

AD/A-004 083

CIVIL ENGINEERING CORROSION CONTROL
VOLUME II. CATHODIC PROTECTION TESTING METHODS AND
INSTRUMENTS

HINCHMAN CORPORATION

PREPARED FOR
AIR FORCE CIVIL ENGINEERING CENTER

JANUARY 1975

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFCEC-TR-74-6 Volume II	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD/A-004083
4. TITLE (and Subtitle) Civil Engineering Corrosion Control, Volume II - Cathodic Protection Testing Methods and Instruments		5. TYPE OF REPORT & PERIOD COVERED Final Report - May 1972 to Nov 1974
		6. PERFORMING ORG. REPORT NUMBER AFCEC-TR-74-6 Volume II
7. AUTHOR(s) Lewis H. West, P.E., The Hinchman Co. Thomas F. Lewicki, P.E. The Air Force Civil Engineering Center		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Civil Engineering Center(AFCEC) Tyndall AFB, FL 32401		12. REPORT DATE Jan 1975
		13. NUMBER OF PAGES 124
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release: distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) Reproduced by NATIONAL TECHNICAL INFORMATION SERVICE U S Department of Commerce Springfield VA 22151		
18. SUPPLEMENTARY NOTES This report is published in three volumes, Vol I - Corrosion Control-General, Vol II - Cathodic Protection Testing Methods and Instruments, Vol III - Cathodic Protection Design.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Civil Engineering, Corrosion, Corrosion Control, Cathodic Protection, Impressed Current Systems, Galvanic Anode System		
PAGES SUBJECT TO CHANGE		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The report is specifically written for Air Force Civil Engineering personnel but can be useful to all Agencies of the Federal Government. It covers mainly Real Property and Real Property Installed Equipment. It deals with corrosion and corrosion control of buried and submerged metal structures. Causes and theory of corrosion, material selection, protective coatings, and cathodic protection application are included. The information contained herein will be useful for solving all corrosion problems		

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Block 20 - Abstract (Cont'd)

encountered on real property and real property installed equip-
ment.

NOV 19 11 10 AM '64

in

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

AFCEC-TR-74-6, VOLUME II

CIVIL ENGINEERING CORROSION CONTROL
VOLUME II - CATHODIC PROTECTION TESTING
METHODS AND INSTRUMENTS

BY

Lewis H. West, P.E.
The Hinchman Company

Thomas F. Lewicki, P.E.
The Air Force Civil Engineering Center

Approved for Public Release, Distribution Unlimited

ib

FOREWORD

This report summarizes work done between May 1972 and Nov 1974. Thomas F. Lewicki was Project Officer. The major portion of the information in this report was compiled by the Fincham Company under Investigation Engineering Project IL 16-72-1, contract number F55615-72-G-0406 from sources listed in the acknowledgements section of this report. The authors contributed the remainder of the information for this report.

This report is published in three volumes, Volume I - Corrosion Control - General, Volume II - Cathodic Protection Testing Methods and Instruments, and Volume III - Cathodic Protection Design.

Approved for public release: distribution unlimited.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Thomas F. Lewicki
THOMAS F. LEWICKI, P.E.
Project Officer

Reproduced from
best available copy.

Robert E. Brandon
ROBERT E. BRANDON, GS-15
Technical Director

William E. Rains
WILLIAM E. RAINS, Col, USAF
Commander

PREFACE

The Air Force's major guide to corrosion control of real property and real property installed equipment has been contained in Air Force Manual 88-9, Chapter 4 which was published August 1962. The corrosion control field has been progressing with new methods, materials and equipment constantly being introduced. Since the Air Force's corrosion manual was old and outdated, a need existed for searching, investigating and documenting the new methods, materials and equipment for corrosion control. It was decided that the most prompt and economical method of accomplishing this task was by procuring the services of a prominent corrosion engineering firm. Because of the large volume of the documented findings of this endeavor, the information has been published in three volumes. The first volume is entitled Corrosion Control - General. The second and third volumes are entitled Cathodic Protection Testing Methods and Instruments and Cathodic Protection Design.

CONTENTS

	Paragraph	Page
Testing Methods -----	1	1
Instruments -----	2	57
References -----		94
Bibliography -----		96
Appendices -----		
Appendix A - Glossary of Corrosion Terms -----		97
Appendix B - Electromotive Force Series -----		101
Appendix C - Galvanic Series -----		102
Appendix D - Underground Corrosion Survey Checklist -----		105
Index -----		112

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Typical Galvanic Anode Circuit	4
2	Current Flow Around Insulating Joints	6
3	Circuit Diagram: Parallel Resistance at Insulating Joint	7
4	Ammeter and Voltmeter in Circuit	8
5	Conventional Meter Hook - Ups	11
6	Structure-to-Electrolyte Potential Measurement	13
7	Structure-to-Soil Voltage - Galvanic Conditions	18
8	Structure-to-Soil Voltage - External Current Conditions	19
9	Comparison of Off-to-Side and Over Structure Readings	21
10	Structure-to-Electrolyte Readings - Current Passing Through Structure	22
11	Null Method of Current Measurement	25
12	Casing-to-Carrier Pipe Resistance Measurement	27
13	Soil Resistivity Measurement	30
14	Soil Resistivity: Four-Pin Alternating Current Method	33
15	Soil Resistivity: Two-Probe Method	34
16	Typical Single-Probe Resistivity Measuring Device	35
17	Voltage vs. pH for Antimony Copper-Copper Sulfate Cell	36
18	Current Requirement Measurement	39
19	Couplings Determined in Current Requirement Tests	41
20	Stray Current Field Measurement	43
21	Record Sheet for Interference Tests	44
22	Correlation Curves	45
23	Locating High-Resistance Joints in Underground Piping	48
24	Coating Conductance Measurement: Short Line	50
25	Coating Conductance Measurement: Long Line	52

<u>Figure</u>		<u>Page</u>
26	Electrical Connections for Duct Slug Test	53
27	Soil Box	56
28	Typical Field Survey Test Equipment	58
29	Galvanometer	60
30	Basic D'Arsonval Movement	60
31	Instrument Bearings	61
32	Taut Band Suspension	62
33	Basic D.C. Ammeter Circuit	64
34	Measurement of Current Flow by the Zero Resistance Ammeter Method	65
35	Basic D.C. Voltmeter Circuit	66
36	Basic D.C. Potentiometer - Voltmeter Circuit	68
37	Basic D.C. Vacuum - Tube Voltmeter Circuit	69
38	Battery and Generator Energized Soil Resistance Tester	72
39	Typical Combination Meter	76
40	Wiring Diagram for Miller Meter, Model M-3-M	78
41	Typical Uses of Low-Resistance and High-Resistance Voltmeter	79
42	Typical Uses of Ammeter and High-Resistance Voltmeter	80
43	Wiring Diagram and Application of Current Interrupter	82
44	Typical Copper-Copper Sulfate Reference Electrode	84
45	Polarization of a Copper-Copper Sulfate Reference Electrode	86
46	Effect of Temperature on a Saturated Copper-Copper Sulfate Reference Electrode	87
47	Calomel Electrode for Seawater Testing	89
48	Typical Silver/Silver Chloride Reference Electrode	90
49	Typical Pipeline Probe and Contact Bar	92

TABLE

<u>TABLE</u>		<u>PAGE</u>
1	Standard Potentials (E°) of Commonly - Used Reference Electrode (Half-Cells)	16
2	Correction Factor for Coating Conductance Calculations	50

ACKNOWLEDGEMENTS

Sections of this report have been prepared from material found in AFM 88-9, Chapter 4 "Corrosion Control" (1 August 1962) and Designing Impressed Current Cathodic Protection Systems with Durco Anodes, edited by William T. Bryan, The Curiron Company, Inc., Dayton, Ohio, 1970. In addition, the following sources have provided data found in tables and figures, sometimes revised or updated:

<u>Figures</u>	<u>Source</u>
15, 23, 26, 27, 34, 43, 44, 45, 46	AFM 88-9, Ch. 4 (1 August 1962)
14	Associated Research, Inc.
32, 39, 40, 41, 42	M.C. Miller Company, Inc.
48	The Corrosion Handbook, H.H. Uhlig, Copyright 1948, John Wiley & Sons, Inc., New York.

<u>Table</u>	<u>Source</u>
1	NACE Basic Course, "Introduction to Corrosion", F.L. LaQue, Copyright 1969, National Association of Corrosion Engineers, Houston, Texas.
2	National Association of Corrosion Engineers Procedure: NACE 2D157

TESTING METHODS AND INSTRUMENTS

1 **TESTING METHODS.** Requirements for any corrosion test program must be tailored to the particular structure or system on which it is to be used. Specific requirements will, therefore, vary with different localities and types of structures. The corrosion engineer must select methods and procedures which best supply information needed to study these problems.

Although other factors are often important, electricity is the basis of the corrosion process. Electrical current leaving a metal surface produces actual metal loss, and a corrosion cell is an electrical circuit. Therefore, quantities associated with this circuit are those most often measured in corrosion testing, although various chemical and physical tests may also be required. Electrical tests usually involve direct current (D.C.) measurement, because this (rather than A.C.) is most often encountered in corrosion cells. Some recent attention has been given to alternating current, but direct current remains most important.

Tests may be made in field or laboratory, depending on specific measurements and equipment employed. Generally, electrical measurements on the actual structure in its actual environment provide most reliable information. Complicated chemical and mechanical analyses may require laboratory measurements, but even these are sometimes included in field testing.

1.1 **Background.** To determine if corrosion is active, how much protection is required, how protective equipment should be installed, and finally whether or not corrosion is being brought under control, it is necessary to take instruments into the field or laboratory, connect them, and measure electrical quantities. Analysis of these quantities gives a solution, or at least a key to the solution, of corrosion problems. Usually several types of measurements are taken before the corrosion behavior can be understood. Success or failure of a corrosion control program depends upon accuracy and proper use of these meter readings. Equally important is proper recording and subsequent analysis of this information.

1.1.1 **Description of Electrical Quantities.** Electrical current can be considered to flow through conductors (materials having the ability to carry it) in the same manner in which fluids flow through pipe lines. The rate of this flow depends upon voltage pushing it through, which is analogous to pressure, and resistance to flow which affects moving electric current as inside pipe walls affect flowing fluid. (A rougher wall surface results in more friction

which is overcome by increasing pressure to maintain constant flow.) Resistance tends to hold back electricity, and voltage pushes it through. As liquids are measured in gallons, electric current is measured in amperes. As fluid pressure is measured in pounds per square inch, electrical voltage is measured in volts. Electrical resistance is measured in ohms. One ampere of current will flow through a conductor of one ohm resistance when pushed by a voltage of one volt. Milliamperes and millivolts, quantities commonly associated with corrosion work, equal one one-thousandth of an ampere and a volt, respectively.

The relationship between basic electrical quantities is given by the all-important Ohm's Law:

$$V = IR$$

where

V = voltage in volts
I = current in amperes, and
R = resistance in ohms.

(If any two of these quantities are known, the third can be found through algebraic solution.)

Some examples of conductors (materials which will pass an electric current when voltage is applied) are pipes, cables, soils, and waters. Coatings and cable insulation are examples of non-conductors (materials which will not pass any appreciable electric current when voltage is applied). The greater the resistance per unit material, the poorer the conductor.

Electrical currents are classified as direct or alternating. Alternating current reverses its direction of flow several times each second, while direct current flows continually in the same direction for longer periods of time. Unless special attachments are provided, current and voltage measuring instruments (ammeters and voltmeters) constructed for the study of alternating currents cannot be used for direct current work. Since direct current is most commonly encountered in corrosion work, it will be the only type referred to in this discussion.

Voltage measurement between two points along the path of flowing current is called voltage drop or loss, as is a difference of pressure between two points in a pipe line. An electrical circuit is the path which flowing current follows and can consist of one or several conductors. Current can be considered to leave its source, flow through the circuit, and return to its source again. The circuit which it follows will always be the path of least resistance. In the

case of a galvanic anode, such as magnesium (Figure 1), current leaves the anodes, passes through backfill and soil respectively, enters the structure, flows along this structure to the anode wire connection, and finally flows through the wire back to the anode. This circuit is made up of four conductors other than the anode itself. These are backfill material, soil, structure, and copper return wire.

1.1.2 General Methods. To study the behavior of electrical circuits, one must first decide what quantity to measure (current, voltage, or resistance), where it can best be done (location in the circuit), what instrument to use, and finally how to connect this instrument. It is often necessary to measure current and voltage across a portion of a circuit in order to determine resistance through that portion. Ammeters, and voltmeters or potentiometers are commonly used to determine current flow and voltage respectively. Instruments which impress a known current and give a resistance reading from the resulting voltage drop are also widely used.

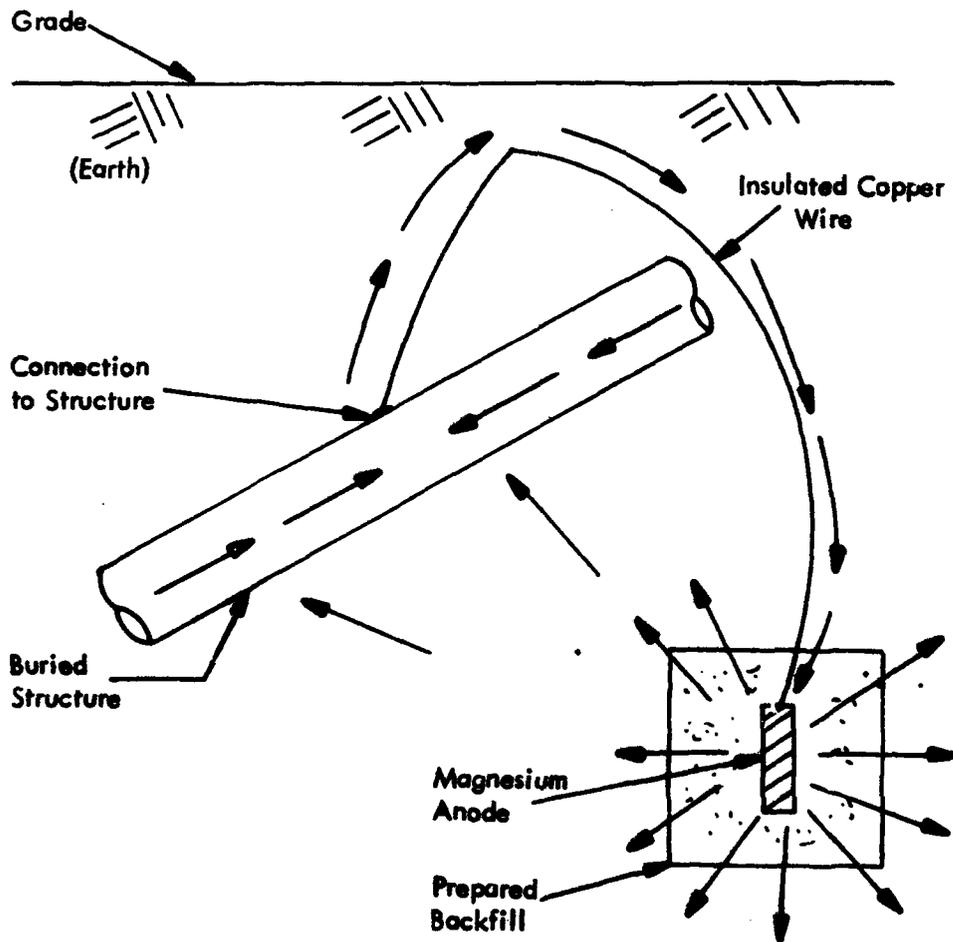
When instruments are connected, they can affect flowing current. If test leads are employed to make contact between meter and structure, considerable resistance might be added at one or all of the following:

1. Where leads contact structure.
2. Where leads contact meter.
3. Through leads themselves.
4. Through the meter.

As mentioned before, any increase in resistance will reduce or hold back flowing current, so the flow might differ after the meter is connected.

a. Current. When current flows through insulated wire, one can usually break the wire at any point, and measure total current flowing simply by connecting an ammeter between the broken ends. However, when this instrument is connected, total circuit resistance is immediately changed by added contact, lead wire, and ammeter resistances. From Ohm's Law, less current flows because of the increased resistance, even though voltage remains constant. Therefore, the measurement is not totally accurate.

Similarly, a pipe line through which electrical current is flowing is cut or two sections of pipe are electrically separated by an insulating joint. An ammeter is connected between the two sections. Current passes through this instrument and is measured. Total circuit resistance is increased with this instrument connected, and less current flows than before.



Note: Arrows Indicate Current Flow

Figure 1
TYPICAL GALVANIC ANODE CIRCUIT

If the pipeline is buried or submerged, additional inaccuracies are introduced, because soil and water are conductors (Figure 2). Any soil or water contacting a metallic structure might carry some percentage of current flowing on the structure. The total circuit contains several possible paths for current flow, each of different resistance (Figure 3). The ammeter measures only that part of the current which flows through it.

Because of these inaccuracies, in corrosion field work current is generally not measured with just an ammeter (paragraph 1.2.1.b).

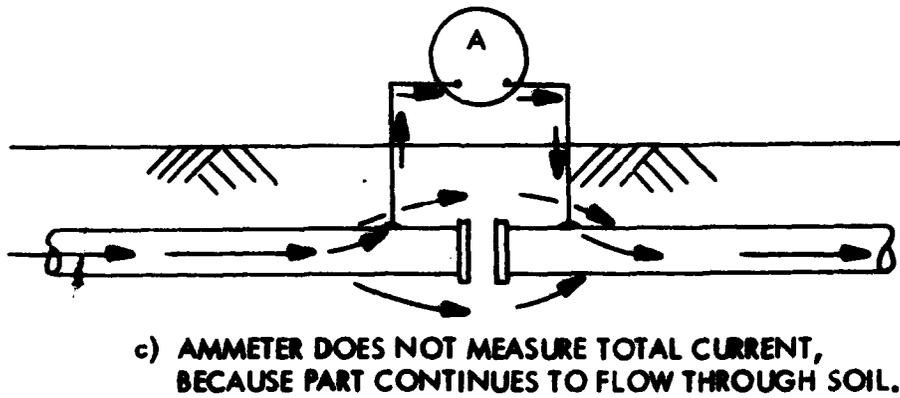
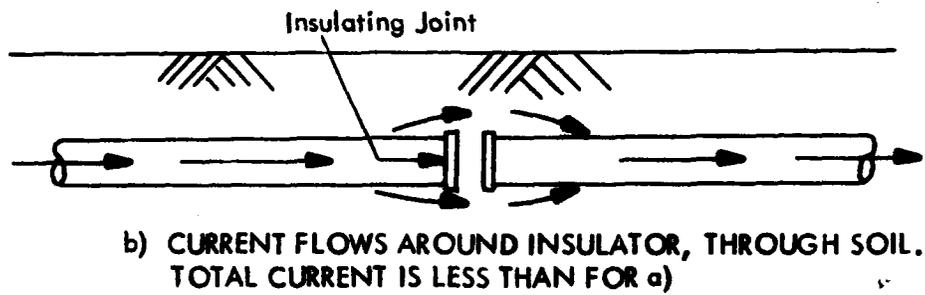
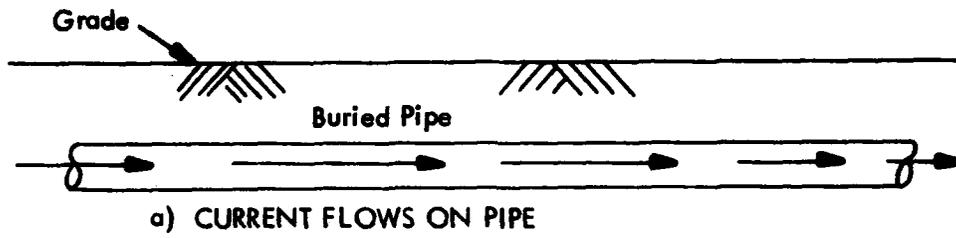
b. Voltage. As fluid needs energy to move in a pipe, electricity requires a "push" along its circuit. The energy or push to electric current is voltage.

To determine the voltage used up between two points, a voltmeter is used. A test lead wire is connected from one terminal of the voltmeter to one point (A) in the circuit and a wire, from the other terminal to the other point (B). The voltage used up between points A and B is read in volts. Current and resistance are not known, but the voltmeter does reveal direction of current flow. That is, when the voltmeter is connected to leads from points A and B, the needle moves either to the left or the right depending upon the direction voltage pushes flowing current.

Points A and B could be two points in the earth or water, two on a structure or A could be a point on a structure while B is a point on another structure or earth (water). Thus, these voltage measurements indicate how much "push" the electrical current is getting whether it is flowing along a buried structure, through an electrolyte, between one structure or another, or between a structure and an electrolyte. In addition, although the amount of current flowing is unknown, one can tell the direction in which voltage pushes current at the location where voltage is measured.

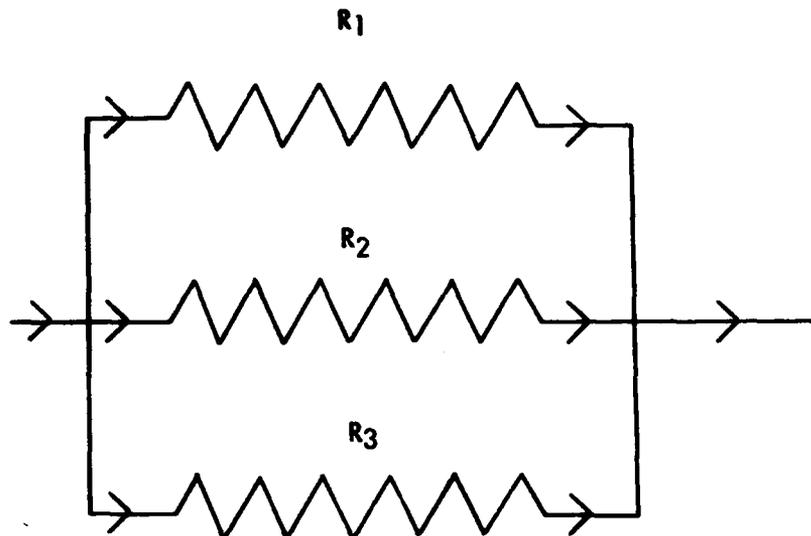
With voltage measuring instruments, an observer can trace the path of electrical current along a buried or submerged structure; determine when it enters or leaves, its direction of flow through earth or water, and whether or not it is entering or leaving from another structure. Although frequently amount of current is unimportant, it is often possible, after gathering some other data, to use the voltage reading to compute current flow in amperes by Ohm's Law.

It is important to remember, here, as with all electrical measurements, that good electrical contact be made at all connections. Rust and dirt on terminals, clips, and probe bars mean trouble and erroneous readings. Contact to the



Note: Arrows Indicate Current Flow

Figure 2
CURRENT FLOW AROUND INSULATING JOINTS



- R1 = Resistance in Ammeter and Test Leads
- R2 = Structure-to-Electrolyte Resistance
(Assume resistance through electrolyte to be negligible)
- R3 = Resistance Through Insulator

Figure 3
CIRCUIT DIAGRAM: PARALLEL RESISTANCES AT INSULATING JOINT

buried or submerged structure is a common source of error and the most difficult to cope with.

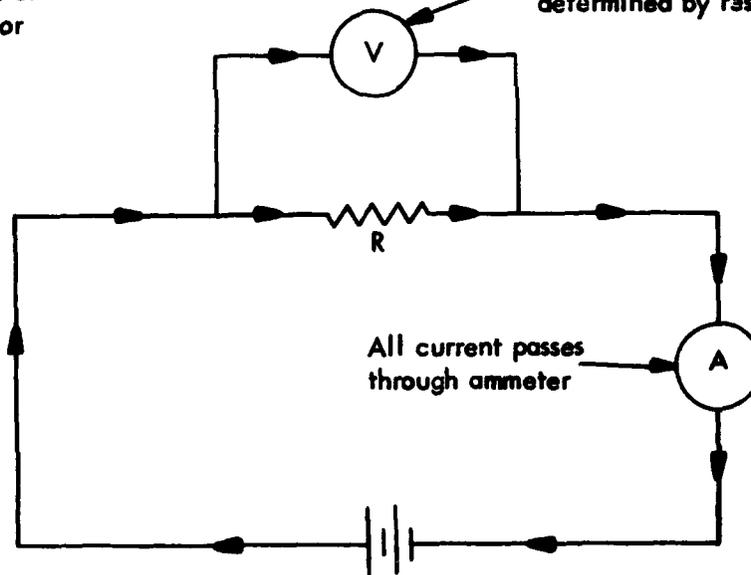
To measure current with an ammeter, connect the instrument so that all current to be measured flows into one terminal and out the other. Voltage measurements require only a small portion of current to flow through the measuring instrument (voltmeter). In fact, many times it is advantageous to use a voltmeter through which only a very, very small portion of total current passes. Figure 4 illustrates the method of connecting both ammeter and voltmeter in circuit.

c. Resistance. Often, it is necessary to determine how much resistance electrical current will encounter. If current and voltage are both known, Ohm's Law can be used to compute resistance. Resistance equals voltage divided by current ($R = V/I$). To determine resistance, one can use an ammeter and a voltmeter connected in separately, or one of several commercially available instruments which read the answer directly in ohms.

Reproduced from
best available copy.

V = Voltmeter
A = Ammeter
R = Resistor

Some current passes
through voltmeter, amount
determined by resistance



All current passes
through ammeter

Note: Arrows signify current flow

Figure 4
AMMETER AND VOLTMETER IN CIRCUIT

Resistance plays an important role in measuring electrical quantities. When test leads are used, they often add resistance in clip and terminal connections because of corrosion products forming on metal surfaces or weak clip springs. Probe bar-to-structure and/or test lead wire-to-structure connections are equally important. When an ammeter is used to measure current, these cannot be tolerated. They will introduce serious errors in some types of voltage measurements. If not understood, they can also cause resistance measurements to give false results.

d. Electrolyte Resistance. Electrical current flows through some soils or waters easier than others. If the same voltage is applied between two contact points in one soil as in another, more current may pass between them in one instance. Resistance is lower in this case. If resistance between outer surfaces of two points and earth is not part of the measured resistance, only current flowing through soil is being considered. Therefore, soil resistance is being measured.

For convenience, when dealing with soil or water, electrolyte resistivity rather than resistance is determined. Resistivity is a property of the material itself, independent

of the amount or geometry of material. Resistance, on the other hand, is a function of the amount and geometry of material. Resistance and resistivity of a sample of material of size L by W by H, are related thus:

$$R = \rho \frac{L}{WH}$$

where

R = resistance in ohms
 ρ = resistivity in ohm-centimeters
L = length in centimeters
W = width in centimeters
H = height in centimeters

From this relationship, it can be seen that resistivity equals the resistance of a cube of material measuring one centimeter on each of its sides. When the length only of this cube is doubled, resistance is doubled. When either the width or the height is doubled, resistance is halved. This is analogous to an electrical circuit in which resistors are placed first in series, then in parallel.

Noting units in the above equation, one can see that resistivity has units of ohm-centimeters, not "ohms per cubic centimeter" or "ohms per centimeter cube" as are often mistakenly used. Units such as "ohm-inch" or "ohm-mile" are technically correct also, but for corrosion control applications the unit "ohm-centimeter" is preferred.

e. Chemical Analysis. In addition to electrical measurements, a partial chemical analysis can often help indicate corrosivity of soil or water. Standard laboratory methods are employed to determine pH, presence of sulfates, or other applicable factors.

1.2 Field Tests. It is important that corrosion field work be performed by experienced personnel. Meaningless measurements or misinterpretations of results are likely when inexperienced people do field survey work. Corrosion testing is widely diversified involving many different techniques, some, highly specialized. Tests may require durations from a few minutes to a year or more, and measurements may vary over wide limits. For example, potential measurements can vary from a few millivolts to hundreds of volts, and currents may be a few milliamperes or hundreds of amperes. Structure size bears no relation to the type tests required. A small complex structure may involve many intricate measurements. Often available data are fragmentary, and conditions that cannot be measured may be of greater significance than those obtainable. Consequently, judgment and experience in field-testing techniques are of great value. Due to the many factors involved, a corrosion investigation may include visual inspection, study of geographical areas, study of records, chemical or metallurgical analyses, electrical

measurements and, sometimes, biological studies. The proper combination of tests depends largely upon available data and local conditions. Here again, the necessity for experienced personnel is evident. Corrosion survey reports should indicate not only the test results, but also reasons particular tests were used or excluded.

1.2.1 Basic Field Tests. Standard test methods are described here; field surveys, often combining several basic measurements, are discussed in paragraph 1.2.2.

A general procedure, common to all field tests using ammeters or voltmeters, involves standard electrical connections. It is common practice to connect the negative meter terminal to the structure being investigated and the positive terminal to the reference electrode (electrolyte contact), foreign line, or other. This arrangement will be followed in this manual and is generally accepted in the corrosion field.

Another convention accepted in this manual concerns designating points in a circuit as "positive" and "negative". Positive and negative terminals of standard instruments are marked by their manufacturer, conventionally with negative terminal on the left and positive terminal on the right, as one faces the meter (Figure 5). When current flows into the positive terminal and out the negative terminal, the instrument pointer moves to the right (clockwise). Conversely, when current flows into the negative terminal and out the positive terminal, the instrument pointer moves to the left (counterclockwise). By knowing where the two terminals are connected, the engineer can easily determine direction of flow and which point is "positive" and which is "negative". For example, to measure IR drop, the meter terminals are connected to two points on the structure as in Figure 5a. If the meter swings to the right (clockwise) as shown, this indicates that current is entering the meter at the positive terminal and leaving at the negative. Therefore, current flows through the structure from right to left as shown on the drawing. (Here, as always, "current" refers to conventional current flow, not electron flow.) By convention, point A is positive to point B.

Figure 5b shows a similar set-up for measuring structure-to-soil potential. As always, the reference electrode (electrolyte contact) is connected to the positive terminal and the structure, to the negative terminal. The meter swings to the left as shown, when current flows through the soil from point B to point A.

Note:
Arrows designate
conventional current
flow

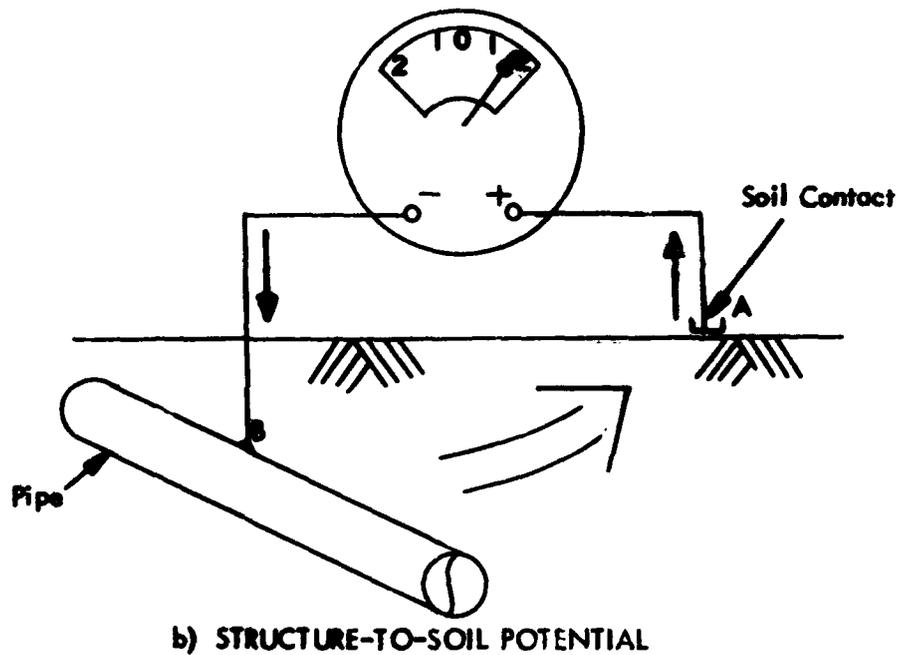
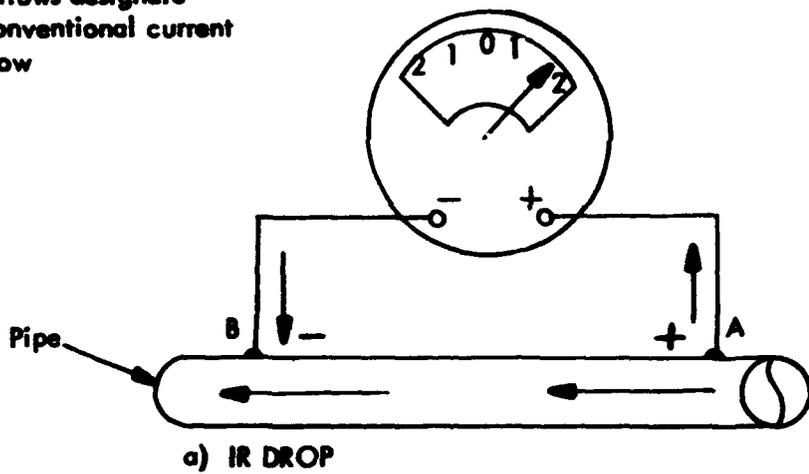


Figure 5
CONVENTIONAL METER HOOK-UPS

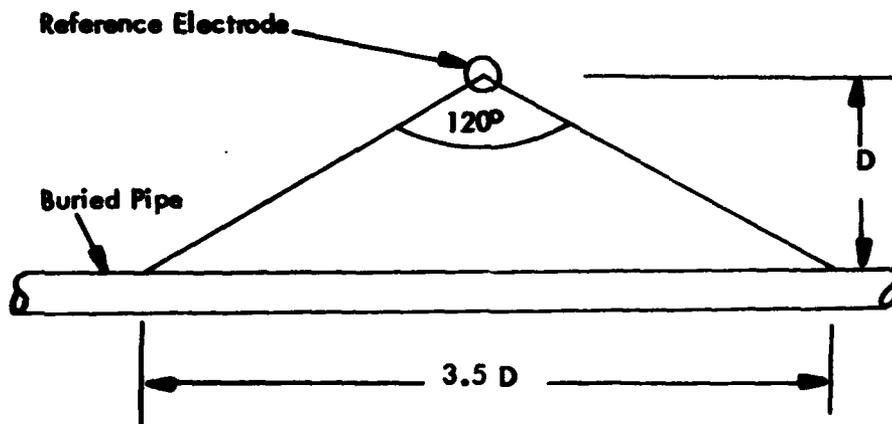
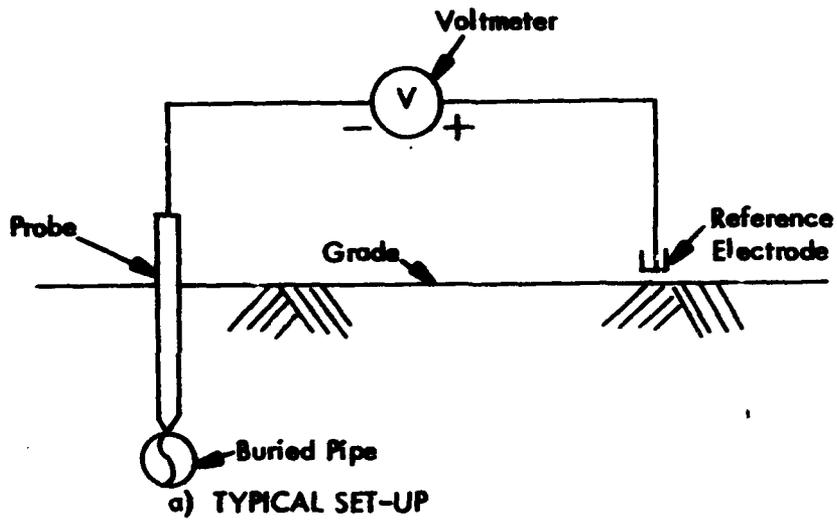
a. Structure-to-Electrolyte Potential. When metals are in contact with an electrolyte such as soil or water, they exhibit a potential, referred to as a "half-cell potential". This potential depends on characteristics of the metal and characteristics of the electrolyte. Various metals exhibit different potentials when subjected to the same electrolyte. In like manner, a metal will exhibit different potentials when subjected to electrolytes of different compositions. Another variable which affects half-cell potential is metal surface, often altered by heat treatment or other processes. Dissolved gases in the electrolyte or gases absorbed or adsorbed on the metal surface also affect half-cell potential.

In the absence of externally impressed currents (stray or cathodic protection), the more negative a metal, relative to its environment, the more it tends to corrode. For this reason, knowledge of structure-to-electrolyte potential is important.

Structure-to-electrolyte potentials are helpful in locating possible corrosive areas on structures. Varying structure-to-electrolyte potentials indicate electrical currents flowing in the electrolyte. Where current leaves the structure, deterioration of metal results. Potential readings are also important in cathodic protection and stray current analysis (paragraph 1.2.2).

(1) Measurement. Potential measurement for a structure relative to its electrolyte requires a voltmeter or other instrument, a dependable contact to structure (from negative meter terminal), and a reference electrode (connected to the positive meter terminal) to contact the electrolyte. Reference electrodes are used because potential is not an absolute quantity; it is measured relative to something of known or assigned potential. A galvanic potential exists between any reference electrode and the metal structure. Therefore, even if no additional current flows, this potential difference registers on a voltmeter and is added (or subtracted) from any measured voltage. For example, a galvanic potential of -0.5 to -0.8 volts is typical between a buried steel structure and a copper-copper sulfate reference electrode. If current enters or leaves the structure, its resulting voltage drop is added to or subtracted from these. This set-up is shown on Figure 6a. Figure 6b indicates the length of pipe observed by the soil contact (about 3.5 times the distance between pipe and that contact).

(a) Contact to Structure. Measurement of potential requires a good contact to structure. This may be achieved through test wires, an accessible section of structures, or a probe bar. Test wires generally provide the best contact and have other advantages.



b) SECTION OF BARE STRUCTURE OBSERVED BY REFERENCE ELECTRODE

Figure 6
STRUCTURE-TO-ELECTROLYTE POTENTIAL MEASUREMENT

If a section of the structure is easily accessible (e.g. above ground), contact can be made there; any paint, corrosion products, or other coverings must first be removed to assure electrical contact. When a probe bar is used, care must be exercised to obtain good metal-to-metal contact with the structure. If the structure is coated and offers high resistance to earth, an insulated probe bar might possibly be necessary to avoid erroneous readings because of probe bar area relative to coated structure area. A bare probe bar, in good contact with a structure, must be considered a part of that structure electrically. Therefore, any electrolyte contact placed close to the bar will yield the same test results as one placed close to the structure.

(b) Voltmeter. Structure-to-electrolyte potential measurement always involves fairly high resistance in the external circuit, because of soil contact resistance. Therefore, a high-resistance voltmeter (100,000 ohms per volt or greater) or preferably a potentiometer or vacuum-tube voltmeter must be used. If a voltmeter is used where circuit resistance is an appreciable percentage of metal internal resistance, the voltmeter reading will be less than the true voltage. In order to correct the reading, external circuit resistance must first be found. Either of the following two methods can be used to determine external circuit resistance:

1. Measure circuit resistance with a resistance-measuring instrument.
2. Read voltage on two different meter scales, then apply the formula:

$$R_E = \frac{R_{M2} R_{M1} (V_2 - V_1)}{R_{M2} V_1 - R_{M1} V_2}$$

where

- R_E = External Resistance (Ohms)
- R_{M1} = Resistance of meter on lower scale (Ohms)
- R_{M2} = Resistance of meter on higher scale (Ohms)
- V_1 = Lower scale meter reading (Volts)
- V_2 = Higher scale meter reading (Volts)

After external circuit resistance has been determined, true voltage can be found from the following:

$$E = \frac{V (R_M + R_E)}{R_M}$$

where

- E = True Voltage (Volts)
- V = Voltmeter reading (Volts)
- R_M = Meter resistance, using scale on which V was read (Ohms)
- R_E = External resistance (Ohms)

When electrical instruments are used in the field, several causes of excessive external circuit resistance should be considered. These may increase resistance in normally low-resistance circuits, producing unexpectedly inaccurate meter readings.

1. Test leads may be in poor condition (broken strands of wire, terminals), or clips may be accidentally disconnected.
2. Instruments and/or test lead terminals may be dirty or corroded.
3. Connection to the structure being tested may be poor (bar or probe contact, or a clip to some exposed portion of the structure).
4. Connection to bar or probe may be poor.

For measuring potentials on long straight pipelines, it often saves time and requires fewer personnel to use a recording voltmeter (paragraph 2.2.3). The meter is located at the connection to structure; the reference electrode is connected to the meter positive terminal through a wire reel. With the equipment set-up, one person can move down the pipeline contacting the electrode to earth where measurements are desired while the meter records readings. This method, then, uses the meter to record potentials at various locations rather than at one location over a period of time. The recording meter should not be used in this manner for short lines or in congested areas.

(c) Contact to Electrolyte -

Reference Electrode (Half-Cell). A metal's potential is not absolute and can best be measured relative to a reference electrode (half-cell). For convenience, a set of Standard Potentials (E° values, see Appendix C.) has been determined relative to the standard hydrogen electrode which is assigned the value of zero. The term "Standard Potential" refers only to potentials measured relative to the standard hydrogen electrode. To avoid confusion, potentials measured relative to other electrodes must be labeled "potential, relative to" that reference (e.g. potential, relative to copper-copper sulfate (saturated) electrode).

Potentials measured relative to one reference electrode can be converted to potentials relative to another according to the equation, using Table 1:

$$E_2 = E_1 + E_1^{\circ} - E_2^{\circ}$$

where

- E_1 = measured potential, relative to reference electrode "1"
 E_1° = Standard Potential of reference electrode "1"
 E_2 = potential relative to reference electrode "2"
 E_2° = Standard Potential of reference electrode "2"

For example, the structure-to-electrolyte potential of a pipe relative to a copper-copper sulfate electrode is found to be -0.7000 volts. All other data were measured earlier, relative to a silver-silver chloride reference electrode, and it is desired to convert this value to be compatible with the others. The Standard Potential of the copper-copper sulfate electrode, from Table 1, is +0.3160 volts; that of the silver-silver chloride electrode is +0.2222 volts. Substituting into the above equation:

$$E_2 = (-0.7000) + (+0.3160) - (+0.2222) = -0.6062$$

we find the converted potential is -0.6062 volts, relative to silver-silver chloride.

Table 1

Standard Potentials (E°) of Commonly-Used Reference Electrode (Half-Cells)

<u>Half Cell</u>	<u>E° (Volts, at 25°C)</u>
Tenth Normal Calomel	+0.3337
Saturated Copper Sulfate	+0.3160
Normal Calomel	+0.2800
Saturated Calomel	+0.2415
Silver-Silver Chloride	+0.2222
Hydrogen	0.0000

Various standard reference electrodes are discussed in paragraph 2.3. For field work, the copper-copper sulfate electrode is the most widely-used reference. It is a simple instrument and very reliable when properly maintained. It should be noted, however, when used in salt water, the cell should be kept completely filled to prevent dilution of the copper sulfate solution, which has a detrimental effect on the cell. The silver-silver chloride electrode and saturated calomel electrode are also used for work in

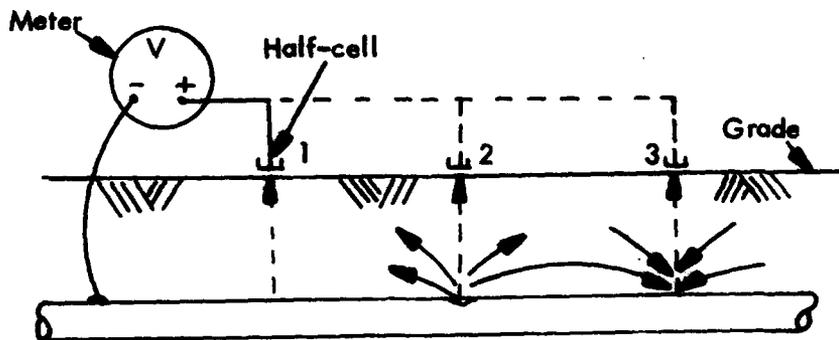
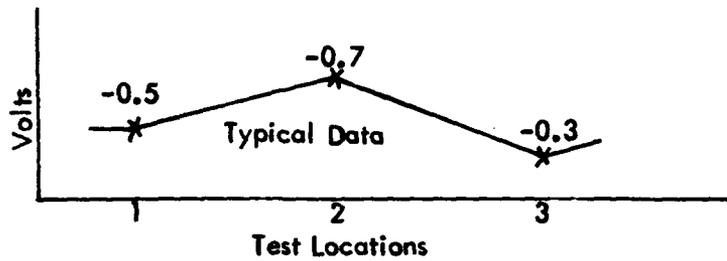
seawater. The lead-lead chloride electrode is sometimes used to measure potential of lead-sheathed cables. In addition, such things as steel bars, lead plates or duct cells, or zinc cells may be used to contact the electrolyte. Reference such as these are not standard, and resulting potential readings will vary greatly with conditions. Such references are useful for voltage change readings, when standard references are not available or practical. In theory, a steel bar used as a reference to a steel structure of identical composition will yield a zero voltage reading if soil makeup and all other conditions are identical and no corrosion is occurring. This is because no galvanic cell would exist under these conditions. Any current read would therefore be due to corrosion of the structure. In reality, these perfect conditions are never found in the field, and a non-zero voltage reading is encountered even with no corrosion.

In any case, good contact between reference electrode-electrolyte is required; with soil, this may require pouring water on the ground before measurements, or varying reference electrode design to increase contact area.

(2) Reference Electrode Location. Location of electrode relative to structure is an important consideration in structure-to-electrolyte potential measurements. Many locations are considered, both near the structure and farther away. As was shown in Figure 6b, the electrode will survey a distance along a bare structure equal to approximately 3.5 times its distance from the structure. (If the structure is well-coated, electrode position is not as critical.) Therefore, the greater the separation between a bare structure and the electrode, the greater the portion of structure viewed. This is true only until a certain critical distance ("Remote Earth") is reached. Beyond this, the reading is constant, and no more of the structure can be included. This point is referred to as the "remote" location. Readings can be taken over the structure, remote, or anywhere between, depending on the information desired. It is important to locate other structures in the area prior to reading structure-to-electrolyte potentials to prevent "shielding". Pipes, tanks, anodes, or other structures located between test structures and electrolyte-contact distort readings.

Structure-to-electrolyte potential readings indicate whether current is entering or leaving a structure. Analysis can be based on comparison of readings; both over-the-structure and farther away from it. Both readings, relative to each other, indicate current flow to or from a structure.

As shown in Figures 7 and 8, a natural potential difference exists between reference electrode and structure. Any



Natural Voltage Between Structure and Half-cell	Anodic Area - Corrosion Current Reinforces Natural Voltage - High Reading	Cathodic Area - Returning Current Opposes Natural Voltage - Low Reading
---	---	---

Figure 7
STRUCTURE-TO-SOIL VOLTAGE - GALVANIC CONDITIONS

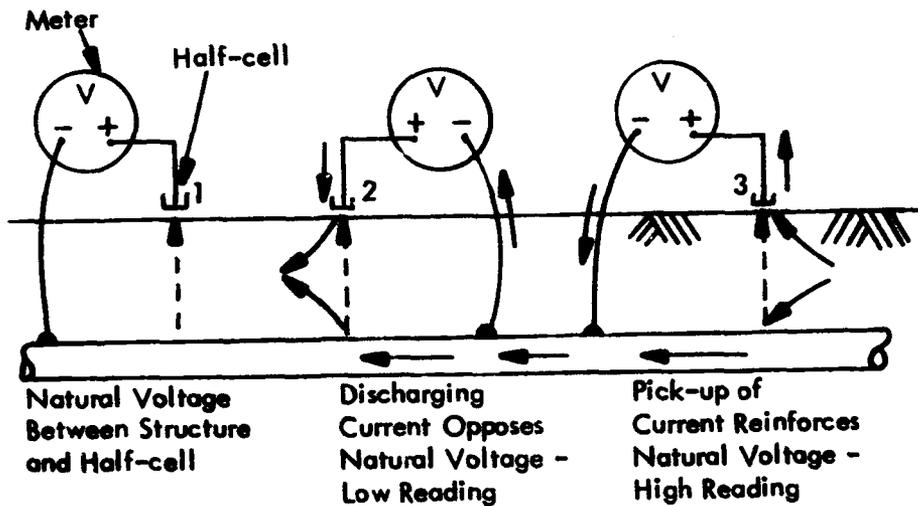
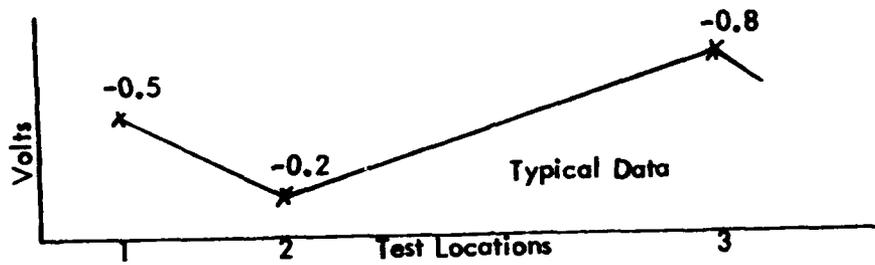


Figure 8
STRUCTURE-TO-SOIL VOLTAGE - EXTERNAL CURRENT CONDITIONS

currents flowing about the structure will either reinforce or oppose this potential difference (depending upon its direction of flow), producing a greater (more negative) or smaller (less negative) voltage reading. Galvanic currents affect the voltage differently than external (stray or cathodic protection) currents.

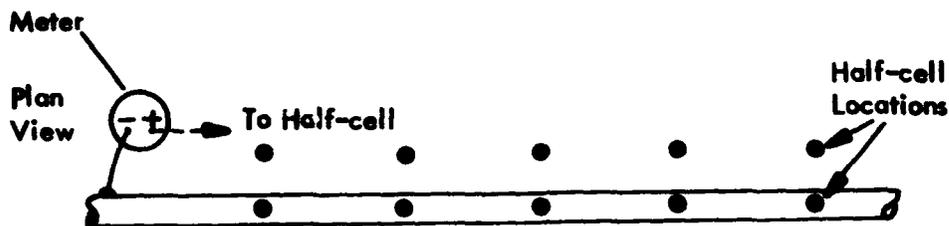
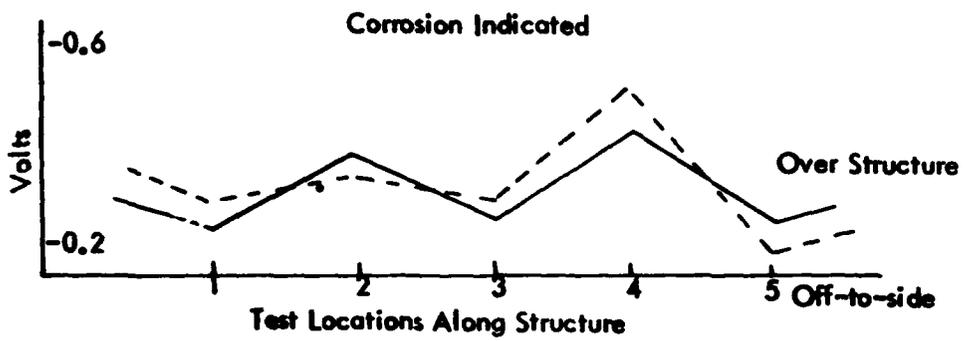
Under galvanic conditions (galvanic or electrolytic cells), corrosion current leaving the structure reinforces the natural potential difference, producing a more negative reading (test location "2" in Figure 7). Where current returns to the structure (test location "3"), the natural potential difference is opposed; a less negative reading results.

Under conditions where external currents (stray or cathodic protection) exist, the reference electrode acts as part of the structure (Figure 8). The electrode picks up current where the structure picks up current (test point "3", in Figure 8); this reinforces the natural potential difference producing a more negative reading. Where stray current discharges from a structure, current also discharges from the electrode, opposing the natural difference (test point "2"). A less negative reading results.

It is often advantageous to measure structure-to-soil voltage with both over and "off-to-the-side" reference electrode placement (Figure 9). Each set of readings can be plotted on the same graph versus distance along structure. Resulting peaks indicate areas of current pick-up or discharge; valleys indicate likewise. Comparison of relative position of the two graphs determines which are which; current discharge is indicated when over-the-structure readings are higher than remote ones (test points "2" and "5").

Sometimes, stray current may pick-up on one side of the structure and discharge from the other (Figure 10). Since a side reading explores only one side of the structure, remote readings on both sides, in addition to over-the-structure, may be required. As above, comparison of readings indicates current discharge wherever over-the-structure readings are higher than remote ones.

Frequently, structure-to-electrolyte potentials are required on the internal surfaces of water storage tanks. Generally, the reference electrode is lowered into the tank through an opening on top of the tank. The electrode must be lowered well into the tank to obtain measurements of the lower surfaces. Often it is difficult to recognize when the electrode is touching the bottom surface, a condition which must be avoided because errors in measurements can result. One method of avoiding this is to fit a plastic cap with slots cut into it over the electrode's porous plug.



Elevation

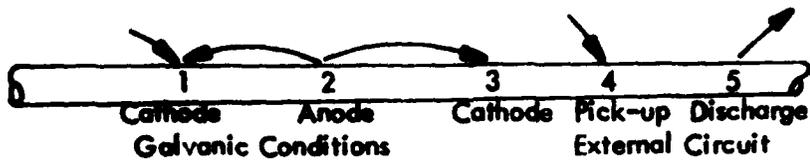


Figure 9
**COMPARISON OF OFF-TO-SIDE AND OVER-STRUCTURE
 STRUCTURE-TO-ELECTROLYTE READINGS**

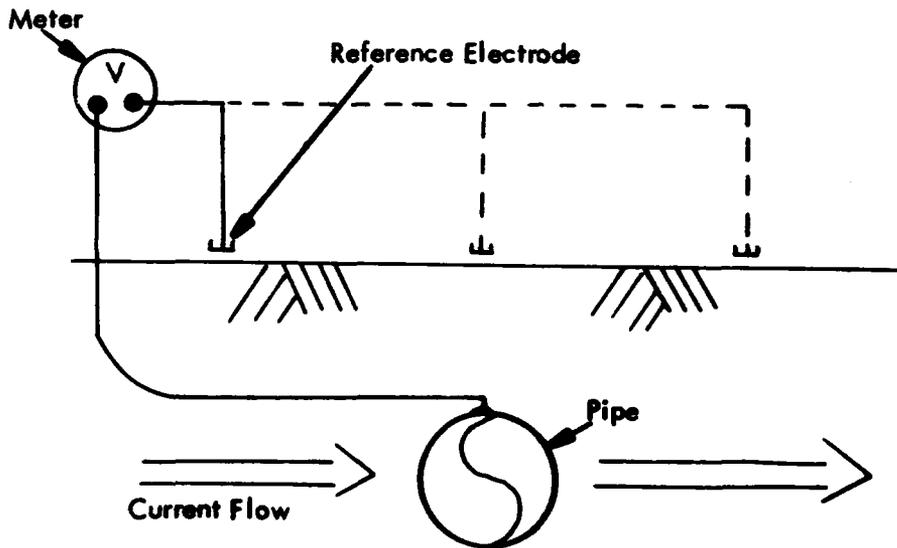
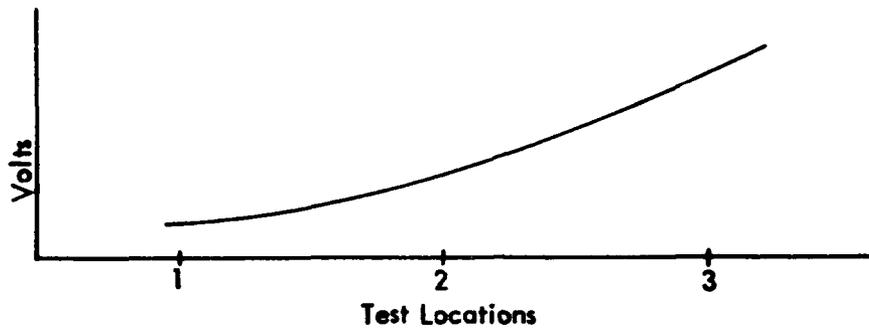


Figure 10
 STRUCTURE-TO-ELECTROLYTE READINGS
 SHOWING CURRENT PASSING THROUGH STRUCTURE

The plastic prevents contact between plug and tank, while slots allow adequate electrode contact to the electrolyte. In addition, it may be necessary to weight the electrode with a thin lead sheath around the body, covered with plastic to prevent contact between lead and tank.

b. Current. It is often desirable to learn quantity and direction of current flowing along a buried structure. Knowing this will help:

Locate active corrosion.

Determine mitigation effectiveness.

Determine mitigative current requirements.

As discussed in paragraph 1.1.2.a, simple ammeter measurements of current cannot be used, so other methods are employed.

(1) Measurement. One of two methods is generally used to determine current flow on a buried structure:

1. Measure IR drop and use Ohm's Law.
2. Use "Null Method".

In the first method, IR drop (voltage) in millivolts along a structure is measured. The structure is contacted at two points, and IR drop is the voltage measured between these points. This reading is then converted to current.

Two practical ways to convert current from millivolt (IR drop) measurements between two points on a structure are:

1. Multiply millivolt reading by the reciprocal of structure resistance for length between the two contact points. Distance between contacts must be measured accurately, and structure resistance per lineal foot is obtained from tables. Temperature changes will affect resistance, and compensation is difficult.
2. Multiply millivolt reading by field measured "calibration factor". This is the same as (1) except tables are not relied upon, and the section between contacts is tested under field conditions so that temperature and other factors are eliminated as sources of error. Permanent test leads can be connected for this use. This factor is determined by impressing a known current on the portion of structure between contacts and measuring the resultant IR drop. From Ohm's Law ($V = IR$), this IR drop (V) divided by the known current (I) yields resistance (R) or "calibration factor" for that section of structures.

When cable sheath, cable or pipe is being observed, a relatively large mass of metal per lineal foot is under consideration. Therefore, small resistance and small voltages result when corrosion current flows. These voltages or IR drops are most often read on a millivoltmeter and recorded as millivolts. A millivoltmeter is generally a

low-resistance instrument and, therefore, reading may need correction before conversion to amperes (paragraph 1.2.1.a for method of correction).

The "Null Method" is another way to measure current flow. This uses a battery with adjustable resistor to buck structure IR drop, a millivoltmeter to indicate balance, and an ammeter (or milliammeter) to read current flow directly. This method of measurement is limited to nonfluctuating current. Equipment is connected as shown in Figure 11. With the switch open, the millivoltmeter indicates direction of current flow. The adjustable resistance "R" is set at maximum resistance, the switch is closed, and the resistance is decreased until the millivoltmeter reads zero. The ammeter then reads current formerly on the structure. When the millivoltmeter reads zero, current between "A" and "B" is reduced to zero by a portion of battery voltage. The remaining battery voltage overcomes IR drop in the battery circuit from "A" to "B". As current increases or decreases, the resistance must be decreased for increased current and increased for decreased current in order to maintain zero IR drop between "A" and "B".

For ease of measuring current flow, IR drop test stations are frequently installed on underground pipelines

These provide good connections to structure, and a constant separation and location for future tests.

The distance between two points, across which current is measured, must be great enough to produce an appreciable reading on the instrument used with significant current flowing. In cable sheath work this is usually a minimum of twenty feet; for larger diameter pipes, it will be in the neighborhood of fifty feet. It is important to remember that small currents may enter and leave the structure between the two contacts. Also, it is possible that all the significant current is either being discharged or received between the two contacts so that total current flow is not being measured.

Current flow measurements are useful as coordination tests when interference from cathodic protection is suspected. These tests show current flow at locations where cable-to-soil potentials give no indication. Also, these IR drops give valuable information on current flowing along down-guys and other above-grade structures.

In fluctuating stray current areas (current from machinery flowing on structure), current flow measurements are valuable for tracing current source and locating the best drainage point. Correlation curves are plotted to obtain

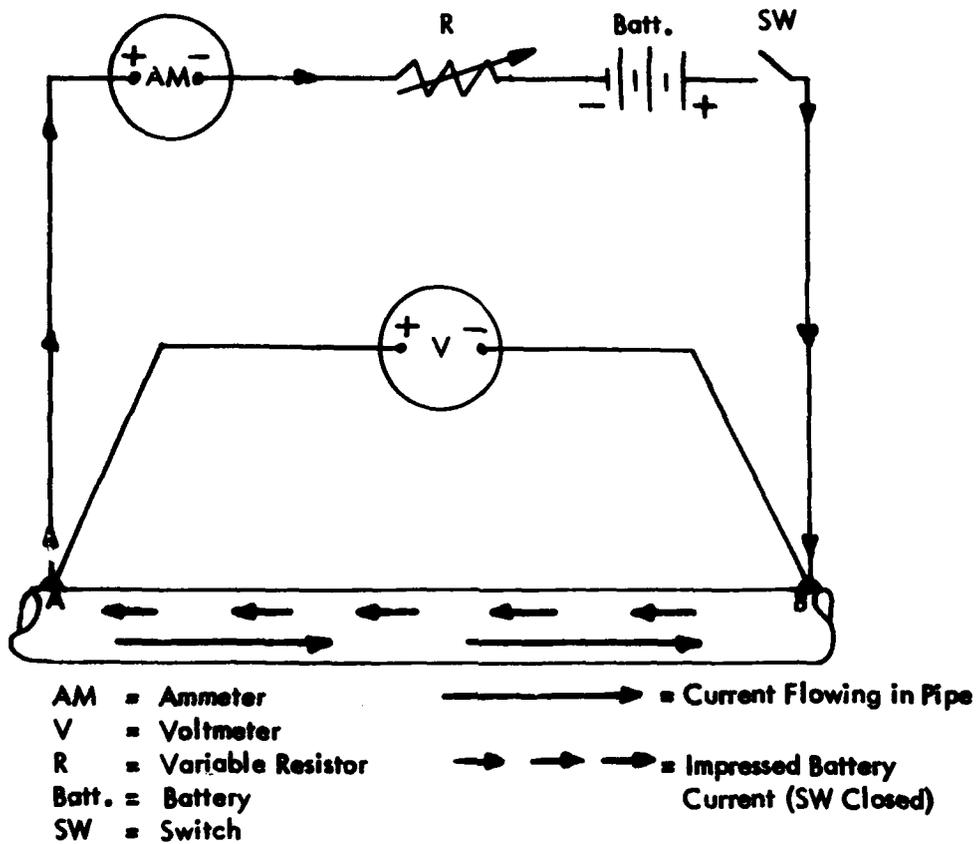


Figure 11
 "NULL METHOD" OF CURRENT MEASUREMENT

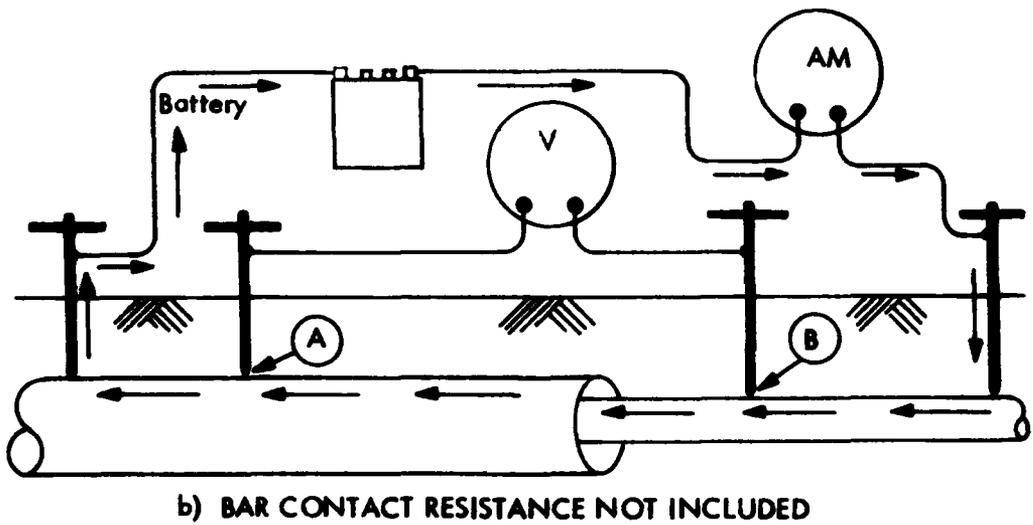
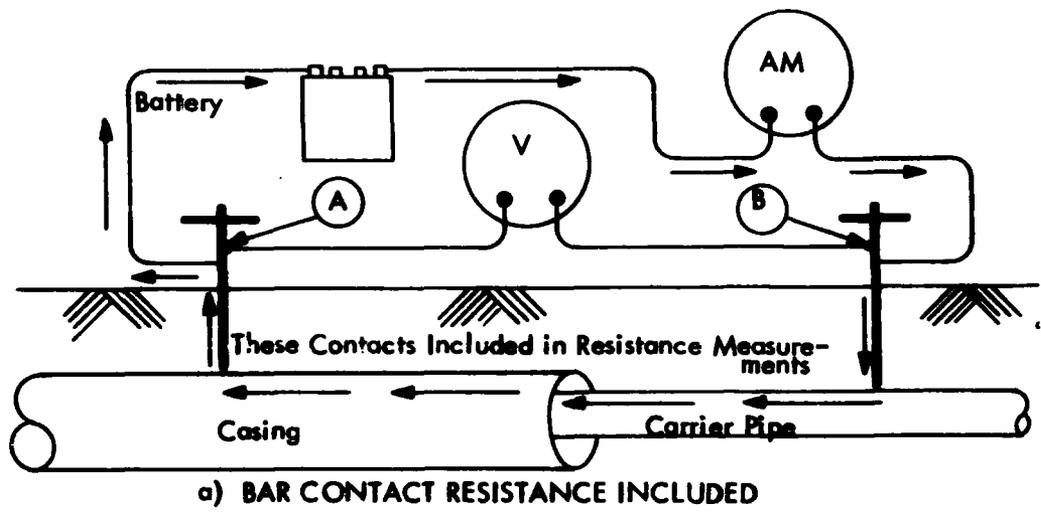
the linear relationship between current flow and structure-to-soil potential at two different locations along the same structure (paragraph 1.2.2.c). For valid correlation, at least twenty to thirty readings per graph are necessary. They must be simultaneous. Therefore, radio communication can be used to advantage.

c. Internal Resistance. It is often necessary to determine electrical resistance between two buried structures, across an insulating joint (between two sections of buried structure separated by an insulating joint), or between a casing and pipe. These measurements, referred to as internal resistance, often give values less than one ohm or, when dealing with bare pipes and cables, sometimes less than one-tenth of an ohm. Therefore, measurements should be taken so as not to include lead wire connection, or instrument resistances.

Generally, two test leads are recommended at each location for ease of measuring internal resistance (two on either side of an insulating joint, two on the casing and two on the pipe, or two on each buried structure). Measured current is applied through one pair and resulting voltage change measured across the other pair. If test leads are not available, other means of contact such as probe bars must be used. Here, an understanding of test lead and contact resistance is particularly important.

For example: It is necessary to measure resistance between a pipe line and casing. Test leads are not available at the location; bars are used. One bar is pushed through earth to contact the casing, and another, to contact the pipe. A battery and ammeter are connected between the two bars so that when an ammeter terminal is touched with the loose test lead, current flows from the battery through the ammeter to the probe bar. It then flows to the pipe, and from the pipe to the soil or point of contact between casing and carrier pipe. It next enters the casing, travels along the other probe bar, the lead wire, and back to the battery (Figure 12a). Flowing current encounters resistance all along its circuit. Of interest is the current's behavior as it flows from casing to pipeline. The pipe may or may not be in electrical contact with the casing. If it is, there is very little resistance for the current to overcome, because metal surfaces touching are a low-resistance path (low voltage required for high current flow).

If the pipe is not touching the inside of the casing and the annular space is clean and dry, it will be necessary for the test battery current to leave the casing outer surface and flow into earth. It passes through soil until reaching the pipe surface where it enters through "holidays" in the coating. Less battery current flows along the path, and more voltage is required to move that which does. Resistance is higher here than in the previous case.



Note: Arrows indicate flowing test current

Figure 12
CASING TO CARRIER PIPE RESISTANCE MEASUREMENT

If no current passes through the above-mentioned circuit when the ammeter terminal is touched, a bad connection somewhere in the test set-up is probably the cause. It is most likely that probe bars are not making good electrical contact with casing and/or pipe. This is fairly simple to correct. However, another inaccuracy still exists, because the voltmeter leads are connected to the wrong place in the circuit. These wires contact the two probe bars. Test current from the battery also passes through these bars on its way into the casing and out the carrier pipe. Because of this, probe bar-to-pipe contact resistances (of both the casing and carrier pipes) are included in the circuit between the two test leads connected to the voltmeter. Substantial resistance is often encountered in probe bar-to-pipe contact and will be part of total computed pipe-to-casing resistance. This added resistance can greatly alter the voltage reading and, therefore, change the resistance. For example, a reasonable pipe-to-probe bar point resistance is 0.25 ohms, so that the two bars together can add 0.50 ohms. With well-coated lines and casing-to-pipe resistances of two or more ohms, this additional value does not have as much effect as with poorly-coated or bare structures and casing-to-pipe resistances of only a few tenths of an ohm. Here, total resistance is often more than doubled.

Probe bar contact resistance can be excluded from resistance measurement by using four probe bars. The voltmeter test leads are removed from the two contact bars, two additional probes are installed (one contacting the pipe, the other contacting casing, as shown in Figure 12b), and these are used only for voltmeter connections. When measured test current is passed between casing and pipe, true change in pipe-to-casing voltage is found. Contact resistance through which test current flows is no longer included between the two voltmeter leads. Therefore, it is no longer included in total computed pipe-to-casing resistance. This calculated resistance is now the correct pipe-to-casing value.

If one test lead were available on each of carrier pipe and casing, contact resistance would probably be less, since a brazed or soldered connection has replaced the probe bar point. However, the possibility of a high-resistant connection always exists and, when measured resistance is less than one ohm, any contact can easily add appreciable error. So it is always desirable to use two connections on each structure when determining resistance.

These same considerations are valid for measuring any internal resistance as between two buried structures or across an insulating joint. In these cases, too, the result will often also be less than one ohm and, with bare pipes and cables, sometimes less than one-tenth of an ohm. Two

contacts on each structure, or two contacts on each side of the insulating joint would be used. Measured current would again be applied through one pair, and resulting voltage change measured across the other pair.

In these resistance determinations one is concerned with change in voltage produced by current supplied from the test battery. That is, voltage is read with and without test current flowing. The difference between these two readings is the voltage change between pipe and casing, between two buried structures, or across an insulating joint produced by measured test current. This change, divided by test current, gives resistance.

Resistance between pipe line and casing, between two buried structures, or across an insulating joint measures opposition encountered by electrical current leaving the surface of one structure, passing through earth or water, and entering the surface of another. The greatest percentage of this resistance is found at structure-to-electrolyte interface. Even if structures are bare, deposits built up on these surfaces are often poor conductors and act as thin coatings, increasing resistance between structure and soil.

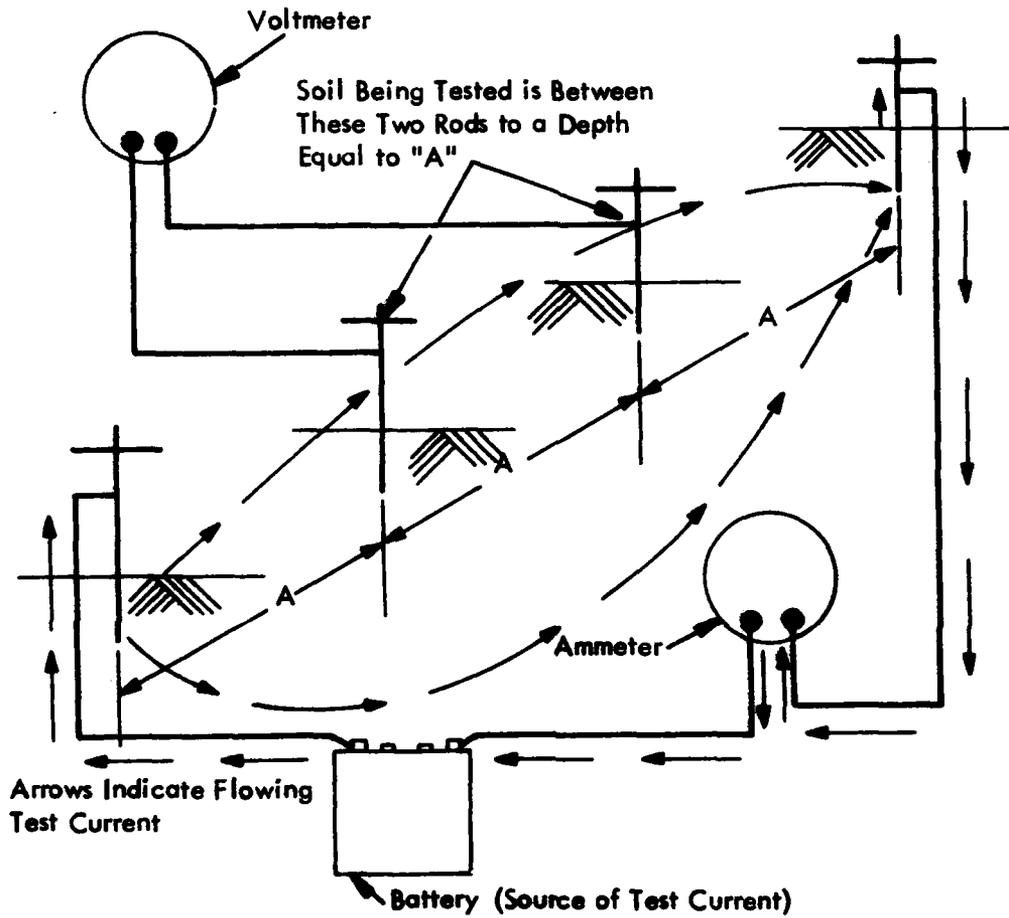
d. Resistivity of Environment. Electrolyte resistivity plays a big part in corrosion rate. However, no single test is an absolute determination of corrosivity. Variations in electrolyte resistivity are often critical. For design of cathodic protection systems, a knowledge of resistivity values in a given area is valuable in locating groundbeds and providing information on current distribution. Resistivity data are also valuable in design of electrical grounding systems. Resistivity data combined with other factors can indicate a potentially corrosive situation. In general, low-resistivity areas are more conducive to corrosion than high-resistivity areas. However, low-resistivity areas are advantageously used in design of groundbeds or galvanic anode placement for cathodic protection systems.

Common methods of measuring resistivity are given below. The voltage drop principle is used to determine soil and water resistivity.

(1) Wenner Four-Pin Method. In this method, soil resistivity is determined by passing a known amount of current through soil and determining the voltage change produced. Four equally spaced rods in straight line configuration are pushed into the earth (Figure 13). Current is passed between the two outer electrodes, and the resulting voltage drop is measured between the two inner electrodes. Assuming that the depth to which pins penetrate soil is small with respect to the spacing between electrodes (which is usually the case), average soil resistivity measured to a depth of "A" is given in ohm-centimeters by the following formula:

Soil Resistivity
(in Ohm-centimeters)

Change in Voltage
Due to Test Current \div Test Current x A (in Feet) x 191.0



Note: Soil resistivity measurement instruments usually include a power source and read directly in ohms.

Figure 13
SOIL RESISTIVITY MEASUREMENT

$$\rho = 2\pi AR$$

From U.S. Bureau of Standards Bulletin No. 258 entitled, "A Method of Measuring Earth Resistivity", by Dr. F. Wenner.

where --

- ρ = average resistivity of soil, ohm-centimeters
- A = distance between electrodes, centimeters
- R = resistance between the two potential electrodes, ohms.

Substituting simplifying relations:

$$R = E/I$$
$$2\pi A = 191.5 D$$

where

- E = measured voltage, volts
- I = current, amperes
- D = distance between electrodes in feet,

so that

$$\rho = 191.5 AE/I$$

By increasing spacing (A), average soil resistivity can be measured to any depth. In practice, soil resistivity measurements usually exceed structure depth by several feet in order to establish general soil conditions. The depth to which pins penetrate soil need be only a few inches so long as moist soil is contacted. For accuracy of measurement, pin depth must be small compared to pin separation.

Soil included between the two inner rods to a depth equal to their spacing is that which is actually measured. Any buried structures in this region will affect results, and care should be taken to keep rods clear of them. The two inside (voltage) rods or electrodes should be kept away from buried structures to a distance of at least one-half the rod spacing. If buried structures are located between these rods, they are included in the measured voltage drop and will lower the computed value of soil resistance. It is good practice to place the electrodes in a straight line perpendicular to buried structures such as pipelines or cables.

The 4-pin soil resistivity measurement is especially accurate because it eliminates soil-to-probe contact resistance. Two-probe methods of measurement, although simpler and often useful, are less accurate because contact resistance is not considered.

(a) Specialized Instruments. In addition to the direct current method using independent D.C. source and voltmeter (illustrated in Figure 13), specialized instruments are available for resistivity measurements. These supply either alternating current or pulsed direct current, and are self-contained 4-terminal instruments. The method of measurement, illustrated in Figure 14, is basically the same as that described in paragraph 1.2.1.(d)(1).

Two terminals supply alternating or pulsed direct current for test purposes. The other two terminals are used to measure IR drop in soil. The current terminals are connected to the two outer pins, C₁ and C₂, and the potential terminals are connected to the two inner pins, P₁ and P₂. The instrument (paragraph 2.2.8) is actuated by pressing a switch button which causes current to flow through the soil. The galvanometer is adjusted to read zero by means of a potentiometer calibrated to read directly in ohms. Therefore, it is necessary only to multiply the instrument reading by 191.5 times the pin spacing in feet to obtain resistivity in ohm-centimeters.

These instruments are particularly useful in stray current areas. Alternating or pulsed direct current minimize effects of stray current on resistivity readings.

(2) Two-Probe Method. This method employs two soil contacts spaced a few inches apart with an instrument that indicates average soil resistivity directly in ohm-centimeters, but only to a depth of approximately 8 inches below the steel probe points. This two-probe measuring device is commonly referred to as "Shepard Canes" (named for the inventor). The probes can be used in inaccessible places or where a large number of measurements are to be made in a short time on the surface of the earth (as in existing excavations). The measurements can be made only in soils which will allow penetration of probes (approximately 1/2 inch in diameter). Where firm earth which will not allow penetration of probes is encountered, small holes may be drilled to the desired depth, and the probes then inserted. For meter arrangement and probes, see Figure 15.

Inaccuracies are encountered with this method because voltage is measured across the same contact resistance through which applied current passes. As a result, probe contact resistance is included as a portion of total measured resistance. Therefore, readings will be larger than actual resistance of the soil under test. Also, since the contacts are so close together, a soil sample truly representative of the particular area is difficult to obtain. However, this test method is useful for field measurement of water, resistance and soil which may come in direct contact with a buried structure (in a ditch-bottom, etc.).

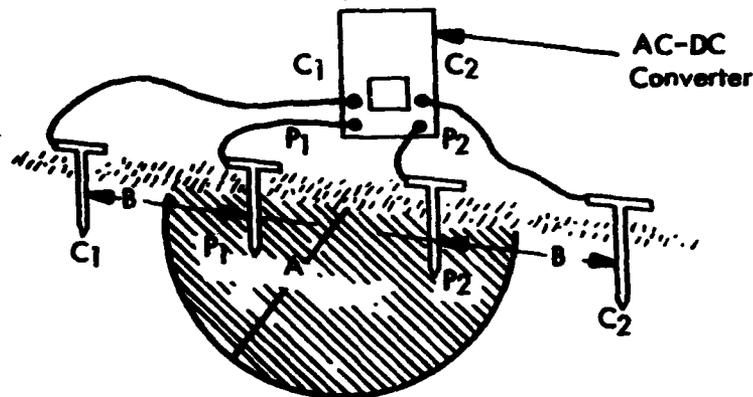


Figure 14

SOIL RESISTIVITY: FOUR-PIN ALTERNATING CURRENT METHOD

(3) Soil-Rod Method. This method is similar to the two-probe method, except both terminals are located in the same rod (Figure 16). One terminal is the small metal tip, insulated from the rest of the rod; the other, the rod's main shank. This is driven into the ground to the desired depth, and resistance of soil at the probe tip is measured with a resistance-measuring device. This may read resistivity directly in ohm-centimeters or may read in ohms and require multiplication by a conversion factor. The instrument uses an AC bridge or other AC measuring circuit to eliminate polarization and stray current effects.

As with other two-terminal devices, contact resistance can introduce inaccuracies. Also, only a small volume of soil is measured. Therefore, it is difficult to obtain good values for average soil resistivity with this instrument.

e. pH of Environment. Acidity or alkalinity of an electrolyte can affect its corrosivity. pH is an indication of these quantities and is often measured in field or laboratory to help determine corrosivity.

One method, which can be used at the site, employs an antimony half-cell. This metal's half-cell potential varies with pH of the electrolyte it contacts. Therefore, measurements of potential between antimony half-cell and reference electrode (usually copper-copper sulfate) can be converted to pH (Figure 17).

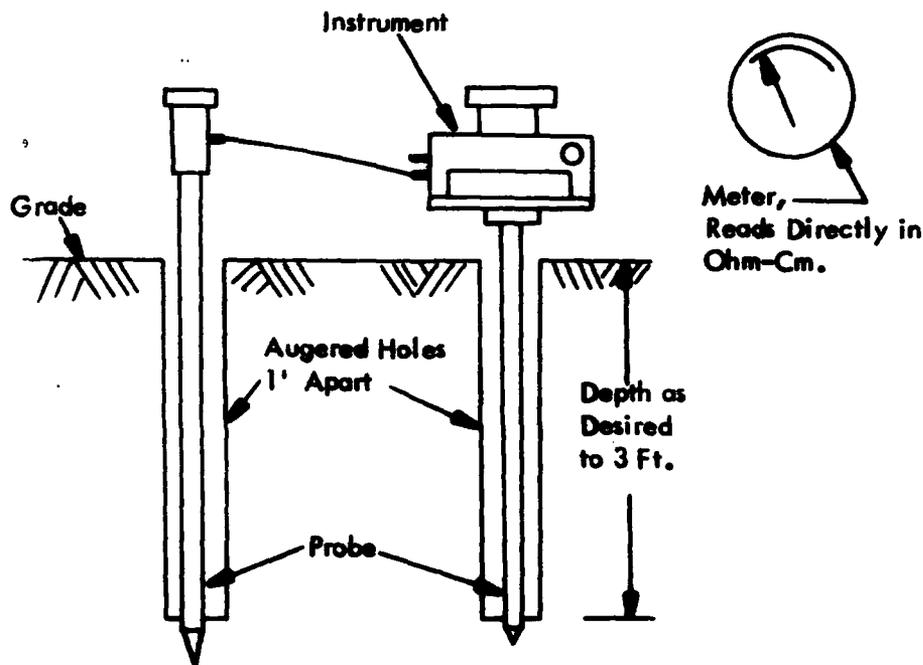


Figure 15
SOIL RESISTIVITY: TWO-PROBE METHOD

Currents flowing in the earth (from cathodic protection systems or stray currents) interfere with true measurement of pH in this manner. Such areas should be avoided. Also, the two electrodes should be placed close together to obtain best results. Care should be taken with antimony electrodes, because this metal shatters easily. In addition, if copper sulfate contacts antimony, copper will plate out on the metal surface, interfering with accuracy.

Other methods of measuring pH commonly used in the laboratory, such as sensitized paper or electrometric analysis, may be employed in the field. These methods are discussed under "Laboratory Tests", paragraph 1.3.1.a.

f. Redox Potential. Redox potential (oxidation-reduction potential) measurements in an electrolyte may be used to give an indication of anaerobic bacterial corrosion. This test is still somewhat experimental and presently not in common use. Potential is measured to an inert metal surface such as platinum, using a calomel half-cell as reference electrode. pH values are taken in conjunction with redox potential. This test does not observe or count bacteria; it merely indicates whether or not the electrolyte tested is favorable to development of anaerobic bacteria (*Sporovibris desulfuricans*). These bacteria reduce sulfate

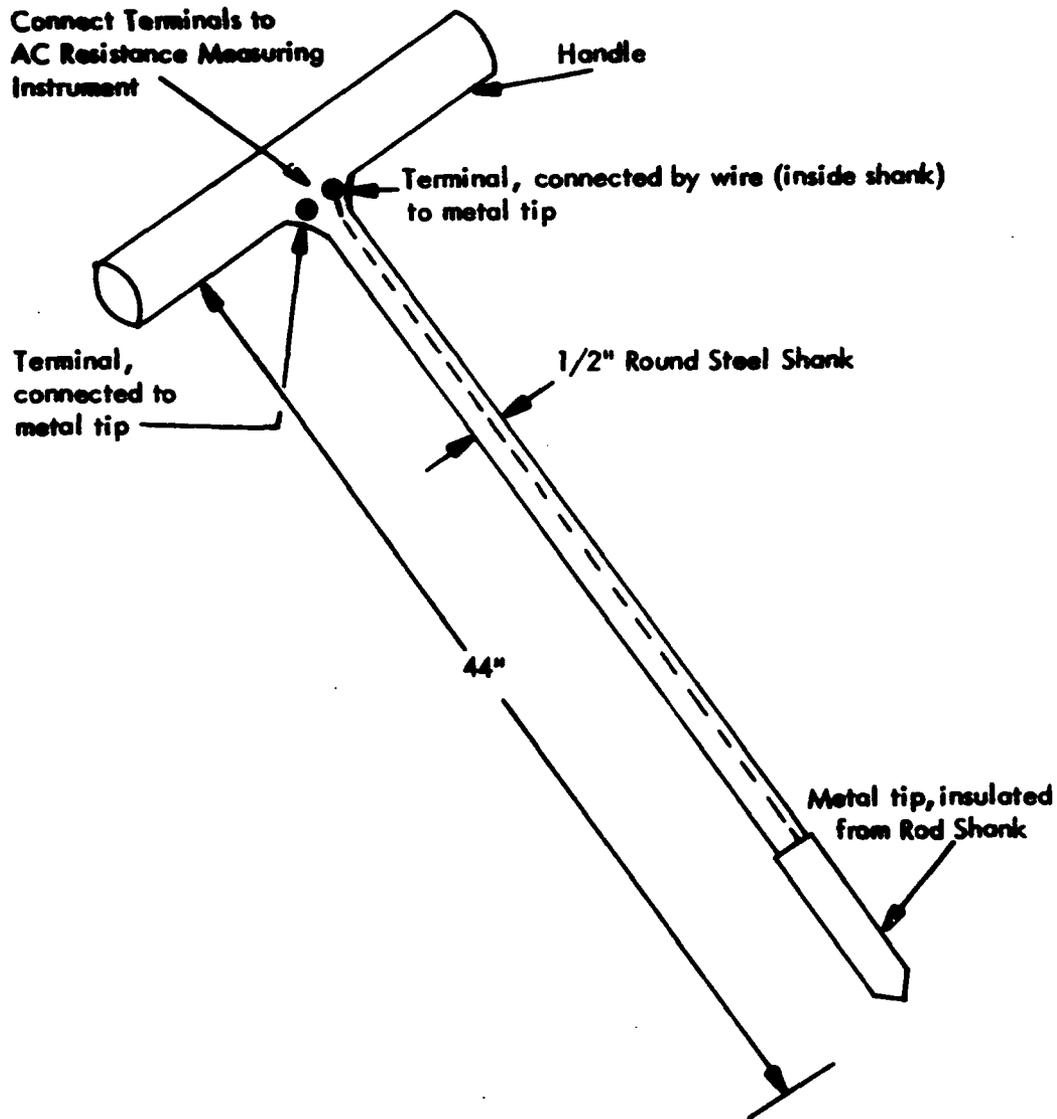
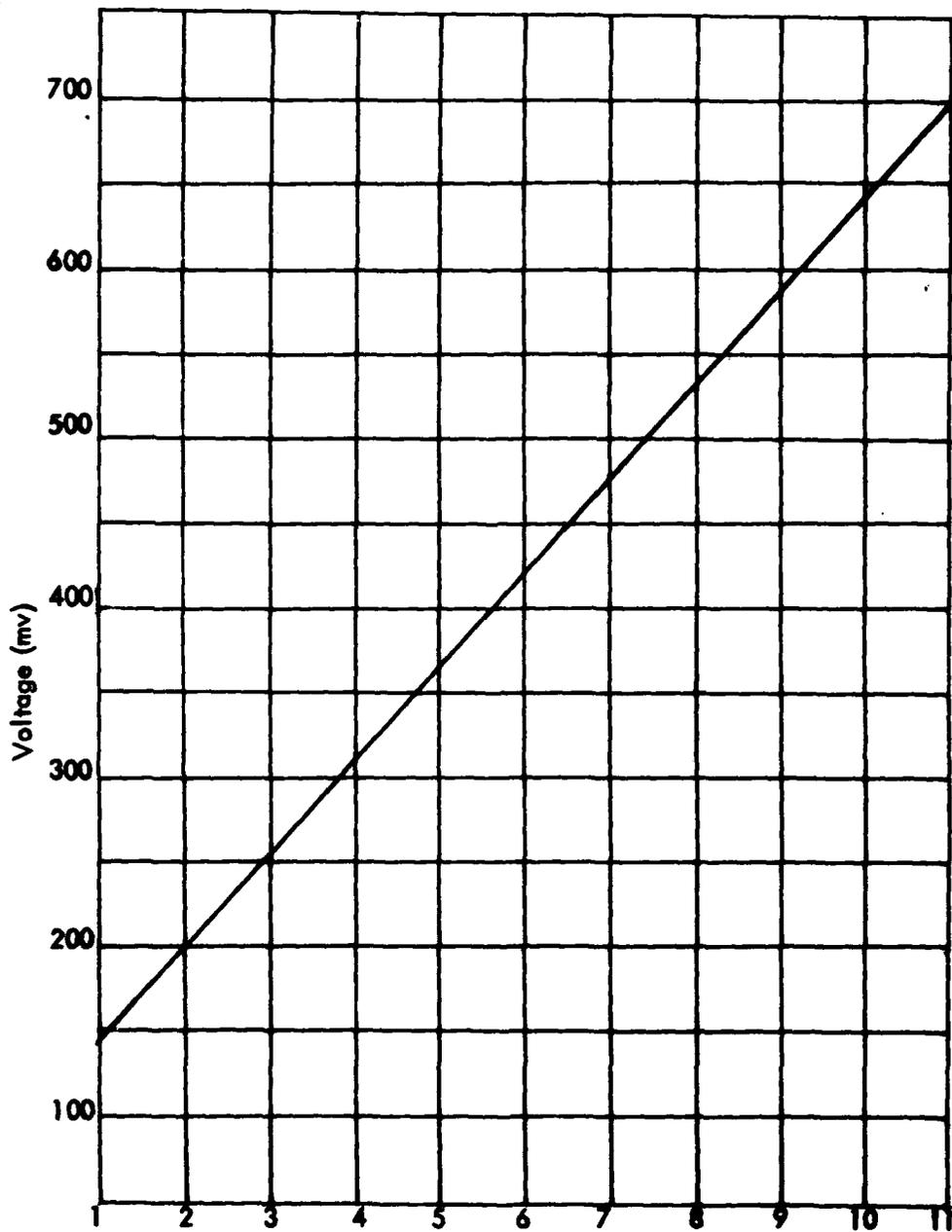


Figure 16
TYPICAL SINGLE-PROBE RESISTIVITY MEASURING DEVICE



pH
Figure 17
VOLTAGE VS. pH FOR ANTIMONY COPPER-COPPER SULFATE CELL

compounds where little or no oxygen is present. They are most often found in environments of near neutral pH (5.5 to 8.5) and low redox potentials (below 100 to 200 millivolts).

For measuring these quantities, a soil probe has been developed. It uses glass and calomel electrodes to determine pH and platinum electrodes for measuring redox potentials. These instruments, however, are expensive and fragile. Generally, simple laboratory measurements of pH and sulfide content (paragraph 1.3.1.b) are used to detect bacteria.

g. Testing Rectifier Efficiency. Rectifiers are the most commonly - used power source for impressed current cathodic protection. One type rectifier, the most common one contains selenium stacks. These stacks age, causing a loss of conversion efficiency from AC to DC power. Selenium rectifier efficiency should be tested regularly, usually once or twice a year. A decrease in efficiency of 20% or greater generally indicates stack replacement is needed.

Rectifier efficiency is calculated by determining the AC input power and the DC output power, and using the relation:

$$\text{efficiency (\%)} = \frac{\text{DC power}}{\text{AC power}} \times 100$$

AC input power is found with a watt-hour meter, substituting into the equation:

$$\text{AC power} = \frac{3600 KN}{T}$$

where

K = meter constant
N = number of disc revolutions
T = time (seconds)

The time interval for testing should be at least sixty seconds, for an accurate measurement.

DC power equals DC voltage in volts multiplied by DC current in amperes. These values may be obtained directly from the rectifier meter(s). If meter accuracy is doubtful, they may be checked using the rectifier shunt.

1.2.2 Surveys. Prior to a corrosion survey, the corrosion engineer must decide which measurements will best describe conditions on the buried or submerged structure. He may determine this from his own past experience, from experience of others operating in the same area, or from available leak or failure history of the structure. A cursory check, prior to more detailed study, can often give some idea of conditions such as galvanic corrosion cells,

stray current and cathodic interference, or bacterial activity. The projected survey can then be tailored to include proper measurements.

After survey data have been studied and protective or mitigative measures designed and installed, further surveys are necessary to determine effectiveness of work done. Measurements included in this field work depend upon what type installations have been employed.

Recording data accurately and neatly is an important part of any survey. Data should be entered in a permanent record arranged systematically for easy reference. A structure history, required by law, reveals changing conditions (soil makeup, coating deterioration, etc.) that may affect corrosion behavior.

A checklist for underground corrosion surveys for both new (or under construction) structures and existing structures is given in Appendix D

a. Current Requirements. Current requirement tests are run to determine amount of current required for cathodic protection, need for dielectric insulation, spread of protection, feasibility of using magnesium anodes or impressed current groundbeds, and effects of protective current on other structures.

Basically, test current is impressed through a temporary groundbed and the effect on structure-to-soil voltages noted. This test is useful in the design of both impressed current and galvanic cathodic protection. Current must be impressed at the point where the rectifier or galvanic anode would be permanently located. A portable rectifier, generator, battery, or other D.C. current source and ammeter, is used to supply known current through a temporary groundbed (Figure 18). The temporary groundbed can be any handy piece of metal - a fence post, section of conduit, etc. - driven into the ground (or water). The metal must not contact the structure directly, and it cannot be receiving any cathodic protection itself. Also, its configuration and size should be roughly that of the anticipated permanent installation. Structure-to-electrolyte potentials are taken at various test points along the structure. It is not necessary to impress sufficient current to bring the structure to the desired level of protection, although test current should approximate actual conditions to avoid distorted readings. Results relate a unit of test current and the resultant structure-to-soil voltage. This is expressed in terms of millivolts change per ampere and is called a "coupling" or "electrical constant". Required current can then be calculated for the millivolt change desired. Results may indicate a change in point of current impression

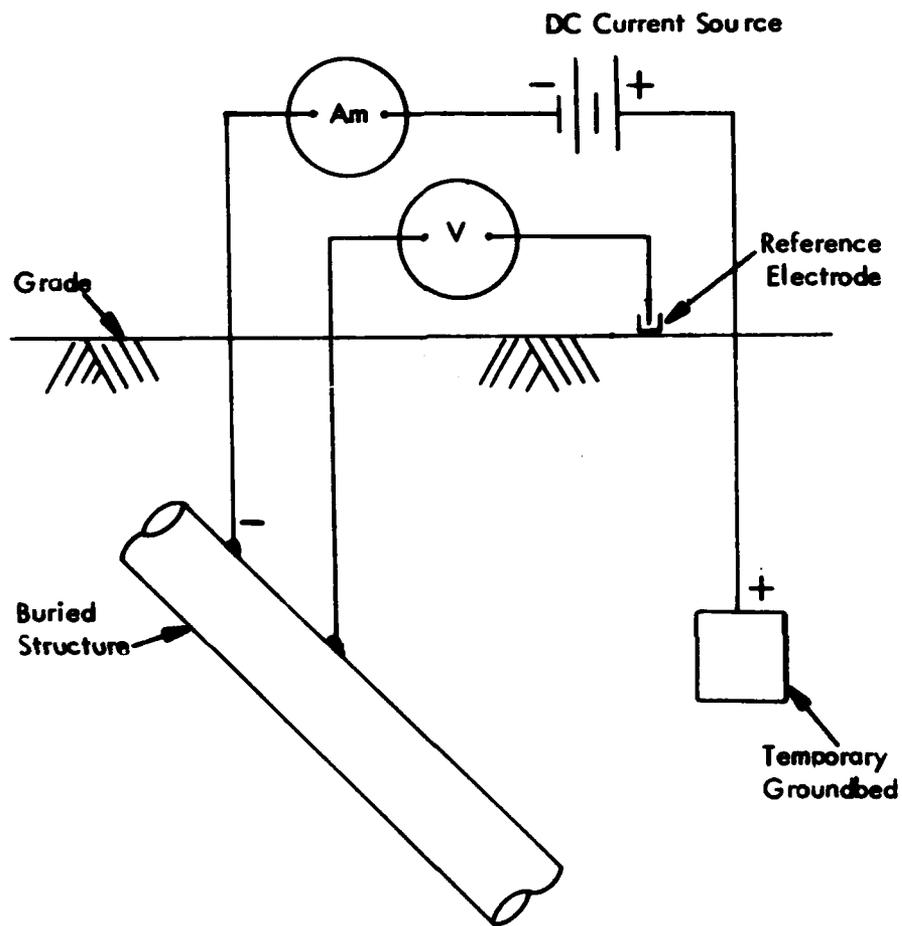


Figure 18
CURRENT REQUIREMENT MEASUREMENT

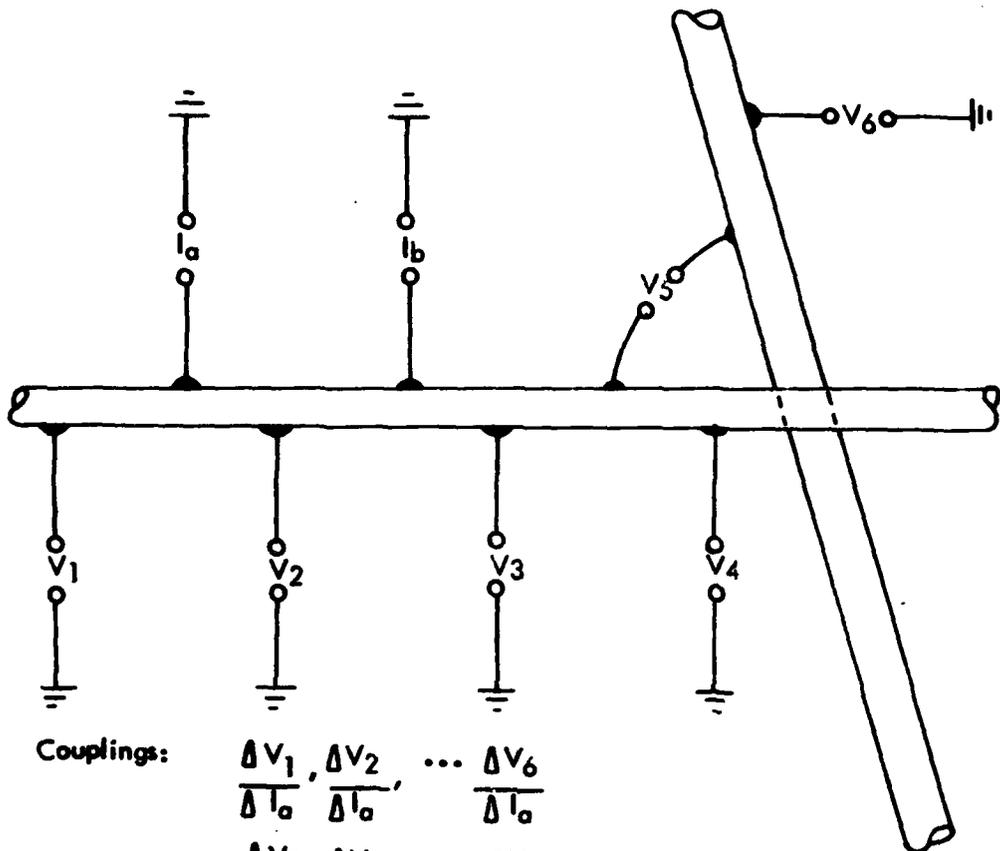
(impressed current or galvanic anode location). Figure 19 is an example of typical couplings for two anode locations (I_a and I_b). Test locations are for five structure-to-electrolyte potentials (V_1, V_2, V_3, V_4, V_6) and a foreign-line-crossing drainage bond (V_5). Resulting couplings indicate voltage changes at Locations 1 through 6 for a given current impressed at anode locations a and b. Each coupling is the millivolt per ampere change, based on one anode location and one test location. For example, $\Delta V_1/\Delta I_a$ is the coupling (or constant) for potential readings at location V_1 and anode location I_a . From these, a couplings and knowledge of the required ΔV at one point, the required ΔI is determined by ratio and proportion. This ΔI is then used to calculate resulting voltage changes at other test points, using the couplings for these points.

Current requirement tests provide only an approximation of real current needs. Many factors affect true requirements: polarization effects, groundbed resistance, anode locations, and others.

b. Interference Tests. Cathodic protection sometimes causes undesirable effects on structures not connected to the protection system. This occurs because some current is picked-up by these "foreign" structures at one point and, in attempting to return to the source, is discharged at another point. Corrosion occurs at the discharge point. Current can cause corrosion damage by passing between two structures or across high-resistance joints in the same structure. Railway signal systems can become inoperative if sufficient cathodic protection current flows on rails. These phenomena are called cathodic interference, discussed in detail in AFM 85-5.

Any cathodic protection system can cause cathodic interference. Impressed current systems are studied and discussed more often because they usually involve more current. Geometric location of anodes with respect to foreign structures is the most important single factor to consider. Bonds are often used to eliminate areas of current discharge. Jointly operated systems are also employed; here two or more companies interconnect their underground structures and jointly apply cathodic protection.

Testing requires cooperation by owners of structures involved. Such cooperation is best effected by a corrosion coordinating committee; all companies operating underground or underwater structures, and particularly those under cathodic protection, should be members of such a committee. A list of most existing committees may be obtained from the



Couplings: $\frac{\Delta V_1}{\Delta I_a}, \frac{\Delta V_2}{\Delta I_a}, \dots, \frac{\Delta V_6}{\Delta I_a}$
 $\frac{\Delta V_1}{\Delta I_b}, \frac{\Delta V_2}{\Delta I_b}, \dots, \frac{\Delta V_6}{\Delta I_b}$

Figure 19
 COUPLINGS DETERMINED IN CURRENT REQUIREMENT TESTS

National Association of Corrosion Engineers, Houston, Texas. Tests must be made on all structures adjacent to a cathodic protection system to determine effects and design mitigation.

Cathodic interference can be detected by measuring structure-to-soil potentials and current flow (IR drop) with cathodic protection on and off. (Changes are noted.) Structure-to-soil potentials will give indications only when measured in an area of current discharge or pick-up. Current flow (IR drop) readings will indicate in between pick-up and discharge areas where structure-to-soil potential would show nothing. Figure 20 illustrates this.

Pipe-to-soil potential and current flow are measured at many locations before the cathodic protection system is turned on. Then measurements are repeated at exactly the same points with the system operating. The algebraic difference between "on" and "off" readings gives the effect of cathodic protection. The location showing greatest pipe-to-soil potential change in the positive direction is called the "critical" or "control" point. This is often at the point where protected and unprotected pipes cross. Mitigation can usually be accomplished by installing a bond between the unprotected structure (at location of natural discharge) and protected structure (as close as possible to the negative connection). Method of calculating bond resistance (to obtain proper current drainage) is covered in AFM 85-5.

Another method of interference testing uses an experimental drainage bond between structures. Proper drainage can be determined by trial-and-error using a variable resistor to alter drainage current. Required drainage current can also be computed from test data. The form shown in Figure 21 is useful for this.

When conducting current requirement tests and/or initially energizing impressed current cathodic protection, all companies owning underground structures in the area should be notified and coordination tests made with those interested. Current drainage requirements for each structure, from tests at various anode locations, can be determined.

c. Fluctuating Stray Current Survey. While interference testing determines effects of steady stray currents, another type stray current survey analyzes fluctuating stray currents. Such analysis is specialized and requires study to master all techniques.

All the basic measurements can be used in studying fluctuating stray currents. Perhaps the most informative are measurements similar to those used in interference testing: structure-to-electrolyte potentials and IR drops along

Pipe-to-Soil Voltage (V) Indicates Pick-up and Discharge, IR Drop Indicates Current Flow

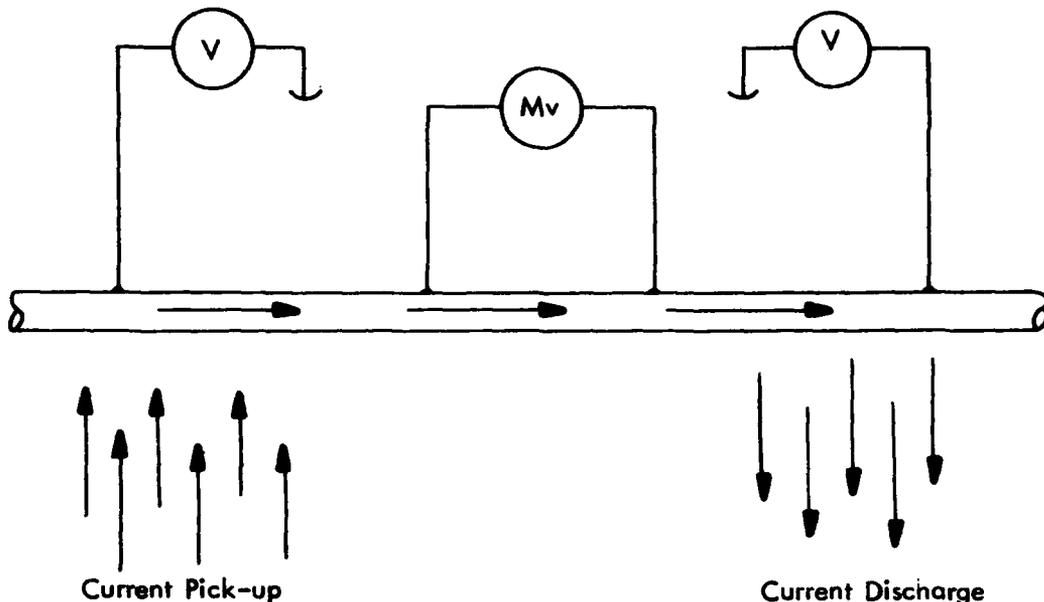


Figure 20
STRAY CURRENT FIELD MEASUREMENT

structure or electrolyte. Methods of analysis, however, are different and specialized equipment is used. The major concern in performing a stray current survey is to ascertain degree of damage and determine source of currents.

Fluctuating or periodic changes in structure-to-electrolyte voltage values and unusual or fluctuating currents are indicative of stray currents. Stray currents may affect structures just as cathodic protection does. Structures may be protected or damaged by stray currents depending upon whether current is flowing to or from the structure.

In order to determine pick-up and discharge points in fluctuating stray current areas, correlation curves are plotted (Figure 22). Values of structure-to-electrolyte potential are plotted against current flow along the structure (calculated from IR drop), (graphs "A" through "E", Figure 22). In addition, current flow at different locations on the same structures are calculated (graphs "A-C" and "C-E"). Where foreign structures are nearby, structure-to-electrolyte

INTERFERENCE TESTS

Structure _____

Date _____

Rectifier Location _____ Rectifier Output _____ Volts _____ Amps

Tests for Determination of Exposure:

Location of Tests _____

- A. Structure to Cu-CuSO₄ - Rectifier On (volts) _____
- B. Structure to Cu-CuSO₄ - Rectifier Off (volts) _____
- C. Voltage between Structures - Rectifier On (volts) _____
- D. Voltage between Structures - Rectifier Off (volts) _____

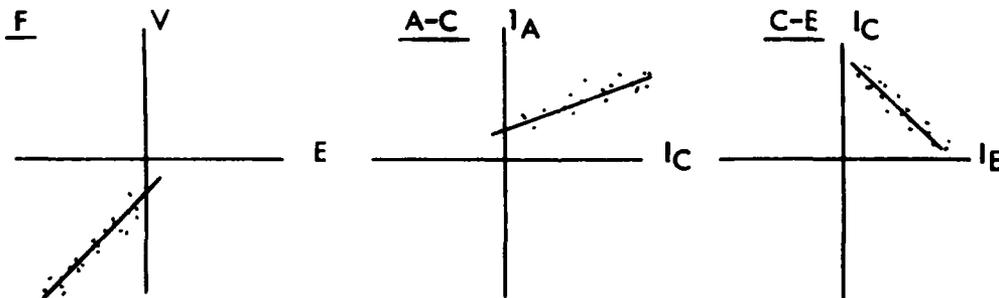
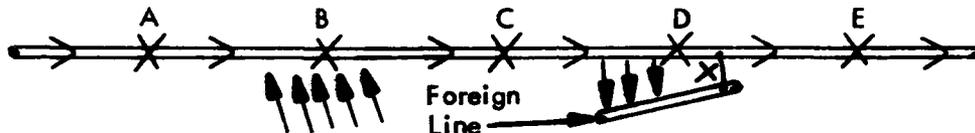
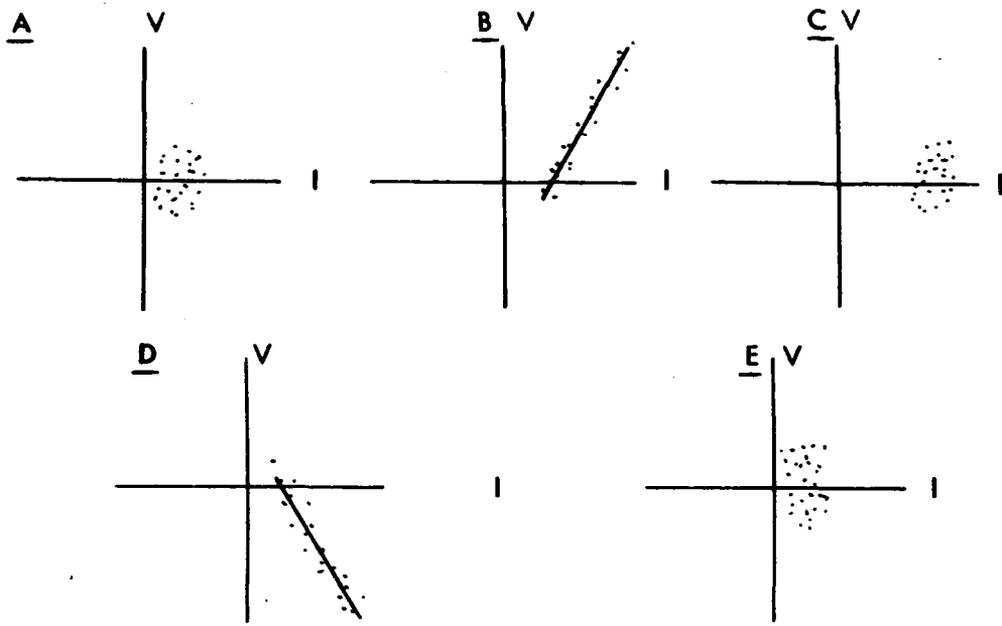
Tests for Determination of Required Drainage Current:
(Using experimental drainage bond between structures)

Location of Experimental Test Drain _____

- E. Current drainage through test drain with rectifier operating (amperes) _____
- F. Structure to Cu-CuSO₄ with test drain connected and rectifier operating (volts) _____
- G. Voltage between structures with test drain connected and rectifier operating (volts) _____
- H. Voltage between structures with test drain connected and rectifier not operating (volts) _____
- I. Volts reduced (F-A) _____
- J. Volts Reduction per ampere $\frac{I}{E}$ _____
- K. REQUIRED DRAINAGE CURRENT in Amperes $\frac{(A-E)}{J}$ _____

Figure 21

RECORD SHEET FOR INTERFERENCE TESTS



V = Structure-to-Soil Potential
 I = Current Flow Along Structure
 E = Voltage Between Structures
 → = Current Flow

Figure 22
CORRELATION CURVES

potentials vs. voltage between structures are related (graph "F"). For each graph, at least 20 to 30 readings are required to provide good correlation. Radio communications may be required, because readings must be simultaneous. So-called "X-Y recorders" can also be used to advantage; these record and plot readings simultaneously. They are also helpful when measurements are desired for long periods of time (say 24 hours). The most effective way to use a recording voltmeter ("X-Y recorder") is to select a location where corrosion has been experienced or an area where stray currents are suspected. Meter range selected should be high enough to assure that voltages to be recorded will remain on the chart and yet be sensitive enough to indicate small voltage variations. The meter should be sheltered from weather and located where it will be free from shock and excessive vibrations. Reliable connections are important and should not be tampered with during recording. Before recording is begun, the meter should be checked for accuracy by comparing readings with another voltmeter, the indicator arm should be adjusted to zero on the chart, and the date should be recorded on the chart. The meter should be turned on to make sure it is recording properly. No special attention is required other than an occasional check to assure the instrument is performing satisfactorily. Charts for recording voltmeters should show the voltage tap used, dates installed and removed, location of test, and any other pertinent data.

d. Continuity. Effective cathodic protection and control of stray or interference currents in an underground structure requires that the structure be metallically continuous to provide a low-resistance path for current to flow. It is often necessary, therefore, to locate and bond nonconducting or high-resistance joints before installing cathodic protection. Such joints are located relatively simply, but the procedure is time-consuming.

(1) Direct Current Method. Direct current voltage is applied to the structure or portion of structure in question causing current to flow in a given direction between two fixed points. A series of voltage drop measurements are taken along the structure to detect any abnormal voltage changes. Where only one insulating joint exists between points of current application, a pronounced voltage change will be observed. Where several high-resistance connections exist, the effect will be less pronounced but usually detectable. Should there be no such joints, a nearly uniform potential drop between the two points of current application will result (assuming the structure to be of uniform size).

A simple, but not positive method of detecting discontinuities in a pipe not uniform in size is by measuring structure-to-electrolyte potential directly above the structure at equal intervals. If soil resistivity and depth of burial are uniform, the structure-to-electrolyte potential will vary uniformly from one end of the section under test to the

other end, except where there are variations in structure conductance. Lack of uniform readings indicates poor continuity or insulating joints. A plot of readings can be helpful, because variations in slope are readily detectable.

If soil resistivity and burial depth are not uniform, a study of IR drop in the structure will give better results. One terminal is connected to a fixed point on the line and the other, successively to equal distances along the line with a contact bar (Figure 23). Again a plot of readings should be made so that irregularities in the curve can be observed and studied. The IR drop method, while slow and tedious, is almost completely independent of outside factors and generally locates all high-resistance and insulating joints with reasonable accuracy. Sometimes a detailed study is required to fully establish location and number of discontinuities.

(2) Alternating Current Method. An alternating current method of testing insulating joints aboveground has proven quite reliable. This method consists of impressing an alternating current voltage across an insulating joint and detecting current flow using a clamp-on device. If the insulating joint is defective, current will flow, and a reading will be noted on a detector meter. If the insulating joint is good, little reading will be noted on the detector meter. The test set consists of a battery which activates a vibrator to convert direct current to alternating current for test purposes. Voltage is stepped up through a transformer and connected to the structure by means of two clamps. A split core armature with wound coil on one end works on the induction principle to detect any current flowing on the structure. The output of the detector coil is connected to a vacuum tube voltmeter or a similar indicating device. This type instrument has high-input impedance, on the order of several million ohms, which requires very little energy for operation. The instrument is capable of detecting leaky as well as defective insulating joints.

e. Coating Conductance. Coating conductance (leakage conductance) of a pipe line is a measure of coating integrity; the greater the conductance, the poorer the coating. Conductance is inverse of resistance and is usually expressed in micromhos per foot. For comparisons on an area basis, the most common unit is micromhos per square foot. An accepted procedure for making coating leakage conductance surveys has been established by the National Association of Corrosion Engineers in their Procedure: NACE 2D157. This method, summarized here, consists of impressing direct current through the coating, measuring voltage drop produced, and calculating conductivity from Ohm's Law and the relationship between conductivity and resistance.

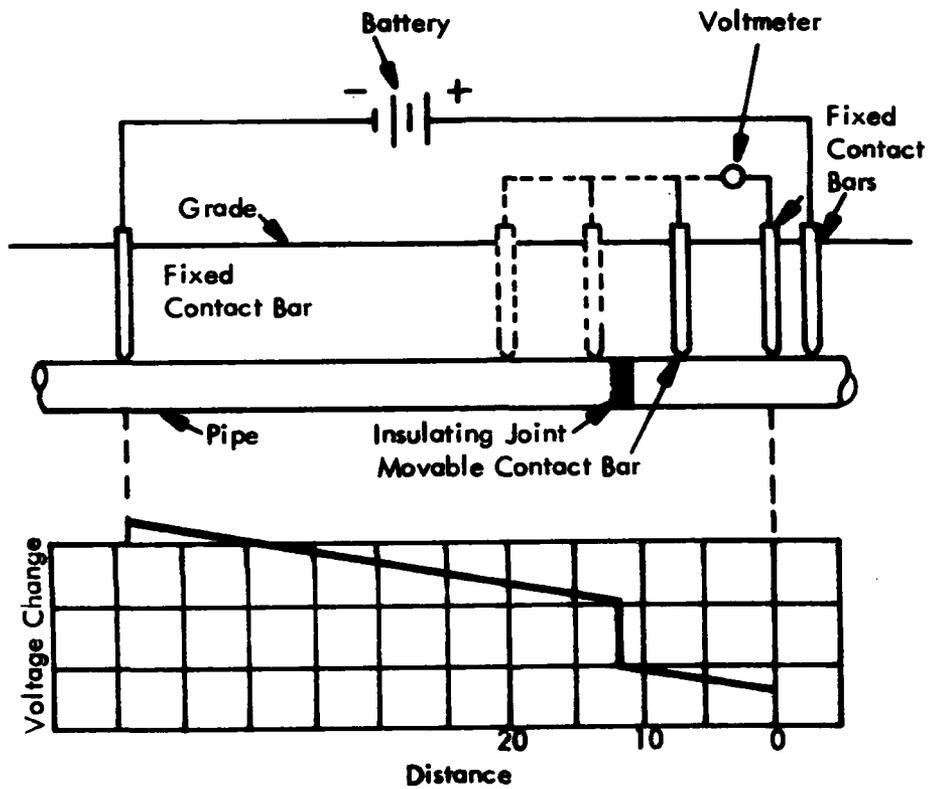


Figure 23
 LOCATING HIGH-RESISTANCE JOINTS IN UNDERGROUND PIPING

A temporary groundbed and D.C. voltage supply are connected to the pipe to be measured; an ammeter for measuring current is included in the circuit. The groundbed should be located 400 feet from the beginning of the pipe section under test. A test current of 2-10 amperes is required. This current is interrupted, and the change in current (ΔI , in amperes) is noted. The corresponding change in pipe-to-soil potential to remote earth is determined at various points and averaged (ΔE , in volts).

Average leakage conductance (k in micromhos per foot) is given by $k = \frac{\Delta I \times 10^6}{\Delta E L}$ where L is the length in feet of the section under test. The section between test stations shall have no electrically connected laterals. Lines to be tested are classified as long or short and different techniques are required for each.

Careful interpretation of field data is very important. Coating conductance is affected by:

- (a) Physical properties and condition of coating
- (b) Conductivity of surrounding soil
- (c) Contact resistance between pipe and soil
- (d) Casings.

(1) Short Line Method. A short line is defined for this discussion as an electrically isolated section of line. Test procedure is shown schematically in Figure 24. If the pipe is not of uniform nominal size and weight, it should be treated as a long line and measured in sections. If this is not possible, the various pipe sizes and locations should be noted in the results.

To determine coating leakage conductance, equipment is set-up as in Figure 24. The direct current source is turned on and current measured with the ammeter in the anode circuit; remote pipe-to-soil potentials are noted at the two test locations. Test current is interrupted, and the change in current (ΔI) and pipe-to-soil voltages (ΔE_1 and ΔE_2) are determined.

If the ratio $\Delta E_1/\Delta E_2$ is greater than 1.6, multiply ΔE_2 by the appropriate factor from Table 2. The factor can be applied to ratios less than 1.6, but the error without the factor is less than 10%. If the ratio $\Delta E_1/\Delta E_2$ exceeds 3.0, measure the line in sections by the long line method. Average coating leakage for the section tested is found from:

$$k = \frac{\Delta I \times 10^6}{\Delta E \text{ ave. } L} \quad (\text{micromhos per foot})$$

where $\Delta E \text{ ave.} = \frac{(\Delta E_1 + \Delta E_2)}{2}$

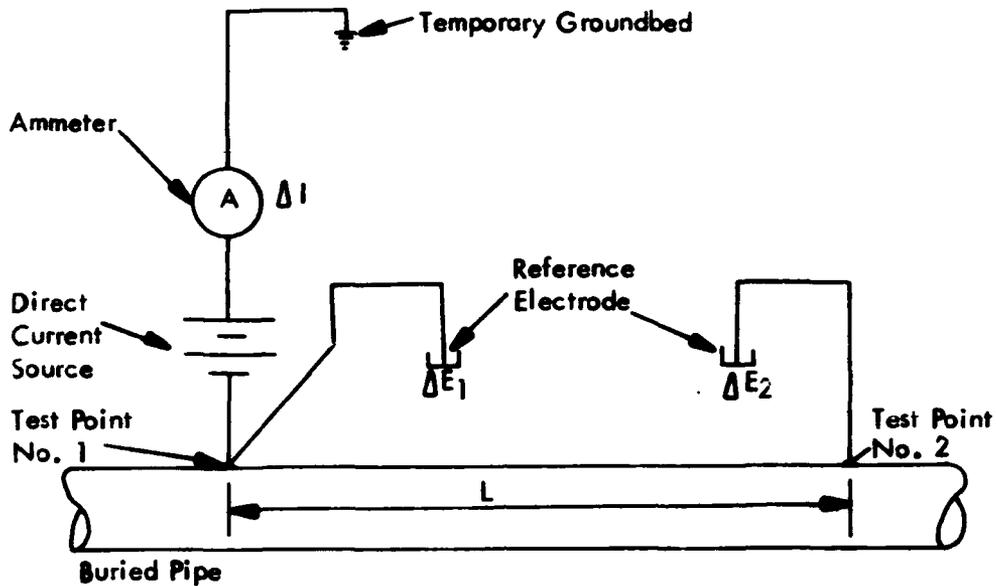


Figure 24
COATING CONDUCTANCE MEASUREMENT: SHORT LINE

Table 2

Correction Factor for Coating Conductance Calculations

$\frac{\Delta E_1}{\Delta E_2}$	Factor	$\frac{\Delta E_1}{\Delta E_2}$	Factor
1.0	1.000	2.1	1.345
1.1	1.032	2.2	1.375
1.2	1.066	2.3	1.404
1.3	1.099	2.4	1.433
1.4	1.130	2.5	1.461
1.5	1.163	2.6	1.492
1.6	1.193	2.7	1.520
1.7	1.224	2.8	1.548
1.8	1.254	2.9	1.576
1.9	1.286	3.0	1.604
2.0	1.315		

(2) Long Line Method. When conditions for the short line method are not met, the line must be measured in sections as shown in Figure 25. Each section should be of uniform nominal pipe size and weight. There is no set length for these sections, but the following is a guide:

(a) Maximum length is that at which the ratio $\Delta E_1/\Delta E_2$ equals 3.

(b) Minimum length is that at which the difference between ΔI_1 and ΔI_2 is 5 ma.

Test current is applied as for the Short Line method, with the temporary grounded 400 feet away from the test section. If the starting point is not at an insulating joint, this separation may be obtained by distance along the line. The set-up is as shown in Figure 25. The direct current source is turned on and current is measured at the two test points by the IR drop method. Contact to pipe should be made with leads attached to the pipe rather than with probe bars. If the near end of the section terminates in an insulated joint or dead end, current may be measured with an ammeter in the anode circuit. Remote pipe-to-soil potentials are noted at the two test points also. The test current is then interrupted and the change in current at the near and far points (ΔI_1 and ΔI_2) and the change in pipe-to-soil potentials at these points (ΔE_1 and ΔE_2) are determined. If the ratio $\Delta E_1/\Delta E_2$ is greater than 1.6, ΔE_2 should be corrected as described in paragraph 6.1.2.2.e.(1). If the ratio $\Delta E_1/\Delta E_2$ exceeds 3.0, the test section should be shortened. Coating leakage conductance is calculated from the equation:

$$k = \frac{(\Delta I_1 - \Delta I_2) \times 10^6}{\Delta E \text{ ave. } L}$$

where

$$\Delta E_{\text{ave.}} = \frac{(\Delta E_1 + \Delta E_2)}{2}$$

f. Duct Slug Survey. A duct survey can be made by pulling a lead slug (reference electrode) through a vacant duct adjacent to ducts carrying cable. Instruments are connected between this electrode and the lead sheath of the adjacent cables as shown in Figure 26. Measurements of potential, current, and resistance are made at 10-foot intervals along a cable run between two adjacent manholes. The duct selected for the survey should be as near to the cables as possible and preferably one of the lower ducts so as to obtain the most severe conditions. The test electrode generally consists of a piece of lead-sheath cable approximately 12 inches long, fitted with two pulling eyes and test lead. The electrode must be as simple and rugged as possible. A small galvanic potential may exist between cable

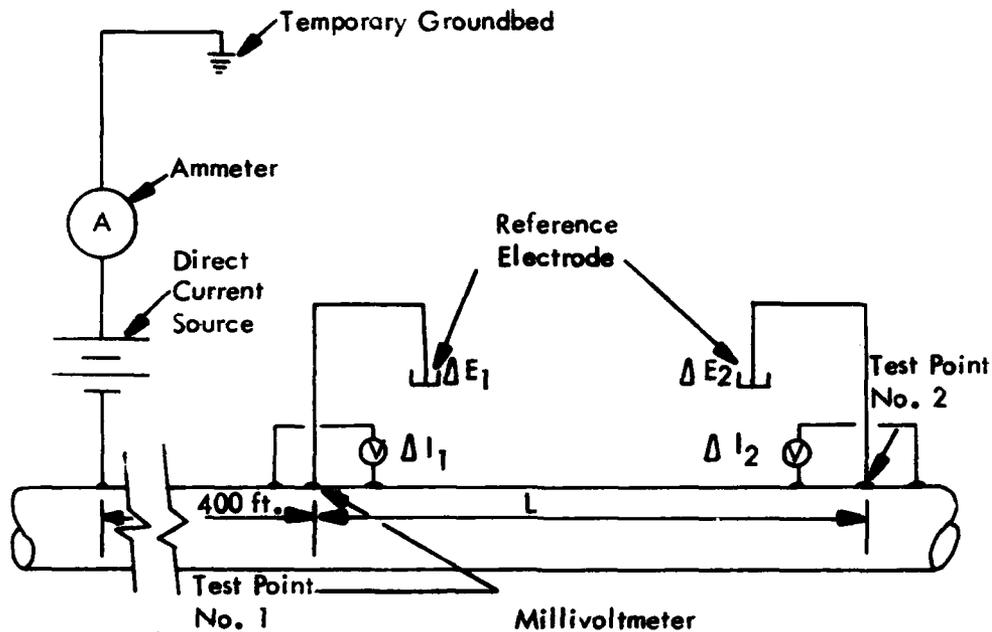


Figure 25
COATING CONDUCTANCE MEASUREMENT: LONG LINE

sheaths and test electrode, although the material in both is the same. This difference is usually negligible (0.01 volt or less) and does not seriously affect results. Potential between cable sheath and lead electrode is measured by the voltmeter connection shown in Figure 26. A potentiometer-voltmeter should be used so as to minimize errors due to electrode contact resistance.

The measurement is a close approximation of cable sheath potential with respect to electrolyte from point to point along the duct run. Cable sheath corrosion is proportional to magnitude and density of current discharge from cable sheath to electrolyte. This current can be estimated from point to point through the duct by connecting reference electrode to cable sheath through a resistance milliammeter. Milliammeter circuit resistance is relatively low, potential will be substantially that of the cable sheath. It may be assumed that current discharge per unit cable area at the test point is approximately the same as that measured through the electrode.

Current flowing from the cable sheath to slug is indicative of corrosion. Duct resistance is an essential factor in determining magnitude of current flow for any given potential. Resistance between the test electrode as one terminal and the adjacent cable sheath as the other is measured at

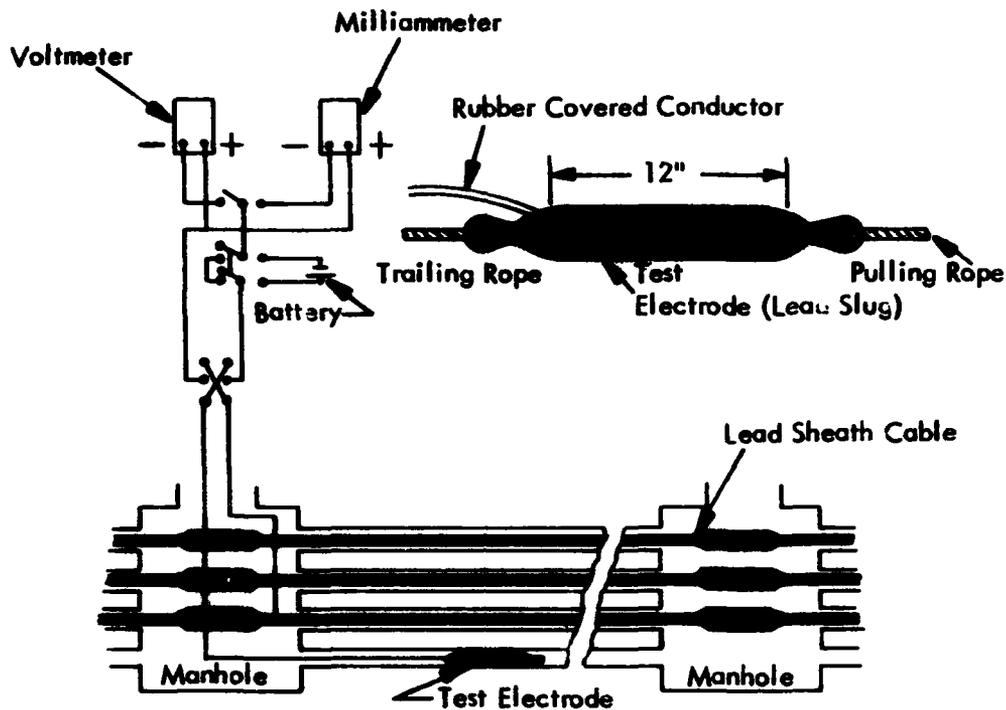


Figure 26
ELECTRICAL CONNECTIONS FOR DUCT SLUG TEST

each test point by connecting a low-voltage battery (1.5 volts dry cell) in series with a sensitive milliammeter (between cable sheath and test electrode). Resistance is computed from battery voltage and measured current. The milliammeter used for this purpose should have a sensitivity of approximately 0.05 milliamperes per division, and its resistance should not exceed 2 to 3 ohms. With suitable shunt resistance, the milliammeter range can be varied to any desired value. The same instrument can be used for both current and resistance measurements through switches, arranged as in Figure 19. Duct resistance as measured is mostly contact resistance between the surface electrode contacting the duct wall. It represents approximately the contact resistance per duct foot of cable when the duct is occupied.

1.3 Laboratory Tests. In addition to field tests, laboratory tests can yield information helpful to the corrosion engineer. Laboratory tests are run on electrolyte or electrode samples, collected in the field and sent to

the laboratory for investigation. Reasons for using laboratory tests instead of field tests, which often supply the same information, may be convenience or necessity. Many laboratory tests, such as most metallurgical analyses, require large and complicated equipment impossible or impractical to bring to the site.

1.3.1 Field-Related Tests. Some laboratory tests, particularly those run on soils, provide information similar to field tests. Such things as soil resistivity and pH, already discussed under field testing, can also be determined in the laboratory. Many of these soil or water tests use simple equipment which could easily be used at the site, as well as in the laboratory. Some important tests of this type are described here.

a. pH of Environment. Common tests for pH determination for small samples of soil or water are based on colorometric or electrometric analysis. In either method, samples of soil are analyzed by first mixing one tablespoon of soil in 15 milliliters of distilled water and filtering the resulting mixture. The pH of the resulting filtrate equals that of the soil sample.

In the colorometric method, the water sample or soil filtrate reacts with sensitized paper or liquid indicators, producing a color characteristic of the pH. Various indicators are available for different pH ranges and accuracies.

The electrometric method uses a pH meter which measures voltage across two electrodes contacting the water sample or soil filtrate. Typically a glass or antimony pH electrode and a calomel or silver-silver chloride reference electrode are used, often combined in a single assembly. The voltage measurement varies with solution pH, and the meter reads directly in units of pH. This is generally faster than color tests, but requires more expensive equipment.

b. Sulfide Content (Anaerobic Bacteria). A simple test for detecting possible presence of anaerobic bacteria is to apply a dilute solution of hydrochloric acid (15%) to corrosion product or to a soil sample near the structure. The familiar odor of hydrogen sulfide (smell of rotten eggs) can be detected if sulfides are present. Sulfides are generally found in soils only where anaerobic (sulfate-reducing) bacteria are present. Sulfides are a by-product of the life process of these bacteria.

c. Chloride Content. The Mohr method, based on differential precipitation of the chloride and chromate ions of silver, is used to determine chloride content of water. Silver nitrate is titrated into the test sample to which potassium chromate has been added as indicator. When all the chloride has precipitated, titration produces a red color due to precipitating silver chromate. This indicates the end point. If presence of sulfites (which can interfere

with test accuracy) are suspected, the test sample is first pretreated with hydrogen peroxide. The amount of chloride present is then calculated from the known amount and concentration of silver nitrate added.

d. Soil (Box) - Resistivity of Environment. Resistivity of a sample of soil or water may be measured by a four-terminal soil box as shown in Figure 27. A direct current source is connected to the current terminals, and a voltmeter is connected to the potential terminals. Measured current is passed through the sample, and the resulting voltage drop is read across the potential pins. Box dimensions are such that no multiplying factor is required to determine resistivity. Potential change in millivolts, divided by current in milliamperes, gives resistance in ohms, which for the soil box is numerically equal to resistivity in ohm-centimeters.

The measurement should be made as quickly as possible after current is turned on to minimize polarization of soil box electrodes. The soil box can be used with a four-terminal alternating current soil resistivity meter to eliminate polarization effects.

Resistivity readings taken at the site using methods discussed in paragraph 1.2.1.d are generally preferred over soil box measurements. Soil removed from the site and tamped into a soil box may take on different characteristics of compaction, moisture and so on. However, where field measurements are impossible or impractical, the soil box can be used.

For determining water resistivity, the soil box is most practical. Also, since water is relatively homogeneous, soil box readings for water samples are generally very accurate.

1.3.2 Sulfate Content. Sulfates in soil or water can destroy concrete, corroding this material and substituting voluminous corrosion products (gypsum - and calcium-sulphoaluminate hydrate crystals) for the initial mix. The pores and voids of concrete become filled with these materials which grow and expand producing internal stresses and destruction.

Sulfates in soil or water can be detected by several methods. Turbidimetric methods are generally used to determine concentrations less than 100 ppm. These are based on precipitation of barium sulfate from the acidified, stabilized test sample. The stabilizer results in a stable suspension of uniform size particles. Turbidity is then measured photometrically, results indicating barium sulfate concentration.

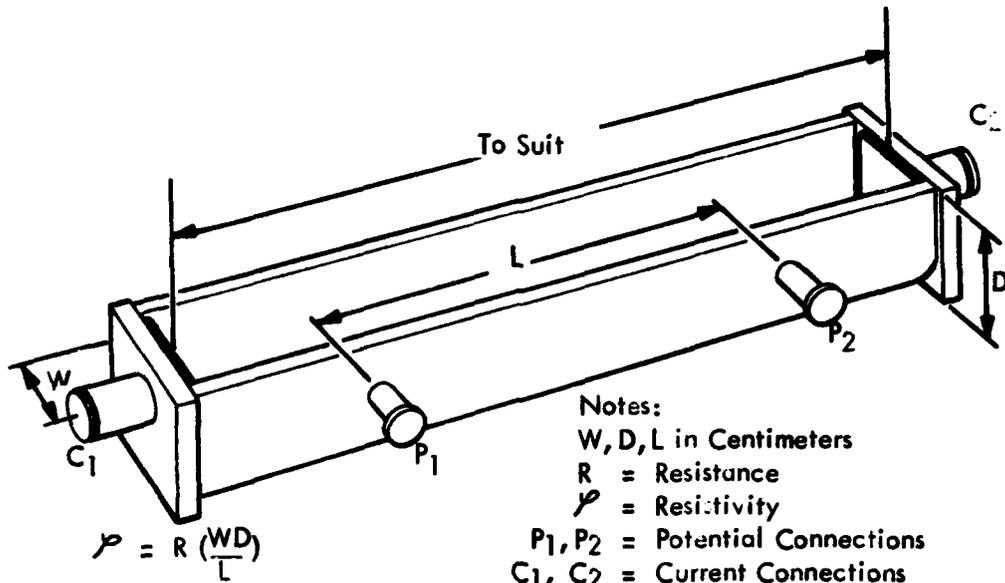


Figure 27
SOIL BOX

The THQ (tetrahydroxylquinone) method is used where higher sulfate concentrations are suspected. Standard barium chloride solution is titrated into the test sample, to which THQ indicator, bromocresol green indicator, and alcohol have been added. Alcohol decreases solubility of barium sulfate. Endpoint is reached when the test sample color changes from yellow to rose. Concentration of sulfate is calculated from the amount of barium chloride added.

1.3.3 Standard Water Analysis. In many cases, a complete water analysis may be required for correct interpretation of corrosion problems. Water treatment may be required to mitigate problems from such sources as: hardness, alkalinity, dissolved oxygen, dissolved metals, nitrates, free carbon dioxide.

2 INSTRUMENTS. As previously mentioned, corrosion of buried or submerged metals is associated with electrical potentials and current. Therefore, proper measurement and evaluation of these quantities are important to corrosion investigation work and cathodic protection. Instrument characteristics and proper use of electrical measuring devices for acquiring field data should be understood. This section describes some basic instruments and shows how they may be effectively applied in the field.

2.1 Why Special Instruments are Required. Because of the wide range of currents and voltages encountered in corrosion test work, test instruments must be designed for maximum usefulness and flexibility. They must be lightweight, sufficiently rugged for field use, and easily readable. There are several manufacturers building combination corrosion meters capable of a variety of measurements with a single instrument. These are desirable, because they reduce both number of instruments required and weight load. However, accuracy is usually not as good as when specialized single-purpose instruments are used. Figure 28 shows some typical instruments and equipment used in corrosion work. Items are identified by numbers as follows:

1. Multipurpose corrosion meter.
2. Storage bottle.
3. Depth gauge.
4. Copper sulfate crystals.
5. Copper-copper sulfate half-cell.
6. Copper-copper sulfate half-cell (with lead wire attached).
7. Selector switch for duct slug test.
8. Volt-ohm meter.
9. Probe resistivity meter.
10. Four-pin resistivity meter.
11. pH meter.
12. Measuring tapes.
13. C clamp.
14. Soil probe pins.
15. Map measure.
16. 100-ampere shunt.
17. Soil box.
18. Equipment box.
19. Probe for soil resistivity measurements.
20. Pipe locator.
21. Current interrupter.
22. Calomel half-cell.
23. Variable resistor.
24. Beryllium scraper (nonsparking).
25. Recording millivoltmeter.
26. Lead wire.
27. Four-pin soil resistivity leads.
28. Lead slug.
29. Beryllium wire brush (nonsparking).
30. Flashlight.

The questions of what instrument to use and where involve study of each individual situation and good working knowledge of all instruments available. All corrosion work, from initial study through design and maintenance, is based upon readings gathered in the field. Therefore, the effectiveness of an entire program is dependent upon reliable readings and proper use of instruments.

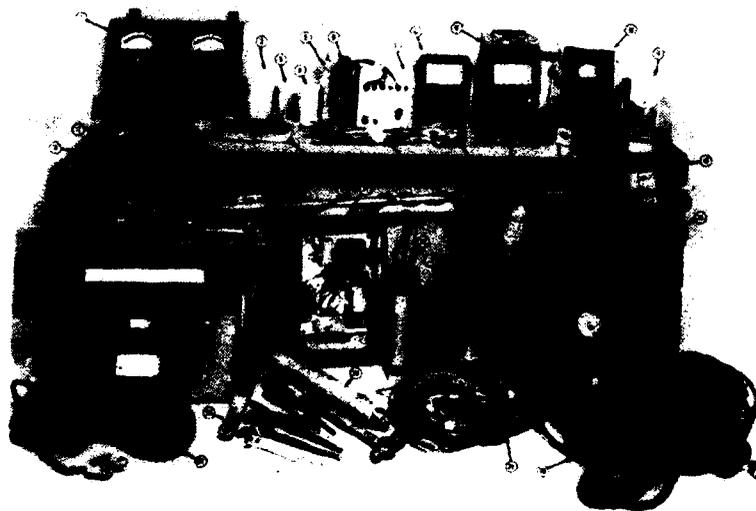


Figure 28
TYPICAL FIELD SURVEY TEST EQUIPMENT

2.1.1 Design and Construction of Field Instruments.

For many years, the basic meter movement found in corrosion instruments was the galvanometric D'Arsonval type. Instruments are still available with this type movement, although the new, more rugged "taut band" suspension is replacing it in some field instruments. These two types are discussed here.

a. D'Arsonval Movement. The basic D'Arsonval meter movement is a galvanometer modified for practical usage. The basic galvanometer (Figure 29) acts on the principle that an electromagnet placed between the poles of a horseshoe magnet and energized by current flow, will act against the tension of a spring which tends to force like poles together. The force thus produced will move a pointer and indicate, on a calibrated scale, the amount of current passing through the electromagnet. The greater the current flow, the stronger the force, and the farther the pointer moves.

In the D'Arsonval meter movement (Figure 30), jewel bearings, adjustable balance springs, and a modified horseshoe magnet are added to the basic galvanometer, and it is usually calibrated to read some electrical quantity directly.

Instruments with D'Arsonval movement can easily be damaged by improper field handling. It is, therefore, as with all instruments, important to have them calibrated at regular intervals. Damage to jewel bearings (Figure 31) or pivot points may cause a pointer to stick. When instruments are dropped or continually jarred (along the axis of pivots), these jewels may crack or break, or pivot points may become blunt or mushroom-shaped. This can happen easily because pressures on the bearings of several tons per square inch are possible with the 300 milligram moving element resting on a .0002" diameter bearing. Dropping or rough handling of these instruments should be avoided. They should be transported with the axes of their pivots parallel to the ground so that the impact of any force will not be directly on the pivot points. A sluggish, or sticking pointer may also result from its jewel bearings being adjusted too tightly, or from an accumulation of dirt. If the permanent magnet of an instrument becomes weak with age, the instrument will no longer read correctly.

b. Taut Band Suspension. Taut-band suspension is a fairly recent innovation. Instruments with this type meter movement have no pivots, jewels, or hair-springs (Figure 32). Instead, taut metal bands support the moving element and carry current to the coil. They act like the hair spring of the D'Arsonval type movement to restrain the turning magnet. A more rugged, more sensitive instrument with frictionless mounting that minimizes wear results. Taut band suspension is well-suited for portable field instruments which are subjected to rough treatment. However,

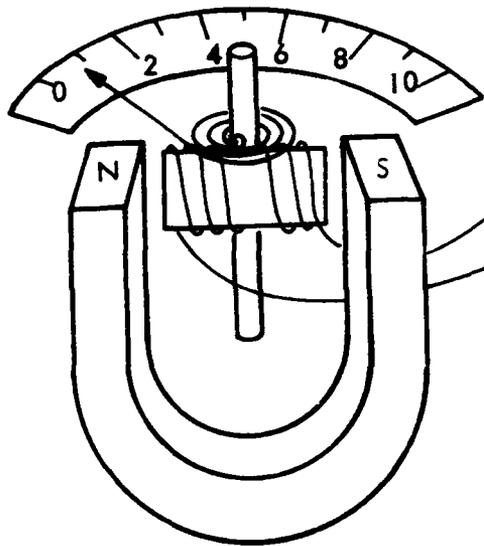


Figure 29
GALVANOMETER

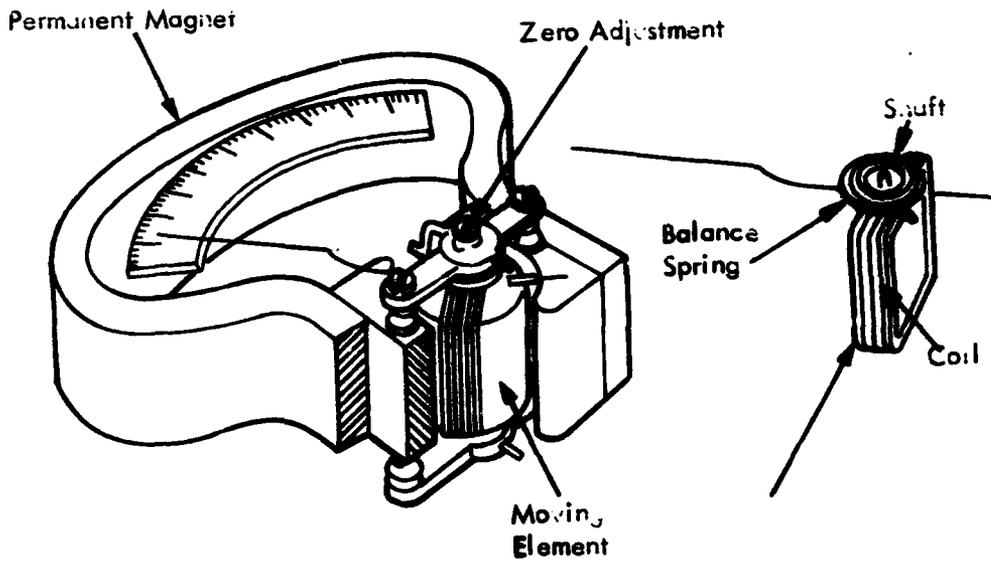
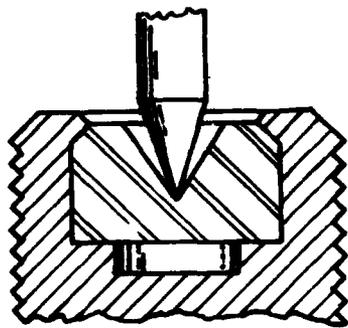
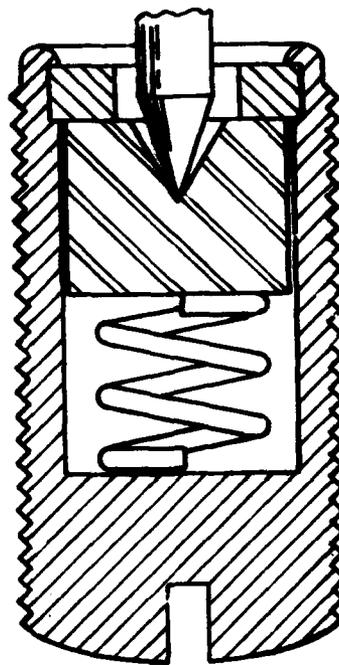


Figure 30
BASIC D'ARSONVAL MOVEMENT

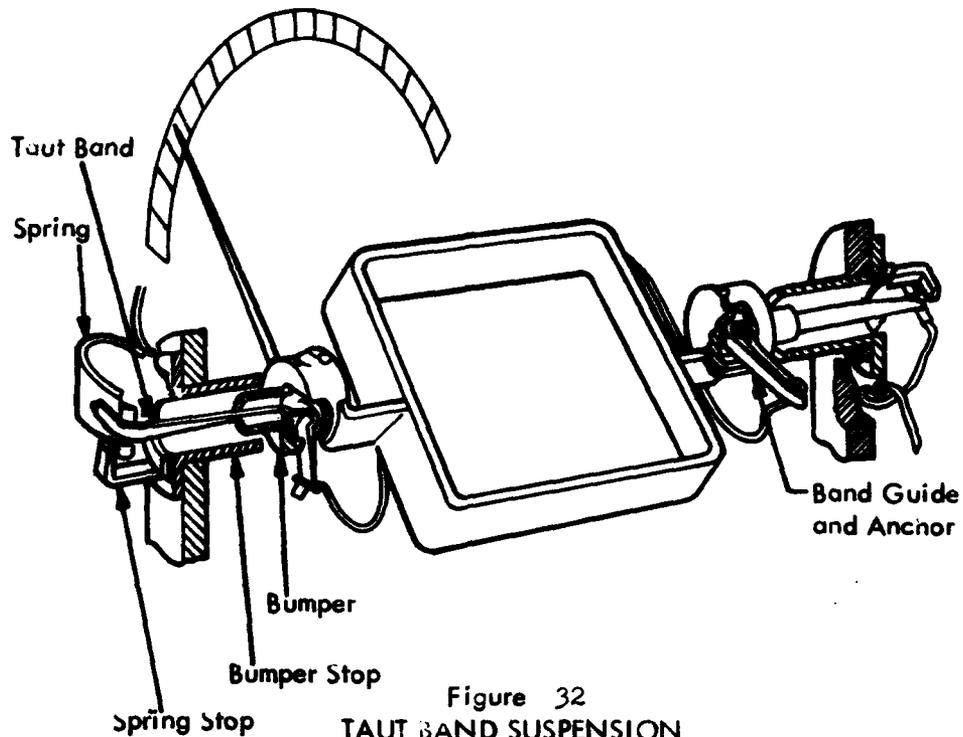


Standard
Jewel Bearing



Ruggedized Type
Jewel Bearing

Figure 31
INSTRUMENT BEARINGS



accuracy at extreme ends of meter scale ranges may be less than with D'Arsonval movements.

2.2 Types of Instruments. In general, high-sensitivity instruments are those requiring a very small amount of current to deflect the pointer (500 microamperes or less). These high-sensitivity instruments are also high-resistance instruments because meter resistance (expressed in ohms per volt) is inversely proportional to current (microamperes or milliamperes) required for full scale deflection of the meter pointer. In use, the pointer of a high-sensitivity meter swings slowly up-scale to the correct position, over travels, swings back and forth (10% to 50%) and gradually stops. There is no sharp division between "low-resistance" and "high-resistance" instruments. However, meters generally considered low-resistance are those having internal resistance of 10,000 ohms per volt or less while high-resistance instruments are in the range 100,000 ohms per volt or greater.

Damping describes control of periodic swing of the moving system, so that the pointer comes to rest more quickly. Aluminum damping vanes are sometimes attached to moving shafts of meter movements for this purpose. Five percent to ten percent overswing is usually considered satisfactory damping.

The period of a meter movement is the length of time required for its pointer to come to rest, after current has been applied to the instrument terminals.

An instrument's accuracy, as given by the manufacturer, is usually stated as percentage of full-scale deflection and not as percentage of actual meter reading. Therefore, a 100-volt instrument which reads 2.0 volts and has an accuracy of 0.5% can be in error by ± 0.5 volts. (0.5% is a common statement of instrument accuracy.)

2.2.1 Ammeters. Simple ammeters such as micro-ammeters, milliammeters, and regular ammeters use the basic meter movement and employ three different circuit arrangements depending upon requirements.

1. All of the current flows through the moving coil. This is applicable to microammeters and milliammeters up to a range of about 200 milliamperes.

2. Part of the current flows through the moving coil and part, through a built-in shunt.

3. Part of the current flows through the meter and part, through an external shunt.

Several shunts may be built into one instrument, so that the same meter movement can be used for various current ranges. Larger shunts, handling heavy currents, are often used externally. It is important to remember that all of the current to be measured must pass through an ammeter. Therefore, the shunt must be large enough to handle this current. A typical ammeter schematic is shown in Figure

33.

Another type ammeter, the zero-resistance ammeter, is actually the combination of a millivolt-voltmeter and an ammeter. These are connected in the circuit so as to measure current flow between two points of different voltage in a given circuit without introducing additional resistance. A simple diagram of the electrical connection for measuring current flow between a galvanic anode and pipe is shown in Figure 34. The zero resistance ammeter operates on the null principle. That is, the open circuit voltage between magnesium (anode) and iron (pipe) registers on the voltmeter or galvanometer. A battery is connected in the circuit with polarity opposite that of the open circuit voltage indicated on the voltmeter. A variable resistor is adjusted to allow sufficient current to flow through resistor (R) until IR voltage drop matches open circuit voltage, and the voltmeter reads zero. True current flowing between anode and pipe when bridged together through zero resistance is then indicated on the ammeter.

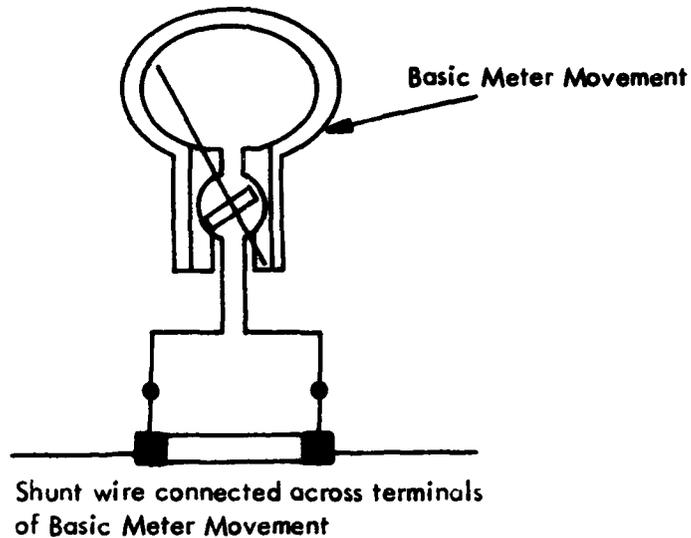


Figure 33
BASIC D.C. AMMETER CIRCUIT

This method eliminates any energy requirement from the voltage source being measured, making this form of measurement desirable where low energy sources are concerned.

2.2.2 Voltmeter - High and Low Resistance. The voltmeter is the most versatile and widely used instrument in corrosion work. It consists of a basic meter movement in series with a multiplier resistor (Figure 35). This series resistor limits current flow through the very fine wire in the meter movement and provides a standard by which voltmeter range can be determined.

Internal resistance of the voltmeter should be high compared to resistance of test leads, reference electrode, and other components that make up the external circuit. Where readings of 1% accuracy are required, instrument resistance must be ninety-nine times greater than total resistance of the external circuit. It is, therefore, important that high-resistance voltmeters be used in most corrosion investigation work. For general use, instrument sensitivity should not be less than 100,000 ohms per volt ("high-resistance voltmeter") so as not to permit current flow great enough to change the potential of the source being measured, or to permit polarization of the reference electrode which can affect its stability as a reference.

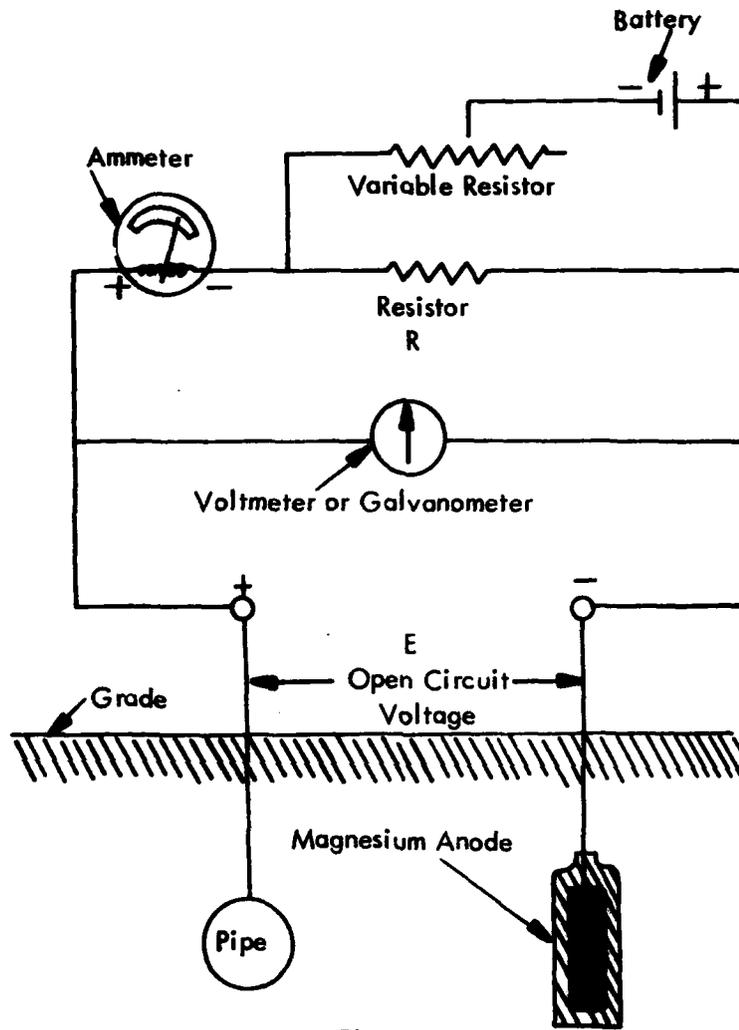


Figure 34
 MEASUREMENT OF CURRENT FLOW BY
 THE ZERO RESISTANCE AMMETER METHOD

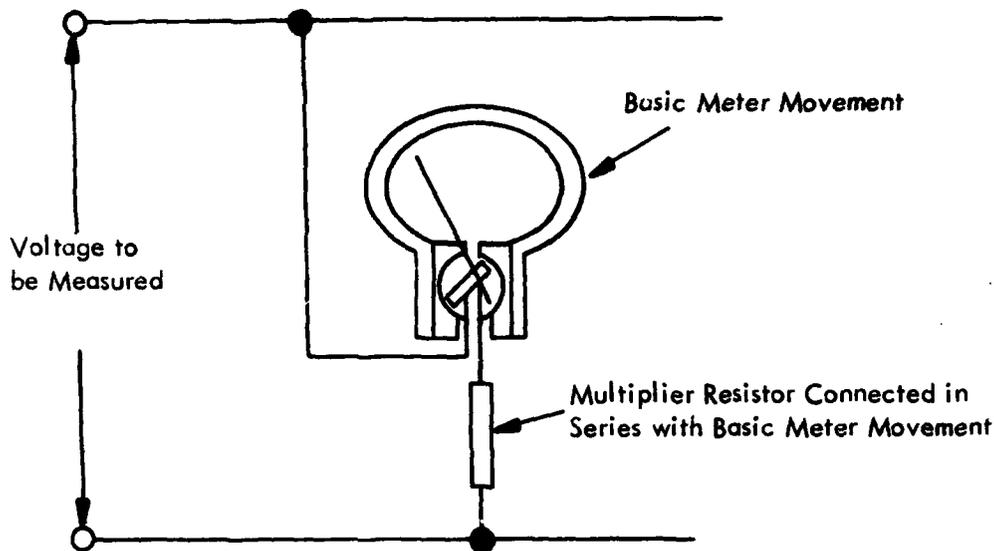


Figure 35
BASIC D.C. VOLTMETER CIRCUIT

For very low voltage readings such as those encountered in IR drops along a structure, however, "low-resistance" (1000 to 2000 ohms per volt) voltmeters are required. Such low voltages cannot force enough current through a high-resistance meter coil to register on the scale. Low-resistance meters require less current to register, and can therefore be used.

Readings made with either type voltmeter are subject to error (true voltage lower than that read) if external circuit resistance is an appreciable percentage of meter internal resistance. Methods of correcting such readings were discussed in paragraph 1.2.1.a(1)(b).

2.2.3 Recorders. Recording instruments periodically or continuously monitor and record on a moving chart readings of direct current or voltage. These are especially useful in areas of fluctuating stray current. The basic recorder is a D.C. meter movement connected to an electrically-powered moving chart. The chart advances with time, providing a record of readings over the period of recording.

The typical chart is advanced by a spring-wound clock mechanism or battery-powered motor. Generally, a bar-tap mechanism periodically records readings: the bar depresses at given intervals of time, marking the chart which is either

pressure-sensitive or smoke-covered. The power source in this type recorder is generally too weak to record continuously, using pen and ink. Continuous recorders are also available which require an external A.C. power source; these are, therefore, not always practical for field use. Battery-powered continuous recorders, using amplifier and self-balancing potentiometer are powerful enough to operate pen and ink.

Recorders are used for purposes other than stray current analysis. They may be employed as labor-saving devices, to take simultaneous readings at various locations. Build-up of polarization potentials can be monitored. Structure-to-electrolyte potentials on cross-country pipelines or cables can be measured by coupling the recorder to a wheel-mounted or other moving reference electrode. The chart is then driven by electrode movement, and records versus distance, not time.

Another recorder is the "X-Y" type, used in making correlation curves (paragraph 1.2.2.c) in stray current surveys. For example: this meter can simultaneously record structure-to-electrolyte potential (y-axis) and IR drop (x-axis) along the structure. Data (automatically plotted by the recorder) are analyzed as in paragraph 1.2.2.c. Any other two voltages may, of course, be simultaneously measured and plotted.

2.2.4 Potentiometer-Voltmeter. The fundamental principle of the potentiometer-voltmeter is to measure potential of a given voltage source without drawing external current. This is accomplished through a special circuit arrangement as in Figure 36. The component parts include internal voltage source, voltmeter, variable resistor, and galvanometer. This combination uses a galvanometer of extreme sensitivity, not suitable for direct measurement purposes, but highly desirable as a null indicator. Since the voltmeter element does not draw current from the external circuit, it can be of the low-sensitivity type with strong springs giving excellent accuracy and durability. The internal voltage source is connected in the circuit with opposite polarity from that of the voltage to be measured.

Operation of the potentiometer-voltmeter is simple. Internal voltage is adjusted by means of the variable resistor until exactly equal and opposite to the voltage being measured. This is indicated by zero deflection on the galvanometer. At this point, no current is drawn from the external circuit, and the effect of infinite resistance is accomplished. The voltmeter then gives the true open circuit potential of the external source.

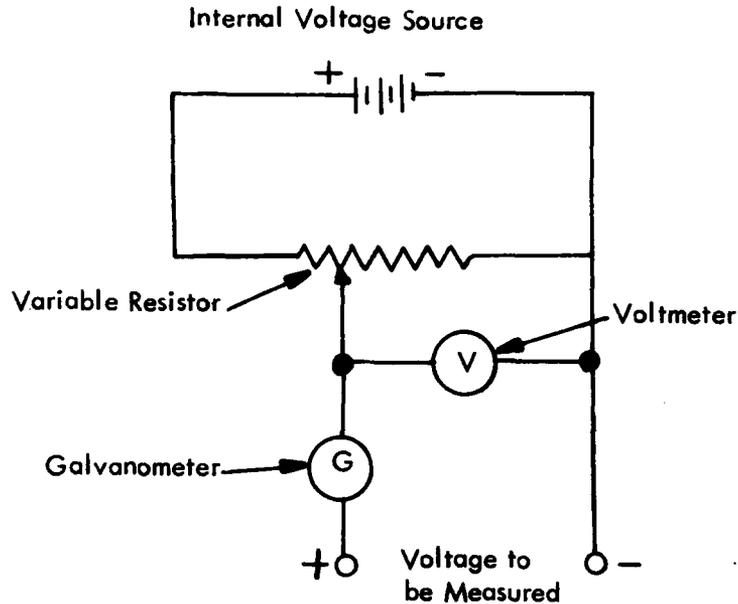


Figure 36

BASIC D.C. POTENTIOMETER-VOLTMETER CIRCUIT

2.2.5 Potentiometer. The potentiometer is generally a laboratory instrument, complex in circuitry and capable of precise potential measurement. The basic instrument is similar to the potentiometer-voltmeter, with the indicating voltmeter replaced by calibrated resistance. Resistance is varied by dials until the galvanometer reads zero; measured voltage is then read directly from the dials.

2.2.6 Electronic and Vacuum-Tube Voltmeter. Electronic and vacuum-tube voltmeters have the high input resistance of a potentiometer without the disadvantage of manual balancing each time the measured voltage changes, permitting their use in fluctuating stray current areas. However, static disturbances can produce errors, and zero drift is sometimes a problem.

The principle of the vacuum-tube voltmeter is illustrated in Figure 37. A minute amount of current (around 10^{-10} amperes) is drained from the external circuit and amplified in the vacuum tube to produce deflection of a voltmeter. Voltage applied to the vacuum-tube grid affects changes in vacuum-tube plate current. Therefore, current taken from the measuring circuit consists only of grid current and leakage current, which can be kept at a low value by proper choice of tube and circuit design. If grid potential is

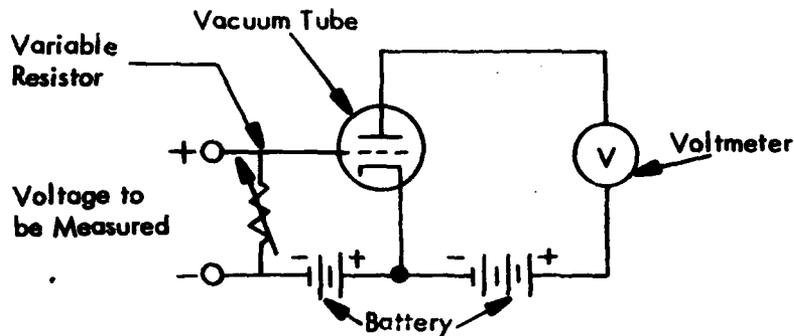


Figure 37
 BASIC D.C. VACUUM-TUBE
 VOLTMETER CIRCUIT

negative with respect to cathode potential, essentially no electrons flow. As grid potential approaches cathode potential, electrons begin to flow from cathode to plate. The higher the grid potential, the greater the flow. The meter movement (calibrated in volts) measures the flow. A vacuum-tube voltmeter requires power to operate the vacuum-tube and power for the D.C. bias circuit.

The newer solid state electronic voltmeter uses a field-effect transistor for amplification instead of a vacuum-tube. The resulting instrument can be used to measure smaller voltages. Battery-powered electronic voltmeters are available. These may be used in the field without A.C. power.

The D.C. solid state amplifier used in electronic voltmeters is available separately, for use with high- or low-resistance instruments. The amplifier increases input resistance greatly and improves response times on lower meter ranges. These battery-operated amplifiers have built-in D.C. bias circuits.

2.2.7 Earth-Current Meter. The earth-current meter can be used to calculate current flowing in earth adjacent to an underground structure. A 2-inch hole must be bored from ground surface to the top of the structure into which a special probe, called a cantilever electrode, is inserted. This probe has four contact points; two are copper-copper sulfate reference electrodes, and two are copper, used to determine relative soil resistivity. Voltage drop, measured between reference electrodes, and relative soil

resistivity data are used to calculate current (density) picked up or discharged from the structure.

The meter consists of battery, high-resistance voltmeter, milliammeter, and current commutator. Commutated battery current flows into earth from the copper contacts, producing AC voltage drop at the reference electrodes. This voltage, commutated to DC voltage, is measured by the voltmeter. A formula, associated with instrument constants, is used to determine earth current:

$$i = \frac{QE_c I_c}{E_c}$$

where

- i = current density in earth
(milliamperes per square foot)
- Q = instrument constant (inverse square feet)
- E_e = voltage between reference electrodes with
instrument in "potential" position (millivolts)
- E_c = voltage between reference electrodes with
instrument at "commutate" position and
commutator on (millivolts)
- I_c = current from battery with instrument as for
E_c (milliamperes)

This instrument finds limited use because it is expensive and relatively complicated to use, requiring a hole to be dug to structure.

2.2.8 Resistance Testers. Basic equipment for measuring soil resistivity consists of a direct current voltmeter, direct current ammeter, voltage source, soil contacts, and test leads. Where direct current is used for resistivity testing, polarity must be reversed and average current values used to eliminate errors from polarization and galvanic effects between electrodes and natural earth currents. Consequently, self-contained instruments are available which change direct current to alternating current for test purposes. Specialized soil resistivity instruments usually incorporate this feature. Soil resistivities in any range can be measured by proper choice of voltages, currents, and measuring devices. Specialized test sets are made to measure to 2 to 3% accuracy resistivity values over wide ranges from sea water, with resistivities of about 26 ohm-centimeters, to soils with resistivities as high as 1,000,000 ohm-centimeters.

a. Instruments Using Four-Electrode Contact to Electrolyte. These instruments are used for measuring resistivity by the Wenner Four-Pin Method (paragraph 1.2.1.d) or with a four-contact soil box. These methods are most accurate because contact resistances are not included.

Terminals of these instruments can be conveniently "shorted out" to make them two or three terminal units, when needed for measurements of circuit continuity or structure-to-soil resistance. Soil contacts connected to the four terminals can be spaced over 100 feet apart without introducing appreciable errors in soil resistance measurements, and both instruments are designed for minimum interference from stray currents.

For special applications, such as large spacings, the Gish-Rooney method of measurement can be used. This method and the instruments used are not commonly used and are therefore not discussed here.

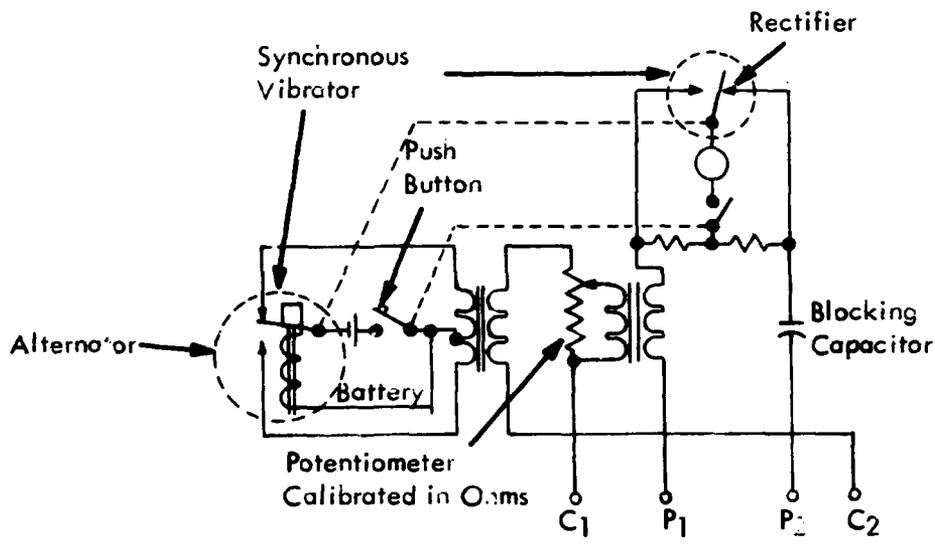
(1) Battery-Operated A.C. Type. The battery-operated, AC type meter is a specialized, self-contained instrument used to measure soil resistivity by the four-electrode method. A schematic wiring diagram for one commonly used design, the "Vibroground", is shown in Figure 38a. If the "push to read" button is pressed, the vibrator is excited by eight flashlight cells. A pair of vibrator contacts connects the dry cells alternately across each half of the transformer primary. A voltage of approximately 125 volts alternating current is inducted in the transformer secondary winding which reaches terminals C₁ and C₂ through the calibrated potentiometer circuit. A voltage drop occurs across the potentiometer, matched against the voltage drop through soil between electrodes P₁ and P₂. When voltage is adjusted so no current flows in the galvanometer, the potentiometer reads directly in ohms.

(2) Hand Generator, Pulse D.C. Type. The hand-generator, pulse D.C. meter is a second type self-contained instrument suitable for four-electrode soil resistivity measurements. A schematic circuit diagram for one frequently used design, the "Megger", is shown in Figure 38b. Test current is supplied to this instrument from a hand-cranked generator; no batteries are required. Current is supplied at approximately 50 cycles and 50 volts when generator turns at recommended speed. (Current output is limited to approximately 0.50 amperes.)

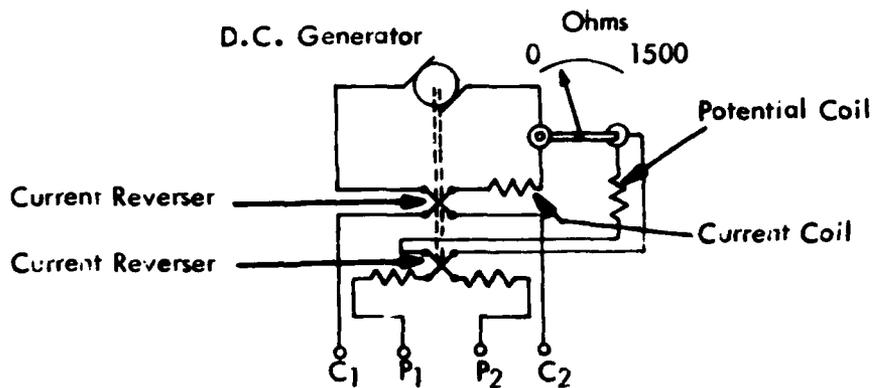
The "Megger" does not use a resistance-comparing circuit with galvanometer but uses, instead, a D.C. ohmmeter with current and potential coils in magnetic opposition.

A second pulse D.C. instrument uses a galvanometer resistance-comparing circuit similar to that described in paragraph 2.2.8.a(1), but with a mechanical rectifier and indicating dials replacing the potentiometer.

b. Instruments Using Two-Electrode Contact to Electrolyte. These instruments measure resistivity using two contacts to the electrolyte. (The two contacts may be on two different rods, or both on one.) This method, less accurate than using four electrodes, includes rod contact



a) BATTERY ENERGIZED TYPE



b) GENERATOR ENERGIZED TYPE

Figure 38
BATTERY AND GENERATOR ENERGIZED SOIL RESISTANCE TESTERS

resistance in the measurement. Like soil boxes, they measure only a small segment of the electrolyte which may not be a true representation of the average soil conditions along the structure right-of-way.

(1) Two Probes. This two-probe earth resistivity meter measures the earth or water resistivity between two electrodes on separate rods (often called "Shepard Canes") located approximately 18 inches apart. It is useful for obtaining resistivity values of liquids or soils in excavations and trenches. Two separate rods can measure slightly larger samples than a single probe (paragraph 2.2.8.b(2), which has fixed electrode separation.

(2) Single-Probe. The single probe contains two electrodes in the same probe-rod: one is the tip; one, the probe body. Electrolyte resistivity, a function of resistance between the two electrodes, is either read directly or calculated from resistance. In either case, the meter employed contains an A.C. bridge or similar circuit to eliminate polarization of the electrodes. Generally, these meters are battery-powered.

2.2.9 Pipe Locator. Pipe locators are used to locate buried metal structures (pipes, cables, tanks, etc.) when precise locations are needed for corrosion testing or other reasons. Most pipe locators impress an alternating current on the structure which is then pinpointed by the electrical field produced. This field is traced with a receiver. The alternating current signal may be impressed directly on the structure through a wire connected to an exposed section (conductive), or it may be induced on the structure (inductive). Some locators work both ways.

With the conductive type, battery-supplied direct current is converted to A.C. by a vibrator circuit and passes through a transformer to produce a maximum of several hundred volts. Voltage is induced in the receiver pick-up coil when near the structure, and this is amplified into headphones. With the receiver horizontal and near the structure, sound is obtained; none is obtained directly over the pipe, because there equal and opposite voltages are induced and cancel out.

The inductive type operates similarly, but no contact to structure is used. The A.C. signal is induced on the structure by a coil in the transmitter and is detected as with the conductive pipe locator. In some models, the transmitter and receiver are mounted together and used just to locate structures. In others, they are separate and may be used to trace long structures such as pipelines.

Some locators include an interrupter to produce pulsation of the signal. This signal can then be distinguished from interference noise produced by other alternating currents in the vicinity.

2.2.10 Holiday Detectors. Holiday detectors, sometimes called "jeeps", use an electrical signal to detect coating faults (holidays). These instruments impress a voltage across the coating. When an electrode is passed over the coated surface, sparks occur between electrode and structure (pipe) at holidays. These sparks set off an electric signal, generally an audible or visual alarm.

Most holiday detectors are battery-operated. They employ a pipe-encircling (spring-coil) electrode for large pipes and a brush-type electrode for smaller pipes and structural surfaces. The detector should be checked regularly to assure proper operation. Also, proper voltage for the coating being tested must be maintained.

The specific voltage required to locate holidays depends on type and thickness of coating. The voltage must be high enough to break down resistance of air of coating thickness, but low enough not to rupture the coating. Since actual coatings are not truly uniform in thickness, proper holiday detector voltages are generally such that locations of very thin coating, as well as holidays, are detected. The applied voltage actually ruptures thin places because of high stresses induced. This situation cannot be avoided, because there is no perfect coating. However, proper voltage levels locate holidays and minimize damage.

Most coating manufacturers indicate a maximum value of volts per mil coating thickness. Below this value, undue rupture should not occur. The National Association of Corrosion Engineers Committee T10D-9A suggests a formula for determining proper voltage for coatings, other than thin film, paint, or fusion types:

$$V = k \sqrt{T}$$

where

V = output voltage, kilovolts

T = coating thickness, mils

k = a constant (from 1.0 to 1.5 depending on type coating)
= 1.25 for coal tar or asphalt

The constant k is near 1.0 for rough coatings and near 1.5 for smooth coatings. This formula is generally valid within 10% accuracy.

For thin film, and other coatings not covered by the above

methods, a voltage output of approximately 100 to 125 times coating thickness in mils is suggested (reference 17). When no accurate means of determining proper voltage output is available, the coating manufacturer should be consulted.

2.2.11 Combination Meters. There are many "combination" instruments useful to the corrosion engineer. These combine features of individual instruments already mentioned and are valuable for measuring several different quantities during a field survey. Two commonly-used types are described here.

a. Volt-Ohm-Milliammeter (VOM). Volt-ohm-milliammeters consist of an AC-DC voltmeter, DC ammeter and DC ohmmeter. The AC-DC voltmeter is generally a basic D.C. meter movement with a rectifier connected to change A.C. to D.C. for measurement. The ohmmeter, powered by low-voltage batteries, is mainly limited to checking circuit continuity through metallic circuits. These instruments are very useful for rectifier repair and maintenance work, and can also be used to "check out" other field test equipment. High-sensitivity type VOM can be used for some structure-to-soil potential measurements.

b. Direct Current Combination Meter. Direct current combination meters are designed specifically for the corrosion engineer. These instruments are available commercially with a variety of alternate features and covering a wide price range.

Basically these instruments consist of two D.C. meter movements mounted in one case. One of these is a high-resistance meter; the other, relatively low-resistance. Included also in the case are selector switches, rheostat controls, and batteries. These meters are used separately or together for various measurements. They can serve as high-resistance voltmeter and low-resistance voltmeter, voltmeter and ammeter, or sometimes zero resistance ammeter, potentiometer-voltmeter (with high-resistance meter as galvanometer and low-resistance meter as indicating meter), and in some models as an electronic voltmeter. Current from the internally-mounted batteries can be controlled by rheostats and routed through the ammeter in order to provide a facility for resistance measurement.

A typical combination meter is shown in Figure 39. This is of the type in common use by the military at this time and is, therefore, described in detail. This instrument, the M.C. Miller Model "M-3-M", contains four specific measuring circuits:

High-Resistance Voltmeter	0.2 to 20 volts
Potentiometer-Voltmeter	0.2 to 3 volts
Low-Resistance Voltmeter	2 mv to 100 volts
Milliammeter/Ammeter	2 ma to 10 amps.

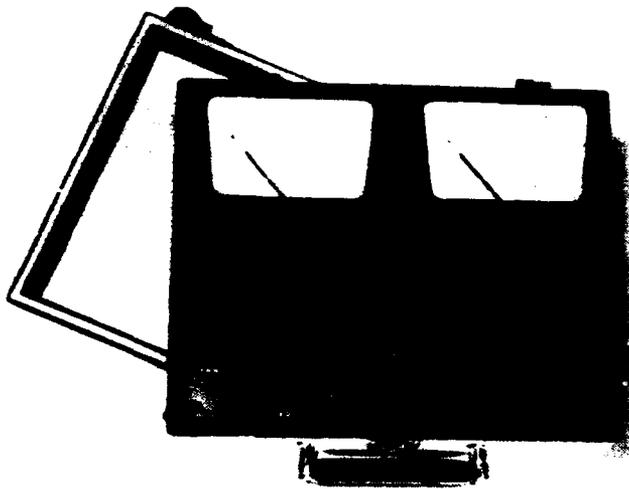


Figure 39
TYPICAL COMBINATION METER

The wiring diagram for this instrument is given in Figure 40. Polarity switches and associated wiring are not shown on this diagram, for simplicity.

This instrument may be used in a variety of ways. The low-resistance and high-resistance voltmeter may be used separately or simultaneously for potential measurements (Figure 41). The low-resistance meter may be used as an ammeter to measure currents, independent from the high-resistance meter, or while the high-resistance meter measures potential (Figure 42). The potentiometer-voltmeter circuit employs both meters, allowing only one measurement at a time; this circuit is useful for voltage measurement where external circuit resistance is high, producing possible errors in readings on the high-resistance meter. Typically, this is encountered with high values of: contact-to-electrolyte resistance (such as in frozen soil, concrete, or blacktop), soil resistivity, or coating resistance on small structures. Readings above 3 volts are not noticeably affected by external circuit resistance and, for these readings, the high-resistance meter will suffice.

2.3 Accessories. In addition to standard instruments, accessories and auxiliary equipment are needed for corrosion survey measurements. A description of these accessories is given here, including:

- portable rectifier
- batteries
- current interrupter
- soil box
- reference electrodes (half-cells)
- shunts
- variable resistors
- soil probe pins
- wire reel
- test leads
- clamps

2.3.1 Portable Rectifier. Portable rectifiers can be used for convenience in determining current requirements for cathodic protection of buried or submerged structures (paragraph 1.2.2.a), testing newly-installed groundbeds, testing older groundbeds with inoperative rectifiers, continuity tests, and resistance tests. This device acts as a permanent rectifier, impressing current on a groundbed (temporary groundbeds are often used). A portable rectifier can consist of a transformer and rectifier for converting A.C. to D.C., and an ammeter and voltmeter for measuring output. An interrupter (paragraph 2.3.3) to allow "on-off" readings is often included as well as a mounted shunt (paragraph 2.3.10). This device is convenient, because it contains

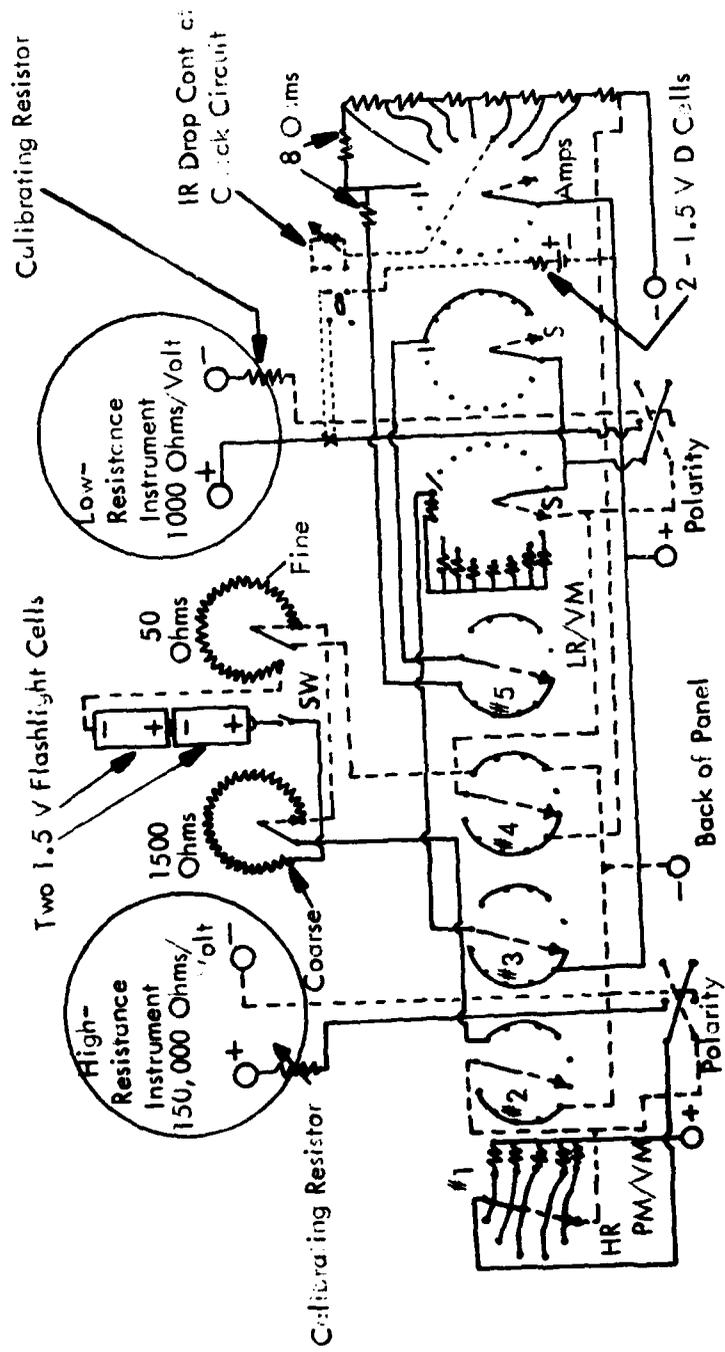
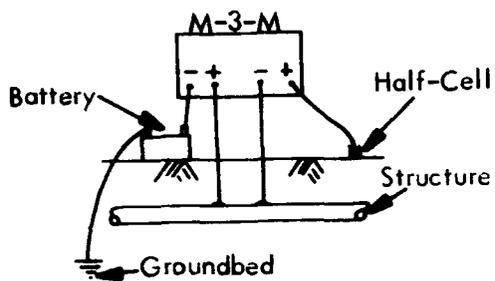
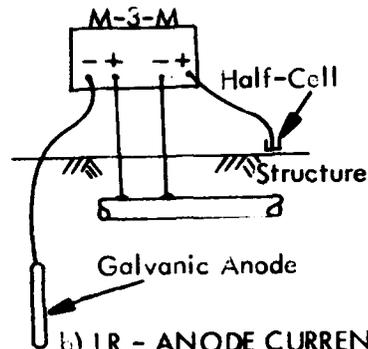


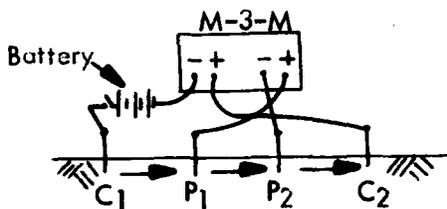
Figure 40
 WIRING DIAGRAM FOR MILLER METER, MODEL M-3-M



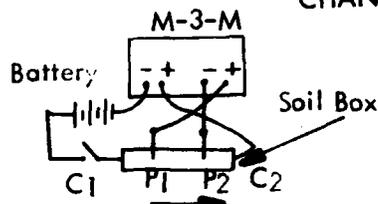
a) LR - TEST CURRENT
 HR - STRUCTURE-TO-SOIL POTENTIAL CHANGE



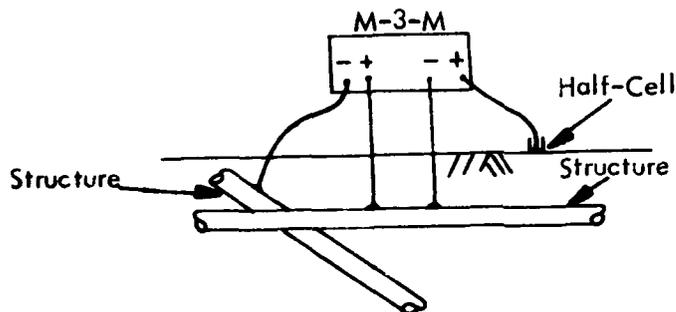
b) LR - ANODE CURRENT
 HR - STRUCTURE-TO-SOIL POTENTIAL CHANGE



c) SOIL RESISTIVITY - 4-PIN METHOD

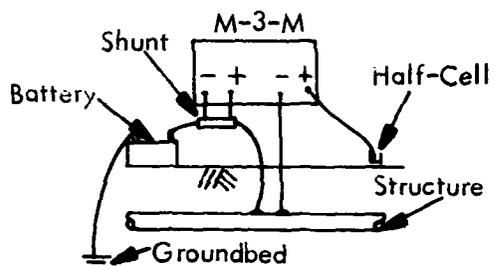


d) SOIL RESISTIVITY - SOIL BOX METHOD

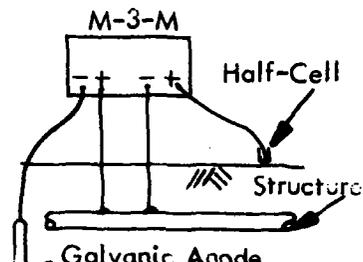


e) LR - CURRENT FLOW BETWEEN STRUCTURES
 HR - STRUCTURE-TO-SOIL POTENTIAL

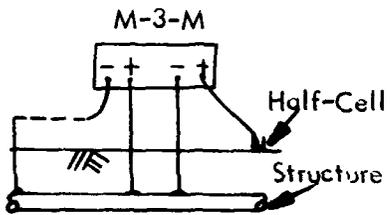
Figure 41
 TYPICAL USES OF LOW-RESISTANCE (LR) AND
 HIGH-RESISTANCE (HR) VOLTMETERS
 (MILLER METER M-3-M)



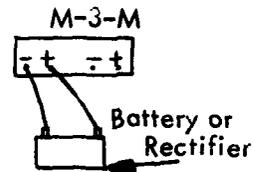
a) LR - TEST CURRENT
HR - STRUCTURE-TO-SOIL POTENTIAL CHANGE



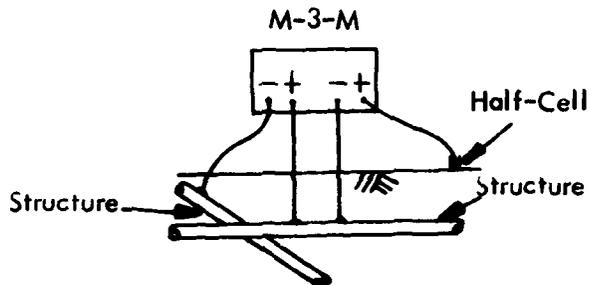
b) LR - ANODE CURRENT
HR - STRUCTURE-TO-SOIL POTENTIAL CHANGE



c) LR - IR DROP ALONG STRUCTURE
HR - STRUCTURE-TO-SOIL POTENTIAL



d) LR OR HR - DC SOURCE POTENTIAL



e) LR - STRUCTURE-TO-STRUCTURE POTENTIAL
HR - STRUCTURE-TO-SOIL POTENTIAL

Figure 42
TYPICAL USES OF AMMETER (LR) AND HIGH-RESISTANCE VOLTMETER (HR)
(MILLER METER M-3-M)

all necessary equipment in one case. An A.C. power source is required to operate the rectifier; this may be a generator power source or connection to service lines.

2.3.2 Batteries. Batteries, like a portable rectifier, are useful in direct current sources or as supplementary D.C. sources in corrosion testing. Six or 12 volt batteries are frequently employed when available equipment is limited, and instruments at hand do not contain built-in batteries. They are used to power such devices as current interrupters, and to supplement existing power when measuring, for example, structure-to-soil potentials in high-resistance soils. Batteries may be used to supply test current for determining current requirements on well-coated structures, or to simulate galvanic anodes. Interrupting current will help conserve battery life.

Storage batteries may be used instead of dry cells, when higher currents are required.

2.3.3 Current Interrupter. A current interrupter is basically a motor-driven cam or electronic circuit which regularly opens and closes a relay. This interrupts current flow on a schedule (such as 20 seconds "on", 10 seconds "off"). This is useful for measuring structure-to-soil potentials and other values with cathodic protection current on and off. It is used in current requirement tests and for checking the effectiveness of cathodic protection.

It is used advantageously on pipelines and complex structures where several potential readings are taken for each current setting. When current is interrupted, readings are taken at various points along the structure. "On" readings are taken just before current is interrupted, and "off" readings are taken as soon as possible thereafter. Switching schedule should be set so there is a noticeable difference between "on" and "off" periods. In this way, readings can be differentiated at a distance.

A wiring diagram for a typical interrupter connected into a cathodic protection circuit is shown in Figure 43. The 6-volt battery which powers the interrupter may be built-in or external. Interrupters are also designed to operate from A.C. power, or from either D.C. or A.C. at the engineer's option.

2.3.4 Soil Box. This measurement of electrolyte resistivity was discussed in paragraph 1.3.1.d. Most accurate is the 4-contact type soil box, made of high-dielectric material (usually plastic) with current contacts at each end and potential contacts along one side (Figure 27). A typical soil box of this type is approximately 8-1/2 inches long by 1-1/2 inches wide by 1-1/4 inches deep (inside

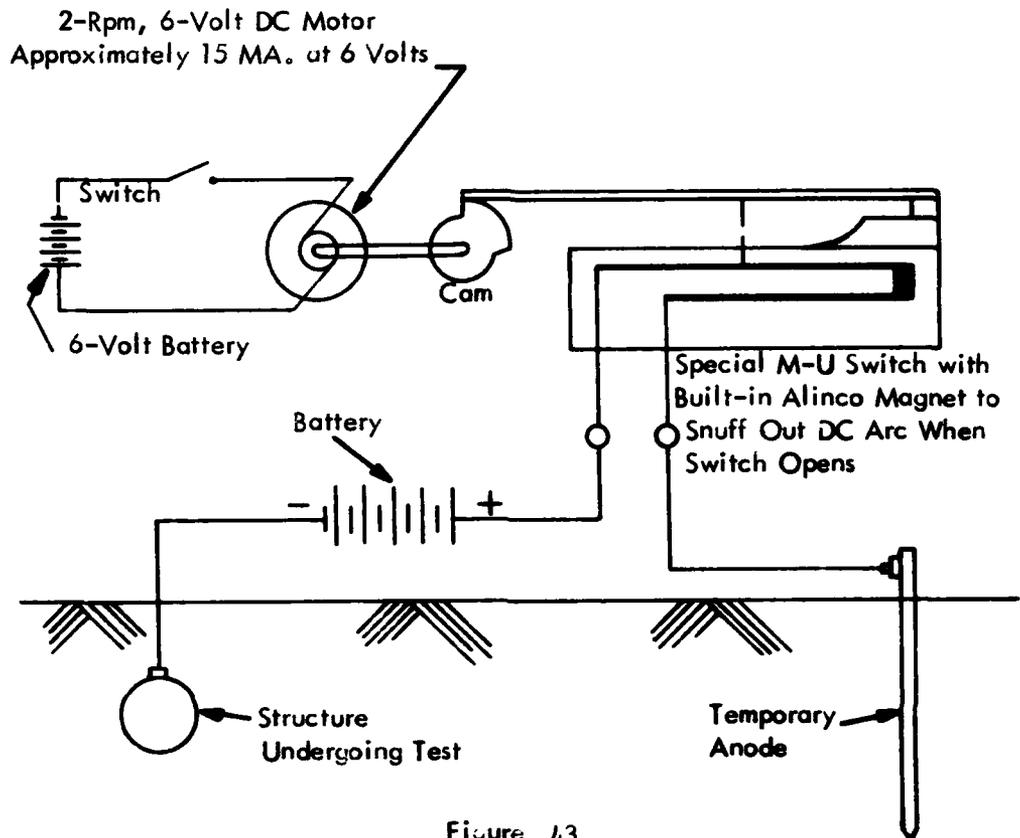


Figure 43
WIRING DIAGRAM AND APPLICATION OF CURRENT INTERRUPTER

dimensions). These measurements are such that resistance in ohms of the sample equals resistivity in ohm-centimeters. Other size boxes are available, each characterized by a "box constant". Resistivity in ohm-centimeters for the electrolyte sample is obtained by multiplying resistance reading in ohms, by the box constant (usually a convenient number such as 1 or 10).

The soil box described above has a volume of 230 cubic centimeters. Its current electrodes are thin metal plates approximately 1-3/8 inches by 1 inch in size. Potential electrodes are metal pins about 1-1/2 inches long by 3/32 inch in diameter, located 1-3/4 inches from the box ends. Effects of contact resistance are overcome with this type (four-connection) soil box, as with other 4-pin methods of measuring resistivity.

A simpler type soil box, less accurate because it does not consider contact resistance, has only two electrodes. These are the metal ends of the box. Construction is similar to that of the 4-electrode soil box, with the two-side (potential) contacts eliminated. This type box is also available in various sizes with characteristic "box constants".

2.3.5 Copper-Copper Sulfate Half-Cells. The copper-copper-sulfate half-cell is the reference electrode most often used. It consists essentially of four parts: copper rod or tubing with necessary provision for connection to voltmeter, saturated solution of copper sulfate contacting the copper, porous plug through which contact to electrolyte is made, and nonconducting container. Figure 44 shows a typical rod-type reference electrode, consisting of plastic tube with watertight cap at the top and porous wooden plug at the bottom. The plastic tube is filled with saturated copper-sulfate solution and contains an excess of crystals to insure saturation. In the half-cell of Figure 44, a copper rod in contact with the solution extends through the cap for connection to voltmeter. A rubber cap may be placed over the porous wooden plug to prevent evaporation when the electrode is not in use.

Another design consists of saturated copper-sulfate solution inside a section of copper tubing, surrounded by a plastic case. A porous plug for contact to electrolyte, and a provision for voltmeter connection are included.

The reference electrode of Figure 44 is standard size, useful for contacting soils under most conditions. Two other sizes (the "long" and the "stubby") are frequently used in corrosion work where the standard size would be impractical. They differ from the standard half-cell in

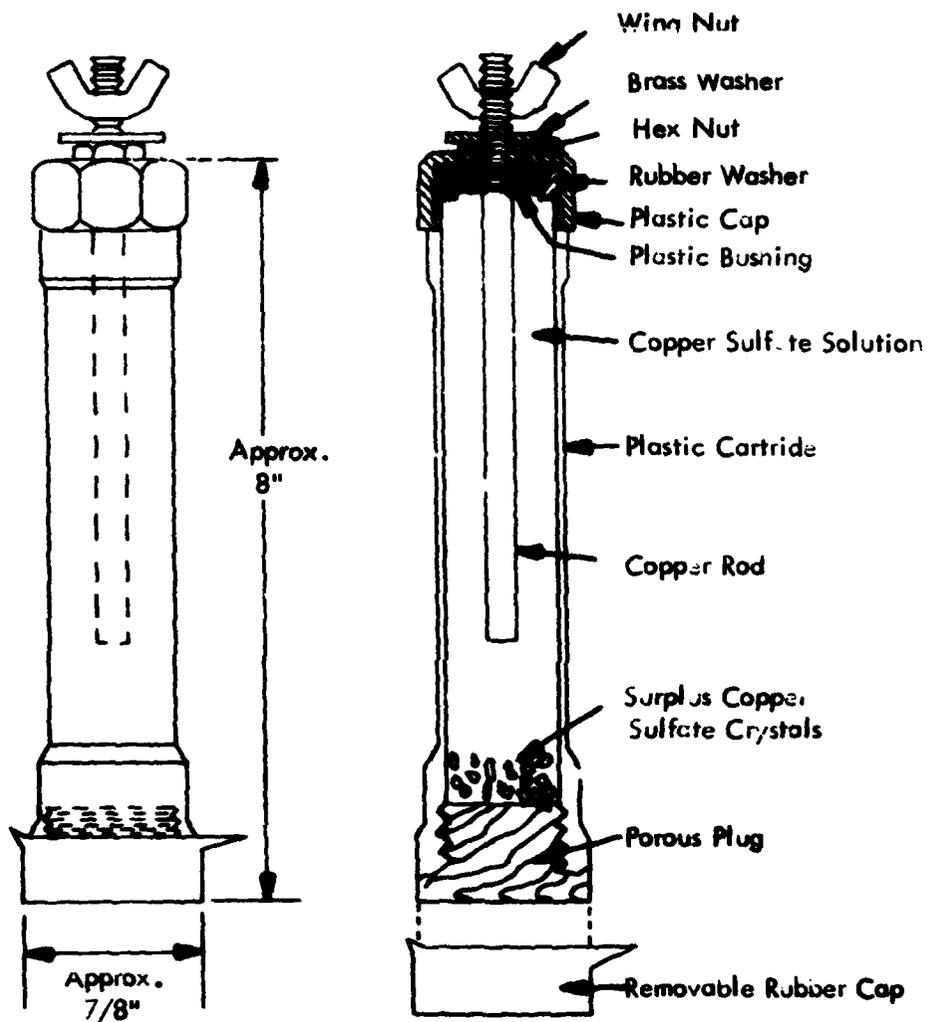


Figure 44
 TYPICAL COPPER-COPPER SULFATE REFERENCE ELECTRODE

dimensions only. The "long" half-cell is identical to the standard, but is 30- or 36-inches long. It is used to contact electrolyte in deep test holes or other places where the standard size would be inadequate or difficult to use. The "stubby" is made in various lengths, but the important feature is its broader base (typically 2-7/8 inch diameter). This improves contact-to-electrolyte where poor contact is anticipated, or when readings are taken through concrete or in frozen ground. Almost any size copper-copper sulfate electrode can be made to order, but the three discussed here facilitate taking readings in soils under most conditions and are therefore generally standard equipment for corrosion field work.

a. Polarization of Copper-Copper Sulfate Half-Cell. With low-resistivity instruments, polarization of copper-copper sulfate half-cells can be a problem. The importance of using high-resistance voltmeters for structure-to-electrolyte potential readings is revealed in Figure 45. Pipe-to-soil voltages, relative to copper-copper sulfate, were taken for various currents using a multirange voltmeter with internal resistance of 1000 ohms per volt. At full scale, current through instrument and electrode is 1 milliampere. A plot of voltage versus current results in a straight line. When polarization occurs, the curve departs materially from linearity. In this case polarization began at 0.9 milliampere. Beyond this point the curve deviates considerably from a straight line indicating that half-cell resistance has changed. Since high-resistance voltmeters require only a few microamperes for full-scale deflection, polarization of the half-cell should not be a problem with these type meters.

b. Temperature Effect on Copper-Copper Sulfate Half-Cell. The copper-copper sulfate half-cell contains crystals of copper sulfate in equilibrium with solution. An increase in temperature causes some crystals to dissolve, increasing solution concentration; a decrease in temperature causes some copper sulfate to precipitate, decreasing solution concentration. A concentration change alters half-cell potential, requiring a correction to potential readings at other than "room temperature" (77°F). The effect of temperature on the copper-copper sulfate half-cell is shown in Figure

46. The temperature correction is about 0.5 millivolt per degree Fahrenheit change. For example, a structure-to-electrolyte potential relative to copper-copper sulfate is taken when the outside temperature is 90°F. The reading is -0.70 volt. From Figure 46, the correction factor for 90°F is +7 millivolts (+0.007 volts). The reading relative to standard copper-copper sulfate half-cell (77°F) would then be:

$$-0.70 + (+0.007) = -0.693 \text{ volts}$$

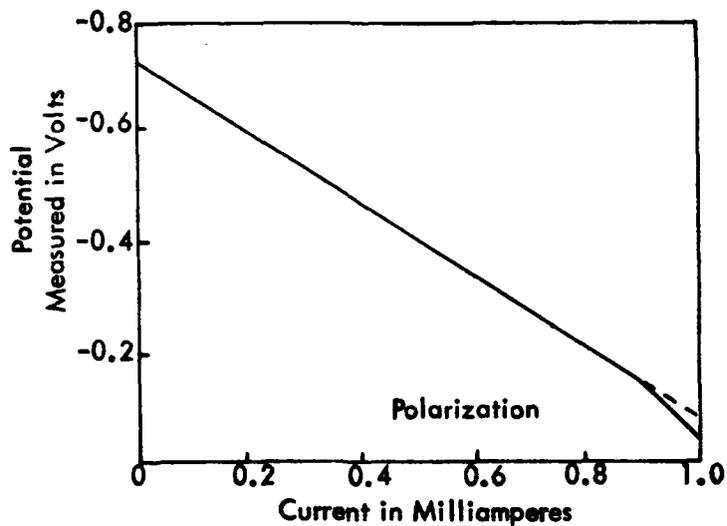


Figure 45

POLARIZATION OF A COPPER- COPPER SULFATE REFERENCE ELECTRODE

The corrected value, -0.693 volts, is still very close to the recorded value, -0.70 volts. Normally, no correction is required for field work except where large temperature changes are encountered. The effect of temperature on a copper-copper sulfate half-cell is provided for information purposes and may be applied if precision of observation warrants it.

2.3.6 Calomel Half-Cells. Although most often used in laboratory, the calomel half-cell also finds application as a reference for underwater measurements. Unlike the copper-copper sulfate electrode which is easily contaminated by saltwater and unable to withstand pressure, the calomel electrode resists contamination and is not affected by low pressures.

The saturated calomel electrode is basically a mercury electrode in contact with a solution of mercury ions; ion concentration is controlled by a saturated solution of mercurous chloride. Other calomel electrodes (non-saturated) contain different concentrations of potassium chloride and therefore have different half-cell potentials. The saturated electrode is most often encountered. Calomel electrodes contact the electrolyte by means of a porous plug, usually glass, and are enclosed in glass. They operate similarly to

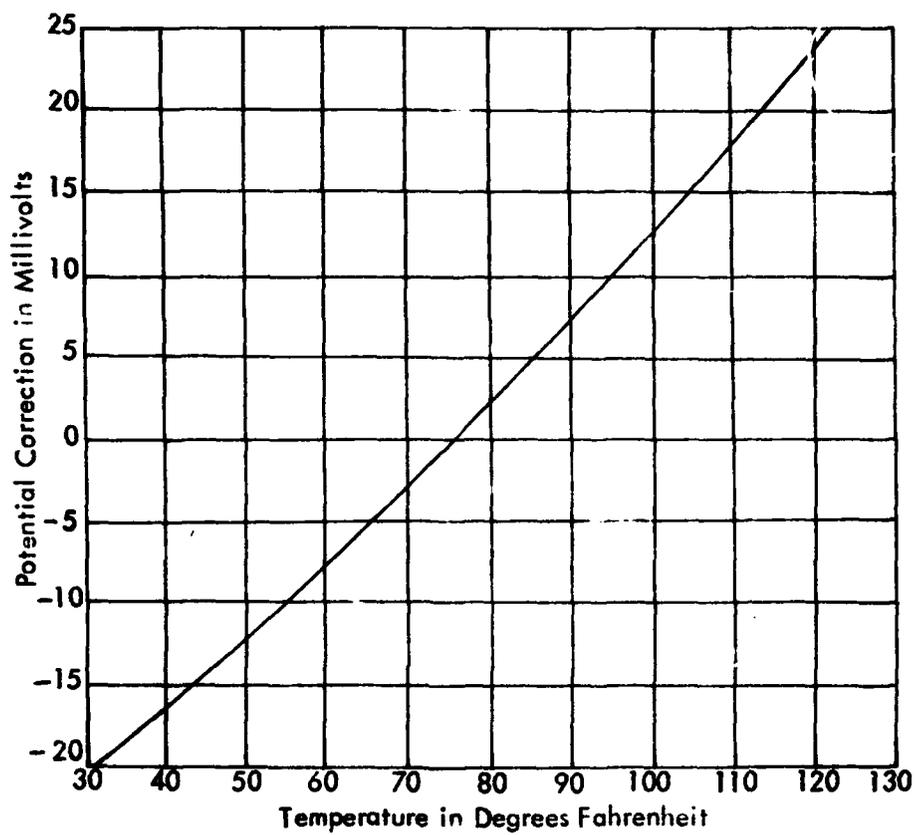


Figure 46
EFFECT OF TEMPERATURE ON A SATURATED
COPPER-COPPER SULFATE REFERENCE ELECTRODE

copper-copper sulfate electrodes, but are less rugged for field work.

The seawater electrode (Figure 47) employs a simple, saturated calomel half-cell as used for laboratory work; this is enclosed in a protective case formed from standard plastic fittings for underwater application. The resulting half-cell is more rugged and is satisfactory for field applications. Lead shot is included for weight.

Half-cell potential of saturated calomel relative to standard hydrogen electrode at 25°C is 0.2415 volts, compared to 0.3160 volts for copper-copper sulfate. This difference necessitates a value other than -0.85 volts structure-to-electrolyte potential as a criterion for adequate cathodic protection of ferrous structures. It is -0.78 for saturated calomel. To convert structure-to-electrolyte readings relative to saturated calomel to equivalent readings relative to copper-copper sulfate, add -0.07 volts. For example, if the potential of a steel pipe relative to saturated calomel is -0.61 volt, the same reading relative to copper-copper sulfate would be:

$$-0.61 + (-0.07) = -0.68 \text{ volts}$$

2.3.7 Silver-Silver Chloride Half-Cells. Another reference electrode used for marine work is the silver-silver chloride half-cell (Figure 48). It consists of silver gauze in contact with a mixture of silver chloride and finely-divided silver. No liquid electrolyte is used, eliminating possible errors at liquid junctions. The silver-silver chloride half-cell is less likely to polarize than the copper-copper sulfate half-cell, and is more rugged than the saturated calomel half-cell. However, its half-cell potential (normally 0.2222 volts, relative to standard hydrogen electrode at 25°C) is dependent on salinity of the water it contacts. Large errors in structure-to-electrolyte potentials can result if variations in salinity exist.

The criterion for adequate cathodic protection of ferrous structures relative to silver-silver chloride is -0.78 volts. To convert structure-to-electrolyte potentials relative to silver-silver chloride to those relative to copper-copper sulfate, add -0.07 volts.

A second type silver-silver chloride electrode, containing 0.1 nitrogen potassium chloride solution, is sometimes used. The values corresponding to those for the above-mentioned electrode are:

$$-0.84 \text{ volts and } -0.01 \text{ volts.}$$

Reproduced from
best available copy.

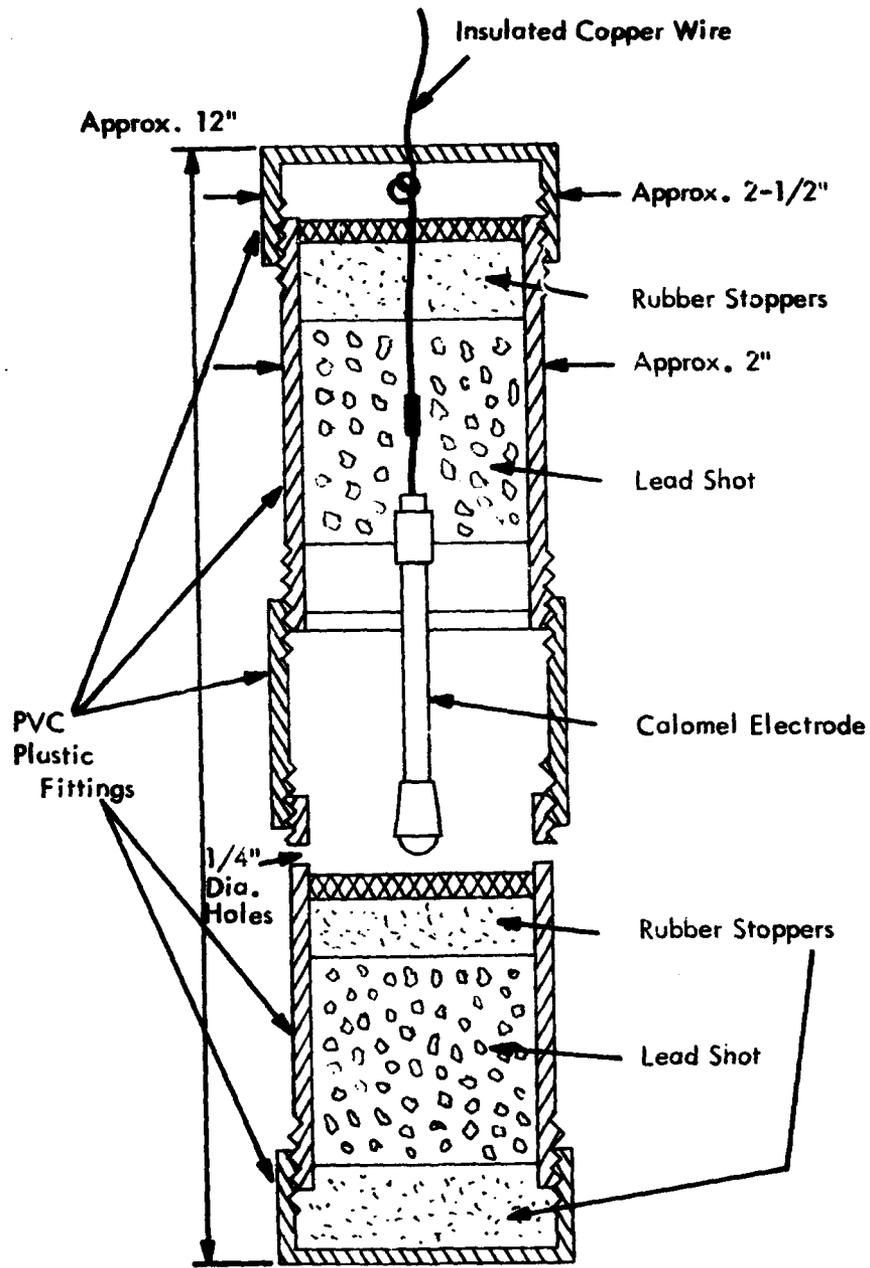


Figure 47
 CALOMEL ELECTRODE FOR SEAWATER TESTING

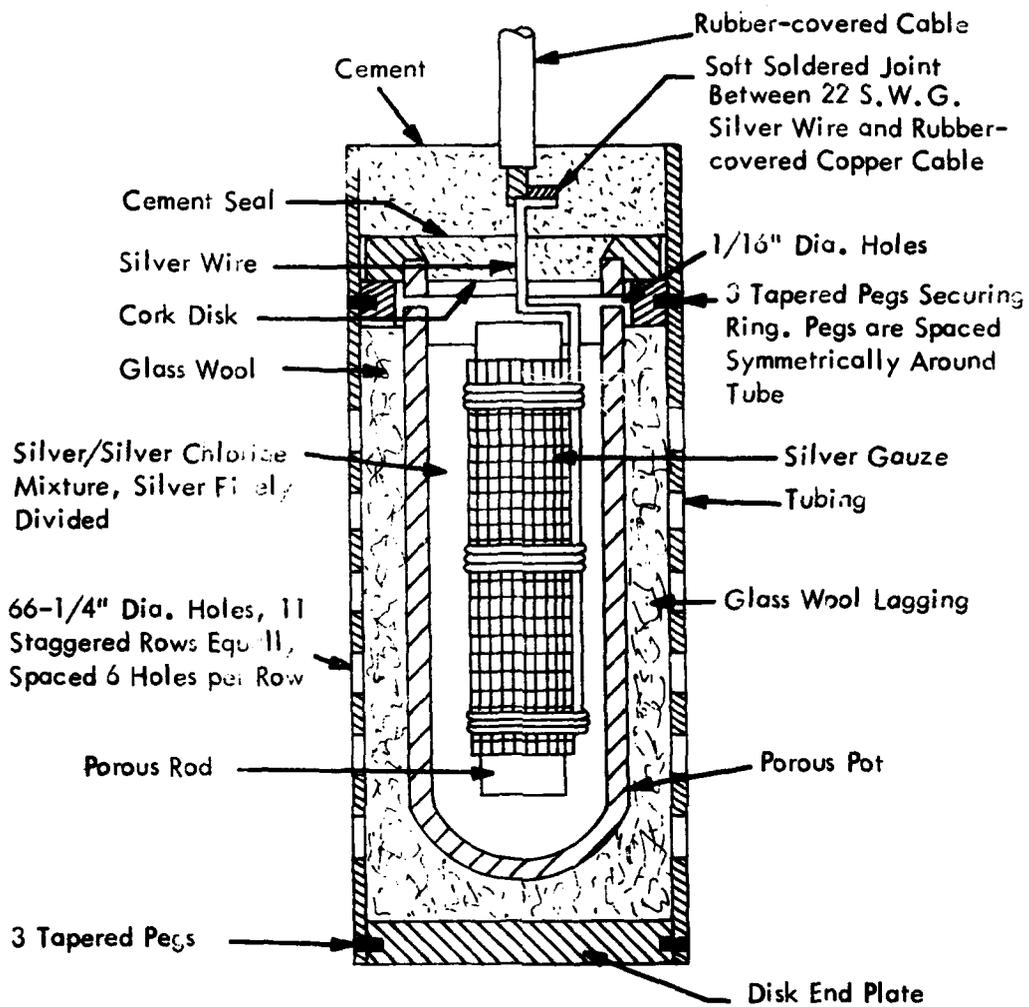


Figure 48
TYPICAL SILVER/SILVER CHLORIDE REFERENCE ELECTRODE

2.3.8 Lead-Lead Chloride Half-Cells. The lead-lead chloride half-cell is sometimes used as reference for measuring structure-to-electrolyte potentials of lead-sheathed cables. This half-cell is constructed similar to the copper-copper sulfate half-cell, with copper rod replaced by lead and copper sulfate solution replaced by a lead chloride-potassium chloride solution. The half-cell potential of this electrode relative to standard hydrogen electrode at 25°C is 0.326 volts. This varies with concentrations of chlorides in solution. The potential is close to that of lead in soil. Therefore, virtually no galvanic potential exists between a buried lead structure and lead-lead chloride half-cell. This is sometimes considered advantageous.

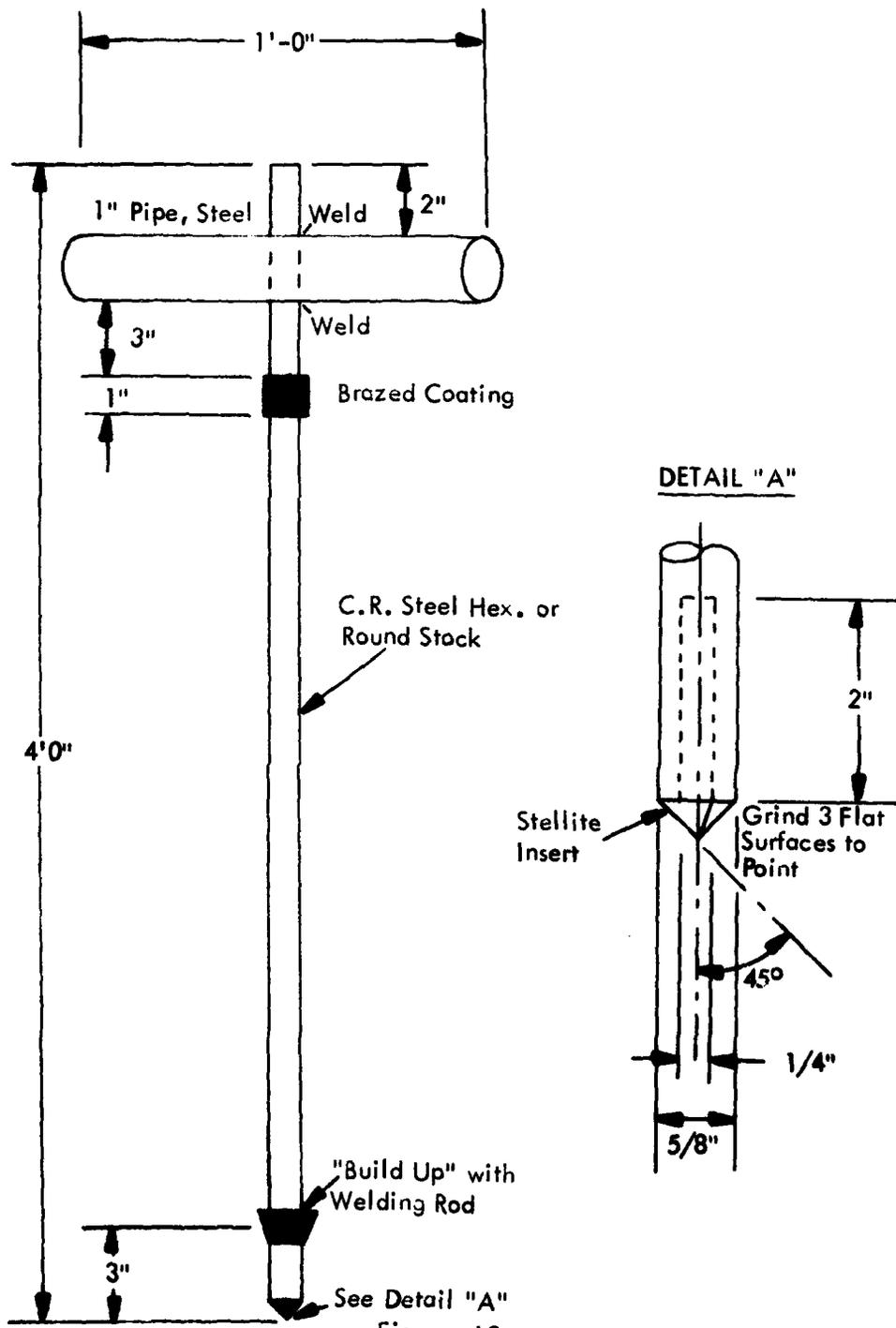
2.3.9 Antimony Half-Cells. The antimony half-cell is used to measure electrolyte pH rather than structure-to-electrolyte potential (paragraph 1.2.1.e). This half-cell consists of a plastic tube with a tip of antimony metal, and terminal for connection to a voltmeter. (Voltage between antimony and copper-copper sulfate half-cell is proportional to pH.)

Antimony is very brittle and the antimony half-cell must be handled with care. Copper sulfate solution must not contact the metal tip for copper will plate out on antimony.

2.3.10 Shunts. Shunts of various sizes are available for measuring current flow. These are calibrated metal resistors in the form of wire or bar with two posts or appendages for connection to a voltmeter. They are made of high-quality metals (such as manganin or constantan) which are virtually unaffected by environment and are therefore considered "constant resistance". A typical size is the 0.001 ohm shunt; voltage reading in millivolts across the shunt equals current in amperes.

2.3.11 Variable Resistors. Variable resistors are useful for estimating required resistance in situations where current splits between two or more paths. Resistors may be needed to obtain proper current division in the various circuits. Examples of situations where installation of resistors may be necessary are current drainage bonds and multi-circuit, impressed current groundbeds.

In the first case, a resistor may be needed to prevent drainage of excess current from a protected structure to a foreign structure. In the second case, one rectifier supplies current to several groundbeds; resistors may be needed to distribute current among the groundbeds so that no groundbed supplies too much or too little current.



TYPICAL PIPELINE PROBE AND CONTACT BAR

When working with variable resistors, contact resistance is sometimes an important consideration. Dirt and corrosion products can accumulate on the exposed portions of resistor wire turns and on the adjustable terminal, increasing contact resistance between the two. These may require cleaning from time to time to assure good contact.

2.3.12 Probe Bars (For Structure Contact). One method of contacting buried structure is by bar or probe pushed through the soil. Figure 49 illustrates a probe bar designed for pipeline corrosion test work. It can be driven through thin blacktop or gravel fill with a minimum of damage to the handle. It is made of cold-rolled steel, a ductile and economical material, with a stellite point. Stellite holds a point well. The thick section of the bar located a few inches above its point aids its removal from moist soil. A brazed surface near the handle reduces possible increased circuit resistance when battery clips are fastened to the probe rod surface which is always subject to build-up of corrosion products. If the bar point is firmly pressed against the buried structure, a simultaneous rotation will tend to penetrate scale or coating.

If a doubt exists as to whether electrical contact to structure has been made, it can be probed at two points. With one test lead clipped to each bar, resistance is measured with a megger, ohmmeter, or vibroground. As an estimate, if two bars are spaced 100 feet apart and number 14 or heavier test wires are used, a circuit resistance below 1.0 ohms indicates a good connection. If it is only practical to use one bar, as is often true with structure-to-soil voltage measurements, two or three repeated readings giving identical results are indicative of a good connection. It is somewhat more difficult to get good probe bar contact in dry soil than moist, and every effort should be made to keep bar points sharp.

2.3.13 Wire Reels. Long, insulated lead wires wound on reels are needed for electrical measurements in field corrosion work. Structure-to-electrolyte voltage surveys for long structures such as pipelines or cables, remote structure-to-electrolyte readings, IR drops where no test leads are available: these and other measurements require a long test lead. A reel facilitates handling.

Metal reels of various types are available; typical reels are hand-held or rest on a stand. The type with stand are generally more rugged, made of heavier material, and have a greater capacity. Wire lengths of 500 feet for the hand-held reel or 1000 feet for the stand-type reel are typical. Stranded copper wire of size 18 with heavy duty insulation is used.

2.3.14 Test Leads. Shorter test leads, 3 to 6 feet or so, are also needed. These may be straight or coiled. No. 18 AWG conductor is a typical size wire. Connectors of various types are used; banana plugs, spring clips, or others are common. Care must be taken when attaching these connectors to minimize contact resistance between cable and connector base. Both parts must be free of dust and corrosion products, and a good, tight connection must be made. A poor connection will introduce errors in measurement.

It is important to have good contact between connector and structure or terminal, also. Clips and plugs must be kept free of dirt, grease, and corrosion products, and paint or build-up on structure must be scraped away. Clean metal-to-metal contact is essential for accurate measurements.

REFERENCES

1. Romanoff, Melvin, "Underground Corrosion", National Bureau of Standards Circular 579, April, 1957.
2. Mears, R. B., "Some Recent Developments in the Study of Cathodic Protection", Gas, December, 1947
3. Romanoff, Melvin, "Corrosion of Steel Pilings in Soils", Journal of Research of the National Bureau of Standards, Vol. 66c, No. 3, July-September, 1962.
4. Sudrabin, R. C., "Foundation Piling Corrosion, Mechanisms and Cathodic Protection", Materials Protection, October, 1963.
5. DeMarco, R. C., "Protection of Underground Steel in a Highly Corrosive Area", Materials Protection, February, 1964.
6. Romanoff, Melvin, "Exterior Corrosion of Cast Iron Pipe", Journal AWWA, 56:1129, September, 1964.
7. Sherer, C. M. and K. J. Granbois, "Study of AC Currents and Their Effect on Lead-Cable Sheath Corrosion", American Institute of Electrical Engineers Transactions, May, 1955.
8. Johnson, W. A., "Pipe Line Leaks Are Not Inevitable", Petroleum Engineer, August, 1953.
9. Wagner, John, "Cathodic Protection and Corrosion Control for Utilities in Urban Areas", Proceedings of the Twelfth Annual Appalachian Underground Corrosion Short Course, 1967. (Technical Bulletin No. 86, Exp. Sta., West Virginia University.)
10. Jbrecht, M. F. and L. L. Quill, "Hot Temperature, Velocity of Potable Water Affect Corrosion of Copper and Its Alloys", Heating, Piping and Air Conditioning, 1960 and April, 1961.
11. Kuhn, R. J., "Casings Promote Corrosion at Crossings Instead of Providing Protection", Oil and Gas Journal, December, 1970.
12. Trouard, S. E., "A Corrosion Engineer Looks at the Problem of Pipelines Crossing Railroads and Highways", A.S.C.E. Committee Meeting, February, 1960.

REFERENCES

13. National Academy of Sciences, Federal Construction Council Technical Report No. 47, Publication 1144, 1963, "Field Investigation of Underground Heating Systems".
14. Hunter, A. D. and C. H. Horton, "Cathodic Protection Checks Corrosion", Underwater Engineering, November, 1960.
15. Wagner, E. F., "Loose Film Wrap as Cast Iron Pipe Protection", Journal AWWA, Vol. 56, March, 1964.
16. Parker, Marshall, (the work of).
17. Eisele, C. W., "Effective Use of Holiday Detectors", Proceedings of the 16th Annual Appalachian Underground Corrosion Short Course, 1971, Technical Bulletin No. 103.
18. "Rectifier Service Manual", Good-All Electric, Inc., 1972.
19. Tudor, S., et al, "Electrochemical Deterioration of Graphite and High-Silicon Iron Anodes in Sodium-Chloride Electrolytes", Corrosion, Vol. 14, No. 2, (Feb. 1958), pp. 53-59.
20. LaQue, F. L. and H. R. Copson, Corrosion Resistance of Metals and Alloys, Reinhold Publishing Company, New York, 1965, p. 604.
21. Literature from Englehard Industries, Inc.
22. Tefankjian, D. A., "Application of Cathodic Protection", Materials Protection, Vol. 11, No. 11, November, 1972.

BIBLIOGRAPHY

LaQue, Wm. T., ed., Designing Impressed Current Cathodic Testing Materials, Proceedings, Vol. 51, 1951.

Mudd, O. C., "Control of Pipe Line Corrosion", Corrosion, Vol. 1, No. 4, December, 1945, pp. 192-218, Vol. 2, No. 1, March, 1946, pp. 25-58.

Parker, Marshall E., "Fundamentals of Corrosion Surveys", The Petroleum Engineer, Vol. 27, No. 3, March, 1955, pp. D22-27.

Parker, Marshall F., Pipe Line Corrosion and Cathodic Protection: a Field Manual, Gulf Publishing Company, Houston, Texas, 1954.

Peabody, A. W., Control of Pipeline Corrosion, National Association of Corrosion Engineers, Houston, 1970.

Uhlig, H. H., Corrosion Handbook, John Wiley and Sons, Inc., New York, 1948.

APPENDIX A.

GLOSSARY OF CORROSION TERMS

(*Definitions from NACE Standard RP-01-69)

Adsorption. The taking up of one substance at the surface of another. The tendency of all solids to condense upon their surfaces a layer of any gas or solute which contact such solids.

Aeration cell (oxygen cell). An electrolytic cell in which a difference in oxygen concentration at the electrodes exists, producing corrosion.

Amphoterics. Materials subject to attack by both acid and alkaline environments. Aluminum, zinc, and lead, commonly used in construction, are examples.

Anaerobic. Free of air or uncombined oxygen; an aerobic bacteria are those which do not use oxygen in their life cycle.

Anion. A negatively charged ion which migrates toward the anode under influence of a potential gradient.

***Anode.** An electrode at which oxidation of its surface or some component of the solution is occurring. Antonym:cathode.

***Bell hole.** An excavation to expose a buried structure.

Cathode. An electrode at which reduction of its surface or some component of the solution is occurring. Antonym:anode.

Cathodic corrosion. Corrosion resulting from a cathodic condition of a structure, usually caused by the reaction of alkaline products of electrolysis with an amphoteric metal.

***Cathodic Protection.** A technique to prevent the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cation. A positively charged ion of an electrolyte which migrates toward the cathode under the influence of a potential gradient.

Concentration cell. An electrolytic cell in which a difference in electrolyte concentration exists between anode and cathode, producing corrosion.

*Continuity bond. A metallic connection that provides electrical continuity.

*Corrosion. The deterioration of a material, usually a metal, because of a reaction with its environment.

*Current density. The current per unit area.

*Electrical isolation. The condition of being electrically separated from other metallic structures or the environment.

*Electro-osmotic effect. Passage of a charged particle through a membrane under the influence of a voltage. Soil may act as the membrane.

*Electrode potential. The potential of an electrode as measured against a reference electrode. The electrode potential does not include any loss of potential in the solution due to current passing to or from the electrodes, i.e. it represents the reversible work required to move a unit charge from the electrode surface through the solution to the reference electrode.

Electrolyte. A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field. Examples are soil and seawater.

Electromotive force series (EMF series). A list of elements arranged according to their standard electrode potentials, the sign being positive for elements having potentials that are cathodic to hydrogen and negative for those elements having potentials that are anodic to hydrogen.

*Foreign structure. Any structure that is not intended as a part of the system of interest.

*Galvanic anode. A metal which, because of its relative position in the galvanic series, provides sacrificial protection to metal or metals that are more noble in the series, when coupled in an electrolyte. These anodes are the current source in one type of cathodic protection.

Galvanic cell. A corrosion cell in which anode and cathode are dissimilar conductors, producing corrosion because of their innate difference in potential.

*Galvanic series. A list of metals and alloys arranged according to their relative potentials in a given environment.

*Holiday. A discontinuity of coating that exposes the metal surface to the environment.

Hydrogen overvoltage. Voltage characteristic for each metal-environment combination above which hydrogen gas is liberated.

*Impressed current. Direct current supplied by a power source external to the electrode system.

*Insulating coating system. All components comprising the protective coating, the sum of which provides effective electrical insulation of the coated structure.

*Interference bond. A metallic connection designed to control electrical current interchange between metallic systems.

Ion. Electrically charged atom or molecule.

*IR drop. The voltage across a resistance in accordance with Ohm's Law.

*Line current. The direct current flowing on a pipeline.

Local action. Corrosion caused by local cells on a metal surface.

Mill scale. The heavy oxide layer formed during hot fabrication or heat-treatment of metals. The term is applied chiefly to iron and steel.

Molality. Concentration of a solution expressed as the number of gram molecules of the dissolved substance per 1000 grams of solvent.

pH. A measure of hydrogen ion activity defined by $\text{pH} = \log_{10} (1/a\text{H}^+)$ where $a\text{H}^+$ = hydrogen ion activity = molal concentration of hydrogen ions multiplied by the mean ion activity coefficient (= 1 for simplified calculations).

Polarization. The deviation from the open circuit potential of an electrode resulting from the passage of current.

*Reference electrode. A device whose open circuit potential is constant under similar conditions of measurement.

*Reverse-current switch. A device that prevents the reversal of direct current through a metallic conductor.

*Stray current. Current flowing through paths other than the intended circuit.

*Stray current corrosion. Corrosion resulting from direct current flow through paths other than the intended circuit.

*Structure-to-electrolyte voltage. (also structure-to-soil potential or pipe-to-soil potential). The voltage difference between a buried metallic structure and the electrolyte which is measured with a reference electrode in contact with the electrolyte.

*Structure-to-structure voltage. (also structure-to-structure potential). The difference in voltage between metallic structures in a common electrolyte.

*Voltage. An electromotive force, or a difference in electrode potentials expressed in volts.

APPENDIX

ELECTROMOTIVE FORCE SERIES

Electrode Reaction	Standard Electrode Potential E° (volts), 25°C.
Potassium = $K^{+} + e^{-}$	-2.922
Calcium = $Ca^{++} + 2e^{-}$	-2.87
Sodium = $Na^{+} + e^{-}$	-2.712
Magnesium = $Mg^{++} + 2e^{-}$	-2.34
Beryllium = $Be^{++} + 2e^{-}$	-1.70
Aluminum = $Al^{+++} + 3e^{-}$	-1.67
Manganese = $Mn^{++} + 2e^{-}$	-1.05
Zinc = $Zn^{++} + 2e^{-}$	-0.762
Chromium = $Cr^{+++} + 3e^{-}$	-0.71
Gallium = $Ga^{+++} + 3e^{-}$	-0.52
Iron = $Fe^{++} + 2e^{-}$	-0.440
Cadmium = $Cd^{++} + 2e^{-}$	-0.402
Indium = $In^{+++} + 3e^{-}$	-0.340
Thallium = $Tl^{+} + e^{-}$	-0.336
Cobalt = $Co^{++} + 2e^{-}$	-0.277
Nickel = $Ni^{++} + 2e^{-}$	-0.250
Tin = $Sn^{++} + 2e^{-}$	-0.136
Lead = $Pb^{++} + 2e^{-}$	-0.126
Hydrogen = $2H^{+} + 2e^{-}$	0.000
Copper = $Cu^{++} + 2e^{-}$	0.345
Copper = $Cu^{+} + e^{-}$	0.522
Mercury = $Hg^{2+} + 2e^{-}$	0.799
Silver = $Ag^{+} + e^{-}$	0.800
Palladium = $Pd^{++} + 2e^{-}$	0.83
Mercury = $Hg^{++} + 2e^{-}$	0.854
Platinum = $Pt^{++} + 2e^{-}$	1.2
Gold = $Au^{+++} + 3e^{-}$	1.42
Gold = $Au^{+} + e^{-}$	1.68

APPENDIX

TABLE D-1

GALVANIC SERIES WITH RESPECT
TO SATURATED CALOMEL ELECTRODE¹

Metal	Negative Potential to Saturated Calomel Electrode, volts ¹
Zinc	1.03
Aluminum (Alclad 3S)	0.94
Aluminum (3S-H)	0.79
Aluminum (61S-T)	0.76
Aluminum (52S-H)	0.74
Cast iron	0.61
Carbon steel	0.61
Stainless steel type 430 17% Cr (active)	0.57
Ni-resist cast iron, 20% Ni	0.54
Stainless steel type 304 18% Cr, 8% Ni (active)	0.53
Stainless steel type 410, 13% Cr (active)	0.52
Ni-resist cast iron, 30% Ni	0.49
Ni-resist cast iron, 30% Ni + Cu	0.46
Naval rolled brass	0.40
Yellow brass	0.36
Copper	0.36
Red brass	0.33
Composition G bronze	0.31
Admiralty brass	0.29
90-10 Cupro nickel, 0.8% iron	0.28
70-30 Cupro nickel, 0.06% iron	0.27
70-30 Cupro nickel, 0.47% iron	0.25
Stainless steel type 430, 17% Cr (passive)	0.22

¹ Based on potential measurements in sea water; velocity of flow, 13 ft. per sec.; temperature 25°C. (77°F).

TABLE 1-1 (Continued)

GALVANIC SERIES WITH RESPECT
TO SATURATED CALOMEL ELECTRODE¹

Metal	Negative Potential to Saturated Calomel Electrode, volts ¹
Nickel	0.20
Stainless steel type 316, 18% Cr, 12% Ni, 3% Mo (active)	0.18
Inconel	0.17
Stainless steel type 410, 13% Cr (passive)	0.15
Titanium (commercial)	0.15
Silver	0.13
Titanium (high purity from iodide)	0.10
Stainless steel type 304, 18% Cr, 8% Ni (passive)	0.08
Hastelloy C	0.08
Monel	0.08
Stainless steel type 316, 18% Cr, 12% Ni, 3% Mo (passive)	0.05

¹ Based on potential measurements in sea water; velocity of flow, 13 ft. per sec.; temperature 25°C. (77°F.).

TABLE 1
 GALVANIC SERIES WITH RESPECT TO
 SATURATED COPPER-COPPER SULFATE ELECTRODE¹

Metal	Negative Potential to Saturated Copper-Copper Sulfate electrode
Magnesium (Galvomag alloy) ^a	1.75
Magnesium (H-1 alloy) ^a	1.55
Zinc	1.10
Aluminum (Alclad 3S)	1.01
Cast iron	0.68
Carbon steel	0.68
Stainless steel type 430, 17% Cr ^b	0.64
Ni-resist cast iron, 20% Ni	0.61
Stainless steel type 304, 18% Cr, 8% Ni ^b	0.60
Stainless steel type 410, 13% Cr ^b	0.59
Ni-resist cast iron, 30% Ni	0.56
Ni-resist cast iron, 20% Ni + Cu	0.53
Naval rolled brass	0.47
Yellow brass	0.43
Copper	0.43
Red brass	0.40
Bronze, composition G	0.38
Admiralty brass	0.36
90:10 Cu-Ni + 0.8% Fe	0.35
70:30 Cu-Ni + 0.06% Fe	0.34
70:30 Cu-Ni + 0.47% Fe	0.32
Stainless steel type 430, 17% Cr ^b	0.29
Nickel	0.27
Stainless steel type 316, 18% Cr, 12% Ni, 3% Mo ^b	0.25
Inconel	0.24
Stainless steel type 410, 13% Cr ^b	0.22
Titanium (commercial)	0.22
Silver	0.20
Titanium (high purity from iodide)	0.17
Stainless steel type 304, 18% Cr, 8% Ni ^b	0.15
Hastelloy C	0.15
Monel	0.15
Stainless steel type 316, 18% Cr, 12% Ni, 3% Mo ^b	0.12

¹ Based on potential measurements in sea water; velocity of flow, 13 ft. per sec.; temperature 25°C. (77°F).

^a Based on data by The Dow Chemical Company.

^b The stainless steels as a class exhibited erratic potentials depending on the incidence of pitting and corrosion in the crevices formed around the specimen supports. The values listed represent the extremes observed and, due to their erratic nature, should not be considered as establishing an invariable potential reaction among the alloys which are covered.

APPENDIX I

UNDERGROUND CORROSION SURVEY
CHECK LIST

New Construction

- I. Meeting with A/E or owner.
 - A. Description of facilities to be constructed.
 1. What is included?
 - a. Gas
 - b. Water
 - c. Buried electrical and grounding system
 - d. Buried communications or signal
 - e. Tanks
 - f. Piling
 - g. Bulkheads
 - h. Building structural members
 - i. Other
 2. Materials to be used and where?
 - a. Steel
 - b. Cast Iron
 - c. Lead
 - d. Concrete
 - e. Copper
 - f. Aluminum
 - g. Other
 3. Construction methods specified.
 - a. Coatings - Types?
 - b. Insulation between structures?
 - c. Are special fills being used?
 - d. Road and railroad casings?
Are they insulated?
 - e. Type pipe joints - weld, flange, dresser, other?
 - f. Type grounding connecting cables?
 - g. Layout of structures (distance between those of varying materials, etc.)?
 - h. Roadways - Will deicing salts leach down into buried structures?
 - i. Lawns - Their location. Is it objectionable to install above grade test stations, etc. in or near them?
 - j. Pavement - Its location and type. What buried facilities will be placed under it?
 - B. Get complete drawings of all facilities.
 1. The following are usually included:
 - a. Electrical
 - b. Mechanical
 - c. Communications
 - d. Fire Protection
 - e. Piling
 - f. Fuel systems

- g. Storage tanks
 - 2. Be sure they are the latest.
 - 3. Ask to be kept advised of any changes.
- C. Ownership of Facilities.
 - 1. Gas, water, power, telephone, e.c. - Which are to be included in project? Which are "utility owned"?
 - 2. Where does utility's ownership and plant's jurisdiction begin?
 - 3. Will the utility install insulation?
- D. What life does the owner expect from his facilities? How many years?
- E. What does a corrosion failure cost? (Each type facility)
- F. Are any facilities extremely critical? (no failures of any kind to be tolerated because of cost or hazard.)
- G. Is direct current being used anywhere in this plant or nearby?
 - 1. Get complete information on where and why.
 - 2. Wiring diagrams and schematics.
 - 3. Method of grounding.
- H. Are any abandoned facilities located in the vicinity? (Metal pipes, etc. might be used as groundbeds.) Are they connected or to be connected to anything else?

II. Field Tests

- A. Soil Resistivity

If site is uniform, take 5' and 10' (usual depth of buried structures) readings at suitably spaced grid. (20' to 100' readings may be required.) Do not exceed 100' spacing with Vibroground instrument. If route of piping or structure known, follow route. Take readings of fill, if any.
- B. Soil pH

Take pH at same places resistivity, if soil is moist.
- C. Soil Samples and/or Water (steam riser, etc.)

Take samples for sulfides and sulfate (and pH) at representative grid locations. (Min. = 6)
- D. Stray Currents

Using 2 copper sulfate cells, take soil potential profile reading in a rosette pattern as necessary.

III. Consulting

- A. Contact Corrosion/Maintenance Engineers of operators in area.
 - 1. Oil Transmission Pipelines
 - 2. Gas Transmission Pipelines
 - 3. Gas Distribution Company
 - 4. Telephone Company

5. Water Department
 6. Electrical Power Company
 7. Manufacturing Plants in area
 8. Corrosion Coordinating Committee
 9. Railroad (do nearby railroads have signal systems?
Electrical Propulsion - AC or DC?)
- B. Data to get from those contacted in A.
1. Failure and corrosion experience.
 2. Is cathodic protection being used?
Type?
Rectifier locations?
 3. Personnel to contact for coordination tests-
names, addresses and telephone numbers.
 4. Place and time of Coordinating Committee meeting.
 5. Is stray current a problem? Its source?
What structures have been affected?
 6. Are deicing salts used in streets?
 7. Are underground structures coated?
Which ones?
Type Coating?
 8. Get drawings and/or other location information on
all structures in the area.
Mark those protected and locations of rectifiers.
 9. Are other new facilities planned for this area?
Utilities, pipelines, etc.
 10. Will these new facilities be coated and/or cathod-
ically protected?
 11. Is it objectionable to use impressed current cath-
odic protection?

Existing Structures

1. Meeting with A/E or owner.
 - A. Find out what facilities are to be covered by this
investigation. Also get data on all others in area.
 1. Look for the following:
 - a. Gas
 - b. Water
 - c. Buried electrical and grounding system
 - d. Buried communications or signal
 - e. Tanks
 - f. Piling
 - g. Bulkheads
 - h. Building structural members
 - i. Other
 2. What materials have been used and where?
 - a. Steel
 - b. Cast iron
 - c. Lead
 - d. Concrete
 - e. Copper

- f. Aluminum
- g. Other
- 3. Construction methods used.
 - a. Coatings - Types?
 - b. Insulation between structures?
 - e. Are special fills being used?
 - d. Road and railroad casings?
Are they insulated?
 - e. Type pipe joints - weld, flange, dresser, other?
 - f. Type grounding connecting cables?
 - g. Layout of structures (distance between those of varying materials, etc.)?
 - b. Roadways - Will deicing salts leach down into buried structures?
 - i. Lawns - Their location. Is it objectionable to install above grade test stations, etc. in or near them?
 - j. Pavement - Its location and type. What buried facilities will be placed under it?
 - k. Have test wires been installed on buried structures?
 - l. Where can connections to buried structures be made? Exposed valves, sections of pipe, etc.
- B. Get complete drawings of all facilities.
 - 1. The following are usually included:
 - a. Electrical
 - b. Mechanical
 - c. Communications
 - d. Fire protection
 - e. Piling
 - f. Fuel systems
 - g. Storage tanks
 - 2. Be sure they are the latest.
 - 3. Ask to be kept advised of any changes.
 - 4. Test station locations.
 - 5. Test station wiring diagrams.
 - 6. Insulation joint locations.
 - 7. Insulation joint types.
- C. Ownership of Facilities.
 - 1. Gas, water, power, telephone, etc. -Which are to be included in project?
Which are "utility owned"?
 - 2. Where does utility's ownership end and plant's jurisdiction begin?
 - 3. Will the utility install insulation?
 - 4. Are utility companies using cathodic protection?
 - 5. Have the utility company's made any tests or investigations on the systems covered by this survey?
- D. What life does the owner expect from his facilities?
How many years?

- E. What does a corrosion failure cost? (Each type facility)
- F. Are any facilities extremely critical? (No failures of any kind to be tolerated because of cost or hazard.)
- G. Have any corrosion failures been experienced?
 - 1. How many?
 - 2. When (dates)?
 - 3. Where? (Mark on drawings)
 - 4. What was their appearance?
- H. Have other failures occurred? (investigate to be sure they were not really corrosion.)
- I. Is direct current being used anywhere in this plant or nearby?
 - 1. Get complete information on where and why.
 - 2. Wiring diagrams and schematics.
 - 3. Method of grounding.
- J. Are any abandoned facilities located in the vicinity? (Metal pipes, etc. might be used as groundbeds.) Are they connected or to be connected to anything else?
- K. Are additional facilities planned? (Immediate or long range) If so, get information.
 - 1. Type and methods of construction.
 - 2. Probable location.
 - 3. How will they be connected to existing facilities?
 - 4. Will direct current be used?

II. Field Tests

- A. Soil Resistivity

If site is uniform, take 5' and 10' (usual depth of buried structures) readings at suitably spaced grid. (20' and 100' readings may be required.) Do not exceed 100' spacing with Vibroground instrument. If route of piping or structure known, follow route. Take readings of fill, if any.
- B. Soil pH

Take pH at same places resistivity, if soil is moist.
- C. Soil Samples and/or Water (steam riser, etc.)

Take samples for sulfides and sulfate (and pH) at representative grid locations. (Min. = 6)
- D. Structure-to-Soil Voltage (at discretion of engineer)
 - 1. Thorough test of bare structure requires one over structure and one on each side every 25'.
 - 2. Coated Structure-less frequent.
- E. I.R. Drop (get at least one on every structure.)
 - 1. Always test external circuit resistance.
 - 2. Correct readings if necessary.
 - 3. Be sure to indicate polarity of all readings.
- F. Voltage between structures. Test voltage between all metallic structures. (Be sure to indicate polarity)

- of each reading.)
- G. Insulating Joint- Test resistance of all known and look for others.
 - 1. Use four connections (two on each side of joint) with D. C. Method.
 - H. Mechanical pipe Joints.
 - 1. Test each piping system to find if mechanical joints exist.
 - 2. Test representative number of mechanical joints to determine quantitative resistance per joint.
 - 3. Be sure to use four point contact method with direct current.
 - I. Electrical and communications cables in duct.
 - 1. All electrical tests at each manhole.
 - a. As in D, E, and F (above),
 - b. Be sure to test voltage between all cables in multiple run duct systems.
 - 2. Visually inspect all hardware in each manhole.
 - a. Brackets
 - b. Bonds
 - c. Condition of cables
 - d. Note material of each component and its condition
 - e. Note fastening methods and insulation between components
 - J. Stray Current Investigation
 - 1. Stray currents will be indicated by abnormal structure-to-soil voltages and/or IR drop. (Either steady or fluctuating.)
 - 2. If stray current is suspected, investigate:
 - a. Any possible source of direct current in area.
 - b. Operating cathodic protection.
 - 3. Have suspected source turned off and on to establish its affect on any structure.
 - 4. Get additional IR and voltage readings to establish circuit.
 - K. Current requirement tests (for cathodic protection). At least cursory current requirement tests should usually be conducted if there is any chance of using cathodic protection at the site.
 - 1. Test using artificial groundbed for both magnesium anode and impressed current design.
 - 2. Extent of testing will be determined by scope of work laid out by client. (Is all design data to be included with this survey?)
 - L. Existing cathodic protection.
 - 1. Visually inspect all equipment.
 - 2. Test to determine protection being afforded and possible interference to other structures.
 - 3. Get operating record.
 - 4. Find out when installed and turned on.
 - M. Miscellaneous - Note any other corrosion problems (chemical, water, atmospheric, etc.) which could use

further detailed study.

III. Consulting

- A. Contact all plant personnel who have knowledge of structures being studied and get all possible information from them.
- B. Contact Corrosion/Maintenance Engineers of operators in area.
 1. Oil Transmission Pipelines
 2. Gas Transmission Pipelines
 3. Gas Distribution Company
 4. Telephone Company
 5. Water Department
 6. Electrical Power Company
 7. Manufacturing Plants in area
 8. Corrosion Coordinating Committee
 9. Railroad (Do nearby railroads have signal systems? Electrical Propulsion - AC or DC?)
- C. Data to get from those contacted in B.
 1. Failure and corrosion experience.
 2. Is cathodic protection being used? Type? Rectifier Locations?
 3. Personnel to contact for coordination tests - names, addresses and telephone numbers.
 4. Place and time of Coordinating Committee meeting.
 5. Is stray current a problem?
Its source?
What structures have been affected?
 6. Are deicing salts used in streets?
 7. Are underground structures coated?
Which ones?
Type coating?
 8. Get drawings and/or other location information on all structures in the area. Mark those protected and locations of rectifiers.
 9. Are other new facilities planned for this area?
Utilities, pipelines, etc.
 10. Will these new facilities be coated and/or cathodically protected?
 11. Is it objectionable to use impressed current cathodic protection.

INDEX

Paragraph

A

Ammeter zero-resistance 2.2.1
Antimony reference electrode 1.2.1e

B

Bacteria, anaerobic 1.2.1f
Batteries 2.3.2

C

Cable ducts, for lead sheath cable 1.2.2f
Cathodic interference 1.2.2b
Chloride content 1.3.1c
Circuit, electrical 1.1.1
Coatings, conductance 1.2.2e
Combination meter 2.2.11
Contact resistance 1.1.2
Continuity tests 1.2.2d
Correlation curves 1.2.1b, 1.2.2c

Current

alternating 1.1.1
direct 1.1.1
interrupter 2.3.3
measurement 1.1.2a, 1.2.1b
"Null Method" of measurement 1.2.1b

D

D'Arsonval movement 2.1.1a
Drainage bonds 1.2.2b
Ducts, cable 1.2.2f

	Paragraph
E	
Electrical connections	1.2.2
Electrical quantities	1.1.1
I	
Instruments	2
accessories	2.3
accuracy	2.2
typical field	2.1
Interference	1.2.2b
testing	1.2.2b
M	
Meter movement	2.1.1
O	
Ohm's Law	1.1.1
P	
pH measurement	1.3.1a,e
Pipe locators	2.2.9
Potential structure-to-electrolyte	1.2.1a
Potentiometer-voltmeter	2.2.4
R	
Recorders	2.2.3
Rectifiers	
efficiency	1.2.1g
portable	2.3.1
Redox	1.2.1f

	Paragraph
Reference electrode	1.2.1a(1)(c)
antimony	2.3.9
calomel	2.3.6
copper-copper sulfate	2.3.5
lead-lead chloride	2.3.8
silver-silver chloride	2.3.7
Remote earth	1.2.1a(2)
Resistance	
contact	1.1.2
external circuit	1.2.1a(1)(b)
internal	1.2.1c
measurement	1.1.2c, 1.2.1c
vs. resistivity	1.1.2d
Resistivity	1.1.2d, 1.2.1d, 2.2.8
meters	2.2.8b
soil box	1.3.1d
Resistor, variable	2.3.11
S	
Shepard canes	2.2.8b
Shunt	2.3.10
Soil	
box	1.3.1d, 2.3.4
rod	1.2.1d(3)
Stray current	1.2.2
Sulfate content	1.3.2
Sulfide content	1.3.1b

	Paragraph
T	
Tanks potential measurement inside	1.2.1a(2)
Taut band suspension	2.1.1b
Testing	1
laboratory	1.3

V

Voltage	
drop	1.1.1
measurement	1.1.2b
Voltmeter	2.2.2
recording	2.2.3
vacuum-tube	2.2.6
Volt-ohm-milliammeter	2.2.11a

W

Water analysis	1.3.3
----------------------	-------