabulated herein. Stabilized corrosion rates, based on polarization measurements made on the wired seven-year pipe specimens in back-filled trenches, are expressed as average penetration and compared with the maximum corrosion observed on piling at the same sites exposed from 11 to 20 years.

Recently, the writer became aware of some isolated steel pipe piles located on the grounds of a sewage disposal plant. It was suggested that it might be of interest to make polarization measurements on one or more of the driven piles which were exposed to the soil for 12 years. The results of measurements and calculated rates of corrosion for two 12.75 in (32.5 cm) diam piles 72 ft (22 m) and 19 ft (5.8 m) long are described.

## 2. Experimental Procedure

### 2.1. Preparation of Pipe and Rod Specimens

Sixteen pipe specimens were prepared for burial at each of four sites. The specimens were cut from standard black iron pipe 1.5 in (3.8 cm) diam to lengths of 14 in (35.5 cm). Loose mill scale was removed and the specimens were deburred, degreased and weighed to the nearest 50 mg. The inside of the pipe was coated with heavy grease and rubber caps were placed over the open ends so as to confine corrosion to the outer surface area 0.5 ft<sup>2</sup> (4.6 dm<sup>2</sup>) approx. One of each set of four specimens, constituting a set for removal, was equipped with an insulated copper wire soldered to the inside of the pipe and brought through a hole in the center of one of the rubber caps. The pipes were placed laterally in the trench about 12 in (30.5 cm) apart and buried horizontally about 3 ft (0.92 m) below the earth's surface. The wires to specimens terminated above ground in boxes mounted on wooden posts.

The number of rod specimens was limited to two at each of the four sites. One of the rods was exposed vertically positioned in back-filled soil and the other rod was driven off to the side about 18 in (46 cm) away. The rods were cut from hot-rolled steel 0.75 in (1.9 cm) diam to 3 ft (0.92 m) lengths. They were cleaned and weighed as previously mentioned for the pipe specimens. Both rods were equipped with insulated copper wires terminating above ground. The top 5 in (12.7 cm) of each rod, including the wire connection, was coated with coal tar.

This again left about 0.5 ft<sup>2</sup> (4.6 dm<sup>2</sup>) of bare surface for exposure to the soil, the same as for the pipe specimens.

### 2.2. Polarization Measurements— Pipe and Rod Specimens

A galvanized steel pipe 1 in (2.54 cm) diam and five ft (1.5 m) long was driven at each site for use as an auxiliary electrode. Polarization measurements were made by the Corps of Engineers [3] at intervals of from 3 to 7 months approximately. When making polarization measurements in soil environments, it is usually necessary to use a bridge circuit because changes in measured potential caused by the IR drop through the soil may be sufficient to obscure changes due to actual polarization. The Holler bridge circuit, originally described by Holler [4] and more recently by Schwerdtfeger [5], was used by the Corps of Engineers at the test sites. For running the polarization curves, equal increments of current were applied at one minute intervals.

### 2.3. Removal of Corrosion Products from the Specimens

The pipe and rod specimens were returned to the Bureau for cleaning after exposure to the soils. They were scrubbed under hot running water to remove soil and loose corrosion products. The rubber caps were removed from the pipe specimens and grease inside the pipes was melted out by applying heat from a torch flame. Following degreasing, the specimens were immersed in a hot solution (150 °F) of 10 percent ammonium citrate neutralized with ammonium hydroxide. Length of immersion time varied with the degree of corrosion, being usually not over five hours. Ammonium hydroxide was added as required to keep the solution on the neutral to alkaline side. Specimens were intermittently scrubbed with a steel-bristle brush to remove corrosion products down to bare metal. The rod specimens were freed of corrosion products in the same way. Solder was melted and scraped from those specimens which had wire leads. Finally, all specimens were again weighed to the nearest 50 mg.

### 2.4. Polarization Measurements on Pipe Piling in Situ

Polarization curves were obtained on bare pipe piling driven 12 years previously on property of the Hiawatha Treatment Plant at Syracuse, N. Y. Measurements were made on two 12 in diam (30.5 cm) pipe piles, 72 ft (22 m) and 19 ft (5.8 m) in length. The auxiliary anode was a third pipe pile driven to a depth of 122 ft (37 m). The piles were separated by a distance of about 5 ft (1.5 m). The reference electrode was copper-copper sulfate placed on the earth's surface at a distance of about 50 ft (15.2 m) from the top of the pile being measured.

An adaptation of the Holler bridge (fig. 1) was used by the Bureau to obtain the polarization curves. It will be noted that terminals are provided for inserting other control resistors,  $R_s$  and  $R_x$ , should specimen size or environmental conditions make that necessary. For running the curves on the piling, the 0.5  $\Omega$  balancing resistor  $R_x$  was used and the other balancing resistors were set at zero. A 12-volt storage battery supplied the polarizing

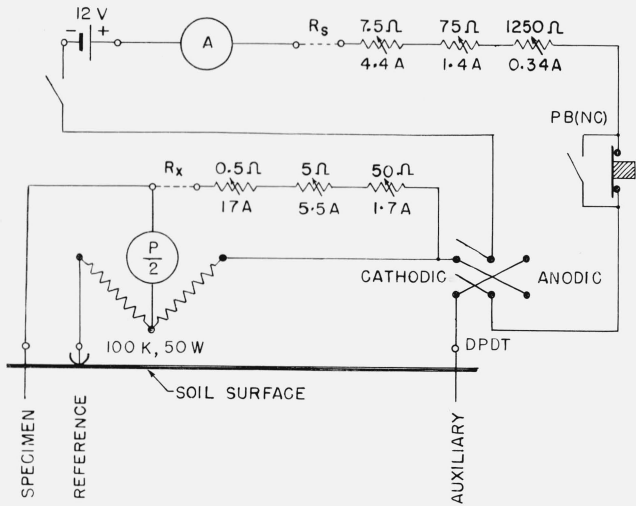


FIGURE 1. Circuit used for obtaining polarization curves on piling.

current. A potentiometer was used in the bridge circuit for measuring potentials. The polarization curves were obtained by applying equal increments of current at one minute intervals. The increments were previously determined by the applied current necessary to change the potential from 2 to 10 mV.

In addition to polarization, soil resistivity in the vicinity of the piling was measured at depths of 3, 12, and 30 ft (0.91, 3.7, 9.1 m) using the 4-pin Wenner method.

The 19 ft (5.8 m) pile was extracted for examination and measurement of depth of pits.

### 3. Results and Discussion

#### 3.1. Corrosion Rates of Pipe Specimens in Back-Filled Trenches

In figure 2 are shown typical polarization curves obtained at periodic intervals on the seven-year pipe specimen at Sardis Dam. Corrosion rates at Sardis Dam were the lowest of the 4 sites. The cathodic curves are those having breaks indicated by  $I_p$ , while breaks in the anodic curves are shown by the currents  $I_a$ . Anodic curves are omitted for data obtained 8-10-60 and 5-1-61 because there was relatively little or no polarization, indicating a value for the current  $I_a$  several times that of the current  $I_p$ . Typical polarization curves obtained on four-year pipe specimens at the 4 test sites are shown in figure 3. The curves were obtained a few months prior to removal of the specimens.

All electrical data obtained on the pipe specimens at the 4 sites are shown in tables 1 through 4. The method used in calculating corrosion currents and metal losses is described in the footnotes of the table. Actual weight losses, after chemical removal of corrosion products, are also shown for comparison. Agreement between actual and calculated values is reasonably good. The calculated values are based on the electrochemical equivalent for ferrous iron. With the exception of the Sardis site which is poorly aerated, where corrosion probably continues in

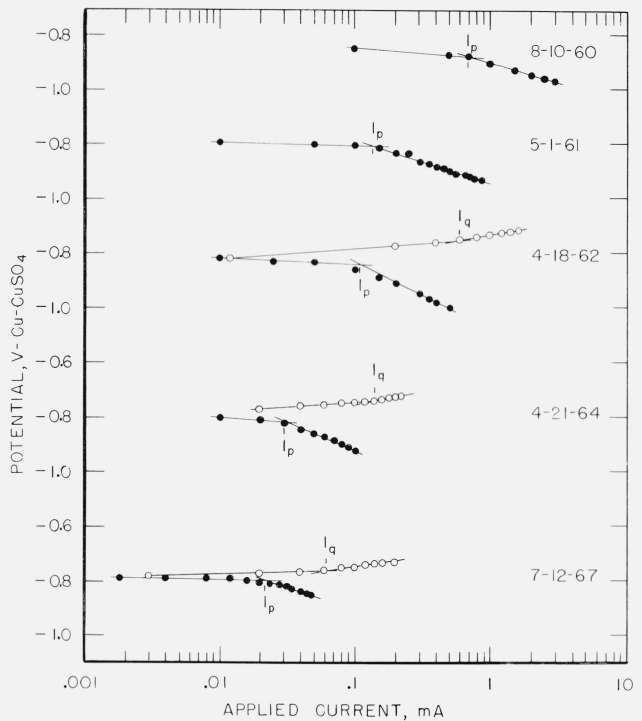


FIGURE 2. Typical polarization curves of underground steel specimen (C8) during seven years of exposure at Sardis Dam site.

● Cathodic ○ Anodic

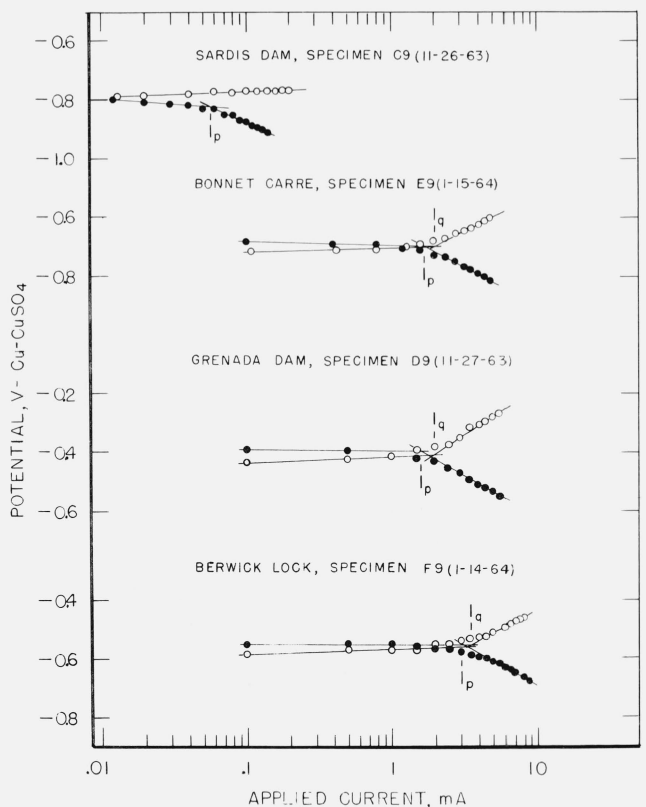


FIGURE 3. Polarization curves of underground specimens Nos. 9 after 45 months of exposure at four soil sites.

● Cathodic ○ Anodic

TABLE 1. Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Berwick Lock

Date	Exposure time cumulative	Corrosion potential Ref-Cu-CuSO <sub>4</sub>	Polarizing Current <sup>a</sup> at break in curve		Corrosion current <i>i</i> <sub>0</sub> <sup>b</sup>	Weight loss	
			Cathodic <i>I</i> <sub>p</sub>	Anodic <i>I</i> <sub>q</sub>		Calculated <sup>c</sup> cumulative	Actual
	days	V	mA	mA	mA	g	g
Specimen F4							
4-05-60	0						
8-23-60	140	-0.780	4.2	2 <i>I</i> <sub>p</sub> <sup>d</sup>	2.8	10	
11-16-60	225	.735	2.7	4.2	1.6	15	
2-07-61	308	.772	2.8	2.8	1.4	18	
5-10-61	400	.762	2.9	4.1	1.7	21	19
Specimen F13							
4-05-60	0						
8-23-60	140	-0.630	6.0	2 <i>I</i> <sub>p</sub> <sup>d</sup>	4.0	14	
11-16-60	225	.640	3.0	3.6	1.6	20	
2-07-61	308	.657	3.6	4.5	2.0	24	
5-10-61	400	.580	5.4	7.4	3.1	30	
9-19-61	532	.655	9.0	11.0	4.9	43	
1-17-62	652	.625	10.0	14.0	5.8	59	
4-25-62	750	.580	6.5	7.6	3.5	70	49
Specimen F9							
4-05-60	0						
8-23-60	140	-0.718	5.6	2 <i>I</i> <sub>p</sub> <sup>d</sup>	3.7	13	
11-16-60	225	.630	3.6	3.6	1.8	19	
2-07-61	308	.700	3.1	4.4	1.8	23	
5-10-61	400	.645	7.0	8.0	3.7	29	
9-19-61	532	.665	6.8	7.5	3.6	40	
1-17-62	652	.642	8.0	11.0	4.6	53	
4-25-62	750	.577	8.0	9.4	4.3	64	
8-29-62	876	.564	7.6	9.6	4.2	78	
1-16-63	1016	.620	9.0	9.0	4.5	93	
5-15-63	1135	.415	6.0	4.5	2.6	103	
9-18-63	1261	.552	3.5	3.5	1.7	110	
1-14-64	1379	.575	2.7	3.2	1.5	115	
4-28-64	1483	.533	4.0	4.0	2.0	119	67
Specimen F8							
4-05-60	0						
8-23-60	140	-0.628	7.4	2 <i>I</i> <sub>p</sub> <sup>d</sup>	4.9	17	
11-16-60	225	.638	3.0	3.7	1.7	24	
2-07-61	308	.635	5.2	4.3	2.3	28	
5-10-61	400	.635	11.5	10.0	5.3	37	
9-19-61	532	.660	7.5	6.5	3.5	51	
1-17-62	652	.553	10.0	10.0	5.0	64	
4-25-62	751	.578	6.8	6.6	3.3	74	
8-29-62	877	.587	13.0	13.0	6.5	90	
1-16-63	1017	.613	13.0	12.0	6.2	112	
5-15-63	1136	.417	4.5	4.0	2.1	124	
9-18-63	1262	.560	4.5	5.2	2.4	131	
1-14-64	1380	.553	3.7	5.0	2.1	138	
4-28-64	1484	.500	4.5	4.5	2.2	143	
9-09-64	1618	.337	3.4	3.4	1.7	150	
12-17-64	1717	.556	2.0	2.0	1.0	153	
5-04-65	1856	.450	1.2	2.4	0.8	156	
1-11-66	2180	.531	1.2	1.4	0.6	161	
5-17-66	2235	.530	0.6	1.0	0.4	162	
10-25-66	2396	.545	0.7	1.4	0.5	164	
7-25-67	2669	.328	0.9	0.7	0.4	167	125

<sup>a</sup> See figure 2.

$$b_{i_0} = \frac{I_p I_q}{I_p + I_q}$$

<sup>c</sup> From Faraday's law, Weight loss (grams) =  $Kti_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/c,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

<sup>d</sup> Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

TABLE 2. Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Bonnet Carre Spillway

Date	Exposure time cumulative days	Corrosion potential Ref-Cu-CuSO <sub>4</sub> V	Polarizing Current <sup>a</sup> at break in curve		Corrosion current <i>i</i> <sub>0</sub> <sup>b</sup> mA	Weight loss		
			Cathodic <i>I</i> <sub>p</sub> mA	Anodic <i>I</i> <sub>q</sub> mA		Calculated <sup>c</sup> cumulative g	Actual g	
			Specimen E4					
4-06-60	0							
8-24-60	140	-0.800	3.0	7.0	2.0	7		
11-17-60	225	.780	2.9	7.3	2.1	11		
2-08-61	308	.770	2.6	2.5 <i>I</i> <sub>p</sub> <sup>d</sup>	1.9	15		
5-11-61	400	.780	3.0	2.5 <i>I</i> <sub>p</sub> <sup>d</sup>	2.1	20		12
Specimen E13								
4-06-60	0							
8-24-60	140	-0.822	2.7	2 <i>I</i> <sub>p</sub> <sup>d</sup>	1.8	6		
11-17-60	225	.786	2.3	2.5 <i>I</i> <sub>p</sub> <sup>d</sup>	1.7	10		
2-08-61	308	.775	2.8	2.5 <i>I</i> <sub>p</sub>	2.0	14		
5-11-61	400	.790	2.8	2.5 <i>I</i> <sub>p</sub>	2.0	18		
9-20-61	532	.790	2.8	2.5 <i>I</i> <sub>p</sub>	2.0	25		
1-18-62	652	.777	2.7	6.7	1.9	31		
4-26-62	750	.770	3.0	8.5	2.2	36		21
Specimen E9								
4-06-60	0							
8-24-60	140	-0.806	2.8	2 <i>I</i> <sub>p</sub> <sup>d</sup>	1.9	7		
11-17-60	225	.790	3.2	2.5 <i>I</i> <sub>p</sub> <sup>d</sup>	2.3	11		
2-08-61	308	.780	2.9	2.5 <i>I</i> <sub>p</sub>	2.1	16		
5-11-61	400	.800	3.5	2.5 <i>I</i> <sub>p</sub>	2.5	21		
9-20-61	532	.799	3.1	2.5 <i>I</i> <sub>p</sub>	2.2	29		
1-18-62	652	.790	3.1	7.8	2.2	35		
4-26-62	750	.800	3.0	8.4	2.2	41		
8-30-62	876	.771	6.4	7.2	3.4	50		
1-17-63	1016	.750	4.4	5.7	2.5	60		
5-16-63	1135	.545	3.0	3.0	1.5	66		
9-17-63	1259	.650	2.4	2.5	1.2	70		
1-15-64	1379	.710	1.7	2.0	0.92	73		
4-29-64	1483	.690	2.1	2.8	1.2	76		41
Specimen E8								
4-06-60	0							
8-24-60	140	-0.812	2.8	2 <i>I</i> <sub>p</sub> <sup>d</sup>	1.9	7		
11-17-60	225	.790	3.2	2 <i>I</i> <sub>p</sub>	2.1	11		
2-08-61	308	.775	3.6	9.0	2.6	10		
5-11-61	400	.795	4.6	2 <i>I</i> <sub>p</sub> <sup>d</sup>	3.1	22		
9-20-61	532	.790	3.5	9.0	2.5	32		
1-18-62	652	.787	3.4	8.0	2.4	39		
4-26-62	751	.780	4.2	12.0	3.1	45		
8-30-62	877	.684	8.6	9.0	4.4	57		
1-17-63	1016	.680	4.9	5.6	2.6	69		
5-16-63	1135	.565	1.7	3.5	1.1	74		
9-17-63	1259	.628	1.5	3.1	1.0	77		
1-15-64	1379	.640	1.6	1.9	0.9	80		
4-29-64	1483	.620	2.0	2.0	1.0	83		
9-10-64	1617	.600	1.9	2.1	1.0	86		
12-18-64	1716	.559	1.4	1.9	0.8	88		
5-05-65	1855	.488	1.3	1.9	0.8	91		
1-12-66	2107	.638	1.1	0.8	0.5	95		
5-18-66	2234	.600	0.8	1.4	0.5	96		
10-26-66	2395	.563	0.9	1.2	0.5	98		
7-26-67	2668	.530	1.1	1.1	0.6	102		71

<sup>a</sup>See figure 2.

$$b i_0 = \frac{I_p I_q}{I_p + I_q}$$

<sup>c</sup>From Faraday's law, Weight loss (grams) =  $K t i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/c,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , here  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

<sup>d</sup>Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

TABLE 3. Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Grenada Dam

Date	Exposure time cumulative	Corrosion potential Ref-Cu-CuSO <sub>4</sub>	Polarizing Current <sup>a</sup> at break in curve		Corrosion current <sup>b</sup> <i>i</i> <sub>0</sub>	Weight loss	
			Cathodic <i>I</i> <sub>p</sub>	Anodic <i>I</i> <sub>q</sub>		Calculated <sup>c</sup> cumulative	Actual
	days	V	mA	mA	mA	g	g
Specimen D4							
3-30-60	0						
8-11-60	134	-0.408	1.9	2.9	1.1	3.7	
11-02-60	217	.403	2.0	2.2	1.0	5.9	
2-16-61	323	.444	3.3	4.1	1.8	9.6	
5-03-61	399	.437	4.0	8.3	2.7	14	17
Specimen D13							
3-30-60	0						
8-11-60	134	-0.452	4.0	4.5	2.1	7	
11-02-60	217	.483	2.2	4.0	1.4	11	
2-16-61	323	.588	7.0	13.0	4.5	18	
5-03-61	399	.560	7.5	9.7	4.2	27	
9-07-61	526	.457	4.5	5.6	2.5	37	
1-26-62	667	.473	5.0	6.4	2.8	47	
4-19-62	750	.500	6.0	6.6	3.1	53	40
Specimen D9							
3-30-60	0						
8-11-60	134	-0.467	2.6	2.7	1.3	4	
11-02-60	217	.433	2.7	3.9	1.6	7	
2-16-61	323	.630	4.3	6.0	2.5	13	
5-03-61	399	.662	4.3	4.3	2.2	17	
9-07-61	526	.495	4.8	5.6	2.6	25	
1-26-62	667	.725	3.1	3.5	1.6	32	
4-19-62	750	.725	2.4	2.6	1.2	35	
9-06-62	890	.265	4.2	5.9	2.4	42	
12-12-62	987	.169	2.4	2.5	1.2	46	
4-04-63	1100	.501	4.2	4.2	2.1	51	
8-29-63	1247	.550	—	—	—	—	
11-27-63	1337	.425	2.5	2.1	1.1	60	
4-22-64	1483	.610	2.0	2.0	1.0	64	63
Specimen D8							
3-30-60	0						
8-11-60	134	-0.388	1.9	3.0	1.2	4	
11-02-60	217	.390	2.2	2.5	1.2	6	
2-16-61	323	.447	3.5	3.9	1.8	10	
5-03-61	400	.457	4.6	5.2	2.4	14	
9-07-61	528	.387	3.0	8.0	2.2	22	
1-26-62	669	.437	3.8	5.5	2.2	30	
4-19-62	752	.465	2.7	5.2	1.8	34	
9-06-62	892	.230	3.0	4.0	1.7	40	
12-12-62	989	.132	1.7	2.6	1.0	43	
4-04-63	1102	.358	3.0	4.3	1.8	47	
8-29-63	1249	.384	2.0	2.2	1.0	53	
11-27-63	1339	.403	1.3	1.9	0.8	55	
4-22-64	1485	.379	1.2	1.1	0.6	57	
8-26-64	1611	.382	0.8	1.2	0.5	59	
1-13-65	1751	.366	0.5	0.8	0.3	60	
4-29-65	1858	.359	0.5	0.7	0.3	61	
12-08-65	2081	.390	0.3	0.4	0.2	62	
5-11-66	2235	.373	0.3	0.5	0.2	63	
10-12-66	2389	.127	0.2	0.3	0.1	63	
7-13-67	2663	.406	0.4	0.4	0.2	64	55

<sup>a</sup> See figure 2.

$$b \ i_0 = \frac{I_p \ I_q}{I_p + I_q}$$

<sup>c</sup> From Faraday's law, Weight loss (grams) =  $K t i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/c,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

TABLE 4. Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Sardis Dam

Date	Exposure time cumulative days	Corrosion potential Ref-Cu-CuSO <sub>4</sub> V	Polarizing Current <sup>a</sup> at break in curve		Corrosion current <i>i</i> <sub>0</sub> <sup>b</sup> mA	Weight loss		
			Cathodic <i>I</i> <sub>p</sub> mA	Anodic <i>I</i> <sub>q</sub> mA		Calculated <sup>c</sup> cumulative g	Actual g	
			Specimen C4					
3-29-60	0							
8-10-60	134	-0.821	0.54	≥ <i>I</i> <sub>p</sub> <sup>d</sup>	0.54	1.8		
11-01-60	217	.802	.16	9 <i>I</i> <sub>p</sub> <sup>d</sup>	.14	2.5		
2-15-61	323	.800	.11	9 <i>I</i> <sub>p</sub>	.10	2.8		
5-01-61	398	.795	.09	9 <i>I</i> <sub>p</sub>	.08	3.0		4.3
Specimen C13								
3-29-60	0							
8-10-60	134	-0.815	0.86	≥ <i>I</i> <sub>p</sub> <sup>d</sup>	0.86	2.9		
11-01-60	217	.806	.35	9 <i>I</i> <sub>p</sub> <sup>d</sup>	.31	4.1		
2-15-61	323	.800	.25	9 <i>I</i> <sub>p</sub>	.22	4.8		
5-01-61	398	.795	.22	9 <i>I</i> <sub>p</sub>	.20	5.2		
9-06-61	526	.799	.32	9 <i>I</i> <sub>p</sub>	.29	6.0		
1-25-62	667	.803	.16	9 <i>I</i> <sub>p</sub>	.14	6.7		
4-18-62	750	.800	.20	9 <i>I</i> <sub>p</sub>	.18	7.1		6.0
Specimen C9								
3-29-60	0							
8-10-60	134	-0.815	0.58	≥ <i>I</i> <sub>p</sub> <sup>d</sup>	0.58	1.9		
11-01-60	217	.808	.28	9 <i>I</i> <sub>p</sub> <sup>d</sup>	.25	2.8		
2-15-61	323	.805	.11	9 <i>I</i> <sub>p</sub>	.1	3.3		
5-01-61	398	.800	.11	9 <i>I</i> <sub>p</sub>	.1	3.5		
9-06-61	526	.800	.09	9 <i>I</i> <sub>p</sub>	.08	3.7		
1-25-62	667	.806	.10	9 <i>I</i> <sub>p</sub>	.09	4.0		
4-18-62	750	.812	.10	9 <i>I</i> <sub>p</sub>	.09	4.2		
9-05-62	890	.800	.08	9 <i>I</i> <sub>p</sub>	.08	4.5		
12-11-62	987	.770	.13	9 <i>I</i> <sub>p</sub>	.12	4.8		
4-03-63	1100	.804	.09	9 <i>I</i> <sub>p</sub>	.08	5.0		
8-28-63	1247	.830	.06	9 <i>I</i> <sub>p</sub>	.06	5.3		
11-26-63	1337	.797	.06	9 <i>I</i> <sub>p</sub>	.05	5.4		
4-21-64	1483	.800	.04	9 <i>I</i> <sub>p</sub>	.03	5.6		4.6
Specimen C8								
3-29-60	0							
8-10-60	133	-0.828	0.68	≥ <i>I</i> <sub>p</sub> <sup>d</sup>	0.68	2.3		
11-01-60	216	.810	.27	9 <i>I</i> <sub>p</sub> <sup>d</sup>	.24	3.2		
2-15-61	322	.810	.14	9 <i>I</i> <sub>p</sub>	.13	3.7		
5-01-61	397	.802	.14	9 <i>I</i> <sub>p</sub>	.13	3.9		
9-06-61	525	.805	.13	0.4	.10	4.3		
1-25-62	666	.808	.12	.8	.11	4.6		
4-18-62	749	.808	.11	1.2	.10	4.8		
9-05-62	889	.799	.10	1.0	.09	5.2		
12-11-62	986	.782	.08	0.8	.07	5.4		
4-03-63	1099	.790	.05	0.3	.04	5.6		
8-28-63	1246	.830	.04	9 <i>I</i> <sub>p</sub> <sup>d</sup>	.04	5.7		
11-26-63	1336	.792	.04	0.1	.03	5.8		
4-21-64	1481	.790	.03	.1	.02	5.9		
8-25-64	1607	.799	.03	3 <i>I</i> <sub>p</sub> <sup>d</sup>	.02	5.9		
1-12-65	1747	.790	.02	0.1	.02	6.0		
4-28-65	1854	.800	.02	.6	.02	6.1		
12-07-65	2078	.787	.01	.4	.01	6.1		
5-10-66	2232	.790	.02	.5	.01	6.2		
11-11-66	2417	.790	.02	.5	.01	6.2		
7-12-67	2660	.797	.02	.6	.02	6.3		4.8

a See figure 2.

$$b \ i_0 = \frac{I_p I_q}{I_p + I_q}$$

c From Faraday's law, Weight loss (grams) =  $Kt i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/c,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

d Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

the ferrous state, the use of the ferric equivalent might be more valid. The use of the ferric equivalent would reduce the calculated weight losses by one-third.

The corrosion potentials at Sardis (table 4) were continuously around 0.8 V, while at other sites the potentials fluctuated and were generally more positive. The high water table at Sardis probably accounted for the relatively high electronegative potentials indicative of a deficiency in oxygen. Poor aeration could also account for the low corrosion rates at the Sardis site.

### 3.2. Comparison of Corrosion on Pipe Specimens and on Piling in the Same Soils

Cumulative weight losses based on polarization curves obtained on the seven-year specimens at the 4 sites are plotted against time in figure 4. These losses after 3.7 years of exposure are converted to corrosion rates expressed as weight loss and average penetration (reduction in cross section) for each site. Corrosion rates are tabulated in table 5 for comparison with corrosion observed on piling at the sites. The maximum reduction in thickness shown for the piling is not an overall average based on weight loss but is based on the average depth of the 25 deepest pits measured in the most corroded spots over an area 1 in<sup>2</sup> (6.5 cm<sup>2</sup>) on the piles and includes both sides of the piling wall. Had the maximum reduction in thickness been based on metal loss for a larger area, such as that of the pipe specimen 72 in<sup>2</sup> (4.6 dm<sup>2</sup>), the percentages shown in table 5 would be considerably lower.

The corrosion data (table 5) pertaining to the pipe specimens, under conditions conducive to maximum rates

of corrosion, show that corrosion is not a serious problem on piling in these particular locations. Pitting is not a limiting factor as it is on pipe lines. Thus, for example, at Berwick Lock (the most corrosive site) the average penetration on the pipe specimens after 3.7 years of exposure was at a rate of about 0.00078 in/yr (20 micrometers/yr). This means that on the piling of 0.375 in (0.95 cm) metal thickness, if corrosion were to occur on both sides in the same area at this rate only 10 percent of the metal thickness would be gone in 24 years. This corrosion would be in the area subject to the severest corrosion, that is, at the water table or in the excavated soil. In these areas on piling, the Corps of Engineers [3] considers a 35 percent reduction in cross section over a 50-year period as an acceptable maximum. At Berwick Lock, even taking into consideration the higher corrosion rate on specimens during the first 3.7 years, the average reduction in wall thickness over a 50-year period would still be under 30 percent, assuming that piling corroded at the same rate.

### 3.3. Polarization Measurements on Driven and on Buried Steel Rods

Electrical measurements on the rods are tabulated in tables 6 through 9. During early exposure, corrosion currents on the buried rods were larger than on the driven rods. As time went on, corrosion currents tended to equalize, except perhaps at Bonnet Carre and at Berwick Lock where corrosion rates on the buried rods appear to be significantly greater than those on the driven rods.

The potentials of the driven rods are apparently less affected by oxygen than are the potentials of the buried rods. A deficiency of oxygen tends to make the corrosion potentials more electronegative. It is interesting to correlate potential changes with pitting on the rods. As reported by the Corps of Engineers [3], except at Sardis Dam, it was observed that the pits were several times deeper on the buried rods than on the driven rods. Such differences were greatest at Bonnet Carre and at Berwick Lock where the differences in corrosion potentials between buried and driven rods was also greatest, the buried rods having potentials which fluctuated to more positive values. The data [3] indicate that the pitting factor (ratio of maximum pit-depth to average penetration) is greater on buried structures than on driven structures. At Sardis Dam this difference was negligible because of the high water table. The data suggest that future experiments along similar lines should be carried out with longer rods.

### 3.4. Corrosion Rates of Pipe Piles as Calculated from Polarization Curves

The Hiawatha Treatment Plant processes sewage for the area of metropolitan Syracuse, N. Y., where the water table is said to be about 10 ft (3 m) from the ground surface. Soil resistivities in the vicinity of the test piles as measured by the 4-pin method at pin spacings of 3 ft (0.91 m), 12 ft (3.7 m), and 30 ft (9.1 m) were respectively, 10,300, 3450 and 800 Ω-cm.

Preliminary polarization indicated that current increments of 40 mA would be satisfactory for obtaining the cathodic polarization curve on the 72 ft (22 m) pile (fig.

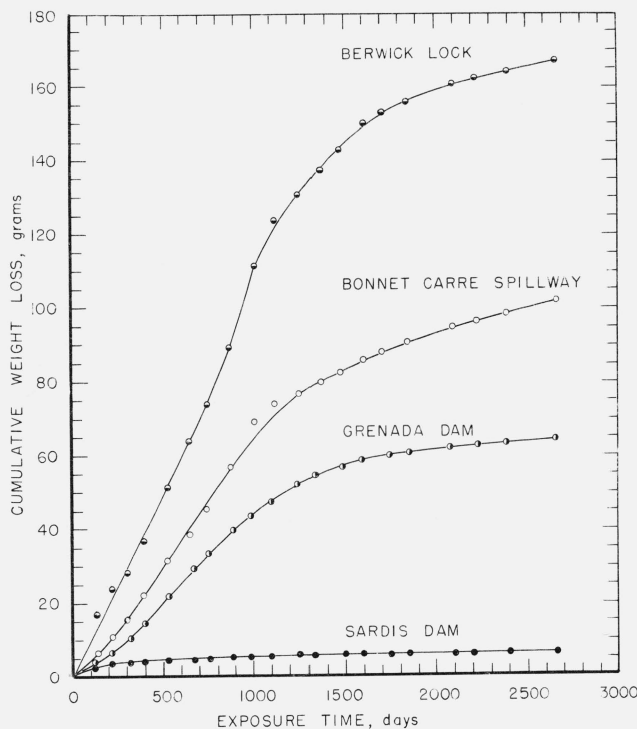


FIGURE 4. Weight loss-time curves, based on polarization curves, obtained on iron specimens (Nos. 8) buried at four back-filled trench sites.



TABLE 5. Comparison of maximum corrosion on driven steel piles with the normal corrosion on steel pipe specimens buried in nearby backfilled trenches

Location	Type of piling	Portion of pile inspected		Exposure at time of inspection	Soil			Effect of soil on piling						Effect of soil on pipe specimens. Corrosion rates from polarization curves based on the weight loss for the last 3.3 years of 7 years of exposure			
		Above water table	Below water table		Type	Resistivity <sup>a</sup>	pH <sup>b</sup>	Surface with mill scale intact			Reduction in thickness in the most corroded spot <sup>d</sup>			Weight loss		Average penetration	
								Above water table	In water table zone	Below water table	Above water table	In water table zone	Below water table				
Berwick Lock, Berwick, La. (westside)	Arch sheet Width, 19.625 in. Thickness, 0.375 in.	4	1	11	Fill-silty clay over natural clay	800-1500	8.1-8.5	60	60	60	8	nil	nil	0.51	4.3	0.78	20
Berwick Lock (eastside)	Arch sheet Width, 19.625 in. Thickness, 0.375 in.	2.5	1	11	Fill-clay over natural clay	750-1610	7.9-8.1	40	40	75	11	8	nil				
Bonnet Carre Spillway, New Orleans, La.	H, 12 in. Thickness, 0.607 in.	2	120	17	Sand, organic silt and clay mixture	400-1050	6.7-8.1	95	0	95	nil	nil	nil	0.43	3.6	0.66	17
Granada Dam, Granada Miss. (northside)	Arch sheet Width, 19.625 in. Thickness, 0.375 in.	14	0	12	Fill-sandy loam and silt over natural shale and organic clay	4000-15,400	3.6-4.9	50	(c)	(c)	8	(c)	(c)				
Granada Dam (northside)	Arch sheet Width, 15 in. Thickness, 0.375 in.	5.5	0	11	Fill-clay, sand and silt loam mixture	2300-16,500	4.0-4.4	20	(c)	(c)	16	(c)	(c)				
Granada Dam (southside)	Arch sheet Width, 15 in. Thickness, 0.375 in.	5.5	0	11	Fill-sandy loam over natural silty sand	2400-8000	4.4-6.9	60	(c)	(c)	19	(c)	(c)	0.17	1.4	0.26	7
Sardis Dam, Sardis, Miss.	Arch sheet Width, 15 in. Thickness, 0.375 in.	2	3	20	Fill-sandy loam over natural clay	3000-50,000	5.4-6.0	90	90	90	nil	nil	4	0.021	0.18	0.032	0.8

<sup>a</sup>Resistivity varied with depth and water content. Maximum values shown were measured in situ by the Wenner 4-pin method and the minimum values are as measured in the laboratory under saturated conditions.

<sup>b</sup>Removed from the site in sealed containers and measured in the laboratory.

<sup>c</sup>Entire piling was well above the water table.

<sup>d</sup>The reduction in thickness is based on the average of 25 measurements in the most severely corroded spot (area of spot, about 1 in; 6.5 cm;) observed.

<sup>e</sup>mdd, milligrams per square decimeter per day.

<sup>f</sup>mpy, mils per year. One mil — .001 in (25 micrometers, approx.)

TABLE 6. Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Berwick Lock

Periodic corrosion rates are based on polarization measurements.

Date	Exposure time cumulative	Corrosion potential Ref-Cu-CuSO <sub>4</sub>		Polarizing current at break in polarization curve <sup>a</sup>				Corrosion <sup>b</sup> current		Weight loss <sup>c</sup> calculated cumulative	
		Driven No. 21	Buried No. 22	Driven		Buried		Driven No. 21	Buried No. 22	Driven No. 21	Buried No. 22
				Cathodic $I_p$	Anodic $I_q$	Cathodic $I_p$	Anodic $I_q$				
	days	V	V	mA	mA	mA	mA	mA	mA	g	g
6-20-62	0	-0.805	-0.787	1.8	$\geq I_p^d$	2.4	$\geq I_p^d$	1.8	2.4		
8-29-62	70	.811	.811	1.7	12	2.6	8.0	1.5	2.0	2.8	3.8
1-16-63	210	.773	.785	1.9	10	3.3	18	1.6	2.8	8.0	12
5-15-63	329	.768	.765	2.1	2.6	3.9	$\geq I_p^d$	1.2	3.9	12	22
9-18-63	455	.800	.770	2.5	10	3.2	3.8	2.0	1.7	17	31
1-14-64	573	.795	.739	1.0	1.0	1.6	2.0	0.5	0.89	21	35
4-28-64	677	.814	.722	1.5	4.0	1.7	2.3	1.1	.98	23	37
9-09-64	811	.790	.660	0.95	1.3	0.95	1.4	0.55	.57	26	40
12-17-64	910	.795	.655	.65	0.65	.75	1.1	.33	.45	27	41
5-04-65	1049	.777	.610	.70	.90	.70	0.90	.39	.39	28	42
9-01-65	1169	.795	.617								
1-11-66	1301	.790	.603	.43	.43	.65	.78	.22	.35	30	45
5-17-66	1427	.793	.601	.63	.63	.70	.70	.31	.35	31	46
10-25-66	1588	.790	.595	.37	.40	.60	.45	.19	.26	32	47
7-25-67	1861	.760	.620	.27	.45	.56	.33	.17	.21	33	49
Actual weight loss										20	28

<sup>a</sup> See figure 2.

$$b \ i_0 = \frac{I_p I_q}{I_p + I_q}$$

<sup>c</sup> From Faraday's law, Weight loss (grams) =  $K t i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/C,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

<sup>d</sup> Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

TABLE 7. Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Bonnet Carre Spillway

Periodic corrosion rates are based on polarization measurements.

Date	Exposure time cumulative	Corrosion potential, Ref-Cu-CuSO <sub>4</sub>		Polarizing current at break in polarization curve <sup>a</sup>				Corrosion <sup>b</sup> current		Weight loss <sup>c</sup> calculated cumulative	
		Driven No. 21	Buried No. 22	Driven		Buried		Driven No. 21	Buried No. 22	Driven No. 21	Buried No. 22
				Cathodic $I_p$	Anodic $I_q$	Cathodic $I_p$	Anodic $I_q$				
days	V	V	mA	mA	mA	mA	mA	mA	g	g	
6-21-62	0	-0.817	-0.781	2.2	$\geq I_p^d$	3.0	$\geq I_p^d$	2.2	3.0		
8-30-62	70	.820	.807	2.8	$5 I_p^d$	4.0	$5 I_p^d$	2.3	3.3	3.8	5.6
1-17-63	210	.801	.780	2.5	15	3.8	13	2.1	2.9	12	16
5-16-63	329	.784	.710	2.5	$5 I_p^d$	4.0	8.0	2.1	2.7	18	25
9-17-63	453	.810	.679	1.9	$1.9 I_p^d$	2.0	3.0	0.95	1.2	22	31
1-15-64	573	.785	.651	1.7	3.0	1.8	1.8	1.1	0.90	25	34
4-29-64	677	.799	.630	1.6	3.0	1.9	2.5	1.1	1.1	28	37
9-10-64	811	.805	.608	1.8	1.8	2.2	2.2	0.90	1.1	32	40
12-18-64	910	.783	.590	1.2	1.2	1.4	1.9	.60	0.81	33	42
5-05-65	1049	.780	.529	1.6	3.0	1.1	1.8	1.1	.68	36	45
9-02-65	1169	.796	.582								
1-12-66	1301	.792	.563	1.0	0.80	0.70	0.70	0.44	.35	41	48
5-18-66	1427	.797	.525	0.80	1.3	1.4	1.4	.50	.70	43	50
10-26-66	1588	.785	.503	.70	0.70	0.85	0.60	.35	.35	44	52
7-26-67	1861	.785	.538	.85	.85	1.1	1.1	.42	.55	47	55
Actual weight loss										27	48

a See figure 2.

$$b \ i_0 = \frac{I_p I_q}{I_p + I_q}$$

c From Faraday's law, Weight loss (grams) =  $K t i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/C,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

d Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

TABLE 8. Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Grenada dam

Periodic corrosion rates are based on polarization measurements.

Date	Exposure time cumulative	Corrosion potential, Ref-Cu-CuSO <sub>4</sub>		Polarizing current at break in polarization curve <sup>a</sup>				Corrosion <sup>b</sup> current		Weight loss <sup>c</sup> calculated cumulative	
		Driven No. 21	Buried No. 22	Driven		Buried		Driven No. 21	Buried No. 22	Driven No. 21	Buried No. 22
				Cathodic $I_p$	Anodic $I_q$	Cathodic $I_p$	Anodic $I_q$				
days	V	V	mA	mA	mA	mA	mA	mA	g	g	
5-15-62	0	-0.821	-0.665	2.5	$\geq I_p^d$	7.4	$\geq I_p^d$	2.5	7.4		
9-06-62	114	.710	.502	4.7	7.0	6.0	7.0	2.8	3.2	7.6	15
12-12-62	211	.603	.550	5.8	6.6	5.0	5.6	3.1	2.7	14	22
4-04-63	324	.735	.635	6.6	10.0	6.3	6.7	4.0	3.3	24	31
8-29-63	471	.695	.568	3.0	3.0	4.0	4.0	1.5	2.0	34	40
11-27-63	561	.651	.515	1.9	1.9	1.9	1.3	1.0	0.74	37	43
4-22-64	707	.770	.717	1.9	23	1.7	1.7	1.0	.85	41	46
8-26-64	833	.670	.440	1.8	3 $I_p^d$	2.0	2.0	1.4	1.0	44	49
1-13-65	973	.691	.499	1.4	1.4	1.4	1.4	0.70	0.70	48	52
4-29-65	1068	.740	.560	1.1	0.90	1.0	0.8	.50	.44	49	54
9-16-65	1208	.546	.325								
12-08-65	1291	.525	.311	0.50	.86	0.78	.72	.32	.37	52	56
5-11-66	1445	.595	.450	.90	.50	.80	.75	.32	.39	53	57
10-12-66	1599	.428	.257	.80	.90	.54	.54	.42	.27	54	58
7-13-67	1873	.543	.480	.65	.65	.45	.70	.32	.27	57	60
Actual weight loss										59	64

<sup>a</sup> See figure 2.

$$b \ i_0 = \frac{I_p I_q}{I_p + I_q}$$

<sup>c</sup> From Faraday's law, Weight loss (grams) =  $K t i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/C,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

<sup>d</sup> Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

TABLE 9. Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Sardis Dam

Periodic corrosion rates are based on polarization measurements.

Date	Exposure time cumulative	Corrosion potential Ref-Cu-CuSO <sub>4</sub>		Polarizing current at break in polarization curve <sup>a</sup>				Corrosion <sup>b</sup> current		Weight loss <sup>c</sup> calculated cumulative	
		Driven No. 21	Buried No. 22	Driven		Buried		Driven No. 21	Buried No. 22	Driven No. 21	Buried No. 22
				Cathodic $I_p$	Anodic $I_q$	Cathodic $I_p$	Anodic $I_q$				
	days	V	V	mA	mA	mA	mA	mA	mA	g	g
5-16-62	0	-0.791	-0.797	0.91	$\geq I_p^d$	1.1	$\geq I_p^d$	0.91	1.1		
9-05-62	112	.773	.772	.60	$9 I_p^d$	1.0	$9 I_p^d$	.54	0.9	2.0	2.8
12-11-62	209	.767	.765	.52	$9 I_p^d$	0.52	$9 I_p^d$	.47	.47	3.3	4.4
4-03-63	322	.790	.787	.50	$9 I_p^d$	.48	$9 I_p^d$	.45	.43	4.6	5.7
8-28-63	469	.772	.716	.70	$9 I_p^d$	.50	$9 I_p^d$	.63	.45	6.6	7.3
11-26-63	559	.760	.740	.54	1.5	.44	0.52	.40	.24	7.8	8.1
4-21-64	705	.778	.770	.47	1.4	.38	.56	.35	.23	9.1	9.0
8-25-64	831	.645	.620	.40	0.45	.52	1.0	.21	.34	10	9.9
1-12-65	971	.763	.762	.35	.35	.29	0.20	.18	.12	11	11
4-28-65	1066	.791	.780	.50	.85	.30	.50	.32	.19	11	11
9-15-65	1206	.610	.624								
12-07-65	1289	.625	.642	.33	.33	.45	.38	.16	.21	13	12
5-10-66	1443	.755	.721	.35	.40	.42	.68	.19	.26	13	13
10-11-66	1597	.657	.631	.35	.35	.52	.62	.18	.28	14	14
7-12-67	1871	.745	.637	.25	.25	.32	.32	.13	.16	15	16
Actual weight loss										31	31

<sup>a</sup> See figure 2.

$$b \ i_0 = \frac{I_p I_q}{I_p + I_q}$$

<sup>c</sup> From Faraday's law, Weight loss (grams) =  $K t i_0$ , where  $K$  = electrochemical equivalent  $2.8938 \times 10^{-4}$  g/C,  $t$  = time (s) for the period between successive readings,  $i_0$  = average current (amperes) for a period. Approximately, weight loss (mg) =  $25 t i_0$ , where  $t$  = days between successive measurements,  $i_0$  = average current (mA) between successive measurements. The values of  $i_0$  at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.<sup>d</sup> Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of  $I_q$  before or after.

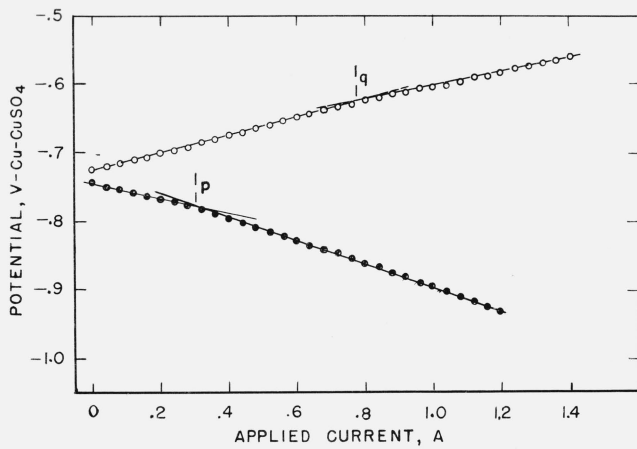


FIGURE 5. Polarization curves of a bare pipe pile, 12.75 in O.D.  $\times$  72 ft. long (32.5 cm  $\times$  22m) after underground exposure for 12 years at the Hiawatha treatment plant, Syracuse, N. Y.

5). The following day, the anodic curve was also obtained by using the same increments of applied current. Both curves are shown plotted on rectangular coordinates in order to verify changes-in-slope (breaks). Based on the Pearson equation [2], the total corrosion current on the bare metallic piling surface was calculated to be 215 mA, or a corrosion rate of 0.9 mA/ft<sup>2</sup> (0.097 mA/dm<sup>2</sup>). Upon learning that one of the other piles in the vicinity (about 5 ft or 1.5 m away) was of the same diameter but only 19 ft (5.8 m) long, the thought occurred that the average corrosion rate of the shorter pile ought to be greater than that of the long pile because a larger percentage of the short one was probably exposed to excavated soil during installation. Time permitted running a cathodic curve on the 19 ft (5.8 m) pile, applied current increments (10 mA) being estimated in the same manner as previously (fig. 6). Time did not permit obtaining the anodic polarization curve; however, it seemed reasonable to assume that the  $I_p/I_q$  ratio would be similar to what was previously observed for the long pile. Based on this assumption, the average corrosion current was calculated to be 79 mA and the corrosion rate 1.3 mA/ft<sup>2</sup> (0.14 mA/dm<sup>2</sup>). Because of the limited data, it could be argued that the corrosion rates of the two piles might not be significantly different, and rightly so. Nevertheless, the second pile measurements add validity to the corrosion rate calculated for the long pile. Validation of the corrosion rate was further emphasized when the continuous

application of 400 mA to the long pile for one hour caused a change in potential of 50 mV, confined strictly to polarization. This indicated that the pile (fig. 5) was being cathodically protected and that the current at the break, about 300 mA, was in excess of the corrosion current (calculated to be 215 mA).

On the basis of soil resistivity as measured in the area where the piles are located, it appears that the greater portion of the 72 ft (22 m) pile is driven into soil having a resistivity of 800  $\Omega$ -cm or less. To further validate the corrosion rate measurements made on the piling other information can be mentioned. The corrosion rates of plain ferrous pipe specimens, based on actual weight loss-time curves involving hundreds of specimens after five years of exposure in 28 soil sites having resistivities between 500 and 3000  $\Omega$ -cm, averaged 1.6 mA/ft<sup>2</sup> [6] (0.17 mA/dm<sup>2</sup>). The specimens had been buried in back-filled trenches (disturbed soils).

One month after making the polarization measurements, the 19 ft (5.8 m) pile was extracted and cleaned for the measurement of pit depths. It was found that 40 to 50 percent of the pile surface was still covered by mill scale after 12 years of exposure. Pitting on the remaining surface was scattered. By far, most of the pitting was in the upper 9 ft (2.75 m). Thirty-four pits ranging in depth from 50 to 100 mils (1.3 to 2.6 mm) were found in the upper 9 ft (2.75 m), most of the other pits being less than 30 mils (0.77 mm). In the lower 10 ft (3.05 m) of the pile, ten pits ranging from 30 to 90 mils (0.77 to 2.3 mm) were observed. Pits less than 30 mils (0.77 mm) were not recorded.

Assuming that piling at the Syracuse Plant corrodes at the rate of 1.3 mA/ft<sup>2</sup> (0.14 mA/dm<sup>2</sup>) for 50 years, the average reduction in metal thickness is of interest. A current density of 1.0 mA/ft<sup>2</sup> (0.11 mA/dm<sup>2</sup>) is approximately equivalent to an overall reduction in wall thickness of 0.5 mils/yr (13 micrometers/yr). Thus, the corrosion current density of 1.3 mA/ft<sup>2</sup> (0.14 mA/dm<sup>2</sup>) for 50 years would cause a reduction in pipe wall thickness of about 33 mils (0.85 mm). As the wall thickness of the pipe under discussion is 0.375 in (9.5 mm), the overall reduction in thickness for 50 years would be less than 9 percent. As previously mentioned, the Corps of Engineers [3] considered a 35 percent loss in cross section as the acceptable maximum for 50 years. Were a similar rate of corrosion taking place on two surfaces (for example on H piling), the reduction in wall thickness would still be within the acceptable maximum.

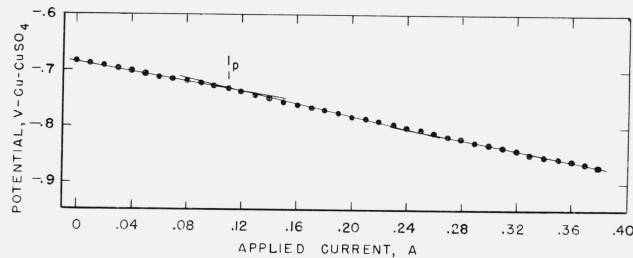


FIGURE 6. Polarization curve of a bare pipe pile, 12.75 in O.D.  $\times$  19 ft. long (32.5 cm  $\times$  5.8 m), after exposure underground for 12 years at Hiawatha treatment plant, Syracuse, N. Y.

#### 4. Conclusions

Polarization curves obtained by the Corps of Engineers (Lower Mississippi Valley Division) on four wired pipe specimens at each of four underground test sites were evaluated by the National Bureau of Standards for accuracy in the calculation of metal loss attributable to corrosion and as a means of estimating corrosion on piling which had been previously examined and exposed to the same environments. At each test site one specimen (wired) along with three identical steel unwired specimens were removed after 1, 2, 4 and 7 years of exposure. The Corps of Engineers periodically had made cathodic and anodic polarization measurements on the wired specimens at intervals varying from 2 to 7 months. Using the changes-in-slope (breaks) in the curves plotted on semi-logarithmic coordinates, the calculated instantaneous rates of corrosion were converted to total metal losses by averaging rates for the intervals. The calculated metal losses were in reasonable agreement with the actual weight losses of the wired specimens and also with the weight losses of the unwired specimens.

The relatively stable rates of corrosion which were observed after about four years of exposure of the wired 7-year pipe specimens are expressed as average penetration (reduction in metal thickness) and compared with the corrosion visually observed on piling in the same area or soil environment. On the basis of a criterion mentioned by the Corps of Engineers and using average penetration rates at the most corrosive of the four sites it was concluded that the corrosion taking place on the bare piling was not a serious problem from the standpoint of loss in structural strength.

Corrosion which had taken place in five years on driven steel rods was compared with the corrosion on identical rods exposed concurrently in nearby excavated soil. The corrosion potentials, measured periodically on the rods in connection with polarization runs, seem to bear some relation to the maximum pit depths reported by the Corps of Engineers. Pits were several times deeper on the buried rods than on the driven rods at the two most corrosive sites where the buried rods fluctuated in corrosion potential to values more electropositive than those of the driven rods. While rod specimens were limited in number, one driven and one buried at each of the four sites, the data do indicate that pitting is deepest on the metal in contact with excavated soil above the water table. The differences in weight losses of driven and buried rods were not always significant; however, the metal losses on the driven rods were generally less.

Cathodic and anodic polarization curves were obtained on two 12 in (32.5 cm) diam pipe piles, 72 ft (22 m) and 19 ft (5.8 m) in length, driven 12 years previously at a sewage disposal plant. The 72 ft (22 m) pile was exposed to soil varying in resistivity from 800  $\Omega$ -cm for the greater part to 10,300  $\Omega$ -cm near the surface. Instantaneous corrosion rates were calculated from the curves. Based on the pipe wall thickness 0.375 in (0.95 cm) the

average reduction in wall thickness of the short pile over a period of 50 years would be less than 9 percent. The polarization curves indicated that the long pile was corroding at a lower rate than the short one; however, as only two piles were involved, the difference may be insignificant. About one month later, the short pile was extracted and examined for general corrosion and pitting. It was found that about 40-50 percent of the surface was still covered with mill scale. Most of the pits under 30 mils (0.77 mm) in depth were in the upper 9 ft (2.75 m) of the pile with 34 pits ranging in depth from 50 to 100 mils (1.3 to 2.6 mm). Only two pits were 100 mils (2.6 mm) deep.

The author is deeply indebted to his former associate Melvin Romanoff (deceased) who made the arrangements with the Corps of Engineers to carry out the visual inspection of piling at the dam sites and the electrical measurements on pipe specimens at the sites.

The financial support of the American Iron and Steel Institute is gratefully acknowledged.

Deserving special recognition is E. Harold Ardahl, U.S. Army Engineer District, Lower Mississippi Valley Division, Vicksburg, Miss., who carried out all electrical measurements on the pipe and rod specimens and together with Mr. Romanoff made physical inspections on excavated and extracted piles at the dam sites.

The author extends his thanks to O. W. Wade, Consultant, who instigated making polarization measurements on isolated piling at the Hiawatha Treatment Plant, Syracuse, N. Y. and for his assistance in performing the measurements. Mr. Wade later evaluated the corrosion on one of the extracted piles.

#### 5. References

- [1] Romanoff, Melvin, Corrosion of steel pilings in Soils, Nat. Bur. Stand. (U.S.), Monogr. 58, 23 pages (Oct. 1962).
- [2] Schwerdtfeger, W. J., A study by polarization techniques of the corrosion rates of aluminum and steel underground for sixteen months, J. Res. Nat. Bur. Stand. (U.S.), **65C** (Eng. and Instr.), No. 4, 271-276 (Oct.-Dec. 1961).
- [3] Corps of Engineers-Lower Mississippi Valley Division, Vicksburg, Miss., Report on Corrosion of Underground Steel Piling, December 1969.
- [4] Holler, H. D., Studies on galvanic couples 1. Measurement of electromotive force and internal resistance of cells during current flow, J. Electrochem. Soc. **97**, 271 (Sept. 1950); Corrosion **7**, 52 (Feb. 1951).
- [5] Schwerdtfeger, W. J., Current and potential relations for the cathodic protection of steel in a high resistivity environment, J. Res. Nat. Bur. Stand. (U.S.) **63C** (Eng. and Instr.), No. 1, 37-45 (July-Sept. 1959).
- [6] Schwerdtfeger, W. J., Soil resistivity as related to underground corrosion and cathodic protection, J. Res. Nat. Bur. Stand. (U.S.), **69C** (Eng. and Instr.), No. 1, 71-77 (Jan.-Mar. 1965).

(Paper 75C2-320)