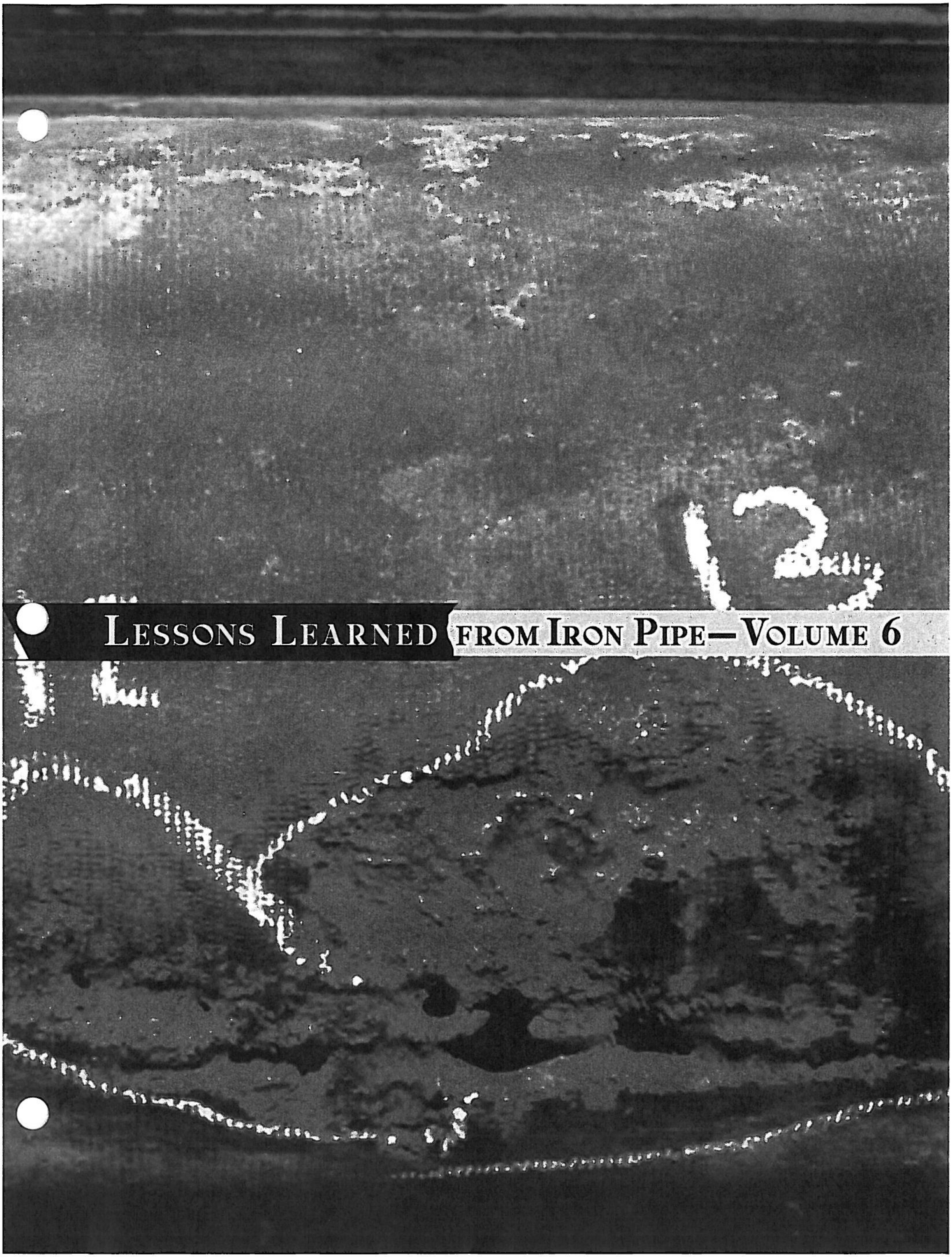
LESSONS LEARNED FROM IRON PIPE—VOLUME 6



LESSONS LEARNED FROM IRON PIPE

ACKNOWLEDGEMENTS

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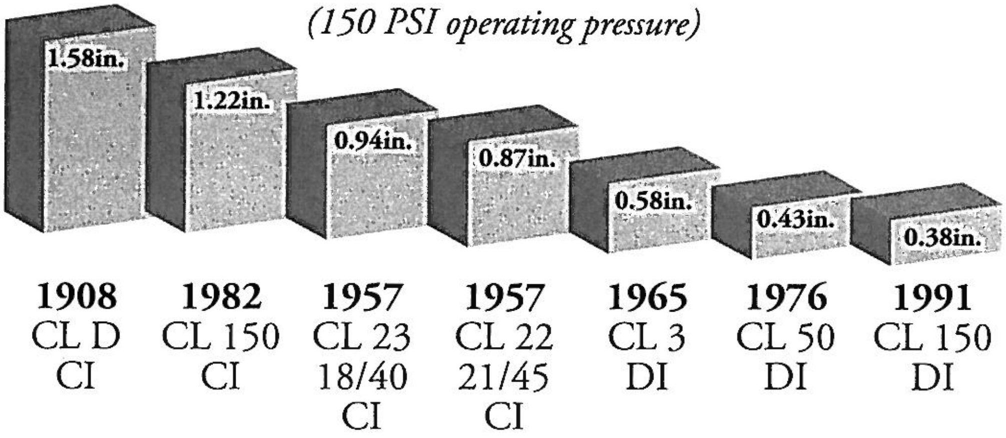
Volume 6

RELATIVE SIZE OF AWWA SPECIFICATION THICKNESS REDUCTIONS FOR 36-INCH DIAMETER CAST AND DUCTILE IRON PIPE 1908 TO PRESENT

(150 PSI operating pressure)



LESSONS LEARNED FROM IRON PIPE—VOLUME 6

INTRODUCTION

Ductile iron pipe (DIP) has been the predominant material for the nation's water and wastewater systems for the last few decades. During this time, failures of DIP due to external corrosion were reported in the early 1980's,[1-3] throughout the 1990's[4-5] and into the 2000's.[6-10] However, the true extent of the corrosion failures is not known because most failures of DIP are repaired by water and wastewater crews without being evaluated for corrosion and without documentation as to the cause of the failure.[11]

The first 5 volumes of "Lessons Learned From Iron Pipe" demonstrate, with examples of operating mains, that DIP corrodes in corrosive soil and requires corrosion protection if failures and premature replacement are to be avoided. Volumes 1 through 5 include case histories of DIP corrosion in water and wastewater systems over a period of 5 to 36 years of service in soil with resistivities from 84 ohm-cm to 220,000 ohm-cm. Figures 1 through 5 depict the case histories discussed in Volumes 1 through 5.

Volumes 2 through 4 also include technical information about reliable corrosion control measures that can be implemented to minimize corrosion damage to DIP in buried environments and prolong the useful life of DIP.

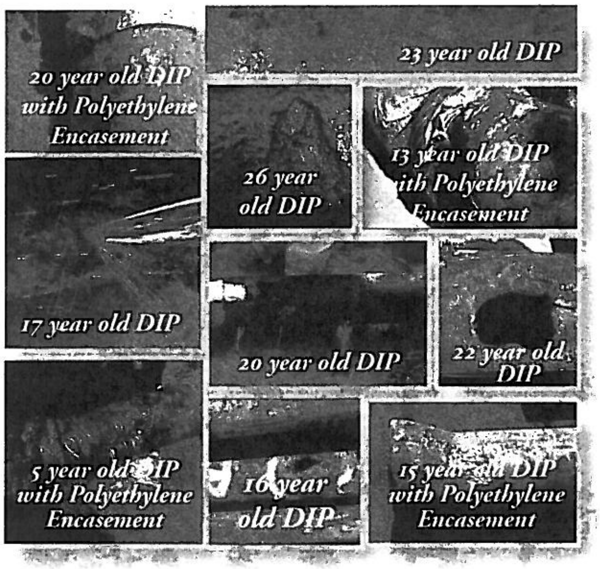


FIGURE 1

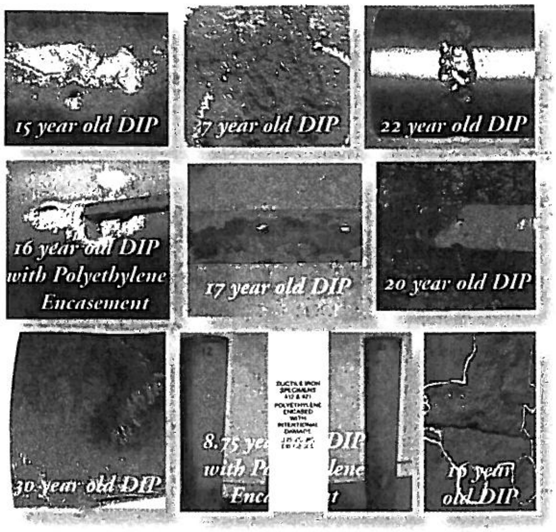


FIGURE 2

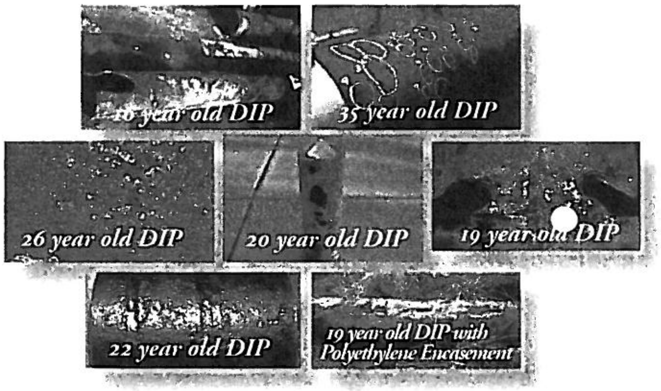


FIGURE 3

The techniques that can be applied to control corrosion of DIP have been used to protect hazardous gas mains for half a century and numerous water mains for at least the last few decades. Figure 6 includes photographs of the four case histories of cathodically protected DIP that are included in Volume 4.

Volume 5 contains data and analyses for 60 incidents of ductile iron pipe corrosion, which include the specific case histories shown in Figures 1 through 5. These pipe projects were evaluated under the 10-Point Soil Test Evaluation Method[12] to determine the corrosivity to DIP of the soils in the buried environment. Those 60 DIP corrosion incidents demonstrate the unreliability of the 10-Point Soil Test Evaluation Method.[12] The 60 incidents also demonstrate that the factory applied asphaltic coating provides no meaningful protection from corrosion. Examples of corrosion that

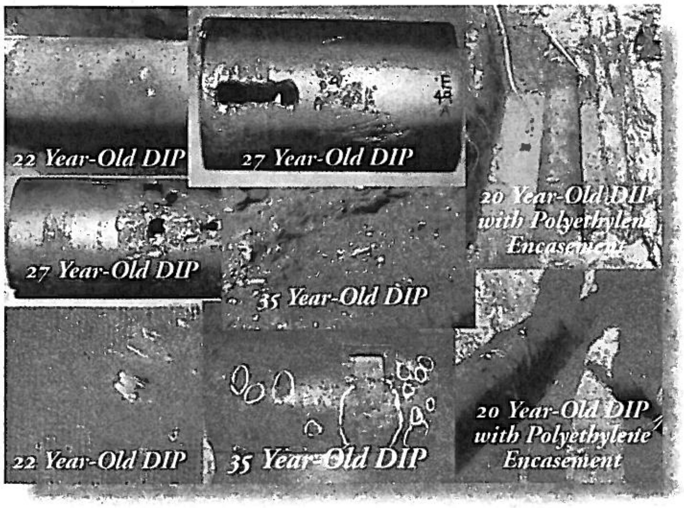


FIGURE 4

occurred at tears in polyethylene encasement and directly under undamaged polyethylene encasement are included in the 60 incidents. Also included in Volume 5, are the corrosion rates in terms of mils (0.001 inch) of metal per year of each specimen.

Volume 6 presents the analyses and results of laboratory corrosion rate measurements of DIP in soils extracted from throughout the United States. The corrosion rate measurement data were obtained using electronic state-of-the-art potentiostat/galvanostat equipment. The corrosion rate data were analyzed and correlated with soil chemistry and electrical characteristics to determine which soil characteristics most accurately impact the rate of DIP corrosion. The corrosion rate data were correlated with the data from the 60 DIP corrosion evaluations discussed in Volume 5 to develop formulas for estimating the time to penetration of DIP. These formulas can be used to estimate the life expectancy of a ductile iron main.

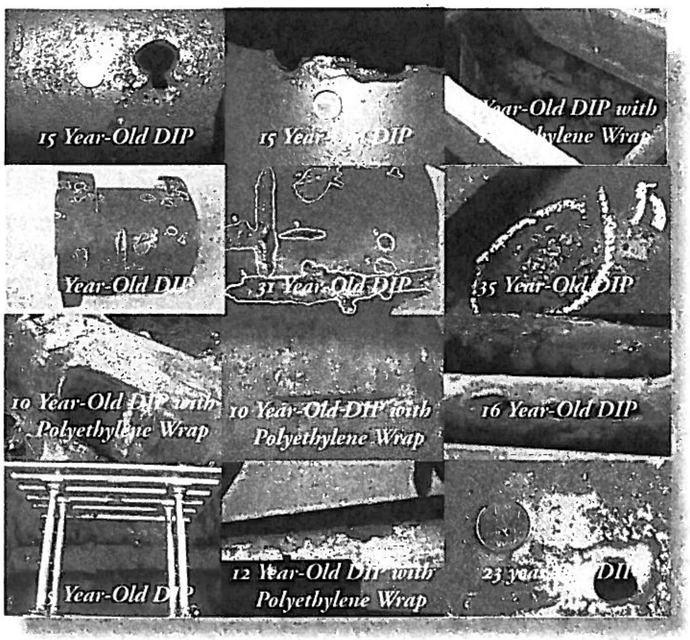


FIGURE 5

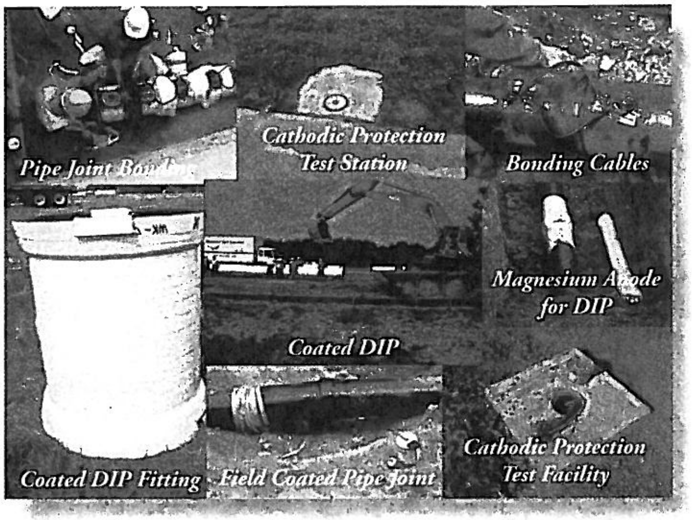


FIGURE 6

Among the most notable conclusions drawn from the analysis of the real-life case histories and information from published technical sources discussed in Volumes 1 through 5 are the following:

- **Cost effective, proven technology exists that can dramatically reduce the risk of DIP corrosion failure.**
- **Various degrees of corrosion protection can be applied to DIP depending on the level of risk that is acceptable to the owner.**
- **According to the Federal Highway Administration (FHWA), corrosion to the nation's infrastructure (not just wastewater and water systems) costs US taxpayers $276 billion per year in direct costs. FHWA further estimates that indirect costs would at least triple that value.[13]**
- **Corrosion failures occur on polyethylene-wrapped ductile iron piping at tears in the polyethylene encasement and directly under undamaged polyethylene encasement.[11]**

- DIP water mains corrode at the same rate as its forerunner product, grey cast iron water mains.[14]
- Typical DIP products have substantially thinner walls than grey cast iron pipe. When compared to the durability of grey cast iron pipe, unprotected DIP in buried environments has more rapid penetration of the pipe wall through pitting corrosion.
- In some cases, polyethylene encasement can elevate the risk of corrosion failures.[7]
- The 10-Point Soil Test Evaluation Method (as described in the AWWA M27 Manual and ANSI/AWWA C105, Standard for Polyethylene Encasement for Ductile-Iron Pipe Systems) is not a reliable indicator of the risk of corrosion.[7, 15]
- The time to external corrosion penetration in pipe is directly related to the wall thickness and the corrosivity of the soil surrounding the buried pipe.[7]
- The internal lining in DIP can delay external leakage from corrosion failures.[15]
- Corrosion risks are not acceptable for pipelines that transport natural gas or other hazardous materials. Similarly, corrosion risks should not be acceptable for pipelines that transport drinking water or wastewater because of the public health risks and property damage that can result from corrosion failures.
- The factory-applied asphaltic coating that is typically provided for DIP provides no appreciable level of corrosion protection to underground piping.[9]
- NACE International Standard RP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems, requires corrosion protection coatings to be adequately bonded to the pipe.[16] Polyethylene encasement, which is a sheet of plastic wrapped around the pipe, does not fulfill this requirement.
- Cathodic protection mitigates corrosion on underground metallic pipelines. It can be applied with or without a coating system.
- Since 1971, the U.S. Department of Transportation Office of Pipeline Safety has required natural gas pipelines to be cathodically protected to prevent corrosion failures.[17]
- Galvanic cathodic protection was first recommended in the United States for cast iron water mains in corrosive soil in 1968.[18]
- Cathodic protection technology is not new and has been applied successfully to numerous ductile iron water and wastewater pipelines. Furthermore, a steel main was protected with cathodic protection during the 1930's in California.[19]
- Soil resistivity is the best single indicator of soil corrosivity.[14]
- Comprehensive corrosion evaluations and corrosion protection designs assure equivalent design lives in cases where alternate pipe material bids are being accepted. In some cases, the application of corrosion protection has resulted in a reduction in overall project costs.[20]
- Increased construction and maintenance costs, limited availability of rights-of-way and current Governmental Accounting Standards Board reporting standards must be considered in the decision process with respect to the level of risk that can be accepted when investing in new infrastructure.

As in previous volumes, Volume 6 case histories are drawn from various regions of the United States and Canada as shown in Figure 7. The case histories identify the locations only by region to preserve the confidentiality of the pipeline operators.

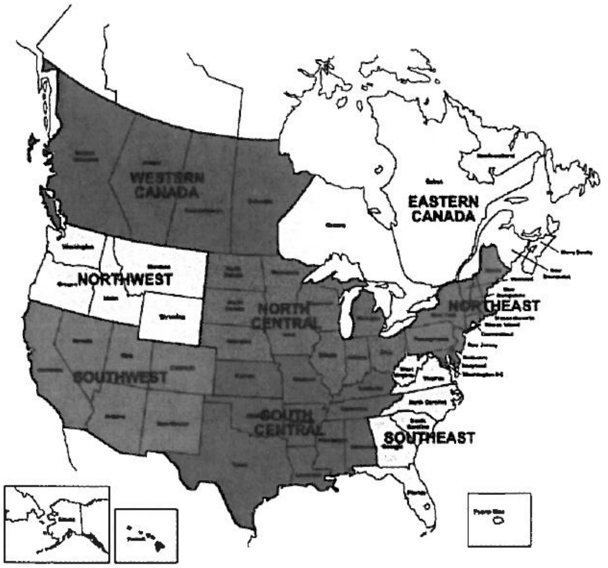


FIGURE 7

Ductile Iron Pipe Corrosion Rate Project - Methods, Analysis and Conclusions

Introduction

While it is well documented that DIP corrodes and fails in corrosive soil, there has been no reliable method for estimating the time to failure of a DIP main. The ability to reasonably estimate the useful life (time to penetration) of a DIP main in a given soil environment would offer valuable information when considering the corrosion control measures required to achieve the desired operating life of the main. For example, if the expected time to failure of Class 52 DIP in a given soil can be reasonably estimated, an informed risk management decision can be made regarding the need for supplemental pipe wall (corrosion allowance), cathodic protection, polyethylene encasement or no protection at all. The risk of unforeseen corrosion failures would be minimized.

The data contained in Volumes 1–6 (from extensive laboratory analyses of soil corrosivity and DIP corrosion rates) have been analyzed. This report describes the process and relevant technology applied in the study and analyses of corrosion rates of ductile iron. Volume 6 applies the results of the study to develop a practical means of predicting the meaningful service life for DIP. The data and relevant conclusions of this study are based on laboratory testing and the performance of operating water and wastewater mains in various soil types.

Since the time to external corrosion penetration in pipe is directly related to the corrosivity of the surrounding soil, determination of the rate of corrosion in a representative sampling of soil environments provided useful data to formulate a predictive model. Development of the model began with isolating soil characteristics and correlating those characteristics with corrosion rates in order to ascertain the relevance of the soil data to the corrosion rate of DIP.

Corrosion Rate Measurement Technique

Corrosion normally occurs at a rate determined by an equilibrium between opposing electrochemical reactions. The first is the anodic reaction, in which a metal is oxidized, releasing electrons into the metal (at the anode metal ions are released into the environment where they combine with oxygen ions to form a stable metal corrosion product). The other is the cathodic reaction, in which a solution species (often 0_2 or H^+) is reduced, due to the removing of excess electrons from the metal (the metal is not corroding at the cathode). When these two reactions are in equilibrium, the flow of electrons from each reaction is balanced, and no net electron flow (electronic current) occurs. The two reactions can take place on one metal or on two dissimilar metals (or metal sites) that are electrically connected. This is a simplified description of electrochemical corrosion theory and textbooks have been published that describe in great detail corrosion theory and electrochemical corrosion testing theory. Two of the most useful are:

1. "Corrosion and Corrosion Control" 3rd edition by Herbert H. Uhlig published by John Wiley and Sons, New York, 1985.
2. "Electrochemical Techniques for Corrosion Engineering" by R. Baboian, Editor, NACE, Houston, 1986.

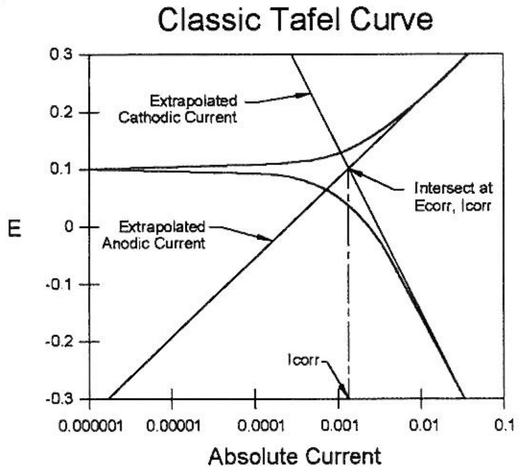


Figure 8[21]

Figure 8 shows that when diagramming the corrosion process, the vertical axis is potential and the horizontal axis is the logarithm of the absolute current. The corrosion current (Icorr), as shown in Figure 8, starts at a point where the current is high and the measured potential is very low. The curve moves upward and to the left with increasing potential and decreasing current. The curve will then turn sharply and level out (horizontally) until it reaches a point where the current is equal to zero. The measured potential at that point is called Ecorr (Corrosion Potential). The curve drawn from the bottom right of the graph to the left is the cathodic reaction. The electrochemical experiment continues with the anodic reaction. The current is increased and the potential continues to rise with the curve moving to the upper right portion of the plot. Straight lines are drawn along the anodic and cathodic curves approximating the straight portions of the curves before they bend towards Ecorr. These two lines will intersect and a straight line is drawn down to the current axis. This point is called Icorr and is the corrosion current of the measurement.

This is a simplified description of the typical corrosion rate curve. Actual experiments will frequently not appear as smooth as the above description. However, the definition of Ecorr and Icorr come directly from the graphing process described herein.

Ductile iron pipe samples were immersed in soil samples from various geographic regions and corrosion rate testing was conducted using the polarization resistance technique. The polarization resistance technique is used to obtain a rapid estimate of the corrosion rate of a metal in an electrolyte. Cell current readings are taken during a very short, slow sweep of the potential. The sweep is typically from -20 to +20 mV relative to Eoc (Open Circuit Potential, which is the equilibrium potential, assumed by a metal in the absence of electrical connections to the metal). Over this range, the current versus voltage curve is roughly linear. The graphical output of the experiment is a plot of log current versus potential. Analysis of the curve determines the corrosion potential, corrosion current and corrosion rate.

When analyzing polarization resistance test data, two points are selected to incorporate the most linear section of the data on either the cathodic or anodic curves and a straight line is drawn between those points. Icorr is determined by the intersection of this line with Ecorr.

Laboratory measurements of corrosion rates were conducted on ductile iron coupons that were placed in soil samples collected from locations throughout the United States (see Figure 9). Each soil sample was placed in an airtight container immediately after extraction and stored in the container until tested in the laboratory. A ductile iron coupon was immersed in each soil sample and the potential of the coupon was monitored until it stabilized (typically within 15 to 30 minutes). The corrosion rate was measured on the stabilized coupon. The coupon was removed from the soil, reinserted and the test repeated. The average of the two measured corrosion rates was calculated. Cleaned coupons to simulate newly installed piping (the coupon was cleaned of corrosion product prior to each measurement) and corroded coupons to simulate older existing piping were utilized for the test measurements.

Corrosion rate testing was performed with Gamry CMS 100 Software and Gamry PC3 Potentiostat/Galvanostat/ZRA equipment in accordance with ASTM Standard G5, Standard Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements.[22] The corrosion rate data were tabulated and are shown in Figure 9. The Gamry software and equipment provide corrosion rate data (Figure 9) that are reflective of uniform corrosion over the entire surface of the test coupon. However, DIP typically fails due to pitting or graphitic corrosion over only a small percentage of the surface of the pipe. Pipe wall penetration occurs faster from pitting corrosion or localized graphitic corrosion than from uniform corrosion due to the concentrated nature of the metal loss. Therefore, an adjustment factor must be applied to the measured uniform corrosion rates shown in Figure 9 to compensate for pitting, rather than uniform corrosion. The adjustment factor for pitting corrosion is discussed in the Uniform Corrosion Versus Pitting Corrosion Data Analysis portion of this report.

Database of Soil Samples

A total of 107 soil samples were extracted from 44 of 50 United States to provide geographically diverse samples. Multiple samples were extracted from the majority of the States and from some of the individual jurisdictions within the States in order to reflect conditions that vary dramatically within individual geographic areas. Figure 9 includes the origin of each soil sample. The data provided are for the individual samples and are not intended to be representative of the conditions in any area or jurisdiction.

Each soil sample was analyzed in the laboratory for the characteristics that influence corrosivity of soil with respect to metals. The characteristics include resistivity (as-is and saturated), pH, chloride ions, sulfate ions and oxygen reduction potential (Redox), as well as the presence of sulfides. The following ASTM Standards were utilized for the test methodology: resistivity ASTM G 57,[23] pH ASTM G 51,[24] chlorides ASTM D 512,[25] sulfates ASTM D 516[26] and Redox ASTM D 1498.[27] Sulfides are detected by the introduction of a 5% HCL solution which results in the evolution of hydrogen-sulfide gas when sulfides are present. The soil corrosivity test data for each sample are shown in Figure 9.

FIGURE 9

CITY OR COUNTY	STATE	LABORATORY RESULTS				
		As-Is Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	pH	Redox Potential (mV)	Chloride Content (ppm)
Coal Fire	AL	630,000	28,000	4.8	440	70
Demopolis	AL	4,000	1,800	5.6	445	45
Fort Smith	AR	3,000	3,000	4.4	470	45
Russellville	AR	8,000	6,400	8.1	285	45
Bullhead City	AZ	7,800	3,000	7.7	290	110
Kingman	AZ	5,300	2,400	7.8	315	45
Berkeley	CA	320,000	2,800	7.0	325	35
Danville	CA	21,000	1,400	8.5	270	45
Oakland	CA	290,000	3,100	7.0	340	45
Arvada	CO	2,400	770	8.4	315	45
Broomfield	CO	21,000	1,300	8.5	280	45
Colorado Springs	CO	12,000	2,200	8.9	300	45
Hartford	CT	2,900	2,200	7.6	340	45
Norwich	CT	34,000	17,000	6.1	370	45
Boyds Corner	DE	170,000	6,600	8.6	280	45
New Castle	DE	2,200	2,000	5.4	235	115
Queenstown	DE	30,000	11,000	8.4	310	45
Smyrna	DE	25,000	15,000	5.8	435	25
Fort Myers	FL	2,400	2,400	8.1	280	20
Fort Myers	FL	7,400	5,200	8.1	280	15
Jacksonville	FL	83,000	3,700	9.0	350	25
Naples	FL	3,900	3,700	7.6	310	10
Orlando	FL	240,000	90,000	8.0	345	25
Kingsland	GA	32,000	10,100	6.2	380	90
Savanah	GA	2,300	2,100	6.7	350	135
Dubuque	IA	17,000	1,500	6.6	250	135
Scott Co.	IA	910	470	7.7	290	620
Post Falls	ID	34,000	4,300	8.8	275	45
Chicago	IL	3,900	1,200	7.9	425	70
Chicago	IL	7,300	1,600	8.0	410	90
Chicago	IL	11,000	1,600	7.2	415	70
Chicago	IL	10,000	1,500	7.6	415	115
Chicago	IL	1,600	1,200	7.6	400	70
Chicago	IL	1,500	1,300	7.6	425	70
Frenchlick	IN	22,000	8,500	6.1	430	45
Southbend	IN	1,500	1,000	7.6	315	310
Olathe	KS	160,000	2,800	8.7	240	250
Fulton	KY	5,900	5,700	6.2	445	45
Paducah	KY	26,000	18,000	8.0	350	110

		Corrosion Rate for Cleaned DI Coupon			Corrosion Rate for Corroded DI Coupon		
		Polarization Resistance			Polarization Resistance		
Sulfate Content (ppm)	Presence of Sulfides	Test 1 (mpy)	Test 2 (mpy)	Average (mpy)	Test 1 (mpy)	Test 2 (mpy)	Average (mpy)
0	None	0.292	0.266	0.279	0.293	0.289	0.291
5	None	1.870	1.868	1.869	2.074	1.989	2.032
60	None	2.282	1.908	2.095	2.722	2.670	2.696
0	None	1.522	1.443	1.483	1.922	1.904	1.913
105	Present	2.497	2.757	2.627	4.612	4.402	4.507
10	None	2.982	2.809	2.896	4.504	4.297	4.401
15	None	3.196	3.283	3.240	2.314	2.262	2.288
10	Present	4.842	4.243	4.543	0.983	1.220	1.102
10	Trace	3.010	2.717	2.864	1.536	1.616	1.576
200	None	15.279	16.210	15.745	1.699	1.640	1.670
0	None	8.794	8.009	8.402	4.951	5.036	4.994
200	Present	4.494	4.347	4.421	2.334	2.326	2.330
145	Trace	2.509	2.308	2.409	2.857	2.832	2.845
0	None	0.558	0.547	0.553	0.658	0.639	0.649
25	Trace	2.029	1.853	1.941	1.714	1.633	1.674
45	Present	2.372	4.072	3.222	4.168	4.016	4.092
10	None	0.969	0.872	0.921	1.149	1.185	1.167
10	None	1.004	0.909	0.957	0.955	0.926	0.941
0	None	2.775	2.618	2.697	7.639	7.308	7.474
15	None	2.722	2.650	2.686	0.508	0.574	0.541
50	Trace	0.756	0.757	0.757	0.799	0.809	0.804
20	Present	2.589	3.035	2.812	4.898	4.756	4.827
65	None	0.212	0.197	0.205	0.182	0.187	0.185
10	None	1.419	1.207	1.313	1.658	1.657	1.658
125	None	3.741	3.772	3.757	4.619	4.395	4.507
50	Present	5.530	5.088	5.309	3.823	3.788	3.806
340	Present	4.253	3.983	4.118	7.641	7.652	7.647
10	None	2.990	3.322	3.156	2.588	2.868	2.728
345	None	7.570	7.390	7.480	10.892	11.064	10.978
20	Trace	8.392	9.129	8.761	10.993	10.412	10.703
0	None	6.183	6.043	6.113	5.004	4.861	4.933
30	None	6.359	6.699	6.529	6.823	6.616	6.720
80	Trace	5.823	5.273	5.548	9.057	8.799	8.928
20	None	4.938	4.344	4.641	9.770	9.511	9.641
0	Trace	1.327	1.295	1.311	1.084	1.022	1.053
55	Trace	3.441	4.090	3.766	5.364	6.150	5.757
145	Present	7.790	7.503	7.647	8.012	8.780	8.396
45	None	1.736	1.694	1.715	2.603	2.597	2.600
85	Present	4.763	4.567	4.665	3.607	3.176	3.392

Figure 9, Con't

CITY OR COUNTY	STATE	LABORATORY RESULTS				
		As-Is Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	pH	Redox Potential (mV)	Chloride Content (ppm)
Minden	LA	1,400	1,200	5.8	425	70
Tallulah	LA	3,300	2,300	7.9	315	45
Biddleford	MA	7,900	5,000	6.1	410	45
Dedham	MA	23,000	13,000	5.1	425	45
Springfield	MA	3,800	2,200	7.3	335	70
Anne Arundel Co.	MD	7,000	1,200	7.4	560	45
Baltimore	MD	22,000	8,800	5.3	545	50
Baltimore	MD	4,100	1,200	7.9	390	340
Baltimore	MD	5,800	2,900	7.6	375	45
Baltimore	MD	32,000	3,300	8.1	675	20
Baltimore	MD	5,100	3,000	8.1	570	45
Baltimore	MD	3,700	1,700	7.6	360	45
Baltimore	MD	2,700	1,100	6.8	680	135
Frederick Co.	MD	12,000	5,400	8.3	310	115
Portland	ME	1,300	790	6.8	360	440
New Buffallo	MI	30,000	10,000	7.5	280	45
Portage City	MI	8,700	3,600	7.9	280	45
Bloomington	MN	8,400	5,700	7.7	345	45
Minneapolis	MN	42,000	4,900	8.0	330	70
St. Louis	MO	260,000	3,500	8.8	280	70
Clinton	MS	1,500	1,500	8.0	320	70
Meridian	MS	66,000	26,000	7.6	335	45
Havre	MT	200,000	4,700	9.3	255	25
Missoula	MT	2,900	2,100	8.1	325	70
Raleigh	NC	103,000	32,000	4.9	580	65
Raleigh	NC	20,000	12,000	5.2	575	45
Fargo	ND	1,100	1,100	8.2	310	50
Lincoln	NE	>1,000,000	1,900	7.8	280	45
Concord	NH	25,000	25,000	6.7	335	45
Portsmouth	NH	9,100	9,100	6.7	435	45
Pennsville	NJ	23,000	3,800	7.6	365	25
Sewaren	NJ	260	150	5.1	440	3285
Trenton	NJ	33,000	3,000	7.0	340	25
Henderson	NV	29,000	4,600	8.4	285	45
Pahrump	NV	5,500	930	7.6	280	110
Garden City	NY	29,000	25,000	6.4	480	20
Westbury	NY	15,000	6,600	5.1	570	65
Columbus	OH	25,000	4,500	8.8	305	70
Dayton	OH	4,800	2,000	7.9	335	45

		Corrosion Rate for Cleaned DI Coupon			Corrosion Rate for Corroded DI Coupon		
		Polarization Resistance			Polarization Resistance		
Sulfate Content (ppm)	Presence of Sulfides	Test 1 (mpy)	Test 2 (mpy)	Average (mpy)	Test 1 (mpy)	Test 2 (mpy)	Average (mpy)
185	None	7.466	7.559	7.513	7.792	8.249	8.021
0	Present	2.864	2.522	2.693	3.479	3.471	3.475
5	Trace	1.809	1.702	1.756	2.047	1.992	2.020
5	None	0.806	0.754	0.780	0.827	0.843	0.835
295	None	4.586	4.522	4.554	4.960	4.800	4.880
110	None	3.757	3.704	3.731	5.803	5.547	5.675
15	None	2.770	2.455	2.613	2.091	2.075	2.083
130	None	3.680	3.727	3.704	5.058	5.090	5.074
90	Present	6.138	5.602	5.870	5.034	4.443	4.739
150	None	6.792	5.888	6.340	7.501	7.065	7.283
5	Present	5.943	5.471	5.707	4.396	3.828	4.112
10	Present	9.380	9.363	9.372	9.444	8.198	8.821
0	None	8.400	7.058	7.729	10.201	12.019	11.110
70	None	2.641	2.255	2.448	5.140	4.841	4.991
45	None	9.372	8.384	8.878	3.377	2.944	3.161
[illegible]	Present	1.128	0.947	1.038	1.083	1.115	1.099
5	Present	1.821	1.606	1.714	1.726	1.605	1.666
40	None	1.836	1.807	1.822	1.278	1.317	1.298
45	None	1.838	1.766	1.802	1.843	1.931	1.887
160	Present	3.171	2.344	2.758	5.640	5.489	5.565
170	None	2.643	2.237	2.440	5.559	5.349	5.454
0	None	1.599	1.471	1.535	3.150	3.164	3.157
10	Present	2.330	2.274	2.302	2.274	2.299	2.287
10	None	3.186	3.074	3.130	1.836	1.922	1.879
40	None	0.683	0.721	0.702	0.933	1.002	0.968
30	None	1.374	1.415	1.395	1.614	1.676	1.645
0	None	2.814	3.315	3.065	3.865	3.930	3.898
0	Trace	4.025	3.692	3.859	3.115	3.129	3.122
0	Trace	0.658	0.643	0.651	0.814	0.797	0.806
10	Present	1.503	1.423	1.463	1.804	1.733	1.769
130	Trace	3.069	3.168	3.119	3.428	3.073	3.251
355	None	4.895	5.244	5.070	15.653	15.966	15.810
15	None	3.936	3.757	3.847	2.474	2.534	2.504
145	Present	4.069	4.053	4.061	3.670	3.686	3.678
135	Present	5.043	5.092	5.068	8.193	8.093	8.143
[illegible]	None	0.653	0.653	0.653	1.064	1.039	1.052
15	Trace	3.777	3.728	3.753	4.807	4.533	4.670
95	Present	4.690	4.657	4.674	4.356	3.971	4.164
20	Present	3.715	3.352	3.534	1.770	1.880	1.825

Figure 9, Con't

CITY OR COUNTY	STATE	LABORATORY RESULTS				
		As-Is Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	pH	Redox Potential (mV)	Chloride Content (ppm)
Medina	OH	20,000	12,000	5.3	480	90
Idabel	OK	16,000	15,000	5.2	490	45
Poteau	OK	10,000	10,000	4.8	505	45
Delaware Co.	PA	10,000	3,500	6.5	570	65
Reading	PA	6,400	2,900	7.4	540	45
Westchester	PA	14,000	8,400	5.5	435	45
Valley Falls	RI	68,000	25,000	6.7	315	45
Westerly	RI	44,000	23,000	5.9	415	45
Florence	SC	2,400	1,900	8.2	320	45
Pocotaligo	SC	34,000	30,000	5.0	450	10
Jackson	TN	13,000	3,200	5.5	400	70
Memphis	TN	15,000	8,500	4.5	485	45
Robstown	TX	2,100	1,600	8.6	290	45
Victoria	TX	1,100	940	7.8	295	45
Cedar City	UT	31,000	1,060	7.8	330	15
St. George	UT	2,200	1,600	7.8	335	70
Lansdowne	VA	45,000	9,400	4.6	690	65
Loudon Co.	VA	12,000	2,800	7.0	465	45
Rollingwood	VA	11,000	4,400	5.8	515	45
Brattleboro	VT	6,900	6,900	8.0	280	45
Hanover	VT	47,000	29,000	8.2	290	45
Anacortes	WA	4,400	4,300	6.9	380	50
Ellensburg	WA	1,100	880	7.9	330	160
Seattle	WA	14,000	7,400	5.1	495	45
Seattle	WA	220,000	14,000	5.7	370	50
Dickeyville	WI	2,000	1,900	7.6	310	70
Janesville	WI	9,400	3,200	7.4	350	70
Charlestown	WV	2,500	2,400	7.4	350	25
Martinsburg	WV	6,700	6,300	7.9	365	25

		Corrosion Rate for Cleaned DI Coupon			Corrosion Rate for Corroded DI Coupon		
		Polarization Resistance			Polarization Resistance		
Sulfate Content (ppm)	Presence of Sulfides	Test 1 (mpy)	Test 2 (mpy)	Average (mpy)	Test 1 (mpy)	Test 2 (mpy)	Average (mpy)
35	None	2.185	2.166	2.176	2.435	2.260	2.348
10	None	0.626	0.623	0.625	0.712	0.695	0.704
10	None	0.881	0.857	0.869	0.950	0.951	0.951
30	None	4.185	4.185	4.185	5.369	4.915	5.142
40	None	3.430	2.868	3.149	6.178	5.887	6.033
10	Trace	2.056	1.937	1.997	2.631	2.954	2.793
0	None	0.608	0.581	0.595	0.739	0.734	0.737
0	None	0.865	0.866	0.866	0.669	0.650	0.660
70	None	2.340	2.282	2.311	5.291	5.217	5.254
10	None	0.910	0.902	0.906	1.168	1.146	1.157
90	Trace	2.482	1.957	2.220	2.770	2.852	2.811
0	None	1.189	1.201	1.195	1.408	1.435	1.422
50	Present	2.505	1.929	2.217	5.242	5.464	5.353
160	Present	9.248	9.761	9.505	4.987	4.928	4.958
880	Present	3.840	3.354	3.597	6.985	7.485	7.235
380	Present	3.054	2.733	2.894	5.754	5.885	5.820
0	None	2.742	2.669	2.706	2.764	2.635	2.700
55	None	3.864	3.654	3.759	7.113	6.955	7.034
20	None	4.676	4.617	4.647	5.048	4.885	4.967
80	Present	1.212	0.812	1.012	2.388	2.244	2.316
5	None	0.339	0.332	0.336	0.334	0.329	0.332
90	None	1.484	1.372	1.428	1.513	1.558	1.536
100	None	5.716	5.267	5.492	3.892	3.922	3.907
0	None	2.929	3.440	3.185	2.728	2.655	2.692
0	None	1.619	1.525	1.572	2.249	2.198	2.224
10	Trace	2.416	2.301	2.359	2.483	2.632	2.558
25	None	3.053	2.648	2.851	1.922	2.003	1.963
35	None	2.578	2.485	2.532	2.693	2.904	2.799
0	Trace	2.152	2.025	2.274	2.109	2.138	2.124

Corrosivity Versus Corrosion Rate Data Analysis

Each soil sample characteristic was correlated to the measured corrosion rates. The average corrosion rates did not correlate well with as-is resistivity, pH, chloride content, sulfate content, Redox Potential or the presence of sulfides individually. However, the study found a meaningful correlation between saturated resistivity and the average corrosion rate data.

R^2 is the Sample Coefficient of Determination which represents the variation in the data in comparison to the best fit data curve. A perfect correlation would be equal to 1.0000 while no correlation would be equal to 0.0000. Figure 10 shows the correlation between the average corrosion rate and the saturated soil sample resistivity for the cleaned to shiny metal (new pipe) DIP coupon (the R^2 value for that correlation is 0.6449).

Figure 11 shows the correlation between the average corrosion rate and the saturated soil sample resistivity for the corroded (old pipe) DIP coupon (the R^2 value for that correlation is 0.5726). The resultant R^2 values indicate that saturated soil resistivity is the best single indicator of soil corrosivity on ductile iron. Wakelin also reported that saturated soil resistivity is the best single indicator of soil corrosivity on iron water mains.[14]

Examination of the saturated resistivity versus corrosion rate correlation curves revealed some individual data points do not correlate well with the other data. In these cases, individual corrosivity data were reviewed to detect one or more characteristics other than saturated resistivity in individual samples that might account for the absence of a direct correlation between saturated resistivity and corrosion rate. In some cases, the corrosion rate of samples with alkaline pH (over 9.0) was lower than expected based on the corrosion rate correlation with saturated resistivity. In some samples with corrosion rates higher than expected by the correlation, sulfides were present in the soil and the soil pH was acidic (5.0 or less). These results suggested the possibility that more variables with respect to soil corrosivity parameters may be useful in developing an equation for corrosion rate based on soil corrosivity. However, a review of the remaining data indicated no consistent pattern with respect to the presence of sulfides or acidic pH and elevated corrosion rates or alkaline pH and a decrease in corrosion rates. Based on the analyses of the data from the test specimens included in this study, the most effective equations for calculating corrosion rate must be based exclusively on saturated resistivity.

The resistivity versus corrosion rate equations for the cleaned and corroded ductile iron coupons indicate only an approximate 7% variation in the respective calculated corrosion rate

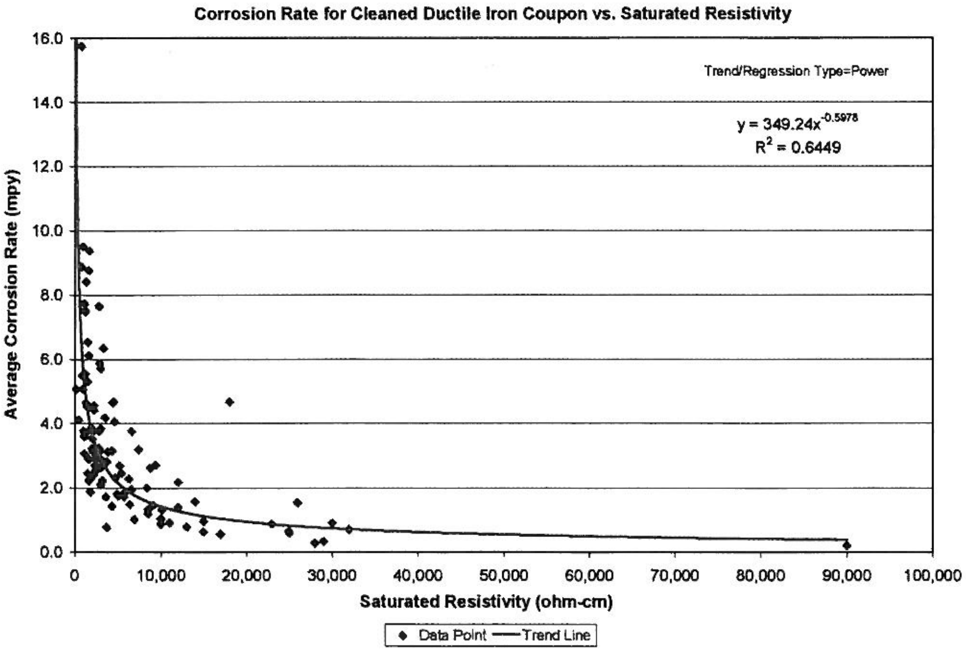


FIGURE 10

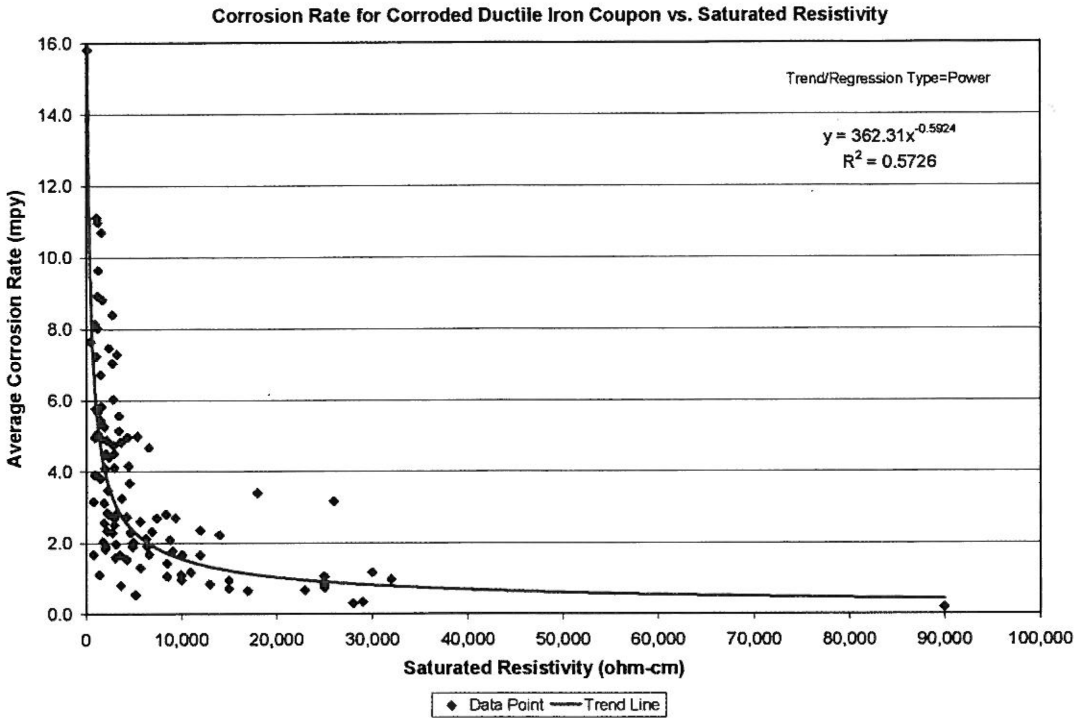


FIGURE 11

values for any given saturated resistivity value. Therefore, the equation with the higher R² (cleaned coupon) should be used for predicting corrosion rates.

Uniform Corrosion Versus Pitting Corrosion Data Analysis

The corrosion rates that result from linear polarization techniques are based on uniform corrosion over the entire surface of the test specimen. However, DIP corrodes by a combination of graphitic corrosion (generally relatively uniform but sometimes localized) and pitting corrosion (localized). Neither graphitic nor pitting corrosion will impact an entire pipe surface. For example, the majority of the 60 DIP incidents discussed in Volume 5 had graphitic or pitting corrosion over only a small percentage of the examined pipe surfaces. Pipe in lower resistivity soil generally exhibited graphitic corrosion over larger areas than pipe in higher resistivity soil. Therefore, adjustment factors to account for the surface area impact that can be expected in different soil resistivity ranges must be applied to the measured corrosion rates to compensate for the localized effect of corrosion on the surface of DIP.

Adjustment factors to be applied to the corrosion rate equation for different resistivity values were developed using the data from the 60 case histories discussed in Volume 5. The case histories were sorted by their saturated resistivity and segregated into three categories: less than 1,000 ohm-cm (extremely corrosive) 1,000 to 5,000 ohm-cm (very corrosive) and 5,001 to 10,000 ohm-cm (corrosive) to correspond to the resistivity ranges shown in Figure 12. Only two of the 60 case histories had saturated resistivity values greater than 10,000 ohm-cm so they were included in the 5,001 to 10,000 ohm-cm category.

The average corrosion rate for the case histories in each of the three categories was calculated. Three case histories in the 5,001 to 10,000 ohm-cm range were eliminated from the calculated average corrosion rate for that range because their elevated corrosion rates likely occurred because of dissimilar soil layers at pipe depth rather than exclusively from the soil corrosivity. An adjustment factor (to accommodate pitting rather than uniform corrosion) was calculated for each of the soil resistivity ranges by dividing the average corrosion rate for each resistivity category by the calculated corrosion rate for the average resistivity in each of the three categories. The adjustment values are 1.458 for the less than 1,000 ohm-cm range, 3.805 for the 1,001 to 5,000

SOIL CORROSIVITY	SOIL RESISTIVITY (OHM-CM)
Extremely Corrosive	Less than 1,000
Very Corrosive	1,000 – 5,000
Corrosive	5,001 – 10,000
Moderately Corrosive	10,001 – 25,000
Mildly Corrosive	Over 25,000

FIGURE 12[11]

ohm-cm range and 6.058 for the greater than 5,000 ohm-cm range. The resultant adjustment factors are based on actual corrosion rates from the 60 case histories and compensate for the variation in the extent of corrosion (in terms of pipe surface area impact) that can be expected in each of the three saturated resistivity ranges. The resultant equations for estimating the rate of corrosion for DIP are based on the equation shown in Figure 4 for the best fit data curve:

Saturated Resistivity Less than 1,000 ohm-cm

$CR = 1.458 \times 349.24 \times X^{-0.5978} = 509.19 \times X^{-0.5978}$

Saturated Resistivity Between 1,000 and 5,000 ohm-cm

$CR = 3.805 \times 349.24 \times X^{-0.5978} = 1328.858 \times X^{-0.5978}$

Saturated Resistivity Over 5,000 ohm-cm

$CR = 6.058 \times 349.24 \times X^{-0.5978} = 2115.696 \times X^{-0.5978}$

Where:

CR = Corrosion Rate (mils per year)
X = Saturated Resistivity (ohm-cm)

The corrosion rate equations were developed based on the direct correlation of saturated soil resistivity and measured corrosion rate resulting from the analyses of the samples included in this study. The three equations can be used to estimate the time to penetration for DIP by dividing the wall thickness (in mils) of DIP (varies with pipe diameter and class) by the calculated corrosion rate (in mils/year).

After the estimated maximum time to penetration is calculated for a specific pipeline project, other conditions that are unique to the project should also be considered. There may be isolated conditions such as the presence of dissimilar soils, dissimilar metals, dissimilar surfaces and differential aeration on a given project that may increase the corrosion rate at certain locations if protection measures are not applied.[28] In many cases, the installation of electrical isolation in key locations will minimize the impact of isolated conditions such as those previously mentioned. For example, it is always good practice to install electrical isolation between different metals (distribution mains and services for example) and to address low oxygen areas such as road crossings individually.

Other isolated conditions that can further accelerate corrosion rates include soil contaminated with sulfate reducing bacteria, elevated chloride ions, and acidic pH, which can have a long term impact on corrosion rates.[28] Over time, sulfate reducing bacteria can accelerate corrosion activity as a bacteria colony grows adjacent to a pipe surface. Chlorides and acidic pH can have long-term depolarizing effects on the establishment of corrosion products on a pipe surface. Typical soil corrosivity analyses include these parameters in order to identify and address such conditions individually. In cases where conditions other than saturated soil resistivity elevate the risk of corrosion in isolated locations, protection measures can be applied selectively. After the time to pipe wall penetration is calculated, other risk factors should be reviewed and addressed individually. The exact increase in the corrosion rate from the minimum values calculated by the equations can only be made by the design engineer on a case-by-case basis.

DIP Project Case Histories - Methods, Analysis and Conclusions

The six specific case histories of DIP corrosion included in this volume were among the 60 DIP corrosion incidents analyzed with the results presented in Volume 5. The detailed discussion in Volume 5 includes an evaluation of the reliability of the 10-Point Soil Test Evaluation Method,[12] the performance of polyethylene encasement, the protective value of the typical factory applied asphaltic coating and the impact of cement mortar linings. They include instances in which corrosion of buried and inadequately protected DIP resulted in failure of the piping. This report used the following previously discussed methodologies to identify instances of external DIP corrosion.

- **Cell-to-cell potential measurements correlated with soil resistivity data to locate active corrosion.**
- **Pipe excavated and exposed during repairs occasioned by a corrosion failure.**
- **Observation of pipe, excavated and made visible, in areas targeted as sites of likely corrosion.**

Soil samples from or near each pipe excavation were analyzed for characteristics that impact the rate of corrosion (soil corrosivity). The case studies rate the corrosivity of buried environments as extremely corrosive, very corrosive, corrosive, moderately corrosive and mildly corrosive as shown in Figure 12. The soil corrosivity data were also used to calculate the 10-Point Values of the samples in accordance with the 10-Point Soil Test Evaluation Method as described in the AWWA M27 Manual[29] and in ANSI/AWWA C105, Standard for Polyethylene Encasement for Ductile Iron Pipe Systems.[12]

29 YEAR OLD DUCTILE IRON PIPE WITH NO EXTERNAL PROTECTION

An 8-inch Class 51 ductile iron force main was installed in the Northeast U.S. without any form of corrosion control other than factory-applied external asphaltic coating. The pipe had an original wall thickness of 0.30 inch. Seven failures occurred on this pipeline with the first failure 22 years after installation. One of failed sections of piping was removed and inspected. Figure 13 shows an overall view of the removed piping after it had been cleaned for inspection. Corroded areas on the pipe are circled in white. Figure 14 shows a view of some of the external pitting and a penetration in the pipe. The corrosion penetrations were due to a combination of internal and external corrosion. This segment of pipe came from a high point in the main where hydrogen sulfide gas could accumulate inside the pipe. External corrosion pitting was widespread on the pipe and the maximum depth of pitting was 0.20 inch, which corresponds to a corrosion rate of 6.9 mils/year.

FIGURE 13

A soil sample from the excavation was analyzed for characteristics that impact the rate of corrosion. The laboratory results were:

- **Resistivity (as collected): 13,000 ohm-cm**
- **Resistivity (saturated): 7,300 ohm-cm**
- **pH: 7.6**
- **Chloride concentration: 45 ppm**
- **Sulfate concentration: 110 ppm**
- **Oxygen reduction potential: 370 millivolts**
- **Sulfides were not present in the sample**

There were no sources of stray DC current in the area and the soil at pipe depth was generally wet with poor drainage.

Using the laboratory results, 10-Point Soil Test Evaluation Method was applied to calculate the corrosivity of the soil. The 10-Point Method calculation equals 2 points - non-corrosive.

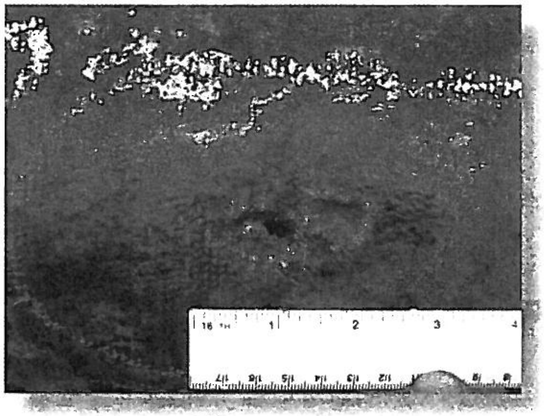


FIGURE 14

The 10-Point Method indicated non-corrosive soil with respect to ductile iron. Examination of the pipe revealed extensive metal loss due to external corrosion, and the factory-applied asphaltic coating provided no appreciable level of corrosion protection. The interior of the pipe should have been provided with a lining resistant to hydrogen sulfide gas to prevent internal corrosion. Cathodic protection should have been installed at the time of pipeline construction to prevent external corrosion and premature replacement.

15 YEAR OLD DUCTILE IRON PIPE WITH NO EXTERNAL PROTECTION

A 6-inch Class 50 ductile iron water main was installed in Eastern Canada. Figure 15 shows the perforations on the top side of the pipe at the time of failure. The perforations ranged in size from 0.1 to 0.3 inch in diameter. The exact age of the pipe is unknown, but was estimated at 15 years. The pipe had an original wall thickness of 0.25 inch, which corresponds to a corrosion pitting rate of 16.7 mils per year given the estimated age of 15 years. The water main was in a residential area, in an area where copper service piping was used. There are no known sources of stray current in the vicinity of the piping. Approximately 30% of the non-perforated pipe surface was corroded to an average depth of 0.12 inch.

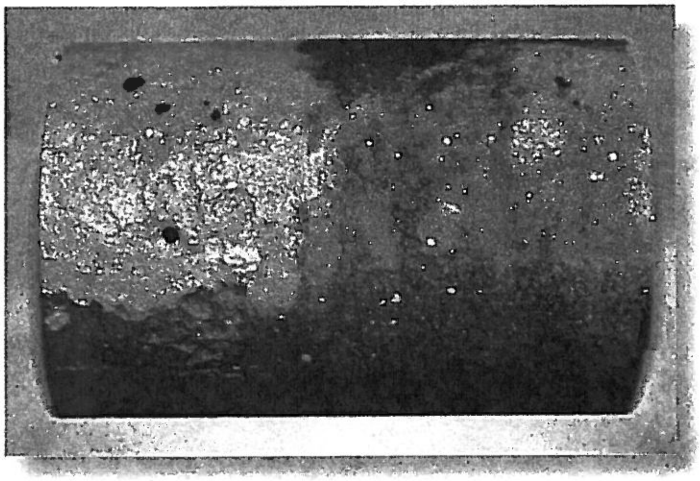


FIGURE 15

A soil sample from wet undisturbed soil adjacent to the main at the edge of the excavation was analyzed for characteristics that impact the rate of corrosion. The laboratory results were:

- **Resistivity (as collected): 1,450 ohm cm**
- **Resistivity (saturated): 1,450 ohm-cm**
- **pH: 9.3**
- **Chloride concentration: 115 ppm**
- **Sulfides were not present in the sample**

Using the soil data shown, the 10-Point Soil Test Evaluation Method was applied to calculate the corrosivity of the soil. The oxygen reduction (Redox) potential of the soil was not tested. If the Redox potential was greater than 100 millivolts, the 10-Point Method calculation would equal 15 points - corrosive. If the Redox potential was negative (worst case condition), the 10-Point Method calculation would equal 20 points - corrosive.

The 10-Point Method indicated corrosive soil with respect to ductile iron. Examination of the pipe revealed extensive metal loss due to corrosion and the factory-applied asphaltic coating provided no appreciable level of corrosion protection. This water main required cathodic protection to prevent its failure due to external corrosion after only 15 years of service.

22 YEAR OLD DUCTILE IRON PIPE WITH NO EXTERNAL PROTECTION

A 16-inch ductile iron force main was installed in the Northeast U.S. without any form of corrosion control other than the factory-applied external asphaltic coating. Two failures have been reported on this 22 year old force main. The original wall thickness of this Class 50 ductile iron pipe was 0.34 inch. A soil resistivity survey was conducted to locate areas of corrosive soil prior to the pipe's excavation and inspection. Figure 16 shows a view of the piping in one of the test pits. Measurements of the remaining pipe wall in non-pitted areas ranged from 0.295 to 0.35 inch. Figure 17 shows a close up of external pitting (0.14 inch in depth) at one location, corresponding to a corrosion rate of 6.4 mils per year.

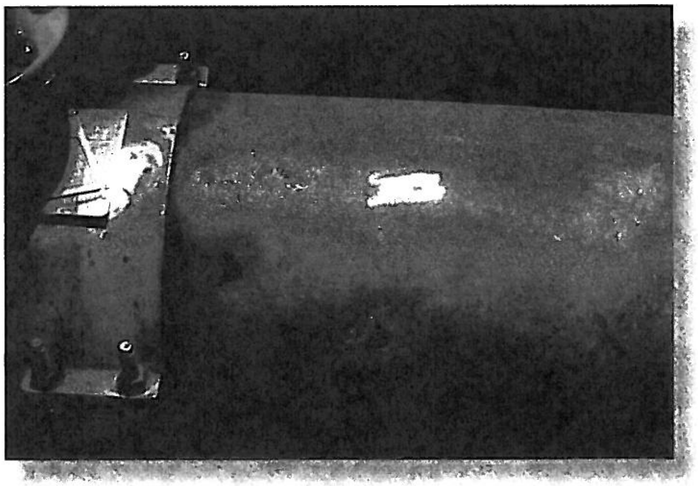


FIGURE 16

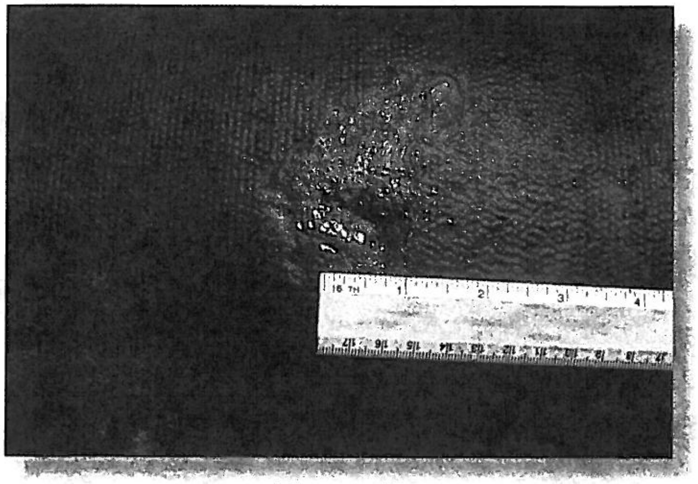


FIGURE 17

A soil sample from the excavation was analyzed for characteristics that impact the rate of corrosion. The laboratory results were:

- **Resistivity (as collected): 2,100 ohm-cm**
- **Resistivity (saturated): 2,000 ohm-cm**
- **pH: 7.6**
- **Chloride concentration: 65 ppm**
- **Sulfate concentration: <150 ppm**
- **Oxygen reduction potential: 380 millivolts**
- **Trace levels of sulfides were present in the sample**

There was no evidence of stray DC current in the area, and the soil at pipe depth was generally moist with good drainage.

Using the soil data shown, the 10-Point Soil Test Evaluation Method was applied to calculate the corrosivity of the soil. The 10-Point Method calculation equals 8 points - non-corrosive.

The 10-Point Method indicated non-corrosive soil with respect to ductile iron pipe. Examination of the pipe revealed metal loss due to corrosion, and the factory-applied asphaltic coating provided no appreciable level of corrosion protection. Cathodic protection should have been applied at the time of pipeline construction to prevent external corrosion and premature replacement caused by failures that occurred at other locations on this force main.

31 YEAR OLD DUCTILE IRON PIPE WITH NO EXTERNAL PROTECTION

A 12-inch ductile iron force main was installed in the Northeast U.S. without any form of corrosion control other than the factory-applied external asphaltic coating. Four failures occurred on this pipeline 31 years after installation. One of the failed sections of piping was removed and inspected. Figures 18 and 19 show the piping after it had been cleaned for inspection. Corroded areas on the pipe are circled in white. Multiple penetrations are visible in the photographs. External corrosion pitting was widespread. Ultra-sonic thickness measurements, in non-pitted areas, indicated that the remaining pipe wall thickness ranged from 0.300 to 0.301

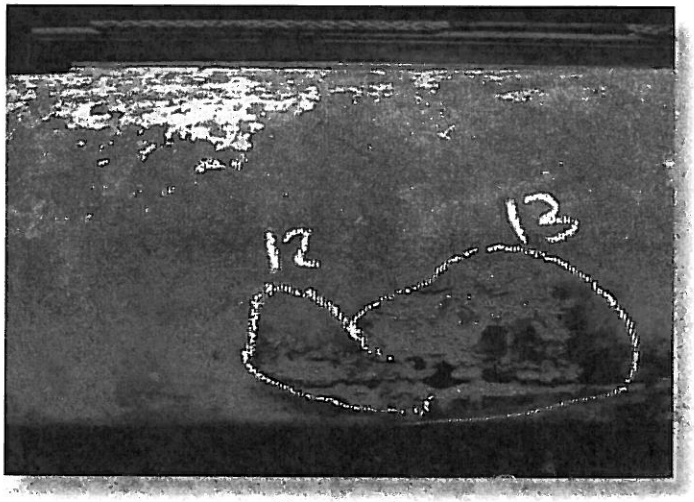


FIGURE 18

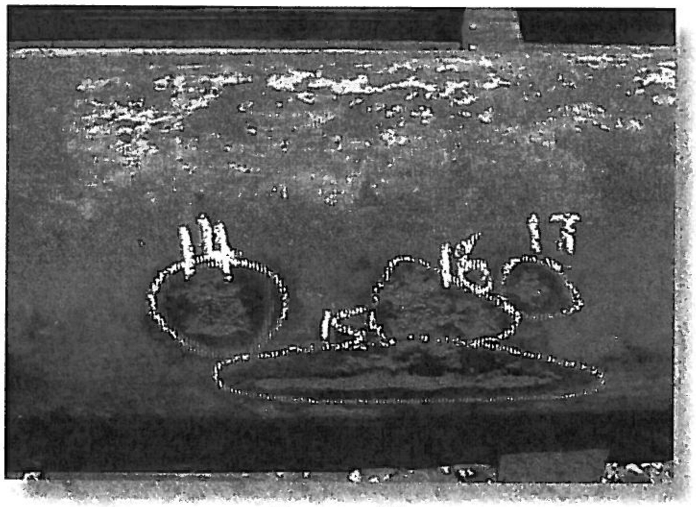


FIGURE 19

inch. The piping is believed to be Class 50 with an original wall thickness of 0.31 inch. The pipe was 31 years old, which corresponds to a corrosion rate of 10 mils/year.

A soil sample from the excavation was analyzed for characteristics that impact the rate of corrosion. The laboratory results were:

- **Resistivity (as collected): 570 ohm-cm**
- **Resistivity (saturated): 550 ohm-cm**
- **pH: 7.2**
- **Chloride concentration: 550 ppm**
- **Sulfate concentration: 165 ppm**
- **Oxygen reduction potential: 230 millivolts**
- **Sulfides were present in the sample**

There were no sources of stray DC current in the area and the soil at pipe depth was generally wet with poor drainage.

Using the laboratory results, the 10-Point Soil Test Evaluation Method was applied to calculate the corrosivity of the soil. The 10-Point Method calculation equals 15.5 points - corrosive.

The 10-Point Method indicated corrosive soil with respect to ductile iron. Examination of the pipe revealed extensive metal loss due to corrosion, and the factory-applied asphaltic coating provided no appreciable level of corrosion protection. Cathodic protection should have been installed at the time of pipeline construction to prevent external corrosion and replacement after only 31 years of service.

24 YEAR OLD DUCTILE IRON PIPE WITH NO EXTERNAL PROTECTION

A 12-inch Class 53 ductile iron water main was installed in Eastern Canada. The pipe was excavated for inspection and found to have a 1-inch diameter penetration. Figure 20 shows the cleaned pipe and penetration. The cement mortar lining was intact when the pipe segment was removed and had prevented the penetration from releasing water. The pipe had an original wall thickness of 0.40 inch. The pipe was 24 years old, which corresponds to a corrosion pitting rate greater than 16.7 mils per year, considering that the cement mortar lining had prevented the pipe from leaking. The water main was along a major roadway, in an area where copper service piping was used. It is not known if there were sources of stray DC current in the vicinity of the piping.

FIGURE 20

A soil sample from moist undisturbed soil adjacent to the main at the edge of the excavation was analyzed for characteristics that impact the rate of corrosion. The laboratory results were:

- **Resistivity (as collected): 300 ohm-cm**
- **Resistivity (saturated): 280 ohm-cm**
- **pH: 8.0**
- **Chloride concentration: 1600 ppm**
- **Sulfides were not present in the sample**

Using the soil data shown, the 10-Point Soil Test Evaluation Method was applied to calculate the corrosivity of the soil. The oxygen reduction (Redox) potential of the soil was not tested. If the Redox potential was greater than 100 millivolts, the 10-Point Method calculation would equal 11 points - corrosive. If the Redox potential was negative (worst case condition), the 10-Point Method calculation would equal 16 points - corrosive.

The 10-Point Method indicated corrosive soil with respect to ductile iron. Examination of the pipe revealed extensive metal loss due to corrosion and the factory-applied asphaltic coating provided no appreciable level of corrosion protection. This water main required cathodic protection to prevent its failure due to external corrosion after only 24 years of service.

26 YEAR OLD DUCTILE IRON PIPE WITH NO EXTERNAL PROTECTION

This 16-inch ductile iron water main was installed in the Northeast U.S. without any form of corrosion control other than factory-applied external asphaltic coating. While no failures have been reported on this 26 year old main, a failure did occur on a ductile iron main installed at the same time immediately east of this main. A cell-to-cell potential survey was conducted to locate areas of active corrosion for excavation and examination. Figure 21 shows an overall view of the piping after it had been cleaned for inspection in one of the test pits. This piping is believed to be Class 53 with an original wall thickness of 0.43 inch. Measurements indicated that graphitic corrosion was 0.12 inch deep and the maximum depth of corrosion pitting was an additional 0.12 inch. Figure 22 is a close-up view of some of the corrosion pitting. The total depth of corrosion due to graphitic and pitting corrosion was 0.24 inch which corresponds to a corrosion rate of 9.23 mils per year.

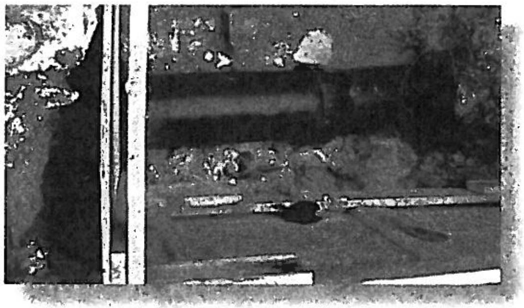


FIGURE 21

A soil sample from near the excavation was analyzed for characteristics that impact the rate of corrosion. The laboratory results were:

- **Resistivity (as collected): 3,500 ohm cm**
- **Resistivity (saturated): 3,500 ohm-cm**
- **pH: 7.5**
- **Chloride concentration: 70 ppm**
- **Sulfate concentration: <150 ppm**
- **Oxygen reduction potential: 120 millivolts**
- **Sulfides were not present in the sample**

There was no evidence of significant stray DC current in the area and the soil at pipe depth was generally moist with fair drainage.

Using the soil data shown, the 10-Point Soil Test Evaluation Method was applied to calculate the corrosivity of the soil. The 10-Point Method calculation equals 2 points - non-corrosive.

The 10-Point Method indicated non-corrosive soil with respect to ductile iron pipe. Examination of the pipe revealed extensive metal loss due to corrosion and the factory-applied asphaltic coating provided no appreciable level of corrosion protection. Cathodic protection should have been installed at the time of pipeline construction to prevent external corrosion.

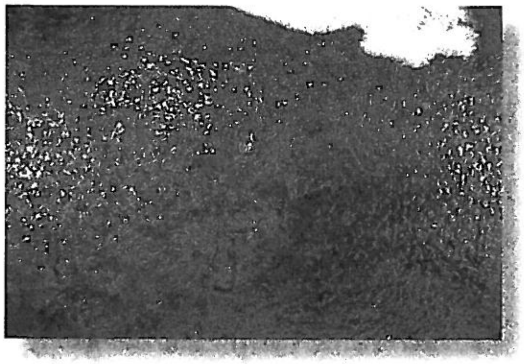


FIGURE 22

LESSONS LEARNED FROM IRON PIPE
VOLUME 6
SUMMARY

It has been well established through the literature and the case histories presented in Volumes 1 through 6 that ductile iron pipe corrodes in aggressive soil. Figure 12 shows the corrosivity ratings in terms of soil resistivity, that have been applied to the case histories included in this study. By compiling and analyzing experiences (lessons learned) with operating DIP, the intent is for pipe users to benefit from the information and the opportunity to control failure risks of water and wastewater mains through informed decisions.

The first 5 volumes of "Lessons Learned From Iron Pipe" provide many examples of ductile iron pipe corrosion, some of which resulted in failures in as little as 5 years. In addition to the relevant soil and corrosion rate data for each DIP corrosion incident, the previous volumes included discussions on basic corrosion, methods for evaluating soil corrosivity and selecting corrosion control measures for DIP, and state-of-the-art corrosion control options that have been used successfully with DIP.

Volume 4 presents the corrosion control options in detail including their benefits and risks (Volume 4, Figure 18). It is important for pipeline owners to be in control of the level of risk, if any, that is considered acceptable for each pipeline project. The decision making process should consider capital and maintenance costs, safety, public relations, environmental issues, customer service/system reliability and any other critical issues associated with the specific system or area. Each risk factor is unique to the system. "Protecting Underground Assets With State-of-the-Art Corrosion Control" (Materials Performance July, 2002)[30] describes how the Howard County, Maryland Department of Public Works developed a corrosion control program with proactive measures to protect existing water mains and to install new mains that will last virtually forever. The Howard County corrosion evaluation procedure for determining requirements for new mains is essentially the same as the comprehensive corrosion evaluation discussed in the "Determination of Corrosion Control Requirements" section of Volume 3.

Volume 5 provides a detailed technical report on the lack of correlation between the 10-Point Soil Test Evaluation Method[12] and the actual condition of exposed operating mains. The benefits and weaknesses of polyethylene encasement, standard asphaltic shop applied coatings and internal linings are also summarized in Volume 5. Relevant ductile iron corrosion and soil corrosivity data from a total of 60 ductile iron pipe corrosion evaluations were included and substantiate the conclusions presented in Volume 5. The data (Figure 14 in Volume 5) provide a useful reference for reviewing the past performance in specific soil environments of operating DIP mains when considering new installations.

One approach to determining corrosion control requirements for new mains is to allow the pipe manufacturer or its representatives to conduct the evaluation. There are two important questions for the owner to consider prior to relying on corrosion control recommendations from the pipe supplier or its representative: 1) what risk factor was used in the analysis? and 2) how long will the pipeline last if those recommendations are implemented?

If the owner prefers to control any risk factors assigned to the pipeline's longevity and wants an estimate of a meaningful service life for the proposed pipeline, the information in this series of reports will be very helpful. A key element in conducting a cost analysis or meaningful evaluation of corrosion control requirements for DIP is the amount of time the main would last in a given soil environment without protection. The data from the total of 60 documented corrosion evaluations and more than 100 corrosion rate tests on DIP samples immersed in soil (Figure 9) were analyzed and equations were developed for estimating the rate of

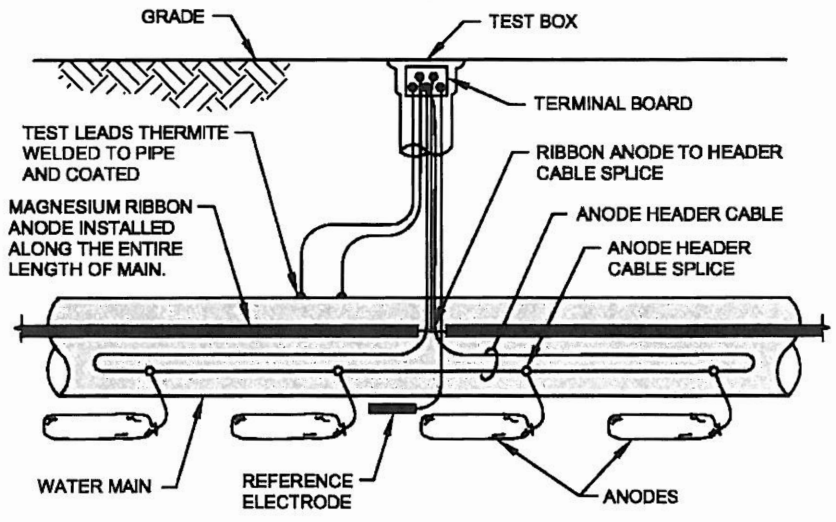


FIGURE 23

corrosion and time to failure for DIP. The equations that are included in this Volume can be used to estimate the rate of corrosion of a DIP main if the saturated soil resistivity is known. The expected wall thickness of the DIP main can be divided by the calculated corrosion rate to determine an approximate time to pipe wall penetration. If the calculated time to penetration is less than the desired service life of the main, corrosion control should be applied to assure that the desired service life is achieved.

Selecting the corrosion control method for DIP is the next challenge and the risk factors must be weighed as discussed in Volume 4. Figure 5 in Volume 4 lists the options for corrosion protection for DIP.

Cathodic protection is one of the methods that are available for controlling corrosion on a ductile iron main. Figure 23 (Figure 6 from Volume 4) shows a typical layout for a cathodic protection system (Volume 4 discusses how the number and size of the anodes are determined). Cathodic protection eliminates virtually all risk of corrosion failures. Another corrosion control option is a corrosion monitoring system which facilitates surveys and failure prediction. Polyethylene encasement can be used to provide moderate protection in some soils. Polyethylene encasement with cathodic protection is another option and provides some protection in some soils. Increased pipe wall is an option that can be factored into the equations in this volume to calculate the added life in terms of years to a water or wastewater main.

As mentioned in previous volumes, the application of corrosion protection to underground pipelines is by no means new technology. The application of corrosion rate measurement techniques to predict pipe longevity is also not new.[31-32] Under stringent regulations for protecting hazardous material pipelines from corrosion, pipeline integrity management is a process that has been implemented by the oil and gas industry. In Application of Corrosion Growth and Analysis in Support of Direct Assessment Reassessment Intervals - Part 1 (Materials Performance September, 2006)[33] Lopez-Garrity, Garrity and Lawson, present four techniques for evaluating corrosion rates (referred to as corrosion growth rates), the most reliable being the linear polarization resistance measurements applied in the evaluation of the DIP corrosion rates in this volume. Much of the corrosion control technology available to the water industry today has the benefit of more than half a century of research and development by the oil and gas industry.

Absent legislation covering external corrosion of water pipelines, the water industry professionals maintain overall responsibility for providing water to their customers safely, reliably and cost effectively. Corrosion analyses and the application of appropriate corrosion control measures to wastewater mains prevents unexpected release of undesirable substances into the environment. The information provided in these volumes will be useful in achieving these goals.

REFERENCES

1. "Accelerating Leak rate in Ductile Cast Iron Water Mains Yields to Cathodic Protection" by F.E. Stetler, MP (Materials Performance) Vol. 19 No. 10 (October 1980), National Association of Corrosion Engineers, Houston, TX.

2. "The Corrosion of Municipal Iron Watermains" by R.A. Gummow, MP (Materials Performance) Vol. 23 No. 3 (March 1984), National Association of Corrosion Engineers, Houston, TX.

3. "Underground Corrosion of Water Pipes in Calgary, Canada" by J.A. Jacobs and F.W. Hewes, MP (Materials Performance) Vol. 26 No. 3 (May 1987), National Association of Corrosion Engineers, Houston, TX.

4. "Controlling Ductile-Iron Water Main Corrosion" by B.J. Doherty, MP (Materials Performance) Vol. 29 No. 1 (January 1990), National Association of Corrosion Engineers, Houston, TX.

5. "Corrosion Failures in the Water Industry" by Michael J. Szeliga, AWWA Chesapeake Annual Conference (1990), AWWA, Denver, CO.

6. "CP Corrosion Control of Municipal Infrastructure" by R.A. Gummow, MP (Materials Performance) Vol. 39 No. 2 (February 2000), National Association of Corrosion Engineers, Houston, TX.

7. "Corrosion of Ductile Iron Pipe: Case Histories" by Michael J. Szeliga and Debra M. Simpson, MP Vol. 40 No. 7 (July 2001), NACE International, Houston, TX.

8. "Corrosion Consideration of Ductile Iron Pipe—A Consultant's Perspective" by Bill Spickelmire, Western Area Corrosion and Education Conference (October 2001) NACE International, Houston, TX.

9. "Evaluating Ductile Iron Pipe Corrosion" by Michael J. Szeliga and Debra M. Simpson, MP Vol. 42 No. 7 (July 2003), NACE International, Houston, TX.

10. "Ductile Iron Corrosion Factors to Consider and Why" by Bill Spickelmire, ASCE International Conference on Pipeline Engineering and Construction (July 2003), ASCE, Reston, VA.

11. "Case Histories: Ductile Iron Pipeline Failures" by Michael J. Szeliga, MP (Materials Performance) Vol. 44 No. 5 (May 2005), NACE International, Houston, TX.

12. "Standard for Polyethylene Encasement for Ductile Iron Pipe Systems" ANSI/AWWA C105/A21.5, 1993, 1999.

13. "Corrosion Costs and Preventative Strategies in the United States" United States Federal Highway Administration, 1999.

14. "A Summary of the Findings of Recent Watermain Corrosion Studies in Ontario" by Robert G. Wakelin, Canadian Region Western Conference, Saskatoon, Saskatchewan, Canada, 1991, NACE International, Houston, TX.

15. "Analyses of Ductile Iron Corrosion Data from Operating Mains" by Michael J. Szeliga, MP (Materials Performance) Vol. 46 No. 2 (February 2007), NACE International, Houston, TX.

16. Standard RP0169 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" NACE International, Houston, TX.

17. "DOT Regulations" by T.K. Spalding and W.R. Lambert, Appalachian Underground Corrosion Short Course, West Virginia University, Morgantown, WV, May 1973.

18. "Corrosion as the Primary Cause of Cast-Iron Main Breaks" by John H. Fitzgerald, III, AWWA Journal Vol. 60 No. 8 (August 1968), American Water Works Association, Denver, CO.

19. "Corrosion Control of Iron and Steel Water Piping—A Historical Perspective" by R.A. Gummow, Northern Area Eastern Conference, Quebec City, Canada, August 2002, NACE International, Houston, TX.

20. "The Application of Corrosion Control Methods to Large Diameter Water and Force Mains" by Michael J. Szeliga, Appalachian Underground Corrosion Short Course, West Virginia University, Morgantown, WV, May 2004.

21. CMS 105DC Corrosion Measurement System Operator's Manual, (July 1994), Gamry Instruments, Inc. Willow Grove, PA.

22. ASTM G 5 "Standard Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements" ASTM, Philadelphia, PA.

23. ASTM G 57 "Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method" ASTM, Philadelphia, PA.

24. ASTM G 51 "Test Method for Measuring pH of Soil for Use in Corrosion Testing" ASTM, Philadelphia, PA.

25. ASTM D 512 "Test Methods for Chloride Ion in Water" ASTM, Philadelphia, PA.

26. ASTM D 516 "Test Method for Sulfate Ion in Water" ASTM, Philadelphia, PA.

27. ASTM D 1498 "Practice for Oxygen-Reduction Potential of Water" ASTM, Philadelphia, PA.

28. Basic Course, Appalachian Underground Corrosion Short Course, West Virginia University, Morgantown, WV.

29. "External Corrosion—Introduction to Chemistry and Control" AWWA Manual M27 Second Edition, American Water Works Association, Denver, CO, 2004.

30. "Protecting Underground Assets with State-of-the-Art Corrosion Control" by Don Lieu and Michael J. Szeliga, MP (Materials Performance) Vol. 41 No. 7 (July 2002), NACE International, Houston, TX.

31. "Electrochemical Techniques for Corrosion Engineering" Robert Baboian Editor (1986), National Association of Corrosion Engineers, Houston, TX.

32. "Corrosion Tests and Standards: Application and Interpretation" Robert Baboian Editor (1995), ASTM, Philadelphia, PA.

33. "Application of Corrosion Growth and Analysis in Support of Direct Assessment Intervals—Part 1" by Aida Lopez-Garrity, Kevin C. Garrity, and Kurt Lawson, MP (Materials Performance) Vol. 45 No. 9 (September 2006), NACE International, Houston, TX.

GLOSSARY

Cathodic Protection: Reduction of corrosion rate by shifting the corrosion potential of the electrode toward a less oxidizing potential by applying an electromotive force.

Corrosion: The deterioration of a material, usually a metal, by reaction with its environment.

Environment: The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

Graphitic Corrosion: Deterioration of gray cast iron in which the metallic constituents are selectively leached or converted to corrosion products leaving the graphite intact.

Pits/Pitting: Localized corrosion of a metal surface that is confined to a small area and takes the form of cavities.

Redox Potential: The equilibrium electrode potential for a reversible oxidation-reduction reaction in a given environment.

Reduction: Gain of electrons by a constituent of a chemical reaction.

Stray Current: Current flowing through paths other than the intended circuit.

Stray Current Corrosion: Corrosion resulting from direct current flow through paths other than the intended circuit. For example, by any extraneous current in the earth.

Tuberculation: The formation of localized corrosion products scattered over the surface in the form of knoblike mounds called tubercles.

The above terms are as defined in the "NACE Corrosion Engineer's Reference Book, Second Edition," R.S. Treseder editor, NACE (National Association of Corrosion Engineers,) Houston, TX, 1991.

The American Concrete Pressure Pipe Association (ACPPA) serves as a resource to its members by facilitating research into issues concerning the water industry. This report focuses on technical considerations affecting the water pipe market. The findings, recommendations and conclusions of this report are those of the authors and do not necessarily reflect the views of the ACPPA or its members. The Association prepared this report for the internal use of its members.