8 Cathodic Protection

APPLICATIONS AND DATA FOR CATHODIC PROTECTION REFERENCE ELECTRODES

Reference Electrode	Me/Me^{+} System	Electrolyte	Potential U_H at 25 °C (V)	Temperature Dependence (mV/°C)	Application
Cu-$CuSO_4$	Cu/Cu^{2+}	Sat. $CuSO_4$	+0.32	0.97	Soils, water
Ag-AgCl	Ag/Ag^{+}	Sat. KCl	+0.20	1.0	Saline and fresh water
Sat. calomel	Hg/Hg_2^{2+}	Sat. KCl	+0.24	0.65	Water, laboratory
1 *M* calomel	Hg/Hg_2^{2+}	1 *M* KCl	+0.29	0.24	Laboratory
Hg_2SO_4	Hg/Hg_2^{2+}	Sat. K_2SO_4	+0.71		Chloride-free water
Mercuric oxide	Hg/Hg_2^{2+}	0.1 *M* NaOH	+0.17		Dilute caustic soda
Mercuric oxide	Hg/Hg_2^{2+}	35% NaOH	+0.05		Concentrated causticsoda
Thalamid	Tl/Tl^{+}	3.5 *M* KCl	−0.57	<0.1	Warm media
Ag-saline	Ag	-	+0.25		Seawater[a]
Pb-H_2SO_4	Pb/Pb^{2+}	-	−2.8		Concentrated sulfuric acid

Reference Electrode	Me/Me$^+$ System	Electrolyte	Potential U_H at 25 °C (V)	Temperature Dependence (mV/°C)	Application
Zn-saline	Rest potential	-	−0.79[b] −0.77 ± 0.01		Seawater and brine
Zn-soil	Rest potential	-	−0.8 ±0.1		Soil
Fe-soil	Rest potential	-	−0.4 ±0.1		Soil
Stainless steel-soil	Rest potential	-	About −0.4 to +0.4		Soil

(a) The reference potential for other solutions containing Cl^- ions must be determined.
(b) Activated with Hg.

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 80. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

CRITERIA FOR CATHODIC PROTECTION

(Criteria listed below are general guidelines resulting from engineering experience and are not always applicable. The reader should use criteria based on the specific application.)

1. Steel and Cast Iron

A negative potential of at least 850 mV to a saturated copper–copper sulfate reference electrode (CSE) with the cathodic protection current applied. Voltage drops other than those across the structure to electrolyte boundary must be considered.

A negative polarized potential of at least 850 mV with respect to CSE.

A minimum of 100 mV of cathodic polarization between the structure and a stable reference electrode. This criterion also applies to steel in concrete.

2. Aluminum

A minimum of 100 mV of cathodic polarization between the structure and a stable reference electrode. Precautions must be taken to prevent overprotection of aluminum.

3. Copper

A minimum of 100 mV of cathodic polarization between the structure and a stable reference electrode.

SUMMARY OF PROTECTION CURRENT DENSITIES USED IN CP APPLICATIONS

Environment	Protection Current Density (mA/m^2)
Soil	
Neutral wall aerated (sandy soil)	30–150
Acid water saturated oil	20–50
Water saturated (clayey soil)	2–20
Anaerobic (presence of SRB)	50–450
Hot pipelines	50–80
Concrete	
Dry	2–20
Water saturated	0.2–2
Water (general)	$i_L = 4FD[O_2]\ Sh/\phi$
Water	
Stagnant	$i_{L.S} \cong C[O_2]$; $[O_2]$ (ppm); $C = 8–10$
Flowing (laminar)	$i \cong i_{L.S}(1 + \sqrt{v})$; v = velocity (m/s)
Flowing (turbulent)	$i \cong i_{L.S}(1 + 0.5v)$; v = velocity (m/s)
Fresh water	
Stagnant	30–50
Flowing (laminar)	50–65
Flowing (turbulent)	50–160
Sea water	
Stagnant	50–110
Flowing (laminar)	60–140
Flowing (turbulent)	80–550
Condensers, Heat exchangers	100–1,300
Hot risers	120–600
Acids	50–1,500
Coated steel	
Soil	0.01–1
Sea water	0.1–10

APPROXIMATE CURRENT REQUIREMENTS FOR CATHODIC PROTECTION OF STEEL

Environmental Conditions	Current Density mA/m²	mA/ft.²
Immersed in Seawater[a]		
Stationary		
Well coated	1 to 2	0.1 to 0.2
Poor or old coating	2 to 20	0.2 to 2
Uncoated	20 to 30	2 to 3
Low velocity[b]		
Well coated	2 to 5	0.2 to 0.5
Poor coating	5 to 20	0.5 to 2
Medium velocity[c]		
Uncoated	50 to 150	5 to 15
Well coated	5 to 7	0.5 to 0.7
Poor coating	10 to 30	1 to 3
Uncoated	150 to 300	15 to 30
High velocity[d]		
Poor coating or uncoated	250 to 1,000	25 to 100
Buried Underground[e]		
Soil resistivity		
0.5 to 5Ω·m	1 to 2	0.1 to 0.2
5 to 15Ω·m	0.5 to 1	0.05 to 0.1
15 to 40Ω·m	0.1 to 0.5	0.01 to 0.05

(a) Structures or vessels.

(b) 0.3 to 1 m/s (1 to 3 ft./s).

(c) 1 to 2 m/s (3 to 7ft./s).

(d) Turbulent flow.

(e) Pipelines or structures, coated or wrapped.

Source: B.P. Bardes, ed., *Metals Handbook,* 9th ed., vol. 1 (Materials Park, OH, USA: ASM International, 1978), p. 758. Reprinted with permission from ASM International.

DESIGN CRITERIA FOR OFFSHORE CATHODIC PROTECTION SYSTEMS

Production Area	Water Resistivity[B] (ohm-cm)	Water Temp. (˚C)	Environmental Factors[A]: Turbulence Factor (Wave Action)	Environmental Factors[A]: Lateral Water Flow	Typical Design Current Density[C] mA/M² (mA/ft.²): Initial[E]	Mean[F]	Final[G]
Gulf of Mexico	20	22	Moderate	Moderate	110 (10)	55 (5)	75 (7)
US West Coast	24	15	Moderate	Moderate	150 (14)	90 (8)	100 (9)
Cook Inlet	50	2	Low	High	430 (40)	380 (35)	380 (35)
Northern North Sea	26–33	0–12	High	Moderate	180(17)	90(8)	120 (11)
Southern North Sea	26–33	0–12	High	Moderate	150(14)	90(8)	100(9)
Arabian Gulf	15	30	Moderate	Low	130(12)	65(6)	90(8)
Australia	23–30	12–18	High	Moderate	130(12)	90(8)	90(8)
Brazil	20	15–20	Moderate	High	180(17)	65(6)	90(8)
West Africa	20–30	5–21			130(12)	65(6)	90(8)
Indonesia	19	24	Moderate	Moderate	110(10)	55(5)	75(7)

(A) Typical values and ratings based on average conditions, remote from river discharge

(B) Water resistivities are a function of both chlorinity and temperature. In the *Corrosion Handbook* by H.H. Uhlig (New York, NY, USA: John Wiley & Sons, Inc., 1948), the following resistivities are given for chlorinities of 19 and 20 parts per thousand:

	Resistivities (ohm-cm)				Temperature (˚C)	
Chlorinity (ppt)	0	5	10	15	20	25
19	35.1	30.4	26.7	23.7	21.3	19.2
20	33.5	29.0	25.5	22.7	20.3	18.3

C) In ordinary seawater, a current density less than the design value suffices to hold the platform at protective potential once polarization has been accomplished and calcareous coatings are built up by the design current density. CAUTION: Depolarization can result from storm action.

(D) Conditions in the North Sea can vary greatly from the northern to the southern area, winter to summer, and storm periods.

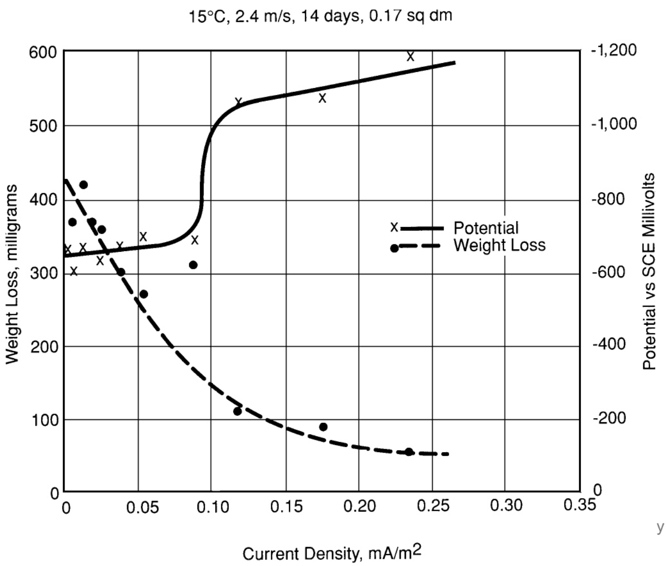
(E) Initial current densities are calculated using Ohm's Law and a resistance equation such as Dwight's or Crennell's (McCoyr's) equation with the original dimensions of the anode. An example of this calculation is given in Appendix D, using an assumed cathode potential of −0.80 V (Ag/AgCl[sw]).

(F) Mean current densities are used to calculate the total weight of anodes required to maintain the protective current to the platform over the design life.

(G) Final current densities are calculated in a manner similar to the initial current density, except that the depleted anode dimensions are used.

Source: H.P. Hack, ed., ASTM STP1370, *Designing Cathodic Protection Systems for Marine Structures and Vehicles* (West Conshohocken, PA, USA: ASTM International, 2000). Reprinted with permission, copyright ASTM.

EFFECT OF APPLIED CATHODIC CURRENT ON CORROSION AND POTENTIAL OF STEEL IN FLOWING SEAWATER



Source: F.L. LaQue, *Marine Corrosion Cause and Prevention* (Hoboken, NJ, USA: John Wiley & Sons, 1975), p. 74. Reprinted with permission from The Electrochemical Society.

SYSTEMS FOR COASTAL AND HARBOR STRUCTURES

Installation	Coating	Splash Zone (m^2)	Current Density ($mA\ m^{-2}$)	Type of Anode	No. of Anodes	Anode Weight (t)	Rectifier Output (A)	Life (years)
Loading pier, Liberia	Tar pitch	5,400	25→6.5	Zn	190	14	–	25
Loading pier, San Salvador	Tarpitch	27,000	70	C	120	–	7 × 300	15
Tanker pier, North Sea	Tarpitch	39,000	30	FeSi-Mo	210	–	65 × 20	15
Ore pier, Malaysia	Tarpitch-epoxy	35,000	15→5	PtTi	30	–	4 × 100	>10
Steel piling, Elbe	Tarpitch-epoxy	25,000	16	FeSi-Cr	380	4	20 × 100	>20
Drawbridge, Wilhelmshaven	Tarpitch-epoxy	22,000	10	FeSi-Mo	160	8	18 × 150	>25
Loading quay, Lomé-Togo	Tarpitch-epoxy	70,000	18	PtTi	71	–	2 × 250 2 × 150	>25
Ferry harbor, Puttgarden	None	8,500 and ca. 5,500 steel-reinforced concrete	160	PtTi	360	–	20 × 100	>10
Tonasa II Indonesia	None	11,250 and 5,140 soil	70→30	PtTi	45	–	1 × 600 2 × 120	>20

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 381. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

CATHODIC PROTECTION OF METALS AND ALLOYS PROTECTION POTENTIALS AND RANGES

System Material	System Medium	Protection Potential/ Region (in volts) U_H	$U_{Cu-CuSO_4}$	Notes/References
Plain carbon and low-alloy ferrous materials	Neutral waters, saline and soil solutions (25 ˚C)	<−0.53	<−0.85	Protection against weight loss corrosion (with film formation U_s is more positive)
	Boiling neutral waters	<−0.63	<−0.95	
	Weak acidic waters and anaerobic media (25 ˚C)	<−0.63	<−0.95	
	High-resistance sandy soils	<−0.43	<−0.75	
		(−0.33)	(−0.65)	
High-alloy steels with >16% Cr (e.g. 1.4301, AISI 304)	Neutral waters and soils (25 ˚C)	<0.2	<−0.1	Protection against pitting and crevice corrosion
	Boiling neutral waters	<0.0	<−0.3	Heating surfaces are more susceptible than cooling surfaces
CrNiMo stainless steels and Cr-rich special alloys	Seawater (25 ˚C) Cl^- containing media	<0.0 (in general more positive; U_{PC} values determine)	<−0.3	U_s becomes more negative with increasing Cl^- concentration and temperature
CrNi stainless steels	Cl^- containing hot water	About <0.0	About <−0.3	Protection against stress corrosion
Plain carbon and low-alloy steels	Warm solutions of			Protection against stress corrosion
	Nitrates	<−0.15	<−0.47	
	Caustic soda	<−0.98	<−1.30	Strain induced
	Na_2CO_3	<−0.68	<−1.00	Strain induced
	$NaHCO_3$	<−0.43	<−0.75	Strain induced
	$(NH_4)_2CO_3$	<−0.35	<−0.67	
Cu, CuNi alloys	Neutral waters and soils (25 ˚C)	<+0.14	<−0.18	Protection against weight loss corrosion
Sn	Neutral waters (25 ˚C)	<−0.33	<−0.65	
Plain carbon and low-alloy ferrous materials	Seawater	<−0.53/ <−0.78	<−0.85 <−1.10	Protection for this films against stress corrosion at fluctuating loads
	Cement, concrete	−0.43/−0.98	−0.75/−1.3	

		Protection Potential/ Region (in volts)		
System Material	System Medium	U_H	$U_{Cu-CuSO_4}$	Notes/References
High-alloy heat-treated Cr steels (R_m > 1,200 N mm^{-2})	Seawater (25 ˚C)	−0.5/−0.0	−0.82/−0.32	Protection against corrosion and H-induced stress pitting corrosion
Pb	Neutral waters and soils (25 ˚C)	−1.4/−0.33	−1.7/−0.65	Protection against hydride formation and weight loss corrosion
Zn	Neutral Waters and soils (25 ˚C)	−1.3/−0.96	−1.6/−1.3	
Al, Al alloys	Cold water			Protection against weight loss corrosion and pitting corrosion
Al Zn 4.5 Mg 1	Fresh Water Seawater Seawater	−1.0/−0.3 −1.0/−0.5 −1.0/−0.7	−1.3/−0.62 −1.3/−0.82 −1.3/−1.02	U_s becomes more negative with decreasing Na^+ concentration
Ti, Ti alloys	Halide-free acids	>0.0	>−0.32	Protection against weight loss corrosion
	Increased concentration and temperature	U_s becomes more positive		
Plain carbon and low-alloy steels (R_p < 600) hardened region	Warm caustic soda (R_m>1000 N mm^{-2}) Warm Na_2CO_3 soln $NaHCO_3$ soln. $(NH_4)_2CO_3$ soln.	−0.6/+0.2 −0.4/+0.2 −0.6/? −0.3/? −0.25/?	−0.9/−0.1 −0.7/−0.1 −0.9/? −0.6/? −0.57/?	Protection against stress corrosion and weight loss corrosion. Strain induced
Fe, plain carbon steels	0.5 M H_2SO_4 (25 ˚C)	0.8/1.6	0.5/1.3	Protection against active and transpassive corrosion
High-alloy steels with >16%Cr	Halide-free cold acids	0.2/1.1	−0.1/0.8	Protection against active and transpassive corrosion
	Boiling conc. H_2SO_4 Cl^- and NO^- containing water (25 ˚C)	1.2/1.6 0.5/1.1	0.9/1.3 0.2/0.8	Protection against pitting corrosion and transpassive corrosion

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COMPOSITION AND PROPERTIES OF SOLID IMPRESSED CURRENT ANODES (WITHOUT COKE BACKFILL)

Type	Composition (wt.%)	Density ($g\ cm^{-3}$)	Anode Current Density ($A\ m^{-2}$) max.	Anode Current Density ($A\ m^{-2}$) avg.	Anode Consumption ($g\ A^{-1}\ a^{-1}$)
Graphite	100 ˚C	1.6 to 2.1	50 to 150	10 to 50	300 to 1,000
Magnetite	Fe_3O_4 + additions	5.2	-	90 to 100	1.5 to 2.5
High-silicon iron	14 Si, 1 ˚C remainder Fe (5 Cr or 1 Mn or 1 to 3 Mo)	7.0 to 7.2	300	10 to 50	90 to 250
Lead-silver Alloy 1	1 Ag, 6 Sb, remainder Pb	11.0 to 11.2	300	50 to 200	45 to 90
Alloy 2	1 Ag, 5 Sb, 1 Sn, remainder Pb	11.0 to 11.2	300	100 to 250	30 to 80
Lead-platinum	Lead + Pt pins	11.0 to 11.2	300	100 to 250	2 to 60

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 212. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

PROPERTIES OF METALS USED IN PLATINUM TYPE IMPRESSED CURRENT ANODES

Property	Pt	Ta	Nb	Ti
Atomic weight	195.09	180.95	92.91	47.90
Crystal structure	FCC	BCC	BCC	CPH
Density, g/cm^2, 20 ˚C	21.45	16.6	8.57	4.54
Meltingpoint, ˚C	1,769	2,996	2,468	1,668
Boilingpoint, ˚C	4,530	5,425	3,300	3,260
Specific heat, cal/gm	0.032	0.036	0.065	0.126
Thermal conductivity				
cal/cm^2/cm/sec/ ˚C	0.17	0.13	0.12	0.04
Electrical resistivity μΩ/cm	10.6	12.4	13.1	42
Linear coefficient of thermal expansion (× 10^4) in./ in./ ˚C	9.1	6.5	7.1	8.5
Tensile strength psi (× 10^{-4}), annealed	18–24	50	50	78.7
Elongation in 2 in., % annealed	30–40	40	30	25

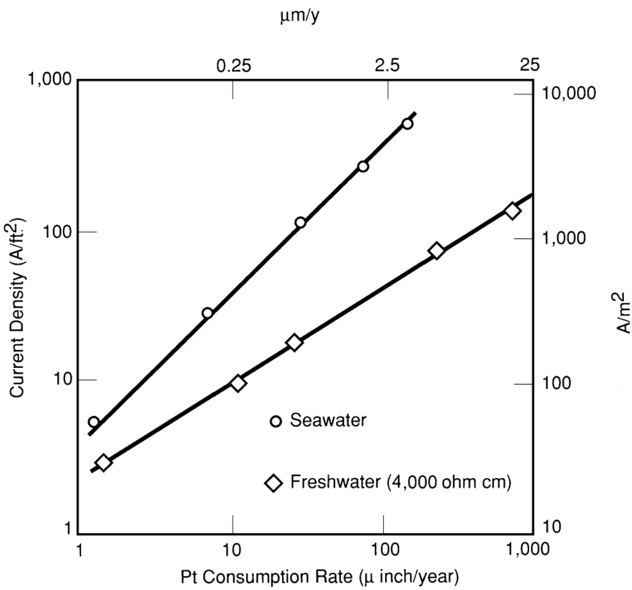
Source: R. Baboian.

COMPOSITION AND PROPERTIES OF NOBLE METAL ANODES

Sub-strate Metal	Density (g cm^{-3})	Coating	Density (g cm^{-3})	Coating Thick-ness (μm)	Anode Cur-rent Density (A m^{-2}) max. avg.	Allowable Maximum Driving Voltage (max/V)	Loss (mg A^{-1} a^{-1})
Platinum	21.45	Platinum	21.45	Solid	$> 10^4$		<2
Titanium	4.5	-		-		12 to 14	
Niobium	8.4	-		-		about 50 (<100)	
Tantalum	16.6	-		-		>100	
Ti, Nb, Ta		Platinum	21.45	2.5 to 10	$>10^3$	600 to 800	4 to 10
Ti, Nb,		Lithium-ferrite	6 to 12	<25	$>10^3$	100 to 600	<1 to 6
Ta Ti		Mixed Metal Oxide	15		$>10^3$	500	10

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 214. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

PLATINUM CONSUMPTION RATES FOR CATHODIC PROTECTION ANODES



Source: R. Baboian.

PROPERTIES OF IMPRESSED CURRENT ANODES FOR SOILS

Anode Material	Iron		High-Silicon Iron			Graphite			Magnetite	Lithium Ferrite on Titanium
Length (m)	1 m NP 30 double T	1 m rail	0.5	1.2	1.5	1	1.2	1.5	0.9	0.5
Diameter (m)	girder ht. 0.3, br. 0.13	0.14, 0.13	0.04	0.06	0.075	0.06	0.06	0.08	0.04	0.016
Weight (kg)	56	43	16	26	43	5	6	8	6	0.2
Density (g cm^{-3})	7.8	7.8	7	7	7	2.1	2.1	2.1	5.18	6 to 12
Practical loss without coke backfill (kg A^{-1} a^{-1})	10	10		0.2–0.3		1	1	1	0.002	0.001
Practical loss with coke backfill (kg A^{-1} a^{-1})	5	5		ca. 0.1			ca. 0.2–0.5		–	< 0.001
Life at 1 A per anode without coke backfill (yrs.)	5	4	50	80	140	5	6	8	200	120
Life at 1 A per anode with coke backfill (yrs.)	10	8	160	260	430	10	12	16	–	> 120
Danger of fracture	None			Moderate			High		Moderate	None
Recommended installation site	Extended anode installation with coke backfill in poorly conducting soils, very economical		Mostly used for impressed current anodes with long life, also without coke backfill			Aggressive soils and aqueous solutions also without coke backfill; relatively economical			Soils Sea-water	Deep anodes Sea-water

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 209. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

PROPERTIES OF GALVANIC ANODES

Anode Material	Density Kilograms Per Cubic m	Current Efficiency %	Consumption Rate Actual (Kg/Amp.-Yr.)	Potential to $CuSO_4$ Electrode (Volts)
Magnesium:	1,936	50	7.9	
Standard Alloy				−1.55
High Potential Alloy				−1.80
Aluminum	2,720	95	3.1	−1.1
Zinc	7,040	90–95	11.8	−1.1

Source: H.P. Hack, ed., ASTM STP1370, *Designing Cathodic Protection Systems for Marine Structures and Vehicles* (West Conshohocken, PA, USA: ASTM International, 2000), p. 56. Reprinted with permission, copyright ASTM.

COMPOSITION (WT. %) AND PROPERTIES OF ALUMINUM ALLOYS FOR ANODES

Type	Hg-Zn (X-Meral)	In-Zn (Galvalum III)	Sn-Zn
Zinc	2.0 to 2.2	3.0	5.5
Mercury	0.045 to 0.055	-	-
Indium	-	0.015	-
Tin	-	-	0.1
Iron	<0.1	-	<0.1
Copper	<0.02	-	<0.005
Silicon	<0.05	0.1	<0.1
Manganese	0.25 to 0.3	-	<0.005
Titanium	0.02 to 0.03	-	<0.04
Magnesium	0.04 to 0.05	-	<0.005
Rest Potential in Seawater			
U_H/V	−0.8/−1.0	~−0.85	~−0.86

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 189. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

COMPOSITION AND PROPERTIES OF MAGNESIUM ANODES[1]

Specific Gravity	1.94
Pounds per Cubic Foot.	121
Theoretical Amp Hours per Pound.	1000
Theoretical Pounds per Amp per Year	8.7
Current Efficiency—Percent	50[2]
Actual Amp Hours per Pound	500[2]
Actual Pounds per Amp per Year	17.4[2]
Solution Potential—Volts to CSE	
Standard H-1 Alloy	−01.50 to −01.55[3]
High Potential Alloy	−01.75 to −01.77[4]
Driving Potential to Pipeline Polarized to −00.90 Volt to $CuSO_4$	
Standard Alloy—Volts	0.55[5]
High Potential Alloy—Volts	0.80[5]

(1) Anodes installed in suitable chemical backfill.
(2) Current efficiency varies with current density. Efficiency given (which results in actual amp hr. per pound and actual pounds per amp per year shown) is at approximately 30 milliamps per sq. ft. of anode surface. Efficiencies are higher at higher current densities, lower at lower current densities.
(3) Alloy with nominal composition % 6 Al, 3 Zn, 0.2 Mn, and balance Mg.
(4) Proprietary alloy–manganese principal alloying element.
(5) Driving potentials allow for anode polarization in service of approximately 0.10 volt which reduces the solution potential by this amount. Driving potential in volts for pipeline polarized to any specific potential (P) in volts = solution potential of magnesium type used minus 0.10 volts minus P.

STANDARD H-1 ALLOY CHEMICAL COMPOSITION

	Weight Content %		
Element	**Grade A**	**Grade B**	**Grade C**
Al	5.3–6.7	5.3–6.7	5.0–7.0
Mn	0.15 min	0.15 min	0.15 min
Zn	2.5–3.5	2.5–3.5	2.0–4.0
Si	0.10 max	0.30 max	0.30 max
Cu	0.02 max	0.05 max	0.10 max
Ni	0.002 max	0.003 max	0.003 max
Fe	0.003 max	0.003 max	0.003 max
Other	0.30 max	0.30 max	0.30 max
Magnesium	Remainder	Remainder	Remainder

HIGH POTENTIAL ALLOY CHEMICAL COMPOSITION

Element	Weight Content %
Al	0.010
Mn	0.50 to 1.30
Cu	0.02 max
Ni	0.001 max
Fe	0.03 max
Other	0.05 each or 0.3 max Total
Magnesium	Remainder

Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion,* 2nd ed. (Houston, TX, USA: NACE International, 2001), p. 181.

COMPOSITION AND PROPERTIES OF ZINC ANODES(1)

Specific Gravity 7

Pounds per Cubic Foot 440

Theoretical Amp Hours per Pound .... 372(2)

Theoretical Pounds per Amp per Year 23.5

Current Efficiency—Percent .... 90(3)

Actual Amp Hours per Pound 335

Actual Pounds per Amp per Year 26

Solution Potential—Volts to CSE .... −1.1

Driving Potential to Pipeline
Polarized to—0.90 Volt to $CuSO_4$ .... 0.2(4)

(1) Anodes installed in suitable chemical backfill.
(2) Zinc used for soil anodes should be high purity zinc such as "Special High Grade" classification which is at least 99.99 percent pure zinc.
(3) Current efficiency of zinc is reasonably constant from low to very high current outputs in terms of milliamperes per sq. ft. of anode surface. This applies when the high purity anode grade zinc is used. The 90 percent efficiency is conservative.
(4) Zinc not subject to significant anodic polarization when used in suitable backfill. Driving potential is zinc solution potential minus polarized potential of protected structure.

CHEMICAL COMPOSITION

Element	Weight Content %	
	MIL-A-18001 (ASTM B-418 Type I)	ASTM B-418 Type II
Al	0.1–0.5	0.005 max
Cd	0.02–0.07	0.003 max
Fe	0.005 max	0.0014 max
Pb	0.006 max	0.003 max
Cu	0.005 max	0.002 max
Zinc	Remainder	Remainder

Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion*, 2nd ed. (Houston, TX, USA: NACE International, 2001), p. 184.

COMPARISON OF ZINC AND MAGNESIUM ANODES FOR SOILS

Soil Resistivity in ohm-cm	Anode Type	Driving Potential in volts with Pipeline Polarized to –0.85V	Maximum Permissible Circuit Resistance in ohms, for 75 mA	Max Permissible Resistance of Anodes and Leads, in ohms, with 2 ohms Pipe-to-Earth Resistance	Number, Size (in inches) and Weight (Each) of Anodes Selected	Resistance of Anode Array Selected in ohms	Actual Total CIrcuit Resistance in ohms	Actual Current in mA with Pipeline Polarized to –1.05V with zinc or to –1.20V with Mg	Indicated Anode Life in Years	Max Current, mA, with Pipe-to-Earth Resistance Dropped to 0.50 and with –0.85V Polarized	Regulation as Ratio of Maximum Current to that Under Initial Conditions	Indicated Anode Life in Years Under Maximum Current Conditions
300	Mag	0.6	8.0	6.0	One 3x3x60, 40-Pound	1.44	3.44	72.8	27.2	403	5.55	4.9
	Zinc	0.25	3.3	1.3	Two 1.4x1.4x60, 30-Pound	0.76	2.76	18.1	107	198	11.0	9.8
500	Mag	0.6	8.0	6.0	One 3x3x60, 40-Pound	2.0	4.0	62.5	31.5	240	3.85	8.2
	Zinc	0.25	3.3	1.3	Two 1.4x1.4x60, 30-Pound	1.07	3.07	16.2	120	159.5	9.85	12.2
1,500	Mag	0.6	8.0	6.0	One 2x2x60, 20-Pound	4.81	6.81	36.6	26.9	113	3.08	8.7
	Zinc	0.25	3.3	1.3	Five 1.4x1.4x60, 30-Pound	1.24	3.24	15.4	315	144	9.35	33.6
3,000	Mag	0.6	8.0	6.0	Two 2x2x60, 20-Pound	4.86	6.86	36.4	55.2	112	3.08	17.6
	Zinc	0.25	3.3	1.3	Two 1.4x1.4x60, 30-Pound	1.3	3.3	15.2	745	139	0.15	83

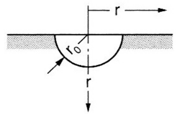
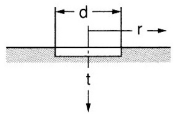
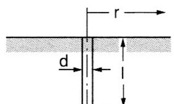
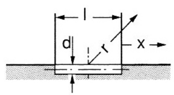
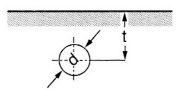
Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion,* 2nd ed. (Houston, TX, USA: NACE International, 2001), p. 181.

RESISTANCE OF GALVANIC ANODES–DWIGHT'S EQUATION

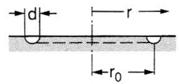
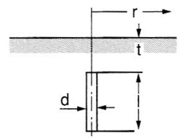
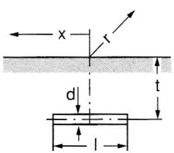
One vertical ground rod: length L, radius a	$R = \frac{p}{2\pi L}\left(\log_n \frac{4L}{a} - 1\right)$
Two vertical ground rods separation s, s > L	$R = \frac{p}{4\pi L}\left(\log_n \frac{4L}{a} - 1\right) + \frac{p}{4\pi s}\left(1 - \frac{L^2}{3s^2} + \frac{2}{5} \cdot \frac{L^4}{s^4} \cdots\right)$
s < L	$R = \frac{p}{4\pi L}\left(\log_n \frac{4L}{a} + \log_n \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \cdots\right)$
Buried horizontal wire, length 2L, depth s/2	$R = \frac{p}{4\pi L}\left(\log_n \frac{4L}{a} + \log_n \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \cdots\right)$
Right-angle turn of wire: length of arm L, depth s/2	$R = \frac{p}{4\pi L}\left(\log_n \frac{2L}{a} + \log_n \frac{2L}{s} - 0.24 + 0.2\frac{s}{L} \cdots\right)$
Three-point star	$R = \frac{p}{6\pi L}\left(\log_n \frac{2L}{a} + \log_n \frac{2L}{s} + 1.1 - 0.2\frac{s}{L} \cdots\right)$
Four-point star	$R = \frac{p}{8\pi L}\left(\log_n \frac{2L}{a} + \log_n \frac{2L}{s} + 3 - \frac{s}{L} \cdots\right)$
Six-point star	$R = \frac{p}{12\pi L}\left(\log_n \frac{2L}{a} + \log_n \frac{2L}{s} + 6.9 - \frac{3s}{L} \cdots\right)$
Eight-point star	$R = \frac{p}{16\pi L}\left(\log_n \frac{2L}{a} + \log_n \frac{2L}{s} + 11 - 5.5\frac{s}{L} \cdots\right)$
Ring of wire, Diameter D of ring, diameter of wire, a depth s/2	$R = \frac{p}{2\pi^2 D}\left(\log_n \frac{8D}{d} + \log_n \frac{4D}{s}\right)$
Buried horizontal strip: length 2L, section a by b depth s/2, b < a/8	$R = \frac{p}{4\pi L}\left(\log_n \frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} + \log_n \frac{4L}{s} - 1 + \frac{s}{2L} - \frac{s^2}{16L^2}\right)$
Buried horizontal round plate radius a, depth s/2	$R = \frac{p}{8a} + \frac{p}{4\pi s}\left(1 - \frac{7a^2}{12s^2} + \frac{33a^4}{40s^4} \cdots\right)$
Buried vertical round plate	$R = \frac{p}{8a} + \frac{p}{4\pi s}\left(1 + \frac{7a^2}{24s^2} + \frac{99a^4}{320s^4} \cdots\right)$

Source: J.H. Morgan, *Cathodic Protection,* 2nd ed. (Houston, TX, USA: NACE International, 1987), p. 104.

CALCULATION FORMULAS FOR SIMPLE ANODES (ANODE VOLTAGE $U_0 = IR$)

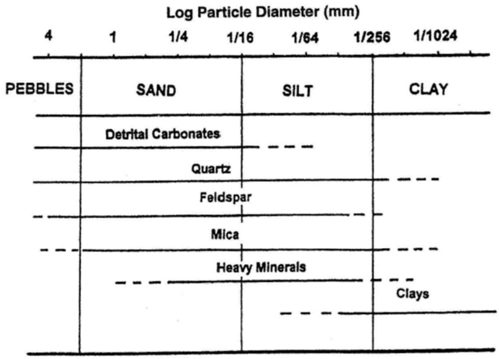
Anode Shape	Anode Arrangement	Grounding Resistance	Remarks	Voltage Cone
Hemisphere, radius r_0, diameter d		$R = \frac{\rho}{\pi d}$	Spherical field	$U_r = U_0 \frac{r_0}{r} = \frac{I\rho}{2\pi r}$
Circular plate, diameter d, radius r_0		$R = \frac{\rho}{2d}$	Surface	$U_r = \frac{2}{\pi} U_0 \arcsin\left(\frac{r_0}{r}\right)$
			Depth	$U_r = \frac{2}{\pi} U_0 \arctan\left(\frac{r_0}{t}\right)$
Rod anode, length l, diameter d		$R = \frac{\rho}{2\pi l} \ln \frac{4l}{d}$	$l \gg d$	$U_r = \frac{I\rho}{2\pi l} \ln\left(\frac{l + \sqrt{l^2 + r^2}}{r}\right)$
Horizontal anode, length l, diameter d		$R = \frac{\rho}{\pi l} \ln \frac{2l}{d}$	$l \gg d$	$U_r = \frac{I\rho}{\pi l} \ln\left(\frac{l}{2r} + \sqrt{1 + \left(\frac{l}{2r}\right)}\right) \approx \frac{I\rho}{2\pi r}$ $U_x = \frac{I\rho}{2\pi l} \ln\left(\frac{2x + l}{2x - l}\right) \approx \frac{I\rho}{2\pi x}$ [the approximation holds for $(r, x) \gg 1$]
Sphere, diameter d, depth below surface t		$R = \frac{\rho}{2\pi}\left(\frac{1}{d} + \frac{1}{4t}\right)$	$t \gg d$	$U_r = \frac{I\rho}{2\pi\sqrt{t^2 + r^2}}$

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), pp. 538, 539. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing.

Anode Shape	Anode Arrangement	Grounding Resistance	Remarks	Voltage Cone
Ring-shaped ground, band width b, radius r_0		$R = \frac{\rho}{2\pi^2 r_0} \ln\left(\frac{16 r_0}{d}\right)$	$d = \frac{b}{2}$	$U_r = \frac{I\rho}{\pi^2 (r_0 + r)} F\left(\frac{2\sqrt{r_0 r}}{r_0 + r}\right)^{a}$
Vertical anode, length l, diameter d, depth below surface t		$R = \frac{\rho}{2\pi l} \ln\left(\frac{2l}{d}\sqrt{\frac{4t+3l}{4t+l}}\right)$	$t \gg d$ $d \ll l$	$U_r = \frac{I\rho}{2\pi l} \ln\left(\frac{t + l + \sqrt{r^2 + (t+l)^2}}{t + \sqrt{r^2 + t^2}}\right)$
Vertical anode		$R = \frac{\rho}{2\pi l} \ln\left(\frac{2l}{d}\right)$	$t \gg l$	$U_r = \frac{I\rho}{2\pi l} \ln \frac{\sqrt{t^2 + r^2 + \left(\frac{l}{2}\right)^2} + \frac{l}{2}}{\sqrt{t^2 + r^2 + \left(\frac{l}{2}\right)^2} - \frac{l}{2}}$
Horizontal anode, length l, diameter d, depth below surface t		$R = \frac{\rho}{2\pi l} \ln\left(\frac{l^2}{td}\right)$	$d \ll l$ $t \ll l$	
Horizontal anode		$R = \frac{\rho}{2\pi l} \ln\left(\frac{2l}{d}\right)$	$t \gg l$	$U_x = \frac{I\rho}{2\pi l} \ln \frac{\sqrt{t^2 + \left(x + \frac{l}{2}\right)^2} + x + \frac{l}{2}}{\sqrt{t^2 + \left(x - \frac{l}{2}\right)^2} + x - \frac{l}{2}}$

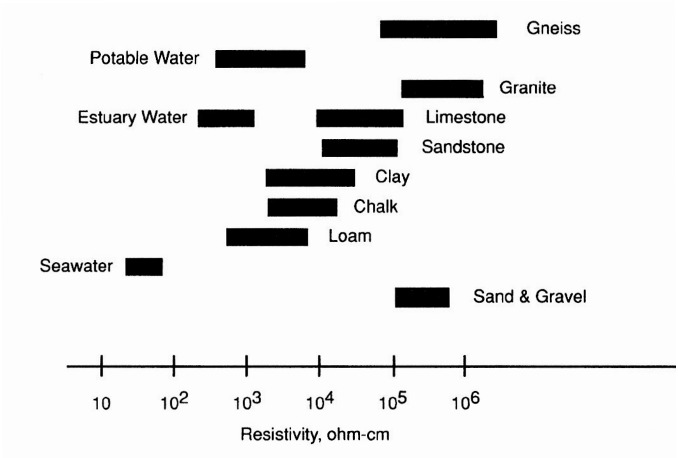
[a] F is an elliptical integral

CLASSIFICATION OF SOILS



Source: R.W. Revie, ed., *Uhlig's Corrosion Handbook,* 3rd ed. (Hoboken, New Jersey, USA: John Wiley & Sons, 2011), p. 336. Reprinted with permission, copyright John Wiley & Sons, Inc.

TYPICAL RESISTIVITIES OF SOME WATERS AND SOIL MATERIALS



Source: J.H. Morgan, *Cathodic Protection,* 2nd ed. (Houston, TX, USA: NACE International, 1987).

SOIL RESISTIVITY VS CORROSIVITY

Soil resistivity (ohm-cm)	Degree of corrosivity
0–500	Very corrosive
500–1,000	Corrosive
1,000–2,000	Moderately corrosive
2,000–10,000	Neglibible

Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion,* 2nd ed. (Houston, TX, USA: NACE International, 2001), p. 88.

SOIL CORROSIVITY CLASSES FOR UNCOATED STEEL

BASED ON: TOTAL ACIDITY, RESISTIVITY-CONDUCTIVITY OF THE SATURATION EXTRACT AND DRAINAGE-TEXTURE-AERATION RELATIONSHIPS.

				General Relationship	
Soil Corrosivity, class	**Total Acidity, meq/ 100g**	**Resistivity, ohm-cm**	**Conductivity, mmho/ cm**	**Drainage-Texture Relationship**	**Water-Air Permeability**
Very low	<4	>10,000	<0.1	Somewhat excessive—excessively drained coarse-textured soils	Rapid to very rapid
Low	4 to 8	5,000 to 10,000	0.1 to 0.2	Well-drained with moderately coarse and medium-textured control section; somewhat poorly drained with coarse-textured control section	Moderate to rapid
Low	8 to 12	2,000 to 5,000	0.2 to 0.4	Well-drained with moderately fine-textured control section; moderately well-drained with medium-textured control section; somewhat poorly-drained with moderately coarse-textured control section; very poorly-drained with high, nonfluctuating water table	Moderately slow to slow
High	12 to 16	1,000 to 2,000	0.4 to 1.0	Well drained and moderately well-drained fine-textured soils; moderately well-drained, moderately fine-textured soils; somewhat poorly-drained; medium and moderately fine-textured control sections; very poorly-drained soils; water table fluctuates with ft of surface.	Slow and very slow; saturated
Very high	>16	<1,000	>1.0	Somewhat poorly to very poorly-drained fine-texture soils; mucks, peats with a fluctuating water table	Very slow; saturated

Source: R. Baboian, S.W. Dean eds., ASTM STP1000, *Corrosion Testing and Evaluation: Silver Anniversary Volume* (West Conshohocken, PA, USA: ASTM International, 1990), p. 129. Reprinted with permission, copyright ASTM.

RESISTIVITY OF VARIOUS MINERALS AND SOILS

Minerals and Soils	Resistivity, Ω-cm
Minerals	
Pyrite	0.1
Magnetite	0.6 to 1.0
Graphite	0.03
Rock Salt (impure)	3,000 to 500,000
Serpentine	20,000
Sederite	7,000
Igneous Rocks	
Granite	500,000 to 100,000,000
Diorite	1,000,000
Gabbro	10,000,000 to 1,400,000,000
Diabase	310,000
Metamorphic Rocks	
Garnet gneiss	20,000,000
Mica chist	130,000
Biotite gneiss	100,000,000 to 600,000,000
Slate	64,000 to 6,500,000
Sedimentary Rocks	
Chattanooga shale	2,000 to 130,000
Michigan shale	200,000
Calumet and hecla conglomerates	200,000 to 1,300,000
Muschelkalk sandstone	7,000
Ferruginous sandstone	18,000
Muschelkalk limestone	18,000
Marl	7,000
Glacial till	50,000
Oil sand	400 to 22,000

Source: Manual 20, *Corrosion Tests and Standards: Application and Interpretation* (West Conshohocken, PA, USA: ASTM International, 1995), p 326. Reprinted with permission, copyright ASTM.

COMPOSITION OF PETROLEUM AND METALLURGICAL COKE BACKFILL

Element	Content %
Petroleum Coke Backfill	
Fixed Carbon	99.77
Ash	0.1
Moisture	0.0
Volatile Matter	0.0
Metallurgical Grade	
Fixed Carbon	85.89
Ash	8–10
Moisture	6–9
Sulfur	0.8
Volatile Matter	0.5

Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion*, 2nd ed. (Houston, TX, USA: NACE International, 2001), p. 174.

WEIGHTS OF CARBONACEOUS BACKFILL

Material	Lb./Ft.^{3}
Coal coke breeze	40 to 50
Calcined petroleum coke breeze	45 to 70
Natural graphite particle	70 to 80
Crushed man-made graphite	70

Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion*, 2nd ed. (Houston, TX, USA: NACE International, 2001), p. 175.

COMPOSITION OF BACKFILL FOR ZINC AND MAGNESIUM ANODES

	Backfill						
	for Mg Anodes				for Zn Anodes		
Specific Soil Resistivity in Ω m	**Gypsum**	**Bentonite**	**Kieselguhr**	**Na_2SO_4**	**Gypsum**	**Bentonite**	**Na_2SO_4**
Up To 20	65	15	15	5	75	25	–
	75	25	–	–	50	45	5
20–100	70	10	15	5	75	20	5
	75	20	–	5	–	–	–
	50	40	–	10	–	–	–
Above 100	65	10	10	15	–	–	–
	50	25	–	25	–	–	–

Source: W. von Baeckman, W. Schwenk, W. Prinz, eds., *Cathodic Corrosion Protection* (Houston, TX, USA: Gulf Publishing, 2000), p. 197. Reprinted with permission from Butterworth-Heinemann/Gulf Professional Publishing

PROPERTIES OF CONCENTRIC STRANDED COPPER SINGLE CONDUCTORS

DIRECT BURIAL SERVICE, SUITABLY INSULATED

Size AWG	Overall Diameter Not Including Insulation (Inches)	Approx. Weight Not Including Insulation (lbs./M ft.)	Maximum Breaking Strength (lbs.)	Maximum D.C. Resistance @20˚C Ohms/ M ft.	Maximum Allowable D.C. Current Capacity (Amperes)
14	0.0726	12.68	130	2.5800	15
12	0.0915	20.16	207	1.6200	20
10	0.1160	32.06	329	1.0200	30
8	0.1460	50.97	525	0.6400	45
6	0.1840	81.05	832	0.4030	65
4	0.2320	128.90	1320	0.2540	85
3	0.2600	162.50	1670	0.2010	100
2	0.2920	204.90	2110	0.1590	115
1	0.3320	258.40	2660	0.1260	130
1/0	0.3730	325.80	3350	0.1000	150
2/0	0.4190	410.90	4230	0.0795	175
3/0	0.4700	518.10	5320	0.0631	200
4/0	0.5280	653.30	6453	0.0500	230
250 MCM	0.5750	771.90	7930	0.0423	255

Data Courtesy of the Rome Cable Division ofALCOA.

Source: W.T. Bryan, The Duriron Company, Inc.

TEMPERATURE CORRECTION FACTORS FOR RESISTANCE OF COPPER

Temperature		Multiply Resistance at 25 °C by:
°C	°F	
−10	14	0.862
−5	23	0.882
0	32	0.901
5	41	0.921
10	50	0.941
15	59	0.961
20	68	0.980
30	86	1.020
35	95	1.040
40	104	1.059

Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion*, 2nd ed. (Houston, TX, USA: NACE International, 2001).

STEEL PIPE RESISTANCE

Pipe Size, Inches	Outside Diameter, Inches	Wall Thick-ness, Inches	Weight Per Foot, Pounds	Resistance	
				Micro ohms Per Foot	Micro ohms Per Meter
2	2.375	0.154	3.65	79.2	260
4	4.5	0.237	10.8	26.8	87.9
6	6.625	0.280	19.0	15.2	49.9
8	8.625	0.322	28.6	10.1	33.1
10	10.75	0.365	40.5	7.13	23.4
12	12.75	0.375	49.6	5.82	19.1
14	14.00	0.375	54.6	5.29	17.4
16	16.00	0.375	62.6	4.61	15.1
18	18.00	0.375	70.6	4.09	13.4
20	20.00	0.375	78.6	3.68	12.1
22	22.00	0.375	86.6	3.34	11.0
24	24.00	0.375	94.6	3.06	10.0
26	26.00	0.375	102.6	2.82	9.25
28	28.00	0.375	110.6	2.62	8.60
30	30.00	0.375	118.7	2.44	8.0
32	32.00	0.375	126.6	2.28	7.48
34	34.00	0.375	134.6	2.15	7.05
36	36.00	0.375	142.6	2.03	6.66

Based on steel density of 489 pounds per cubic foot and steel resistivity of 18 microhm-cm.

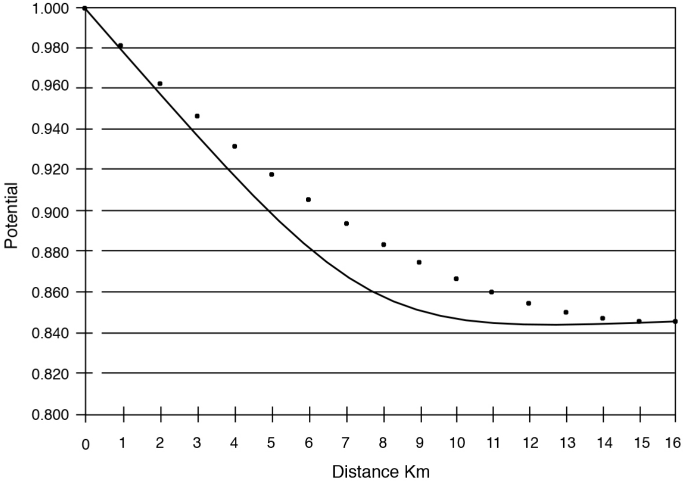
Source: A.W. Peabody, R.L. Bianchetti, eds., *Peabody's Control of Pipeline Corrosion,* 2nd ed. (Houston, TX, USA: NACE International, 2001).

ALLOY PIPE RESISTANCE

Resistance of alloy piping can be estimated using the factor below, which is the ratio of alloy resistivity to that of a typical carbon steel (18 microhm-cm):

304 SS	4.0
316 SS	4.1
410 SS	3.2
400 Alloy	3.1
Al 3003	0.19
OF Copper	0.09

TYPICAL ATTENUATION ON A PIPELINE



Typical attenuation on a pipeline.

Source: R.W. Revie, ed., *Uhlig's Corrosion Handbook,* 2nd ed. (Hoboken, New Jersey, USA: John Wiley & Sons, 2000), p. 1,077. Reprinted with permission, copyright John Wiley & Sons, Inc.

CORROSION OF STEELS, COPPER, LEAD, AND ZINC IN SOILS

Maximum penetration in mils (1 mil = 0.001 in. = 0.025 mm) for total exposure period. Average corrosion rates in g m^{-2} d^{-1} (gmd).

	Open Hearth Iron 12-Year Exposure		Wrought Iron 12-Year Exposure		Bessemer Steel 12-Year Exposure		Copper 8-Year Exposure		Lead 12-Year Exposure		Zinc 11-Year Exposure	
Soil	**gmd**	**mils**	**gmd**	**mils**	**gmd**	**mils**	**gmd**	**mils**	**gmd**	**mils**	**gmd**	**mils**
Average of several soils	0.45 (44 soils)	70	0.47 (44 soils)	59	0.45 (44 soils)	61	0.07 (29 soils)	< 6	0.052 (21 soils)	> 32	0.3 (12 soils)	> 53
Tidal marsh, Elizabeth, New Jersey	1.08	90	1.16	80	1.95	100	0.53	< 6	0.02	13	0.19	36
Montezuma clay, Adobe, San Diego, California	1.37	> 145	1.34	> 132	1.43	> 137	0.07	< 6	0.06 (9.6 years)	10	–	–
Merrimac gravelly sandy loam, Norwood, Massachusetts	0.09	28	0.10	23	0.10	21	0.02 (13.2 years)	< 6	0.013	19	–	–

Source: M. Romanoff, *Underground Corrosion* (Gaithersburg, MD, USA: National Institute of Standards and Technology, 1957).

EFFECT OF CHLORIDES, SULFATES, AND pH ON CORROSION OF BURIED STEEL PIPELINES

Concentration (ppm)	Degree of Corrositivity
Chloride[1]	
>5,000	Severe
1,500–5,000	Considerable
500–1,500	Corrosive
<500	Threshold
Sulfate[1]	
>10,000	Severe
1,500–10,000	Considerable
150–1,500	Positive
0-150	Negligible
pH[2]	
<5.5	Severe
5.5–6.5	Moderate
6.5–7.5	Neutral
>7.5	None (alkaline)

(1) Source: Building Code 318, American Concrete Institute.

(2) Source: M. Romanoff, *Underground Corrosion* (Gaithersburg, MD, USA: National Institute of Standards and Technology, 1957).

EFFECTS OF ENVIRONMENTAL FACTORS ON CORROSION OF STEEL IN SOILS[(a)]

Environmental Factor	Overall Corrosion Rate (mm/year) Maximum	Overall Corrosion Rate (mm/year) Minimum	Overall Corrosion Rate (mm/year) Average	Maximum Pitting Rate (mm/year) Maximum	Maximum Pitting Rate (mm/year) Minimum	Maximum Pitting Rate (mm/year) Average
Resistivity ($\Omega \cdot cm$)						
<1,000	0.063	0.018	0.033	0.31	0.11	0.20
1,000–5,000	0.058	0.006	0.017	>0.45[(b)]	0.05	0.14
5,000–12,000	0.033	0.005	0.018	0.23	0.06	0.14
>12,000	0.036	0.003	0.014	0.26	0.03	0.11
Drainage						
Very poor	0.058	0.038	0.046	>0.45[(b)]	0.16	0.28
Poor	0.037	0.010	0.024	0.23	0.05	0.14
Fair	0.063	0.018	0.022	0.31	0.08	0.16
Good	0.022	0.003	0.010	0.18	0.03	0.11
Air-pore space (%)						
<5	0.033	0.010	0.021	0.20	0.05	0.13
5–10	0.063	0.009	0.024	0.31	0.10	0.17
10-20	0.037	0.006	0.017	0.26	0.05	0.15
20-30	0.058	0.012	0.025	>0.45[(b)]	0.10	0.20
>30	0.038	0.004	0.013	0.23	0.03	0.09

(a) Original data are based on NBS field tests on open-hearth steel for 12 years at 44 locations in the United States.
(b) Perforated.

Source: M. Romanoff, *Underground Corrosion* (Gaithersburg, MD, USA: National Institute of Standards and Technology, 1957).

CORROSION RATES OF ZINC COATING ON STEEL IN SOILS AT VARIOUS LOCATIONS

No.[a,b]	Soil Type	ρ(Ω-cm)	pH	*R* (μm/year)
1	Allis silt loam—Cleveland, OH	1,215	7.0	11.8
2	Bell clay—Dallas, TX	684	7.3	1.5
3	Cecil clay loam—Atlanta, GA	30,000	5.2	1.7
4	Chester loam—Jenkintown, PA	6,670	5.6	7.9
5	Dublin clay adobe—Oakland, CA	1,345	7.0	7.7
6	Everett gravelly sandy loam—Seattle, WA	45,100	5.9	0.5
7	Maddox silt loam—Cincinnati, OH	2,120	4.4	10.8
8	Fargo clay loam—Fargo, ND	350	7.6	3.2
9	Genesee silt loam—Sidney, OH	2,820	6.8	5.0
10	Gloucester sandy loam—Middleboro, MA	7,460	6.6	5.2
11	Hagerstown loam—Loch Raven, MD	11,000	5.3	3.7
12	Hanford fine sandy loam—Los Angeles, CA	3,190	7.1	2.2[c]
13	Hanford very fine sandy loam—Bakersfield, CA	290	9.5	3.7
14	Hempstead silt loam—St. Paul, MN	3,520	6.2	1.1
15	Houston black clay—San Antonio, TX	489	7.5	1.5
16	Kalmia fine sandy loam—Mobile, AL	8,290	4.4	4.2
17	Keyport loam—Alexandria, VA	5,980	4.5	14.8[d]
19	Lindley silt loam—Des Moines, IA	1,970	4.6	2.9
20	Mahoning silt loam—Cleveland, OH	2,870	7.5	4.9

(a) Average coating thickness, 121 microns.

(b) Original soil identification.

(c) Sheet specimens.

(d) Data includes corrosion of steel.

Source: M. Romanoff, *Underground Corrosion* (Gaithersburg, MD, USA: National Institute of Standards and Technology, 1957).

CORROSION OF GALVANIZED PIPE IN VARIOUS SOILS

Weight loss (oz./ft.^{2}) and maximum pit depth (mil) after burial period 12.7 years

	oz./ft.^{2}	mil
Inorganic oxidizing acid soils		
Cecil clay loam	0.6	<6
Hagerstown loam	0.6	<6
Susquehanna clay	0.8	<6
Inorganic oxidizing alkaline soils		
Chino silt loam	1.1	<6
Mohave fine gravelly loam	1.1	<6
Inorganic reducing acid soils		
Sharkey clay	1.1	6
Acadia clay	-	-
Inorganic reducing alkaline soils		
Docas clay	1.6	<6
Merced silt loam	1.3	8
Lake Charles clay	13.8	66
Organic reducing acid soils		
Carlisle muck	3.4	<6
Tidal marsh	4.8	52
Muck	10.7	76
Rifle peat	19.5	88
Cinders	11.9	48

Nominal weight of coating–3 oz./sq. ft. (915 g/m^2) of exposed area.

Source: C.J. Slunder, W.K. Boyd, *Zinc, Its Corrosion Resistance,* 2nd ed., International Lead Zinc Research Organization, 1983, p. 101. Reprinted with permission from the International Lead Zinc Research Organization.

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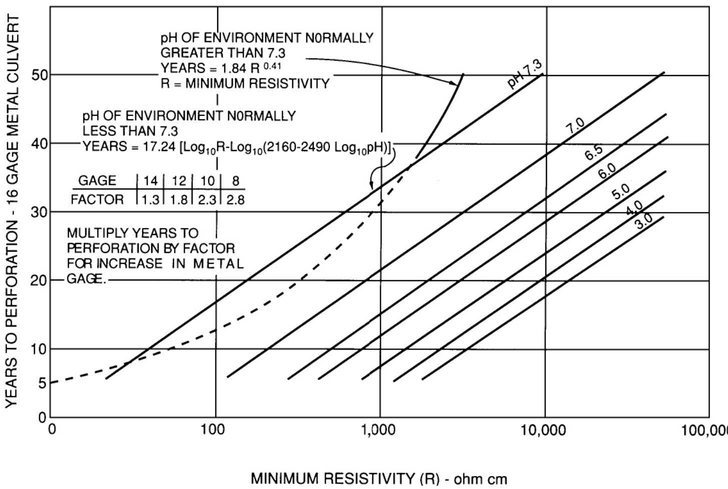
ESTIMATING SERVICE LIFE OF GALVANIZED STEEL IN SOILS



Method developed by the California Division of Highways for estimating services life of galvanized steel culverts, based on correlations involving pH and resistivity of soil. Base case is 16-gage galvanized steel pipe with a zinc coating thickness of 1.6 mm (0.064 in.).

Source: NACE International-Ohio State University Corrosion Course.