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RECLAMATION

Technical Memorandum 8540-2024-13

Corrosion Mitigation for Buried Metallic Water Pipe

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Technical Memorandum 8540-2024-13

Corrosion Mitigation for Buried Metallic Water Pipe

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Corrosion Mitigation for Buried Metallic Water Pipe

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Acronyms and Abbreviations

2004 TM	<i>Corrosion Considerations for Buried Metallic Water Pipe</i> , Technical Memorandum No. 8140-CC-2004-1, July 2004
ANSI	American National Standards Institute
ASTM	ASTM International
AWWA	American Water Works Association
Corrpro	Corrpro Companies
CP	cathodic protection
CSC	concrete steel cylinder
DoD	U.S. Department of Defense
DI	ductile iron
DIPRA	Ductile Iron Pipe Research Association
FY	fiscal year
GACP	galvanic anode cathodic protection
HDPE	high-density polyethylene
ICCP	impressed current cathodic protection
ISO	International Organization for Standardization
LCCA	life-cycle cost analysis
MIC	microbiologically influenced corrosion
NACE	National Association of Corrosion Engineers
NRC	National Research Council of the National Academies
Ω -cm	ohm-centimeter
OM&R	operation, maintenance, and replacement
PCCP	prestressed concrete cylinder pipe
ppm	parts per million
PVC	polyvinyl chloride
Reclamation	Bureau of Reclamation
RCP	reinforced concrete pipe
RCPP	reinforced concrete pressure pipe
SRB	sulfate-reducing bacteria
ST	steel
TM	Technical Memorandum

UFC	Unified Facilities Criteria
U.S.	United States
USCS	Unified Soil Classification System
USDA	U.S. Department of Agriculture
Virginia Tech	Virginia Polytechnic Institute and State University
WSSC	Washington Suburban Sanitary Commission.

Symbols

>	greater than
≥	greater than or equal to
<	less than
≤	less than or equal to

DRAFT For External Review

Contents

	Page
Summary	1
1.0 Introduction.....	5
1.1 Background.....	5
2.0 Corrosion of Metallic Pipe Materials.....	6
2.1 Steel Pipe	6
2.2 Ductile Iron Pipe	6
2.3 Reinforced Concrete Pipe	7
2.4 Prestressed Concrete Cylinder Pipe	7
2.5 Metallic Appurtenances on Non-Metallic Pipe.....	8
3.0 Determination of Corrosion Mitigation Measures.....	9
3.1 Soil Corrosivity Parameters	9
3.1.1 Resistivity	9
3.1.2 Chlorides.....	11
3.1.3 Sulfates.....	11
3.1.4 Soil pH	12
3.1.5 Drainage Class	14
3.1.6 Other Factors.....	15
3.2 Consequences of Pipe Failure.....	16
3.2.1 Location	16
3.2.2 Pipe Diameter.....	17
3.2.3 Redundancy.....	17
3.2.4 Pressure.....	17
3.2.5 Water Delivery Needs.....	17
3.2.6 Other Considerations	18
3.2.7 Life-Cycle Costs	18
3.3 Typical Corrosion Mitigation Methods	19
3.3.1 Bare Metal Pipe.....	19
3.3.2 Bonded Dielectric Coatings	19
3.3.3 Polyethylene Encasement	19
3.3.4 Corrosion Monitoring	20
3.3.5 Cathodic Protection.....	20
3.3.6 Corrosion Inhibitors.....	21
3.3.7 General Recommendations for Corrosion Mitigation.....	21
3.3.8 Approaches Taken by Other Federal Agencies	21
3.4 Minimum Recommendations for Corrosion Mitigation.....	22
3.5 Client Requested Deviation from Corrosion Mitigation Minimum Recommendations for Ductile Iron Pipe.....	23
4.0 Peer Review of Reclamation Corrosion Mitigation Approach.....	23
5.0 References.....	25

Tables

1.—Soil corrosivity determination.....	2
2.—Consequences of pipe failure determination.....	3
3.—Pipe group matrix.....	4
4.—Corrosion mitigation minimum recommendations	4
5.—Literature and industry values relating soil resistivity to corrosivity	10
6.—Literature and industry values relating soil chloride content to corrosivity	11
7.—Literature and industry values relating soil sulfate content to corrosivity.....	12
8.—Literature and industry values relating soil pH to corrosivity	13
9.—USDA and USCS soil classifications	14
10.—Literature and industry values relating soil drainage class to corrosivity.....	15

Figures

1.—Flowchart for determination of corrosion mitigation minimum recommendations.....	1
2.—Schematic of lined and embedded cylinder-type PCCP.	8

Appendices

- A Life-Cycle Cost Analysis for Buried Pipe
- B Peer Review Report

Summary

The Bureau of Reclamation (Reclamation) employs various corrosion mitigation measures to maintain the integrity and extend the useful life of its buried metallic pipeline infrastructure. Since 2004, Reclamation has used Corrosion Considerations for Buried Metallic Water Pipe, Technical Memorandum No. 8140-CC-2004-1 (2004 TM) [1], to define minimum recommendations for corrosion mitigation on its buried metallic pipelines. Metallic pipe is defined as steel, ductile iron, or any concrete pipe containing ferrous elements. This technical memorandum (TM) supersedes the recommendations identified in the 2004 TM. This revision details Reclamation’s transition from a soil resistivity-based methodology to an approach that analyzes multiple environmental factors to determine the likelihood of a corrosion-related failure and multiple design factors to assess the consequences of such a failure. This multi-factor analysis can then inform the selection of an appropriate combination of corrosion mitigation techniques, such as pipe material selection, corrosion monitoring, protective coatings, and cathodic protection (CP). The corrosion mitigation measures identified in this TM are also applicable to metallic fittings associated with non-metallic pipe. This TM does not address internal pipe corrosion.

Corrosion criteria and minimum mitigation recommendations for buried metallic pipe on Reclamation projects should be determined using the following risk-informed approach, which includes consideration of corrosivity factors and the consequences of failure (table 1 through 4). A flowchart providing an overview of the process is shown in figure 1. Soil corrosivity and consequences of pipe failure determinations that form the basis of this approach can be found in table 1 and 2, respectively. Specific to individual pipeline projects, points are applied for each parameter in the tables and summed to arrive at the severity rating shown at the bottom of each table. The severity rating obtained from tables 1 and 2 can then be used to identify the pipe group in table 3. Finally, the corrosion protection minimum recommendations for each pipe group can be found in table 4. Project designers and/or project decision makers may choose to install corrosion mitigation measures exceeding the minimum recommendations in table 4.

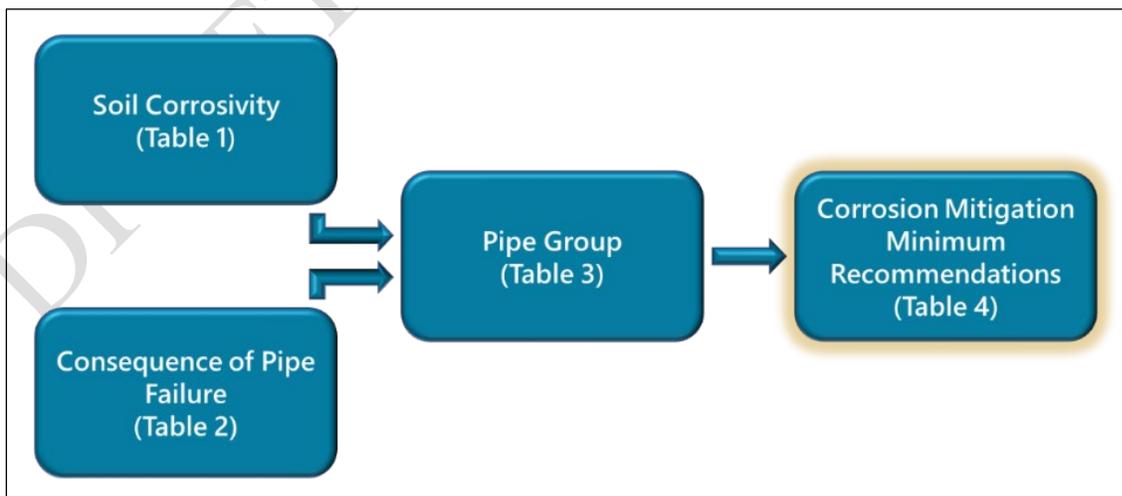


Figure 1.—Flowchart for determination of corrosion mitigation minimum recommendations.

Technical Memorandum No. 8540-2024-13
Corrosion Mitigation for Buried Metallic Water Pipe

Table 1.—Soil corrosivity determination

Parameter ¹	Value	Points
Resistivity (Ω-cm)	≤500	25
	>500–2,000	20
	>2,000–5,000	15
	>5,000–10,000	10
	>10,000	0
Chlorides (ppm)	>500	10
	100–500	6
	<100	0
Sulfates (ppm)	>20,000	5
	>2,000–20,000	3
	>1,000–2,000	1
	≤1000	0
pH	0–4	5
	>4–6	3
	>6–9	0
	>9	3
Drainage Class	Poorly Drained	5
	Somewhat Poorly Drained	4
	Moderately Well Drained	3
	Well Drained	2
	Excessively Drained	0
Other Considerations ¹	Stay Current Microbiologically Influenced Corrosion Existing Structure Performance Backfill Wet-Dry Cycling	0–5
Where:	>30 points = Severe 21–30 points = High 11–20 points = Moderate 5–10 points = Low 0–4 points = Negligible	

Note: Ω-cm = ohm-centimeter and ppm = parts per million.

¹ Including, but not limited to, those listed.

Table 2.—Consequences of pipe failure determination

Parameter	Value	Points
Location	Urban or populated areas	22
	Areas near or adjacent to significant structures, rivers, or railroads	18
	Beneath rural roads	8
	Rural remote areas	0
Pipe diameter (inch/inches)	≥48	15
	42–48	12
	30–36	10
	12–24	6
	0–10	3
Redundancy (alternate water supply available for duration of repair)	None	7
	Reduced flowrate alternate water supply	3
	Yes	0
Pressure (pounds per square inch)	≥250	3
	>150–250	2
	>0–150	1
	0	0
Water delivery needs	Municipal/industrial	3
	Irrigation	2
Other considerations	Environmental (rivers, wetlands, etc.)	0–5
	Cultural	
	Replacement time	
Where:	>30 points = Severe 21–30 points = High 11–20 points = Moderate 6–10 points = Low 0–5 = Negligible	

Table 3.—Pipe group matrix

Soil Corrosivity	Consequences of Pipe Failure				
	Negligible	Low	Moderate	High	Severe
Severe	Pipe Group A	Pipe Group A	Pipe Group A	Pipe Group A	Pipe Group A
High	Pipe Group B	Pipe Group A	Pipe Group A	Pipe Group A	Pipe Group A
Moderate	Pipe Group C	Pipe Group B	Pipe Group B	Pipe Group B	Pipe Group B
Low	Pipe Group D	Pipe Group C	Pipe Group C	Pipe Group C	Pipe Group B
Negligible	Pipe Group D	Pipe Group D	Pipe Group D	Pipe Group C	Pipe Group C

Table 4.—Corrosion mitigation minimum recommendations

Corrosion Mitigation Minimum Recommendations ^{1, 2}			
Pipe Group	Pipe Materials	External Mitigation	Corrosion Mitigation
Pipe Group A ³	Steel	Bonded dielectric coating	Cathodic protection
	Ductile Iron	Bonded dielectric coating	Cathodic protection
	RCP/RCP and PCCP	Corrosion inhibitor in mix design for pipe wall (RCP/RCP) or mortar coating (PCCP)	Cathodic protection
Pipe Group B	Steel	Bonded dielectric coating	Cathodic protection
	Ductile Iron	Metalized zinc coating and polyethylene encasement	Cathodic protection
	RCP/RCP and PCCP	None	Cathodic protection
Pipe Group C	Steel	Bonded dielectric coating	Corrosion monitoring
	Ductile Iron	Metalized zinc coating and polyethylene encasement	Corrosion monitoring
	RCP/RCP and PCCP	None	Corrosion monitoring
Pipe Group D	Steel	Bonded dielectric coating	Corrosion monitoring
	Ductile Iron	Polyethylene encasement	Corrosion monitoring
	RCP/RCP and PCCP	None	Corrosion monitoring

Note: RCP = reinforced concrete pipe, RCP = reinforced concrete pressure pipe, and PCCP = prestressed concrete cylinder pipe.

¹ This table recommends minimum corrosion protection recommendations for a pipeline corrosion mitigation system design. Projects may choose to install corrosion mitigation measures exceeding the minimum recommendations in this table (see table 3 for Pipe Group designations).

² See section 3.5, "Client Requested Deviation from Corrosion Mitigation Minimum Recommendations for Ductile Iron Pipe," in this TM for deviation from the recommendations in this table applicable to ductile iron pipe.

³ Pipe Group A with resistivity values below 500 Ω-cm require a life-cycle cost analysis of all pipe materials under consideration, including non-metallic options (see appendix A for details).

1.0 Introduction

Reclamation constructs and manages hundreds of miles of pipeline systems in the 17 Western States, many of which are large diameter, nonredundant water transmission systems serving large numbers of users. Failure of these systems could have major economic and public health consequences. Therefore, corrosion mitigation is an integral part of the design, construction, and maintenance of Reclamation pipeline infrastructure. When properly designed and maintained, corrosion mitigation systems reduce the corrosion of buried metallic structures, thereby reducing the likelihood of premature failure due to corrosion and the resulting consequences.

Many factors are considered when Reclamation designs or reviews designs for external corrosion mitigation of pipelines. This updated TM transitions Reclamation from a soil resistivity-based methodology to an approach that analyzes multiple environmental factors to determine the likelihood of a corrosion-related failure and multiple design factors to assess the consequences of such a failure. This multi-factor analysis can then inform the selection of an appropriate corrosion mitigation system. Factors will be evaluated along an entire pipeline alignment to ensure consistency in corrosion mitigation measures. The corrosion mitigation measures identified in this TM are also applicable to metallic fittings associated with non-metallic pipe. This TM does not address internal pipe corrosion. For the purposes of this TM, metallic pipe refers to pipe composed of steel, ductile iron, or concrete with reinforcing steel.

1.1 Background

Reclamation has a long history of employing corrosion mitigation measures to maintain the integrity of its infrastructure and extend its useful life. Reclamation finalized the 2004 TM in July 2004 [1]. The 2004 TM was a formalization of what had been an evolutionary process in dealing with corrosion mitigation for metallic pipelines.

A July 16, 2003, House of Representatives Committee on Appropriations report accompanying the fiscal year 2004 Energy and Water Development Appropriations Act directed Reclamation to “conduct a study on the current corrosion criteria and report to the Committee on Appropriations by March 1, 2004, on its recommendations for a more definitive standard” [2]. This study led to Reclamation’s development of the 2004 TM, which included Reclamation’s conclusion that a bonded dielectric coating is needed for all metallic pipe in severely corrosive soils. The 2004 TM provides an extensive background of events leading to its final development. Since publication of the 2004 TM, the Ductile Iron Pipe Research Association (DIPRA) and various ductile iron pipe manufacturers have questioned Reclamation’s corrosion mitigation recommendations for ductile iron pipe in severely corrosive soils. The ductile iron pipe industry’s position is that unbonded polyethylene encasement, or zinc coating with polyethylene encasement, provides sufficient mitigation for their pipe in all but uniquely severe environments. In 2008 and 2009, the National Research Council of the National Academies (NRC) conducted a detailed and independent study of the 2004 TM [3]. The concluding report supported Reclamation’s technical position identified in the 2004 TM but recommended collection of additional data on pipeline reliability.

A fiscal year 2012 Consolidated Appropriations Act conference report directed Reclamation to follow the NRC recommendation to assemble data on pipeline reliability for all types of pipe specified in the 2004 TM, along with the specified corrosion mitigation. The Act also directed Reclamation to conduct an analysis of the performance of these types of pipe, including an analysis of economics, cost-effectiveness, and life-cycle costs [4]. In 2015, Reclamation contracted with Virginia Polytechnic Institute and State University (Virginia Tech) to perform this study. The report documenting this work, *Collection and Compilation of Water Pipeline Field Performance Data*, was published on their website on April 23, 2021 [5]. The report has since been evaluated by Reclamation and is considered in this revision of the 2004 TM and Reclamation's corrosion mitigation guidelines.

2.0 Corrosion of Metallic Pipe Materials

2.1 Steel Pipe

Fundamentally, steel is an alloy composed primarily of iron with varying levels of carbon, typically less than 0.5 percent. Steel pipe is susceptible to corrosion when exposed to water and oxygen. The corrosion experienced on buried metallic pipelines is more dependent on the environmental characteristics than the compositional variations (amount and types of metal) within a specific type of pipe. It is widely accepted that steel, ductile iron, and cast iron corrode at similar rates in similar soils [6, 7, 8].

Installation of steel pipe can involve the use of many kinds of joints. Where necessary, bonding cables can be attached, often by exothermically welding, to adjoining sections of pipe or fittings for the purpose of maintaining electrical continuity. Field-welded joints provide electrical continuity without the use of bonding cables. Non-welded joints are not considered to be reliably electrically continuous, and joint bonds should be installed to ensure continuity [9].

The Virginia Tech report determined a failure rate of 2.9 failures per 100 miles per year (section 4, table 21) and a mean estimated service life of 77 years for large-diameter (greater than 36 inches) steel pipe (report 4, table 68) [5]. These numbers are for all failure types and are highly dependent on the environment in which the pipe is placed.

2.2 Ductile Iron Pipe

Ductile iron pipe is also primarily composed of iron but contains a significantly higher percentage of carbon than steel, upwards of 3.5 percent. Additional elements are added to produce the required shape of graphite, which gives the material its ductility. Under the same environmental conditions, ductile iron pipes corrode at approximately the same nominal rate as steel pipes [10].

For installation, several types of rubber-gasket joints are available with ductile iron pipe and fittings to accommodate a wide variety of applications. The most prevalent are the push-on joint and the mechanical joint [11]. Because these are non-welded joints, bonding cables across each joint are required to be electrically continuous [9].

The Virginia Tech report determined a failure rate of 20.2 failures per 100 miles per year (report 4, table 21) and a mean estimated service life of 53 years for large-diameter (greater than 36 inches) ductile iron pipe (report 4, table 68) [5]. These numbers are for all failure types and are highly dependent on the environment in which the pipe is placed.

2.3 Reinforced Concrete Pipe

Reinforced concrete pipe (RCP) and reinforced concrete pressure pipe (RCPP) are composite pipes composed of concrete with reinforcement typically made of steel [12, 13]. The pipe may be manufactured offsite (precast) or constructed onsite (cast-in-place). The concrete provides the overall strength and structure of the pipe, while the steel reinforcement enhances its ability to withstand tensile loads and pressures. RCP/RCPP relies on the alkalinity present in concrete or mortar coatings to encapsulate the steel in a passivated environment to prevent corrosion.

When exposed to environments containing sulfates, a chemical reaction occurs between sulfates and the cement paste matrix of the concrete or mortar known as sulfate attack. Sulfate attack can lead to cracking or softening of the matrix and the eventual deterioration of mechanical properties. Cracks can allow moisture to reach steel reinforcement, resulting in corrosion and further loss of mechanical integrity.

To maintain electrical continuity, reinforcing steel in RCP/RCPP must be electrically bonded within each pipe section and to the joint rings. Adjacent sections must also be bonded to each other to ensure electrical continuity along an alignment [14].

The Virginia Tech report determined a failure rate of 0.4 failures per 100 miles per year (report 4, table 21) and a mean estimated service life of 81 years for large-diameter (greater than 36 inches) RCP/RCPP pipe (report 4, table 67) [5]. These numbers are for all failure types and are highly dependent on the environment in which the pipe is placed.

2.4 Prestressed Concrete Cylinder Pipe

As a subset of RCPP, prestressed concrete cylinder pipe (PCCP) is a composite pipe composed of concrete with reinforcement made of steel, or, in the case of PCCP, prestressed steel wires. A schematic of this type of pipe can be seen in figure 2. The concrete cylinder provides the overall structure of the pipe; however, the steel wires almost entirely provide the pipe with the ability to withstand tensile loads and pressures. PCCP also relies on the alkalinity present in the mortar coating, typically only 1/2- to 1-inch thick, to encapsulate the steel prestressing wire in a passivated environment to prevent corrosion.

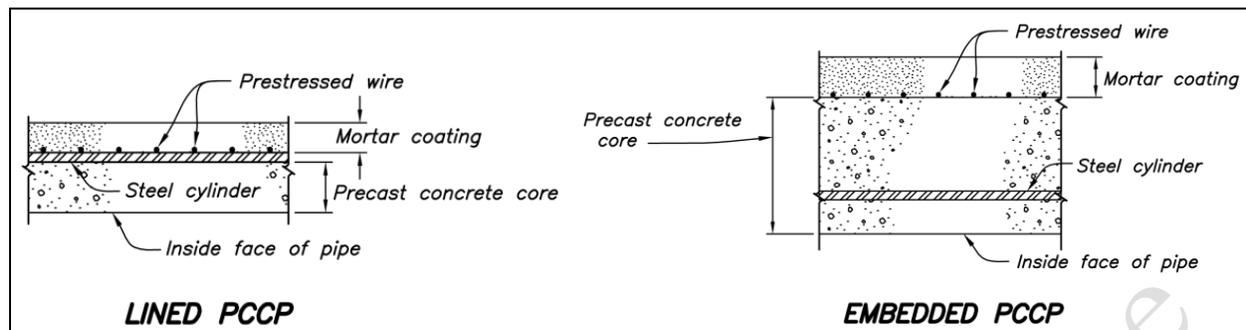


Figure 2.—Schematic of lined and embedded cylinder-type PCCP.

A key difference in PCCP failures lies in the role of the steel prestressing wires and the impact of corrosion on their failure. Corrosion of the steel prestressing wires leads to a reduction in cross-sectional area that weakens their ability to maintain the intended prestressing force that opposes internal pipe pressures. Because the mechanical integrity of the pipe relies almost entirely on the prestressing wires, when enough wires corrode and break, the tensile load restraint is lost and the pipe section fails, often catastrophically. In most cases, the series of events leading to failure is cracking of the mortar coating (from sulfate attack or by any mechanical stresses imposed on the exterior mortar), corrosion of the prestressing wires, and eventual failure.

Shorting straps, a strip of metal directly under the prestressed wires, can be used to maintain electrical continuity in the event of a wire break and reduce electrical attenuation along the prestressing wire within each section of PCCP. The prestressing wire can be electrically connected to the steel cylinder during manufacture. Joint bonds are required to ensure electrical continuity between sections along an alignment [14].

The Virginia Tech report determined a failure rate of 2.4 failures per 100 miles per year (report 4, table 21) and a mean estimated service life of 65 years for large-diameter (greater than 36 inches) PCCP pipe (section 4, table 67) [5]. These numbers are for all failure types and are highly dependent on the environment in which the pipe is placed.

2.5 Metallic Appurtenances on Non-Metallic Pipe

Many projects consider non-metallic pipe options in the design, especially when soil corrosivity is in the high or severe ranges. When plastic or composite carrier pipe is selected, metallic fittings and appurtenances are often specified. In these cases, the risk-informed approach outlined in this document should be used to determine appropriate corrosion mitigation methods for metallic features associated with the non-metallic pipeline. Typically, fittings and appurtenances are supplied with a factory-applied, bonded dielectric coating. CP may also be required, depending on the service environment.

3.0 Determination of Corrosion Mitigation Measures

3.1 Soil Corrosivity Parameters

Soil burial is one of the most aggressive exposures encountered by Reclamation's metallic pipelines. Soil corrosivity provides an indication of how aggressive a soil environment is to metallic pipe, fittings, and appurtenances and is a function of several, often interacting, parameters. A review of these parameters is presented below; corrosivity values from literature and industry standards are included for the primary factors.

3.1.1 Resistivity

Soil resistivity is a measure of the soil's ability to resist the flow of electrical current. Faraday's Law states that the amount of metal lost due to corrosion is directly proportional to the amount of electrical charge (current) that passes through the corroding metal. Soil resistivity, therefore, plays a significant role in the corrosion of steel buried underground. When the soil resistivity is low, it means that the soil can easily conduct electricity, and the corrosion rate of steel is high. In contrast, high soil resistivity means that the soil cannot easily conduct electricity, resulting in a lower corrosion rate for steel. Soil resistivity is affected by several factors, including soil water content, soil type, and the presence of dissolved salts. Soil resistivity at discrete locations is determined using ASTM International (ASTM) G57 or equivalent [15]. Because soil resistivities can show considerable scatter along a pipe alignment, Reclamation then calculates a comprehensive design soil resistivity for the entire alignment using the 10-percent soil resistivity statistical method [16].

To assign a soil corrosivity rating for resistivity, a review of standard practices across multiple references and organizations was completed. Reclamation threshold value range delineations were informed by this review. The following resistivity values were obtained from the sources noted in table 5:

Table 5.—Literature and industry values relating soil resistivity to corrosivity

Source	Range (Ω -cm)	Points/Severity Rating
AWWA, Manual 27, Third Edition [17]	<1500	10/10
	\geq 1500–1800	8/10
	>1800–2100	5/10
	>2100–2500	2/10
	>2500–3000	1/10
	>3000	0/10
Corrosion 98, Paper 667 [18]	0–1000	Very corrosive
	1000–2000	Corrosive
	2000–10000	Mildly corrosive
	>10000	Progressively less corrosive
Roberge, Corrosion Basics: An Introduction, Second Edition [19]	<1000	Extremely corrosive
	1000–3000	Highly corrosive
	3000–5000	Corrosive
	5000–10000	Moderately corrosive
	10000–20000	Mildly corrosive
	>20000	Essentially noncorrosive
Corrpro/DIPRA, The Design Decision Model [20]	<500	30/30
	\geq 500–1000	25/30
	>1000–1500	22/30
	>1500–2000	19/30
	>2000–3000	10/30
	>3000–5000	5/30
	>5000	0/30
Peabody, Control of Pipeline Corrosion, Second Edition [21]	0–500	Very corrosive
	500–1000	Corrosive
	1000–2000	Moderately corrosive
	2000–10000	Mildly corrosive
	>10000	Negligible
WSSC, Pipeline Design Manual [Common Design Guidelines] [22]	<1000	10/10
	1000–1500	8/10
	1500–2500	6/10
	2500–5000	4/10
	5000–10000	2/10
	>10000	0/10

Note: Ω -cm = ohm-centimeter, AWWA = American Water Works Association, Corrpro = Corrpro Companies, DIPRA = Ductile Iron Pipe Research Association, and WSSC = Washington Suburban Sanitary Commission.

3.1.2 Chlorides

High chloride concentrations in the soil can significantly increase the corrosion rate of steel. Chloride ions can penetrate the passive oxide layer on the steel surface, making it easier for the corrosive agents to react with the metal. The presence of chloride ions in the soil can also increase the solubility of iron ions, resulting in a higher concentration of iron ions in the soil solution and accelerating the corrosion process. Chloride concentration is determined using the sample preparation method Tex-620-J and ion chromatography per ASTM D4327, or equivalent [23, 24].

To assign a soil corrosivity rating for chlorides, a review of standard practices across multiple references and organizations was completed. Reclamation threshold value range delineations were informed by this review. The following chloride values were obtained from the sources noted in table 6:

Table 6.—Literature and industry values relating soil chloride content to corrosivity

Source	Range (ppm)	Points/Severity Rating
Corrpro/DIPRA, The Design Decision Model [20]	>100	8/8
	50–100	3/8
	<50	0/8
Peabody, Control of Pipeline Corrosion, Second Edition [21]	>5000	Severe
	1500–5000	Considerable
	500–1500	Corrosive
	<500	Threshold
WSSC, Pipeline Design Manual [Common Design Guidelines] [22]	>1000	10/10
	500–1000	6/10
	200–500	4/10
	50–200	2/10
	0–50	0/10

Note: Corrpro = Corrpro Companies, DIPRA = Ductile Iron Pipe Research Association, ppm = parts per million, and WSSC = Washington Suburban Sanitary Commission.

3.1.3 Sulfates

Sulfate attack on concrete occurs when sulfate ions in the soil react with the cement paste matrix of concrete or mortar. This can lead to the formation of compounds that expand and disrupt the concrete’s structure, causing cracking and eventual delamination. These cracks can allow

moisture to reach steel reinforcement (as would be found in RCP/RCP or PCCP), resulting in corrosion. Corrosion compounds formed on the reinforcing steel are also expansive, causing additional cracking and further deterioration of the concrete. Sulfate concentration is determined using the sample preparation method Tex-620-J and ion chromatography per ASTM D4327 or equivalent [23, 24].

To assign a soil corrosivity rating for sulfates, a review of standard practices across multiple references and organizations was completed. Reclamation threshold value range delineations were informed by this review. The following sulfate values were obtained from the sources noted in table 7:

Table 7.—Literature and industry values relating soil sulfate content to corrosivity

Source	Range (ppm)	Points/Severity Rating
AWWA, Manual 27, Third Edition [17]	Positive	3.5/3.5
	Trace	2/2
	Negative	0/2
Corrpro/DIPRA, The Design Decision Model [20]	Positive (≥ 1)	4/4
	Trace ($>0, <1$)	1.5/4
	Negative (0)	0/4
Peabody, Control of Pipeline Corrosion, Second Edition [21]	> 10000	Severe
	1500–10000	Considerable
	150–1500	Positive
	0–150	Negligible

Note: AWWA = American Water Works Association, Corrpro = Corrpro Companies, DIPRA = Ductile Iron Pipe Research Association, and ppm = parts per million.

3.1.4 Soil pH

Soil pH affects the corrosion of steel, where corrosion rates generally increase as soil pH becomes more acidic. A low pH (acidic) soil environment can lead to the formation of a more aggressive corrosion cell on the metal surface, as well as increased solubility of metallic ions and a reduction in the thickness of the corrosion product layer. The corrosion process is facilitated by the presence of aggressive ions, such as chlorides, which are more mobile in acidic conditions. When the soil pH is high (alkaline), the formation of protective oxide layers on the metal surface can mitigate corrosion. When iron and steel are exposed to a highly alkaline environment, such as being coated with mortar or encased in concrete, the potential corrosive effects of the soil are reduced. Soil pH is determined in accordance with ASTM G51 or equivalent [25].

To assign a soil corrosivity rating for pH, a review of standard practices across multiple references and organizations was completed. Reclamation threshold value range delineations were informed by this review. The following pH values were obtained from the sources noted in table 8:

Table 8.—Literature and industry values relating soil pH to corrosivity

Source	Range	Points/Severity Rating
AWWA, Manual 27, Third Edition [17]	0–2	5/5
	2–4	3/5
	4–6.5	0/5
	6.5–7.5	0/5 or 3/5 if sulfides are present and low or negative redox potential
	7.5–8.5	0/5
	>8.5	3/5
Corrpro/DIPRA, The Design Decision Model [20]	0–4	4/4
	4–6	1/4
	6–8 (with sulfides and low or negative redox potential)	4/4
	>6	0
Peabody, Control of Pipeline Corrosion, Second Edition [21]	<5.5	Severe
	5.5–6.5	Moderate
	6.5–7.5	Neutral
	>7.5	None (alkaline)
WSSC, Pipeline Design Manual [Common Design Guidelines] [22]	0–2	5/5
	2–4	3/5
	4–8.5	0/5
	>8.5	3/5

Note: AWWA = American Water Works Association, Corrpro = Corrpro Companies, DIPRA = Ductile Iron Pipe Research Association, and WSSC = Washington Suburban Sanitary Commission.

3.1.5 Drainage Class

Different types of native soil have different capacities to retain water, which affects their water content and resistivity. For example, clayey soils tend to have a higher water content and retain more water than sandy soils. Soil texture, structure, and organic matter content also influence the ability of the soil to retain water. Additionally, soil compaction and drainage can affect the water content of the soil. For this TM, at the planning level of designs, soil drainage class is defined by the U.S. Department of Agriculture’s (USDA) Soil Survey Manual [26]. Classification is based on the USDA’s Web Soil Survey tool for a selected area of interest in the region where the project will be located [27]. When geologic data from site-specific field investigations are available prior to the 30% or 60% Final Design milestones, classification can instead be in accordance with the Unified Soil Classification System (USCS) using laboratory grain size distribution and Atterberg limits data or from field hand tests (i.e., visual classification). Classification using site-specific geologic data is preferred over USDS’s Web Soil Survey tool. Table 9 provides an approximate translation between the USDA and USCS classifications to be used for this application [28].

Table 9.—USDA and USCS soil classifications

USDA Textural Soil Classification	Most Probable USCS Soil Classification	Other Possible USCS Soil Classification(s)
Sand	SP	SW, GP, GW, SP-SM, GP-GM, SM, GM
Loamy Sand	SM	GM, SC, GC, CL
Sandy Loam	SM	GM, SC, GC, ML, CL
Sandy Clay Loam	SC	SC, GC, CL
Sandy Clay	SC	CL
Loam	CL	ML
Silt Loam	ML	SM, CL
Silt	ML	—
Clay Loam	CL	MH
Silty Clay Loam	CL	ML, CH
Clay	CH	SC, GC, CL
Silty Clay	CH	CL, MH

To assign a soil corrosivity rating for drainage class, a review of standard practices across multiple references and organizations was completed. Reclamation threshold value range delineations were informed by this review. The following drainage class values were obtained from the sources noted in table 10.

Table 10.—Literature and industry values relating soil drainage class to corrosivity

Source	Range	Points/Severity Rating
AWWA Manual 27, Third Edition [17]	Poor drainage, continuously wet	2
	Fair drainage, generally moist	1
	Good drainage, generally dry	0
Roberge, Corrosion Basics: An Introduction, Second Edition [19]	Poor drainage, continuously wet	2
	Fair drainage, generally moist	1
	Good drainage, generally dry	0
Corrpro/DIPRA, The Design Decision Model [Moisture Content] [20]	>15% = Wet	5/5
	5–15% = Moist	2.5/5
	<5% = Dry	0/5
WSSC, Pipeline Design Manual [Common Design Guidelines] [Soil Description] [22]	Clay (Blue-Gray)	10
	Clay/Stone	5
	Clay	3
	Silt	2
	Clean Sand	0

Note: AWWA = American Water Works Association, Corrpro = Corrpro Companies, DIPRA = Ductile Iron Pipe Research Association, and WSSC = Washington Suburban Sanitary Commission.

3.1.6 Other Factors

3.1.6.1 Stray Currents

Stray currents are also a common cause of underground pipeline corrosion. For stray current corrosion, current from a foreign source, such as a nearby CP system or electrified railway, is required. Current is collected at some surfaces (cathodes) of the pipeline and discharged from other surfaces (anodes) as the current returns to the originating source. The metal corrodes at the anodic sites. The extent and intensity of stray current corrosion are related to the driving voltage of the stray current, the circuit resistance, the geometric relationship between the source of earth currents and the pipeline, the axial resistance of the pipeline, the dielectric properties and continuity of the pipe coating, and the soil conductivity. The vulnerability of metallic pipes to stray current corrosion is dependent on proximity to stray current sources, exposed metal surface area, dielectric properties of the coating, and pipeline continuity.

3.1.6.2 Microbiologically Influenced Corrosion

Microbiologically influenced corrosion (MIC) of metallic structures is caused by microorganisms that thrive in soil, water, and other environments. These microorganisms can produce corrosive byproducts that can react with metal surfaces, leading to corrosion. MIC can be influenced by factors such as soil water content, temperature, pH, and the presence of nutrients. The type and concentration of microorganisms can affect the rate and type of

corrosion, with sulfate-reducing bacteria (SRB) and acid-producing bacteria being the most common types associated with MIC. SRB can accelerate the corrosion of carbon steel by producing hydrogen sulfide. As a supply of nutrients for SRB, high sulfate concentrations have been associated with increased corrosion rates. Additionally, the formation of various corrosion products, such as iron sulfides, contributes to the loss of metal mass.

3.1.6.3 Existing Structure Performance

When assessing soil corrosivity for new pipelines in an area with existing infrastructure, the existing infrastructure can serve as an indicator of soil corrosivity and how well corrosion mitigation measures perform within that local environment. If existing structures are experiencing significant corrosion, a more robust approach to corrosion mitigation should be considered for new infrastructure.

3.1.6.4 Backfill

Cut-and-cover installation of a buried pipeline requires excavating a trench, preparing the invert bedding, installing the pipe, backfilling with special material to support the pipe, and filling the remainder of the trench to the original ground surface. This sequence ensures an abundant supply of both oxygen and water in the pipe trench. The trench intercepts, collects, and conveys water, which may contain dissolved salts from both surface runoff and the native backfill. Oxygen enrichment and cyclic wetting-drying concentrate the groundwater salts within the backfill, thus increasing the soil corrosivity over time.

3.1.6.5 Wet-Dry Cycling

Locations that experience a fluctuating water table, periodic surface runoff, flooding, or other forms of frequent wet-to-dry cycling tend to see higher rates of corrosion compared to pipelines with a more static environment. Cyclic wetting-drying leads to higher concentrations of sulfates and chlorides and provides both the water and oxygen needed for corrosion, thus, additional corrosion mitigation measures may be needed.

3.2 Consequences of Pipe Failure

The consequences of pipe failure in water conveyance systems encompass a range of intricate considerations that impact communities, infrastructure, and public well-being. A single failure within these complex networks can trigger a cascade of effects, ranging from localized disruptions to widespread implications. Factors such as location, pipe diameter, redundancy, pressure, and water delivery needs play a pivotal role in shaping the outcome of the failure.

3.2.1 Location

Pipeline location can influence the extent of failure impacts. Failures in urban areas can lead to more immediate and widespread consequences due to high population density, infrastructure density, and disruptions to commercial and public services. In rural areas, failures might have

less local impact but can still disrupt water supply to critical downstream facilities like farms, industrial facilities, and residential communities. Additionally, a failure can compromise the terrain in which the pipeline is installed (i.e., hillside), requiring extensive remediation. For this TM, an urban area is defined by the U.S. Census Bureau as an area that encompasses at least 5,000 people or at least 2,000 housing units [29]. A pipeline failure near or under structures such as roads, railroads, buildings, commercial establishments, or industrial facilities can pose a threat to life as well as property damage and disruption of critical services. In both urban and rural cases, the accessibility of the pipeline, including its remoteness, burial depth, pavements, traffic, and location relative to other structures, can impact response times for emergency repairs.

3.2.2 Pipe Diameter

The diameter of a pipe directly affects the volume of the water being conveyed. Smaller-diameter pipes restrict water volume and flow when compared to larger-diameter pipes. In the event of a failure, larger-diameter pipes can release a larger volume of water more quickly, causing greater damage downstream from the failure. Pipe diameter is also a measure of downstream user impacts because larger-diameter pipes transport more water, and curtailment of deliveries would negatively impact more people and/or acreage. As well, replacement sections of larger-diameter pipe are more difficult to transport and coordinate equipment for repair, which can result in longer outages.

3.2.3 Redundancy

Redundancy in the context of water conveyance systems refers to having backup or duplicate components, pipelines, or systems that can take over the function of a failed element. Redundancy can have a significant positive impact on reducing the consequences of pipe failure by minimizing service disruption, allowing faster restoration, and ensuring water delivery needs are met while repairs are being made.

3.2.4 Pressure

The pressure within a pipeline system can impact the severity and extent of damage resulting from a pipe failure. Higher pressures in the system can lead to a greater volume of water being released into the environment, as well as high-force impacts on nearby infrastructure and natural features that can cause property damage or loss of life.

3.2.5 Water Delivery Needs

In residential areas, failures can result in inconvenience, property damage, and a loss of access to water necessary for drinking, sanitation, and hygiene. Water delivery to critical facilities like hospitals, fire stations, and other emergency services can be essential for public safety; a failure

that affects these facilities could lead to life-threatening situations. Agricultural areas dependent on water for irrigation can experience crop losses with high economic impacts, especially during growing seasons.

3.2.6 Other Considerations

3.2.6.1 Environmental Impact

The environmental impact of a pipeline failure depends on factors like the location of the failure, the volume of water released, and the nature of the surrounding ecosystem. Some potential impacts include contamination of nearby water bodies, habitat disruption to local flora and fauna, soil erosion, and the inundation of nearby wetland or riparian zones.

3.2.6.2 Cultural Impact

Pipelines often traverse through regions with historical, cultural, or spiritual significance to local communities. A failure can damage or disturb these sites, causing emotional distress and impacting the community's sense of identity. Further, many communities have connections to their local environment. A pipeline failure can disrupt these connections, negatively impacting traditional practices such as fishing, hunting, or farming.

3.2.6.3 Replacement Time

The replacement time for pipeline sections depends on various factors like the size and complexity of the section, the availability of materials, specialized equipment needs, access, pipeline operations, and required deliveries. Consideration should also be given to engineering design, procurement, construction timeframes, and environmental and safety regulations associated with potential repairs and replacements. Especially in situations where a non-redundant water source is available, replacement time should be given the maximum points.

3.2.7 Life-Cycle Costs

Life-cycle costs for a pipeline project include initial capital costs as well as periodic operation, maintenance, and replacement (OM&R) costs incurred throughout the economic life of the project. Reclamation designs pipelines to meet the hydraulic performance requirements of each project in the most economical manner possible. When determining suitable pipe materials for projects being constructed in severely corrosive soils, initial capital costs and major operational costs for the corrosion mitigation of the pipeline can be analyzed for each pipe type to determine the lowest life-cycle cost of the pipeline system. See appendix A for more information on life-cycle costs for buried pipe.

3.3 Typical Corrosion Mitigation Methods

3.3.1 Bare Metal Pipe

Because of the inherent potential for metal pipes to corrode, Reclamation practice is to use some form of protective coating, as well as corrosion monitoring, on all buried metallic pipe, even in low-corrosivity soils. Bare pipe may provide the lowest initial capital costs, but it is likely to have the highest maintenance costs.

3.3.2 Bonded Dielectric Coatings

A bonded dielectric coating is a protective barrier coating system that tightly adheres to the surface on which it is applied, often through a combination of chemical bonds and mechanical interlocking, and provides high electrical resistivity. The coating effectively physically and electrically isolates the metal from the soil, thus protecting the metal against corrosion. Common bonded dielectric coatings for metallic pipelines are epoxies and polyurethanes. However, factory-applied bonded dielectric coatings are not always defect-free and can be unknowingly damaged during installation. A good bonded dielectric coating in conjunction with CP is considered by Reclamation to be the best defense against pipeline corrosion. As the coating ages and the exposed pipeline surface area increases, the CP current is increased to maintain a consistent level of mitigation.

3.3.3 Polyethylene Encasement

Polyethylene encasement is a dielectric material that is not bonded to the underlying metallic surface and is thus considered an encasement rather than a coating. It is typically used with ductile iron pipe and provides better mitigation than bare pipe. Polyethylene encasement is relatively inexpensive when compared to bonded dielectric coatings.

Polyethylene encasement can be installed with enhancements such as metalized zinc coatings and corrosion inhibitors. Metalized zinc coatings employ a protective layer of zinc bonded to the surface of the metallic substrate. In addition to providing a physical barrier between the substrate and the environment, the coating also provides corrosion mitigation through galvanic CP. Zinc is more reactive than steel or iron, and it acts as a sacrificial barrier and corrodes in place of the underlying metal. Because zinc metal is consumed in the process, the life of the zinc coating is necessarily limited. Polyethylene encasement with corrosion inhibitors can help reduce high initial corrosion rates and MIC; these inhibitor products are also depleted over time.

Like bonded dielectric coatings, no polyethylene encasement will be defect-free. Defects within the polyethylene encasement can occur during manufacturing or installation. In accordance with AWWA C105, cuts, tears, punctures, or other damage to the polyethylene encasement shall be repaired [30]. However, defects can persist through installation. Although polyethylene encasement can be used in conjunction with CP, opinions on combining these techniques vary

within the water industry. Should soil or water enter the encasement, there is a concern that the polyethylene will act as a dielectric shield and prevent CP current from reaching corroding areas, thus allowing corrosion to progress under the encasement [31]. A metalized zinc coating would provide localized corrosion mitigation underneath the intact polyethylene until it is consumed, after which there is no secondary mitigation mechanism for the metallic pipe wall.

3.3.4 Corrosion Monitoring

Irrespective of the amount of environmental testing that is conducted prior to pipeline design, there is always a potential for a buried metallic pipeline to have corrosion-related problems. If a corrosion-related problem is identified, a corrosion monitoring system provides a means to investigate, identify, and address the problem. Without a corrosion monitoring system, the options available are limited and often require unearthing the pipeline.

A corrosion monitoring system requires the pipeline to be electrically continuous along the alignment, and connections to the pipeline are provided in test stations at prescribed intervals along the pipeline. Providing electrical continuity on a pipeline will increase the probability of corrosion resulting from stray currents; however, a corrosion monitoring system can be used to investigate, identify, and mitigate long-line and stray current corrosion. A corrosion monitoring system can also provide the needed structure connection to install a CP system in the future without unearthing the pipeline, should the need arise. Reclamation believes the benefits of a corrosion monitoring system far exceed the risk associated with stray currents and recommends that all buried metallic pipelines be installed with corrosion monitoring systems.

3.3.5 Cathodic Protection

Corrosion mitigation using CP is a means of reducing the corrosion of a buried metallic pipeline by causing direct current to flow from an external source through the soil and onto the structure to be protected. The system, thereby, shifts the exposed surface of the structure to a uniform and protective potential. There are two types of CP systems used to protect buried metallic pipe: galvanic anode and impressed current.

Galvanic anode cathodic protection (GACP) systems, also known as sacrificial anode CP, provide direct current by galvanic corrosion, i.e., by sacrificing the anode material to prevent corrosion of the pipeline. Sacrificial anodes, often made of magnesium or zinc, are buried at an offset from the pipeline and connected to the pipeline directly or through a test station or junction box. GACP systems are typically used to protect structures with small, exposed surface areas and, therefore, low current requirements. All sections of buried pipe that are to be protected must be bonded for electrical continuity. These systems are relatively low maintenance, requiring periodic replacement of anodes but no external power.

Impressed current cathodic protection (ICCP) systems provide direct current using an external power source. The power source, typically a transformer-rectifier, forces current to discharge from buried anodes, through the soil, and onto the buried structure to be protected. ICCP systems for buried applications typically use corrosion-resistant anode materials such as graphite, high-silicon cast iron, or mixed metal oxides on titanium or niobium. All sections of buried pipe that are to be protected must be bonded for electrical continuity. ICCP systems, while needing more attention than GACP systems, can protect large or poorly coated structures with high current requirements. ICCP is also more effective than GACP in high-resistivity soils and can be installed in a deep-well anode bed configuration if a small footprint is required.

CP systems for buried metallic pipe should meet the performance requirements in NACE SP0169 [9]. Cathodic protection systems for concrete pressure pipes (RCP/RCPP and PCCP) should meet the performance requirements in NACE SP0100 [14].

3.3.6 Corrosion Inhibitors

When concrete is in contact with severely corrosive soils, corrosion inhibitors can be used as part of a corrosion mitigation strategy to provide additional corrosion mitigation to reinforcing steel in RCP/RCPP and PCCP. Corrosion inhibitors are chemical admixtures that can be added to a mortar or concrete mix during production. These inhibitors typically bind to the surface of the steel and create a protective film. A wide variety of corrosion inhibitors are commercially available; inhibitors that provide stable, long-term mitigation should be used.

3.3.7 General Recommendations for Corrosion Mitigation

Corrosion mitigation should be considered early in a pipeline design project. Field Exploration Requests to determine the soil corrosivity and Design Data Requests related to determining the consequence of failure should be completed during the *concept* phase of Reclamation's Final Design Process. By 30% Final Design, a preliminary design should be in place so that a corrosion mitigation system can be included in quantity estimates for the project and a life-cycle cost analysis (LCCA) can be conducted, if needed.

3.3.8 Approaches Taken by Other Federal Agencies

To provide context, a review of the current policies and procedures of other government agencies related to corrosion mitigation was completed; the following summarizes those findings:

- Since 1970, the U.S. Department of Transportation has not allowed non-adhered coatings, polyethylene encasement included, on natural gas pipelines [32]. Additionally, CP is required on all gas pipelines installed after July 31, 1971, with certain exceptions noted.

- The U.S. Department of Defense (DoD) Unified Facilities Criteria (UFC) requires the use of CP systems and bonded protective coatings on buried steel and ductile iron pipe where the resistivity is less than 30,000 Ω -cm. Unbonded protective coatings such as polyethylene wraps are not permitted except in Navy projects [33].

3.4 Minimum Recommendations for Corrosion Mitigation

Corrosion mitigation criteria and minimum recommendations for buried metallic pipe on Reclamation projects should be determined using the risk-informed approach described in this TM, which includes consideration of corrosivity factors and the consequences of failure. A flowchart providing an overview of the process is shown in figure 1. Corrosivity and consequences of pipe failure determinations that form the basis of this approach can be found in tables 1 and 2, respectively. Corrosivity parameters and ranges were developed with consideration of literature values and industry standard practices; see relevant sections for referenced data [17, 18, 20, 21, 22, 34]. In both tables, points are applied for each parameter and summed to arrive at the severity rating shown at the bottom of each table.

Maximum point values were determined by a panel of Reclamation subject matter experts using a decision matrix methodology. To arrive at a numerical solution, a criterion scoring matrix was first constructed that compared each parameter side-by-side. The parameter with the greatest perceived importance was chosen, and the degree of difference in preference was given a point value between 1 and 3; any comparison between parameters believed to be of equal importance was given a value of 0. A point value of 1 was considered a minor preference, while a point value of 3 was considered a major preference. After all comparisons were made, the points for each parameter were summed to arrive at an overall score. Parameters receiving an overall score of 0 were given a rating of 1.

Once all panelists had submitted their scores for each matrix independently, an average of the overall scores was taken and used for weighting the total point distribution out of 50 possible points. The weighted scores were then compared against similar industry approaches to identify any major discrepancies and develop the intermediate severity rating values. Lastly, case studies were performed using Reclamation projects to validate the results.

The number of points applied for a given parameter is based on corresponding values specific to each pipeline project and summed up to provide a severity rating. The severity rating is then used to identify the pipe group, with Pipe Group A having the most risk and Pipe Group D the least (table 3). Finally, the corrosion mitigation minimum recommendations for each pipe group can be determined (table 4). Projects may choose to install corrosion mitigation measures exceeding the minimum recommendations.

3.5 Client Requested Deviation from Corrosion Mitigation Minimum Recommendations for Ductile Iron Pipe

If the entity that will be the ultimate owner and/or will fully assume OM&R responsibility requests a deviation from the corrosion mitigation recommendations that Reclamation proposes for such a project, Reclamation will accept the request without requiring the entity to follow the deviation process identified in Reclamation Manual Policy FAC P03, “Performing Design and Construction Activities,” if: 1) such a request is stamped by a professional engineer currently registered/licensed in the United States in an applicable discipline who is employed or contracted by the ultimate owner and/or entity who will fully assume OM&R responsibility for the pipeline; and 2) if the proposed system consists of ductile iron pipe with a metalized zinc coating, polyethylene encasement, and CP. Ductile iron pipe with a metalized zinc coating and traditional or V-Bio enhanced polyethylene encasement shall be in accordance with current versions of both ISO 8179-1 and ANSI/AWWA C105/A21.5 [35, 30]. Additionally, construction specifications shall require a representative of the pipe manufacturer to be onsite full-time during the first 60 days of pipe installation and at least monthly onsite inspections thereafter to ensure the installation takes place in accordance with the most current revision of ANSI/AWWA C105/A21.5. All other applicable Reclamation policy and design guidance shall remain in full effect.

4.0 Peer Review of Reclamation Corrosion Mitigation Approach

In accordance with Public Law 113-76, section 203, subsection (c), this revision to the 2004 TM was subjected to peer review by appropriate experts not employed or selected by Reclamation and in accordance with the standards referenced in the Office of Management and Budget memoranda, “Final Information Quality Bulletin for Peer Review” and “Improving Implementation of the Information Quality Act.” In addition, this revision was promulgated in accordance with the requirements of Reclamation’s Design Standards No. 1 and other applicable law, regulation, and agency processes, including opportunities for meaningful public participation and input [36, 37, 38, 39]. The results of this peer review were incorporated into this TM, and the peer review report is included as appendix B.

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Appendix A

Life-Cycle Cost Analysis for Buried Pipe

DRAFT FOR External Review

1.0 Overview

This appendix communicates an approach for life-cycle cost analysis (LCCA) to obtain approximate estimates of initial construction field costs and corrosion-related operation, maintenance, and replacement (OM&R) costs associated with different pipe materials under consideration for installation on Reclamation projects. The pipe materials include polyvinyl chloride (PVC), high-density polyethylene (HDPE), steel (ST), ductile iron (DI), reinforced concrete pipe/reinforced concrete pressure pipe (RCP/RCP), and prestressed concrete cylinder pipe (PCCP). Any Reclamation pipeline proposed to be installed in soil with less than 500 Ω -cm resistivity requires a life-cycle economic analysis. For comparison purposes, each study will base analyses on a representative section of pipeline 100 miles long with a consistent diameter over a 100-year life cycle for OM&R.

Note: This LCCA approach considers only corrosion-related OM&R, such as maintenance of the cathodic protection (CP) system or repairs/replacement of pipe due to corrosion-related failures and does not account for costs due to non-corrosion-related maintenance or failures.

The LCCA will be at the appraisal level, and it is intended to be used solely as a planning aid in comparing pipe material options for pipelines identified as Pipe Group A with resistivity values below 500 Ω -cm (see table 4 in this Technical Memorandum [TM]). Appraisal cost estimates are not suitable for requesting project authorization or construction fund appropriations from Congress. The estimates are intended to be used only for corrosion-related approximate relative cost comparisons of various pipe materials. The general process for the LCCA is hereinafter described.

2.0 Cost Estimates

2.1 Origin and Source of the Cost Estimates

Cost estimates will be prepared before the 60% Final Design milestone in accordance with Reclamation Manual Policy FAC P09, "Cost Estimating," and Reclamation Manual Directives and Standards FAC 09-01, "Cost Estimating," and FAC 09-03, "Representation and Referencing of Cost Estimates in Bureau of Reclamation Documents Used for Planning, Design and Construction" [40, 41, 42].

2.2 Purpose and Intended Use of LCCA Estimates

Appraisal-level cost estimates will be prepared for all pipe material options that could be reasonably installed given the hydraulic performance requirements of a particular project, including PVC, HDPE, ST, DI, RCP/RCP, and PCCP. The estimates will include the field cost

to construct selected pipeline features only and will not include the cost to construct other pipeline features that may be required, such as ground and surface water diversion and control, pumping plants, valve structures, road crossings, dust abatement, traffic control, etc.

In addition to estimating the cost to construct selected pipeline features, costs will also be estimated to operate and maintain each pipeline and periodically replace components during a 100-year period at a specific discount rate. OM&R costs include ongoing, regular, or routine operation, maintenance, repairs, replacements, and other activities necessary for the continued operational reliability of the corrosion mitigation features to ensure the delivery of water. OM&R costs also include anticipated periodic non-routine repairs and replacements of the carrier pipe due to corrosion-related failures. OM&R costs are costs incurred after the project is constructed and brought into service. They can be further categorized as periodic costs or annual costs.

In accordance with Reclamation Manual Directives and Standards FAC 09-01, appraisal cost estimates are intended to be used as an aid in comparing options. Appraisal cost estimates are not suitable for requesting project authorization or construction fund appropriations from Congress. Due to the early project stage and limited design data, appraisal designs are typically not mature enough to determine and establish project budgets. The estimates are intended to be used for approximate relative cost comparisons only.

To simplify the comparison, do not include non-contract costs in the field cost estimates. From a comparison standpoint, non-contract costs can be assumed to be the same for each pipeline material option.

2.3 Price Level

Interest rates and inflation affect the purchasing power of a dollar in future years. Therefore, all costs will be discounted and reported as present value dollars. The Reclamation fiscal year plan formulation rate (discount interest rate) for the year of the LCCA study will be applied as the discount rate for calculating the total present value of the various OM&R costs. All costs noted in the LCCA represent present-value dollars.

2.4 Basis of Cost Estimate

Field cost estimates and OM&R costs will be developed from approximate quantities, existing data, and appraisal-level designs and drawings. Field cost estimates will include an initial one-time expenditure for the construction of each pipeline material option and corrosion-related OM&R costs for the life cycle of 100 years.

2.4.1 Field Costs

The field cost is an estimate of the capital costs of a feature or project from award to construction closeout. The field cost equals the contract cost plus construction contingencies. Unit prices will be based on historical bid information, detailed estimates of selected items, and industry-standard cost estimate reference data. Pipe installation production rates vary depending on the pipe material, and actual project pipeline alignments and site conditions are considered. A corrosion mitigation system for a given pipe material will be selected based on the risk-informed methodology in this TM.

Field costs do not include non-contract costs. From a comparison standpoint, non-contract costs are assumed to be similar for each pipeline material option and not a significant factor in pipe material selection. Field costs will include:

- *Subtotal Pay Items.* —Field costs include material and installation costs for pipe and corrosion mitigation systems only.
- *Mobilization.* —Mobilization costs include contractor bonds, mobilizing (and demobilizing) contractor personnel and equipment to and from the project site, and initial project startup.
- *Design Contingencies.* —Design contingencies are intended to account for three types of uncertainties inherent to a project as it advances from the planning stage through final design: 1) minor unlisted items, 2) minor design and scope changes, and 3) minor cost estimating refinements.
- *Allowance for Procurement Strategies.* —A line-item allowance for procurement strategies may be included in appraisal cost estimates to anticipate additional costs when solicitations will be advertised and awarded under conditions other than full and open competition. These include solicitations that will be set aside under socio-economic programs, along with solicitations that may limit competition or allow awards to other than the lowest bid or proposal.
- *Construction Contingencies.* —Construction contingencies are intended to account for the completeness and reliability of the engineering design data, geological information, adequacy of projected quantities, general knowledge of site conditions, and engineering judgment of the major pay items. Appraisal estimates include a percentage allowance for construction contingencies to cover minor differences in actual and estimated quantities, unforeseeable difficulties at the site, changed site conditions, possible minor changes in plans, and other uncertainties.

2.4.2 Operation, Maintenance, and Replacement Cost Estimates

OM&R costs will not include non-contract costs. OM&R cost estimates will include costs associated with operating, maintaining, and periodically replacing components for a corrosion mitigation system and periodically replacing pipeline sections due to corrosion-related failures over a 100-year service life, including:

- **Annual Costs.** —Annual costs include the estimated costs for operation and maintenance of a corrosion mitigation system over a period of one calendar year. Operation costs include costs for operating the corrosion mitigation system. Maintenance costs include costs associated with maintaining the corrosion mitigation system in satisfactory condition.
- **Periodic Costs.** —Replacement costs are periodic as they occur at a term that is less frequent than annually. Periodic costs include the costs for the removal and replacement of CP system components and pipe materials upon the end of their service life or due to corrosion-related failure. The quantities and intervals for these periodic costs will be developed based on site conditions, historical data from similar pipelines, and engineering judgment of the years at which components need to be replaced and/or refurbished.
- **Pipe Material Replacement Rates.** —A pipe material replacement rate was determined based on published failure rates for each pipe material, where a failure is defined as any damage that requires the replacement of an individual section of pipe due to emerging or impending water loss. Data from the National Research Council of the National Academies (NRC) and Virginia Polytechnic Institute and State University (Virginia Tech) publicly available reports were used to extrapolate the number of 20-foot-long sections of pipe that would need to be replaced over a 100-year lifespan due to corrosion-related failures only (see subsection 2.4.2.1) [3, 5].
- **Cathodic Protection System Maintenance and Replacement Rates.** —The maintenance and replacement requirements for a CP system will be dependent on the design and operation of the system.

Typical field costs and OM&R costs that will be used in an LCCA for pipe, fittings, and a corrosion mitigation system are presented in tables A-1 and A-2, respectively.

Table A-1.—Field cost estimate items

Item Description (Furnish and Install)	Unit
Transmission and/or Distribution Pipeline	
Line pipe (specify material type)	linear ft
Joints	each
Casings	linear ft, each
Miters	linear ft, each
Other appurtenances	each
Corrosion Mitigation System	
Impressed Current Cathodic Protection (ICCP) System on Buried Metallic Pipeline: ICCP anodes (mixed metal oxide, high silicon cast iron, graphite) with anode cable Deep well components: vent pipe, conduit, coke breeze, aggregate, pea gravel, clay seal Rectifier Junction box with shunts and variable resistors Structure cable and weld supplies	each
Galvanic Anode Cathodic Protection (GACP) System on Buried Metallic Pipeline: GACP anodes (magnesium) Junction box or test station with shunts and variable resistors Structure cable and weld supplies	each
Corrosion Monitoring System or Cathodic Protection Test System: Test station Structure cable, casing cable, and weld supplies	each
Cable and Weld Supplies for Joint Bonds	linear ft

Table A-2.—OM&R cost estimate items and frequency

Item Description	Duration	Frequency
Transmission and/or Distribution Pipeline Replacement	Project-specific based on pipe material and size, and site conditions	Based on corrosion-related failure rate
Polyvinylchloride (PVC)		02 replacements
High-density polyethylene (HDPE)		02 replacements
Ductile iron with polyethylene encasement and CP		26 replacements
Steel with bonded dielectric coating and CP		09 replacements
RCP/RCP with CP		01 replacement
PCCP with CP		04 replacements
Corrosion Mitigation System Replacement		
Test stations (1% of all in system) (GACP and ICCP)	60 minutes per test station	Annually
GACP anode bed		Every 20 years
ICCP anode bed		Every 20 years
Rectifier		Every 40 years
Operating, Maintenance, and Inspection Costs		
Power for ICCP system		Billed monthly
Rectifier inspection	15 minutes per rectifier	Every 3 months
Rectifier adjustment	10 minutes per rectifier	Annually
Potential survey (all system types)	05 minutes per test station	Annually
Close interval potential survey (GACP and ICCP)	02 miles per hour	Every 5 years

2.4.2.1 Pipeline Replacement Frequency Calculations

To arrive at the replacement rates shown in table A-2, failure rate data were compiled as shown in table A-3. Of the references noted, the NRC report contained the only population of failures related specifically to corrosion, but it was limited to ductile iron pipe. The Utah State study report, “*Water Main Break Rates in the USA and Canada: A Comprehensive Study*” published in 2018 and updated in 2023, collected data on many miles of pipeline; however, it did not include specific break rates for HDPE, RCP/RCP, and PCCP [43, 44]. The Virginia Tech report contained the largest population of pipe failures and included all pipe types and diameters; it was used in the calculations for this study (table A-4).

Based on Reclamation’s inventory, it was assumed that the pipe diameter would be greater than or equal to 24 inches. The failure rates for population groups 16 to 36 inches and greater than 36 inches were used to arrive at a single weighted linear-combined failure rate for each pipe type (table A-4, step 1). PVC and HDPE had no data for greater than 36 inches in diameter, so the 18- to 36-inch diameter failure rate was used. To attempt to obtain a failure rate limited to

corrosion-related failures, the weighted linear combined failure rates were normalized to the DI pipe failure rate and then multiplied by the corrosion-specific failure rate for DI pipe from the NRC report (table A-4, steps 2 and 3).

The authors of the NRC report noted that the pipelines studied were in service for less than 50 years, and the expected failure rate would increase with age. To calculate a replacement rate, the corrosion-related failure rate was assumed to be static for the first 50 years of service and double every 10 years, from 50 to 100 years (table A-4, steps 4 through 9). The resulting failure rates were used to calculate the replacement rate for each pipe material over a 100-year life cycle (table A-5). A fractional failure was rounded to assume that an entire 20-foot section of pipe was replaced.

Table A-3.—Reference failure rate data

Reference	PVC	HDPE	DI	Steel	RCP/ RCPP ¹	PCCP
NRC (corrosion related failures/year/100 miles) [3]			0.038			
Virginia Tech 16- to 36-inch diameter failure rate (all failures/year/100 miles) [5]	1.9	1.3	33.4	18.4	1.4	5.3
Length by diameter 16 to 36 inches (miles) [5]	3293	379	8137	1877	816	1943
Virginia Tech >36-inch diameter failure rate (all failures/year/100 miles) [5]			20.2	2.9	0.4	2.4
Length by diameter >36 inches (miles) [5]	63	1	772	1903	458	1397
Utah State all diameters (all failures/year/100 miles) [43, 44]	2.9		5.1	9.2	3.1	

¹ The Utah State study report cites a break rate for concrete steel cylinder (CSC) pipe, listed here under RCP/RCPP. This value is taken from their 2018 report, as there is no break rate cited for CSC within their 2023 report.

Table A-4.—Steps taken to estimate failure rate

Step	Calculation	PVC	HDPE	DI	Steel	RCP/ RCP	PCCP
1	Total mileage for all pipe >16 inches in diameter	3356	380	8909	3780	1274	3340
2	Weighted linear-combined failure rate	1.90	1.30	32.3	10.6	1.04	4.09
3	Failure rates normalized to DI pipe	0.059	0.040	1.000	0.329	0.032	0.127
4	Years 0–50 failure rate: normalized rate multiplied by corrosion-related failure rate	0.002	0.002	0.038	0.012	0.001	0.005
5	Years 50–60 failure rate: failure rate doubles every 10 years	0.004	0.003	0.076	0.025	0.002	0.010
6	Years 60–70 failure rate	0.009	0.006	0.152	0.050	0.005	0.019
7	Years 70–80 failure rate	0.018	0.012	0.304	0.100	0.010	0.039
8	Years 80–90 failure rate	0.036	0.025	0.608	0.200	0.020	0.077
9	Years 90–100 failure rate	0.072	0.049	1.216	0.399	0.039	0.154

Table A-5.—Estimated corrosion-related replacement rate by pipe material to be used for LCCA

Corrosion-Related Replacement Rate	PVC	HDPE	DI	Steel	RCP/ RCP	PCCP
0–50 years	0.112	0.077	1.900	0.624	0.061	0.241
50–60	0.045	0.031	0.760	0.250	0.025	0.096
60–70	0.090	0.061	1.520	0.499	0.049	0.193
70–80	0.179	0.123	3.040	0.999	0.098	0.385
80–90	0.358	0.245	6.080	1.997	0.196	0.770
90–100	0.716	0.490	12.160	3.995	0.392	1.541
Total	1.500	1.026	25.460	8.364	0.821	3.226
Total number of pipe sections to be replaced per 100 miles per 100 years ¹	2	2	26	9	1	4

¹ The values shown assumes ductile iron pipe with polyethylene encasement, with or without cathodic protection. If pipe is furnished with bonded dielectric coating and cathodic protection, use the same values as steel.

Appendix B

Peer Review Report

(being conducted by a third-party contractor in concurrence with the public review period)

DRAFT FOR External Review

DRAFT FOR External Review