Advanced Chapter 1
Pipe-to-Soil Potential Surveys and Analysis

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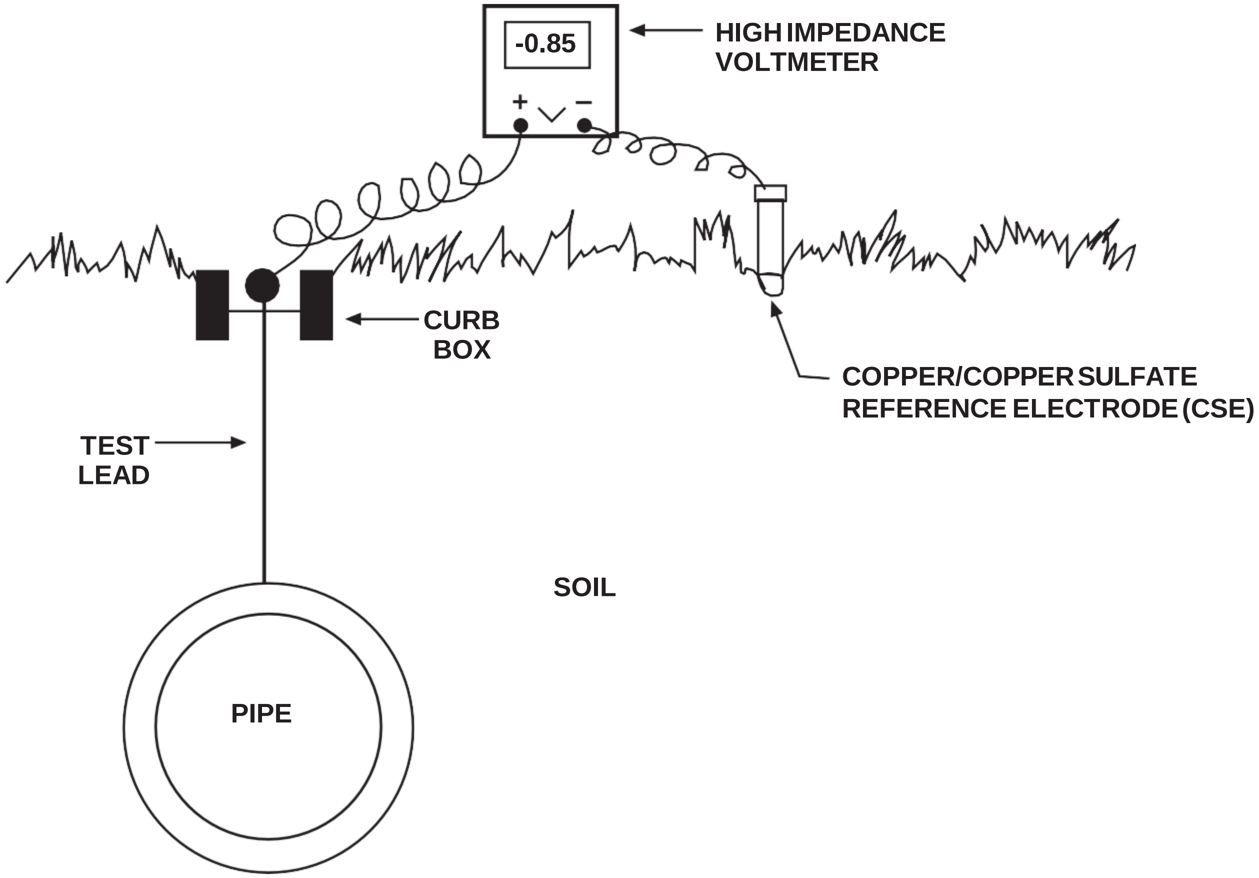
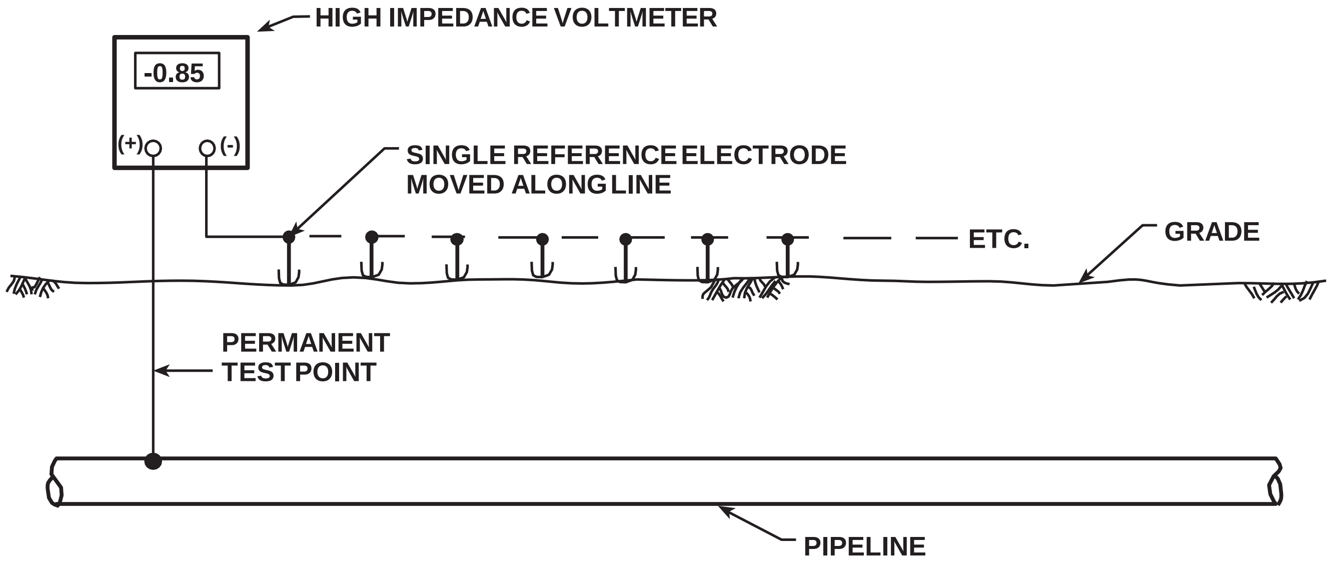
Appalachian Underground Corrosion Short Course



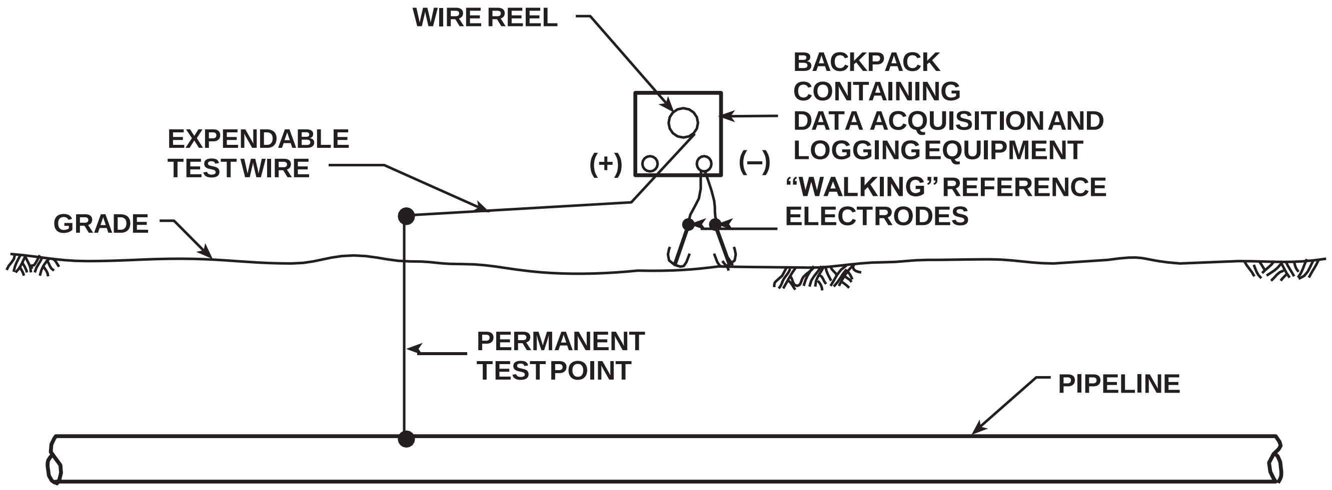
PIPE-TO-SOIL POTENTIAL MEASUREMENT

FIGURE 1-1



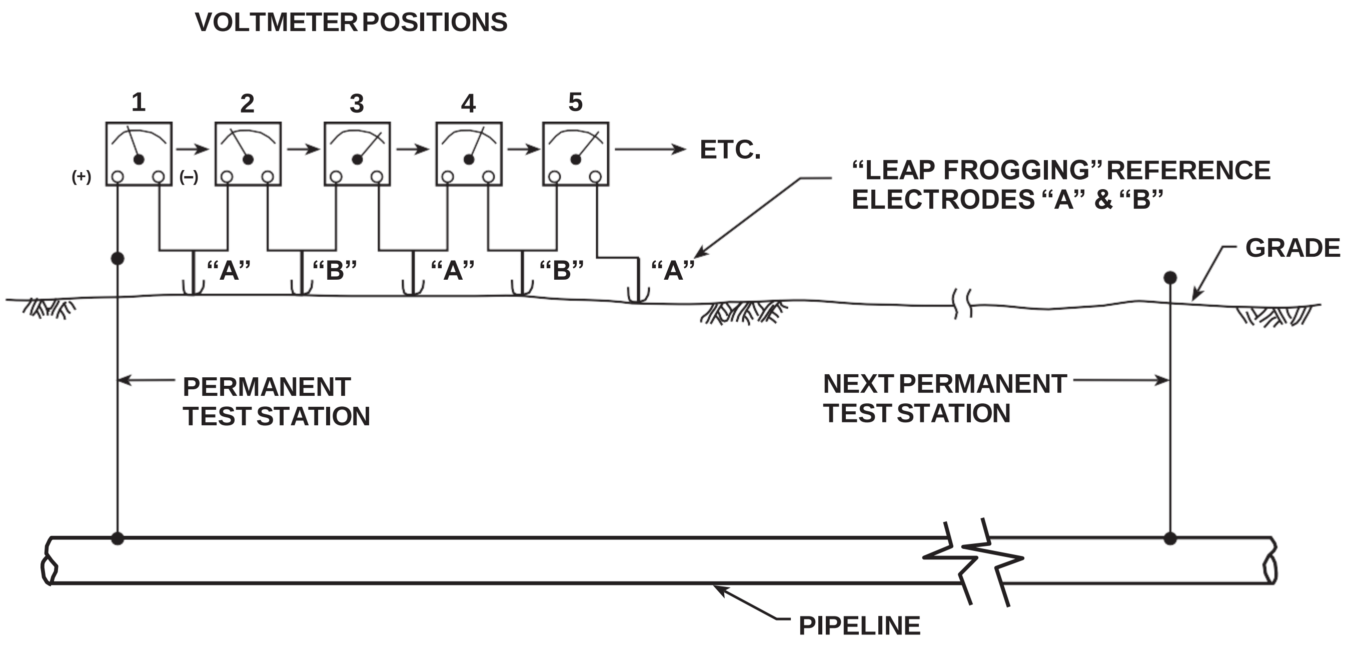
SINGLE ELECTRODE POTENTIAL SURVEY

FIGURE 1-2



TYPICAL COMPUTERIZED POTENTIAL SURVEY

FIGURE 1-3



TWO ELECTRODE POTENTIAL SURVEY

FIGURE 1-4

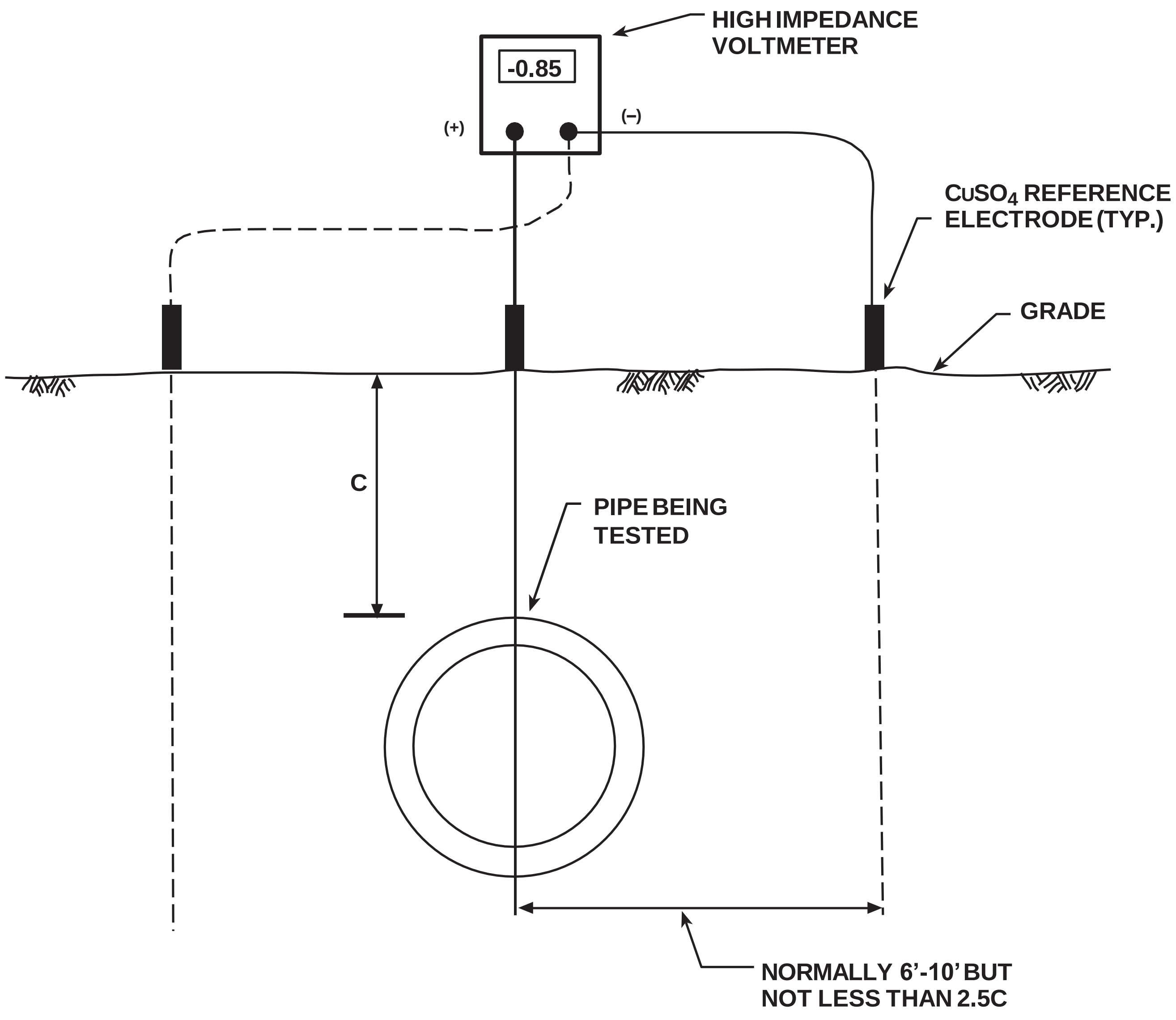
TABLE 1-1

Typical Data Record For Two Electrode Potential Survey Conducted on a Cathodically Protected Pipeline

A	B	C	D	Comments
1	--	-	-0.860(1)	--
2	0.035	+	-0.895	--
3	0.021	+	-0.916	--
4	0.065	-	-0.851	--
5	0.092	-	-0.759	Unprotected Area
6	0.045	+	-0.804	Unprotected Area
7	0.063	+	-0.867	--
8	0.011	+	-0.878	--
9	0.020	-	-0.858	--
10	0.032	+	-0.890	--

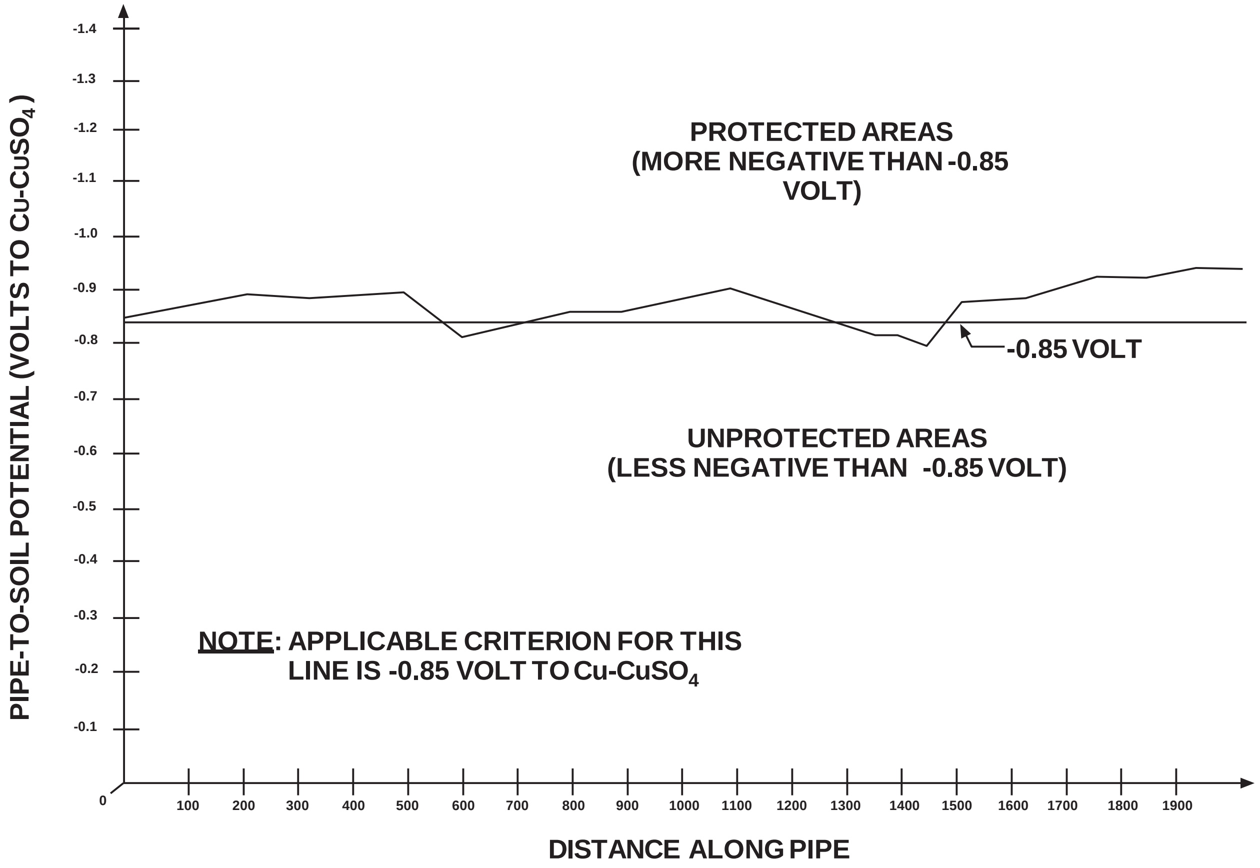
Where:
A = position or pipeline section
B = potential drop from electrode at last position (volts)
C = polarity of forward electrode
D = pipe to CSE (volts)

Note: (1) Initial value measured via direct pipeline contact at Position 1



TYPICAL TEST SET UP FOR SIDE DRAIN MEASUREMENTS

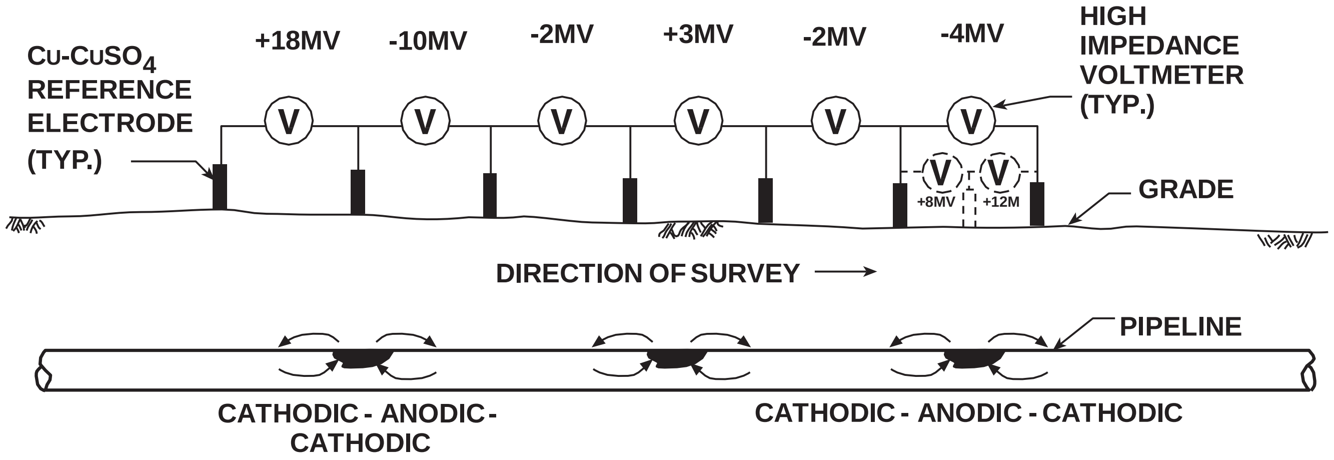
FIGURE 1-5



NOTE: APPLICABLE CRITERION FOR THIS LINE IS -0.85 VOLT TO $Cu\text{-}CuSO_4$

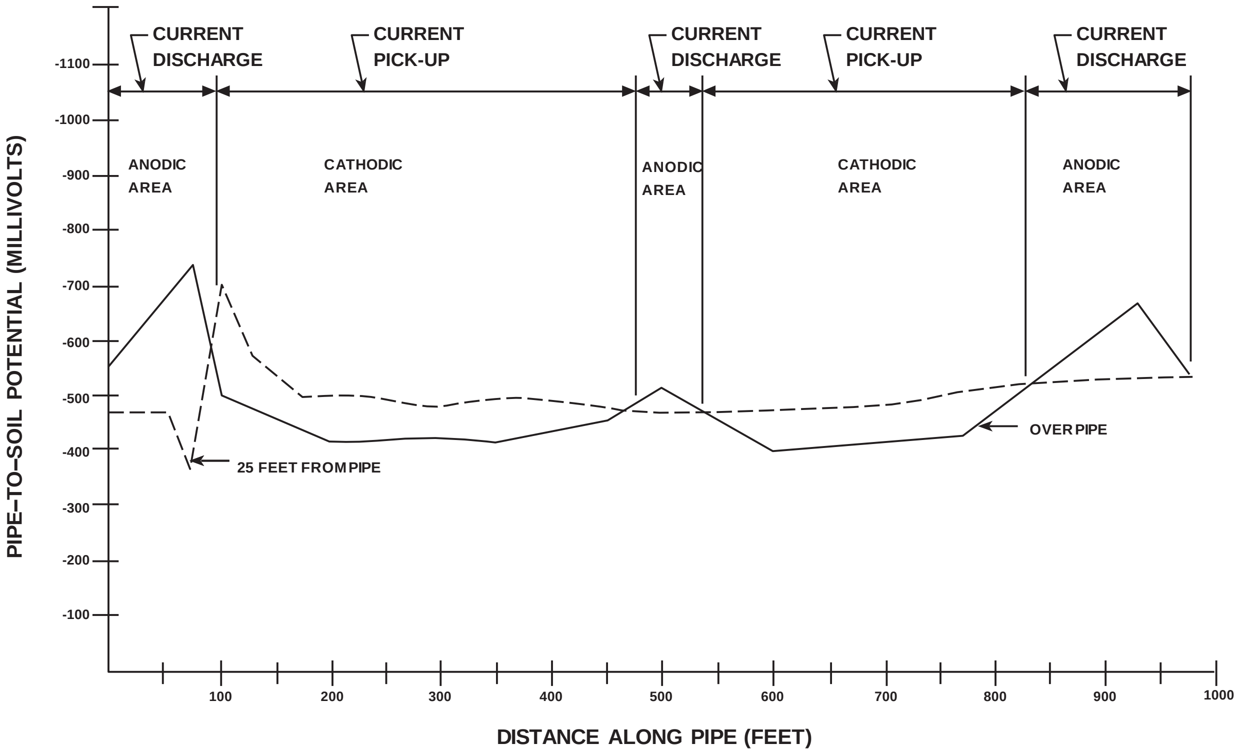
TYPICAL POTENTIAL PLOT OF A
CATHODICALLY PROTECTED PIPELINE

FIGURE 1-6



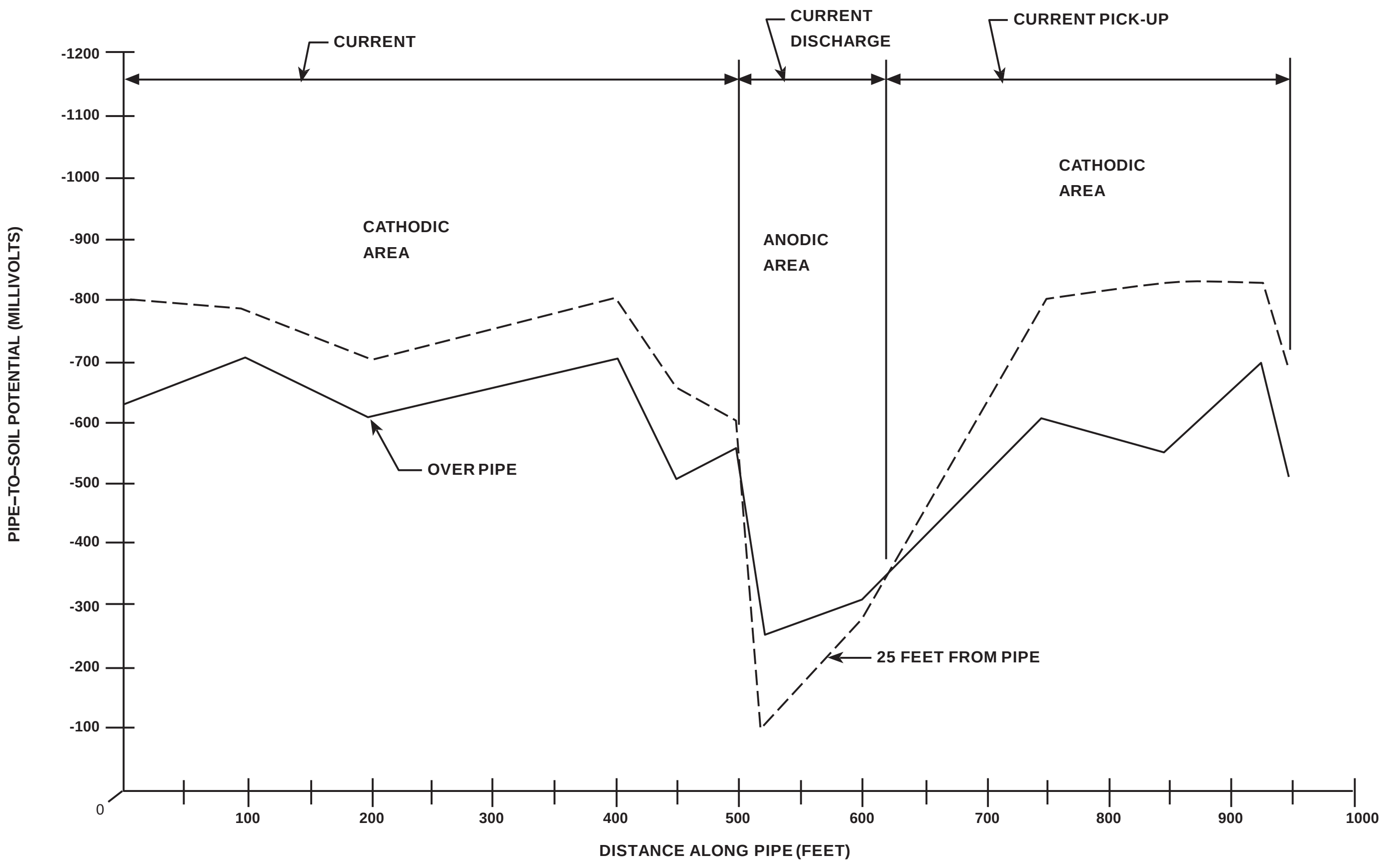
SCHEMATIC SURFACE POTENTIAL SURVEY

FIGURE 1-7



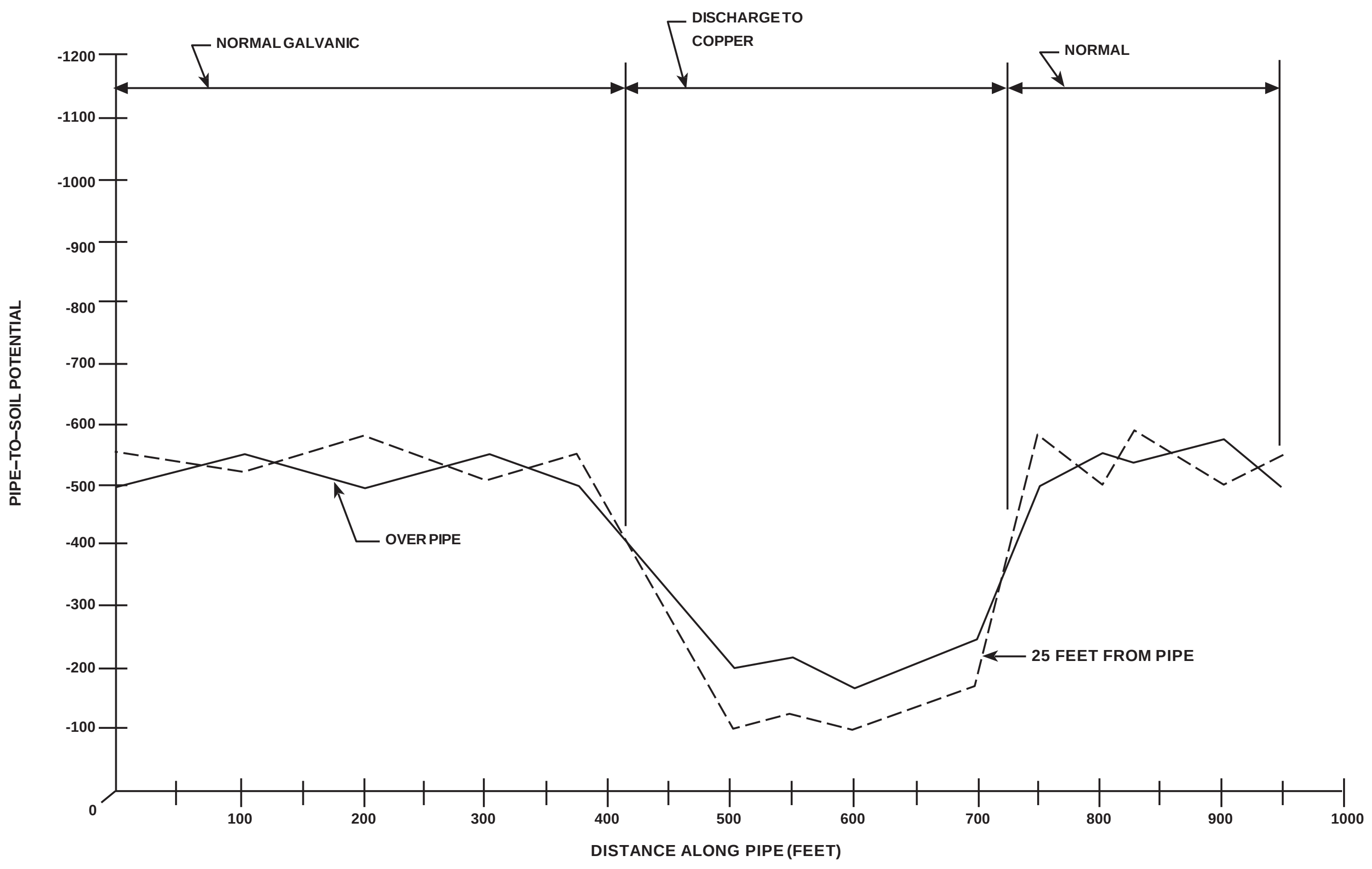
POTENTIAL PROFILE SHOWING
GALVANIC CORROSION ACTIVITY

FIGURE 1-8



POTENTIAL PROFILE OF PIPE EFFECTED
BY STRAY CURRENT INTERFERENCE

FIGURE 1-9



POTENTIAL PROFILE SHOWING BIMETALLIC EFFECT

FIGURE 1-10

TABLE 1-2

Potential Measurements

Test Station Location No.	Description of Location	Pipe-to-Soil Potential (mV to CSE)
21	Crestdale Regulator Station	-703
22	North side of Blue River on Rt. 95	-700
24	South side of Blue River	-735
26	Linden Metering Station	-542
26	Valve box approximately 7.8 miles South of Blue River	-730
28	Creek, 10.2 miles south of Blue River	-674
30	Atlantic Regulator Station	-563
31	Glendale Metering Station	-780
32	Crossing of railroad near Glendale	-506
33	Forest Park Regulator No. 1	-480
35	Forest Park Regulator No. 2	-537

Advanced Chapter 2

Evaluation of Underground Coatings Using Aboveground Techniques

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PIPELINE LOCATING CREW CLEARING PATH AND MARKING PIPELINE CENTERLINE

FIGURE 2-1

PIPELINE LOCATION STATIONING FLAGS NUMBERED FOR PRECISE DATA ALIGNMENT

FIGURE 2-2

ANALOG DCVG METER

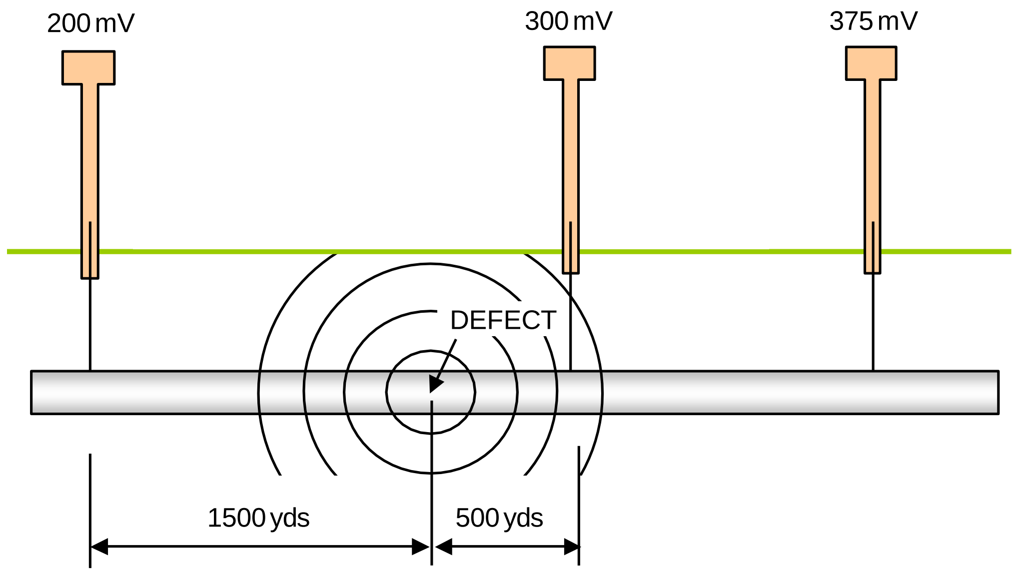
FIGURE 2-3

DCVG SURVEYOR MEASURING VOLTAGE GRADIENT
ABOVE PIPELINE

FIGURE 2-4

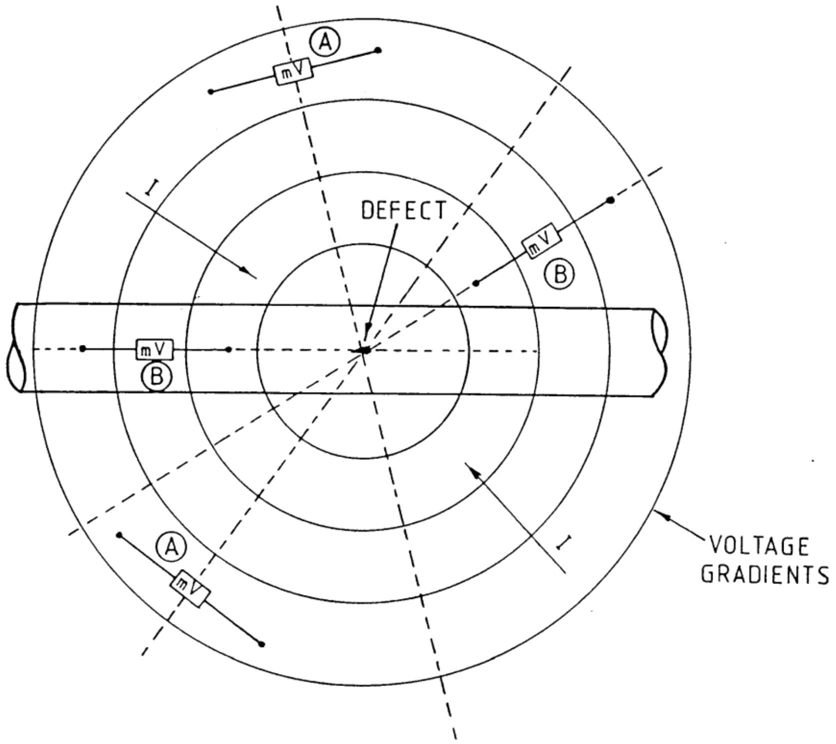
DCVG SURVEY COMPLETED ON WET ASPHALT IN MAJOR CITY

FIGURE 2-5



DCVG SIGNAL STRENGTH

FIGURE 2-6

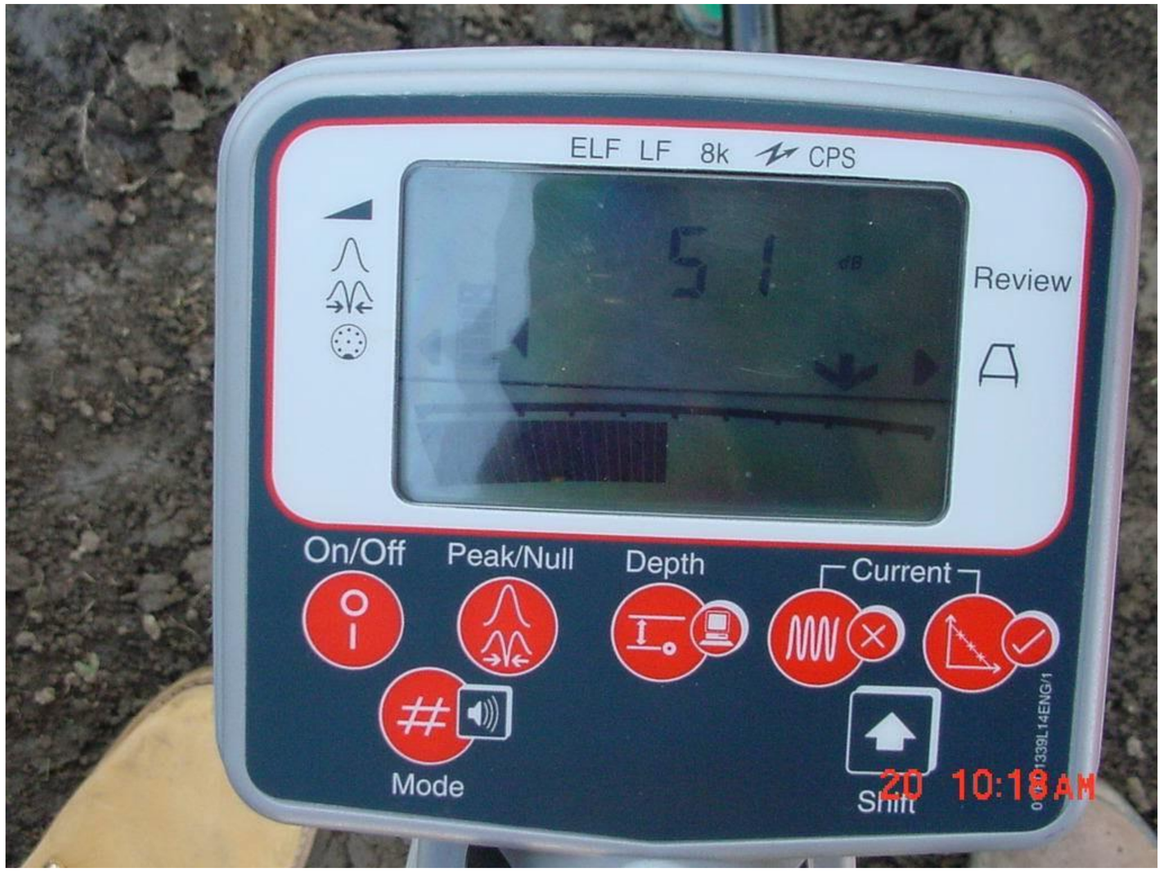


DCVG VOLTAGE GRADIENTS

FIGURE 2-7

ACVG SURVEY ABOVE PIPELINE LOCATING COATING HOLIDAYS

FIGURE 2-8



AC CURRENT ATTENUATION RECEIVER FACE

FIGURE 2-9

CLOSE-INTERVAL SURVEY TECHNICIAN WITH DATALOGGER, REFERENCE ELECTRODE, AND WIRE DISPENSERS

FIGURE 2-10

AC CURRENT ATTENUATION TRANSMITTER

FIGURE 2-11

TECHNICIAN MEASURING AC CURRENT ATTENUATION
WITH RECEIVER

FIGURE 2-12

Advanced Chapter 3
Materials for Cathodic Protection

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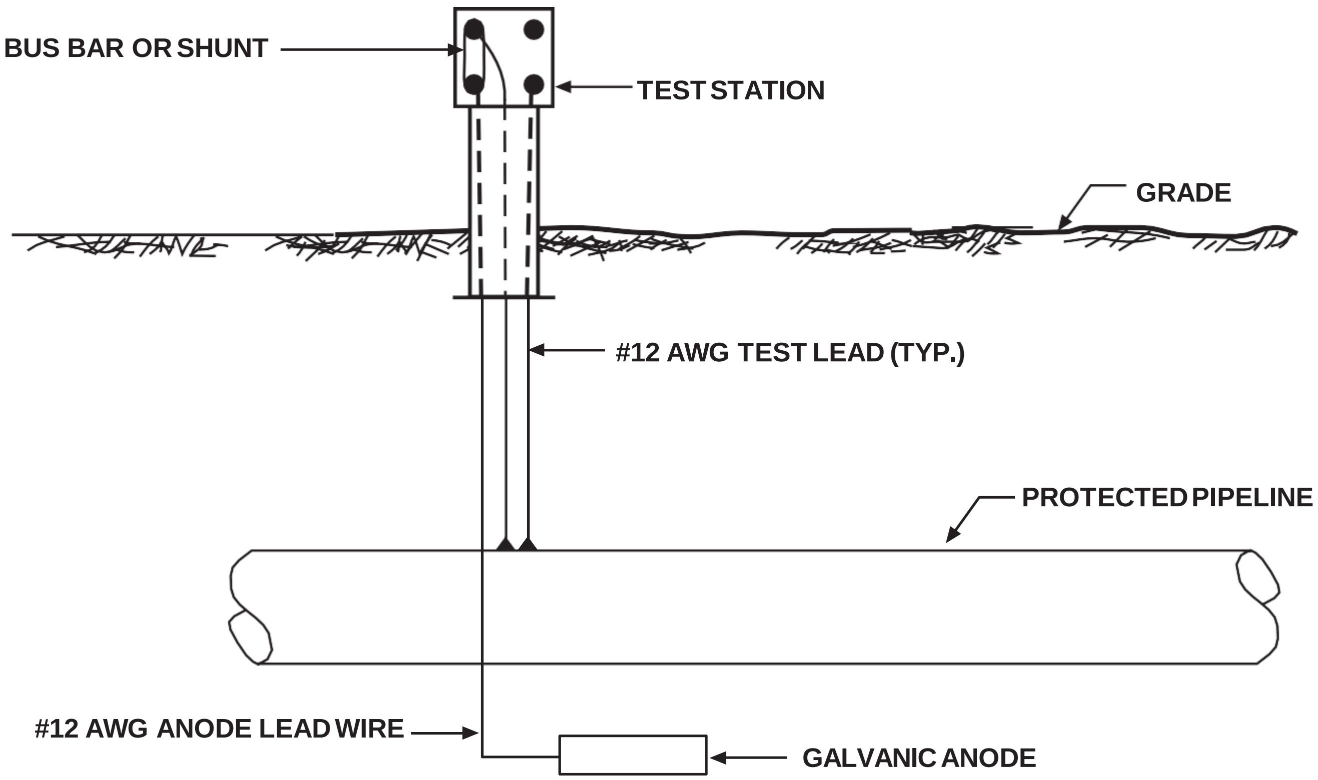


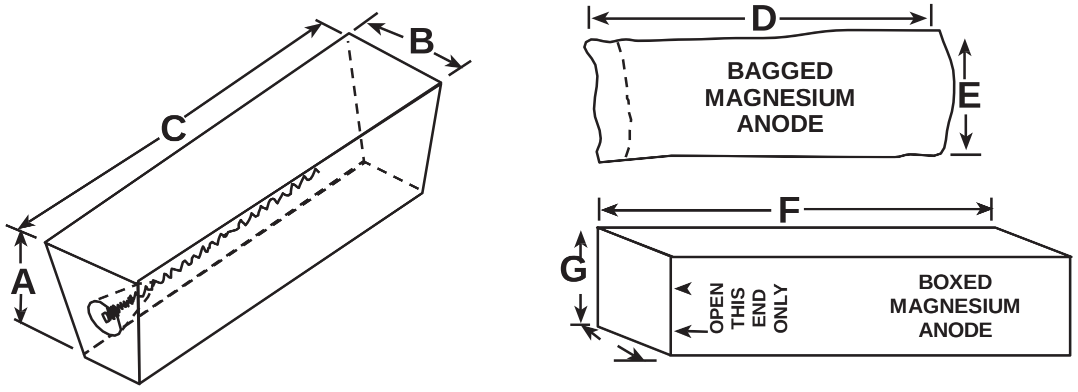
TYPICAL GALVANIC ANODE INSTALLATION

FIGURE 3-1

TABLE 3-1
Capabilities and Consumption Rates of Galvanic Anodes

Type	Potential* (volts to CSE)	Current Capacity (A-hrs/lb)	Consumption Rate (lb/A-yr)
Magnesium			
H-1C AZ-63D Alloy	-1.4 to -1.5	250 to 470	19 to 36
High Potential Alloy	-1.7 to -1.8	450 to 540	16 to 19
Zinc			
ASTM B418-01			
Type I (saltwater)	-1.1	354	24.8
Type II (soil)	-1.1	335	26.2
Aluminum			
Mercury Alloys	-1.10	1250 to 1290	6.8 to 7.0
Indium Alloys	-1.15	1040 to 1180	7.4 to 8.4

* Copper/Copper Sulfate Reference Electrode - Open circuit practical values as shown



BARE AND PACKAGED MAGNESIUM ANODES

FIGURE 3-2

TABLE 3-2
Magnesium Anode Dimensions and Weights

	Nominal Dimensions (Inches) - See Figure 3-2							
Alloy	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Packaged Weight (lbs)**
1 AZ63	3.2	Rd	2	6	6	-	-	3.6
3 H.P./AZ63	3	3	6	8	6	-	-	9
5 H.P./AZ63	3	3	10	12	5	-	-	12
6 H.P./AZ63	3	3	10	-	-	12.5	5	14
9 H.P./AZ63	3	3	13.5	17	6	-	-	27
12 AZ63	4	4	12	18	7.5	-	-	32
17 H.P.	3.5	3.5	25.5	30	6	-	-	42
17 AZ63	3.5	3.5	28	-	-	32	5.5	45
20 H.P.	2	2	60	-	-	71	4.5	65
32	5.5	5.5	21	25	8	-	-	72
32	5.5	5.5	21	-	-	24	7.5	70
40 H.P.	3.5	3.5	60	64	6	-	-	105
48 H.P.	5.5	5.5	32	36	8	-	-	106
50 AZ63	7	7	15	24	10	-	-	110
60 H.P.	4	4	60	64	5.75	-	-	130

Magnesium Extruded Ribbon and Rods

Size (Inches)	Weight (lb/ft)	Core (Inches)
dx ¾	0.24	0.125
0.750	0.36	0.125
0.840	0.45	0.125
1.050	0.68	0.125
1.315	1.06	0.125
1.561	1.50	0.125
2.024	2.50	0.125

* Data compiled from literature provided by various vendors and may vary slightly.

TABLE 3-3
Composition of Magnesium Alloy

Element	AZ63B (H1A)	AZ63C (H1B)	AZ63D (H1C)	M1C (High Potential)
Aluminum (Al)	5.3 - 6.7%	5.3 - 6.7%	5.0 - 7.0%	< 0.01%
Zinc (Zn)	2.5 - 3.5%	2.5 - 3.5%	2.0 - 4.0%	-
Manganese	0.15 - 0.7%	0.15 - 0.7%	0.15 - 0.7%	0.5 - 1.3%
Silicon (Si)	< 0.10%	< 0.30%	< 0.30%	< 0.05%
Copper (Cu)	< 0.02%	< 0.05%	< 0.10%	< 0.02%
Nickel (Ni)	< 0.002%	< 0.003%	< 0.003%	< 0.001%
Iron (Fe)	< 0.003%	< 0.003%	< 0.003%	< 0.03%
Others (each)	-	-	-	< 0.05%
Others (total)	< 0.30%	< 0.30%	< 0.30%	< 0.30%
Magnesium	Balance	Balance	Balance	Balance

Performance Characteristics*

	AZ63B (H1A)	AZ63C (H1B)	AZ63D (H1C)	M1C (HP)
Potential (Volts to CSE)	-1.60	-1.55	> -1.40	-1.75
Theoretical Current Capacity (A-hrs/lb)	1000	1000	1000	1000
Actual Current Capacity (A-hrs/lb)	450 - 580	300 - 470	250 - 470	400 - 540
Current Efficiency (%)	45 - 58	30 - 47	25 - 47	40 - 54
Actual Consumption Rate (lb/A-yr)	18 - 15	33 - 19	35 - 19	19 - 16

* Using ASTM Standard G97-97 “Standard Test Method for Laboratory Evaluation of Magnesium Sacrificial Anode Test Specimens for Underground Applications”.

TABLE 3-4
Zinc Anode Dimensions and Weights

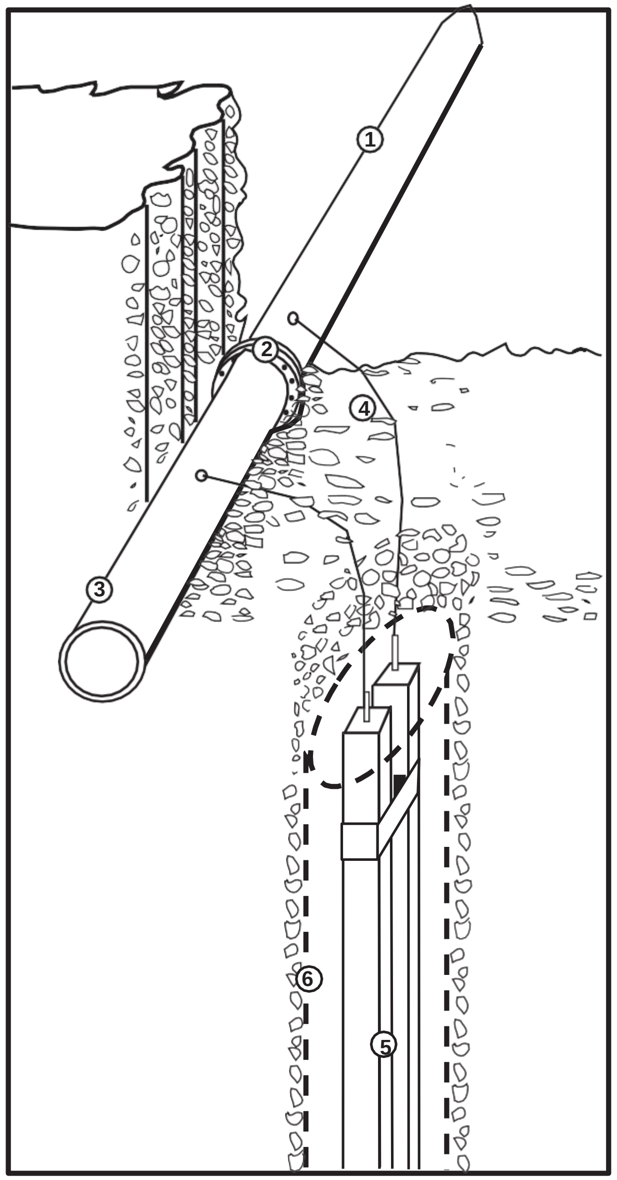
Weight (lbs)	Height	Width	Length	Core (dia.”)
Bare Zinc Anodes				
5	1.4	1.4	9	0.250
12	1.4	1.4	24	0.250
18	1.4	1.4	36	0.250
30	1.4	1.4	60	0.250
30-A	2.0	2.0	30	0.250
45	2.0	2.0	45	0.250
60	2.0	2.0	60	0.250
Zinc Ribbons				
2.4	1.0	1.250	--	0.185
1.2	0.625	0.875	--	0.135
0.6	0.500	0.563	--	0.130
0.25	0.344	0.469	--	0.115

TABLE 3-5
Zinc Alloy Compositions

Element	ASTM B418-01 Type I (sea water)	ASTM B418-01 Type II (soil)
Aluminum	0.1 - 0.5%	< 0.005%
Cadmium	0.025 - 0.07%	< 0.003%
Iron	< 0.005%	< 0.0014%
Lead	< 0.006%	< 0.003%
Copper	< 0.005%	< 0.002%
Others	—	0.1%
Zinc	Balance	Balance

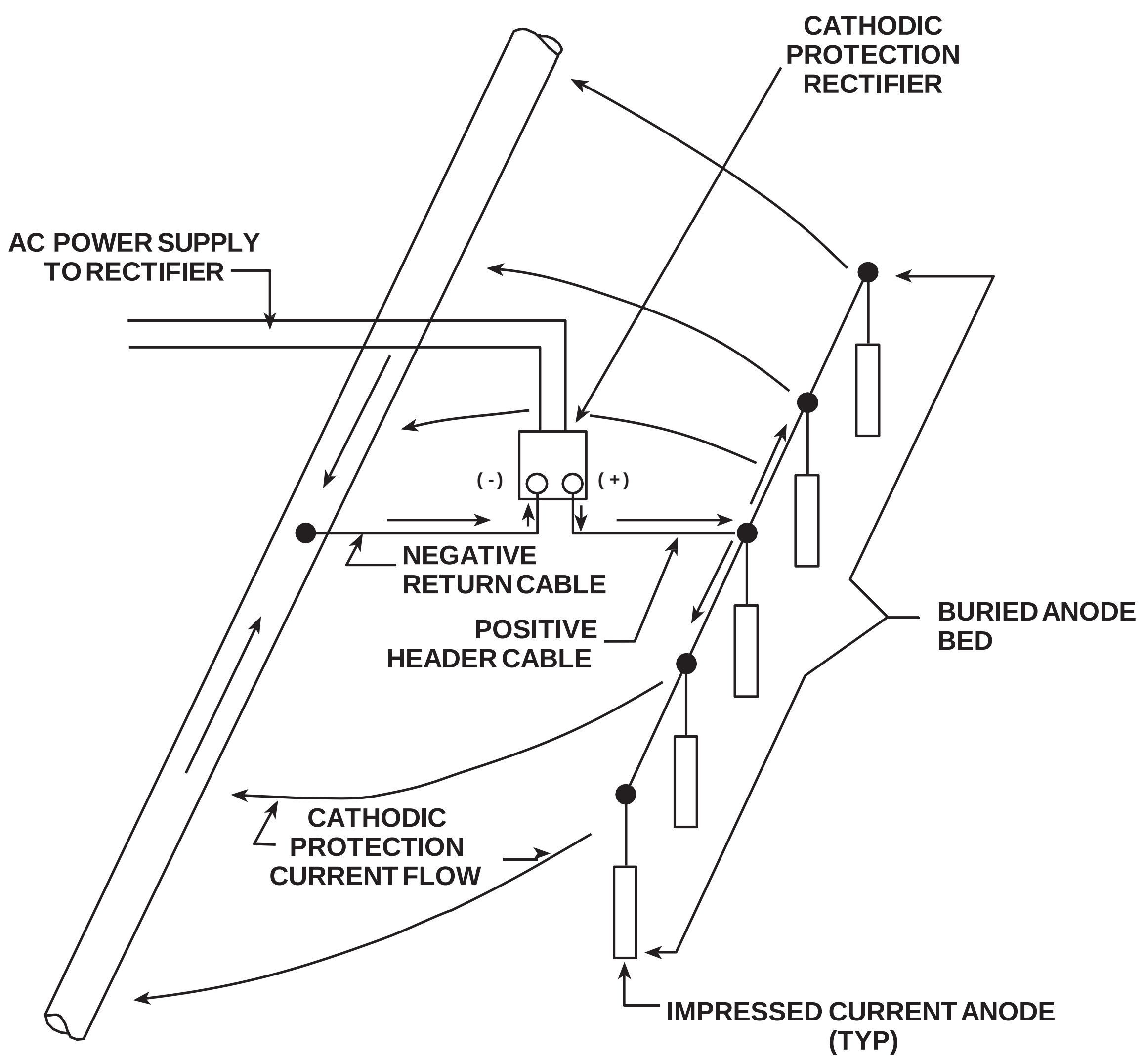
TABLE 3-6
Aluminum Alloy Composition and Performance

Element	Mercury Family Al/Hg/Zn	Indium Family Al/In/Zn
Zinc (Zn)	0.35 - 0.60%	2.8 - 6.5%
Silicon (Si)	0.14 - 0.21%	0.08 - 0.2%
Mercury (Hg)	0.035 - 0.060%	---
Indium (In)	---	0.01 - 0.02%
Copper (Cu)	0.004% max	0.006% max
Iron (Fe)	0.10% max	0.12% max
Aluminum (Al)	Balance	Balance
Consumption Rate (lb/A-y)	6.8 - 7.0	7.4 - 8.4
Current Capacity (A-hrs/lb)	1250 - 1290	1040 - 1180
Potential to Ag/AgCl	-1.05	-1.10
to $Cu/CuSO_4$	-1.10	-1.15



TWO UNIT ZINC GROUNDING CELLS

FIGURE 3-3



TYPICAL IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM

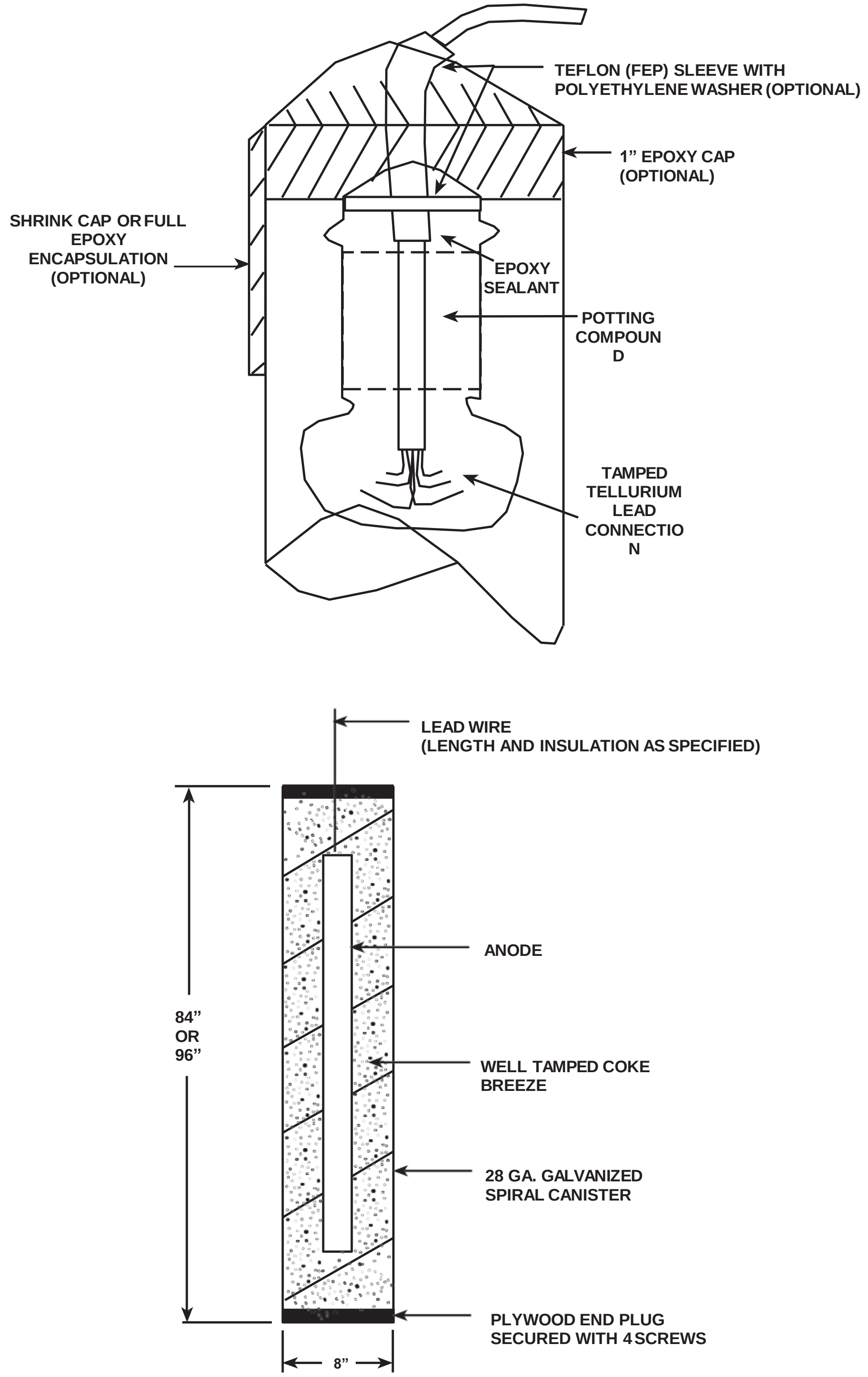
FIGURE 3-4

TABLE 3-7
Cast Iron Composition
ASTM A518 Grade 3

ELEMENT	COMPOSITION
Silicon	14.2 - 14.75%
Carbon	0.70 - 1.10%
Manganese	1.50% max
Molybdenum	0.20%
Chromium	3.25 - 5.00%
Copper	0.50% max
Iron	Balance

TABLE 3-8
Typical Cast Iron Rod Anode Dimensions

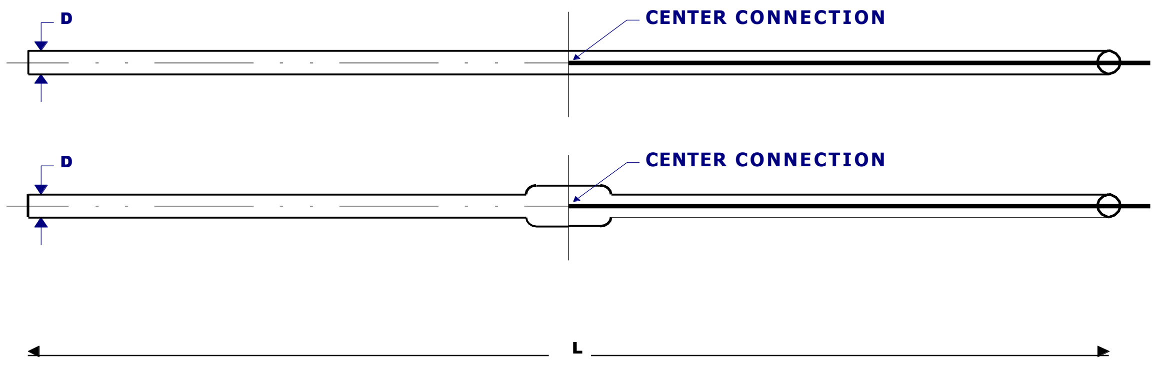
NOMINAL WEIGHT lbs (kgs)	NOMINAL DIAMETER in (mm)	NOMINAL LENGTH in (mm)	NOMINAL AREA ft^2 (m^2)
1.0 (.5)	1.1 (28)	9 (230)	.22 (.02)
5.0 (2.3)	2.0 (51)	9 (230)	.39 (.04)
9.0 (4.1)	2.5 (64)	9 (230)	.50 (.05)
26 (12)	1.5 (38)	60 (1520)	2.0 (.19)
43 (20)	2.0 (51)	60 (1520)	2.6 (.24)
44 (20)	2.0 (51)	60 (1520)	2.6 (.24)
60 (27)	2.0 (51)	60 (1520)	2.7 (.25)
110 (50)	4.0 (102)	60 (1520)	4.0 (.37)
220 (100)	4.5 (114)	60 (1520)	5.5 (.51)



TYPICAL CAST IRON ANODE LEAD WIRE CONNECTION AND PACKAGING

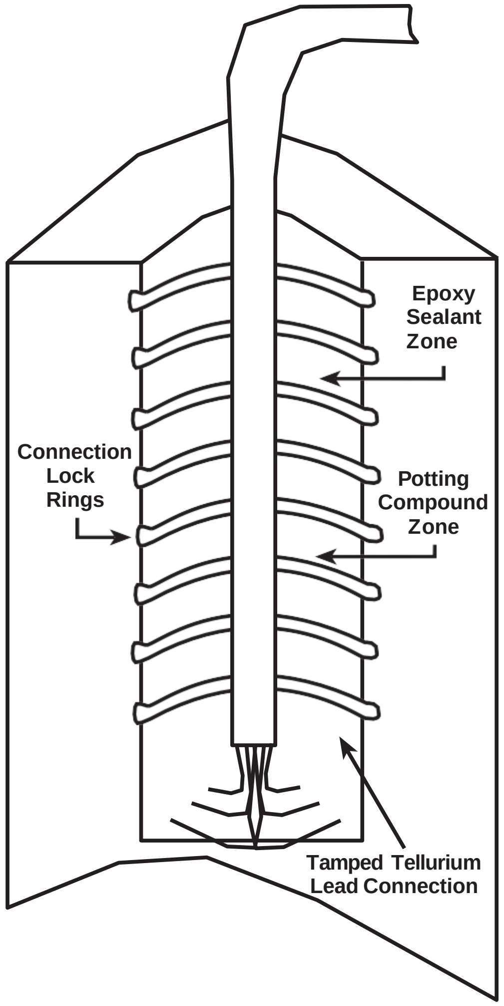
FIGURE 3-5

NOMINAL WEIGHT lbs (kgs)	NOMINAL DIAMETER in (mm)	NOMINAL LENGTH in (mm)	NOMINAL AREA ft^2 (m^2)
31 (14)	2.6 (66)	41 (1067)	2.4 (.22)
50 (23)	2.6 (66)	60 (1520)	3.5 (.33)
46-50 (21-23)	2.2 (56)	84 (2130)	4.2 (.39)
63-70 (29-32)	2.6 (66)	84 (2130)	4.9 (.46)
85-95 (39-43)	3.8 (97)	84 (2130)	7.0 (.65)
110-122 (50-55)	4.8 (122)	84 (2130)	8.8 (.82)
175-177 (79-80)	4.8 (122)	84 (2130)	8.8 (.82)
230 (104)	4.8 (122)	84 (2130)	8.8 (.82)
260 (118)	6.7 (170)	76 (1981)	11.4 (1.06)
270 (122)	6.7 (170)	84 (2130)	12.3 (1.14)



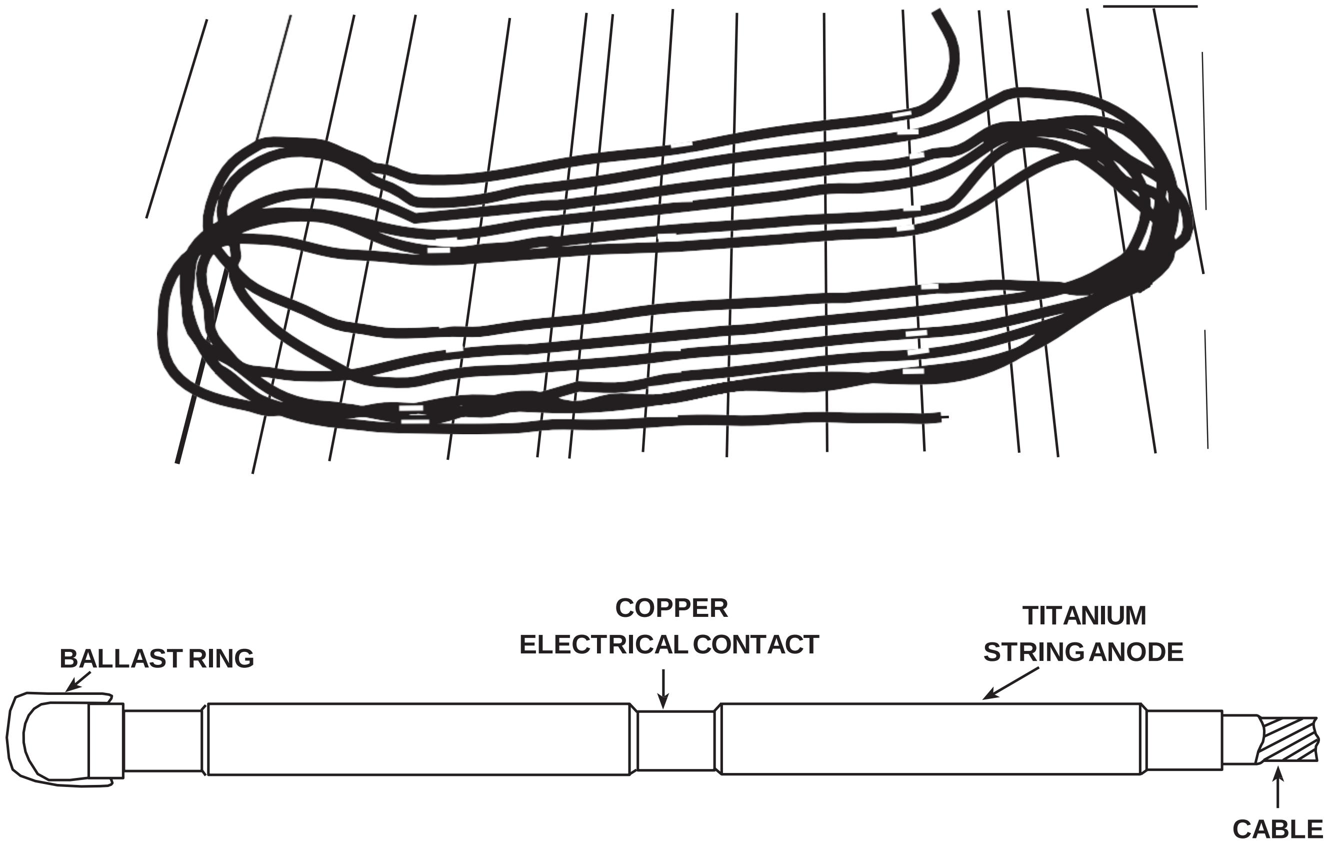
TYPICAL TUBULAR ANODE DIMENSIONS

FIGURE 3-6



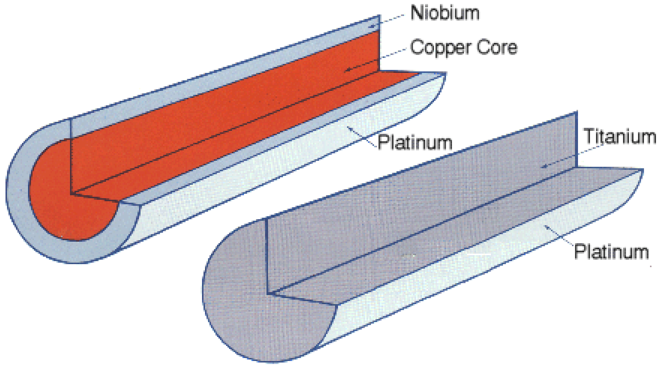
TYPICAL GRAPHITE ANODE
LEAD WIRE CONNECTION

FIGURE 3-7



MIXED METAL ANODE

FIGURE 3-8



20% Niobium

Diameter Inches	Nb Thickness Inches	Resistance microhm/ft	Pt Thickness µ-in (2X)*
.750	.038	22	300 (600)
.500	.025	50	200 (400)
.375	.019	89	150 (300)
.250	.013	201	100 (200)
.188	.009	356	75 (150)
.125	.006	806	50 (100)

40% Niobium

Diameter Inches	Nb Thickness Inches	Resistance microhm/ft	Pt Thickness µ-in (2X)*
.375	.038	113	150 (300)
.250	.025	256	100 (200)
.188	.019	453	75 (150)
.125	.013	1025	50 (100)
.093	.010	1822	38 (75)
.063	.007	4102	25 (50)
.031	.0035	16,408	12.5 (25)

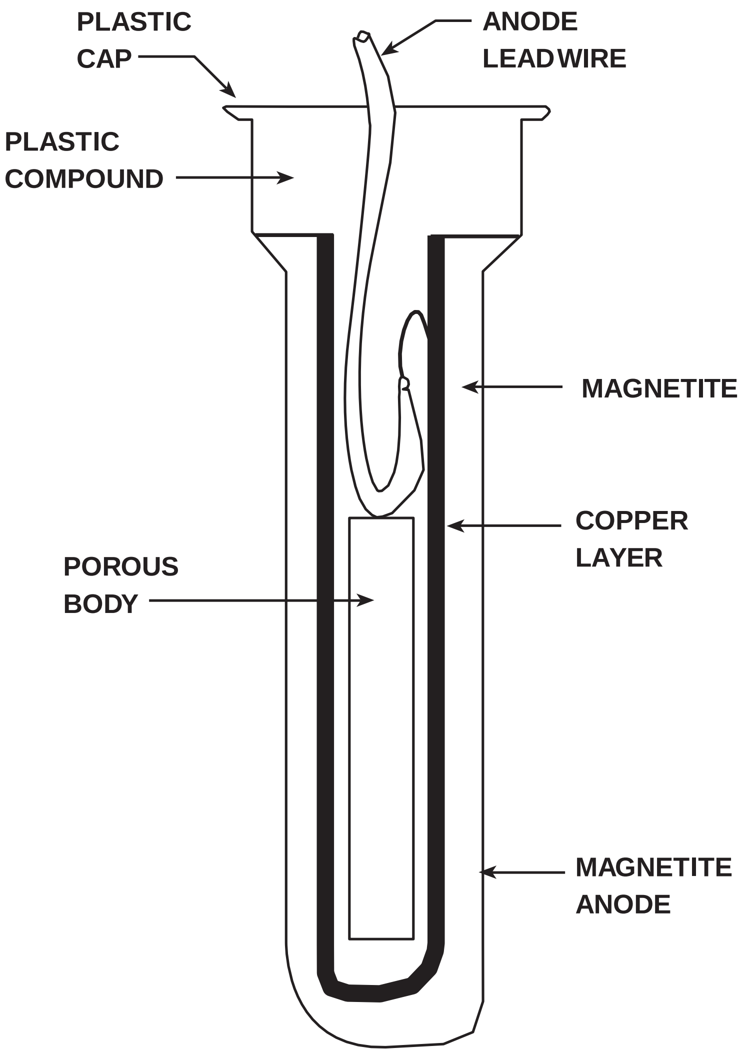
100% Titanium

Diameter Inches	Ti Thickness Inches	Resistance microhm/ft	Pt Thickness µ-in
.750	Solid	468	300
.500	Solid	1054	200
.375	Solid	1874	150
.250	Solid	4215	100
.188	Solid	7454	75
.125	Solid	16,862	50

* Double Platinum Thickness

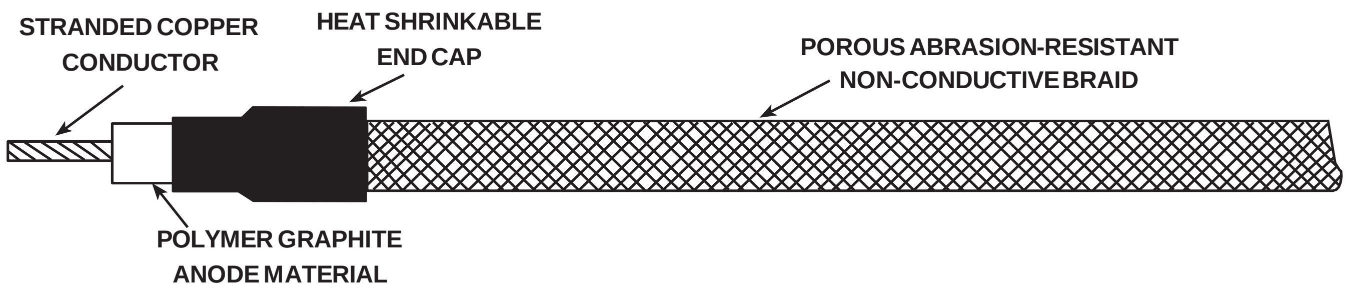
PLATINUM ANODES

FIGURE 3-9



TYPICAL MAGNETITE ANODE

FIGURE 3-10



POLYMER ANODE

FIGURE 3-11

TABLE 3-9
Coke Breeze Composition

Type	Bulk Density (lb/cu ft)	Porosity (%)	Carbon (lb/cu ft)
Metallurgical	45	48.0	32.51
Petroleum, calcined			
Delayed	48	59.5	47.76
Fluid	54	56.7	49.93
	70	44.0	64.73
	74	40.8	68.53

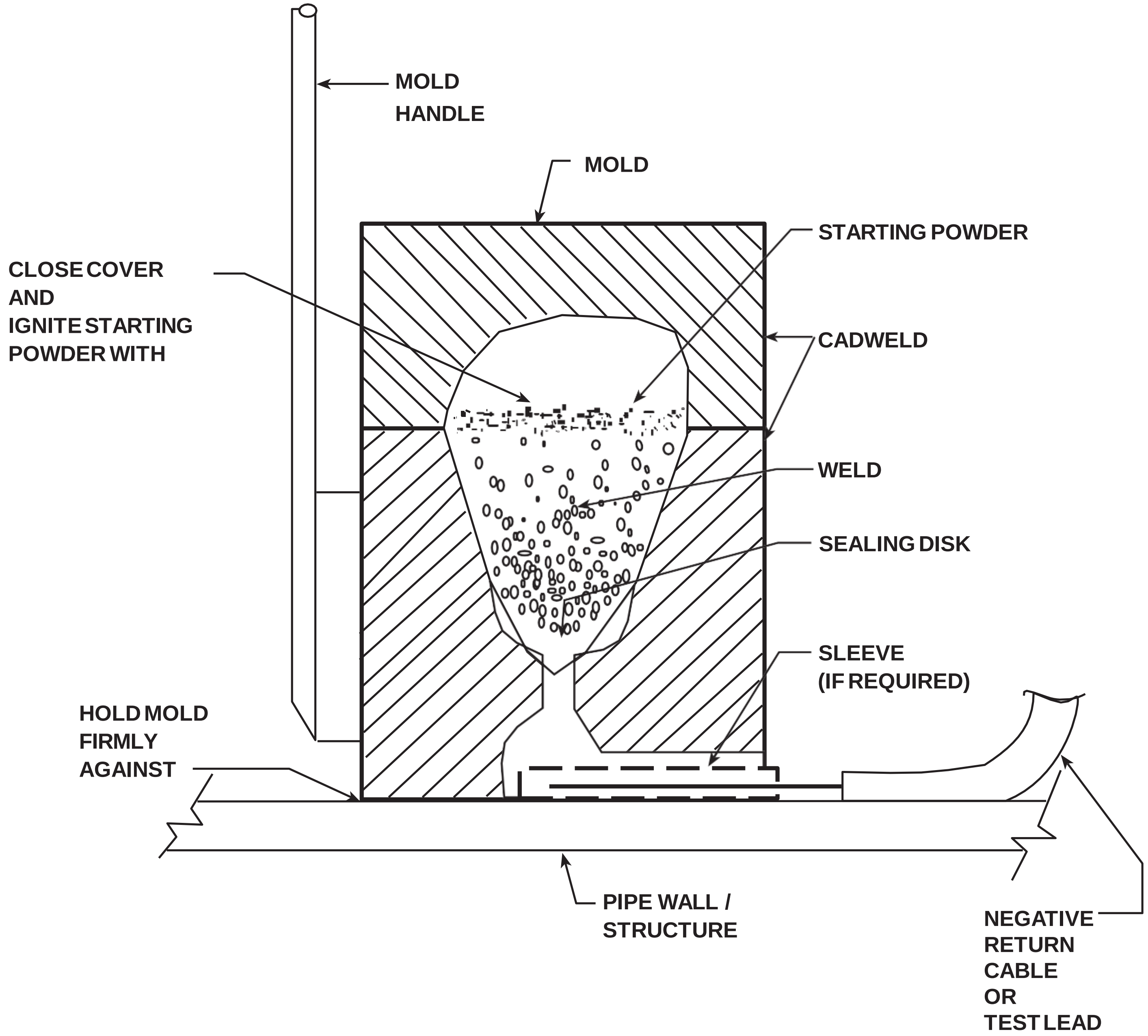
TABLE 3-10
Wire And Cable Insulation Designations

Designation	Insulation	Thick (in)	Cable Size	Specification
HMWPE	High Molecular Weight Polyethylene	.110 .125	No 8 - No 2 No 1 - 4/0	D-1248, Type 1 Class C, Cat. 5
TW	Polyvinyl Chloride (PVC)	.030 .034 .060	No 14 - No 10 No 8 No 6-No 2	U.L. Standard 83 (60º C wet/dry)
THW	Polyvinyl Chloride (PVC)	.045 .060	No 14 - No 10 No 8 - No 2	U.L. Standard 83 (75º C wet/dry)
THHN	PVC/Nylon Jacket (.0004” Nylon)	.015 .020	No 14 - No 12 No 10	U.L. Standard 83 (90º C dry)
THWN	PVC/Nylon Jacket (.004” Nylon)	.015 .020	No 14 - No 12 No 10	U.L. Standard 83 (75º C wet)
PVF/HMWPE	Polyvinylidene (.020”) HMWPE jacket (.065”)	.085	No 8 - No 2	Kynar™ ASTM D-257
ECTFE/HMWPE	Ethylene Chlorotriflora-ethylene (.020”) HMWPE jacket (.065”)	.085	No 8 - No 2	Halar™

TABLE 3-11
Conductor Ampacities And Resistances
NACE Corrosion Engineer’s Reference Book

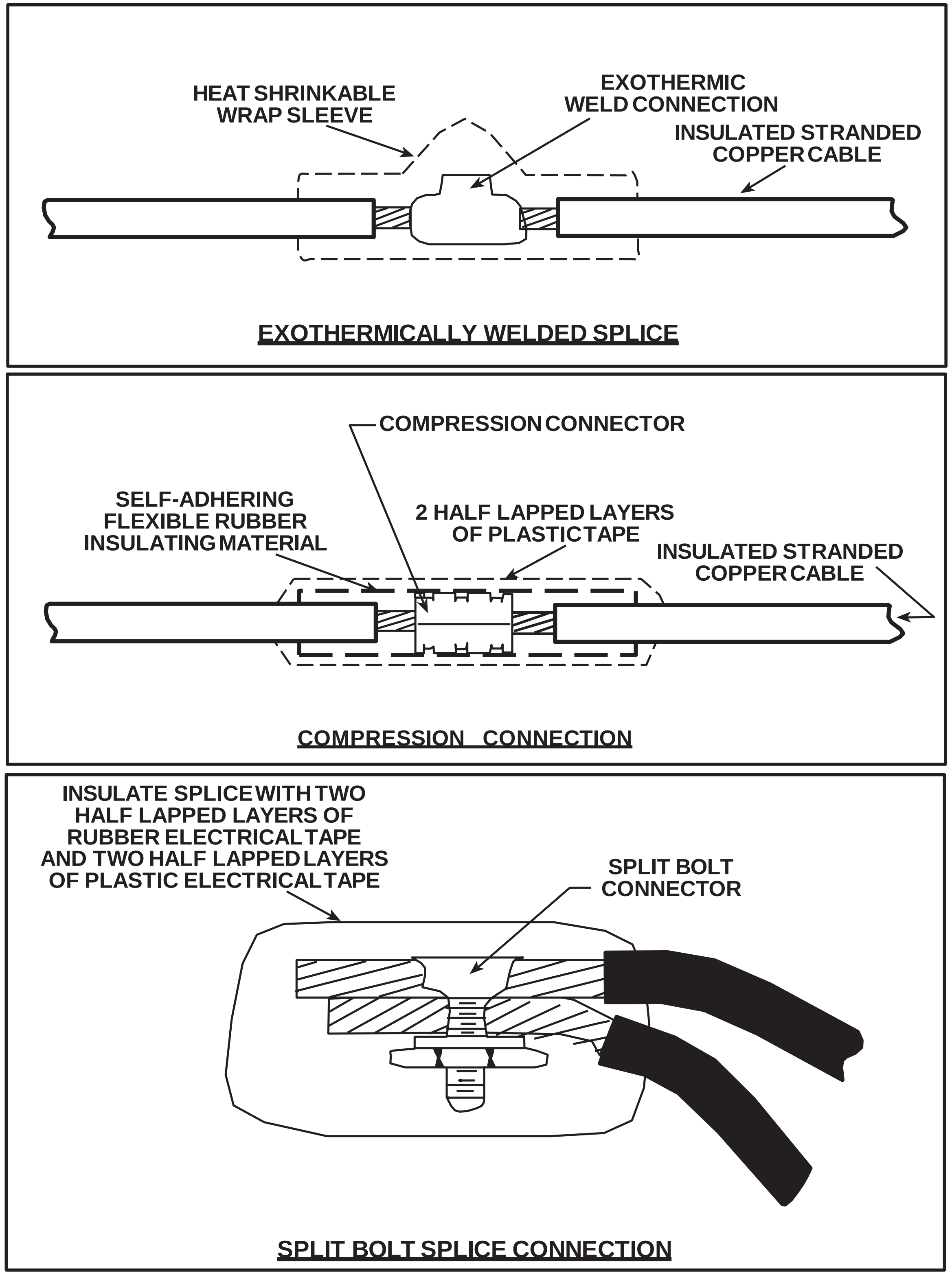
Size AWG	Ampacity* (Copper)	Resistance (Ohms/1000 ft @ 25º C)
No. 16	6	4.18
No. 14	15	2.62
No. 12	20	1.65
No. 10	30	1.04
No. 8	50	0.652
No. 6	65	0.411
No. 4	85	0.258
No.2	115	0.162
No. 1	130	0.129
No. 1/0	150	0.102
No. 2/0	175	0.0811
No. 3/0	200	0.0642
No. 4/0	230	0.0509
250 MCM	255	0.0423
300 MCM	285	0.0353
350 MCM	310	0.0302
400 MCM	335	0.0264
500 MCM	380	0.0212

* Ampacity based on THW and HMWPE insulation



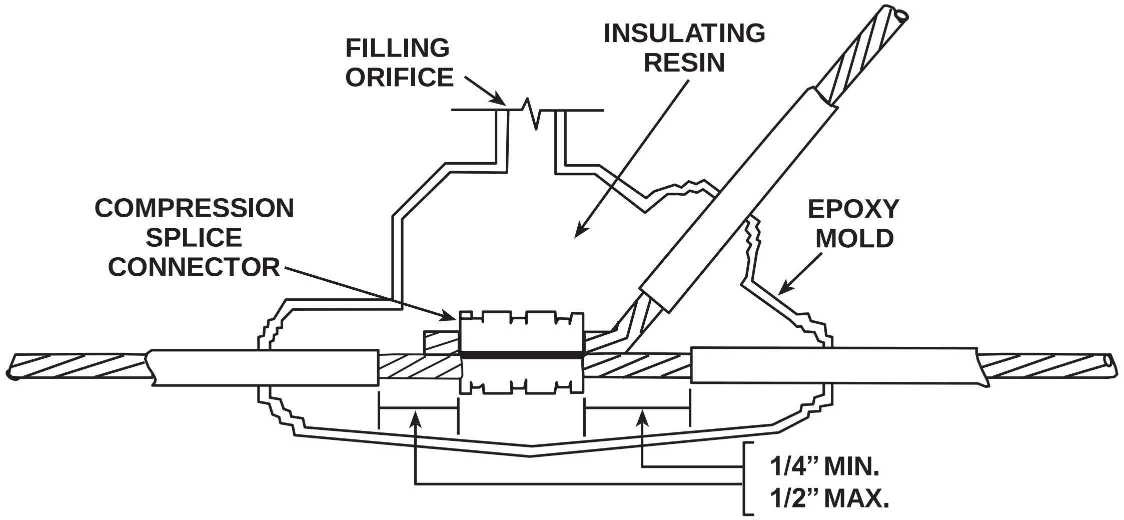
TYPICAL EXOTHERMIC WELD
PROCESS

FIGURE 3-12



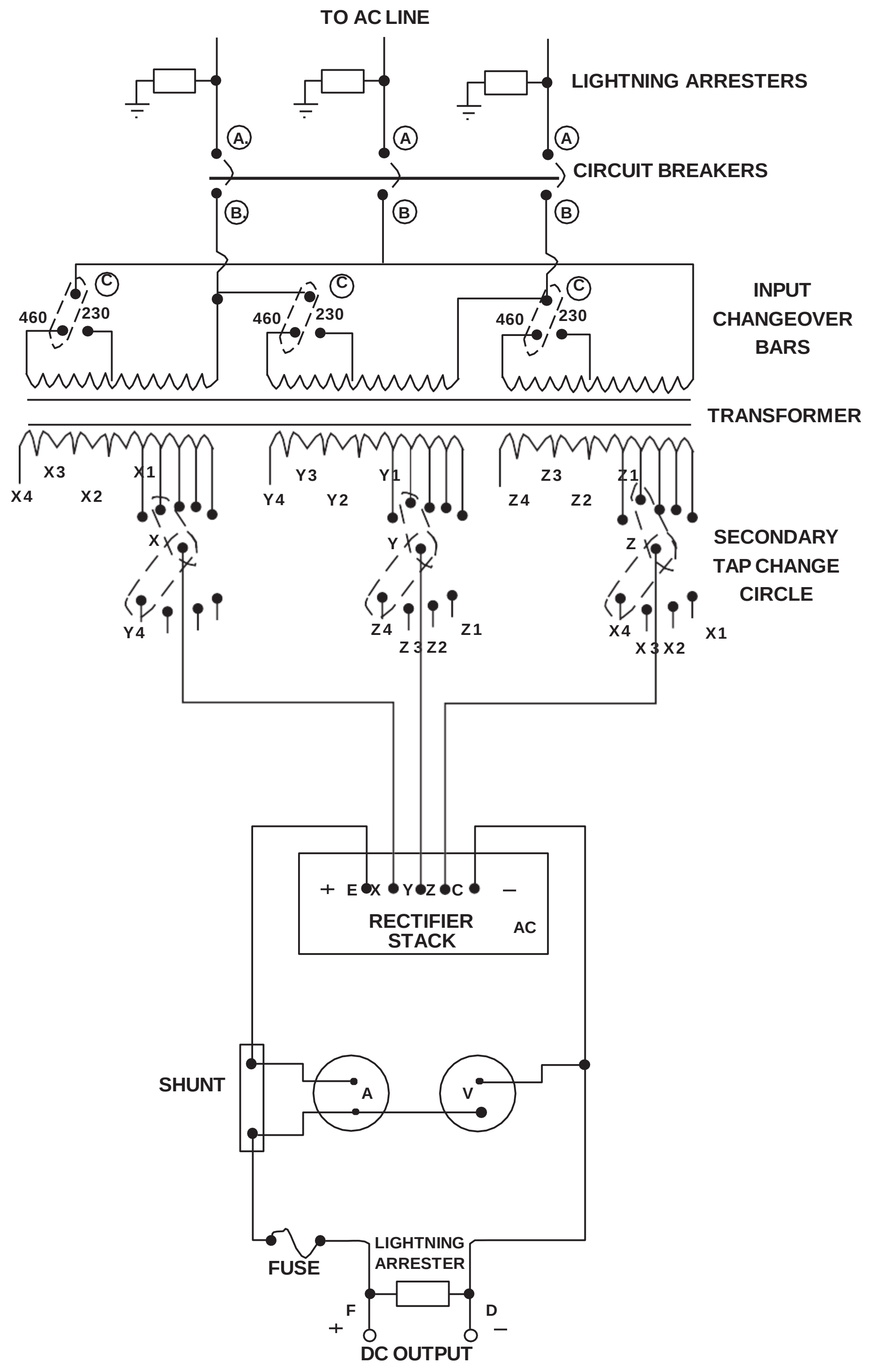
CABLE SPLICE CONNECTIONS

FIGURE 3-13



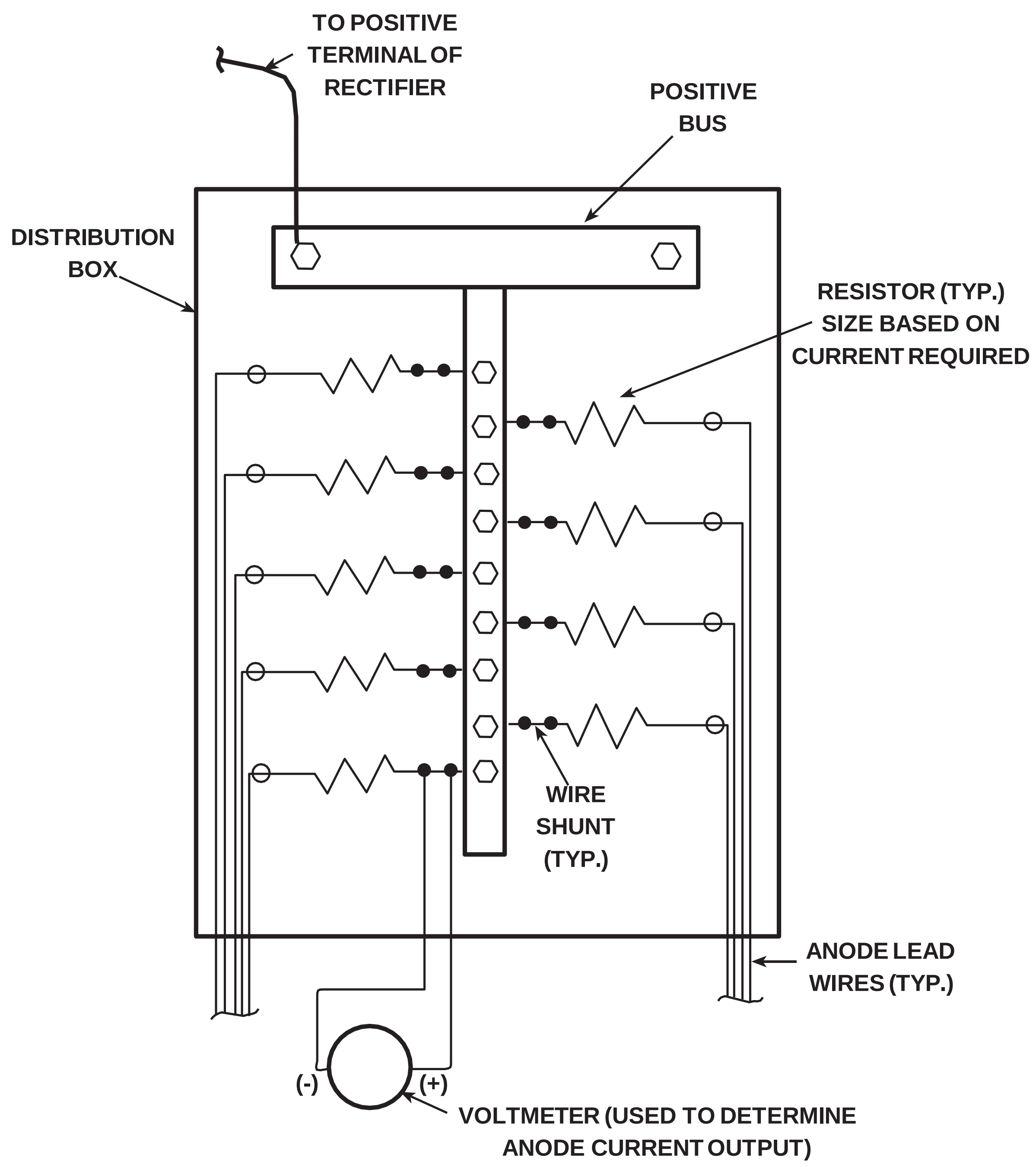
EPOXY ENCAPSULATED SPLICE

FIGURE 3-14



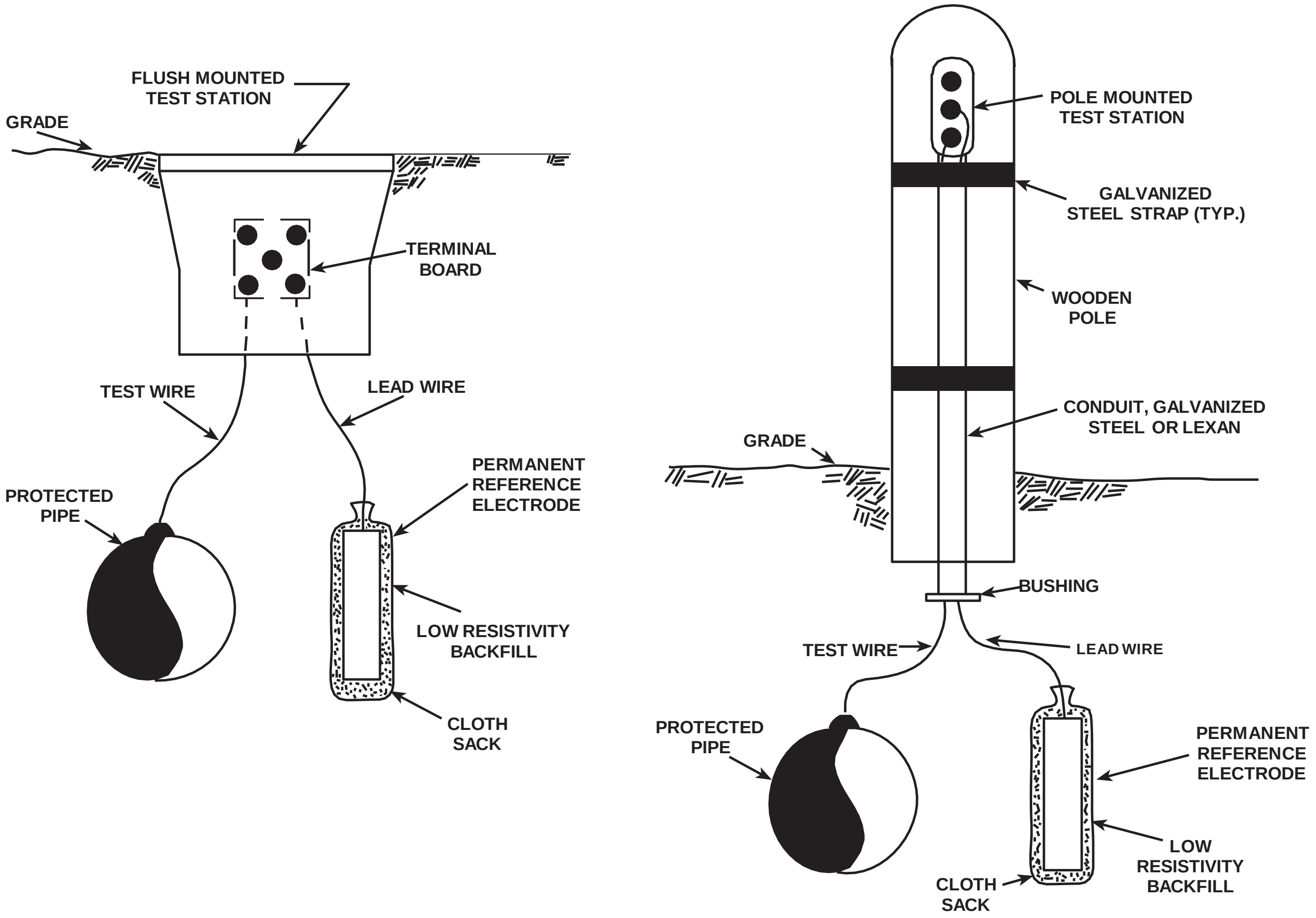
TYPICAL RECTIFIER CIRCUIT

FIGURE 3-15



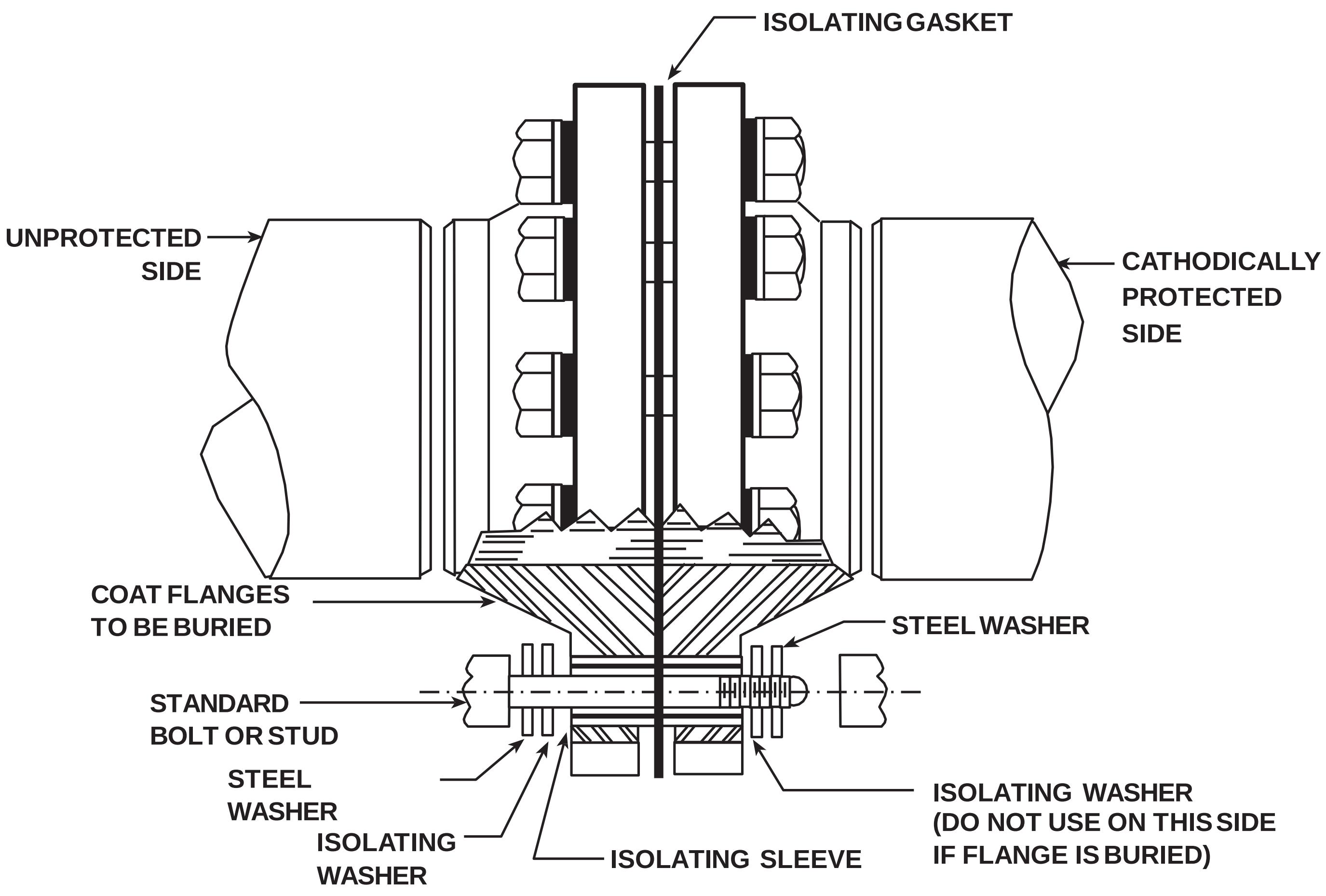
TYPICAL JUNCTION BOX WITH SHUNTS

FIGURE 3-16



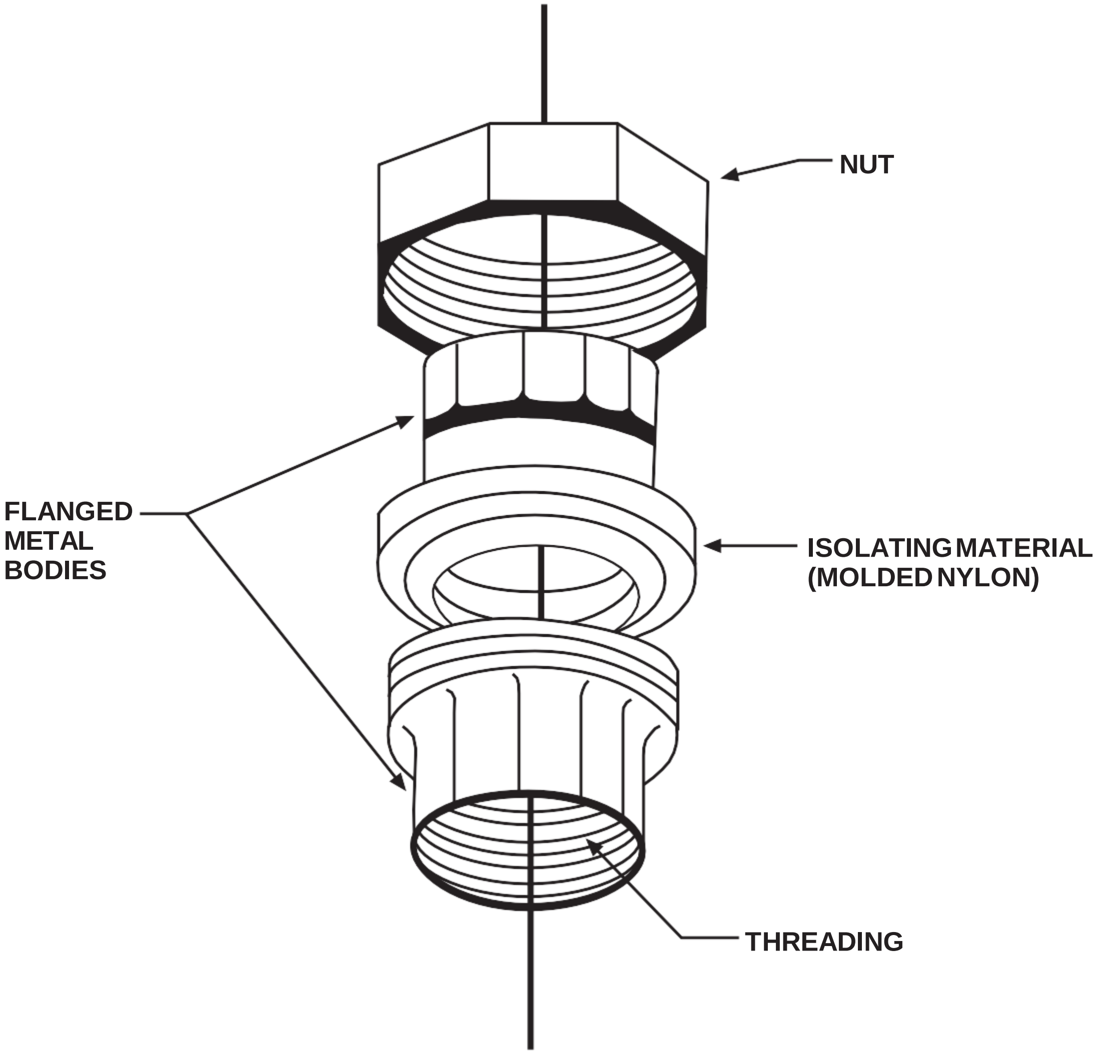
TYPICAL CATHODIC PROTECTION SYSTEM
TEST STATION INSTALLATIONS

FIGURE 3-17



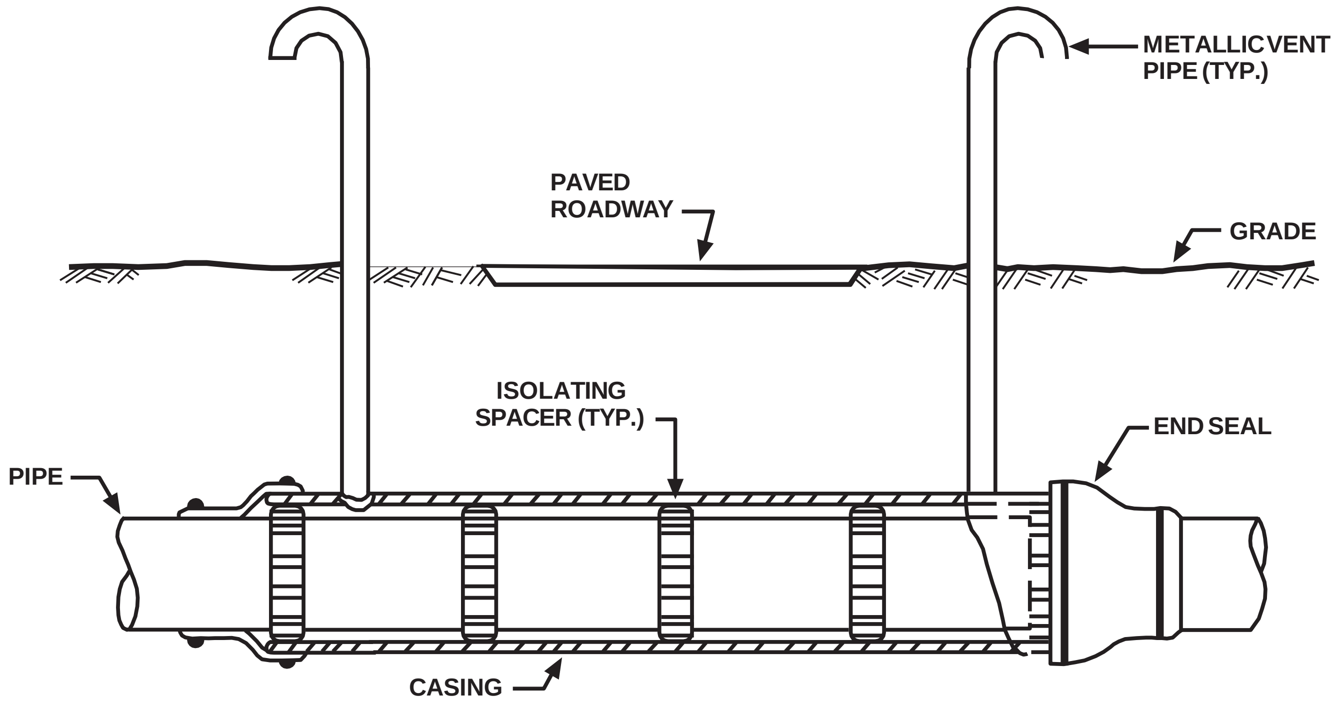
TYPICAL ISOLATING FLANGE
ASSEMBLY

FIGURE 3-18



TYPICAL ISOLATING UNION DETAIL

FIGURE 3-19



TYPICAL ISOLATED CASING DETAIL

FIGURE 3-20

Advanced Chapter 4
Dynamic Stray Current Analysis

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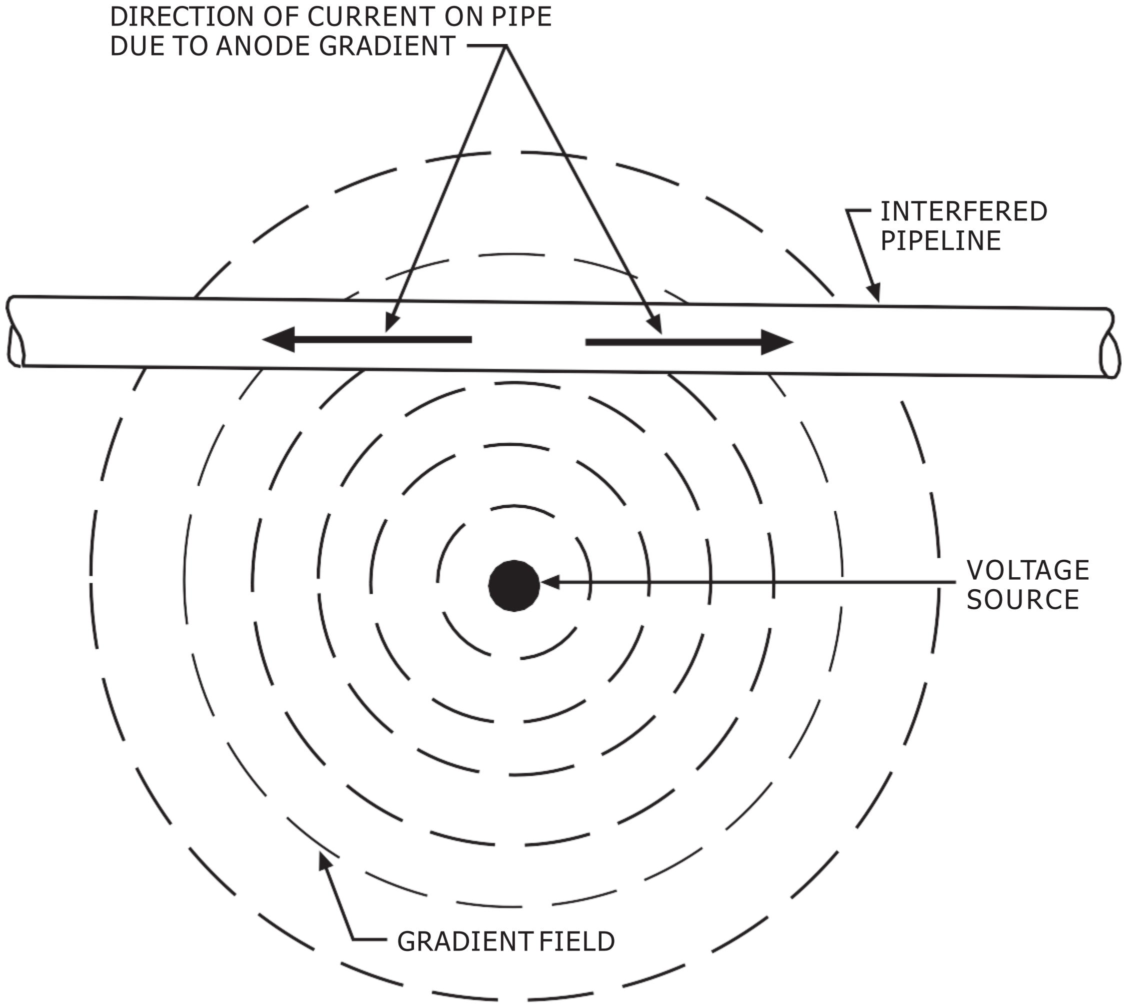
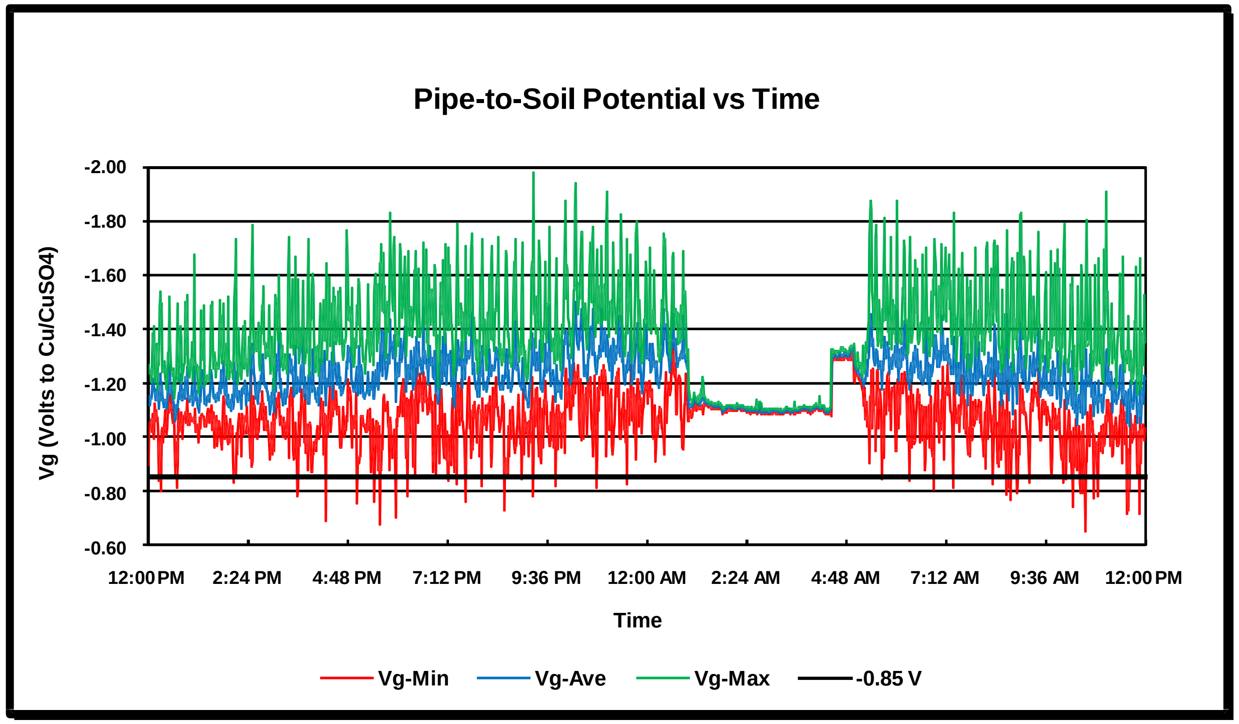


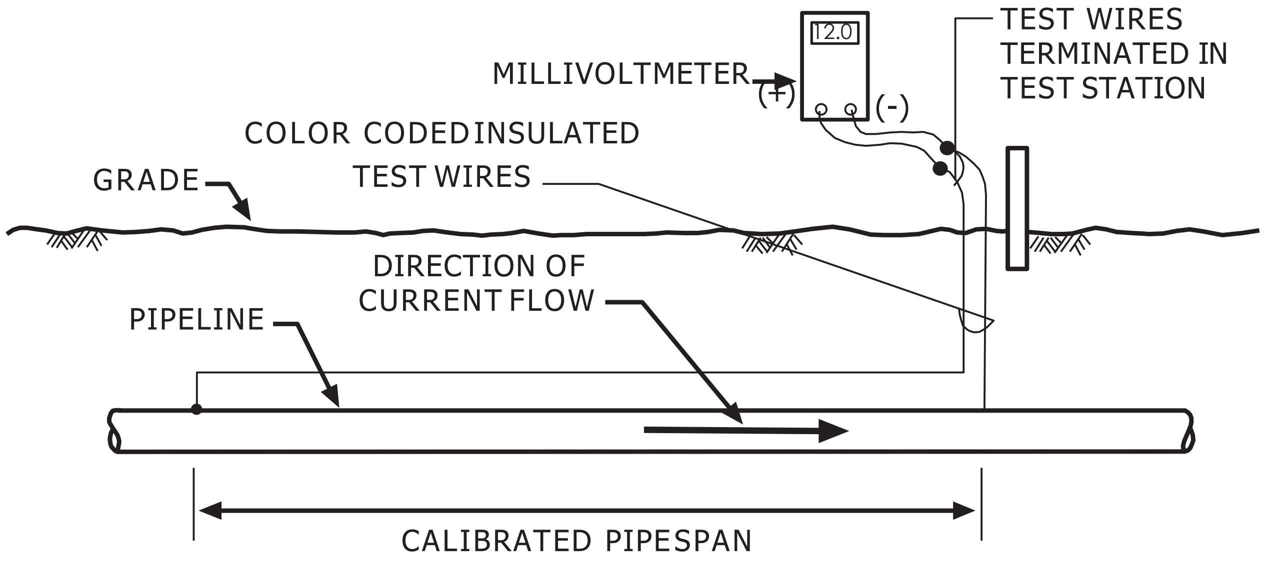
CURRENT FLOW CAUSED ON STRUCTURE WITHIN A VOLTAGE GRADIENT FIELD

FIGURE 4-1



TYPICAL PIPE-TO-SOIL POTENTIAL (Vg) PROFILE
INDICATING DYNAMIC STRAY CURRENT

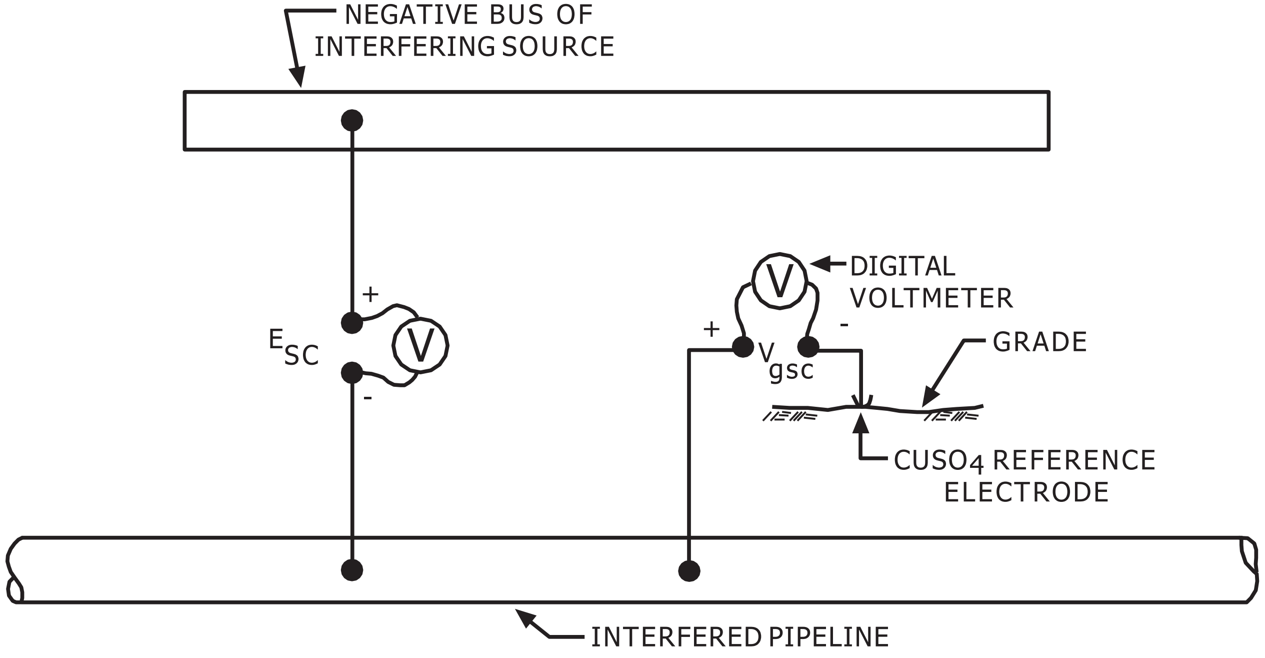
FIGURE 4-2



NOTE: POSITIVE POTENTIALS MEASURED WITH METER HOOK-UP AS SHOWN INDICATES CURRENT FLOW IN DIRECTION SHOWN

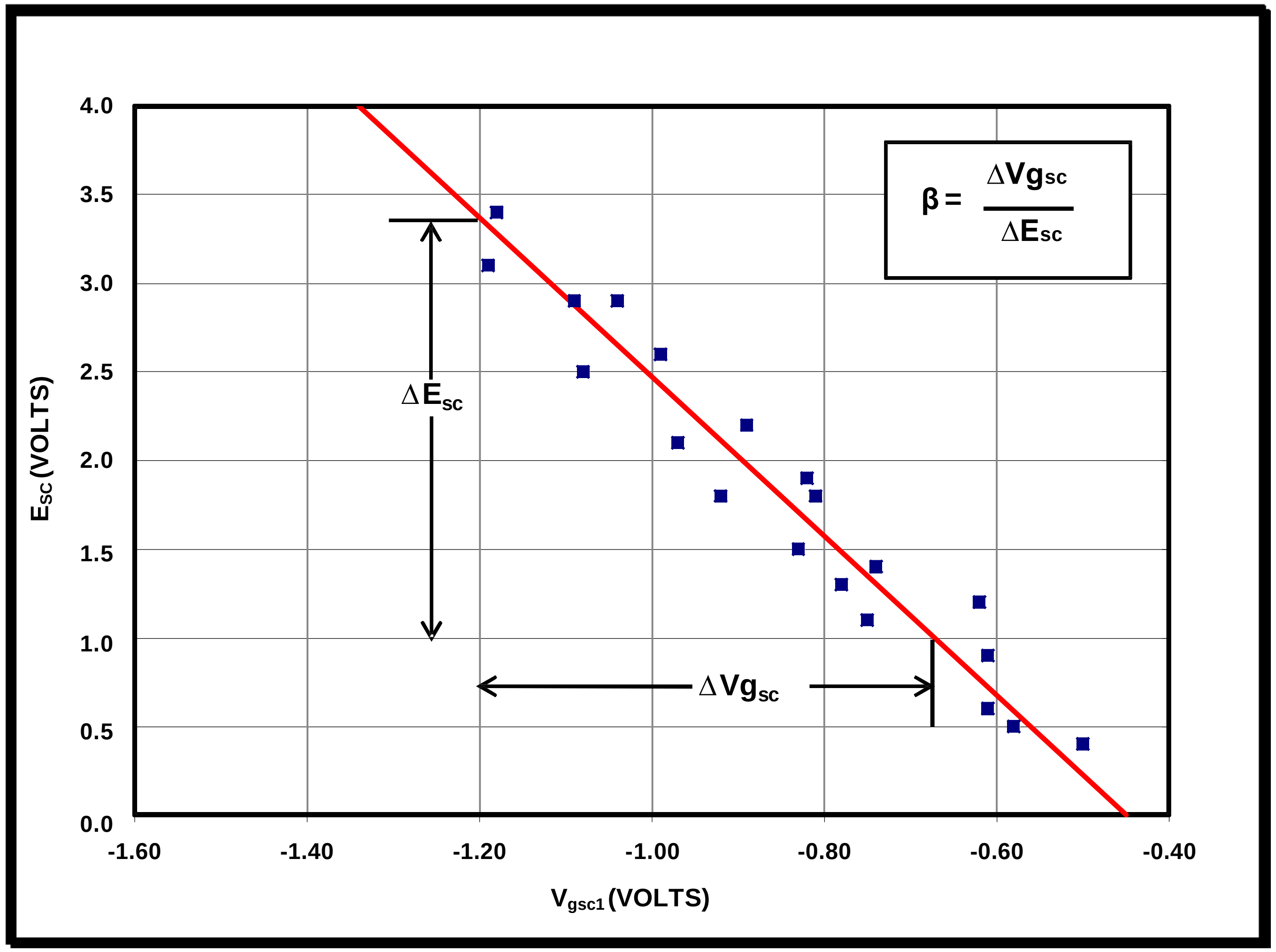
DETERMINING DIRECTION OF LINE CURRENT FLOW

FIGURE 4-3



TYPICAL TEST SET-UP USED TO LOCATE POINT OF MAXIMUM EXPOSURE

FIGURE 4-4



TYPICAL BETA CURVE - PICKUP AREA

FIGURE 4-5

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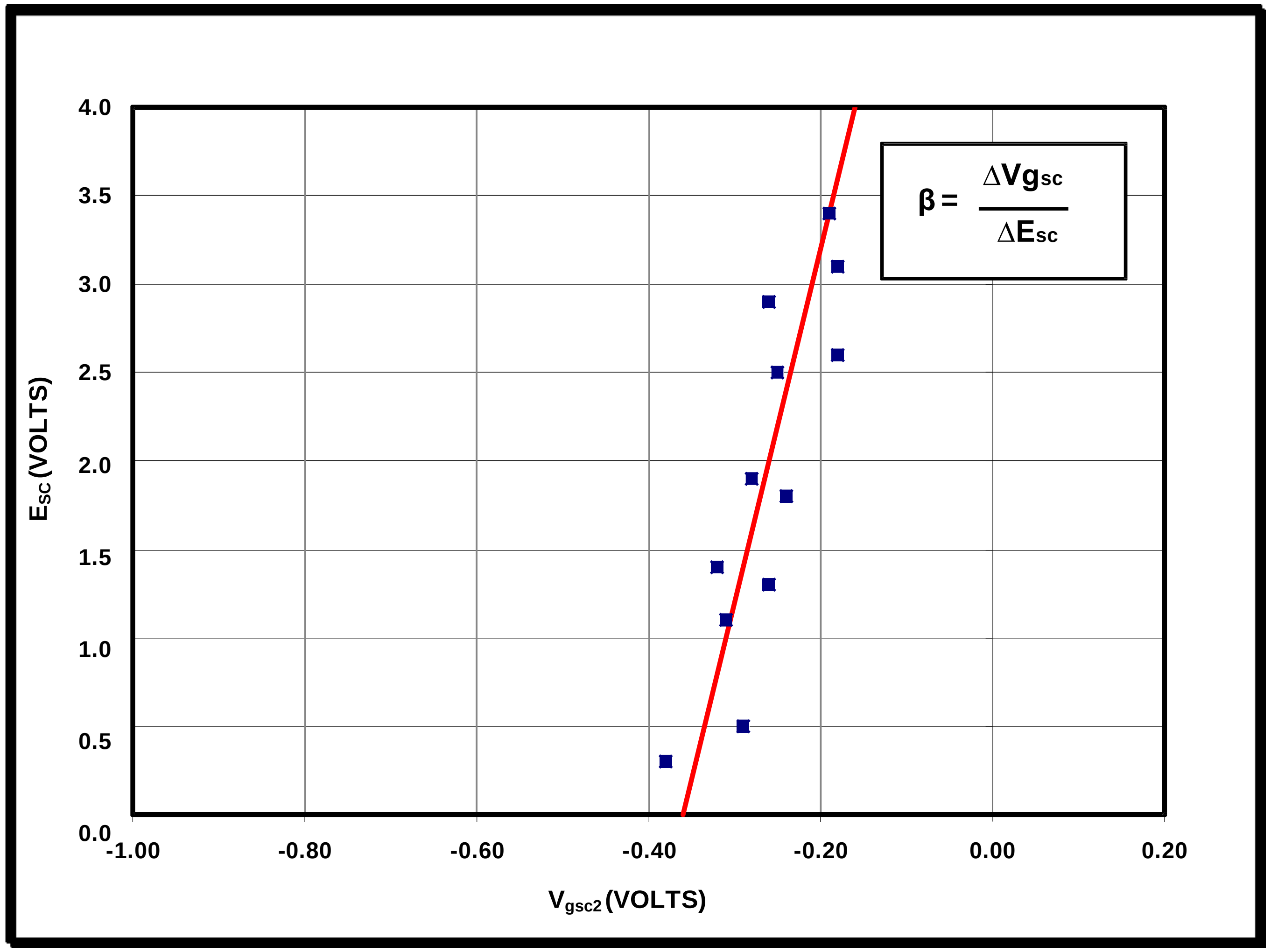
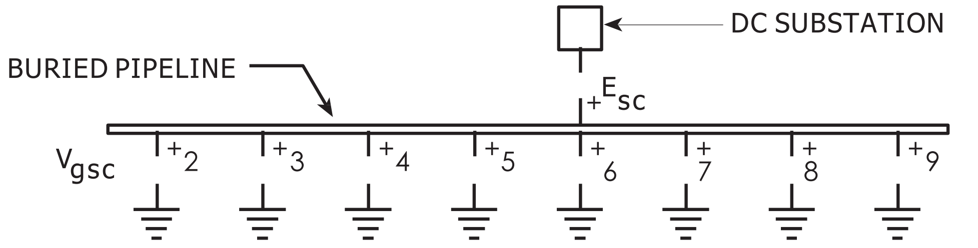
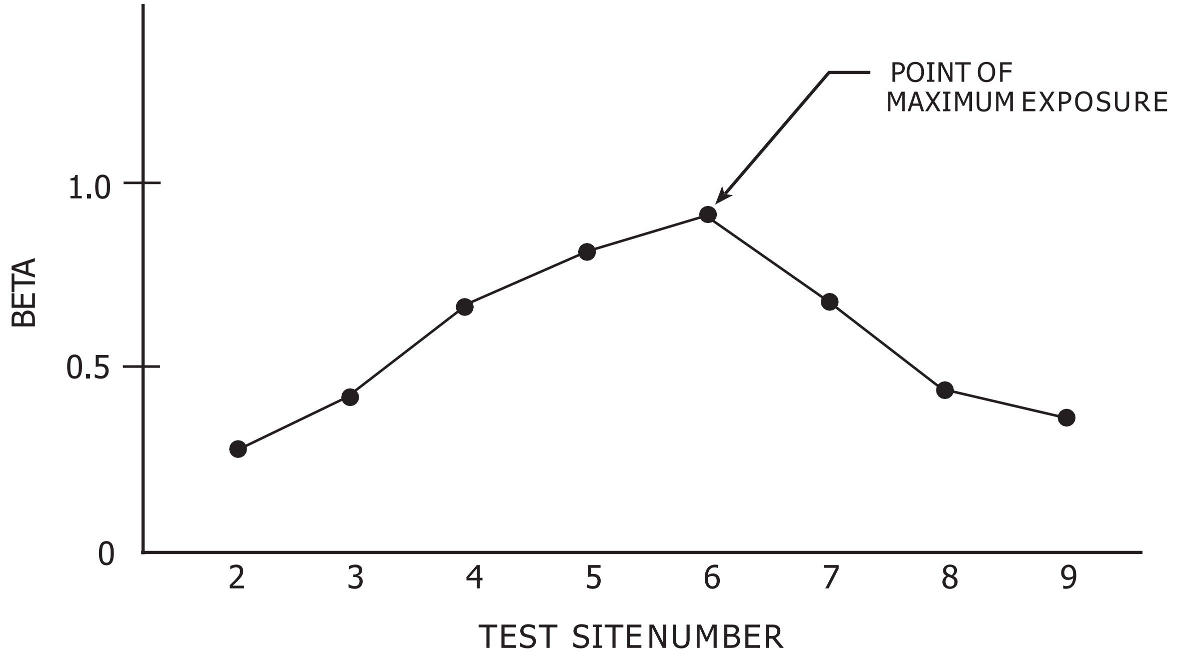


TYPICAL BETA CURVE - DISCHARGE AREA

FIGURE 4-6

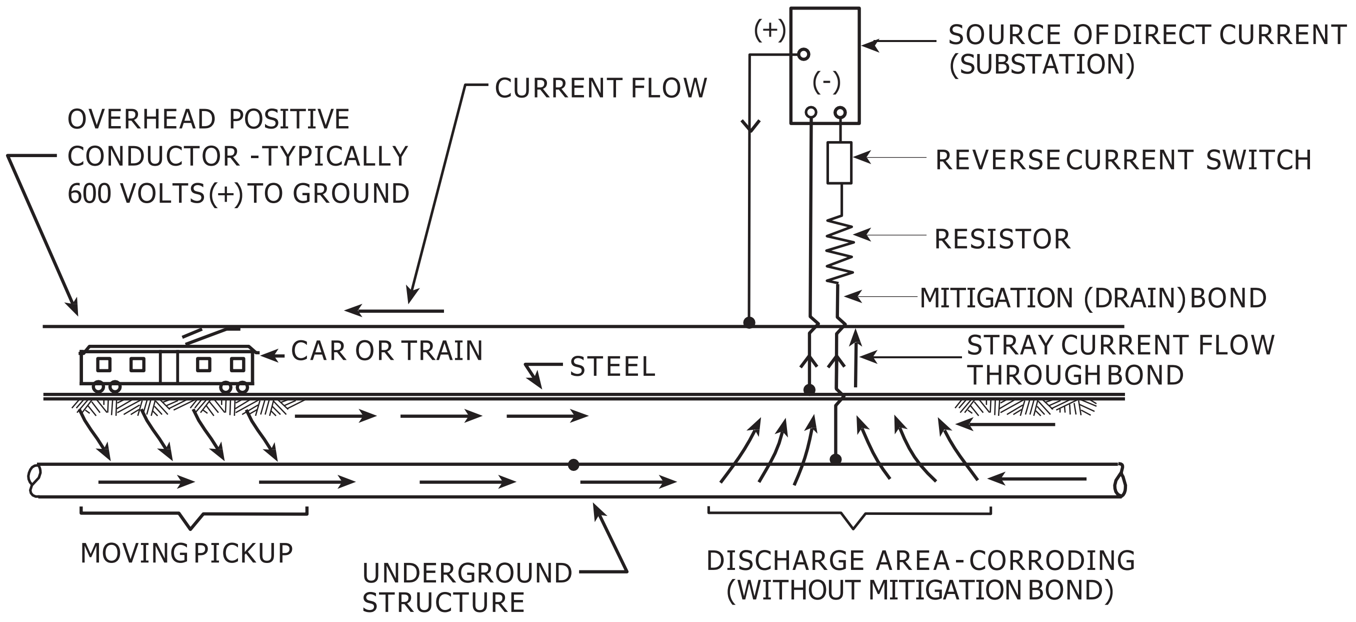
Appalachian Underground Corrosion Short Course





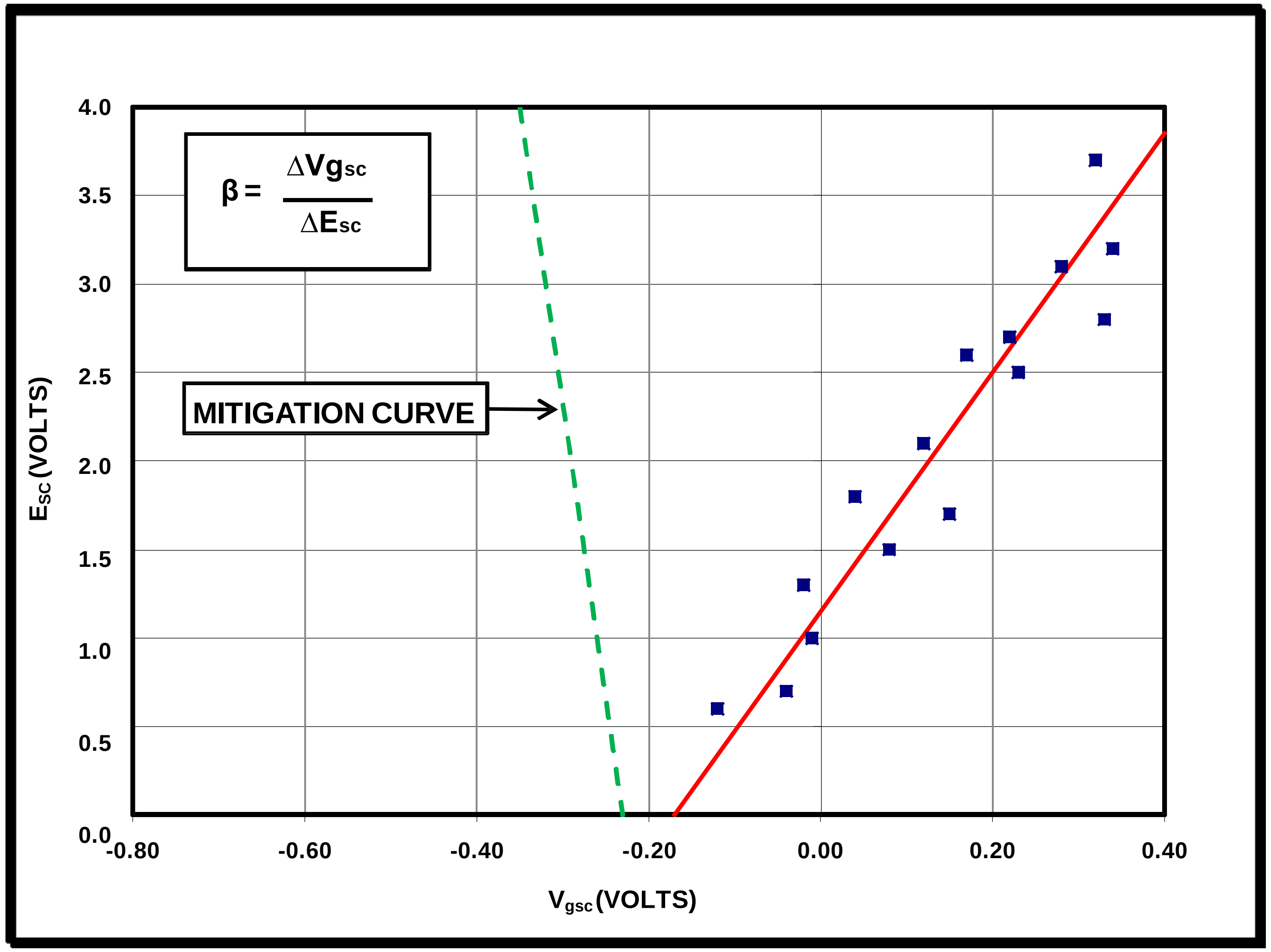
LOCATING THE POINT OF MAXIMUM EXPOSURE FROM A BETA PROFILE

FIGURE 4-7



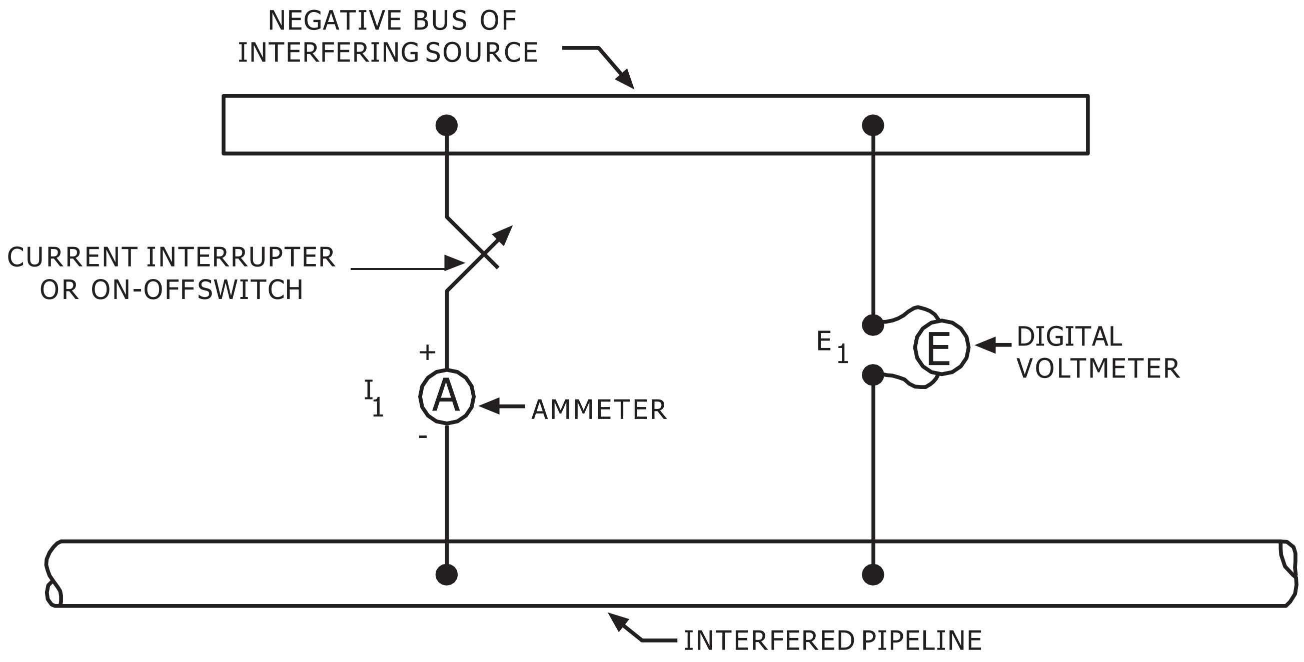
INSTALLATION OF A MITIGATION BOND ON A DC TRANSIT SYSTEM TO PREVENT STRAY CURRENT CORROSION

FIGURE 4-8



TYPICAL BETA CURVE - DISCHARGE AREA
(MITIGATION CURVE)

FIGURE 4-9



Several sets of data are taken by interrupting the current circuit. Current and voltage are taken simultaneously with the switch closed (on) and open (off: $I_1 = 0$). The resistance between the two structures (R_{1-1}) is calculated from Ohm's Law:

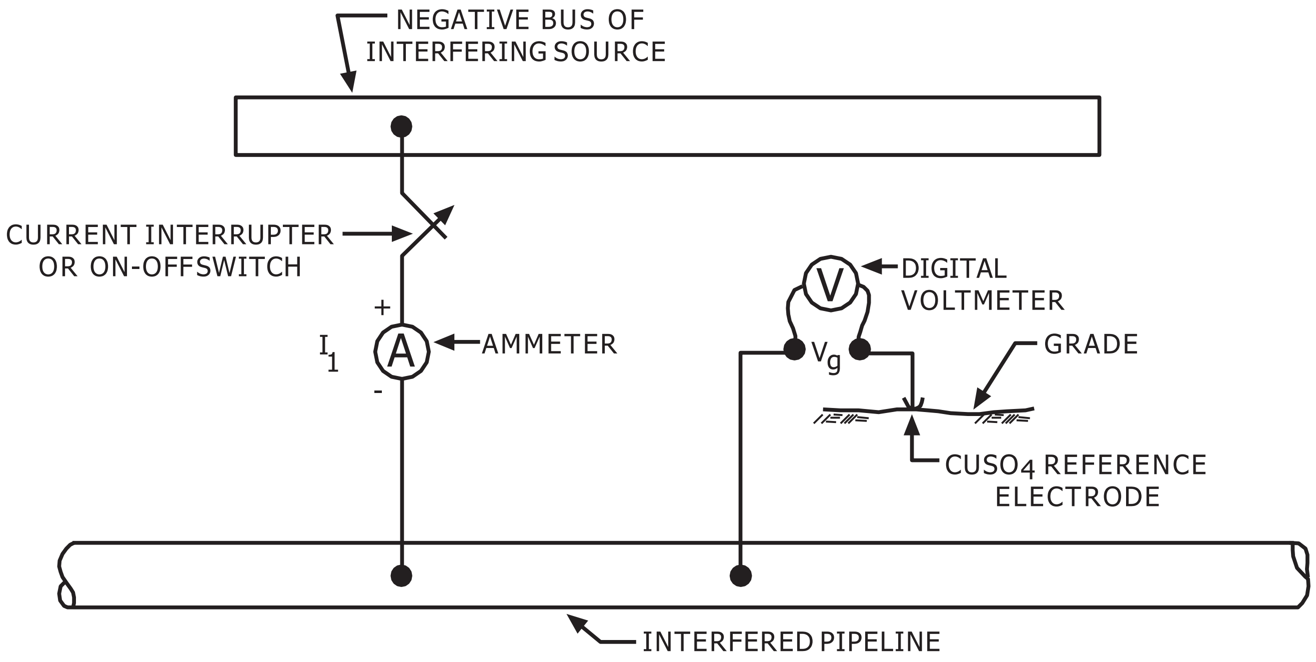
$$\Delta E_1 = E_{1ON} - E_{1OFF}$$

$$\Delta I_1 = I_{1ON} - I_{1OFF} \ (I_{1OFF} = 0)$$

$$R_{int} = \Delta E_1 / \Delta I_1$$

TYPICAL TEST SET-UP USED TO DETERMINE INTERNAL RESISTANCE (R_{int}) BETWEEN THE PIPE AND NEGATIVE BUS

FIGURE 4-10



Several sets of data are taken by interrupting the current circuit. Current and pipe to soil potential readings are taken simultaneously with the switch closed (on) and open (off: $I_1 = 0$). The change in pipe to soil potential per ampere of current flow ($\Delta V_g / I_1$) is calculated from Ohm's Law and is expressed as volts per ampere (V/A):

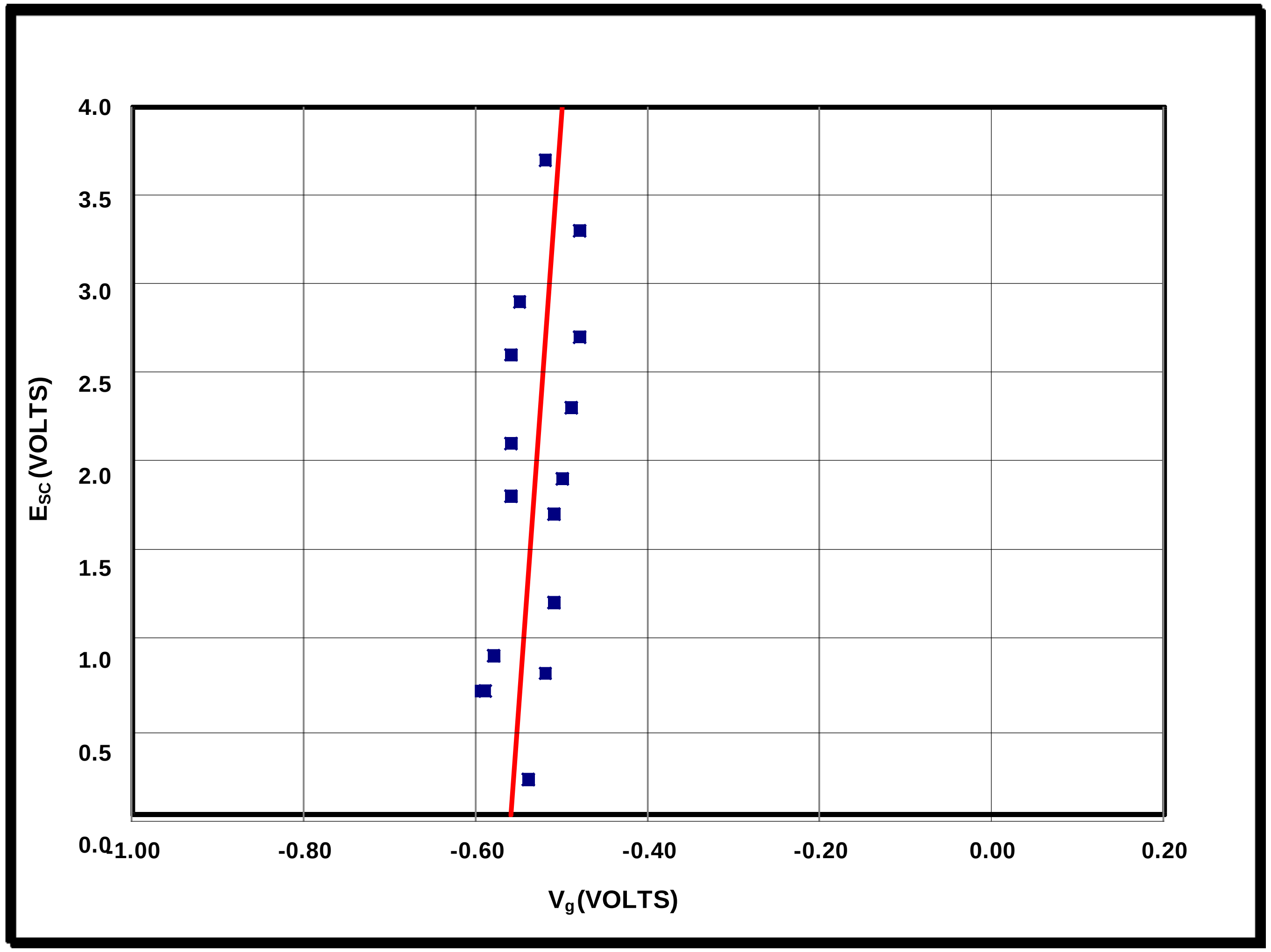
$$\Delta V_g = V_{gON} - V_{gOFF}$$

$$\Delta I_1 = I_{1ON} - I_{1OFF} \; (I_{1OFF} = 0)$$

$$V/A = \Delta V_g / \Delta I_1$$

TYPICAL TEST SET-UP USED TO DETERMINE PIPE TO SOIL POTENTIAL CHANGE PER AMPERE OF DRAINAGE CURRENT

FIGURE 4-11



BETA CURVE PLOTTED AT POINT OF MAXIMUM EXPOSURE

FIGURE 4-12

Appalachian Underground Corrosion Short Course

TABLE 4-1

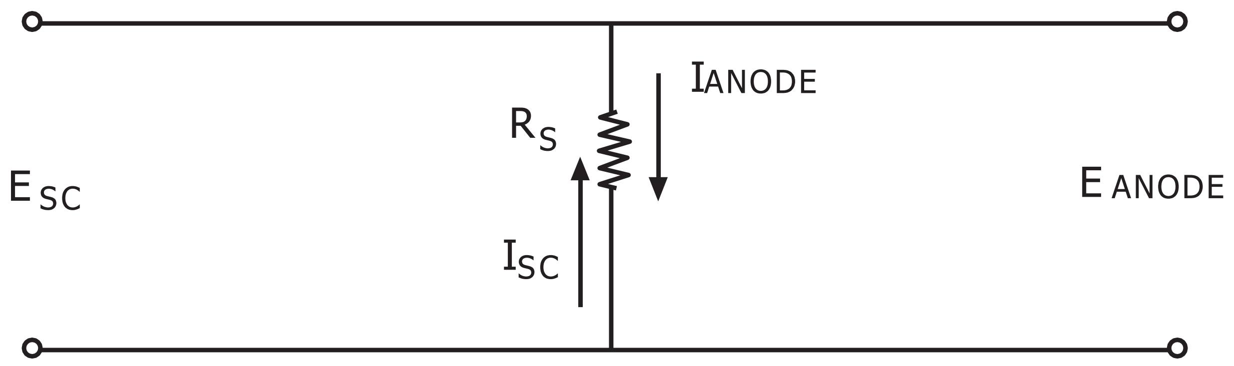
R_{int} Data - See Figure 4-10

	E_1 (Volts)	I_1 (Amperes)	R_{int} (ohms)
On	+1.30	36.0	
Off	-1.15	0	
Delta	+2.45	36.0	0.068
On	+0.80	39.0	
Off	-1.80	0	
Delta	+2.60	39.0	0.067
On	+0.50	41.0	
Off	-2.30	0	
Delta	+2.80	41.0	0 .068
On	+2.10	29.0	
Off	0.00	0	
Delta	+2.10	29.0	0.072
On	+2.00	29.5	
Off	-0.15	0	
Delta	+2.15	29.5	0.073
On	+1.30	35.0	
Off	-1.25	0	
Delta	+2.55	35.0	0.073
On	+0.35	43.0	
Off	-2.65	0	
Delta	+3.00	43.0	0.070
		Average R_{int} =	**0.070**

TABLE 4-2

)V_g/I_1 Data - See Figure 4-11

	V_g (Volts)	I_1 (Amperes)	)V_g/I_1 (V/A)
On	0.645	34.0	
Off	0.590	0	
Delta	0.055	34.0	0.00162
On	0.635	23.0	
Off	0.600	0	
Delta	0.035	23.0	0.00150
On	0.770	82.0	
Off	0.620	0	
Delta	0.150	82.0	0.00183
On	0.770	86.0	
Off	0.625	0	
Delta	0.145	86.0	0.00168
		Average)V_g/I_1 =	**0.00169**



R_S - RESISTANCE OF STRUCTURE TO EARTH
I_{SC} - STRAY CURRENT
E_{SC} - VOLTAGE GRADIENT OF STRAY CURRENT

WHEN E-ANODE $> E_{SC}$ - GALVANIC DRAINS FUNCTION TO PRODUCE A NET PROTECTIVE FLOW
WHEN E-ANODE $< E_{SC}$ - GALVANIC DRAINS INEFFECTIVE

SIMPLE EQUIVALENT CIRCUIT FOR GALVANIC ANODE DRAIN

FIGURE 4-13

Advanced Chapter 5
Design of Impressed Current Cathodic Protection

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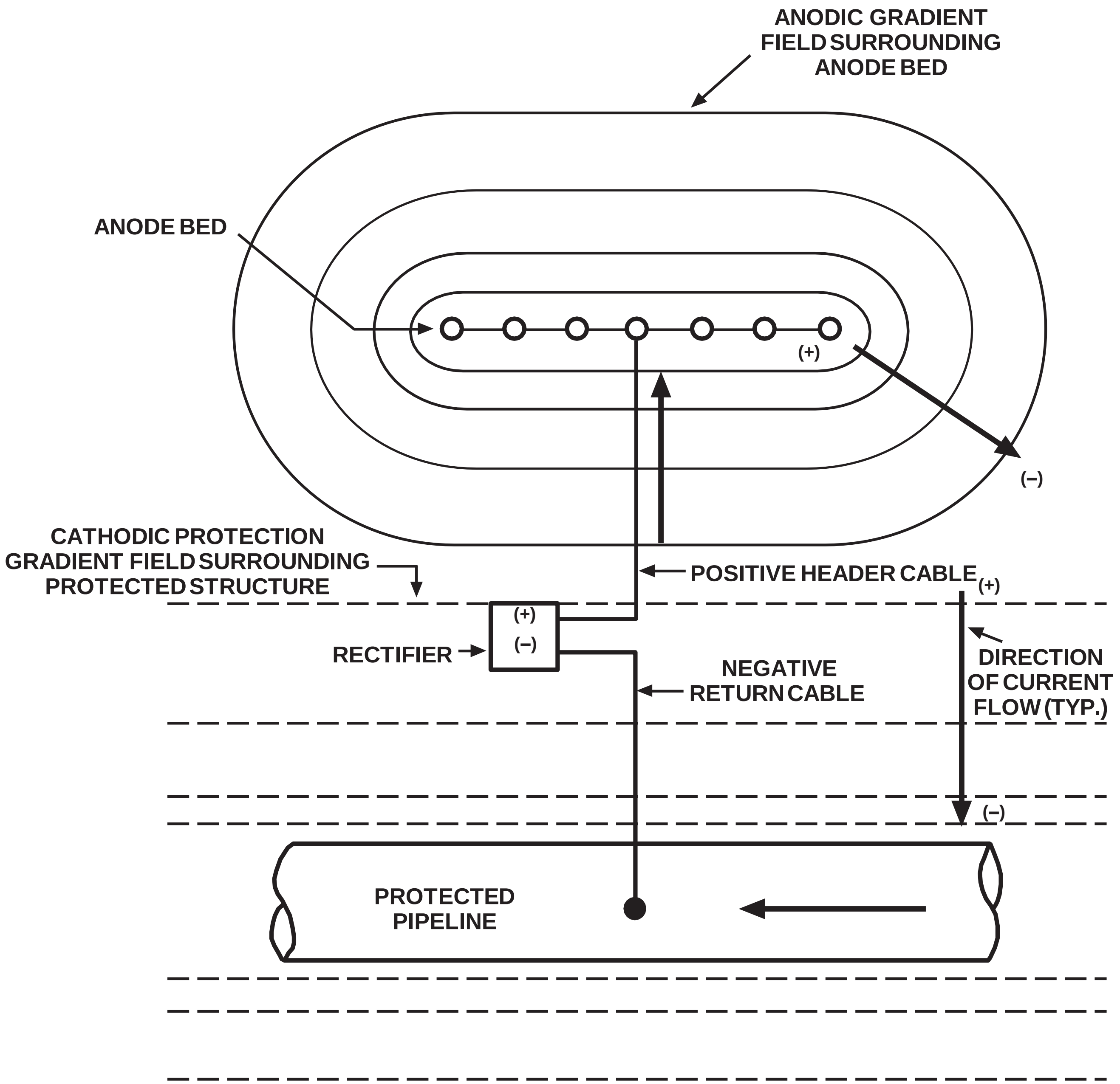
Appalachian Underground Corrosion Short Course

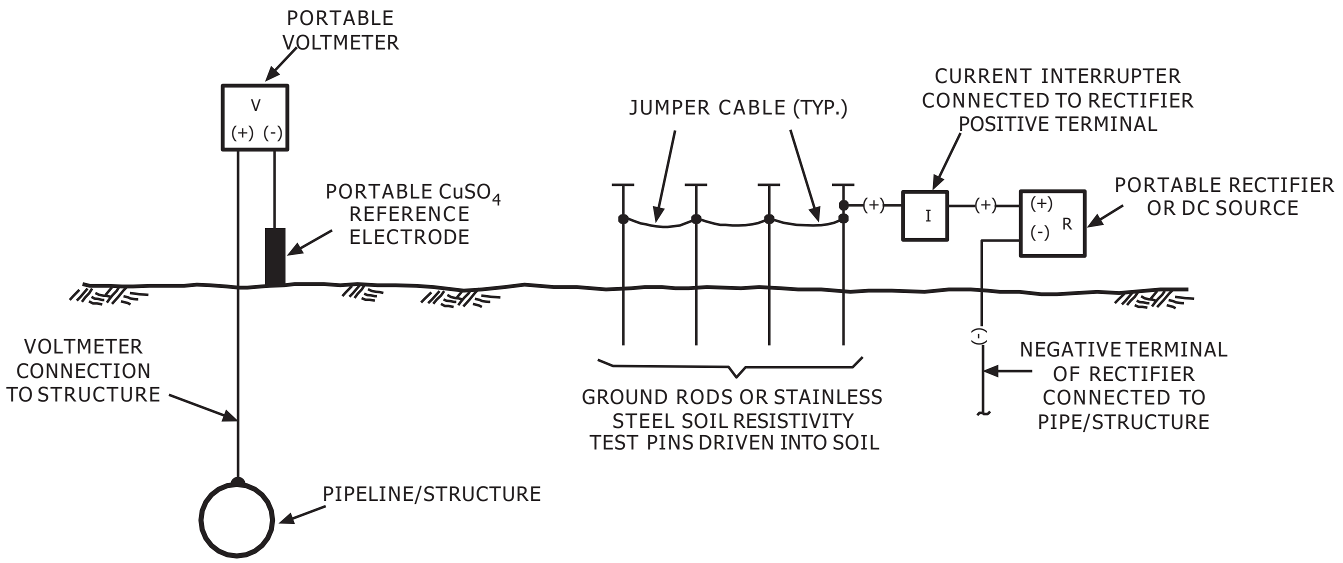


REMOTE ANODE BED OPERATION

FIGURE 5-1

TABLE 5-1
Typical Soil Resistivity Data

Galvanometer Dial Reading	Multiplier Setting	Resistance (Ohms)	Spacing (ft)	Factor	Resistivity (Ohm-cm)
2.4	10	24	2.5	191.5	11,490
1.6	10	16	5	191.5	15,320
10.2	1	10.2	10	191.5	19,533
6.2	1	6.2	15	191.5	17,801
2.6	1	2.6	20	191.5	9,958
8.2	0.1	0.82	25	191.5	3,926



TYPICAL CURRENT REQUIREMENT TEST SET UP

FIGURE 5-2

TABLE 5-2
Typical Current Requirements Based On Coating System Effective Resistance

Effective Coating Resistance (1) (ohm-ft^2)	Current Requirement (Amperes)
Bare Pipe (2)	187.50
10,000	3.73
25,000	1.49
50,000	0.75
100,000	0.37
500,000	0.075
1,000,000	0.0373
5,000,000	0.007
"Perfect Coating"	0.000015

(1) Effective coating resistance, as defined in the above table, of 10,000 to 25,000 ohm-ft^2 indicates poor application or handling during installation. Resistance of 100,000 to 5,000,000 ohm-ft^2 indicates good to excellent application. Installation in 1,000 ohm-cm soil.

(2) Bare pipe in this table is assumed to require a minimum of 1.5 milliamperes per sq. ft. of pipe surface. In practice, most design engineers use 2 milliamperes per sq. ft. for pipe-in-soil, unless the environment is acidic, contains high concentrations of chlorides, bacteria, or the pipe is operating at elevated temperatures. In these cases, as much as 3.5 to 5.0 milliamperes per sq. ft. may be required.

Determining Current Requirements for an Existing Structure - Example #2

A temporary anode bed is set up using 5 ground rods and a portable rectifier. The ground rods are driven approximately 1½ feet into the ground at 10-foot spacing. The measured output of the rectifier is 34 volts and 0.40 amperes. While interrupting the rectifier output, the following pipe-to-soil potential readings were taken at various locations with respect to a CSE, placed directly over the pipeline in the area under the influence of the temporary anode bed, and the change in potential (ΔV) was calculated.

PIPE-TO-SOIL POTENTIAL (Volts to CSE)			
Location	V-On	V-Off	ΔV
1	-0.592	-0.561	-0.031
2	-0.570	-0.523	-0.047
3	-0.603	-0.545	-0.058
4	-0.598	-0.527	-0.071
5	-0.693	-0.575	-0.118
6	-0.833	-0.635	-0.198
7	-0.865	-0.650	-0.215
8	-0.814	-0.611	-0.203
9	-0.731	-0.605	-0.126
10	-0.655	-0.590	-0.065
11	-0.630	-0.575	-0.055
12	-0.640	-0.580	-0.060

Step No. 1 - Using the lowest voltage shift (ΔV) measured during the tests, calculate the voltage shift required to satisfy the -0.85 volt On cathodic protection criterion.

ΔV-Low = Lowest Voltage Shift = -0.031 Volts at Location #1.

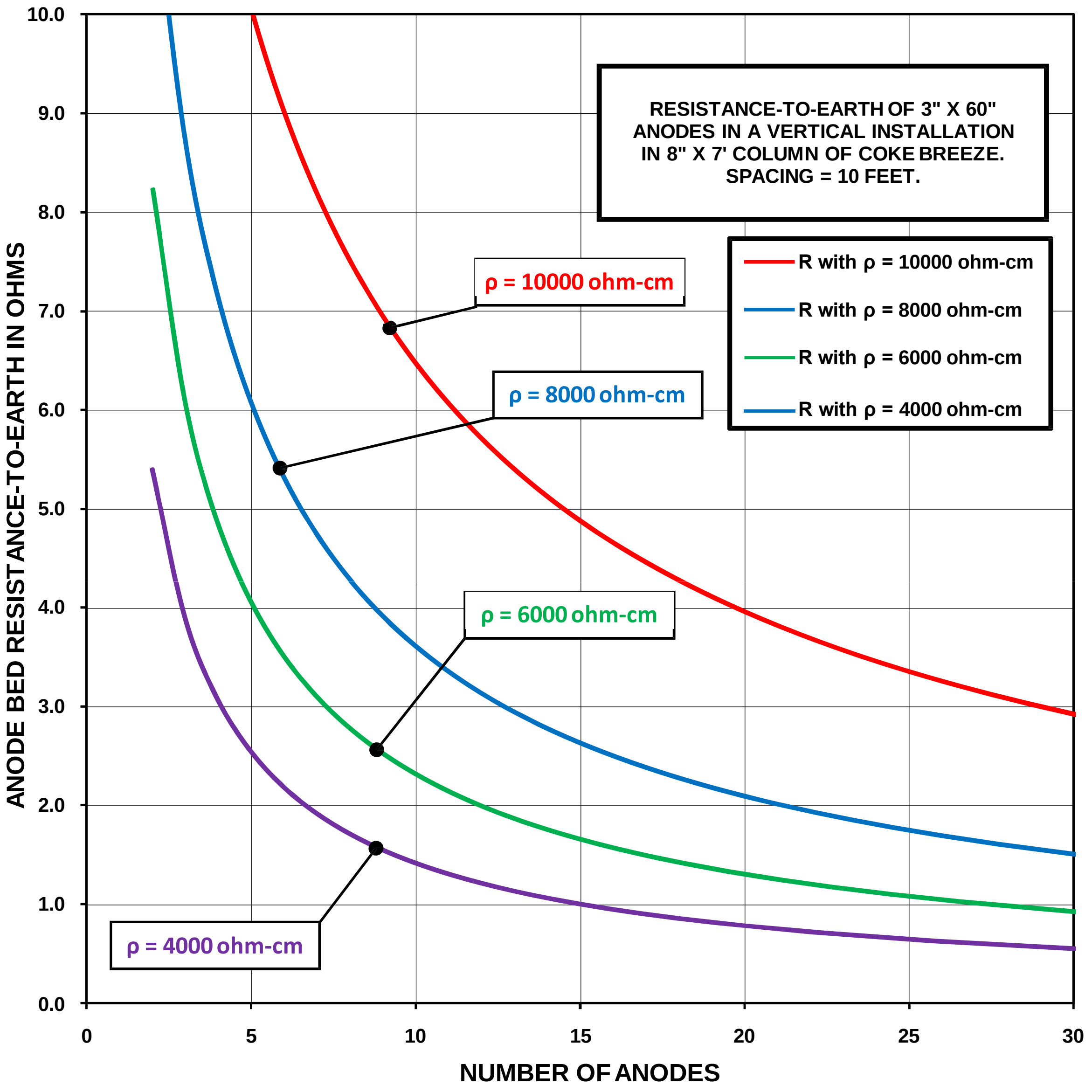
V-Off = -0.561 at Location #1.

ΔV-Req = Required Voltage Shift = -0.850 - (-0.561) = -0.289 Volts

TABLE 5-3

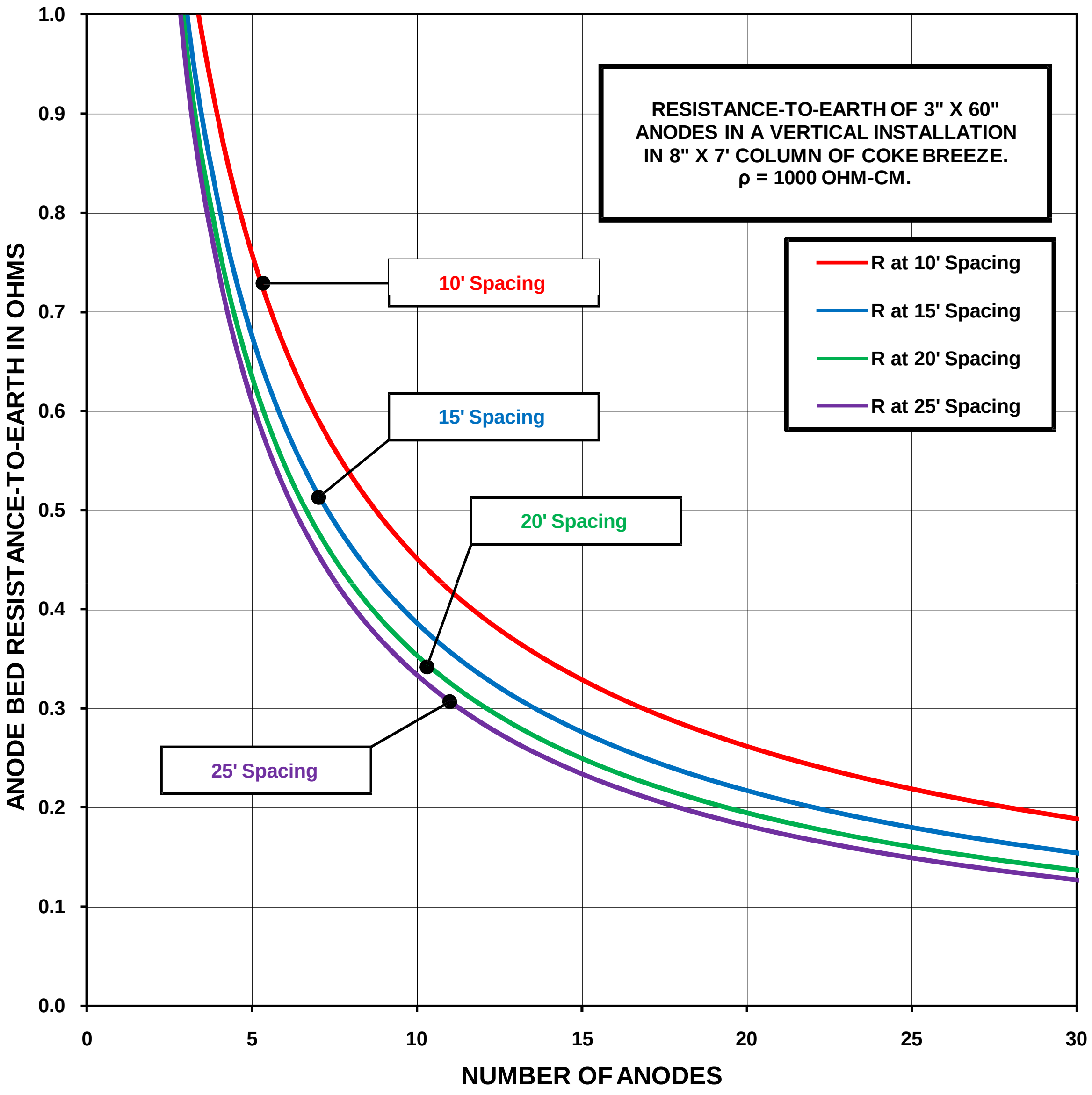
Approximate Current Requirements for Cathodic Protection of Steel

Environment		mA/ft^2
Sea Water	- Cook Inlet	35 - 40
	−North Sea	8 -15
	−Persian Gulf	7 -10
	−US -West Coast	7 -8
	−Gulf of Mexico	5 -6
	−Indonesia	5 -6
Bare Steel in Soil		1 -3
Poorly Coated Steel in Soil or Water		0.1
Well Coated Steel in Soil or Water		0.003
Very Well Coated Steel in Soil or Water		0.003 or less



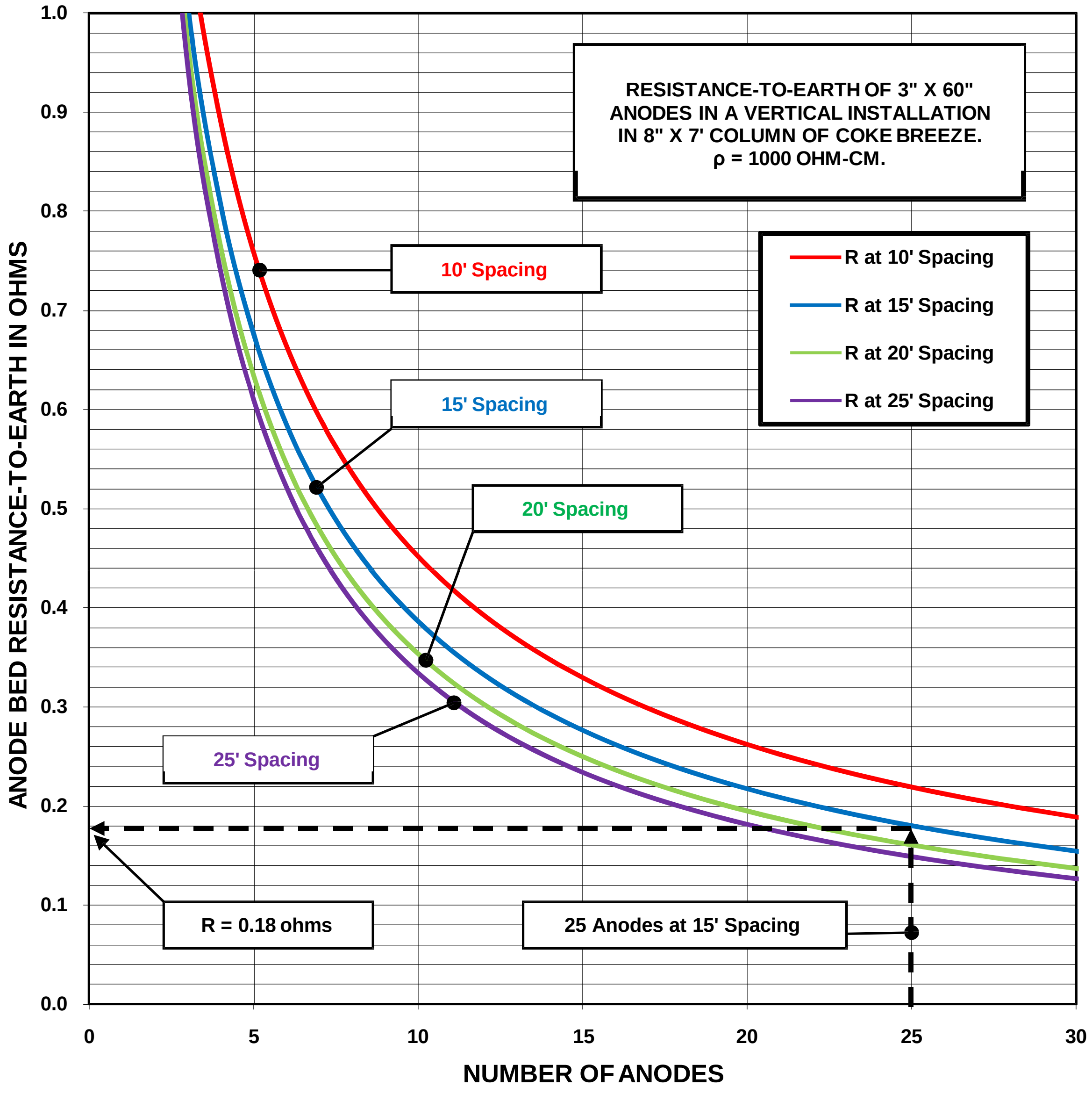
ANODE BED RESISTANCE-TO-EARTH
OF 8" x 7' ANODES AT 10 FT SPACING
AT VARIOUS SOIL RESISTIVITY VALUES

FIGURE 5-3



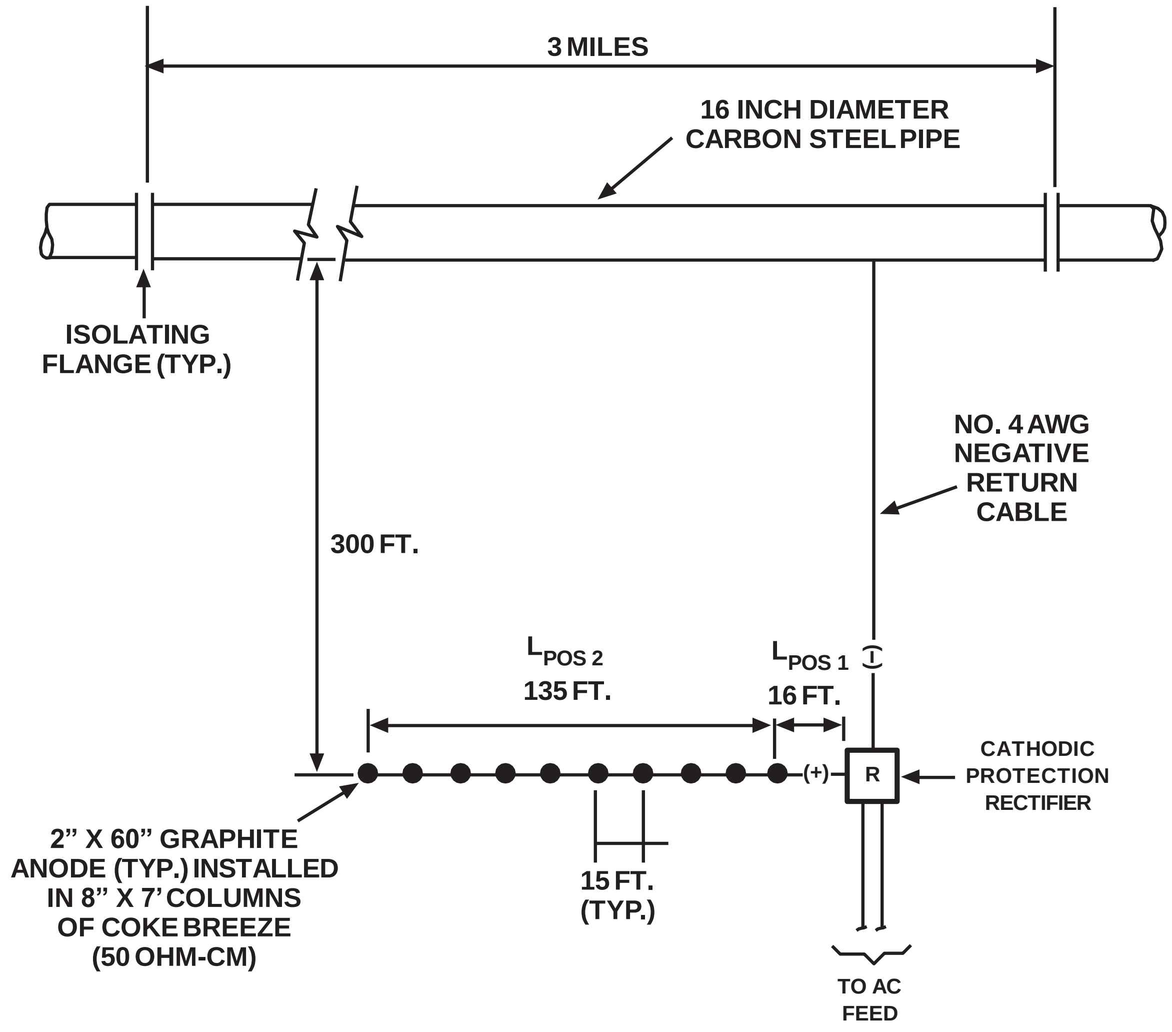
ANODE BED RESISTANCE-TO-EARTH
OF 8" x 7' ANODES IN 1000 OHM-CM SOIL
AT VARIOUS SPACINGS

FIGURE 5-4



USING A GRAPH TO DETERMINE ANODE BED RESISTANCE-TO-EARTH

FIGURE 5-5

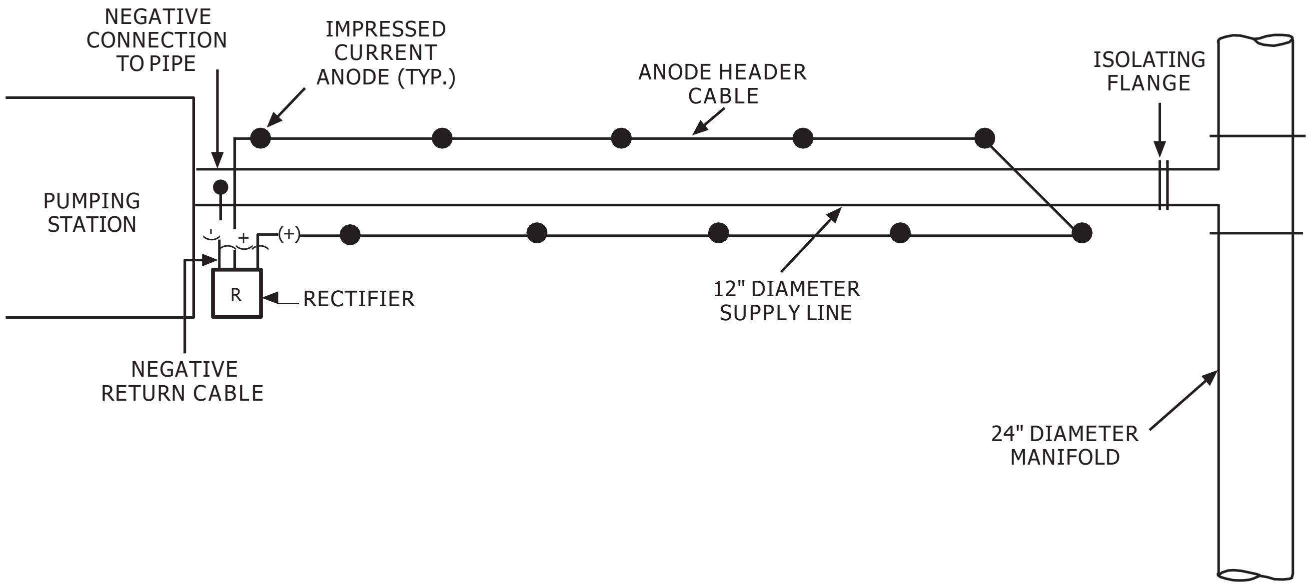


TYPICAL REMOTE ANODE BED DESIGN

FIGURE 5-6

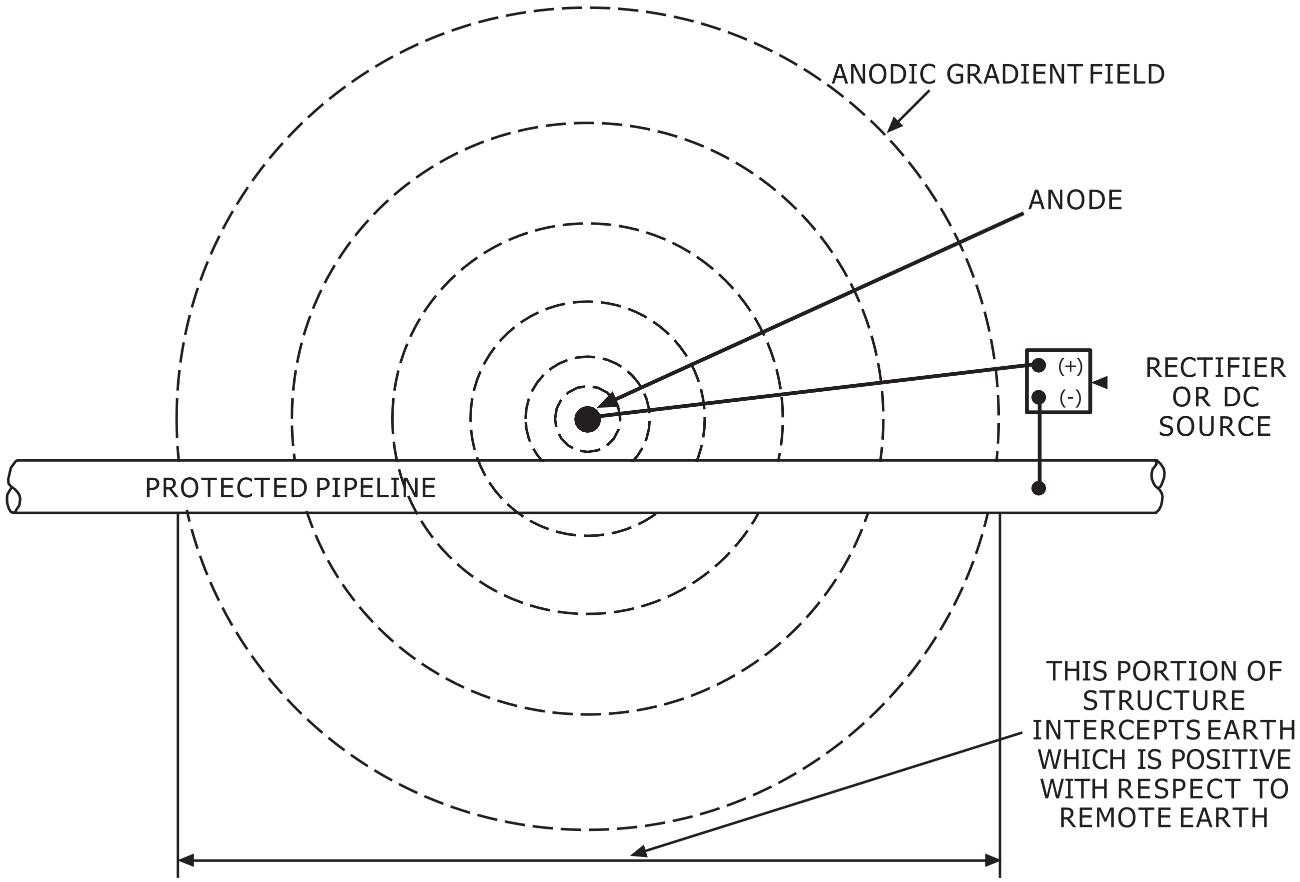
TABLE 5-4
Concentric Stranded Single Conductor Copper Cable Parameters

Size AWG	Overall Diameter Not Including Insulation (Inches)	Maximum DC Resistance @ 20°C (Ohms/1000 ft)	Maximum Allowable DC Current Capacity (Amperes)
14	0.0726	2.5800	15
12	0.0915	1.6200	20
10	0.1160	1.0200	30
8	0.1460	0.6400	45
6	0.1840	0.4030	65
4	0.2320	0.2540	85
3	0.2600	0.2010	100
2	0.2920	0.1590	115
1	0.3320	0.1260	130
1/0	0.3730	0.1000	150
2/0	0.4190	0.0795	175
3/0	0.4700	0.0631	200
4/0	0.5280	0.0500	230
250 MCM	0.5750	0.0423	255



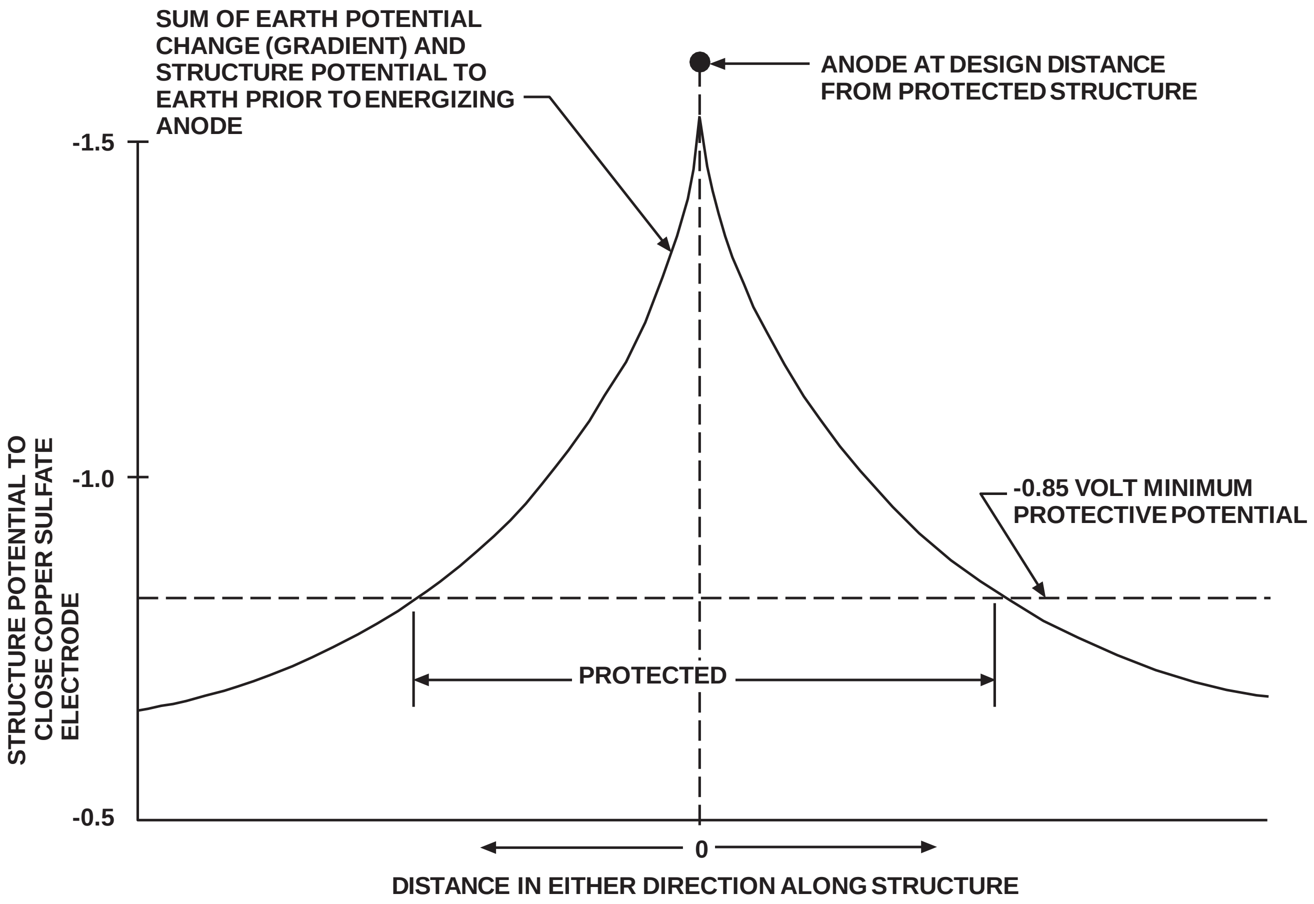
TYPICAL DISTRIBUTED IMPRESSED CURRENT ANODE SYSTEM

FIGURE 5-7



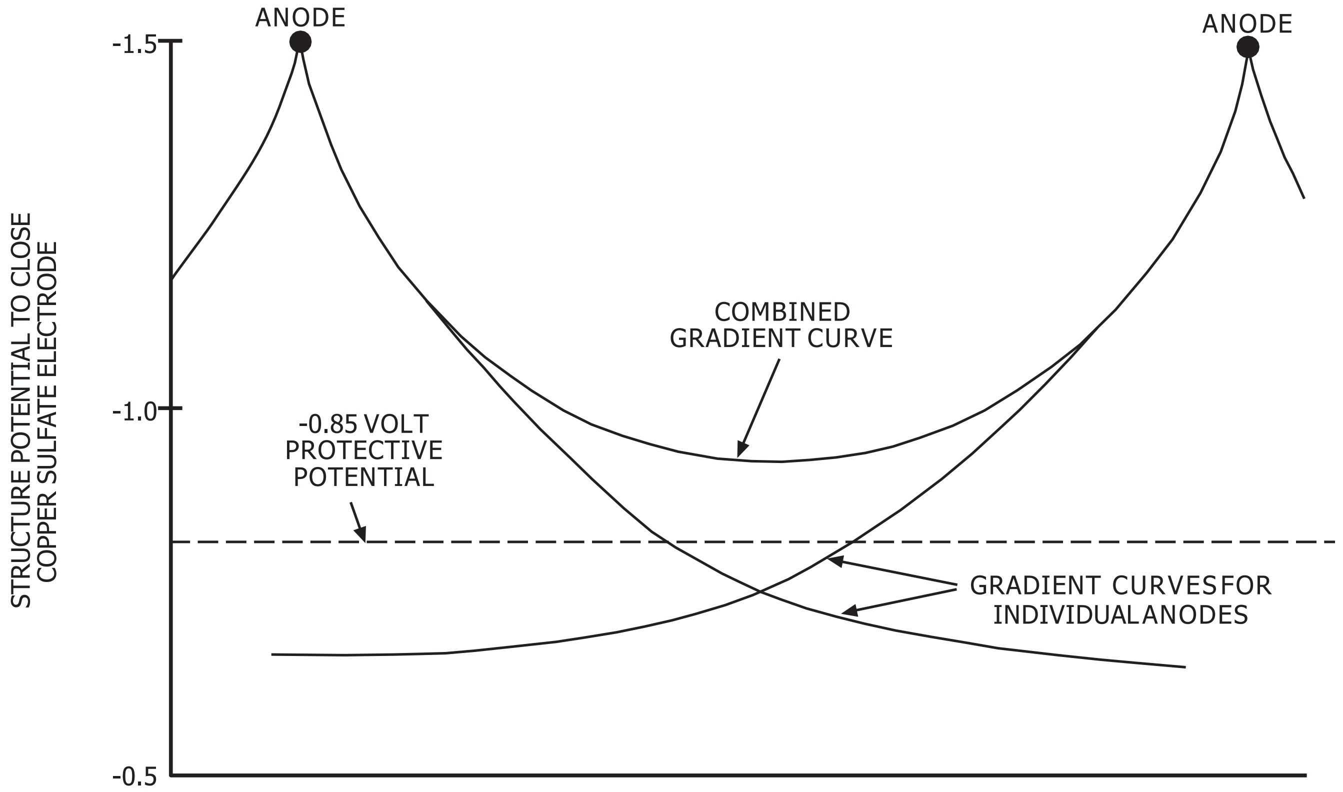
ANODE BED ARRANGEMENT FOR EARTH POTENTIAL SWING CATHODIC PROTECTION

FIGURE 5-8



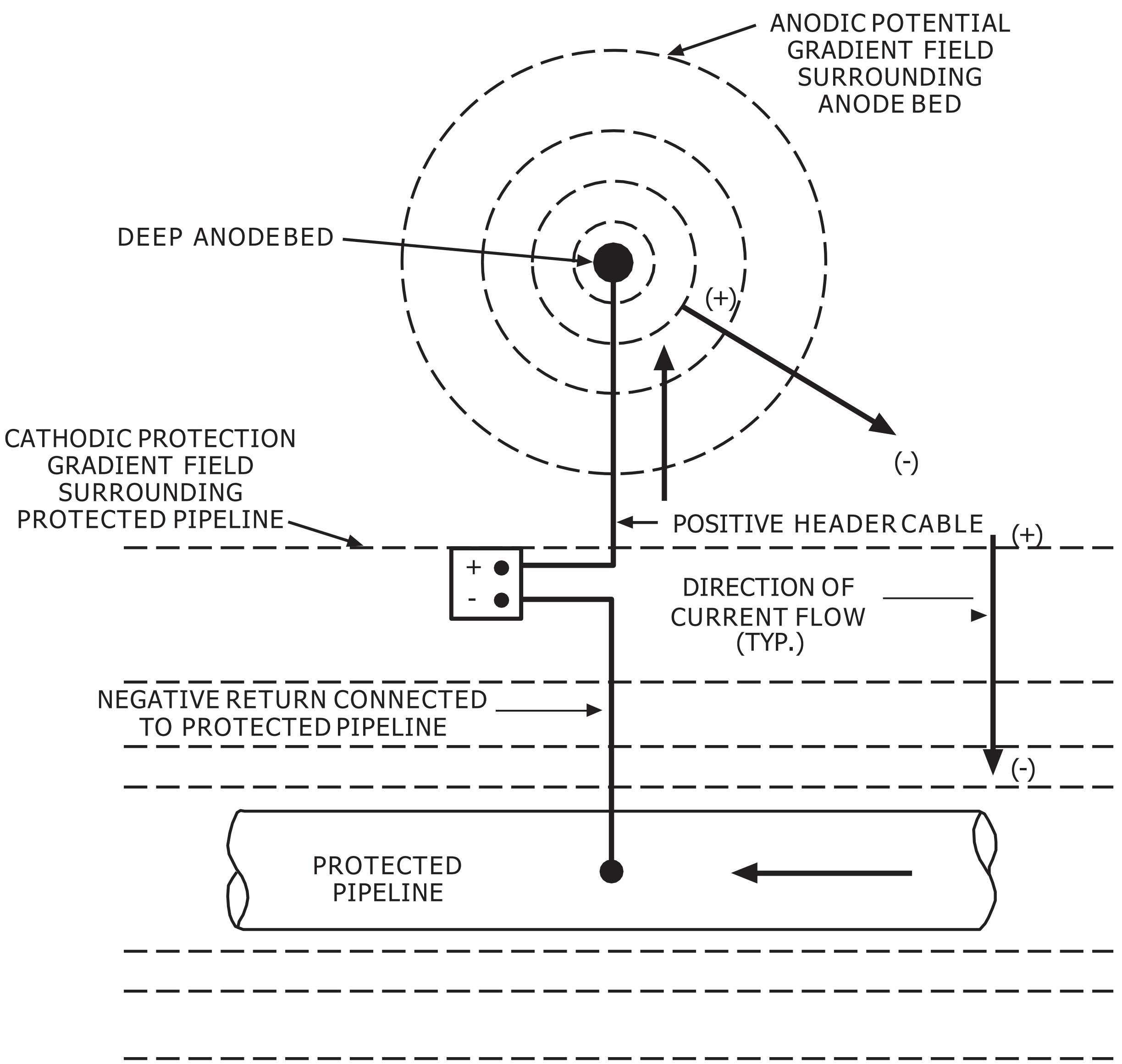
POTENTIAL GRADIENT FIELD AROUND A VERTICAL ANODE

FIGURE 5-9



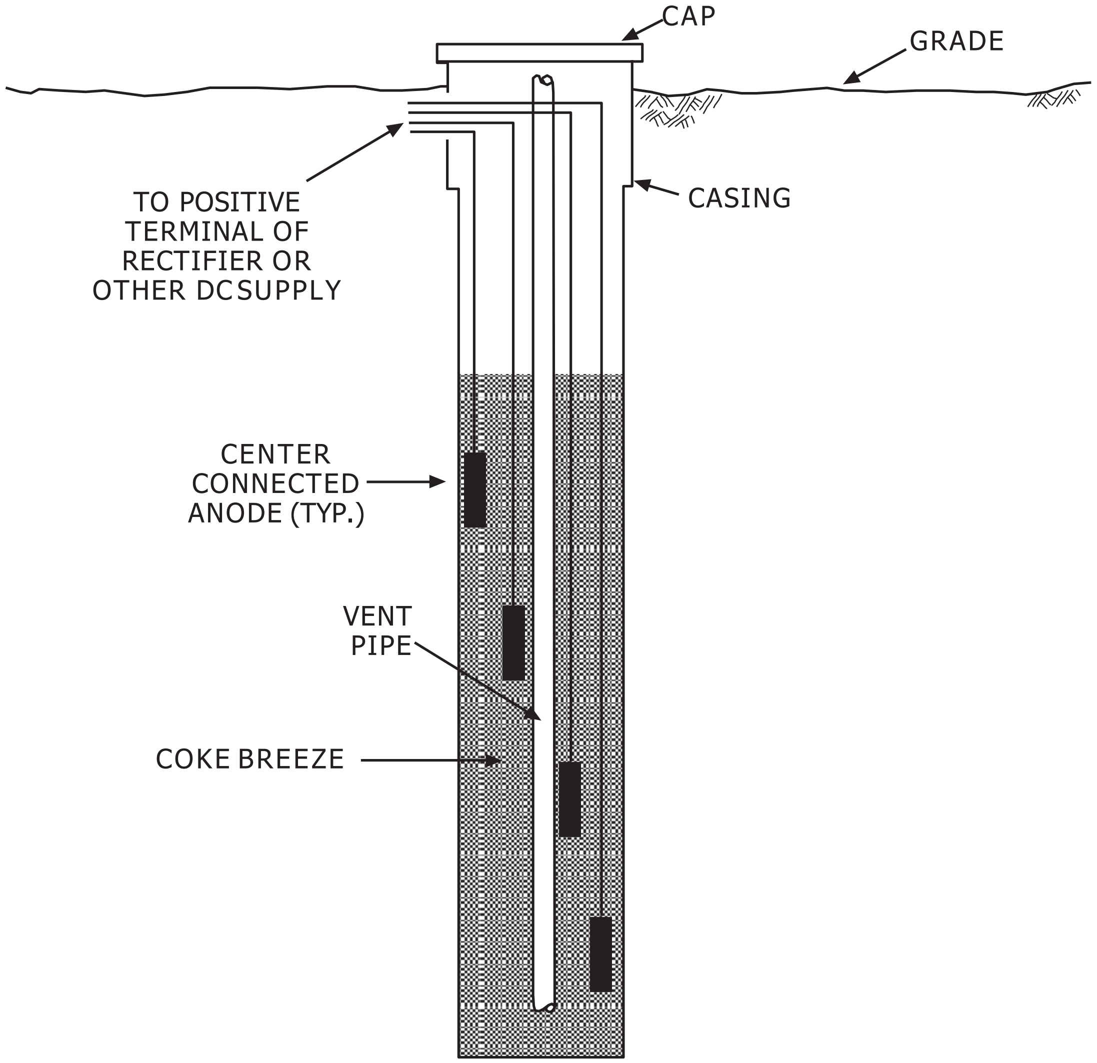
INTERACTION BETWEEN ADJACENT DISTRIBUTED ANODES

FIGURE 5-10



TYPICAL DEEP ANODE BED OPERATION

FIGURE 5-11



TYPICAL DEEP ANODE BED

FIGURE 5-12

Advanced Chapter 6
Design of Galvanic Anode Cathodic Protection

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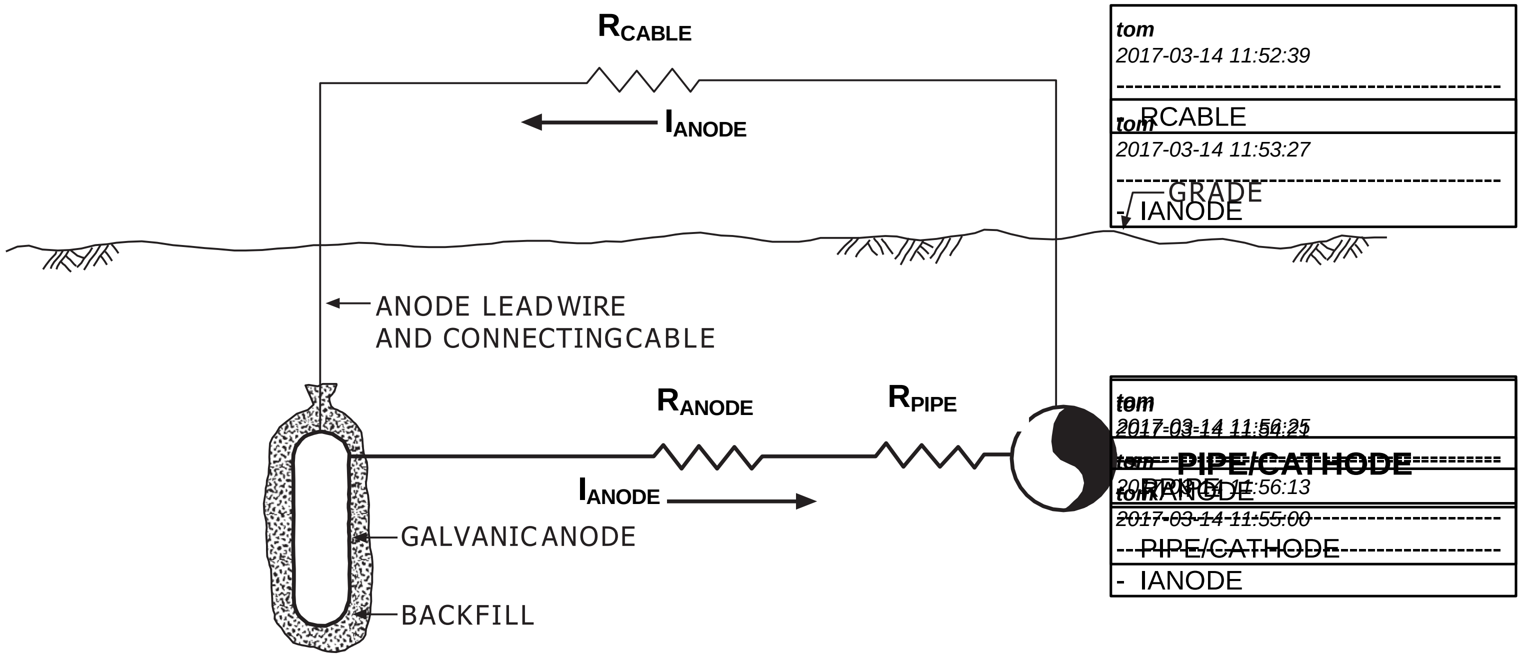
TABLE 6-1
Typical Operating Characteristics of Galvanic Anodes

Galvanic Anode Material	Theoretical Capacity (amp-hr/lb)	Actual Capacity* (amp-hr/lb)	Consumption Rates (lb/amp-yr)	Current Efficiency	Negative Potential to CSE (Volts)
Zinc (Mil-A-18001 U)	370	370	23.7	90%	1.10
Magnesium (H-1 Alloy)	1000	250 - 580	15 - 35	25 - 58%	1.40 - 1.60
Magnesium (High Potential)	1000	450 - 540	16 - 19	45 - 54%	1.70 - 1.80

* Based on shown current efficiencies.

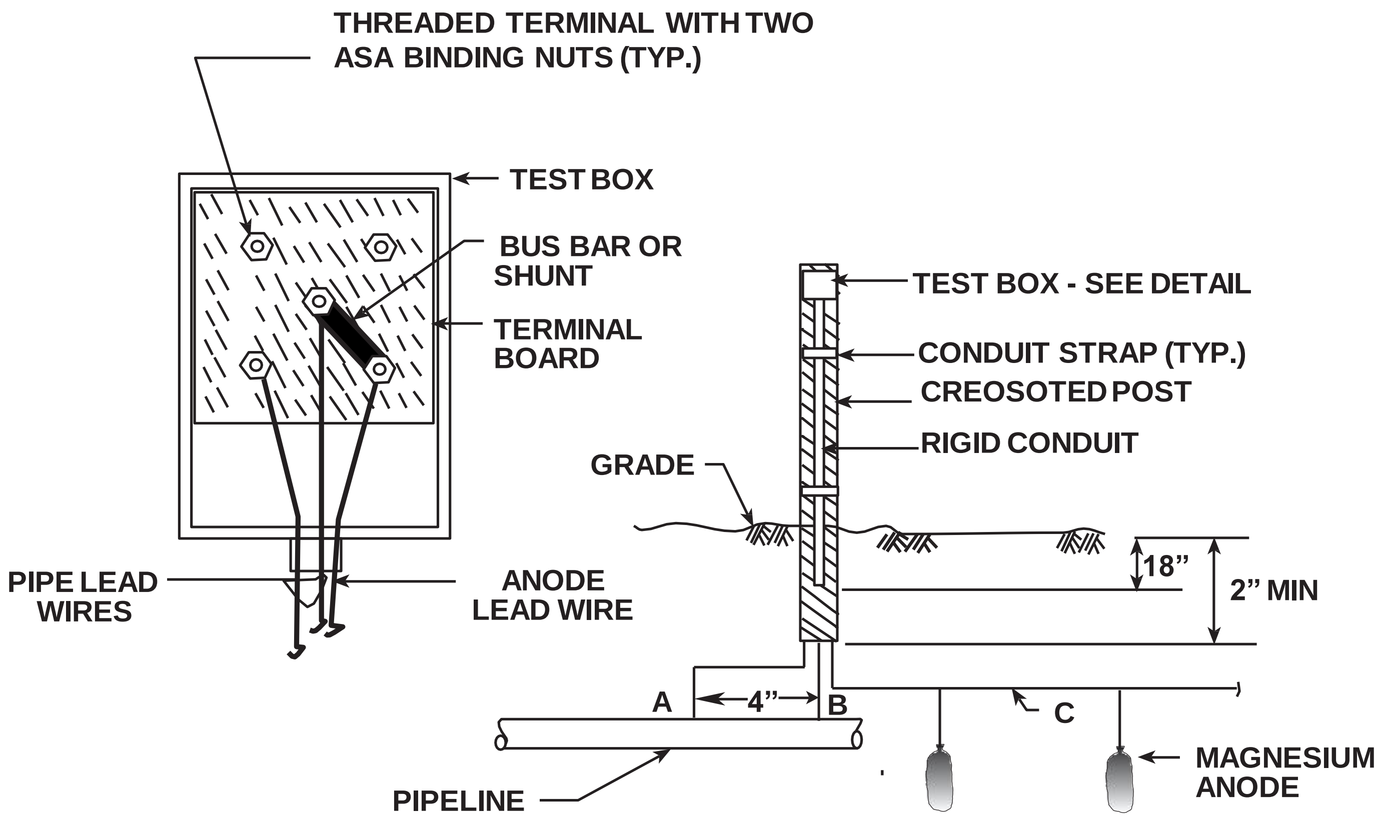


GALVANIC ANODE SYSTEM
ELECTRICAL CIRCUIT

FIGURE 6-1

TABLE 6-2
Resistance of Concentric Stranded Copper Single Conductors

Size AWG	Max. DC Resistance @ 20º C (ohms/1000 ft)
14	2.5800
12	1.6200
10	1.0100
8	0.6400
6	0.4030
4	0.2540
3	0.2010
2	0.1590
1	0.1260
1/0	0.1000
2/0	0.0795
3/0	0.0631
4/0	0.0500
250 MCM	0.0423



TYPICAL GALVANIC ANODE SYSTEM INSTALLATION

FIGURE 6-2

TABLE 6-3
Anode Shape Factors (F)

Anode Weight (lbs)	Anode	Factor (F)
Standard Anodes		
3	(Packaged)	0.53
5	(Packaged)	0.60
9	(Packaged)	0.71
17	(Packaged)	1.00
32	(Packaged)	1.06
50	(Packaged - anode dimension 8" dia x 16")	1.09
50	(Packaged - anode dimension 5" x 5" x 31")	1.29
Long Anodes		
9	2.75" x 2.75" x 26" backfill 6" x 31"	1.01
10	1.50" x 4.50" x 72" backfill 4" x 78"	1.71
18	2.00" x 2.00" x 72" backfill 5" x 78"	1.81
20	2.50" x 2.50" x 60" backfill 5" x 66"	1.60
40	3.75" x 3.75" x 60" backfill 6.5" x 66"	1.72
42	3.00" x 3.00" x 72" backfill 6" x 78"	1.90
Extra-Long Anodes		
15	1.6" dia x 10' backfilled to 6" dia	2.61
20	1.3" dia x 20' backfilled to 6" dia	4.28
23	2.0" dia x 10' backfilled to 8" dia	2.81

TABLE 6-4
Driving Voltage Correction Factors (Y)

P/S	Standard Magnesium	High-Potential Magnesium	Zinc
-0.70	1.21	2.14	1.60
-0.80	1.07	1.36	1.20
-0.85	1.00	1.29	1.00
-0.90	0.93	1.21	0.80
-1.00	0.79	1.07	0.40
-1.10	0.64	0.93	--
-1.20	0.50	0.79	--

TABLE 6-5
Multiple Anode Adjustment Factors

No of Anodes in parallel	Adjustment Factors (anode spacing in feet)			
	5'	**10'**	**15'**	**20'**
2	1.839	1.920	1.946	1.965
3	2.455	2.705	2.795	2.848
4	3.036	3.455	3.625	3.714
5	3.589	4.188	4.429	4.563
6	4.125	4.902	5.223	5.411
7	4.652	5.598	6.000	6.232
8	5.152	6.277	6.768	7.035
9	5.670	6.964	7.536	7.876
10	6.161	7.643	8.304	8.679

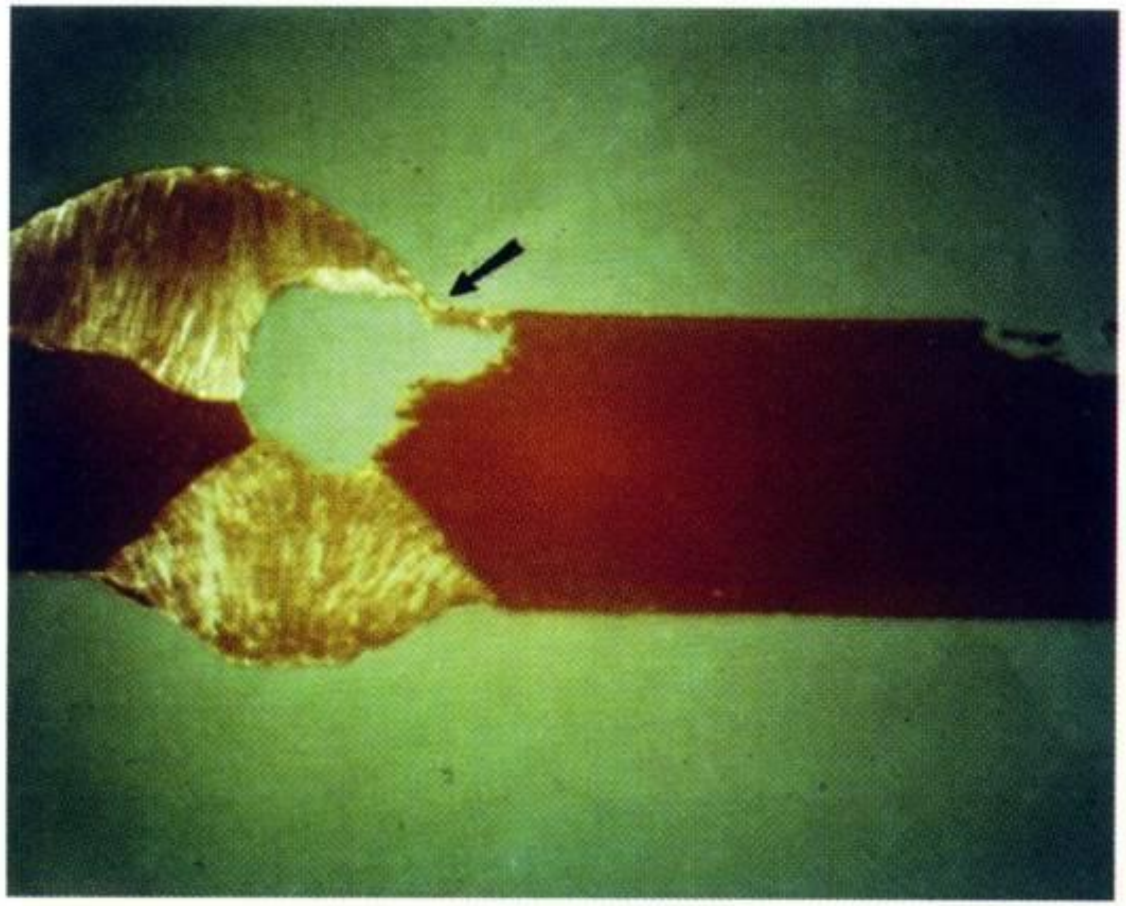
Advanced Chapter 7
MIC Inspection and Testing

AUCSC

Appalachian Underground Corrosion Short Course

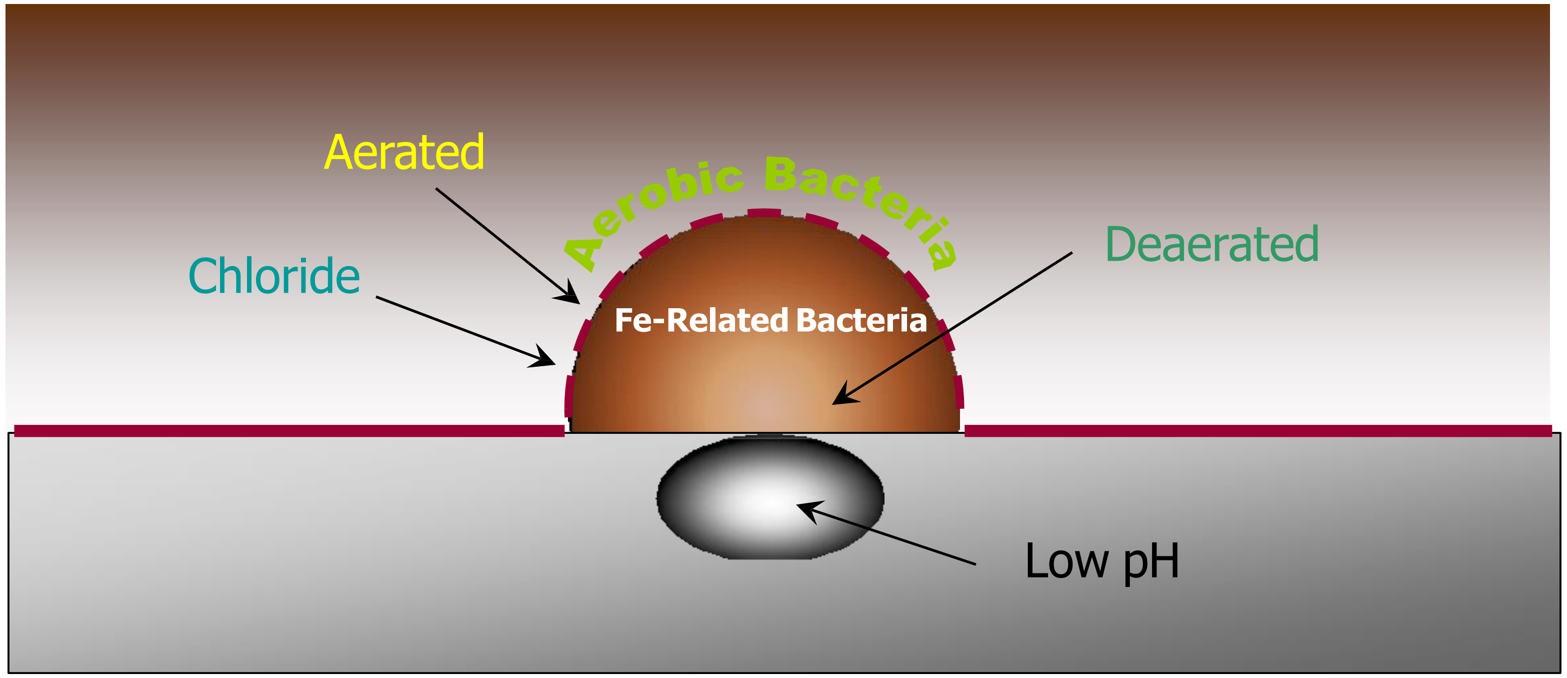
MIC OF 304 SS WELD

Under Tubercle Illustrated



From Little, Wagner,
and Mansfeld

TUBERCLE BUILD-UP WITH IRON-RELATED BACTERIA

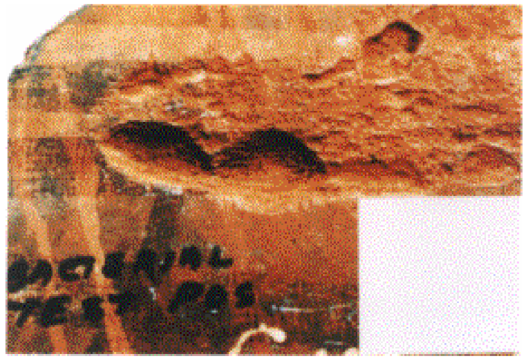


IRB Create a Differential Oxygen Corrosion Cell with Low pH Environment

METALLURGICAL

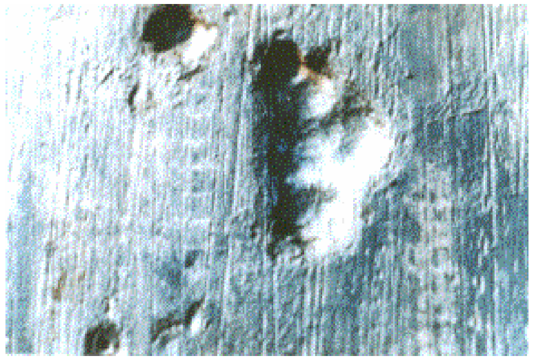
Pope and GRI

a. Striations in cupped pit bottoms



b. Corrosion in pit

c. Pit products in b. removed



d. Brushed cupped pits in c.

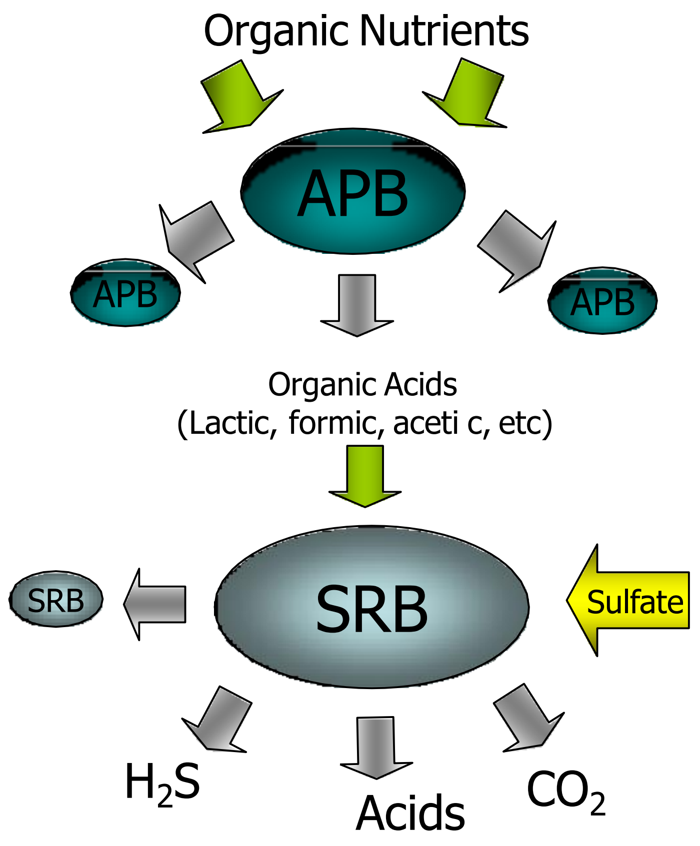
MICROBIOLOGICAL
Aerobic and Anaerobic

- Aerobic Require O_2 and Nutrient
- Consume O_2 and Produce Organic Acids Corrosive to Steel
- Protection Requirements Less Well Defined

- Occur with Anaerobic Bacteria
- Form Complex Communities Dominated by Acid Producing Bacteria
- MIC a Result of Microbe Community, Not SRB Alone

MICROBIOLOGICAL COMMUNITY
Example APB and SRB

- Organic Nutrients Feed APB
- APB Products Nutrients for SRB
- SRB Fed by Organic Acids and Sulfate
- Produce more APB and SRB
- Chlorides with Acids (H^+) Lower pH and Corrode Steel



MICROBIOLOGICAL
SRB Theory (Anaerobic)

- $8H_2O \Rightarrow 8OH^- + 8H^+$
- $4Fe \Rightarrow 4Fe^{+2} + 8e^-$ (A)
- $8H^+ + 8e^- \Rightarrow 8H$ (C)
- $SO_4^{-2} + 8H$ +Bacteria $\Rightarrow$ $\Rightarrow$ $S^{-2} + 4H_2O$
- $Fe^{+2} + S^{-2} \Rightarrow FeS$ (A)
- $3Fe^{+2} + 6OH^- \Rightarrow 3Fe(OH)_2$ (A)
- FeS Depolarizes

- Need Nutrient
  - Soil biomass
  - Coating adhesive
- Need No or Low O_2
  - Wet soil
  - Low areas
  - Crevices
- More Protection (Current) Needed to Overcome Effects

MIC TESTING

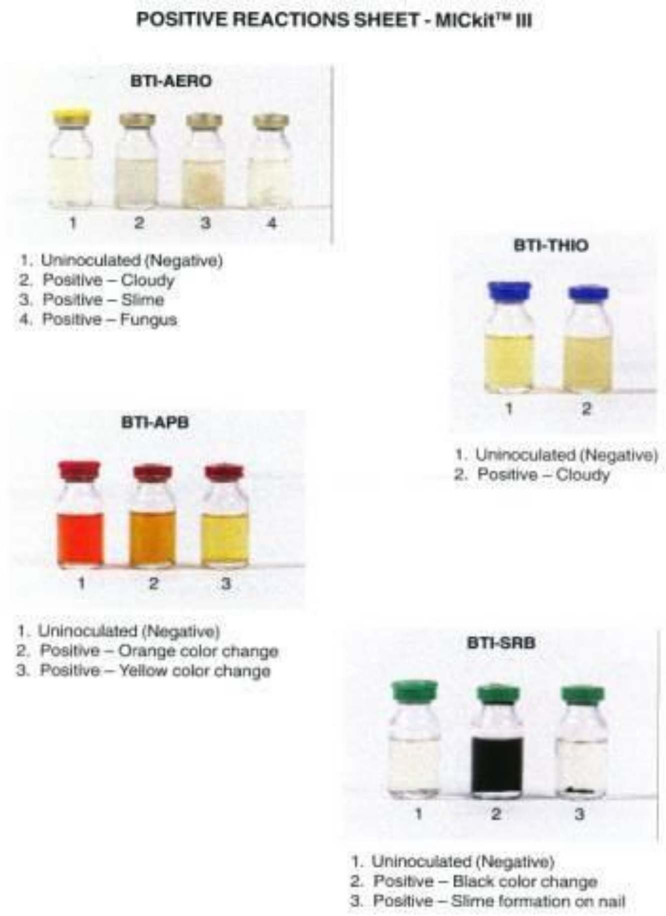
- Field Test Kits for Viable Bacteria
  - SRB, APB, anaerobic, aerobic, iron related
  - Bacteria count—10 to 10^5 (10^4) colonies/ml
- Test Soil or Surface Product
- Create Slurry
- Inoculate Culture Media Vials
- Compare After 2 - 5 Days, 15 Days

TEST KIT INTERPRETATION

- Presence of Bacteria Not Conclusive of MIC
- SRB Often Do Not Dominate
- Not Uncommon to Find All Tested Bacteria Present
- Interpret Indications with Caution
  - 1 to 3 bottles – may have problem
  - 1 to 5 bottles – possible problem

CULTURE TEST

Results



POSITIVE REACTIONS SHEET - MICkit™ III

BTI-AERO

1. Uninoculated (Negative)
2. Positive – Cloudy
3. Positive – Slime
4. Positive – Fungus

BTI-THIO

1. Uninoculated (Negative)
2. Positive – Cloudy

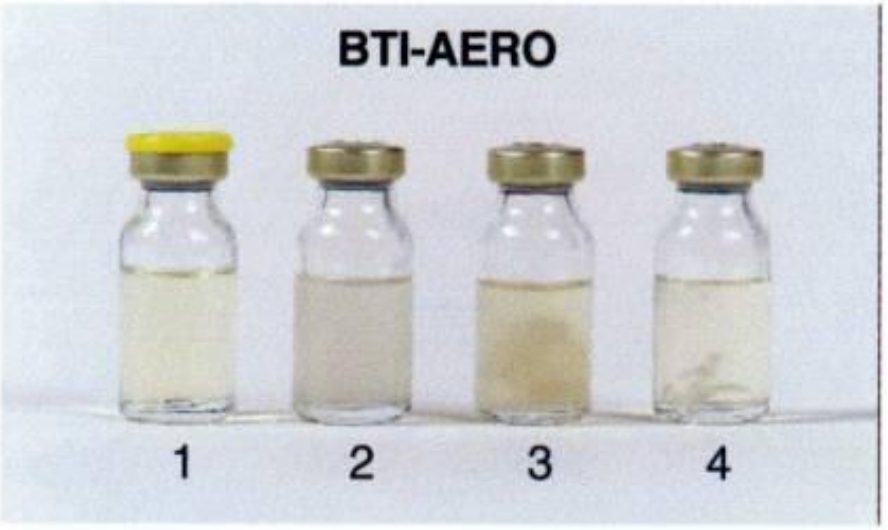
BTI-APB

1. Uninoculated (Negative)
2. Positive – Orange color change
3. Positive – Yellow color change

BTI-SRB

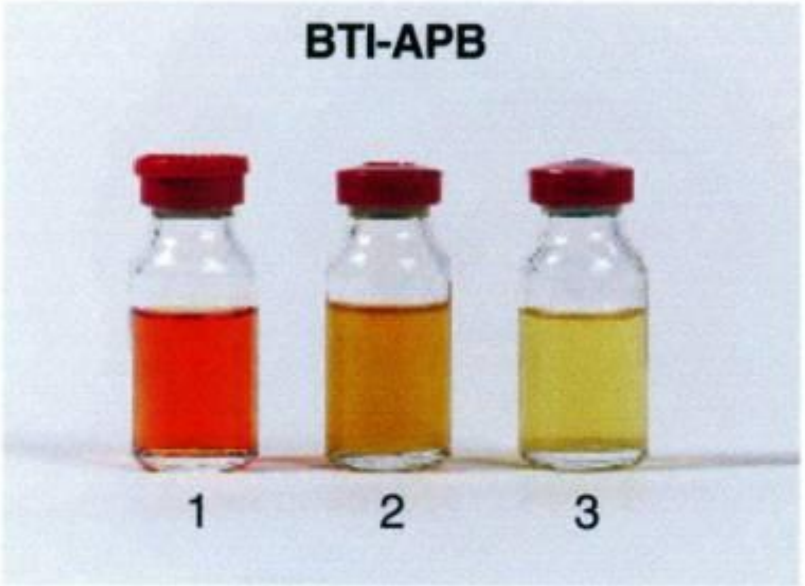
1. Uninoculated (Negative)
2. Positive – Black color change
3. Positive – Slime formation on nail

Aerobic Bacteria Test



1. Uninoculated (Negative)
2. Positive – Cloudy
3. Positive – Slime
4. Positive – Fungus

APB Bacteria Test



1. Uninoculated (Negative)
2. Positive – Orange color change
3. Positive – Yellow color change