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Technical Memorandum No. 8540-2024-13

Corrosion Mitigation for Buried Metallic Water Pipe

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Technical Memorandum No. 8540-2024-13

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
AC	alternating current
AMPP	Association for Materials Protection and Performance
ANSI	American National Standards Institute
ASTM	ASTM International
AWWA	American Water Works Association
Corrpro	Corrpro Companies
CP	cathodic protection
CSC	concrete steel cylinder
DC	direct current
DI	ductile iron
DIPRA	Ductile Iron Pipe Research Association
ECHO	Enforcement and Compliance History Online
EPA	U.S. Environmental Protection Agency
FRS	Facility Registry Service
FY	fiscal year
GACP	galvanic anode cathodic protection
HDPE	high-density polyethylene
HVAC	heating ventilation and air conditioning
ICCP	impressed current cathodic protection
ISO	International Organization for Standardization
LCCA	life-cycle cost analysis
MIC	microbiologically influenced corrosion
NACE	NACE International, now AMPP (formerly the 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
RCP	reinforced concrete pipe
RCPP	reinforced concrete pressure pipe
Reclamation	Bureau of Reclamation
SME	subject matter expert

SRB	sulfate-reducing bacteria
ST	steel
TM	Technical Memorandum
UFC	Unified Facilities Criteria
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
$\geq$	greater than or equal to
$<$	less than
$\leq$	less than or equal to
%	percent

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Executive Summary

The Bureau of Reclamation (Reclamation) employs various corrosion mitigation measures to maintain 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 table 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 table 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 table 1 and table 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.

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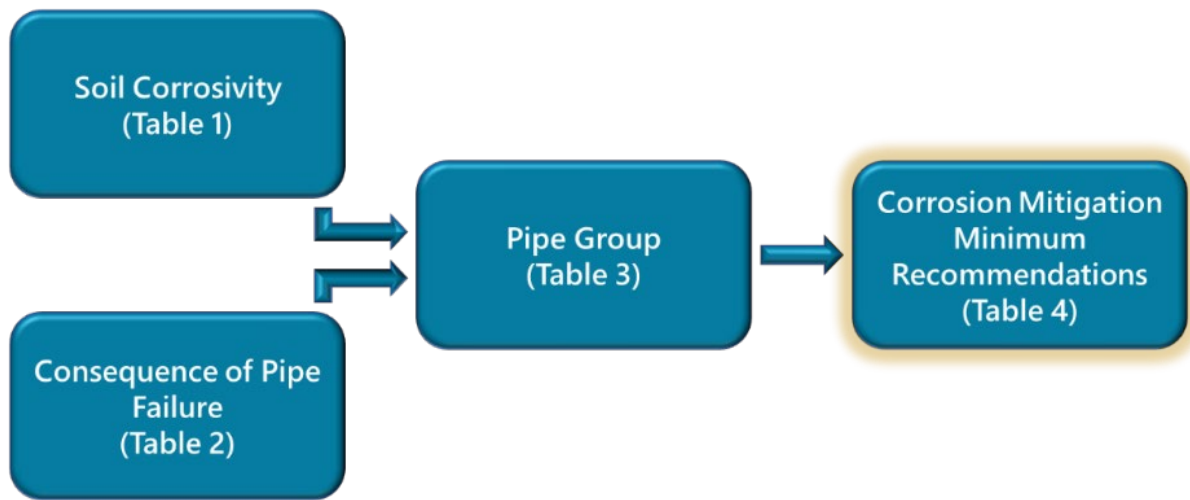


Figure 1.—Flowchart for determination of corrosion mitigation minimum recommendations.

Table 1.—Soil corrosivity determination

Parameter	Value	Points (Metallic Pipe)	Points (Concrete Pipe)
Resistivity (Ω -cm)	< 500	25	25
	500–2,000	20	20
	2,000–5,000	15	15
	5,000–10,000	10	10
	> 10,000	0	0
Chlorides (ppm)	> 500	10	10
	100–500	6	6
	< 100	0	0
Sulfates (ppm)	> 10,000	–	5
	2,000–10,000	–	3
	1,000–2,000	–	1
	$\leq$ 1,000	–	0
Sulfides (ppm)	Positive (> 1)	5	–
	Trace (0-1)	2	–
	Negative (0)	0	–
pH	0–4	5	5
	4–6	3	3
	6–9	0	0
	> 9	3	3
Drainage class	Poorly drained	5	5
	Somewhat poorly drained	4	4
	Moderately well drained	3	3
	Well drained	2	2
	Excessively drained	0	0

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Parameter	Value	Points (Metallic Pipe)	Points (Concrete Pipe)
Site-Specific Factors: Stray current and AC-influenced corrosion ^{1,2}	Documented interference	5	5
	Within an interference corridor but no measured interaction	2–4	2–4
	No adjacent interference source	0–1	0–1
Site-Specific Factors: Microbiologically influenced corrosion	Confirmed SRB/MIC activity	5	5
	Multiple supporting conditions co-present	2–4	2–4
	Aerobic, well-drained soil, no indications	0–1	0–1
Site-Specific Factors: Existing structure performance	Significant corrosion	5	5
	Moderate corrosion	2–4	2–4
	None/performing well	0–1	0–1
Site-Specific Factors: Backfill	Native backfill, not compatible with pipe and coating or encasement	5	5
	Native backfill, limited heterogeneity	2–4	2–4
	Engineered select backfill, compatible with pipe and coating or encasement	0–1	0–1
Site-Specific Factors: Wet-dry cycling (including coastal/tidal influences)	Coastal/tidal influence, saltwater intrusion or frequent flooding	5	5
	Occasional seasonal variation	2–4	2–4
	Static moisture, deep stable water table, or arid conditions	0–1	0–1

Where:

> 30 points = Severe

21–30 points = High

11–20 points = Moderate

5–10 points = Low

0–4 points = Negligible

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

¹ Each Site-Specific Factor listed are those most encountered and are not exhaustive.

² Category-Elevation Override: A purely additive score can underestimate risk when a single condition is severe enough to independently drive failure, even if other factors in this category are low. To account for this, if any single Site-Specific Factor is scored 5 (for example, confirmed active stray current, confirmed MIC conditions, or corrosion on comparable nearby structures meeting the rubric's threshold for a 5), the overall soil corrosivity category shall be raised one level above the category otherwise calculated from table 1 (not to exceed "Severe"). This override may be waived only where documented engineering justification, reviewed and approved Reclamation's lead corrosion engineer, demonstrates that the specific condition does not represent an elevated risk to the structure under evaluation.

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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 ¹	Replacement time	0–5
	Cultural	
	Environmental (rivers, wetlands, etc.)	

Where:

>30 points = Severe

21–30 points = High

11–20 points = Moderate

6–10 points = Low

0–5 = Negligible

¹ Other considerations include, but are not limited to, those listed.

Table 3.—Pipe group matrix

Soil Corrosivity ¹	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 B	Pipe Group B	Pipe Group A	Pipe Group A	Pipe Group A
Low	Pipe Group C	Pipe Group B	Pipe Group B	Pipe Group B	Pipe Group A
Negligible	Pipe Group C	Pipe Group C	Pipe Group C	Pipe Group B	Pipe Group B

¹ See table 1 for Pipe Group designations.

Table 4.—Corrosion mitigation minimum recommendations

Corrosion Mitigation Minimum Recommendations ^{1, 2}			
Pipe Group	Material (Pipe or Appurtenance)	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)	Bonding straps, Cathodic protection
Pipe Group B	Steel	Bonded dielectric coating	Corrosion monitoring
	Ductile iron	Bonded dielectric coating	Corrosion monitoring
	RCP/RCP and PCCP	None	Bonding straps, Corrosion monitoring
Pipe Group C	Steel	Bonded dielectric coating	Corrosion monitoring
	Ductile iron	Metalized zinc coating and polyethylene encasement	Corrosion monitoring
	RCP/RCP and PCCP	None	Bonding straps, Corrosion monitoring

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 requires 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 thousands 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 ferrous elements. Corrosion mitigation strategies should be tailored to the site-specific variability of soil conditions and construction practices encountered along a pipeline alignment; as such, a single point of analysis or an average soil condition may not be appropriate for the entire length of a project.

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 considering and designing 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, rather than one typically applied in the field via a loose polyethylene wrap, is needed for all metallic pipe in severely corrosive soils. The 2004 TM provides an extensive background of events leading to its final development. After publication of the 2004 TM, the Ductile Iron Pipe Research Association (DIPRA) and some ductile iron pipe manufacturers 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 typically applied in the field, 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 NRC's concluding report supported Reclamation's technical position identified in the 2004 TM that ductile iron pipe with polyethylene encasement and cathodic protection is not likely to provide a reliable 50-year service life in highly corrosive soils, 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 pipes specified in the 2004 TM, along with the specified corrosion mitigation. The conference report 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. Publications of the U.S. Army Corps of Engineers relating to soil classification and cathodic protection also informed the development of this TM.

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 and corresponding installation methods through 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]. Although nominal corrosion rates in comparable soil environments may be similar for steel, ductile iron, and cast iron, the materials differ in wall thickness, microstructure, and failure mechanisms. As a result, the distribution of corrosion damage and the modes by which each material reaches failure can differ significantly, and these differences should be considered in material selection and mitigation design.

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 and corresponding installation methods through 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, ferrous elements 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/RCP pipe (report 4, table 67) [5]. These numbers are for all failure types and are highly dependent on the environment and corresponding installation methods through which the pipe is placed.

2.4 Prestressed Concrete Cylinder Pipe

As a subset of RCP, 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.

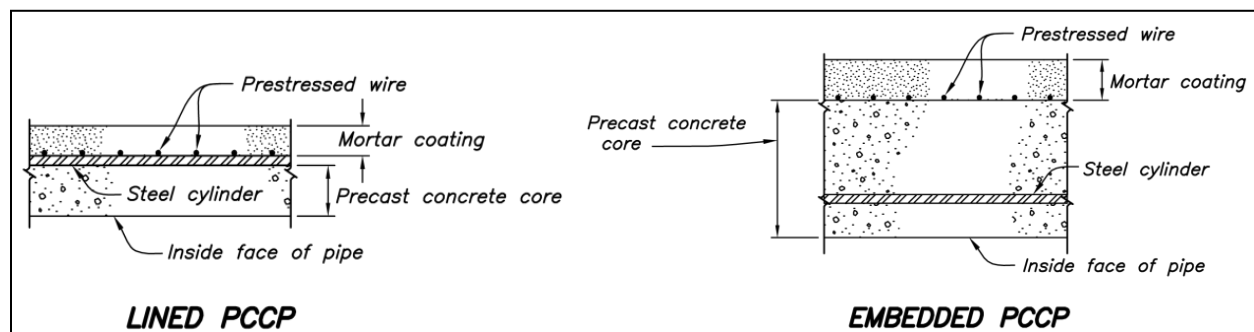


Figure 2.—Schematic of lined and embedded cylinder-type PCCP.

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, are typically provided to maintain electrical continuity in the event of a wire break and reduce electrical attenuation along the prestressing wire within each section of PCCP. Where PCCP will be monitored electrically or protected cathodically, continuity provisions such as shorting straps should be included unless

project-specific conditions justify an alternative approach. 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 and corresponding installation methods through 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], which provides apparent resistivity from soundings taken at multiple pin spacings. While G57 describes manual measurements taken at a limited number of discrete spacings, it also addresses automated multi-electrode acquisition, in which multiple equally spaced pins are driven and the instrument switches among four-pin combinations to collect apparent resistivity. Reclamation recommends that field resistivity data be collected using an automated multi-electrode resistivity system configured for continuous data acquisition, which apply the same Wenner array principles but collect apparent resistivity data at many electrode spacings and configurations along a single line. This approach provides denser, more continuous data with depth and along the alignment that can practically be achieved using manual four-pin soundings at only three spacings. Apparent resistivities are processed through a mathematical inversion model to obtain true resistivities for each soil layer at pipe depth. 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]. Barnes Layer Analysis may be used to evaluate soil-layering effects where only limited sounding data are available.

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
	$\geq$ 1,500–1,800	8/10
	> 1,800–2,100	5/10
	> 2,100–2,500	2/10
	> 2,500–3,000	1/10
	> 3,000	0/10
Corrosion 98, Paper 667 [18]	0–1,000	Very corrosive
	1,000–2,000	Corrosive
	2,000–10,000	Mildly corrosive
	> 10,000	Progressively less corrosive
Roberge, Corrosion Basics: An Introduction, Second Edition [19]	< 1,000	Extremely corrosive
	1,000–3,000	Highly corrosive
	3,000–5,000	Corrosive
	5,000–10,000	Moderately corrosive
	10,000–20,000	Mildly corrosive
	> 20,000	Essentially noncorrosive
Corrpro/DIPRA, The Design Decision Model [20]	< 500	30/30

Source	Range (Ω -cm)	Points/Severity Rating
	≥ 500 –1,000	25/30
	> 1,000–1,500	22/30
	> 1,500–2,000	19/30
	> 2,000–3,000	10/30
	> 3,000–5,000	5/30
	> 5,000	0/30
Peabody, Control of Pipeline Corrosion, Third Edition [21]	0–500	Very corrosive
	500–1,000	Corrosive
	1,000–2,000	Moderately corrosive
	2,000–10,000	Mildly corrosive
	> 10,000	Negligible
WSSC, Pipeline Design Manual [Common Design Guidelines] [22]	< 1,000	10/10
	1,000–1,500	8/10
	1,500–2,500	6/10
	2,500–5,000	4/10
	5,000–10,000	2/10
	> 10,000	0/10

Ω -cm = ohm-centimeter, AWWA = American Water Works Association, Corpro = Corpro 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, Third Edition [21]	> 5,000	Severe
	1,500–5,000	Considerable
	500–1,500	Corrosive
	< 500	Threshold
WSSC, Pipeline Design Manual [Common Design Guidelines] [22]	> 1,000	10/10
	500–1,000	6/10
	200–500	4/10
	50–200	2/10
	0–50	0/10

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

3.1.3 Sulfates and Sulfides

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 spalling. These cracks can allow moisture to reach steel reinforcement (as would be found in RCP/RCP or PCCP), resulting in corrosion. Corrosion products formed on the ferrous elements are also expansive, causing additional cracking and further deterioration of the concrete. Sulfides are a byproduct of sulfate-reducing bacteria (SRB) activity and are associated with microbiologically influenced corrosion (MIC) of steel and ductile iron. Sulfate concentration is determined using the sample preparation method Tex-620-J and ion chromatography per ASTM D4327 or equivalent [23, 24]. Sulfide presence is determined by a qualitative field test (e.g., lead-acetate) or quantitative laboratory determination.

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 sulfide/sulfate content to corrosivity

Source	Range (ppm)	Points/Severity Rating
(Sulfide) AWWA, Manual 27, Third Edition [17]	Positive	3.5/3.5
	Trace	2/2
	Negative	0/2
(Sulfide) Corrpro/DIPRA, The Design Decision Model [20]	Positive (≥ 1)	4/4
	Trace ($> 0, < 1$)	1.5/4
	Negative (0)	0/4
(Sulfate) Peabody, Control of Pipeline Corrosion, Third Edition and Reclamation Concrete Manual 8th Edition [21, 25]	$> 10,000$	Severe
	1,500–10,000	Considerable
	150–1,500	Positive
	0–150	Negligible

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 [26].

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, Third 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

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 [27]. 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 [28]. When geologic data from site-specific field investigations are available prior to the 30 Percent (%) 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 USDA’s Web Soil Survey tool. Table 9 provides an approximate translation between the USDA and USCS classifications to be used for this application [29].

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

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

3.1.6 Site-Specific Factors

The following factors capture site-specific conditions that can control localized corrosion and premature failure. They are not a residual or minor category; any one factor may independently produce a highly corrosive environment. Each factor is scored 0–5 using the rubrics below and entered in table 1. Where two or more factors are present, score toward the high end of each, because these conditions frequently interact and their combined effect can exceed the sum of the individual effects.

Category-Elevation Override: A purely additive score can underestimate risk when a single condition is severe enough to independently drive failure, even if other factors in this category are low. To account for this, if any single Site-Specific Factor is scored 5 (for example, confirmed active stray current, confirmed MIC conditions, or corrosion on comparable nearby structures meeting the rubric’s threshold for a 5), the overall soil corrosivity category shall be raised one level above the category otherwise calculated from table 1 (not to exceed “Severe”). This override may be waived only where documented engineering justification, reviewed and approved Reclamation’s lead corrosion engineer, demonstrates that the specific condition does not represent an elevated risk to the structure under evaluation.

3.1.6.1 Stray Currents and AC Interference

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. Alternating-current (AC) interference can also occur where a pipeline shares a right-of-way with a high-voltage AC transmission corridor and should be evaluated alongside direct current (DC) stray-current sources. Proximity to existing infrastructure with active cathodic protection (e.g., co-located oil or gas pipelines) or to DC-powered electrified transit systems should be assigned a high point value (4 or 5) for the stray current parameter in table 1 unless site-specific field testing and interference analysis demonstrate negligible interaction.

Suggested scoring:

- **5:** confirmed active stray-current discharge or measured interference
- **2–4:** within an HVAC corridor, adjacent to foreign CP systems, or within the influence zone of DC transit/electrified rail, with no measured interaction
- **0–1:** no DC traction/transit, foreign CP, or HVAC corridor nearby

3.1.6.2 *Microbiologically Influenced Corrosion*

Microbiologically influenced corrosion 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.

Suggested scoring:

- **5:** confirmed SRB/MIC activity or documented MIC failures in similar nearby soils
- **2–4:** one or more supporting conditions present (low/negative redox, near-neutral pH, poorly drained or organic-rich soil)
- **0–1:** aerobic, well-drained soil, no indications positive redox

Note: Score site conditions and confirmed activity; do not re-count the sulfide value already scored as a primary parameter in table 1.

3.1.6.3 *Existing Structure Performance*

When existing infrastructure is present in the area of a new pipeline, its field performance is often the strongest available indicator of local soil corrosivity and how well corrosion mitigation measures perform in that environment. Where existing comparable structures (similar pipe material, soil environment, and cathodic protection status) show significant corrosion, designers should elevate mitigation measures for the new pipeline even if the table 1 point total would otherwise suggest a lower severity category.

Suggested scoring:

- **5 (significant):** external corrosion on comparable nearby structures that has caused leaks, repairs, or replacements, or has produced measurable section loss (deep pitting, graphitization, wire breaks in PCCP) that threatens service life.
- **2-4 (moderate):** external corrosion is present and progressing beyond surface staining, general or localized attack visible on the structure, but has not yet caused loss of function, leaks, or repairs.
- **0–1:** comparable nearby structures performing well with only superficial/cosmetic corrosion, or no comparable structures present.

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. Furthermore, the intermingling of distinct soil strata during excavation and backfilling can create localized corrosion cells. The mixing of materials with varying chemical and physical properties can result in a non-uniform environment along the pipe surface, potentially increasing localized corrosion rates beyond those predicted by initial testing of undisturbed soil layers.

Suggested scoring:

- **5:** native corrosive backfill, heterogeneous, and incompatible with the selected pipe and coating/encasement
- **2–4:** native backfill with limited heterogeneity, or native backfill with significant strata intermixing or known-corrosive constituents
- **0–1:** engineered select backfill, homogeneous, compatible with the selected pipe and coating/encasement.

Note: For the purposes of this factor, compatible backfill is engineered select backfill that is free of sharp or angular material that could puncture a coating or encasement during installation and does not introduce corrosive constituents or heterogeneity that would create localized corrosion cells.

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. Coastal environments, areas subject to saltwater intrusion, and zones with tidal or storm-driven wetting and drying can significantly increase corrosion potential and should be evaluated as high-severity wet-dry cycling conditions.

Suggested scoring:

- **5:** coastal/tidal influence, saltwater intrusion, or frequent flooding/inundation
- **2–4:** occasional seasonal variation, regular wet-dry cycling, or fluctuating water table
- **0–1:** static moisture, deep stable water table, or arid setting.

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.

For the purposes of this Technical Memorandum, a failure is defined as any condition of the pipeline or its appurtenances that requires repair or replacement to restore structural integrity or to stop or prevent loss of water. Failures generally fall into two categories:

- **Leak:** A defect leading to loss of water—whether gradual or sudden—that necessitates excavation and repair or replacement of a pipe section or appurtenance.
- **Rupture:** A sudden, structural failure resulting in uncontrolled release of water, typically involving significant loss of cross-sectional capacity or breakage of load-bearing components. The soil-corrosivity scoring (table 1) and consequence-of-failure scoring (table 2) do not differentiate numerically between leaks and ruptures. The leak/rupture terminology is provided for clarity and aligns with Reclamation’s failure-data practices, where failures are recorded and characterized as leaks or ruptures for long-term reliability analysis.

3.2.1 Location

Pipeline location influences the extent of failure impacts. Failures in urban areas, defined by the U.S. Census Bureau as an area that encompasses at least 5,000 people or at least 2,000 housing units [30], 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, failure can compromise the terrain in which the pipeline is installed (e.g., hillside), requiring extensive remediation.

Proximity to other infrastructure also affects consequence severity; a pipeline failure near or under structures such as roads, railroads, other buried utilities (particularly those with active cathodic protection), 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.

A review of adjacent and historical land use can also reveal conditions affecting current or future soil corrosivity, such as industrial sites, mining or coal residue, or former pipe-manufacturing, foundry, or landfill areas. Publicly available tools such as the U.S. Environmental Protection Agency’s (EPA’s) Enforcement and Compliance History Online (ECHO) database and Facility Registry Service (FRS) records can support this review during the design phase.

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. Also, 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 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 pipes.

3.2.7 Other Considerations

3.2.7.1 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.

3.2.7.2 Cultural Impact

Pipelines often traverse through regions with historical, cultural, or spiritual significance to local communities. 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.

3.2.7.3 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.

3.3 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 pipes, even in low-corrosivity soils. Bare pipe may provide the lowest initial capital costs, but they are likely to have the highest maintenance costs and a shorter overall service life.

3.3.2 Bonded Dielectric Coatings

A bonded dielectric coating is a protective barrier coating system, typically applied in a pipe-manufacturing facility, 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 include epoxies and polyurethanes.

Reclamation considers bonded dielectric coating in combination with cathodic protection (CP) to be the best defense against pipeline corrosion. As factory-applied bonded dielectric coatings are not always defect-free and can be unknowingly damaged during installation, CP can be used to mitigate corrosion at coating holidays. As the coating ages and the exposed pipeline surface area increases, the CP current must be increased to maintain a consistent level of mitigation.

Surface preparation and coating application should follow manufacturer-approved procedures and applicable industry standards. Proper surface preparation is especially critical to ensure long-term adhesion and performance of bonded coatings on ductile iron surfaces, which may have different preparation requirements than steel. When using concrete pipe in severe soil environments with elevated chlorides, sulfates, acidic conditions, or other aggressive exposures, project teams may consider supplemental exterior barrier systems (e.g., epoxy or polyurethane) for RCP, RCPP, or PCCP as an additional protective measure. These systems, applied to the pipe exterior, may provide added resistance to chemical degradation where compatible with manufacturer capabilities and construction practices. Because Reclamation has limited data on these systems in buried applications at Reclamation projects, supplemental exterior barriers are considered optional, project-specific enhancements rather than part of the minimum recommendations in table 4.

3.3.3 Polyethylene Encasement

Polyethylene encasement is a dielectric material typically installed in the field 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 may provide 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 [31]. However, defects can persist through installation and be very difficult to detect. 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 [32]. 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.

Installation of polyethylene encasement and metalized zinc coatings requires careful consideration of environmental and construction factors. These systems are most effective in compatible backfill free of sharp or angular material that could puncture the encasement during installation. Because the corrosion mitigation these systems provide relies on a finite supply of sacrificial zinc, highly acidic soils, which accelerate zinc consumption, can shorten their effective service life. Designers should evaluate the use of bonded dielectric coatings in environments where severe acidity or aggressive installation conditions are anticipated.

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 and electrically isolated from other buried metallic structures and grounding systems to prevent excessive current drain and premature anode depletion. 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. All sections of buried pipe that are to be protected must be bonded for electrical continuity. 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.

ICCP systems can protect large or poorly coated structures with high current requirements and are more effective than GACP in high-resistivity soils. They can be installed in a deep-well anode bed configuration if a small footprint is required. Because ICCP systems operate at higher driving voltages than GACP, they require more design and operational attention, including monitoring of the power supply and evaluation for stray current interference on nearby foreign structures. Care should also be taken to avoid overprotection. Potentials that are driven too electronegative can result in cathodic disbondment of the coating and hydrogen evolution, which may lead to hydrogen embrittlement. This is a significant concern for high-strength steels, such as the prestressing wires used in PCCP, and can lead to sudden structural failure.

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 ferrous elements 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 [33]. Additionally, CP is required for all gas pipelines installed after July 31, 1971, with certain exceptions noted.
- The U.S. Department of Defense 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 [34]. This and other U.S. Army Corps of Engineers publications on soil classification and cathodic protection informed portions of this TM.

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 table 1 and table 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, 35]. 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 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 scores for each matrix were determined, an average of the overall scores was taken and used for weighing 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 C 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. the 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;
2. the proposed system consists of ductile iron pipe with a metalized zinc coating, polyethylene encasement, and CP; and
3. the requesting entity's engineer of record has evaluated, and the stamped request documents, the long-term compatibility of the zinc and polyethylene system with site-specific soil pH and anticipated backfill conditions.

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 [36, 31]. 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*. The independent peer review was performed by three subject matter experts selected through an external blind selection process: Cortney Chalifoux, Ph.D., P.E., PCS (Pond & Company); James A. Ellor, P.E. (Elzly Technology Corporation); and Andrew Haiko (CDM Smith). 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 [37, 38, 39, 40]. The results of this peer review were incorporated into this TM; the peer review reports are included as appendix B, and Reclamation's responses to the peer review comments are included as appendix C.

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Appendix A

Life-Cycle Cost Analysis for Buried Pipe

Appendix A: Life-Cycle Cost Analysis for Buried Pipe

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/RCPP), 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 replacement rates and deterioration patterns used in this appendix are intended as screening-level comparative assumptions rather than predictions of actual field service life. They allow for consistent, order-of-magnitude comparison among pipe materials, but should not be interpreted as service-life estimates for any specific pipeline.*

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). Because the underlying replacement and deterioration assumptions are screening-level rather than predictive, appraisal cost estimates produced using this approach 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.

Cost Estimates

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* [41, 42, 43].

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.

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.

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 on the construction of each pipeline material option and corrosion-related OM&R costs for the life cycle of 100 years.

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 Technical Memorandum.

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 de-mobilizing) 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.

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.
- **Appraisal-Level Quantity Logic:** Quantities used for the LCCA are developed using representative values and simplified units to facilitate a consistent comparison between different pipe materials. These estimates are intended to capture the relative requirements for typical line sections and necessary appurtenances based on standard design practices; they do not represent final construction quantities.

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 foot
Joints	Each
Casings	Linear foot, each
Miters	Linear foot, 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 foot, each

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)		2 replacements
High-density polyethylene (HDPE)		2 replacements
Ductile iron with polyethylene encasement and CP		26 replacements
Steel with bonded dielectric coating and CP		9 replacements
RCP/RCP with CP		1 replacement
PCCP with CP		4 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	30 minutes per rectifier	Every 3 months
Rectifier adjustment	2 hours per rectifier	Annually
Potential survey (all system types)	5 minutes per test station	Annually
Close interval potential survey (GACP and ICCP)	2 miles per hour	Every 5 years

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 [44, 45]. 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 ductile-iron (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]	3,293	379	8,137	1,877	816	1,943
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	1,903	458	1,397
Utah State all diameters (all failures/year/100 miles) [44, 45]	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 rate¹

Step	Calculation	PVC	HDPE	DI	Steel	RCP/ RCPP	PCCP
1	Total mileage for all pipe > 16-inch diameter	3,356	380	8,909	3,780	1,274	3,340
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

¹ Note: Doubling intervals and totals are calculated using full numerical precision in the underlying model. Values displayed in this table are rounded for presentation purposes, which may result in minor apparent discrepancies in manual cross-calculations.

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Appendix A

Table A-5.—Estimated corrosion-related replacement rate by pipe material to be used for LCCA¹

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 ²	2	2	26	9	1	4

¹ Note: Doubling intervals and totals are calculated using full numerical precision in the underlying model. Values displayed in this table are rounded for presentation purposes, which may result in minor apparent discrepancies in manual cross-calculations.

² 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

Independent Peer Reviewer Reports of Findings

(Conducted by third-party contractors in concurrence with the public review period)

REPORT

APRIL 2025

Independent Scientific Peer Review of TM 8540-2024-13 Corrosion Mitigation for Buried Metallic Water Pipe



Prepared for:

Bureau of Reclamation

AWARD #: 140R4026P0013





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Acronyms and Abbreviations (LFT Acronym Heading)

AMPP	Association for Materials Protection and Performance
ASTM	ASTM, International
CFR	Code of Federal Regulations
CP	Cathodic Protection
MIC	Microbiologically Induced Corrosion
NRC	National Research Council of the National Academies
PCCP	Prestressed Concrete Cylinder Pipe
PIPEiD	PIPELINE infrastructure DATABASE
SP	Standard Practice
SWIM	Sustainable Water Infrastructure Management



Executive Summary

The Bureau of Reclamation (Reclamation) constructs and manages hundreds of miles of pipelines in the 17 Western United States. As part of their design considerations, external corrosion of underground metallic piping is evaluated. In 2004, Reclamation created Technical Memorandum No. 8140-CC-2004-1 Corrosion Considerations for Buried Metallic Water Pipe in response to a House of Representatives Committee on Appropriations report as part of the 2004 Energy and Water Development Appropriations Act. This report 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.” The Technical Memorandum™ was finalized in July 2004, and has been in use since. Concerned third parties questioned the corrosion control requirements provided for Ductile Iron pipe in the 2004 TM leading to the National Research Council of the National Academies (NRC) to conduct a detailed and independent study of the 2004 TM in 2008 and 2009. This independent study supported Reclamations technical position while simultaneously recommending collection of additional data on pipeline reliability. As per a fiscal year 2012 Consolidated Appropriations Act conference report, Reclamation followed the NRC recommendation and evaluated pipeline reliability data for all pipe types discussed in the 2004 TM along with corrosion control measures thereof. As part of the evaluation, life-cycle costs, cost-effectiveness, and a general analysis of the economics was performed in conjunction with the pipe type performance. Virginia Polytechnic Institute and State University (Virginia Tech) was contracted to perform the study and produced Collection and Compilation of Water Pipeline Field Performance Data in April, 2021. This report was utilized as part of the revisions to the 2004 TM.

The 2004 TM was revised to draft Technical Memorandum No. 8540-2024-13 Corrosion Mitigation for Buried Metallic Water Pipe (TM 2024). TM 2024 is required by Federal law (Public Law 113-76 Section 203, subsection c) to include independent scientific review by appropriate Subject Matter Experts (SME) not employed or selected by the Bureau of Reclamation. CDM Smith was chosen to provide one of the SMEs to perform the Technical Peer Review of the draft TM 2004. An in-depth review of the draft TM 2024 and its associated reference material was performed, and a compilation of comments and recommendations created, along with this report which details the findings of the review. In addition, the draft TM 2024 was opened to public comments. CDM Smith reviewed the public comments as part of the evaluation and incorporated the information into a summary table for inclusion with this review.

The Peer Review was tasked with determining the answer to three main questions:

1. Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?
2. Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years?
3. Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?

The Peer Review indicated that there are adjustments which can be made to strengthen the criteria and weighting to further develop the consequences of pipe failure, and the Public Comments agreed that there are gaps which can be filled in the evaluation.

The ability to meet the minimum service life through the proposed corrosion control requirements left the most room for additional review, with the use of polyethylene encasement, with or without zinc coating, requiring further review and evaluation.

The Life Cycle Cost Analysis portion of the draft TM 2024 requires the least amount of review and revision, and was overall very well presented.



1.0 Introduction

The Bureau of Reclamation (Reclamation) undertook revision to their corrosion control guidelines to update Technical Memorandum Number (No.) 8140-CC-2004-1: Corrosion Considerations for Buried Metallic Water Pipe, which has been in use since 2004. Reclamation is moving from a soil resistivity-based methodology to a more robust approach which evaluates additional environmental and external factors along with soil analysis to create a risk-based approach to corrosion protection. The draft Technical Memorandum 8540-2024-13 Corrosion Mitigation for Buried Metallic Water Pipe (TM 2024) is required by Federal law (Public Law 113-76 Section 203, subsection c) to include independent scientific review by appropriate Subject Matter Experts (SME) not employed or selected by the Bureau of Reclamation. CDM Smith was chosen as one of the third parties to provide subject matter expertise in the review of the draft Technical Memorandum. This report details the Methodology, Key Findings, Conclusions, and Recommendations of the SME Peer Review undertaken by CDM Smith.



2.0 Methodology

The independent scientific review of the draft TM 2024 consisted of a multi-step process to determine the technical merit of the new process and to determine any gaps. The first stage was the review of the revised draft TM 2004 and its associated reference documentation. This review was of only the scientific information provided within the draft TM 2024 and how it complies with current industry standards; any decision-making and policy interpretation are sole responsibility of the Government. The next step of the review consisted of evaluation of the Public Review Comments and the backup information provided with the associated comments. A compiled matrix of the public comments was created and is included as part of the overall evaluation. These comments were used to provide additional clarity and to provide additional points of consideration within the technical review of the draft TM 2024, but were not individually scored in any way, and have not been incorporated as revisions to the document. A Comment Matrix was developed detailing the findings and recommendations of the review of the draft TM 2024, and will be discussed in detail in the following sections of this report. Particular emphasis was given to the following Review Questions:

4. Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?
5. Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years?
6. Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?



3.0 Key Findings

The following section discusses each of the findings from the technical review. A small portion of the comments are editorial in nature and will not include significant narrative response. Technical comments/recommendations will include additional information to clarify the reasoning behind each.

3.1 AMPP (Association for Materials Protection and Performance)

Add AMPP (Association for Materials Protection and Performance) to the list of Acronyms and Abbreviations.

3.2 National Association of Corrosion Engineers

Remove NACE from the Acronym and Abbreviations list. Conversely, keep NACE, but reference that the Association is now AMPP, since AMPP still references both NACE and SSPC standards. Do not say that NACE is the National Association of Corrosion Engineers, though, as that is not accurate. It can be written as "NACE International (formerly the National Association for Corrosion Engineers)"

3.3 Stray Current

Revise "Stay" to "Stray" in Table 1

3.4 Table 1 – Stray Current

Under "Other Considerations", stray current can have profound effects on corrosion, and is known to be significantly more aggressive than any soil parameters in areas of significant stray current levels. Steel/ductile iron can lose up to 20 pounds per amp per year from corrosive discharge. While dynamic stray current (from dc powered transit systems) fluctuates over time, and do not present continuous discharge as the effects are dependent upon vehicle headways, they also can discharge hundreds of amperes off of metallic structures, which leads to very rapid deterioration, as stray current effects typically discharge off of a very small area. Static stray current does not typically carry such heavy loads, but is a continuous discharge concern. Ranking of stray current 0-5 underestimates stray current effects significantly. Reconsider stray current as its own line item, rather than part of "Other Considerations".

3.5 Table 2

The Points value column numbers do not align with the Value descriptions, making it difficult to read the correlations correctly between the columns. For example, the row for Redundancy has spaced the Points column to match with the Value column. Align the two columns for clarity.

3.6 Table 4 - Pipe Group B

The use of cathodic protection with polyethylene encasement is debatable. A non-bonded system may shield the pipe from the cathodic protection, and active corrosion may occur beneath the polyethylene encasement which may preclude the CP from preventing the corrosion due to the shielding. Pipe group B seems to be of such a level that consideration should be given to also require a bonded coating system

and cathodic protection to ensure the desired 100 year design life in lieu of utilizing polyethylene encasement.

3.7 Table 4 – Pipe Group B

Ductile iron with metallized zinc coating and polyethylene encasement with cathodic protection is NOT equivalent to steel with a bonded coating and cathodic protection. Neither the Code of Federal Regulations (49 CFR - Part 192 (Gas) and Part 195 (Hazardous Liquids)) nor NACE SP-0169 discuss the use of non-bonded coating systems. The CFR does not allow its use, and requires bonded coating systems. Reconsider the allowance of a non-bonded coating system with the use of cathodic protection.

3.8 Table 4 - Pipe Group C and Pipe Group D

The use of a bonded dielectric coating for the steel piping without also using cathodic protection may create localized corrosion at coating faults (holidays). Bonded coatings are an effective means of preventing corrosion only where the coating is effective. At locations of coating faults (holidays) or other damage (such as from backfilling operations) active corrosion may occur at locations where the coating is no longer effective. As these areas are typically very small, rather than a general corrosion attack, a localized attack may occur which may lead to rapid corrosion. The cathodic protection (CP) system is designed to protect these areas from corrosion. Without CP, the bonded dielectric coating may actually create a worsened condition than having bare pipe due to the localized corrosion attack. Always include cathodic protection with bonded coating application.

3.9 Ferrous Elements

The Summary sections uses the terminology "ferrous elements" rather than reinforcing steel (1.0 Introduction). "Ferrous elements" is a more accurate term, as it includes elements such as strands, where "reinforcing steel" typically brings to mind rebar in particular, rather than all types of ferrous reinforcement. Recommend revising "reinforcing steel" to "ferrous elements".

3.10 Barnes Layer Analysis

It is recommended that ASTM G57 be used in conjunction with Barnes Layer Analysis (Soil Investigation Employing A New Method of Layer-Value Determination for Earth Resistivity Interpretation/Peabody) to determine the layer resistivity rather than point resistivities. Point resistivities do not take into consideration the affects that layering of soils have on the corrosivity. The layer resistivity may show significantly more corrosivity than just the point values at depth due to changes in the soil content as the depths change. The single data point at pipe depth may be considered in one of the non-aggressive ranges, whereas the layer resistivity between data points in which the pipe is installed (for example - if the pipe is installed at 4 foot depth, the layer analysis between 2.5 feet and 5 feet) may fall into one of the corrosive soil categories. Utilize the Barnes Layer Analysis rather than only relying on the point resistivity readings to ensure the most corrosive soil levels are evaluated.

3.11 Soil Layering Effects

The 10-percent soil resistivity statistical method does not consider layering effects, as discussed in the previous comment. As discussed, the effects of layering on soil corrosivity should be considered. Utilize

the Barnes Layer Analysis rather than only relying on the point resistivity readings to ensure the most corrosive soil levels are evaluated.

3.12 Peabody, Control of Pipeline Corrosion

There is a new Edition of Peabody - "Peabody, Control of Pipeline Corrosion, Third Edition". It is recommended to review the latest edition of the document to ensure that there have been no changes.

3.13 Backfill

If using the existing soils as backfill, the various soil compositions will also intermix, which can increase the corrosivity from what was anticipated/measured. Intermixing of backfill materials may lead to altered soil conditions from what was measured initially, as the backfilling procedure will mix the existing soil layers into new compositions. This can change the corrosivity of the localized soils. Add a discussion on the effects of soil intermingling due to backfilling operations.

3.14 New Section 3.1.6.6 Adjacent Property Review

A historical review of adjacent properties can uncover significant conditions which may affect the corrosivity of the soil, if not now, in the near future, which otherwise may not been found during the initial field testing. Having the foreknowledge of future corrosivity concerns provides the ability to address these concerns during the design phase

3.15 Coated Piping with No Cathodic Protection (CP)

Coated pipe with no CP can lead to accelerated localized corrosion at holidays, even in relatively non-corrosive soils. The use of bonded coatings without CP may lead to localized corrosion at locations of holidays/coating failure. Include CP with all bonded coatings.

3.16 Polyethylene Encasement

The use of Polyethylene Encasement does not always provide better mitigation than bare pipe. There are existing studies where accelerated corrosion occurred underneath the polyethylene encasement in soil conditions which would not have otherwise been considered aggressive (An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe. Jul 17, 2008 Michael J Szeliga - for example). Revise to state "may provide better protection".

3.17 Cathodic Protection

For galvanic CP, the sections must also be isolated for the CP to be effective. A grounded section with galvanic CP applied will rapidly deplete the sacrificial anodes due to large cathode/small anode effects. Include a statement that the section to be protected using galvanic CP must be electrically isolated.

3.18 Cathodic Protection – Impressed Current

Hydrogen embrittlement concerns exist for prestressing cables in PCCP pipe. Too much cathodic protection can cause a condition known as Hydrogen Embrittlement. The diffusion of hydrogen into the material from the cathodic reduction reaction can cause the reduction of ductility and fracture toughness in metals (primarily high-strength steels). Stresses on the structure can then cause

unanticipated failure modes. Include a statement on the effects of overprotection from Impressed Current Cathodic Protection systems.

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

Suggest limiting this to exclude Pipe Group A (and possibly B) and other pipes with high consequence of failure. Polyethylene encasement alone may not provide adequate levels of corrosion control for critical infrastructure, no matter the entity to be the ultimate owner. Critical piping systems in corrosive conditions should not be provided the opportunity to lower the corrosion control requirements. Exclude piping in Group A (and possibly B) along with other pipes with high consequence of failure.

3.20 Table A-1 Cable and Wire Supplies for Joint Bonds

Confirm how these values are calculated in linear feet. There are typically two bonds at each pipe joint, located every 20 feet (typically), but appurtenances (valves, tees, crosses, etc.) will require different lengths and numbers of bond cables. How are the appurtenances factored into the per foot calculation? The length of bond cables and weld supplies will vary greatly depending on the number of bends, valves, tees, etc. included in the piping system. A general linear foot length of pipe may greatly underestimate the actual required materials. Clarify how these are calculated.

3.21 Table A-2 Operating, Maintenance, and Inspection Costs

How is travel time built into this? Depending on the location, there may be difficulty accessing locations. The ability to both access and find rectifiers and test stations should be considered in the time calculations. The timing at each locations seems reasonable, but the time to get from location to location and/or find/access the locations should be factored into the calculations. Include other factors into the anticipated time for each location.

3.22 Table A-2. Potential Survey (All System Types)

Are all test stations to be monitored periodically, or only a select few repeated yearly to track changes over time? What is the anticipated schedule - all test stations each survey, all test stations on a rotating basis, or select test stations repeated annually? This will factor into the ease of locating the test stations annually. If rotating, finding test facilities after many years will add difficulty and increase the time needed for each location. Clarify the proposed test procedure for the surveys.

3.23 Table A-4 / Table A-5

Assuming there are rounding errors. For example: 0.004 should double to 0.008, then 0.016, 0.032, and 0.064. Typical comment for Table A-4 and Table A-5. The number of significant digits used in the calculations does not match the data presented in the tables. Clarify the tables/significant digits utilized.



4.0 Conclusions

The review of the draft TM 2024 was to consider three questions:

1. Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?
2. Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years?
3. Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?

4.1 Criteria and Weighting

In general, the process used to determine the criteria and weighting used to categorize soil corrosivity and consequences of pipe failure was well thought out and provided a strong sampling of concern outside of just soil resistivity and considers other elements which may lead to premature failure for buried metallic piping. There exists room to make the process stronger, however. As discussed in Section 3.4, above, stronger weighting for stray current corrosion may be warranted. In addition, the Public Comments indicate that Microbiologically Induced Corrosion (MIC) may also require further consideration. Consideration should also be given to utilizing additional analysis tools to determine soil resistivity, including the Barnes Layer Analysis as discussed in Section 3.11. Public comments also present concerns with how dependent the draft TM 2024 is on the Design Decision Model and its proprietary process. Other Public Comments refer to concerns with the usage of the Virginia Tech SWIM PIPEiD reports in determining the failure rate data utilized in the draft TM 2024.

4.2 Minimum Service Life

In most cases, the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years for Pipe Group A. The exception is the allowance for 3.18 Client Requested Deviation from Corrosion Mitigation Minimum Recommendations for Ductile Iron Pipe, as discussed in Section 3.18, and in the Public Comments. It is highly recommended that for Pipe Group A this variance not be allowed in order to reliably provide a minimum service life of 50 to 100 years. Consideration of the same should also be given to pipe Group B and other locations which would have significant consequence of failure. The use of non-bonded coating systems for Pipe Group B should also be reconsidered, as discussed in Section 3.7 and in the Public Comments, as there is mixed historical data on the use of polyethylene encasement, with or without CP, and the use of metallized zinc coating with polyethylene encasement, while researched, does not have a long historical record. For Pipe Groups C and D, the use of a bonded coating without cathodic protection may accelerate localized corrosion at holidays, and the additional cost of adding supplemental cathodic protection to these pipe groups should be taken under advisement to provide for the proposed design life.

4.3 Life Cycle Cost Analysis

The estimated replacement rates proposed for Life Cycle Cost Analysis are in general appropriate. Sections 3.19, 3.20, and 3.20 provide additional considerations for review of the costs for various cathodic protection materials and testing. Additionally, the Public Comments include areas where further evaluation may be warranted to provide more accurate costing information. This area of the report was well developed, and does not require significant further reevaluation from what is presented.



5.0 Recommendations

The following presents the recommendations for additional review of the draft TM 2024:

5.1 AMPP (Association for Materials Protection and Performance)

Add AMPP (Association for Materials Protection and Performance) to the list of Acronyms and Abbreviations.

5.2 National Association of Corrosion Engineers

Remove NACE from the Acronym and Abbreviations list or revised to reference that the Association is now Association for Materials Protection and Performance (AMPP).

5.3 Stray Current

Revise “Stay” to “Stray” in Table 1

5.4 Table 1 – Stray Current

Reconsider stray current as its own line item, rather than part of "Other Considerations".

5.5 Table 2

Align the Points Value and Value Descriptions columns for clarity.

5.6 Table 4 - Pipe Group B

Provide consideration for Pipe Group B to also require a bonded coating system and cathodic protection to ensure the desired 100 year design life in lieu of utilizing polyethylene encasement.

5.7 Table 4 – Pipe Group B

Reconsider the allowance of a non-bonded coating system with the use of cathodic protection.

5.8 Table 4 - Pipe Group C and Pipe Group D

Include cathodic protection with bonded coating application.

5.9 Ferrous Elements

Recommend revising "reinforcing steel" to "ferrous elements".

5.10 Barnes Layer Analysis

Utilize the Barnes Layer Analysis rather than only relying on the point resistivity readings to ensure the most corrosive soil levels are evaluated.

5.11 Soil Layering Effects

Utilize the Barnes Layer Analysis rather than only relying on the point resistivity readings to ensure the most corrosive soil levels are evaluated.

5.12 Peabody, Control of Pipeline Corrosion

Review the latest edition of the document to ensure that there have been no changes.

5.13 Backfill

Add a discussion on the effects of soil intermingling due to backfilling operations.

5.14 New Section 3.1.6.6 Adjacent Property Review

Add a new Section 3.1.6.6 Adjacent Property Review. Text to read “When building new pipelines, conduct an EPA ECHO search of adjacent properties. Check FRS registry records. Any industrial properties that could have coal residue (mining), broken concrete (old pipe factory and/or pre-caster sites). A GeoTech engineer should investigate for leach fields from old factory properties, investigate for tree root oxidation, and leaching from clay bottom ponds and land fills.” or similar.

5.15 Coated Piping with No Cathodic Protection (CP)

Include CP with all bonded coatings.

5.16 Polyethylene Encasement

Revise to state that use of polyethylene encasement “may provide better protection”.

5.17 Cathodic Protection

Include a statement that the section to be protected using galvanic CP must be electrically isolated.

5.18 Cathodic Protection – Impressed Current

Include a statement on the effects of overprotection from Impressed Current Cathodic Protection systems.

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

Exclude piping in Group A (and possibly B) along with other pipes with high consequence of failure.

5.20 Table A-1 Cable and Wire Supplies for Joint Bonds

Clarify how the per foot costs are calculated.

5.21 Table A-2 Operating, Maintenance, and Inspection Costs

Include other factors into the anticipated time for each location.

5.22 Table A-2. Potential Survey (All System Types)

Clarify the proposed test procedure for the surveys.

5.23 Table A-4 / Table A-5

Clarify the tables/significant digits utilized.

5.24 Public Comments

Review the Public Comments for additional subject matter expertise not provided in the Independent Scientific Peer Reviews to evaluate for inclusion in the draft TM 2024.

REPORT OF FINDINGS

Independent Scientific Peer Review of TM 8540-2024-13 Corrosion Mitigation for Buried Metallic Water Pipe

Award Number: 140R4026P0015

Pond & Company Project No.: 1260178

Date: April 20, 2026

Prepared For:

United States Bureau of Reclamation



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EXECUTIVE SUMMARY

Pond performed a technical review of Technical Memorandum No. 8540-2024-13 Corrosion Mitigation for Buried Metallic Water Pipe (TM 8540-24), which is a revision of Technical Memorandum No. 8140-CC-2004-1 (2004 TM). TM 8540-24 adopts a multi-factor risk-informed framework that evaluates multiple corrosivity factors together with consequence of failure, then links those results to minimum corrosion mitigation measures for steel pipe and appurtenances, ductile iron pipe, and reinforced/prestressed concrete pipe. This approach is consistent with the literature reviewed and provides a stronger basis for corrosion mitigation decisions than 2004 TM. Pond's review supports the overall framework in TM 8540-24, and identifies several areas where technical accuracy, transparency, and consistency of application can be refined.

The review supports the structure of the scoring framework for soil corrosivity and consequences of pipe failure determination to determine the minimum corrosion control recommendations for underground water pipe. TM 8540-24 also includes the use of conditional service-life expectations and a life-cycle cost analysis as a planning tool. The principal opportunities for improvement of TM 8540-24 include more specific treatment of material-dependent corrosion mechanisms, clearer scoring guidance for "other considerations," and stronger treatment of severe environments for concrete pipe systems. The life-cycle cost analysis for buried pipe (TM 8540-24 Appendix A), could also be improved by either considering the analysis as a screening tool only, or incorporating and citing more corrosion-based data in the assumptions made. Those refinements would strengthen the document without changing its overall approach.

The review also finds that long service life is supportable when the selected mitigation system is matched to the material and environment and the project is executed with high-quality design, installation, operation, monitoring, and maintenance. However, the 50-year service life goal for ductile iron pipe in severe soil, cannot be confirmed based on the data that has been collected.

1 INTRODUCTION

Pond's Principal and Program Director, Cortney Chalifoux, PhD, PE, PCS, performed a technical review of Technical Memorandum No. 8540-2024-13 Corrosion Mitigation for Buried Metallic Water Pipe (TM 8540-24). TM 8540-24 was prepared and extensively reviewed by corrosion and pipeline experts internally within the Government. Pond's review is a final peer review to ensure technical merit and alignment with current industry practices. This is a single review cycle, and there will not be feedback from the Government with follow-up review from Pond.

1-1 SCOPE OF THE REVIEW

Pond was retained to review TM 8540-24 against current state of the practice in corrosion prevention and control. Dr. Chalifoux performed a general review of the technical merit of the document and provided comments and recommendations in this report both in narrative and matrix form. The findings include responses to the following Review Questions provided by the Bureau of Reclamation as well as additional recommendations:

- Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?
- Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years?
- Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?

Concurrently with Pond's review, the Government conducted a public review of TM 8540-24. Comments collected by the government from the public were used as reference to this document and were only included where relevant.

Pond delivered their findings through this report, which includes Pond's methods of evaluation, responses to curated questions, and recommendations both in matrix and narrative form.

1-2 LIMITATIONS

The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Pond's comments and recommendations are based solely on the scientific information provided and how the information complies with current industry standards. Pond did not address any decision-making and policy interpretation, as that is sole responsibility of the Government. The scope of services performed may not adequately address the needs of other users of this data, and any re-use of this information is at the sole risk of the user. No guarantee or warranty as to future life or performance of systems is expressed or implied. Every effort has been made to accurately and completely review all areas of concern during the technical assessment. If there are perceived omissions or misstatements in this report regarding any aspect of this work, Pond asks that they be brought to our attention as soon as possible so that we can fully address them.

2 METHODOLOGY

Dr. Chalifoux performed an independent technical review of TM 8540-24 referencing current scientific publications, industry best practices, and her individual knowledge and experience. Dr. Chalifoux's review began with a thorough review of the technical content and references included in TM 8540-24.

All documents were reviewed for technical content and relevance. Next, Dr. Chalifoux performed an independent literature review to identify any additional relevant studies that were not included in the memorandum. Relevant documents were used to generate scientific backed responses to the review questions and generate additional recommendations for TM 8540-24. Finally, Dr. Chalifoux reviewed the public's comments and incorporated any relevant findings into the review. All additional comments and recommendations are included in the Comment Matrix, as included in this report as Appendix A.

3 KEY FINDINGS

TM 8540-24 is consistent with the current studies and publications in that it moves away from a soil-resistivity-only method and toward a multi-factor framework that combines corrosivity drivers with consequence of failure. That shift is technically justified and materially improves the document. Targeted revisions should still be considered to improve technical accuracy (based on current literature), increase transparency, and better distinguish between material classes.

3-1 REVIEW QUESTION RESPONSE

The technical and literature-based responses to each of the Bureau of Reclamations review questions are provided below.

3-1.1 Criteria and Weighting

Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?

Response: Yes, in structure. The multi-factor scoring system is supported by the current literature reviewed.

3-1.1.1 Soil Corrosivity Criteria and Weighting

TM 8540-24 expressly adopts a risk-informed approach that scores soil resistivity, chloride content, sulfate content, soil pH, drainage class, and other considerations including but not limited to stray current, microbiological influenced corrosion (MIC), exiting structure performance, backfill, and wet-dry cycling. These factors are scored separately from consequence of failure. The tool then combines the results of soil resistivity and consequence of failure categories through a pipe-group matrix. The weighting methodology was developed using a decision-matrix process, compared with literature and industry practice, and checked using independent and Government funded case studies.^{1,2} The structure is consistent with current literature showing that corrosion in buried pipe depends on multiple interacting variables rather than any single soil property. Improvements can be made to the soil corrosivity category criteria and weighting in two ways.

First, sulfate values do not align with literature regarding the severity points scale. Peabody classifies 10,000 ppm or greater as a severe degree of corrosivity in buried steel pipe.³ The American Concrete Institute (ACI) 201.2R-10⁴ classifies 10,000 ppm or greater as a Class 3 concrete exposure, which is the

¹ B. Rajani and Y. Kleiner, "Protection of Ductile Iron Water Mains Against External Corrosion: Review of Methods and Case Histories," *Journal of the American Water Works Association*, vol. 95, no. 11, pp. 110-125, 2003. [Ref. 2]

² S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

³ A. Peabody, *Peabody's Control of Pipeline Corrosion*, 2 ed., Houston, TX: NACE International, 2001. [Ref. 4]

⁴ American Concrete Institute, "ACI 515.2R-13: Guide to Selecting Protective Treatments for Concrete," 2013. [Ref. 5]

highest exposure in concrete. Table 1 indicates that the most severe soil corrosivity (ranking of 5) is greater than 20,000 ppm. TM 8540-24 should lower this limit to 10,000 ppm to be aligned with the literature. Sulfates are chemically harmful and highly corrosive to both metals and concrete in soils, additionally they can be converted directly to sulfides by anaerobic sulfate reducing bacteria (SRB) and contribute to MIC.⁵

Secondly, the current 0–5 “other considerations” rating combines stray current, MIC, existing structure performance, backfill, and wet-dry cycling into one category. TM 8540-24 is correct to include those factors, but the literature shows that they are not minor variables.^{6,7} Those factors should remain in the framework, but they would be more technically useful if scored separately and more transparently.

3-1.1.2 Consequence of Failure Criteria and Weighting

The consequence of failure categories in TM 8540-24 are appropriate for a high-level prioritization framework for underground water pipelines. The factors used in TM 8540-24 Table 2, location, pipe diameter, redundancy, pressure, water-delivery needs, and other considerations, are reasonable indicators of how disruptive a failure would be, how difficult it would be to repair, and how broadly the effects would be felt. On that basis, the consequence framework is sound in structure.

One improvement would be to update the matrix to address the different consequences of failure by material or expected failure mode. The consequence of failure for localized leaking, the most common external corrosion failure mode in low pressure water steel and ductile iron piping, will be much lower than the consequence of failure by a catastrophic rupture of a prestressed concrete pipe. The critical consequence of a catastrophic rupture is not captured in the criteria, weighting, or pipe group matrix.

The consequence-of-failure criteria should also account for the presence of adjacent utilities with active cathodic protection systems. The consequence of pipe failure rating should be elevated where a proposed water line (or its cathodic protection system) could interfere with the corrosion protection on an existing protected utility, such as a gas pipeline, because the potential effects extend beyond the new water line and may create unanticipated corrosion, operational, and public-safety risks on neighboring infrastructure. An additional category, or inclusion under “Other considerations” could address this recommendation.

3-1.2 Minimum Service Life

Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years?

Response: Yes, conditionally, for all but ductile iron in high or severe soil corrosivity.

Given appropriate design quality, installation quality, correct operating conditions, and long-term monitoring and maintenance, the corrosion-mitigation approach in TM 8540-24 can support a service life on the order of 50 to 100 years based on the reviewed literature, except for ductile iron in high or severely corrosive soil. In several of the published risk-based models, the minimum corrosion mitigation

⁵ H. M. Farh, M. E. A. Ben Seghier, R. Taiwo and e. al., "Analysis and Ranking of Corrosion Causes for Water Pipelines: A Critical Review," *npj Clean Water*, vol. 6, p. 65, 2023. [Ref. 6]

⁶ A. Spark, K. Wang, I. Cole, D. Law and L. Ward, "Microbiologically Influenced Corrosion: A Review of the Studies Conducted on Buried Pipelines," *Corrosion Reviews*, vol. 38, no. 3, 2020. [Ref. 7]

⁷ H. M. Farh, M. E. A. Ben Seghier, R. Taiwo and e. al., "Analysis and Ranking of Corrosion Causes for Water Pipelines: A Critical Review," *npj Clean Water*, vol. 6, p. 65, 2023. [Ref. 6]

recommendations in TM 8540-24 exceed the published risk-based models and the corresponding corrosion rates would provide a minimum service life of 50-100 years for all materials.^{8,9,10} Moreover, the requirement for corrosion monitoring or cathodic protection on all metallic pipelines in TM 8540-24 supports high-quality operation, maintenance, and early corrosion remediation, which will contribute to a 50-to-100-year service-life expectation.

The one qualification to the 50-year service-life discussion applies to ductile iron pipe in severe and highly corrosive soils, as represented by TM 8540-24 as Pipe Groups A and B. The National Research Council of the National Academies (NRC) found that polyethylene (PE) encasement with cathodic protection (Pipe Group B) was not likely to provide reliable 50-year service under those corrosion mitigation and high and severe soil corrosivity conditions. Although the report identified bonded dielectric coating with cathodic protection (Pipe Group A) as the more effective alternative, it concluded that the currently available studies were insufficient to confirm that this system would reliably achieve the 50-year benchmark.¹¹ It is important to note that the NRC explicitly stated that it did not perform an economic analysis. It is possible that properly applied bonded dielectric coatings with CP could produce a 50-year service life and be a more cost-effective corrosion mitigation strategy than PE encasement with a zinc coating in high and severe soil corrosivity; More studies are needed to support this conclusively.

3-1.3 Life Cycle Cost Analysis

Are the estimated replacement rates proposed for Life Cycle Cost Analysis (LCCA) appropriate?

Response: The replacement rates are appropriate as screening-level comparative assumptions for life-cycle cost analysis, but not as validated forecasts of actual corrosion-driven replacement rates for each pipe material and site condition.

The main limitations with the replacement rate methods are within two of the underlying assumptions. First, the data sets used were normalized to rates of failures of ductile iron pipe, which may not be consistent with failure rates in new materials nor the expected failure rates of other material groups with appropriate corrosion mitigation strategies. Second, the rate of replacement is assumed to double every 10 years after the first 50 years of service. These assumptions do not provide a corrosion-driven estimate, but rather a screening tool based on needs to organize data available. Details of the two assumptions are described below.

3-1.3.1 Normalizing the datasets

TM 8540-24 states that the only corrosion-specific failure dataset used was the NRC which only includes ductile-iron pipe that was in service for less than 50 years.¹² The broader all-material failure data came

⁸ H. M. Farh, M. E. A. Ben Seghier, R. Taiwo and e. al., "Analysis and Ranking of Corrosion Causes for Water Pipelines: A Critical Review," *npj Clean Water*, vol. 6, p. 65, 2023. [Ref. 6]

⁹ M. D. Gaston, "The Everglades as Host to Zinc Coated Ductile Iron Pipe," in *Proceedings of CORROSION 2020*, Houston, TX, 2020. [Ref. 8]

¹⁰ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

¹¹ National Research Council, "Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe," Washington, DC, 2009. [Ref. 9]

¹² B. Rajani and Y. Kleiner, "Protection of Ductile Iron Water Mains Against External Corrosion: Review of Methods and Case Histories," *Journal of the American Water Works Association*, vol. 95, no. 11, pp. 110-125, 2003. [Ref. 2]

from the Virginia Tech report,¹³ but includes failures that are not due to corrosion alone. Specifically, the Virginia Tech report indicates that 92% of ductile iron failures and 88% of PCCP failures were attributed to manufacturing defects. A study from Utah State provided data on water main breaks through 2023, but did not include PCCP/RCP/RCPP; TM 8540-24 Appendix A substitutes the reported failures of concrete steel cylinder (CSC) pipe for RCP/RCPP in their dataset.¹⁴ In an attempt to obtain a failure rate limited to corrosion-related failures based on a compilation of all data, TM 8540-24 Appendix A normalized all of the failure rates to the ductile iron corrosion-specific rate provided in the NRC data set.

The first recommendation would be to extract data that is more representative of corrosion related failures, and separate the data based on material. Additionally, where corrosion related failures are accounted for, the environmental severity combined with the method of corrosion mitigation has not been normalized for in these data sets. It is possible that some corrosion mitigation strategies were below the minimum requirements set forth in TM 8540-24, and failed prematurely. For example, ductile iron pipe with bonded dielectric coating and CP, will behave considerably differently than uncoated ductile iron piping in the same soil corrosivity category.

Historical corrosion mechanisms in ductile iron pipe (graphitic corrosion)¹⁵ and prestressing wire failures in PCCP¹⁶ have been addressed and generally mitigated by modern manufacturing of these materials. These failures could also have been categorized by the “manufacturing defects”, though it is unclear by the text in the Virginia Tech study.¹⁷ The historic failure rates could be artificially higher than failure rates in modern piping materials.

Finally, there is no reference to what type of operational maintenance or monitoring was used for these failures. Both of which could contribute to failures that are either not associated with corrosion mitigation or could have been mitigated with appropriate corrosion mitigation strategies.

3-1.3.2 Doubling the Failure Rate Every 10 Years After 50 Years

The second assumption lies in the way the failure rate was predicted after the first 50 years. Appendix A assumed the corrosion-related failure rate was static for the first 50 years and doubled every 10 years from 50 to 100 years. Based on that assumption, the number of fractional failures was determined and rounded up to cover the replacement of 20-foot sections.

The assumed post-50-year doubling rule should be treated as a scenario assumption, not a generally validated rule for corrosion-driven failure. TM 8540-24 adopts that escalation because the NRC pipelines were in service for less than 50 years and an increase with age was expected. That is a reasonable planning choice, but the literature reviewed in this document does not establish a universal decade-by-decade doubling relationship for all pipe materials and environments. Rajani and Kleiner describe several cathodic-protection case histories in which failure rates were reduced or stabilized after intervention. It is possible that with cathodic protection or corrosion monitoring, failure rates could be lower than historically measured.

¹³ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

¹⁴ S. Folkman, "Water Main Break Rates in the USA and Canada: A Comprehensive Study," Logan, UT, 2018. [Ref. 10]

¹⁵ E. Larkin, M. Zamanzadeh, A. Ulmer, N. Pace and A. K. Chikkam, "Watermain Breaks – Materials Does Matter," in *AMPP Conference*, Denver, CO, 2023. [Ref. 11]

¹⁶ R. Nixon, "Conducting Precast Concrete Cylinder Pipe Condition Assessment by Matching Corrosion Damage Mechanisms to Diagnostic Methods," in *AMPP Conference Proceedings*, San Antonio, TX, 2022. [Ref. 12]

¹⁷ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

Moreover, a sensitivity assessment can be performed or included to show that the absolute number of replacements are being driven in large part by the assumed post-50-year deterioration path rather than by the base replacement data alone. An example of the basis of a sensitivity analysis is shown in the table below. Holding all other assumptions constant, delaying the start of escalation from year 50 to year 60 reduces the estimated 100-year corrosion-related replacement burden by about 46%, while reducing the decadal multiplier from 2.0x to 1.5x reduces it by about 63%, and to 1.25x reduces it by about 77%. Appendix A therefore appears to model age-based replacement frequency, not corrosion kinetics. This type of sensitivity study could be incorporated into the document to provide a more customizable use of the data.

Scenario	Escalation starts	Decadal multiplier after start	Purpose
Base case (Appendix A)	50 years	2.0x	Current Appendix A assumption
Low deterioration	60 years	1.5x	Tests slower aging
Managed system	50 years	1.25x	Tests effect of effective monitoring/maintenance
High deterioration	40 or 50 years	2.5x	Tests aggressive aging / poor field performance

In summary, the methods used in Appendix A of TM 8540-24 should be reassessed or clarified, because as presented the pipe replacement rates do not appear to align with corrosion related failures.

3-2 OTHER RECOMMENDATIONS

3-2.1 Pipe Group A: Supplemental Exterior Protection for RCP/RCP and PCCP

For severe environments, TM 8540-24 should consider supplementing the current Pipe Group A RCP/RCCP and PCCP recommendation with an exterior barrier system rather than relying only on inhibitor in the pipe wall or mortar coating alone. TM 8540-24 currently specifies corrosion inhibitor in the mix design for RCP/RCP or in the mortar coating for PCCP, together with CP. The American Concrete Pressure Pipe Association (ACPPA) identifies high chlorides, high sulfates, severe acid conditions, and stray current as adverse environments for concrete cylinder pipe,¹⁸ and ACI 515.2R states that one established method of mitigating chemical attack is to isolate concrete from the aggressive agent by using a suitable coating, overlay, lining, or barrier.¹⁹ Other literature also indicates that durability of underground reinforced concrete pipe depends on chloride ingress, sulfate or acid exposure, and transport conditions at the steel-concrete interface.^{20,21} In severe environments, a supplemental exterior barrier should therefore be evaluated as part of the minimum system.

¹⁸ American Concrete Pressure Pipe Association, "External Protection of Concrete Cylinder Pipe: Guidelines for Supplemental Protection of Pipelines in Adverse Environments," 2011. [Ref. 15]

¹⁹ American Concrete Institute, "ACI 515.2R-13: Guide to Selecting Protective Treatments for Concrete," 2013. [Ref. 5]

²⁰ R. Nixon, "Conducting Precast Concrete Cylinder Pipe Condition Assessment by Matching Corrosion Damage Mechanisms to Diagnostic Methods," in *AMPP Conference Proceedings*, San Antonio, TX, 2022. [Ref. 12]

²¹ Q. D. Nguyen and A. Castel, "Long-Term Durability of Underground Reinforced Concrete Pipes in Natural Chloride and Carbonation Environments," *Construction and Building Materials*, vol. 394, 2023. [Ref. 14]

Figure 1 provides a table with ACI's recommended protective barrier systems for concrete in mild, intermediate, and severe environments.²² All soils are considered "mild" severity for concrete. A polyurethane or epoxy would be a good solution to prevent against acidic soils and ion contamination.

Table 7.1—Protective barrier systems—General categories (from ACI 515.1R)

Severity of chemical environment	Total nominal thickness range	Typical protective barrier systems	Typical but not exclusive uses of protective systems in order of severity
Mild	Under 40 mil (1 mm)	Polyvinyl butyral, polyurethane, epoxy, acrylic, styrene-acrylic copolymer asphalt, coal tar, chlorinated rubber, vinyl, neoprene, coal-tar epoxy, coal-tar urethane	• Protection against deicing salts • Improve freezing-thawing resistance • Prevent staining of concrete • Use for high-purity water service • Protect concrete in contact with chemical solutions having a pH as low as 4, depending on the chemical
Intermediate	125 to 375 mil (3 to 9 mm)	Sand-filled epoxy, sand-filled polyester, sand-filled polyurethane, bituminous materials	• Protect concrete from abrasion and intermittent exposure to dilute acids in chemical, dairy, and food-processing plants
Severe	20 to 250 mil (1/2 to 6 mm)	Glass-reinforced epoxy, glass-reinforced polyester, procured neoprene sheet, plasticized polyvinyl chloride sheet	• Protect concrete tanks and floors during continuous exposure to dilute material (pH is below 3), organic acids, salt solutions, strong alkalies
Severe	20 to 280 mil (1/2 to 7 mm) Over 250 mil (6 mm)	Composite systems: (a) Sand-filled epoxy system topcoated with a pigmented but unfilled epoxy (b) Asphalt membrane covered with acid-proof brick using chemical-resistant mortar	• Protect concrete tanks during continuous or intermittent immersion, exposure to water, dilute acids, strong alkalies, and salt solutions • Protect concrete from concentrated acids or combinations of acids and solvents.

Figure 1: Table 7.1 showing the protective barrier systems for concrete. Soil is considered a mild chemical environment for concrete.²³

3-2.2 Clarify Material-Specific Corrosion Mechanisms and Protection Systems

Section 2.1 of TM 8540-24 states that steel, ductile iron, and cast iron corrode at similar rates in similar soils. In context, however, that statement is too broad for a corrosion-mitigation framework because it can be read as implying that these materials behave similarly from a design and protection standpoint. The failure modes and mechanisms for water pipe failure differ depending on material and environment.²⁴ TM 8540-24 itself distinguishes corrosion mitigation systems for each material: steel is fundamentally protected with a bonded dielectric coating plus cathodic protection system; ductile iron can be protected with bonded coatings plus cathodic protection system, a polyethylene encasement, or zinc-plus-polyethylene encasement depending on severity; and RCP/RCP and PCCP rely primarily on the alkalinity of concrete or mortar to maintain embedded steel or prestressing wire in a passivated condition, with bonding, monitoring, or cathodic protection and supplemental inhibitors when the passivating environment may be compromised. Making the distinction between corrosion mechanisms and protection mitigation designs for each material explicit in the main text would better align Section 2.1 with the remainder of TM 8540-24 and would strengthen the weighting discussion in Section 3-2 and the service-life discussion in Section 3-3.

3-2.3 Requirement for Shorting Straps in PCCP

Where PCCP is to be monitored electrically or protected cathodically, shorting straps should be required rather than optional. TM 8540-24 Section 2.4 states that shorting straps *can* be used to maintain

²² American Concrete Institute, "ACI 515.2R-13: Guide to Selecting Protective Treatments for Concrete," 2013. [Ref. 5]

²³ American Concrete Institute, "ACI 515.2R-13: Guide to Selecting Protective Treatments for Concrete," 2013. [Ref. 5]

²⁴ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

electrical continuity in the event of a wire break, and Section 3.3.5 states that corrosion monitoring systems require electrical continuity along the alignment. ACPPA also identifies “bond and monitor” as a solution where stray current is anticipated.²⁵ Given the consequence of PCCP rupture and the need to preserve continuity for monitoring and CP, this measure should be treated as a required design feature where electrical monitoring or CP is part of the mitigation strategy.

3-2.4 Expand the Discussion for “Other Considerations” for Soil Corrosivity

In Section 3.1.6, TM 8540-24 is correct to include stray current, microbial induced corrosion (MIC), existing structure performance, backfill, and wet-dry cycling in the corrosion framework. The weakness is not inclusion, but the lack of scoring guidance. Literature and TM 8540-24 both show that these factors can dominate local performance. The most practical improvement is to retain the category but split it into explicit subfactors or provide a scoring rubric for each.

3-2.4.1 Stray Currents

TM 8540-24 appropriately identifies the principal drivers of stray-current corrosion, including proximity to the source, exposed metal area, coating dielectric properties, pipeline continuity, and soil conductivity. Because corrosion occurs where foreign current discharges from the pipeline, stray current should be evaluated as a localized interference risk rather than a general project condition. TM 8540-24 would therefore be improved by adding a segment-specific ranking for stray current that considers source proximity, known or suspected discharge locations, measured or inferred current intensity, variation in current flow over time, and the presence of adjacent utilities with cathodic protection systems. Nearby CP systems should be treated as potential interference sources, with their location, relative alignment, available operating history, and any evidence of prior interference incorporated into the stray-current ranking and the selection of mitigation measures.

3-2.4.2 Microbial Induced Corrosion (MIC)

MIC should be treated as an explicit design check where sulfate-bearing, waterlogged, poorly drained, or biologically active soils are known to be present. Spark et al. describe MIC as unpredictable and strongly localized, and they note that CP can, under some sulfate-reducing-bacteria conditions, favor microbial growth and pitting beneath biofilms even when uniform corrosion is reduced.²⁶ These findings suggest that additional corrosion mitigations may be required for localized areas. TM 8540-24 already recognizes MIC, but the scoring impact should be segment specific based on historic conditions and soil analysis.

3-2.4.3 Existing Structure Performance

Existing structure performance is one of the most useful local indicators of how the soil environment and current protection practice are actually performing. TM 8540-24 states that existing infrastructure can indicate both local soil corrosivity and corrosion-mitigation performance. TM 8540-24 should therefore require a documented review of prior failures, retained pipe sections, leak clusters, and prior failure reports where such information exists. Rankings could be based on failure mechanisms previously encountered.

²⁵ American Concrete Pressure Pipe Association, "External Protection of Concrete Cylinder Pipe: Guidelines for Supplemental Protection of Pipelines in Adverse Environments," 2011. [Ref. 15]

²⁶ A. Spark, K. Wang, I. Cole, D. Law and L. Ward, "Microbiologically Influenced Corrosion: A Review of the Studies Conducted on Buried Pipelines," *Corrosion Reviews*, vol. 38, no. 3, 2020. [Ref. 7]

3-2.4.4 Backfill and Wet-Dry Cycling

TM 8540-24 already states that trench backfill increases oxygen and water supply to the pipe zone and that wet-dry cycling concentrates chlorides and sulfates. Literature on metallic pipe has shown that corrosion increases with moisture up to a critical point (which is reflected in the soil resistivity), however corrosion then declines as oxygen supply decreases.²⁷ This critical point is determined by soil type, metal type, and exposure duration (wet-dry cycling). The criticality of soil compression, water content, and particle size in oxygen transport and corrosion-current distribution is also proven.²⁸ For concrete pressure pipe, Nixon identifies acidic groundwater and sulfate-bearing groundwater as principal soil-side deterioration mechanisms. Those factors warrant direct incorporation into segment scoring.²⁹

The Virginia Tech study also showed that ductile iron pipes had lower service life estimates in coastal conditions compared to other environmental conditions.³⁰ The decrease in service life was attributed to saltwater intrusion-based corrosion caused by flooding events or sea-level rise. TM 8540-24 could consider including location-based soil corrosivity ratings, specifically for coastal environments.

Ductile iron guidance allows suitable native trench soil in some laying conditions,³¹ whereas steel-pipe practice more commonly uses select, free-draining embedment. That distinction matters to corrosion because backfill controls moisture movement, oxygen access, soil homogeneity, and the risk of damage to coatings or encasement. Additionally, literature shows that pitting increases with soil inhomogeneity.³² Backfill selection should therefore be treated as part of the corrosion protection system and evaluated for compatibility with the pipe material, coating or encasement, groundwater conditions, and CP strategy.

3-2.4.5 Interaction of Corrosion Factors

The literature suggests that the interaction between factors is itself important. Spark et al. show that localized corrosion in soil is tied to soil heterogeneity, backfill, moisture, oxygen distribution, and microbial changes.³³ Farh et al. similarly describe soil resistivity as the product of moisture, chemistry, and temperature acting together.³⁴ For that reason, the TM 8540-24 should make clear that the “other considerations” score is not a residual convenience category. Rather, it is the part of the framework intended to capture the site-specific conditions that often control localized corrosion and premature failure.

3-2.4.6 Metallic Appurtenances on Non-Metallic Pipe

²⁷ H. M. Farh, M. E. A. Ben Seghier, R. Taiwo and e. al., "Analysis and Ranking of Corrosion Causes for Water Pipelines: A Critical Review," *npj Clean Water*, vol. 6, p. 65, 2023. [Ref. 6]

²⁸ A. Spark, K. Wang, I. Cole, D. Law and L. Ward, "Microbiologically Influenced Corrosion: A Review of the Studies Conducted on Buried Pipelines," *Corrosion Reviews*, vol. 38, no. 3, 2020. [Ref. 7]

²⁹ R. Nixon, "Conducting Precast Concrete Cylinder Pipe Condition Assessment by Matching Corrosion Damage Mechanisms to Diagnostic Methods," in *AMPP Conference Proceedings*, San Antonio, TX, 2022. [Ref. 12]

³⁰ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

³¹ Ductile Iron Pipe Research Association, "Applications of Ductile Iron Pipe for Wastewater Applications," 2016. [Ref. 17]

³² H. M. Farh, M. E. A. Ben Seghier, R. Taiwo and e. al., "Analysis and Ranking of Corrosion Causes for Water Pipelines: A Critical Review," *npj Clean Water*, vol. 6, p. 65, 2023. [Ref. 6]

³³ A. Spark, K. Wang, I. Cole, D. Law and L. Ward, "Microbiologically Influenced Corrosion: A Review of the Studies Conducted on Buried Pipelines," *Corrosion Reviews*, vol. 38, no. 3, 2020. [Ref. 7]

³⁴ H. M. Farh, M. E. A. Ben Seghier, R. Taiwo and e. al., "Analysis and Ranking of Corrosion Causes for Water Pipelines: A Critical Review," *npj Clean Water*, vol. 6, p. 65, 2023. [Ref. 6]

The matrix in Table 4 of TM 8540-24 should include corrosion mitigation recommendations for metallic appurtenances on non-metallic pipe. Section 2.5 provides guidance, in that each component should have factory applied dielectric coatings and that CP may be required depending on the soil corrosivity. A simple solution could be to update the “Steel” designation under “Pipe Materials” in Table 4 to “Steel Pipe and Metallic Appurtenances”.

3-2.5 Bonded Dielectric Coatings on Ductile Iron Pipe

Bonded dielectric coatings on ductile iron pipe require ductile-iron-specific surface preparation and application procedures and should not be treated as directly equivalent to carbon steel coating practice. The NRC report noted that U.S. manufacturers had cited surface preparation and application difficulties as reasons for not supplying bonded-coated ductile iron pipe.³⁵ At the same time, NRC found that most major coating manufacturers and several U.S. applicators believed they had developed workable surface preparation and coating application procedures for ductile iron, and one manufacturer stated that coating ductile iron was not materially more difficult than coating steel when performed by a knowledgeable applicator. The same report also noted that bonded dielectric coatings continue to be used internationally, including more than 3,000 miles of polyurethane-type coating reportedly applied to ductile iron pipe in Asia. In Europe, the report states that additional top coatings are commonly applied over the as-cast external surface, with polyurethane as the principal system requiring abrasive blasting, and that joints are typically protected with thin epoxy coatings or other supplemental joint-protection systems in more aggressive soils.

To mitigate failures due to improper surface preparation and application, Section 3.3.2 of TM 5840-24 should indicate that the coating system must be specified with manufacturer-approved, ductile-iron-specific preparation, application, and joint-protection procedures and applied by quality applicators.

3-2.6 Polyethylene (PE) Encasement

In Section 3.3.3, TM 5840-24 should include installation limitations, including backfill compatibility requirements, and highlight limitations for zinc and PE encasement in acidic soil.

While polyethylene (PE) encasement is commonly applied as a corrosion protection measure for ductile iron pipelines, its effectiveness is highly dependent on installation practices and backfill conditions.³⁶ Available literature and industry guidance indicate that the use of PE encasement introduces specific constraints that must be carefully considered during design and construction.³⁷

One of the primary concerns is the susceptibility of PE encasement to mechanical damage during installation. Studies and industry references have shown that sharp or angular backfill materials can puncture, tear, or otherwise compromise the integrity of the polyethylene wrap.³⁸ Such damage can

³⁵ B. Rajani and Y. Kleiner, "Protection of Ductile Iron Water Mains Against External Corrosion: Review of Methods and Case Histories," *Journal of the American Water Works Association*, vol. 95, no. 11, pp. 110-125, 2003. [Ref. 2]

³⁶ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

³⁷ B. Rajani and Y. Kleiner, "Protection of Ductile Iron Water Mains Against External Corrosion: Review of Methods and Case Histories," *Journal of the American Water Works Association*, vol. 95, no. 11, pp. 110-125, 2003. [Ref. 2]

³⁸ B. Rajani and Y. Kleiner, "Protection of Ductile Iron Water Mains Against External Corrosion: Review of Methods and Case Histories," *Journal of the American Water Works Association*, vol. 95, no. 11, pp. 110-125, 2003. [Ref. 2]

create localized exposure points, significantly reducing the effectiveness of the encasement as a corrosion barrier and potentially leading to accelerated corrosion at defect locations.

Guidance documents, including TM 8540-24, emphasize the need for appropriate backfill selection when PE encasement is specified.³⁹ In particular, these guidelines suggest that backfill materials should be free of sharp, angular, or abrasive constituents that could damage the encasement during placement or subsequent soil settlement. However, this requirement introduces a key limitation when compared to standard ductile iron pipe installation practices.

The Ductile Iron Pipe Research Association (DIPRA) has historically promoted the inherent structural strength of ductile iron pipe, noting that it can be installed under relatively less stringent bedding and backfill conditions.⁴⁰ For example, DIPRA installation guidance includes simplified trench conditions, such as “flat-bottom trench with loose backfill,” where native excavated soil, free of large rocks and debris, is considered acceptable.⁴¹

This conventional installation approach is not compatible with the use of PE encasement. Loose or native backfill, even when screened for large debris, may still contain smaller angular particles or debris capable of damaging the polyethylene material. Additionally, the lack of controlled placement and compaction associated with loose backfill increases the risk of differential settlement, which can further stress and abrade the encasement over time.

As a result, when PE encasement is utilized, more stringent backfill requirements must be implemented, typically involving the use of select, non-angular, and well-graded materials along with controlled placement procedures. This requirement effectively negates one of the key installation and cost advantages of ductile iron pipe: its tolerance for less restrictive trench and backfill conditions.

In summary, the use of PE encasement imposes additional installation constraints and introduces potential risks related to material damage and long-term performance. These factors should be carefully evaluated when selecting corrosion protection strategies, particularly in projects where standard ductile iron installation practices or variable backfill conditions are anticipated.

Literature has also shown that the protective zinc-corrosion-product layer does not form in acidic soils.⁴² For that reason, Table 4 in TM 8540-24 should include a footnote indicating that bonded dielectric coating should be used in place of metalized zinc coating and polyethylene encasement in acidic soils. Additionally, the client-deviation provision in Section 3.5 of TM 8540-24 allowing zinc-plus-PE systems in high or severe environments should explicitly exclude acidic soils unless additional justification is provided.

3-2.7 Include Precautions in CP Design for Each Pipe Material

In Section 3.3.5, TM 8540-24 should include material-specific cautions for CP design. CP effectiveness depends on electrical continuity and on current reaching the exposed metal; each material and

³⁹ S. K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," Blacksburg, VA, 2021. [Ref. 3]

⁴⁰ Ductile Iron Pipe Research Association, "Applications of Ductile Iron Pipe for Wastewater Applications," 2016. [Ref. 17]

⁴¹ Ductile Iron Pipe Research Association, "Applications of Ductile Iron Pipe for Wastewater Applications," 2016. [Ref. 17]

⁴² B. Rajani and Y. Kleiner, "Protection of Ductile Iron Water Mains Against External Corrosion: Review of Methods and Case Histories," *Journal of the American Water Works Association*, vol. 95, no. 11, pp. 110-125, 2003. [Ref. 2]

corrosion mitigation strategy has different parameters that could compromise the effectiveness of cathodic protection. TM 8540-24 already provides warnings throughout the document, for example, that non-welded steel joints are not reliably electrically continuous unless bonded, that RCP/RCP reinforcing steel and joint rings must be bonded for continuity, and that soil or water inside PE encasement can shield CP current from corroding areas. These precautions should also be included in Section 3.3.5 to emphasize the importance of these factors in the proper use of cathodic protection.

One additional precaution is to mitigate hydrogen embrittlement in PCCP. Hall recommends a minimum - 100 mV polarization or depolarization criterion but limits polarization to no more negative than - 1000 mV CSE to avoid hydrogen embrittlement of prestressing wire.⁴³ Section 3.3.5 of TM 8540-24 recommends that CP for concrete pressure-pipe meets the performance requirements in NACE SP0100; adding Halls precautions would make that section more actionable.

4 CONCLUSIONS

TM 8540-24 is technically sound in its overall direction and represents a meaningful improvement in the evaluation of external corrosion risk for buried pipe. Its transition from a resistivity-only method to a multi-factor, consequence-informed framework is supported by the literature reviewed and provides a stronger basis for selecting corrosion mitigation measures.

The review supports the core framework of TM 8540-24. The criteria used to assess soil corrosivity and consequence of failure are appropriate for screening-level use, the minimum mitigation measures can support long service life when matched to the material and environment and maintained over time. Mitigation strategies that incorporate CP or corrosion monitoring will enable constant feedback for corrosion issues allowing for response and remediation prior to failure.

The principal improvements recommended in this review are primarily refinements rather than changes in overall direction. The most significant recommendation is to reassess the pipe replacement rates in Appendix A. Several underlying assumptions may lead to inaccuracies in the absolute value of pipes identified for replacement and should be refined. Additional recommendations include more clearly distinguishing between corrosion mechanisms for steel, ductile iron, and concrete pipe; strengthening the treatment of severe exposure environments for concrete pipe; and providing more explicit scoring guidance for “other considerations”.

With those revisions, TM 8540-24 will provide a stronger and more consistent basis for corrosion mitigation decisions across the range of buried water-pipe materials addressed in the document.

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⁴³ S. C. Hall, "Cathodic Protection Criteria for Prestressed Concrete Pipe—An Update," *Materials Performance*, vol. 57, no. 3, pp. 34-41, 2018. [Ref. 20]

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APPENDIX A: COMMENT MATRIX

Comment No.	TM 8504-24 page number	TM 8504-24 paragraph/section number	Summary of the comment	Rationale for comment	Proposed change / recommendation	Comment Type (Administrative/Technical)
1	2 and 11-12	Table 1; Section 3.1.3; Table 7	Strengthen the treatment of sulfates for RCP/RCPP and PCCP in the criteria tables. Include explanation for sulfates in metallic corrosion as described by Peabody.	Table 1 assigns relatively low sulfate points compared with resistivity and chloride, while Section 3.1.3 correctly states sulfate attack can degrade concrete or mortar and expose reinforcement. ACI classifies 10,000 ppm for the highest sulfate exposure in concrete. Peabody recommends 10,000 ppm for highly corrosive soils for metallic structures in soil. Sulfate is highly corrosive to concrete, yet can also cause significant damage to steel when in certain environments.	Keep Table 1 as a general screen, but add a concrete-pipe supplemental sulfate evaluation for RCP/RCPP/PCCP, especially in Group A and Group B conditions. Change the highest ranked sulfate value to 10,000 ppm to be consistent with literature.	Technical
2	2 and 18	Table 1; Section 3.1.6	Expand the scoring guidance for "Other Considerations" for soil corrosivity.	Table 1 combines stray current, MIC, existing structure performance, backfill, and wet-dry cycling into a single 0-5 input. The literature identifies these as interacting, site-specific drivers of localized corrosion rather than minor secondary issues.	Break "Other Considerations" into subfactors or provide an explicit scoring rubric for each item so the method is applied consistently. Add additional details to Section 3.1.6 for each category to support proper ranking and highlight critical considerations.	Technical

Report of Findings

3	3 and 8	Table 2; Section 2.4	Add a material/failure-mode consequence modifier, especially for PCCP in severe environments.	Table 2 captures location, diameter, redundancy, pressure, and replacement time, but it does not expressly account for the different credible failure modes of leakage versus rupture. Section 2.4 states PCCP can fail catastrophically.	Add guidance to Table 2 that consequence may be increased where the material-environment combination changes the likely failure mode from leakage to structural failure or rupture.	Technical
4	3	Table 2	The consequence-of-failure criteria should also account for the presence of adjacent utilities with active cathodic protection systems.	The consequence of pipe failure rating should be elevated where a proposed water line (or its cathodic protection system) could interfere with the corrosion protection on an existing protected utility, such as a gas pipeline, because the potential effects extend beyond the new water line and may create unanticipated corrosion, operational, and public-safety risks on neighboring infrastructure.	Add an additional category, either in "Other considerations", or separate to account for other energized utilities.	Technical

5	A-6 - A-8	Appendix A: Sections 2.4.2 and Tables A-3 to A-5	Clarify that Appendix A replacement rates are comparative planning assumptions, and add a sensitivity analysis.	Appendix A uses data that accounts for all failures, not just corrosion related failures, then normalizes data to the NRC ductile-iron corrosion rate, uses a CSC proxy for RCP/RCPP, assumes corrosion-related failure is static through year 50, then doubles every 10 years from 50 to 100 years, and rounds fractional failures to replacement of a full 20-foot section. Those are useful planning assumptions, but not validated material-specific deterioration laws. Moreover, by basing the failure predictions on historical data, the set is not accounting for the use of modern materials and mitigation strategies.	State explicitly that the Appendix A replacement rates are screening-level comparative values. Reassess the normalization of the data from the three studies. Modify the escalation rate after 50 years to ensure that the failure rates are not highly sensitive to that underlying assumption in the escalation rate or include additional options for the escalation rates based on a sensitivity analysis. Continue to capture data from utilities to supplement the current studies.	Technical
6	4, and 17-18	Table 4; Sections 2.3 and 2.4	Consider supplemental exterior barrier protection for concrete pressure pipe in the most aggressive environments.	TM 8540-24 currently uses inhibitor and CP for Group A RCP/RCPP/PCCP. The concrete-pipe literature supports inhibitors and CP, but ACI 515.2R also recognizes barrier isolation as a standard method to protect concrete from aggressive exposure, and recent durability literature emphasizes chloride ingress, carbonation, and transport conditions at the steel-concrete interface.	Include polyurethane or epoxy barriers for the external mitigation of Pipe Group A RCP/RCPP/PCCP, for the total system of "Polyurethane or Epoxy outer barrier and corrosion inhibitor in mix design for pipe wall (RCP/PCPP) or mortar coating (PCCP)."	Technical

Report of Findings

7	6, 16-18	Sections 2.1, 3-2, and 3-3	The statement that steel, ductile iron, and cast iron corrode at similar rates in similar soils is misleading and should be modified to address the different failure mechanisms and failure modes in each material-environment consideration.	TM 8540-24 distinguishes between different materials and corrosion protection systems in Table 4, this type of description and distinction should be carried out through the full document.	Clarify that the mechanism and modes of failure will be different in each material in Section 2.1. Add a material-specific note or modifier to the weighting discussion in Section 3-2 and the service-life discussion in Section 3-3.	Technical
8	8 and 21	Sections 2.4 and 3.3.5	For PCCP, strengthen the requirement for shorting straps for electrical continuity.	Section 2.4 states shorting straps can be used to maintain continuity if prestressing wires break, and Section 3.3.5 states all sections to be protected must be bonded for continuity. For PCCP, continuity is central to both CP effectiveness and monitoring reliability.	Change “can be used” to stronger design guidance where PCCP will be monitored electrically or protected cathodically; at minimum, require a design decision and justification if shorting straps are omitted.	Technical
9	2 and 15	Section 3.1.6.1; Table 1	Update risk assessment for stray currents as a localized assessment rather than a general project consideration.	TM 8540-24 already recognizes stray-current corrosion and notes that nearby CP systems can be interference sources, but the scoring framework does not clearly show how adjacent protected utilities affect local risk. Because corrosion occurs where foreign current discharges from the pipeline, stray current should be evaluated as a localized interference risk rather than a general project condition.	Add guidance that nearby cathodically protected utilities and electrified infrastructure should raise the local stray-current score unless field testing shows negligible interaction.	Technical

Report of Findings

10	2 and 16	Sections 3.1.6.5; Table 1	Incorporate coastal environment into the risk categories	The Virginia Tech study showed that ductile iron pipes had lower service life estimates in coastal conditions compared to other environmental conditions. The decrease in service life was attributed to saltwater intrusion-based corrosion caused by flooding events or sea-level rise.	TM 8540-24 could consider including location-based soil corrosivity ratings, specifically for coastal environments. This also could be accounted for in the Wet-Dry Cycling rating in Table 1 and discussion in Section 3.1.6.5.	Technical
11	16	3.1.6.4	Expand the discussion regarding backfill weighting.	Section 3.1.6.4 discusses the implications of using the correct backfill, but it does not address the different strategies used for backfilling different pipe materials. Ductile iron specifically requires a more specialized backfill when it uses a PE encasement.	Include more detailed instructions on how the backfill will be ranked. For example, if native backfill will be used, this would be a higher ranking than specialized backfill.	Technical
12	16	Section 3.1.6	Include discussion regarding the interaction of factors influencing soil corrosivity.	The literature suggests that the interaction between factors is itself important. For example, the combination of soil heterogeneity and wet-dry cycling will be much more corrosive than either alone.	TM 8540-24 should make clear that the “other considerations” score is not a residual convenience category. Rather, it is the part of the framework intended to capture the site-specific conditions that often control localized corrosion and premature failure.	Technical
13	4	Table 4; Section 2.5	Metallic Appurtenances on Non-Metallic Pipe	The matrix in Table 4 of TM 8540-24 should include corrosion mitigation recommendations for metallic appurtenances on non-metallic pipe.	Update the “Steel” designation under “Pipe Materials” in Table 4 to “Steel Pipe and Metallic Appurtenances”.	Technical

Report of Findings

14	19	Section 3.3.2	Clarify that bonded dielectric coatings on ductile iron require ductile iron specific surface preparation and manufacturer-approved procedures.	TM 8540-24 correctly identifies bonded dielectric coatings as the best defense, but it does not explain that ductile iron surface preparation is not the same as steel.	Add ductile iron-specific language requiring manufacturer-approved procedures for surface preparation and coating application.	Technical
15	19-20 and 23	Sections 3.3.3 and 3.5	Tighten the severe-service language for zinc and PE encasement on ductile iron.	The use of PE encasement imposes additional installation constraints and introduces potential risks related to material damage and long-term performance. These factors should be carefully evaluated when selecting corrosion protection strategies, particularly in projects where standard ductile iron installation practices or variable backfill conditions are anticipated. Additionally, zinc will provide the long-term protection expected in acidic soils. Bonded dielectric coatings should be considered for acidic soils over zinc and PE encasement.	In Section 3.3.3, TM 5840-24 should include installation limitations, including backfill compatibility requirements, and highlight limitations for zinc and PE encasement in acidic soil. These considerations should also be reiterated in Section 3.5 if deviations are requested.	Technical

Report of Findings

16	20-21	Section 3.3.5	Include Precautions in CP Design for Each Pipe Material	TM 8540-24 already includes several precautions for the use of cathodic protection throughout the document. These precautions should be compiled and included together in Section 3.3.5 Cathodic Protection. One additional precaution is to mitigate hydrogen embrittlement in PCCP. Hall provides explicit precautions that would supplement the requirements in NACE SP0100 and would make the section more actionable.	In Section 3.3.5, include the specific precautions mentioned for each material and corrosion mitigation strategy that will be used in conjunction with cathodic protection (shielding, hydrogen embrittlement, and electrical continuity needs).	Technical
17	2	Table 1	Correct “Stay Current” to “Stray Current.”	Table 1 currently lists “Stay Current” under “Other Considerations,” which appears to be a typographical error for the recognized corrosion factor stray current. Leaving it unchanged may confuse scoring and design review.	Revise the term to Stray Current and define how it is to be scored.	Administrative



**Elzly Technology Corporation
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Reston, VA 20190
703/738-6624 (p)**

April 17, 2026

**Re: Contract No. 140R4026P0014, Independent Technical Review of Draft
Technical Memorandum 8540-2024-13, Corrosion Mitigation for Buried
Metallic Water Pipe**

Ed Frazar, P.E.
Senior Advisor
US Bureau of Reclamation
Technical Service Center
Denver, CO 80225

Via: e-mail to: efrazar@usbr.gov

Mr. Frazer:

Please find attached a copy of my technical review of the subject draft Technical Memorandum. I include the comment matrix as an appendix in the report, and the same words are also in an Excel sheet.

Please let me know if you have any questions or concerns.

Very truly yours,

A handwritten signature in blue ink that reads "James A. Ellor".

James A. Ellor, P.E.
Senior Consultant



**Technical Review of Bureau of Reclamation Technical
Memorandum 8540-2024-13
Corrosion Mitigation for Buried Metallic Water Pipe**

Prepared by: James A. Ellor, P.E.

Elzly Technology Corporation

April 2026

**Prepared for: U.S. Bureau of Reclamation, Technical Service Center
Denver, CO**

Contract No.: 140R4026P0014

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Technical Review of Bureau of Reclamation Technical Memorandum 8540-2024-13

Corrosion Mitigation for Buried Metallic Water Pipe

Executive Summary

The following provides a technical review of the USBR Draft Technical Memorandum 8540-2024-13, “Corrosion Mitigation for Buried Metallic Water Pipe.” The topic of corrosion mitigation for buried steel structures has been a focus of the corrosion engineering community for nearly 100 years. While significant progress has been made, there is still no perfect model or prediction method for assessing corrosion risk. Corrosion control is also highly dependent on the quality of the preservation materials and installation practices.

The USBR-recommended process and matrices seem mostly reasonable for assessing corrosion risk, evaluating the consequences of pipe failure, and recommending corrosion control measures. The corrosion risk matrix might benefit from greater inclusion and higher weighting of issues related to stray current, microbiologically induced corrosion, and wet-dry cycling. The knowledge of individual utilities on the performance of materials within their existing systems should also likely be more significant in the matrix.

Achieving a 50-100-year design life with a high degree of reliability is possible. The performance of buried oil and gas lines with extensive corrosion-control design and monitoring demonstrates this. This obviously comes with a cost tradeoff. In some areas, water utilities are already seeing such lifetimes in less corrosive areas. In highly corrosive areas, moving more toward bonded coatings with cathodic protection will improve the longevity of the water pipe; however, the design must be accompanied by high-quality installation and ongoing corrosion monitoring and testing.

The proposed LCCA model pipe replacement seems reasonable for the ductile iron and steel pipe in highly corrosive environments. In the absence of corrosion-specific failure rates for alternative reinforced concrete pipe and plastic pipe, the projected failure rates assigned to these materials seem questionable. Yet better data for such projects is likely lacking.

Introduction

The following provides a technical review of the USBR (Draft) Technical Memorandum 8540-2024-13, “Corrosion Mitigation for Buried Metallic Water Pipe.” The contract requested the following:

- A general review of the technical merit of the document and delivery of comments and recommendations in a prescribed matrix format.
- A narrative response to three Review Questions.
 - Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?
 - Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipes reliably provide a minimum service life of 50 to 100 years?
 - Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?

The review also considered any public comments provided on the draft Technical Memorandum as a resource only. The present effort focused on scientific data and current industry practices in considering the merit of the Technical Memorandum. The following narrative supports answers to the specific Review Questions. Appendix A at the end of this document provides the general review matrix.

Methodology

The technical review included a read-through of the draft Technical Memorandum (TM). As needed, this lead to a review of the underlying supporting documentation. Of particular importance is the USBR-sponsored work by Virginia Tech on the life assessment of various pipeline materials used in U.S. water utilities.¹ Additional key reports reviewed for perspective included reports from Utah State University², the National Research Council³, and the National Academies of Science.⁴

An initial task was to review the parameters incorporated into the Soil Corrosivity Determination (Table 1) of the draft TM against other industry standards and the common literature on soil corrosion.

For quantified parameters (e.g., resistivity), the ranges for corrosivity classifications were arranged from least to most corrosive, and averages or medians were calculated across

¹ S.K. Sinha, "Collection and Compilation of Water Pipeline Field Performance Data," SWIM Center at Virginia Tech, Blacksburg, VA April 2021

² S. Barfuss, "Water Main Break Rates in the USA and Canada: A Comprehensive Study," Utah State University, December 2023

³ National Research Council, "Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe," Washington D.C., 2009

⁴ National Academies of Sciences, Engineering, and Medicine, "Corrosion of Buried Steel at New and In-Service Infrastructure," Washington D.C. 2022

sources. An indicated range, such as 5,000-10,000 ohm-cm, was recorded as 7,500 ohm-cm. These averages were compared to the ranges within the draft TM for consistency.

Key Findings

The overall risk cube model includes two components, Soil Corrosivity and Consequences of Pipe Failure. In the draft TM, Table 1 presents the soil characteristics of concern and the score sheet for each parameter. Table 2 presents the Consequences of Pipe Failure.

Soil Corrosivity Determination

Concerning the individual parameters in the draft TM for soil corrosivity determination and their derivation, Exhibit 1 provides a summary of the individual resistivity data ranges from the referenced sources, suggested averages, and the draft TM values. For resistivity, the draft TM captures the other standards well.

Exhibit 1. Resistivity Range in Referenced Sources vs. Draft TM

Resistivity	AWWA	Corrosion 98	Roberge	Corrpro/ DIPRA	WSSC	Peabody	Average	Draft TM
Least Corrosive	3000	10000	20000	5000	10000	10000	9667	>10,000
	2750	6000	15000	4000	7500	6000	6875	5,000-10,000
	2300		7500	2500	3750		4013	2,000-5,000
	1950		4000	1750	2000			
	1650	1500	2000	1250	1250	1500	1885	500-2,000
	1500	500	500	500	500	500		
Most Corrosive				250		250	563	< 500

Resistivity is the most common parameter in all soil corrosivity models. For chlorides and pH, there were three referenced sources for the draft TM to consider. The limited data preclude the need for detailed analysis. For chlorides, the referenced sources range from 100 to 5,000 ppm for assigning a maximum point value. The draft TM uses 500 ppm as the threshold for assigning the maximum point value. The 5,000 ppm level (Peabody) is extremely high for most soil measurements, and the draft TM seems reasonable. The draft TM soil pH rankings are similar to the referenced sources.

Regarding sulfate, the draft TM paragraph 3.1.3 and Table 7 misidentify the AWWA and DIPRA/Corrpro parameters for sulfide as sulfate. This will need to be corrected. As discussed

below regarding reinforced concrete pipe (RCP), there may still be reasons to include sulfate measurements in a corrosivity model. The draft TM mimics the sulfate suggestion of Peabody.

On a comprehensive basis, there are six (6) parameters in Table 1 that determine soil corrosivity: resistivity, chloride content, drainage class, sulfates, pH, and “other considerations.” Exhibit 2 presents these parameters along with similar parameters from three of the referenced, comprehensive alternative methodologies (DIPRA/Corrpro, WSSC, and AWWA). The percentages show the maximum value for the identified parameter divided by the total maximum score. The higher-percentage items have the highest probability of determining the ultimate corrosivity ranking.

Exhibit 2. Soil Corrosivity Characteristics in Draft TM vs. Alternative Standards

Parameter	DIPRA	WSSC	AWWA	Draft TM
Resistivity	50%	25%	39%	45%
Chlorides	13%	25%		18%
Moisture Content / Drainage Class	8%		8%	9%
Ground Water Influence	8%			
pH	7%	13%	20%	9%
Sulfide	7%		14%	
Redox	3%	13%	20%	
Bi-Metallic	5%			
Soil Description		25%		
Sulfates				9%
Other Considerations (Stray Current, MIC, Existing Structure Performance, Backfill, Wet Dry Cycling)				9%

Regarding the information, the draft TM places (nominally) a similar high emphasis on soil resistivity, chlorides, pH, and moisture content/drainage class. The draft TM does not place

a significant factor on sulfide⁵ or redox potential. These terms are generally associated with the potential for microbiologically induced corrosion (MIC), which the draft TM includes among several “other considerations.” The draft TM does include a concern for sulfates, which some have used as a convenient analog to MIC (from sulfate-reducing bacteria). With the inclusion of many factors into the single “other consideration” score—itsself limited to 9% of the total--there might be situations where such “other considerations” do not carry an appropriate weight. Any one of those “other considerations” may produce a highly corrosive environment.

Conceptually, the “other considerations” row could be expanded as suggested in Exhibit 3.

Exhibit 3. Expansion of “Other Considerations”

Other Consideration	Score
Stray Current	
Adjacent DC power source (e.g., transit)	5
Adjacent CP systems	2
No known local DC power sources	0
MIC Concern	
Positive sulfide/negative redox	5
Negative sulfide/positive redox	0
Other sulfide/redox	2
Wet-Dry Cycling	
Periodic groundwater contact	5
Constant immersion	2
No groundwater contact	0
Existing Structure Performance	
Significant corrosion (absent protection) ⁶	5
No known problems	0

An expansion of the present “other consideration” line in TM Table 1 to allow consideration of four (4) separate factors, with a total maximum score of 20 points instead of 5, provides better alignment with the additional soil parameters expressed in the alternative standards. It provides for more consideration of MIC and wet-dry cycling (groundwater influence).

Reinforced concrete materials will fail via a different mechanism than steel and ductile iron. The chemical attack of the concrete or protective mortar may be more related to sulfates,

⁵ The draft TM confuses sulfide and sulfate, as discussed.

⁶ Substantial corrosion on an existing adjacent/similar line that included robust corrosion control practices should be an automatic “flag” that the local soil is highly corrosive.

wet-dry cycling, and local pH. A supplemental analysis may be required to ensure the use of RCP in select environments.

Consequences of Pipe Failure Determination

Most of the consequences of pipe failure determinations and their relative ranking fall within the realm of public policy, specifically excluded from this review. The following are offered for possible consideration:

- The TM intends to promote long-life pipelines, of 50-100 years. The consequences of pipe failure might extend beyond the present-day situation. Many urban areas continue to expand, and what was once sparsely populated is now densely developed. There might be some consideration of any local master plans, where available, to better understand where pipe access and pipe failure might be much more critical in 20 years than they are today.
- Additional score might be considered where the water supply plays a significant role in public safety, e.g., fire protection.
- Perhaps embedded in the other parameters of line diameter and pressure, but a parameter that estimates the number of impacted homes, people, businesses, etc. Perhaps this is too difficult. It just seems like a small point differential included in the pipe diameter and pressure may not reflect drastically different numbers of affected people.
- Although Table 2 appears to have multiple options, water lines planned for urban areas start with a point value of 22, thus are immediately high consequence. The application of virtually any of the point values (some of which have to be assigned for all but the smallest diameter lines) will shift the consequence into the Severe category. In the presence of moderate, high, or severe soil corrosivity, most urban projects will include supplemental external mitigation and cathodic protection.

Corrosion Prevention Supporting a 50-100 Year Service Life

The focus of the draft TM is to determine the appropriate level of corrosion control methodology to ensure a long pipeline life under a variety of soil conditions. An initial consideration might be, to what degree does metallic corrosion influence pipeline life? Referring to the work from VA Tech¹ Volume 4-Descriptive Analytics, Figure 44 (reproduced below) indicates that 92% of the pipe failures for ductile iron are associated with a “manufacturing flaw.” Only 4% is “exterior corrosion.”

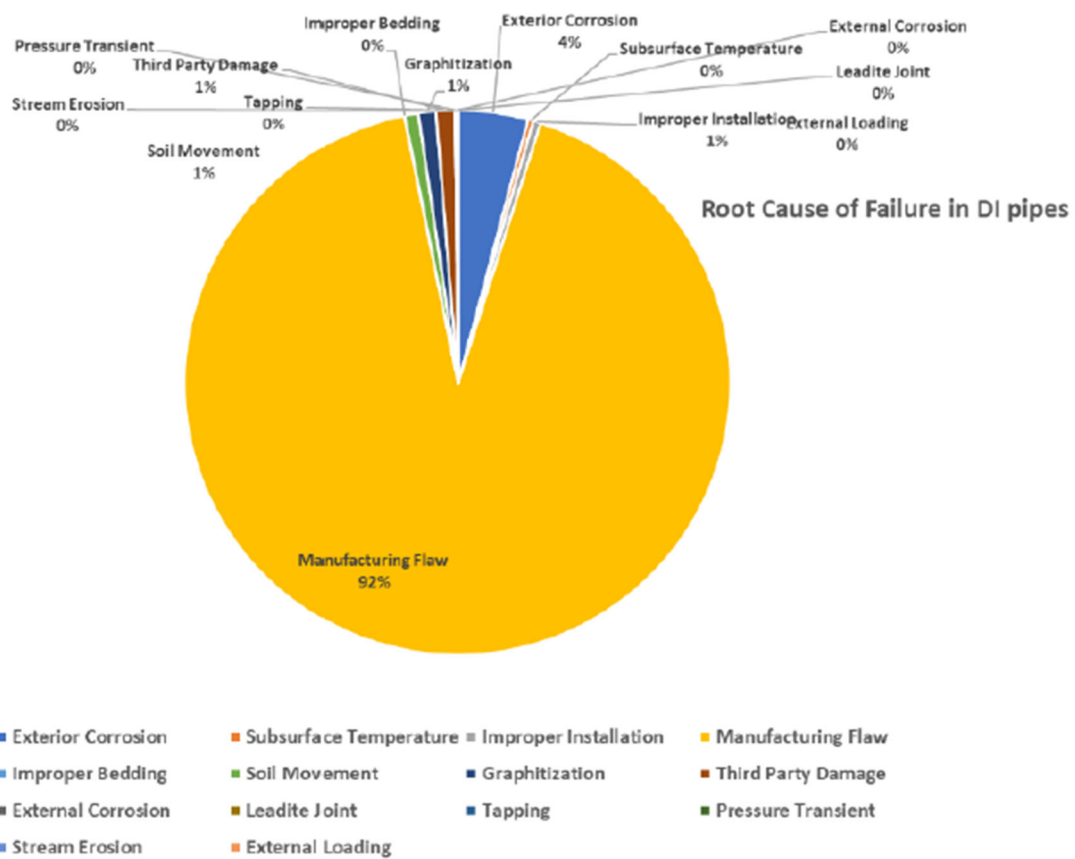


Figure 44: Root Cause of Failure for DI pipes

Conversely, Figure 50 (reproduced below) shows that for steel pipe, 58% of the failures are due to external corrosion and another 14% to coating failure (presumably leading to external corrosion). This is 72%.

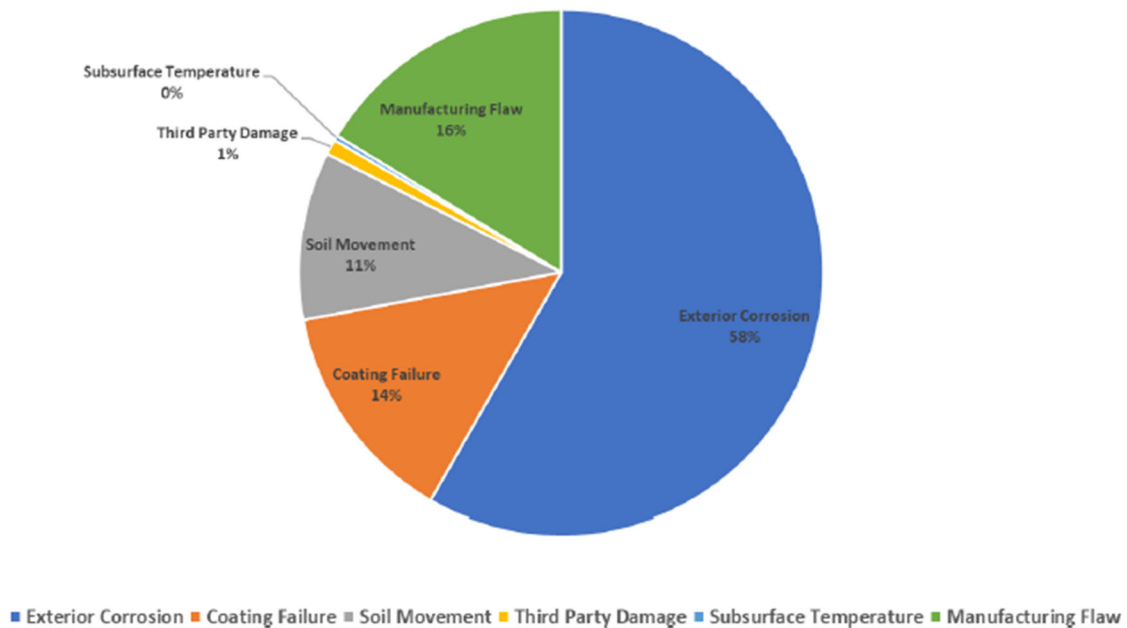


Figure 50: Root Cause of Failure for Steel pipes

At face value, this suggests that application of perfect corrosion control methods would eliminate only 4% of failures on ductile iron materials yet 72% on steel pipe.

Intuitively, the discrepancy in the magnitudes of corrosion-related root causes does not make much sense, given that both products are ferrous metals. The root-cause failure-mode data collected from field inspections are likely inadequate. Alternatively, the steel materials may be applied more often in corrosive soils, and thus the failure data set may be more likely to list corrosion as a primary root cause. But the point remains, corrosion control will only be impactful when corrosion is a significant root cause.

PVC or HDPE materials do not suffer from the same corrosion mechanisms as steel or ductile iron or the steel reinforcement within RCP. Corrosion prevention for steel appurtenances used with PVC/HDPE may benefit from corrosion control measures, but not for the plastic material itself. Various mechanical damage will remain the primary modes of failure.

The work from VA Tech (Vol. 4, Figure 48) indicated that 5% of RCP (PCCP) failures were associated with external corrosion.

VA Tech collected a large database concerning pipe failures from water utilities. As with most large data collection efforts, each reporting entity can provide varying levels of detail regarding the installation methods, operations, and failures of its infrastructure. When the

data are stratified to identify the impact of independent variables (such as corrosion protection methods), the subsets examined can vary across analyses.

The VA Tech work reported overall failure rates (failures/100 miles/year) ranging from 11.8 to 33.4 for ductile iron piping. Steel ranged from 2.9 to 55.8, considering all available data (Vol. 4, Table 21). When the larger dataset was stratified to determine the impact of corrosion protection methods (Vol. 4, Table 38), the failure rate for ductile iron with an asphaltic coating ranged from 13.6 (in high soil corrosivity) to 6.4 (in low corrosivity). Assuming these datasets represent similar age ranges, this suggests that even a moderate level of corrosion control is beneficial. With polyethylene encasement and cathodic protection, failure rates decrease to (nominally) zero (0). With a bonded dielectric coating, data showed no reported pipe failures. Low sample sizes precluded a similar analysis of failure rates on steel materials.

In detailed examinations of the relationships between corrosion control and coating failure, the NRC³ identified some small datasets concerning corrosion failures on ductile iron pipe with both polyethylene encasement and cathodic protection. Based on only three (3) corrosion failures in a total of 353 miles of pipeline in an average of 22.5 years, a failure rate of 0.038 failures/100 miles/year was identified.⁷

In addition to failure rates, VA Tech determined Mean Time to Failure (MTTF) estimates for the different materials. The expected service life (Vol. 4, Table 76) for ductile iron in high-corrosivity soils, for various protection methods, ranged from 43 to 50 years. Steel pipe analysis suggested a life of 29 to 42 years in high-corrosivity soils, with various external corrosion protection measures. The report authors note that the data for this analysis were “limited.” The “estimates shown in Table 76 might show lower numbers than what common knowledge dictates.” It appears that the authors felt the actual life exceeded the data-predicted values.

For larger-diameter metallic lines, the spread of service life between the 25th and 75th percentiles was 34-100 years for ductile iron pipe and 29-97 years for steel pipe (Vol. 4, Table 68). For both materials, service life increased as the soils shifted from highly corrosive to low-corrosivity soils. The differences between highly corrosive soils and moderately corrosive soils were much less significant. This suggests that it is easier to characterize low-corrosivity environments than to distinguish moderate and highly corrosive environments.

⁷ This data point is the same value used in the LCCA of Appendix A of the draft TM.

Life Cycle Cost Analysis

The draft TM Appendix A outlines a process for a life cycle cost analysis for pipelines in highly corrosive environments (resistivity < 500 ohm-cm). The intent is to focus only on corrosion-related failures. In summary, the LCCA process focuses on determining the initial construction costs for each pipeline material and the corrosion-related operation, maintenance, and repair (OM&R) costs over a 100-year period. The initial construction costs include the corrosion mitigation methods for alternative pipe materials as determined by the corrosivity criteria. The long-term OM&R costs include consideration of monitoring the existing corrosion control methods, periodic replacement of anodes/rectifiers etc., and repairing pipeline failures still likely to occur due to corrosion.

The analysis is laid out in Tables A-4 to A-5 of the draft TM Appendix A. Table A-4, Step 2 shows a weighted failure rate based on the VA Tech analysis. The selected data are for the overall failure rate of piping materials. The analysis is subsequently keyed off the expected corrosion-related failure rate for ductile iron pipe as developed by the NRC.⁷ This is a value of 0.038 failures/100 miles/year. The draft TM analysis assumes this is a fixed value for the first 50 years, then doubles in each subsequent decade, up to 100 years.

For ductile iron over the first 50 years, the number of failures with polythene encasement and cathodic protection in highly corrosive soil is projected to be $(0.038 \times 50) 1.9$ failures. In subsequent decades, the failure rate doubled; in years 50-60, the number of failures would be $(2 \times 0.038 \times 10) 0.76$. In years 60-70, it would be $(4 \times 0.038 \times 20) 1.52$. These data are summed in the TM Appendix A Table A-5.

Lacking other reliable corrosion-related failure rate data for the alternative materials incorporating corrosion control measures, the LCCA assumes that the corrosion-related failure rate for the alternative pipe materials is directly proportional to the ratio of their overall failure rates.⁸ For steel with a weighted-average failure rate of 10.6 failures/100 miles/year vs. the ductile iron failure rate of 32.3 failures/100 miles/year, the corrosion-related failure rate for steel was estimated as $(10.6 \times 0.038 / 32.3) = 0.012$ failures/100 miles/year. This value is then applied to the 0-50 year period and subsequently doubled in each successive decade.

Ultimately, the predicted number of pipe replacements for all materials for the purposes of the LCCA are proportional to the overall material failure rates. Based on the MTTF data for ductile iron vs. steel pipes in highly corrosive soils (Vol. 4, Table 76), the expected life of each material appears to fall within the same range, or arguably, the steel life was shorter, not longer. (Again, note that the report authors questioned those projections.) For the large

⁸ For pipe sizes > 16"

diameter lines (>36”), the VA Tech report (Vol. 4, Table 68) showed a similar useful life estimate for ductile iron and steel materials in high corrosion environments (these data were not segregated with forms of external corrosion control).

The NRC study included a comparison of the failure rate for ductile iron with encasement and cathodic protection to that of steel lines with a bonded coating and cathodic protection. The failure rate for the ductile iron was the aforementioned 0.038 failures/100 miles/year. The failure rate for the steel lines was 0.0044 failures/100 miles/year, or about 10x less than for ductile iron. The data set for the ductile iron was only for 353 miles, a very small exposure, but one that was well documented. The data set for the steel lines comprised 93,523 miles.

The ductile iron corrosion rates were also applied on a proportional basis to PVC and HDPE materials. These materials do not suffer from such corrosion phenomena. Perhaps the application of this criterion is to consider metallic appendages within an otherwise plastic system, but this is unclear.

The corrosion (i.e., chemical deterioration) of concrete or mortar on RCP occurs by a different mechanism than metallic corrosion. Such is a precursor to metallic corrosion of the reinforcement. So it is unclear whether the failure rate of ductile iron is related to RCP.

Conclusions

Question 1 - Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?

- 1) The criteria and weighting used for soil corrosivity are generally consistent with the primary parameters used in most soil corrosivity characterizations. No single set of alternative parameters has proven uniquely superior for assessing the probability of corrosion failure over an extended period.
- 2) However, given the propensity of design engineers to use Table 1 “as is” in scoring corrosivity, the scoring constraint of 5 points for stray current concerns, microbiologically induced corrosion, lessons learned from existing structures, and wet-dry cycling seems a potential weakness.
- 3) The technical memorandum needs to spell out the specific testing protocols for the parameters that are in the corrosivity model. Much is left to the discretion of the individuals interpreting the test methods, making it less likely that a uniform practice will be established. This applies to virtually all the parameters in the model.
- 4) The consequences of failure, Table 2, seem reasonable. The weightings are largely a matter of public policy, i.e., what aspect of serving the public is most important. Any

safety-related use of water from a utility may warrant additional consideration. The planning horizon for long-life infrastructure might also benefit from a “look-ahead” rather than the present day.

Question 2 - Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipes reliably provide a minimum service life of 50 to 100 years?

5) The question of service life is complicated. In low-corrosivity environments, the current service data suggest that a service life of 50+ years is being achieved.

6) The application of corrosion prevention standards, regardless of the environment, can only extend the service life where corrosion is a main contributor to the pipe failure. For materials such as PCCP or (apparently, in many cases) ductile iron, corrosion is not a significant factor in their failure rate.

7) Should the question apply only to buried metallic pipe in severe environments, the application of enhanced corrosion control methods, such as bonded coatings and cathodic protection, does assist in reducing corrosion-related failures and extending life. The similarity in reduced service life between what may be considered moderate-corrosivity environments and high-corrosivity environments supports more, not less, use of the best corrosion-control methods for metallic pipe or metallic appendages in plastic lines.

8) Age alone does not strongly correlate with pipe failure; other factors, such as coating quality, proper installation, and a corrosion monitoring program, are also critical to extending service life. The drastic difference in failure rates between highly regulated oil- and gas-transmission mains and water lines underscores the benefits of rigorous corrosion control.

Question 3 - Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?

9) The estimated replacement rates proposed for the LCCA are derived from a small, yet detailed study on ductile iron pipe with encasement and cathodic protection in a corrosive environment. Given the general paucity of other reliable failure-rate data under documented conditions, the replacement rate for ductile iron seems reasonable.

10) The application of this rate to other materials on a proportional basis of overall failure rates for materials across all environments and forms (or no forms) of protection is questionable. The lower projected rate for steel lines with a bonded coating and cathodic protection, compared with encapsulation and cathodic

protection, makes sense, given industry knowledge of encapsulation in the most corrosive locations. Further applications to concrete and, even more so, to plastic pipe are less reasonable.

Recommendations

- 1) Correct the technical memorandum confusion of sulfide and sulfate analysis as part of the corrosion models.
- 2) Consider expanding the value and impact of the terms presently in “Other Considerations” to better reflect the knowledge and concerns in industry today of root causes for corrosion.
- 3) Include by reference or inclusion the tests and analysis procedures for assessing the parameters in the corrosion model. The ASTM tests can be conducted in the field or in the laboratory and can yield very different results. Consider including sampling frequency based on the proposed right-of-way.
- 4) Consider the development of a supplemental model to address corrosion of RCP products. The model should consider factors that lead to concrete or mortar failure as precursors to corrosion of the metallic reinforcement.
- 5) Consider including in the Technical Memorandum guidance on the minimum requirements for quality control in the application of corrosion control methods and operational monitoring to assist in establishing the longest possible service life.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
1	James Ellor	pp. 1-3	Tables 1 & 2	The soil corrosivity and failure consequences will not be identical along the line. Will need a concept or recommended practice to identify the worst case or to consider non-uniform protection methods along the entire transmission line.	From a risk standpoint, you cannot use a single point as the design basis for an entire transmission line.	At the end of the final paragraph on page 1, recommend adding language to remind the user that site conditions along the pipeline ROW can vary considerably. Using tables based on average or worst-case conditions may not be appropriate for the entire line. The corrosion control practices may vary along the ROW. Recommended corrosion control measures should also consider the proposed construction practices, which themselves can vary along the line ROW.
2	James Ellor	p. 2	Table 1	The word stray is misspelled as "stay" in the row for Other Considerations.		Correct to the word "stray."
3	James Ellor	p. 2	Table 1	This section ("Other Considerations") may also benefit from the inclusion of concerns about AC-induced corrosion in pipelines within an HVAC corridor		Include AC Corrosion along with Stray Current, etc.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
				ROW. AC-induced corrosion is not mentioned elsewhere in the document.		
4	James Ellor	p. 2	Table 1	The footnote "1" appears twice in the table, which is a bit confusing. And the footnote itself, "Including but not limited to, those listed," is unclear. Is this intended to only refer to the table entries for "Other Considerations" or to all of the Parameters? If this applies only to "Other Considerations," it seems one can assign a value of 0-5 based on some of the listed considerations or on any other issue one might be concerned about.		Better define what footnote 1 means and use separate footnotes, if needed, for the column header Parameters and the entry for "Other Considerations."
5	James Ellor	p. 2	Table 1	By itself, a single parameter, such as the presence of stray current activity, might justify a higher level of corrosion risk, regardless of the		Consider breaking out the items in "Other Considerations" - one example is provided in the narrative of the report.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
				scores for other soil characteristics. While USBR acknowledges that a utility can always use higher levels of corrosion mitigation, those relying solely on the score sheet may not reach the same conclusion.		
6	James Ellor	p. 2	Table 1	The soil characteristics that affect steel/DI pipe are not the same as those that affect concrete. USBR should consider adding a separate ranking scheme for concrete pipe vs. steel or DI.	It is likely to encounter soil conditions acceptable to steel/DI but not to concrete pipe (PCCP), or vice versa.	Complete updates to the present Table 1, as otherwise discussed herein, and establish a separate rating scheme for concrete pipe. Key parameters (AWWA Manual M-9) might include: * chlorides (> 400 ppm) * local stray currents * sulfates (> 2,000 ppm) * pH < 5, with high total acidity * dissolved CO₂
7	James Ellor	p. 4	Table 4	Why not include protective coatings and/or high-performance concrete mixes for RCP in		Organic coatings applied to RCP and/or sulfate-resistant cements as external mitigation.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
				most corrosive environments?		
8	James Ellor	p. 9	3.1.1	The text describes soil resistivity measurements via ASTM G57 (or equivalent) and the application of a USBR 10% soil resistivity statistical method. It is not clear from the present document how measurements should be taken to use the score sheet in Table 1. This comment applies not just to soil resistivity but to the other measurements as well. Are the resistivity and pH data based on in-field measurements or in samples returned to the lab? Chloride and sulfate determinations require materials returned to the lab.	Need to ensure that data are being collected using a common method, consistent with those used in the references from which USBR derived their common score sheet of Table 1.	For all scored soil parameters, there should be a specific reference to the test method, how to address options within the method, and the data analysis. Consideration should also be given to listing a sampling plan for the specific pipeline ROW.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
				At what depth are the data collected? At the prospective pipeline depth?		
9	James Ellor	p. 12	Table 7	Table 7 indicates a listing of industry values relating sulfate ion concentration to soil corrosivity. Yet the table and sulfate discussion fail to recognize that two of the references (AWWA and Corrpro/DIPRA DDM) actually refer to sulfide not sulfate.	This needs to be corrected. Sulfides are a typical indicator or particular MIC species corrosive to underground metals. Sulfates contribute to overall soil conductivity and can relate to deterioration	Segregate the discussion of sulfides and sulfates. Retain sulfates in the ranking scheme, as they can relate to deterioration of concrete (and hence RCP), Add sulfides to the ranking table as a concern for steel and DI materials.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
					of concrete but are not a direct indicator of MIC conditions.	
10	James Ellor	p. 14	3.1.5	TYPO - USDS's Web Soil Survey tool is incorrect.		Change to USDA's Web Soil Survey tool
11	James Ellor	p. 16	3.1.6.3	This is such a key issue and should be emphasized more as a data point.	While there are ongoing discussions about the accuracy of corrosion models, the utility often has the best experiential data within its system.	Might consider adding a footnote to the final Table 1, where you list "Existing Structure Performance"—currently this is limited to a total score of 5. The footnote might take the reader to 3.1.6.3. And the last sentence might say, "If existing systems are experiencing significant corrosion with a particular combination of material and corrosion prevention, an alternative material and corrosion prevention scheme is warranted irrespective of the Table 1 score."

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
12	James Ellor	p. 16	3.2	Define "failure?"	Minor leaks are a form of failure as is complete line rupture. The probability of each as a function of line type is not well defined, but for the purposes of this TM, some additional emphasis should be placed on the definition of failure. Perhaps in terms of the level of repair, loss of service, etc.	

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
13	James Ellor	p. A-6	Table A-2	The cost estimates (time estimates) for rectifier adjustment (10 minutes) and test station readings (5 minutes) are extremely optimistic. Perhaps this does not matter, as the costs are small by comparison and will be largely discounted over the years, but often, especially on older systems, it can take an hour just to find a test station. Rectifier adjustments can take two trips to ensure that the adjustment has brought the line into the correct potential.		Increase the time per rectifier adjustment to 2 hours (allowing for polarization to occur), and a test station read to be closer to 30 minutes. The read itself may take 5 minutes, but getting to and finding the test station can be time-consuming.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
14	James Ellor	p. A-6	Appendix A, Section 2.4.2.1 and Table A-5	The predicted number of pipe section replacements in Table A-5 is considered those associated with corrosion. The predictions in Table A-5 are predicated on the inputs in Table A-4. Table A-4 shows the results of a two-step process of normalizing failure rates by (a) examining the material failure rate for all causes (ref. [5], Vol. 4, Table 21) and (b) the corrosion-specific failure rate of DI (ref. [3]). This process is simple, yet it seems to mesh together many unrelated phenomena. Consider the plastic pipe materials PVC and HDPE. Plastic materials do not corrode in the same sense as metallic	Need a method that relates the investment in a material and corrosion control to the net benefit in reduced pipeline repair when in service.	Without access to the raw data of the VA Tech work, it is challenging to list a specific change. Conceptually, one might take the raw data comprising overall failures, e.g., Figure 44 (ref. [5], Vol. 4), and segregate the results for "highly-corrosive" environments. Then, referring to the impact of corrosion control methods as in Table 38 (ref [5], Vol. 4), determine what percentage of the corrosion-related failures were eliminated by the application of the corrosion control method. These failures also need to be segmented over time and not treated as a constant failure rate as the materials age. Referring again to Figure 44, 92% of DI failures are attributed to a manufacturing flaw. If this remains true in highly corrosive environments across all ages,

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
				materials. Assigning a pro-rata share based on the ratio of the overall failure rate of plastic vs. DI and the failure rate for DI in a corrosive environment does not make sense if the plastic material does not corrode in a relatable manner. Corrosion (presumably of a metal appendage used with plastic) is not listed as a root cause of pipe failure in the work by VA Tech [ref. [5]. Vol. 4, p. 70). The same argument might be made for concrete materials. The soil parameters affecting concrete differ from those affecting metals, at least initially, in the deterioration of the exterior concrete coating.		there is little benefit to applying corrosion control methods.

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
15	James Ellor	p. A-7	Table A-3	The overall failure rate data from the VA Tech report form the basis of proportionality for coming up with the expected number of pipe replacements. Although a common term for considering failure across an entire utility, failure rates among different age groups can vary widely. The VA Tech Vol. 4 Table 72 (only data for 36"+ lines) suggests that the data sets for PVC and HDPE are substantially younger than for the metallic or concrete materials. The lower failure rates in Table A-3 for the PVC and HDPE materials may relate to the age of the pipes more so than ultimate performance. Figure 60 suggests that the failure rate for these materials is	The low failure rate used for the plastic materials (albeit that they do not "corrode" in a traditional sense), is low in part due to age of the cohort, providing a lower projected replacement schedule.	

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Comment #	SME Name	Page #	Paragraph /Section #	Comment	Rationale	Proposed Change (Optional)
				now increasing. Just not sure that the failure rates in Table A-3 are properly normalized among each other.		

Appendix C

Final Reclamation Response to Independent Peer Review Comments

Appendix C: Final Reclamation Response to Independent Peer Review Comments

Overview

This appendix documents Reclamation's final responses to the comments received during the independent scientific peer review of Technical Memorandum No. 8540-2024-13.

The Review Panel

Three independent scientific peer reviewers were contracted through an external blind selection process to review Reclamation's revision of the Technical Memorandum. The panel consisted of the following subject matter experts (SMEs):

- Cortney Chalifoux (Pond & Company)
- James A. Ellor (Elzly Technology Corporation)
- Andrew Haiko (CDM Smith)

The panel reviewed the document, completed a general comments matrix, and provided feedback on three review questions:

- Were appropriate criteria and weighting used to categorize soil corrosivity and consequences of pipe failure?
- Will the corrosion prevention minimum requirements outlined in this report for buried metallic pipe reliably provide a minimum service life of 50 to 100 years?
- Are the estimated replacement rates proposed for Life Cycle Cost Analysis appropriate?

The feedback provided by the reviewers ensures this risk-informed framework is technically robust, consistent with current industry standards, and applicable to the diverse environmental conditions found across Reclamation's infrastructure.

Reclamation Response

Reclamation accepted most of the reviewers' proposed changes and implemented them through editorial corrections, terminology updates, threshold refinements, and narrative clarifications in this revision of the Technical Memorandum.

The dispositions in the table below fall into three categories:

- Accepted: the recommendation was incorporated as proposed.
- Accepted with modification: the intent of the recommendation was addressed through an alternative approach.
- Not accepted: the recommended change was not incorporated as proposed.

The table that follows records each recommendation as received from the reviewers—comment, rationale, and proposed change—together with Reclamation's response and the completed action, organized by the section of the Technical Memorandum to which each applies.

Final Response Table

Table C-1.—Summary of Reclamation’s responses and actions for each reviewer recommendation

SME Name	Section	Summary/Comment ¹	Rationale ¹	Proposed Change ¹	Reclamation Response	Completed Action
Andrew Haiko	Acronyms and Abbreviations	Add AMPP (Association for Materials Protection and Performance)	NACE, International and SSPC merged to form AMPP. NACE is no longer an entity	Add AMPP (Association for Materials Protection and Performance) to the list of Acronyms and Abbreviations	Accepted. Reflects the NACE/SSPC merger.	Added AMPP to the Acronyms and Abbreviations list.
Andrew Haiko	Acronyms and Abbreviations	Remove NACE National Association of Corrosion Engineers	NACE, International has merged with SSPC to create AMPP. Additionally, NACE has not been the National Association for Corrosion Engineers for many years - the association changed their name to NACE, International and NACE was no longer an acronym for anything	Remove NACE from the Acronym and Abbreviations list. Conversely, keep NACE, but reference that the Association is now AMPP, since AMPP still references both NACE and SSPC standards. Do not say that NACE is the National Association of Corrosion Engineers, though, as that is not accurate. It can be written as "NACE International (formerly the National Association for corrosion Engineers)"	Accepted. Provides accurate historical and current industry context.	Revised NACE entry to "NACE International, now AMPP (formerly the National Association of Corrosion Engineers)."
James A Ellor	0 Summary, Table 1	The word stray is misspelled as "stay" in the row for Other Considerations.		Correct to the word "stray."	Accepted. Typographical error.	Corrected "stay" to "stray" throughout.
James A Ellor	0 Summary, Table 1	This section ("Other Considerations") may also benefit from the inclusion of concerns about AC-induced corrosion in pipelines within an HVAC corridor ROW. AC-induced corrosion is not mentioned elsewhere in the document.		Include AC Corrosion along with Stray Current, etc.	Accepted. AC interference is a valid consideration.	Added AC interference to the Stray Currents discussion (Section 3.1.6.1) and renamed the Table 1 factor to "Stray Current and AC-Influenced Corrosion."
James A Ellor	0 Summary, Table 1	The footnote "1" appears twice in the table, which is a bit confusing. And the footnote itself, "Including but not limited to, those listed," is unclear. Is this intended to only refer to the table entries for "Other Considerations" or to all of the Parameters? If this applies only to "Other Considerations," it seems one can assign a value of 0-5 based on some of the listed considerations or on any other issue one might be concerned about.		Better define what footnote 1 means and use separate footnotes, if needed, for the column header Parameters and the entry for "Other Considerations."	Accepted. Clarifying footnotes improves document usability.	Revised Table 1 footnotes; renamed the group to "Site-Specific Factors" and clarified footnote 1 to reference the Section 3.1.6 scoring rubric.
James A Ellor	0 Summary, Table 1	By itself, a single parameter, such as the presence of stray current activity, might justify a higher level of corrosion risk, regardless of the scores for other soil characteristics. While USBR acknowledges that a utility can always use higher levels of corrosion mitigation, those relying solely on the score sheet may not reach the same conclusion.		Consider breaking out the items in "Other Considerations" - one example is provided in the narrative of the report.	Accepted. Individually scoring these factors improves transparency and consistent application.	Split "Other Considerations" into five individually scored Site-Specific Factors (0–5 each): Stray Current & AC Interference, MIC, Existing Structure Performance, Backfill, and Wet-Dry Cycling.
James A Ellor	0 Summary, Table 1	The soil characteristics that affect steel/DI pipe are not the same as those that affect concrete. USBR should consider adding a separate ranking scheme for concrete pipe vs. steel or DI.	It is likely to encounter soil conditions acceptable to steel/DI but not to concrete pipe (PCCP), or vice versa.	Complete updates to the present Table 1, as otherwise discussed herein, and establish a separate rating scheme for concrete pipe. Key parameters (AWWA Manual M-9) might include: * chlorides (> 400 ppm) * local stray currents * sulfates (> 2,000 ppm)	Accepted. Separate metallic and concrete scoring columns account for differing material susceptibilities.	Separated metallic/concrete scoring columns in Table 1 addressing the material distinction.

SME Name	Section	Summary/Comment ¹	Rationale ¹	Proposed Change ¹	Reclamation Response	Completed Action
				* pH < 5, with high total acidity * dissolved CO2		
Cortney Chalifoux	0 Summary, table 1	Correct “Stay Current” to “Stray Current.”	Table 1 currently lists “Stay Current” under “Other Considerations,” which appears to be a typographical error for the recognized corrosion factor stray current. Leaving it unchanged may confuse scoring and design review.	Revise the term to Stray Current and define how it is to be scored.	Accepted. Typographical error.	Corrected (see above).
Andrew Haiko	0 Summary, Table 1	Stray Current written incorrectly as Stay Current	spelling error	revise "Stay" to "Stray"	Accepted. Typographical error.	Corrected (see above).
Andrew Haiko	0 Summary, Table 1	Under "Other Considerations", stray current can have profound effects on corrosion, and is known to be significantly more aggressive than any soil parameters in areas of significant stray current levels	Steel/ductile iron can lose up to 20 pounds per amp per year from corrosive discharge. While dynamic stray current (from dc powered transit systems) fluctuates over time, and do not present continuous discharge as the effects are dependent upon vehicle headways, they also can discharge hundreds of amperes off of metallic structures, which leads to very rapid deterioration, as stray current effects typically discharge off of a very small area. Static stray current does not typically carry such heavy loads, but is a continuous discharge concern. Ranking of stray current 0-5 underestimates stray current effects significantly.	Reconsider stray current as its own line item, rather than part of "Other Considerations"	Accepted. Stray current can dominate corrosion risk and warrants individual scoring.	Stray Current established as its own individually scored Site-Specific Factor (0–5) in Table 1, with a category-elevation override when scored 5.
James A Ellor	0 Summary, Table 1, Table 2	The soil corrosivity and failure consequences will not be identical along the line. Will need a concept or recommended practice to identify the worst case or to consider non-uniform protection methods along the entire transmission line.	From a risk standpoint, you cannot use a single point as the design basis for an entire transmission line.	At the end of the final paragraph on page 1, recommend adding language to remind the user that site conditions along the pipeline ROW can vary considerably. Using tables based on average or worst-case conditions may not be appropriate for the entire line. The corrosion control practices may vary along the ROW. Recommended corrosion control measures should also consider the proposed construction practices, which themselves can vary along the line ROW.	Accepted. Site-specific variability is a key implementation factor.	Added language to the Introduction noting that soil corrosivity and construction practices vary along the alignment and that a single/average condition may not represent the full line.
Cortney Chalifoux	0 Summary, Table 1; 3.1.3, Table 7	Strengthen the treatment of sulfates for RCP/RCP and PCCP in the criteria tables. Include explanation for sulfates in metallic corrosion as described by Peabody.	Table 1 assigns relatively low sulfate points compared with resistivity and chloride, while Section 3.1.3 correctly states sulfate attack can degrade concrete or mortar and expose reinforcement. ACI classifies 10,000 ppm for the highest sulfate exposure in concrete. Peabody recommends 10,000 ppm for highly corrosive soils for metallic structures in soil. Sulfate is highly corrosive to concrete, yet can also cause significant damage to steel when in certain environments.	Keep Table 1 as a general screen, but add a concrete-pipe supplemental sulfate evaluation for RCP/RCP/PCCP, especially in Group A and Group B conditions. Change the highest ranked sulfate value to 10,000 ppm to be consistent with literature.	Accepted with modification. Threshold aligned to industry literature; a separate supplemental concrete-sulfate evaluation was not added.	Set the highest sulfate tier to >10,000 ppm in Table 1 and separated sulfate (concrete) from sulfide (metallic) treatment in Section 3.1.3 and Table 7.
Cortney Chalifoux	0 Summary, Table 1; 3.1.6	Expand the scoring guidance for “Other Considerations” for soil corrosivity.	Table 1 combines stray current, MIC, existing structure performance, backfill, and wet-dry cycling into a single 0–5 input. The literature identifies these as interacting, site-specific	Break “Other Considerations” into subfactors or provide an explicit scoring rubric for each item so the method is applied consistently. Add additional details to Section 3.1.6 for each	Accepted. Explicit per-factor rubrics support consistent application.	Broke the category into five scored subfactors with explicit 0–5 rubrics in Section 3.1.6; added guidance on factor interaction.

SME Name	Section	Summary/Comment ¹	Rationale ¹	Proposed Change ¹	Reclamation Response	Completed Action
			drivers of localized corrosion rather than minor secondary issues.	category to support proper ranking and highlight critical considerations.		
Cortney Chalifoux	0 Summary, Table 1; 3.1.6.1	Update risk assessment for stray currents as a localized assessment rather than a general project consideration.	TM 8540-24 already recognizes stray-current corrosion and notes that nearby CP systems can be interference sources, but the scoring framework does not clearly show how adjacent protected utilities affect local risk. Because corrosion occurs where foreign current discharges from the pipeline, stray current should be evaluated as a localized interference risk rather than a general project condition.	Add guidance that nearby cathodically protected utilities and electrified infrastructure should raise the local stray-current score unless field testing shows negligible interaction.	Accepted. Proximity to other systems increases the risk profile.	Added guidance in Section 3.1.6.1 that proximity to CP-protected utilities or electrified infrastructure raises the local stray-current score (4–5) absent field testing showing negligible interaction.
Cortney Chalifoux	0 Summary, Table 1; 3.1.6.5	Incorporate coastal environment into the risk categories	The Virginia Tech study showed that ductile iron pipes had lower service life estimates in coastal conditions compared to other environmental conditions. The decrease in service life was attributed to saltwater intrusion-based corrosion caused by flooding events or sea-level rise.	TM 8540-24 could consider including location-based soil corrosivity ratings, specifically for coastal environments. This also could be accounted for in the Wet-Dry Cycling rating in Table 1 and discussion in Section 3.1.6.5.	Accepted with modification. Existing structure accounts for factors more generally. Environmental factors like coastal/tidal influences are best addressed through narrative clarification rather than a structural scoring change.	Added coastal/tidal and saltwater-intrusion conditions as high-severity cases within the Wet-Dry Cycling factor (Section 3.1.6.5 and Table 1).
Cortney Chalifoux	0 Summary, Table 2	The consequence-of-failure criteria should also account for the presence of adjacent utilities with active cathodic protection systems.	The consequence of pipe failure rating should be elevated where a proposed water line (or its cathodic protection system) could interfere with the corrosion protection on an existing protected utility, such as a gas pipeline, because the potential effects extend beyond the new water line and may create unanticipated corrosion, operational, and public-safety risks on neighboring infrastructure.	Add an additional category, either in "Other considerations", or separate to account for other energized utilities.	Accepted with modification. The risk associated with energized CP on adjacent utilities is captured within the Other Considerations - Stray Current section on Table 1.	Strengthened Sections 3.1.6.1 (Stray Current) and 3.2.1 (Location) to explicitly include adjacent buried utilities and those with active CP.
Andrew Haiko	0 Summary, Table 2	The Points value column numbers do not align with the Value descriptions, making it difficult to read the correlations correctly between the columns	For example, the row for Redundancy has spaced the Points column to match with the Value column	Align the two columns for clarity	Accepted. Value and Points columns were misaligned.	Reformatted Table 2 so Value and Points columns align.
Cortney Chalifoux	0 Summary, Table 2; 2.4	Add a material/failure-mode consequence modifier, especially for PCCP in severe environments.	Table 2 captures location, diameter, redundancy, pressure, and replacement time, but it does not expressly account for the different credible failure modes of leakage versus rupture. Section 2.4 states PCCP can fail catastrophically.	Add guidance to Table 2 that consequence may be increased where the material-environment combination changes the likely failure mode from leakage to structural failure or rupture.	Accepted with modification. Maintaining numeric scoring simplicity is preferred, though failure mode nuance is relevant.	Added narrative in Section 3.2 noting that where the material-environment combination shifts the credible failure mode from leak to rupture (e.g., PCCP), consequence should be weighted toward the high end. Numeric scoring retained.
James A Ellor	0 Summary, Table 4	Why not include protective coatings and/or high-performance concrete mixes for RCP in most corrosive environments?		Organic coatings applied to RCP and/or sulfate-resistant cements as external mitigation.	Accepted. Recognizes supplemental protection options used in the industry.	Added a note in Section 3.3.6 on project-specific supplemental exterior barriers and sulfate-resistant cements for concrete pipe.
Andrew Haiko	0 Summary, Table 4 - Pipe Group B	The use of cathodic protection with polyethylene encasement is debatable, as discussed later in the document.	A non-bonded system may shield the pipe from the cathodic protection, and active corrosion may occur beneath the polyethylene encasement which may preclude the CP from preventing the corrosion due to the shielding effects.	Pipe group B seems to be of such a level that consideration should be given to also require a bonded coating system and cathodic protection to ensure the desired 100-year design life in lieu of utilizing polyethylene encasement and metalized zinc coating	Accepted with modification. Addressed by eliminating former Group B rather than adding a bonded-coating requirement to it.	Eliminated former Pipe Group B; its cells merged into Group A (bonded coating + CP), removing the zinc/PE-plus-CP configuration from the matrix. Tables 3 and 4 renumbered to three groups.

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Corrosion Mitigation for Buried Metallic Water Pipe
Appendix C

SME Name	Section	Summary/Comment ¹	Rationale ¹	Proposed Change ¹	Reclamation Response	Completed Action
Andrew Haiko	0 Summary, Table 4 - Pipe Group B	Ductile iron with metallized zinc coating and polyethylene encasement with cathodic protection is NOT equivalent to steel with a bonded coating and cathodic protection.	Neither the Code of Federal Regulations (49 CFR - Part 192 (Gas) and Part 195 (Hazardous Liquids) nor NACE SP-0169 discuss the use of non-bonded coating systems. The CFR does not allow its use and requires bonded coating systems.	Reconsider the allowance of a non-bonded coating system with the use of cathodic protection	Accepted. Interaction risks (shielding) are noted.	Addressed via elimination of former Group B (above); added language on shielding limitations of non-bonded systems with CP in Section 3.3.3.
Andrew Haiko	0 Summary, Table 4 - Pipe Group C and Pipe Group D	The use of a bonded dielectric coating for the steel piping without also using cathodic protection may create localized corrosion at coating faults (holidays)	Bonded coatings are an effective means of preventing corrosion only where the coating is effective. At locations of coating faults (holidays) or other damage (such as from backfilling operations) active corrosion may occur at locations where the coating is no longer effective. As these areas are typically very small, rather than a general corrosion attack, a localized attack may occur which may lead to rapid corrosion. The cathodic protection system is designed to protect these areas from corrosion. Without CP, the bonded dielectric coating may actually create a worsened condition than having bare pipe due to the localized corrosion attack	Always include cathodic protection with bonded coating application	Not accepted. Reclamation risk-informed guidance allows for monitoring only in low-severity or low-consequence environments (Group C and D). The monitoring system would allow CP application should corrosion become a concern.	No change made. Risk-informed guidance retains monitoring-only options for low-severity/low-consequence groups; CP can be added later via the monitoring system if needed.
Cortney Chalifoux	0 Summary, Table 4; 2.5	Metallic Appurtenances on Non-Metallic Pipe	The matrix in Table 4 of TM 8540-24 should include corrosion mitigation recommendations for metallic appurtenances on non-metallic pipe.	Update the "Steel" designation under "Pipe Materials" in Table 4 to "Steel Pipe and Metallic Appurtenances".	Accepted with modification. Better reflects the actual scope of the guidance; however, change should be made to the heading, not the cells.	Revised the Table 4 material column header to "Material (Pipe or Appurtenance)."
Cortney Chalifoux	0 Summary, Table 4; 2.3; 2.4	Consider supplemental exterior barrier protection for concrete pressure pipe in the most aggressive environments.	TM 8540-24 currently uses inhibitor and CP for Group A RCP/RCP/PCCP. The concrete-pipe literature supports inhibitors and CP, but ACI 515.2R also recognizes barrier isolation as a standard method to protect concrete from aggressive exposure, and recent durability literature emphasizes chloride ingress, carbonation, and transport conditions at the steel-concrete interface.	Include polyurethane or epoxy barriers for the external mitigation of Pipe Group A RCP/RCP/PCCP, for the total system of "Polyurethane or Epoxy outer barrier and corrosion inhibitor in mix design for pipe wall (RCP/PCPP) or mortar coating (PCCP)."	Accepted. Recognizes supplemental protection options used in the industry.	Added a note in Section 3.3.6 on project-specific use of epoxy/polyurethane exterior barriers for RCP/RCP/PCCP.
Andrew Haiko	1	The Summary sections uses the terminology "ferrous elements" rather than reinforcing steel	"Ferrous elements" is a more accurate term, as it includes elements such as strands, where "reinforcing steel" typically brings to mind rebar in particular, rather than all types of ferrous reinforcement	revise "reinforcing steel" to "ferrous elements"	Accepted. More inclusive and technically accurate terminology.	Updated terminology to "ferrous elements."
Cortney Chalifoux	2.1; 3.2; 3.3	The statement that steel, ductile iron, and cast iron corrode at similar rates in similar soils is misleading and should be modified to address the different failure mechanisms and failure modes in each material-environment consideration.	TM 8540-24 distinguishes between different materials and corrosion protection systems in Table 4, this type of description and distinction should be carried out through the full document.	Clarify that the mechanism and modes of failure will be different in each material in Section 2.1. Add a material-specific note or modifier to the weighting discussion in Section 3-2 and the service-life discussion in Section 3-3.	Accepted. Material failure mechanisms are technically distinct.	Added a sentence in Section 2.1 noting that failure modes and damage distribution differ by material despite similar nominal corrosion rates.
Cortney Chalifoux	2.4; 3.3.5	For PCCP, strengthen the requirement for shorting straps for electrical continuity.	Section 2.4 states shorting straps can be used to maintain continuity if prestressing wires break, and Section 3.3.5 states all sections to be protected must be bonded for continuity.	Change "can be used" to stronger design guidance where PCCP will be monitored electrically or protected cathodically; at minimum, require a design decision and justification if shorting straps are omitted.	Accepted. Strengthens the technical recommendation for continuity.	Revised Section 2.4 to state that shorting straps should be provided where PCCP is monitored or cathodically protected.

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			For PCCP, continuity is central to both CP effectiveness and monitoring reliability.			
James A Ellor	3.2	Define "failure?"	Minor leaks are a form of failure as is complete line rupture. The probability of each as a function of line type is not well defined, but for the purposes of this TM, some additional emphasis should be placed on the definition of failure. Perhaps in terms of the level of repair, loss of service, etc.		Accepted. Standardized definitions improve document clarity.	Added a definition of failure in Section 3.2, distinguishing leaks from ruptures.
Andrew Haiko	3.5	Suggest limiting this to exclude Pipe Group A (and possibly B) and other pipes with high consequence of failure	Polyethylene encasement alone may not provide adequate levels of corrosion control for critical infrastructure, no matter the entity to be the ultimate owner. Critical piping systems in corrosive conditions should not be provided the opportunity to lower the corrosion control requirements	Exclude piping in Group A (and possibly B) along with other pipes with high consequence of failure	Not accepted. The existing deviation provision is retained in this revision.	No change made to Section 3.5 in this revision.
James A Ellor	3.1.1	The text describes soil resistivity measurements via ASTM G57 (or equivalent) and the application of a USBR 10% soil resistivity statistical method. It is not clear from the present document how measurements should be taken to use the score sheet in Table 1. This comment applies not just to soil resistivity but to the other measurements as well. Are the resistivity and pH data based on in-field measurements or in samples returned to the lab? Chloride and sulfate determinations require materials returned to the lab. At what depth are the data collected? At the prospective pipeline depth?	Need to ensure that data are being collected using a common method, consistent with those used in the references from which USBR derived their common score sheet of Table 1.	For all scored soil parameters, there should be a specific reference to the test method, how to address options within the method, and the data analysis. Consideration should also be given to listing a sampling plan for the specific pipeline ROW.	Not accepted. Soil sampling plans and testing frequencies are highly project-specific and must be tailored to site-specific geology and construction constraints.	No change made. Sampling plans and testing frequencies remain project-specific to preserve engineering flexibility.
Andrew Haiko	3.1.1	It is recommended that ASTM G57 be used in conjunction with Barnes Layer Analysis (Soil Investigation Employing A New Method of Layer-Value Determination for Earth Resistivity Interpretation/Peabody) to determine the layer resistivity rather than point resistivities	Point resistivities do not take into consideration the affects that layering of soils have on the corrosivity. The layer resistivity may show significantly more corrosivity than just the point values at depth due to changes in the soil content as the depths change. The single data point at pipe depth may be considered in one of the non-aggressive ranges, whereas the layer resistivity between data points in which the pipe is installed (for example, if the pipe is installed at 4 foot depth, the layer analysis between 2.5 feet and 5 feet) may fall into one of the corrosive soil categories.	Utilize the Barnes Layer Analysis rather than only relying on the point resistivity readings to ensure the most corrosive soil levels are evaluated	Accepted with modification. Barnes Layer analysis can be useful when limited soil resistivity information is available from ASTM G57 testing. Reclamation prefers to use multi-channel resistivity sounding coupled with inversion modeling to determine soil resistivity at the pipe depth.	Clarified Section 3.1.1: apparent resistivity (ASTM G57 Wenner soundings) is processed through computerized inversion to obtain true layer resistivities at pipe depth; Barnes Layer Analysis noted as an option where sounding data are limited.
Andrew Haiko	3.1.1	The 10-percent soil resistivity statistical method does not consider layering effects, as discussed in the previous comment	As discussed, the effects of layering on soil corrosivity should be considered	Utilize the Barnes Layer Analysis rather than only relying on the point resistivity readings to ensure the most corrosive soil levels are evaluated	See above response.	Addressed via the Section 3.1.1 clarification above.

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Andrew Haiko	3.1.1, Table 5	There is a new Edition of Peabody - "Peabody, Control of Pipeline Corrosion, Third Edition"	It is recommended to review the latest edition of the document to ensure that there have been no changes	Utilize the latest edition (typical)	Accepted for evaluation. Best practice for standard references.	Updated Peabody citations to the Third Edition throughout (Tables 5, 6, 7, 8 and References).
James A Ellor	3.1.4, Table 7	Table 7 indicates a listing of industry values relating sulfate ion concentration to soil corrosivity. Yet the table and sulfate discussion fail to recognize that two of the references (AWWA and Corpro/DIPRA DDM) actually refer to sulfide not sulfate.	This needs to be corrected. Sulfides are a typical indicator or particular MIC species corrosive to underground metals. Sulfates contribute to overall soil conductivity and can relate to deterioration of concrete but are not a direct indicator of MIC conditions.	Segregate the discussion of sulfides and sulfates. Retain sulfates in the ranking scheme, as they can relate to deterioration of concrete (and hence RCP), Add sulfides to the ranking table as a concern for steel and DI materials.	Accepted. Distinguishing between these two provides better technical precision.	Relabeled Table 7 to identify sulfide vs. sulfate references; revised Table 1 sulfide row to Positive (≥ 1 ppm)/Trace (>0 – <1 ppm)/Negative and separated the discussion in Section 3.1.3.
James A Ellor	3.1.5	TYPO - USDS's Web Soil Survey tool is incorrect.		Change to USDA's Web Soil Survey tool	Accepted. Updates to current terminology.	Corrected to "USDA."
Cortney Chalifoux	3.1.6	Include discussion regarding the interaction of factors influencing soil corrosivity.	The literature suggests that the interaction between factors is itself important. For example, the combination of soil heterogeneity and wet-dry cycling will be much more corrosive than either alone.	TM 8540-24 should make clear that the "other considerations" score is not a residual convenience category. Rather, it is the part of the framework intended to capture the site-specific conditions that often control localized corrosion and premature failure.	Accepted. Clarifying the intent of this category is important for proper use.	Added language in Section 3.1.6 stating that Site-Specific Factors capture dominant, often-interacting site conditions and directing scoring toward the high end where multiple factors co-occur.
James A Ellor	3.1.6.3	This is such a key issue and should be emphasized more as a data point.	While there are ongoing discussions about the accuracy of corrosion models, the utility often has the best experiential data within its system.	Might consider adding a footnote to the final Table 1, where you list "Existing Structure Performance"—currently this is limited to a total score of 5. The footnote might take the reader to 3.1.6.3. And the last sentence might say, "If existing systems are experiencing significant corrosion with a particular combination of material and corrosion prevention, an alternative material and corrosion prevention scheme is warranted irrespective of the Table 1 score."	Accepted. Field performance is a critical risk indicator.	Added a Table 1 footnote referencing Section 3.1.6.3 and a reinforcing statement that significant corrosion on comparable structures warrants elevated mitigation regardless of the numerical score.
Cortney Chalifoux	3.1.6.4	Expand the discussion regarding backfill weighting.	Section 3.1.6.4 discusses the implications of using the correct backfill, but it does not address the different strategies used for backfilling different pipe materials. Ductile iron specifically requires a more specialized backfill when it uses a PE encasement.	Include more detailed instructions on how the backfill will be ranked. For example, if native backfill will be used, this would be a higher ranking than specialized backfill.	Accepted. Detailed ranking rubrics for backfill will be updated for consistency.	Backfill established as a scored Site-Specific Factor with a 0–5 rubric and expanded discussion in Section 3.1.6.4; a detailed material-specific ranking rubric is deferred to a future revision.
Andrew Haiko	3.1.6.4	If using the existing soils as backfill, the various soil compositions will also intermix, which can increase the corrosivity from what was anticipated/measured	Intermixing of backfill materials may lead to altered soil conditions from what was measured initially, as the backfilling procedure will mix the existing soil layers into new compositions. This can change the corrosivity of the localized soils	Add a discussion on the effects of soil intermingling due to backfilling operations	Accepted. Relevant to localized corrosion cell formation.	Added discussion in Section 3.1.6.4 on intermixing of soil strata during backfilling and resulting localized corrosion cells.
Andrew Haiko	3.1.6.5	Recommend including a new section entitled 3.1.6.6 Adjacent Property Review	A historical review of adjacent properties can uncover significant conditions which may affect the corrosivity of the soil, if not now, in the near future, which otherwise may not been found during the initial field testing. Having the foreknowledge of future corrosivity concerns provides the ability to address these concerns during the design phase	Add 3.1.6.6 Adjacent Property Review: When building new pipelines, conduct an EPA ECHO search of adjacent properties. Check FRS registry records. Any industrial properties that could have coal residue (mining), broken concrete (old pipe factory and/or pre-caster sites). A GeoTech engineer should investigate for leach fields from old factory properties, investigate for tree root oxidation, and leaching from clay bottom ponds and land fills.	Accepted. The inclusion of adjacent property reviews is a standard requirement on Reclamation projects and was evaluated for inclusion in this corrosion-mitigation-specific document.	Incorporated as narrative in Section 3.2.1 (Location), including EPA ECHO/FRS review of adjacent and historical land uses during design, rather than as a separate Section 3.1.6.6.

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Andrew Haiko	3.3.1	Coated pipe with no CP can lead to accelerated localized corrosion at holidays, even in relatively non-corrosive soils	The use of bonded coatings without CP may lead to localized corrosion at locations of holidays/coating failure	Include CP with all bonded coatings	Not accepted. Reclamation risk-informed guidance allows for monitoring only in low-severity or low-consequence environments (Group C and D). The monitoring system would allow CP application should corrosion become a concern.	No change made (same rationale as Groups C and D above).
Cortney Chalifoux	3.3.2	Clarify that bonded dielectric coatings on ductile iron require ductile iron specific surface preparation and manufacturer-approved procedures.	TM 8540-24 correctly identifies bonded dielectric coatings as the best defense, but it does not explain that ductile iron surface preparation is not the same as steel.	Add ductile iron-specific language requiring manufacturer-approved procedures for surface preparation and coating application.	Accepted. Proper surface preparation is a critical variable in the long-term adhesion and performance of bonded coatings on ductile iron.	Updated Section 3.3.2 to require manufacturer-approved, ductile-iron-specific surface preparation and coating procedures.
Andrew Haiko	3.3.3	The use of Polyethene Encasement does not always provide better mitigation than bare pipe	There are existing studies where accelerated corrosion occurred underneath the polyethylene encasement in soil conditions which would not have otherwise been considered aggressive (An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe Jul 17, 2008 Michael J Szeliga - for example)	revise to state "may provide better protection"	Accepted. More accurate phrasing for technical guidance.	Revised text to "may provide better mitigation than bare pipe."
Cortney Chalifoux	3.3.3; 3.5	Tighten the severe-service language for zinc and PE encasement on ductile iron.	The use of PE encasement imposes additional installation constraints and introduces potential risks related to material damage and long-term performance. These factors should be carefully evaluated when selecting corrosion protection strategies, particularly in projects where standard ductile iron installation practices or variable backfill conditions are anticipated. Additionally, zinc will provide the long-term protection expected in acidic soils. Bonded dielectric coatings should be considered for acidic soils over zinc and PE encasement.	In Section 3.3.3, TM 5840-24 should include installation limitations, including backfill compatibility requirements, and highlight limitations for zinc and PE encasement in acidic soil. These considerations should also be reiterated in Section 3.5 if deviations are requested.	Accepted. Environmental and installation constraints are important considerations for these systems.	Added installation and backfill-compatibility limitations and acidic-soil cautions for zinc/PE encasement in Section 3.3.3.
Cortney Chalifoux	3.3.5	Include Precautions in CP Design for Each Pipe Material	TM 8540-24 already includes several precautions for the use of cathodic protection throughout the document. These precautions should be compiled and included together in Section 3.3.5 Cathodic Protection. One additional precaution is to mitigate hydrogen embrittlement in PCCP. Hall provides explicit precautions that would supplement the requirements in NACE SP0100 and would make the section more actionable.	In Section 3.3.5, include the specific precautions mentioned for each material and corrosion mitigation strategy that will be used in conjunction with cathodic protection (shielding, hydrogen embrittlement, and electrical continuity needs).	Accepted. Compiling precautions improves the technical clarity of the CP section.	Individual CP precautions (isolation, shielding, embrittlement) are present in Section 3.3.5; consolidation into a single by-material summary is deferred to a future revision.
Andrew Haiko	3.3.5	For galvanic CP, the sections must also be isolated for the CP to be effective	A grounded section with galvanic CP applied will rapidly deplete the sacrificial anodes due to large cathode/small anode effects.	Include a statement that the section to be protected using galvanic CP must be electrically isolated	Accepted. Essential technical requirement for galvanic systems.	Added a statement in Section 3.3.5 that galvanically protected sections must be electrically isolated.
Andrew Haiko	3.3.5	Hydrogen embrittlement concerns exist for prestressing cables in PCCP pipe.	Too much cathodic protection can cause a condition known as Hydrogen Embrittlement. The diffusion of hydrogen into the material from the cathodic reduction reaction can cause the reduction of ductility and fracture	Include a statement on the effects of overprotection from Impressed Current Cathodic Protection systems.	Accepted. Important safety and performance consideration.	Added a statement in Section 3.3.5 on the risk of hydrogen embrittlement from ICCP overprotection, particularly for PCCP prestressing wire.

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			toughness in metals (primarily high-strength steels). Stresses on the structure can then cause unanticipated failure modes.			
Andrew Haiko	A2.4.2, Table A-1	How is this calculated? There are typically two bonds at each pipe joint, located every 20 feet (typically), but appurtenances (valves, tees, crosses, etc.) will require different lengths and numbers of bond cables. How are the appurtenances factored into the per foot calculation?	The length of bond cables and weld supplies will vary greatly depending on the number of bends, valves, tees, etc. included in the piping system. A general linear foot length of pipe may greatly underestimate the actual required materials	Clarify how these are calculated	Accepted with modification. While the high-level logic can be clarified, the full derivation is outside the scope of this guidance document.	Updated Table A-1 joint-bond units to "linear ft, each" and added a narrative note in Section 2.4.2 on appraisal-level representative quantities.
Andrew Haiko	A2.4.2, Table A-2	How is travel time built into this? Depending on the location, there may be difficulty accessing locations	The ability to both access and find rectifiers and test stations should be considered in the time calculations. The timing at each locations seems reasonable, but the time to get from location to location and/or find/access the locations should be factored into the calculations	Include other factors into the anticipated time for each location	Accepted with modification. Appendix A uses high-level screening assumptions for comparative analysis. However, some of the estimated durations were adjusted.	Added a note that durations are comparative planning assumptions and increased the rectifier-adjustment and test-station durations in Table A-2.
Andrew Haiko	A2.4.2, Table A-2	Are all test stations to be monitored periodically, or only a select few repeated yearly to track changes over time?	What is the anticipated schedule - all test stations each survey, all test stations on a rotating basis, or select test stations repeated annually? This will facto into the ease of locating the test stations annually. If rotating, finding test facilities after many years will add difficulty and increase the time needed for each location	Clarify the proposed test procedure for the surveys	Not accepted. The durations and frequencies in Table A-2 are intended as simplified, appraisal-level assumptions to provide a consistent basis for comparing the life-cycle costs of different pipe materials.	No change made. Durations/frequencies are simplified appraisal-level assumptions; the Appraisal-Level Quantity Logic note clarifies their intended use.
James A Ellor	A2.4.2, Table A-2	The cost estimates (time estimates) for rectifier adjustment (10 minutes) and test station readings (5 minutes) are extremely optimistic. Perhaps this does not matter, as the costs are small by comparison and will be largely discounted over the years, but often, especially on older systems, it can take an hour just to find a test station. Rectifier adjustments can take two trips to ensure that the adjustment has brought the line into the correct potential.		Increase the time per rectifier adjustment to 2 hours (allowing for polarization to occur), and a test station read to be closer to 30 minutes. The read itself may take 5 minutes, but getting to and finding the test station can be time-consuming.	Accepted with modification. Appendix A uses high-level screening assumptions for comparative analysis. However, some of the estimated durations were adjusted.	Increased Table A-2 durations (rectifier adjustment to 2 hour; potential survey to 30 minutes) and added the comparative-planning note.
James A Ellor	A2.4.2.1, Table A-3	The overall failure rate data from the VA Tech report form the basis of proportionality for coming up with the expected number of pipe replacements. Although a common term for considering failure across an entire utility, failure rates among different age groups can vary widely. The VA Tech Vol. 4 Table 72 (only data for 36"+ lines) suggests that the data sets for PVC and HDPE are substantially younger than for the metallic or concrete materials. The lower failure rates in Table A-3 for the PVC and HDPE materials may relate to the age of the pipes more so than ultimate performance. Figure 60 suggests that the failure rate for these materials is now	The low failure rate used for the plastic materials (albeit that they do not "corrode" in a traditional sense), is low in part due to age of the cohort, providing a lower projected replacement schedule.		Accepted with clarification. The screening-level intent of the failure rate data is noted.	Added a statement in Appendix A on the screening-level intent and limitations of the comparative failure-rate data.

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		increasing. Just not sure that the failure rates in Table A-3 are properly normalized among each other.				
Cortney Chalifoux	A2.4.2.1, Table A-3, Table A-4, Table A-5	Clarify that Appendix A replacement rates are comparative planning assumptions and add a sensitivity analysis.	Appendix A uses data that accounts for all failures, not just corrosion related failures, then normalizes data to the NRC ductile-iron corrosion rate, uses a CSC proxy for RCP/RCP, assumes corrosion-related failure is static through year 50, then doubles every 10 years from 50 to 100 years, and rounds fractional failures to replacement of a full 20-foot section. Those are useful planning assumptions, but not validated material-specific deterioration laws. Moreover, by basing the failure predictions on historical data, the set is not accounting for the use of modern materials and mitigation strategies.	State explicitly that the Appendix A replacement rates are screening-level comparative values. Reassess the normalization of the data from the three studies. Modify the escalation rate after 50 years to ensure that the failure rates are not highly sensitive to that underlying assumption in the escalation rate or include additional options for the escalation rates based on a sensitivity analysis. Continue to capture data from utilities to supplement the current studies.	Accepted with modification. Implementation of extensive re-modeling is outside the current scope.	Added a statement that Appendix A replacement rates are screening-level comparative values and a note on sensitivity analysis for future revisions.
Andrew Haiko	A2.4.2.1, Table A-4, Table A-5	Assuming there are rounding errors. For example: 0.004 should double to 0.008, then 0.016, 0.032, and 0.064. Typical comment for Table A-4 and Table A-5	The number of significant digits used in the calculations does not match the data presented in the tables	Clarify the tables/significant digits utilized.	Accepted with clarification. Apparent discrepancies result from rounding values for table presentation while maintaining full precision in the underlying LCCA model.	Added a footnote to Tables A-4 and A-5 noting full-precision calculation with rounded display values.
James A Ellor	A2.4.2.1, Table A-5	The predicted number of pipe section replacements in Table A-5 is considered those associated with corrosion. The predictions in Table A-5 are predicated on the inputs in Table A-4. Table A-4 shows the results of a two-step process of normalizing failure rates by (a) examining the material failure rate for all causes (ref. [5], Vol. 4, Table 21) and (b) the corrosion-specific failure rate of DI (ref. [3]). This process is simple, yet it seems to mesh together many unrelated phenomena. Consider the plastic pipe materials PVC and HDPE. Plastic materials do not corrode in the same sense as metallic materials. Assigning a pro-rata share based on the ratio of the overall failure rate of plastic vs. DI and the failure rate for DI in a corrosive environment does not make sense if the plastic material does not corrode in a relatable manner. Corrosion (presumably of a metal appendage used with plastic) is not listed as a root cause of pipe failure in the work by VA Tech [ref. [5]. Vol. 4, p. 70). The same argument might be made for concrete materials. The soil parameters affecting concrete differ from those affecting metals, at least initially, in the deterioration of the exterior concrete coating.	Need a method that relates the investment in a material and corrosion control to the net benefit in reduced pipeline repair when in service.	Without access to the raw data of the VA Tech work, it is challenging to list a specific change. Conceptually, one might take the raw data comprising overall failures, e.g., Figure 44 (ref. [5], Vol. 4), and segregate the results for "highly-corrosive" environments. Then, referring to the impact of corrosion control methods as in Table 38 (ref [5], Vol, 4), determine what percentage of the corrosion-related failures were eliminated by the application of the corrosion control method. These failures also need to be segmented over time and not treated as a constant failure rate as the materials age. Referring again to Figure 44, 92% of DI failures are attributed to a manufacturing flaw. If this remains true in highly corrosive environments across all ages, there is little benefit to applying corrosion control methods.	Not accepted. The high-level segmentation and temporal modeling requested exceed the statistical resolution of the currently available industry datasets for large-diameter infrastructure.	No change made. Requested segmentation/temporal modeling exceeds the resolution of available industry datasets.