CATHODIC PROTECTION:
THEORY AND EXPERIMENTATION

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CATHODIC PROTECTION: THEORY AND EXPERIMENTATION

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INTRODUCTION

SCOPE OF THE RESEARCH:

Cathodic Protection is a relatively new field of engineering endeavor. Only in the past fifteen years has it been subjected to extensive study, application, and research. Cathodic Protection is of an electrical character from its conception to its application. Electrical measurements of potential and current are the means used to determine when and where protection should be applied. Electrical measurements are the means by which the success of the protection is judged. Between the initial and the final measurements is the installation of Cathodic Protection, which is itself the controlled application of electrical voltage and current.

The object of this dissertation is to present a unified analysis of Cathodic Protection beginning with the fundamental theory and ending with experimental results and new methods of research experimentation. By representing Cathodic Protection in equivalent circuit form, the writer has found it possible to derive each of the two known fundamental theories from a more general expression obtained by circuit analysis. After this verification of equivalent-circuit representation, a new extension to the fundamental theory is made which includes the important effect of the resistivity of the earth; this effect has not been considered in either of the two known theories. Reliable methods of measuring potential and current are presented in detail; the methods are applicable to many types of buried structures. A method more general than the classical method of calculating electrode resistance-to-ground is given with a comparison of the two methods.

Experimental results are usually presented with no more than a qualitative reference to the fundamental theory. This tends toward the inference that Cathodic Protection is entirely empirical. The experimental results presented herein are correlated with the fundamental theory in what is believed to be the first analytical expression of such results in the exact mathematical form of known functions. The previous theory was expressed in equations containing terms written in general functional notation because the particular functions could not be expressed in terms of known functions which would apply to experimental results in general. The author has developed a single empirical equation in literal terms which can be easily fitted to any particular set of experimental data of characteristic form. Of most importance, the characteristic form is the only known quantitative method of determining the proper magnitude of current for protection of a buried structure either proposed or already in existence. A complete numerical example of fitting the literal empirical equation to a set of experimental results is given in Chapter V. This powerful analytical correlation of theory and experimentation is believed to be both original and unique.

The final chapter of the thesis proper is devoted to methods of conducting fundamental research studies in experimentation. Two types of basic experimentation have been recommended previously for universal adoption, but to date no successful methods of performing the two types of experiments have been published. In Chapter VI are three methods of performing one type of experiment, two of which are original and one adapted from another source; and two methods of performing the second type of experiment, one of which is original and the other adapted. All of the methods embody the use of electronic circuits. Test results of the performance of the electronic circuits are given in graphical form which indicates the reliability of the circuits.

Successful Cathodic Protection, based on sound knowledge of the principles of both theory and experimentation, saves many dollars for each dollar spent.

CHAPTER I

ELECTROCHEMICAL CORROSION

Corrosion has been compactly defined as destruction of a metal by chemical or electrochemical reaction with its environment[1]. This form of metallic disintegration is thus distinguished from erosion, which is destruction of a metal by mechanical means. Much corrosion is largely an electrochemical phenomenon characterized by the flow of an electric current, particularly in regard to corrosion of ferrous metallic structures buried in the earth.

Historically, the earliest attempt at prevention of corrosion preceded a sound quantitative theory of corrosion itself. In 1824, Sir Humphry Davy, renowned British scientist of the early nineteenth century, reported[2] the use of zinc in the protection of copper-sheathed ship hulls immersed in sea water. Only a few years later, in 1833, Michael Faraday, the greatest of the experimental researchers in electricity and magnetism, was led to the conclusion that electricity might be atomic in nature, based on results of his studies in electrolysis. The results showed that passage of a definite quantity of electricity through an electrolyte caused the deposition out of the solution of a definite quantity of the

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[1] H. H. Uhlig, Editor, The Corrosion Handbook (New York, 1948), p. 3.

[2] Philosophical Transactions of the Royal Society of London, CXIV (London, 1824), p. 151.

material composing the electrolyte. Faraday's experiments in electrolysis further led him to believe that a finite, small, indivisible quantity of electricity existed. However, it was more than a half-century later, in 1894, that the smallest quantity of electricity, the electron, was identified and measured by Sir J. J. Thomson. The experiments of Faraday were performed many years before the atomic structure of matter was accepted as scientific fact, which in turn preceded investigations into the structure of the atom itself——both of which led eventually to our present-day belief that all matter is electrical in nature. Acceptance of the atomic theory of matter came when the development of chemistry culminated in the Periodic Table of the Elements, by Mendeleef in 1870. Probably because chemistry then dealt primarily with reactions between atoms rather than with the internal structure of the atom, the belief that the atom was the smallest individual particle of matter was held until Thomson's measurement of the ratio of charge-to-mass of the electron.

The portions of Faraday's volumes of publications, "Experimental Researches in Electricity", that are devoted to electrolysis repeatedly emphasized the connection between the chemical action and the passage of an electric current. The basic mathematical equation relating the metal dissolved at an anode, or deposited at a cathode, with the electric current flow through an electrolyte between anode and cathode was formulated in 1837 as Faraday's Law:

$$(1\text{-}1) \qquad M = \frac{WQ}{96{,}500n}$$

where M is the mass of matter in grams, W is the atomic weight of the substance, n is the valence (number of electrons that may be gained or lost by an atom), and Q is the quantity of electricity in coulombs. This equation can be written

$$M = \frac{WIt}{96{,}500n} \tag{1-2}$$

if the current I, in amperes, is constant in time, and t is the time in seconds. Though I is usually considered to be a "direct" current, it is more proper to consider it as a unidirectional current: one whose direction of flow is constant but whose magnitude may vary with time. An exact method of accounting for time-variation is to write Faraday's Law as

$$M = \frac{W}{96{,}500n} \int_0^t I \, dt \tag{1-3}$$

where I = f(t), a function of time. Faraday's Law was the result of electrolysis experimentation utilizing an external source of electric current, but it is equally applicable to the usual cases of corrosion in which the current is maintained by attack of the metal itself.

The flow of an electric current in the corrosion process suggests differences of potential. The potential of a metal is usually explained with the aid of half-cells. Thus, the normal electrode potential of a metal is the potential difference of a half-cell composed of the metal in a solution containing normal ionic concentration of ions of the metal. Some standard of reference must be chosen for comparison of the normal electrode potentials of the various metals. The arbitrary zero of reference in general use is hydrogen, so that the normal electrode potentials can be expressed on the

Hydrogen Scale. The particular electrode potential is then numerically equal to the voltage measured between 1) the metal immersed in a solution of salt of the metal containing normal activity of ions, and 2) black platinum, saturated with hydrogen, in acid with normal activity of hydrogen ions (the two solutions in electrical contact). This can be shown schematically as the voltage of a cell composed of two half-cells[3].

(1-a) Metal	Solution of salt of the metal containing normal activity of ions.	Acid with normal activity of hydrogen ions.	Black platinum saturated with hydrogen at 1 atmosphere pressure.

Table I lists the normal electrode potentials of some of the more important metals[4]. For each metal listed, the potential is the voltage of a half-cell composed of the metal immersed in a solution of ions of the metal containing normal ionic activity.

The location of the potential difference within the half-cell is of interest. It is usually regarded as a difference of potential situated at the interface of the metal and the solution. Therefore, in a cell composed of two half-cells, the voltage of the cell would be the algebraic difference of the potential drops of the two half-cells at the interfaces of the two metals and their solutions. However, if the two metals forming the electrodes of the cells are joined together externally to the cell, then a potential difference

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[3] U. R. Evans, Metallic Corrosion, Passivity, and Protection, (London, 1946), p. XXIII.

[4] The values are from Standard Handbook for Electrical Engineers, (New York, 1941), p. 1917.

TABLE I

THE POTENTIAL SERIES OF THE METALS

METAL	VALENCE	POTENTIAL, (VOLTS)
Gold	2	+0.985
Platinum	3	+0.86
Silver	1	+0.799
Mercury	1	+0.793
Copper	2	+0.347
Hydrogen	1	0.0
Lead	2	-0.132
Tin	2	-0.146
Nickel	2	-0.20
Cobalt	2	-0.23
Iron (ferrous)	2	-0.34
Cadmium	2	-0.42
Chromium	2	-0.47
Zinc	2	-0.77
Aluminum	3	-1.337
Magnesium	2	-1.8
Sodium	1	-2.715
Potassium	1	-2.925

will be situated at the interface of the two dissimilar metals[5]. This is the contact potential difference, which is equal to the difference of the work functions, in electron-volts, of the two dissimilar metals. The work function of a metal is the work of removing electrons from the atoms of the metal, and is the same work function considered in the thermionic emission of electrons from metals. The voltage of a cell can, then, be regarded as the contact potential difference of the two metal electrodes modified by corrections for the actual potential differences existing at the interfaces. It is interesting that there are two alternative explanations for the potential difference of a cell. Though the contact potential viewpoint is apparently quite correct, the concept of the potential drop at the interface of metal and solution seems to be more widely accepted.

The positive and negative signs assigned to the potentials of the metals in Table I are in accordance with the direction of flow of the <u>conventional</u> current in the circuit <u>external</u> to the cell. Instead of two distinct half-cells——valuable in the explanation of the reference standard of potentials of the metals——the usual cell is composed of two metal electrodes immersed in a single electrolyte, as in Figure I. For a specific example, M_1 can be taken as copper, M_2 as zinc, and the electrolyte as sulfuric acid. The cell is then as shown in

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[5] Irving Langmuir, "The Relation Between Contact Potentials and Electrochemical Action", Transactions of the Electrochemical Society, XXIX (1916), pp. 125-183.

Figure 2. The copper and zinc electrodes are joined externally through a switch by a copper wire. If the switch S is closed, the conventional current, i, flows from positive to negative in the external circuit. This flow is opposite to the external flow of electrons from the zinc to the copper because of the difference in work functions of the two metals. In the electrolyte, there is no flow of electron current: the current flow is a flow of ions, a characteristic of electrolytes. The current flow in the electrolyte of Figure 2 is the result of the motion of two types of ions: negatively-

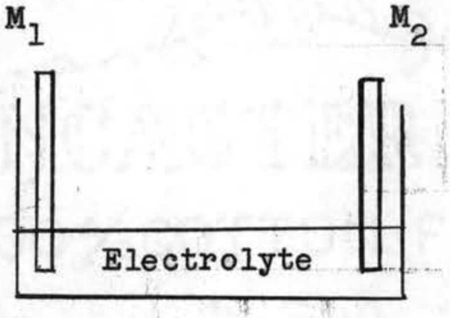

Figure 1. An Electrolytic Cell.

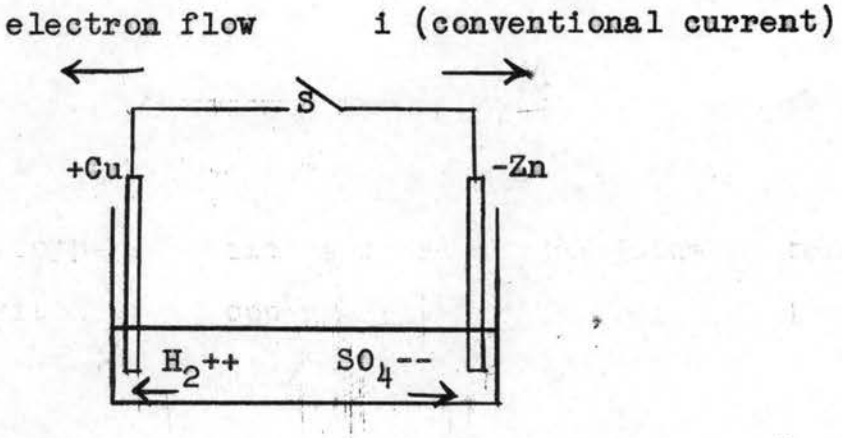

Figure 2. An Electrolytic Cell.

charged ions, or anions, which flow to the anode (zinc); and positively-charged ions, or cations, which move to the cathode (copper). Since negative ions are moving to the negative electrode and positive ions are moving to the positive electrode, the fundamental notion of like electrical charges repelling and unlike charges attracting is seemingly violated. This apparent discrepancy can be dispelled by tracing the continuity of current flow in the entire closed circuit. Because of the difference in work functions of the zinc and copper, electrons will be given up by the zinc to the copper in a flow as indicated in the external circuit. These electrons on arrival at the copper electrode will combine with the positive hydrogen ions flowing in the electrolyte to the copper electrode. At the same time, the negatively-charged ions flowing in the electrolyte to the zinc will yield their excess electrons to the zinc and thus replace the electrons lost by the zinc to the copper in the external circuit. The continuity of current flow is thus established and confirmed.

This cell exhibits a potential difference, as predicted by values in Table I, and there is a current flow. Therefore, electrical energy is being generated by the cell as a source. This energy is derived from the zinc electrode, with the result that the zinc is consumed in the process as indicated by Faraday's Law. The anode corrodes and the cathode remains intact in the cell. The flow of ionic current in the electrolyte and the removal of matter from the anode are bound together as cause and effect. The electron current flow in the external circuit leaves this circuit intact, as this current is a drift of free electrons from atom to atom in the external conductor and does not alter the substance of the conductor.

The potential difference of the cell as measured with the external circuit open is somewhat different from the value measured while a current flows in the cell. Prior to closing the switch in the circuit of Figure 2, there is a tendency for the positively-charged metallic zinc ions to go into solution. This is a tendency of any metal partly immersed in an electrolyte. The transfer of the positive ions to the solution leaves a surplus of free electrons on the zinc plate. Accumulation of the negative charge on the plate builds up a force of attraction for the positive ions which holds them close to the plate. Therefore, a positive space-charge exists, in the solution, whose electrostatic force of repulsion prevents more positive ions from entering the solution. The potential gradient is relatively high in the region immediately surrounding the zinc, because of the proximity of positive and negative charges——another indication that the potential difference is concentrated in the region of the metal-solution interface. Closure of the switch completes the electrical circuit, the positive ions are set into motion, and the electrostatic field is weakened. The positive zinc ions combine with the negative SO_4 ions to form zinc sulfate, $ZnSO_4$, which instantly dissolves in the solution. The positive ion that actually reaches the copper is the hydrogen ion from the solution. As these positive hydrogen ions accumulate on the copper, they form a sheath about the copper electrode which both shields it electrically from the solution and also reduces its effective area presented to positive ions moving through the solution.

Electrolytes conform to the empirical law for resistances,

(1-4) $$R = \rho \frac{L}{A}$$

if the potential gradient does not exceed 300 to 400 volts per centimeter. Ohm's Law relating current, voltage, and resistance, also holds for electrolytes, within the same limitations

(1-5) $$E = IR$$

established for equation (1-4). Because of the accumulation of positive ions at the cathode, and the consequent reduction of the effective cathodic surface area, the ohmic resistance of the cathode increases. As the positive ion sheath becomes more nearly complete, it replaces the copper electrode as the cathode, and the net potential difference of the cell is thereby decreased. The change in the potential difference of the cell is called polarization, and the amount of the change is the polarization electromotive force (voltage). So, with a current flow in the cell, both the (IR) ohmic resistance voltage drop and the polarization emf——a back emf within the cell——tend to decrease the terminal voltage. The open-circuit potential of a cell is dependent almost entirely upon the materials of which the electrodes are composed; it is independent of the kind of electrolyte and of the size and position of the electrodes, but varies somewhat with the ionic concentration of the cell and only slightly with temperature. The internal ohmic resistance of the cell varies with the size and position of the electrodes and with the concentration of the electrolyte.

The specific resistance, or resistivity, of an electrolyte is very high compared with most metals, and it varies with the ionic concentration. Typical values[6] of resistivities for some common electrolytes are given in Table II.

TABLE II

RESISTIVITIES OF ELECTROLYTES

Electrolyte	Resistivity, ohm-cm at 20°C
H_2O (distilled)	$5x10^5$
NaCl (saturated)	4.4
$CuSO_4$ (saturated)	29.0
KCl (normal)	9.8
H_2SO_4 (normal)	4.8
KOH (normal)	5.2
$AgNO_3$ (normal)	14.3

ELECTROLYSIS AND NATURAL CORROSION

The two common types of electrochemical corrosion, 1) electrolysis and 2) natural corrosion, will be compared in order to distinguish the basic meanings of the two terms.

The application of an external direct-current source, such as a generator or battery, to a simple cell can cause either electrode of the cell to be the anode or cathode, depending only upon the relative polarity of the external source. The circuit is shown in Figure 3.

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[6] W. J. Creamer, Elements of Electrical Engineering (New York, 1948), p. 105.

M_1 and M_2 may be of the same metal, or they may be dissimilar metals. Either may be made anodic simply by reversing

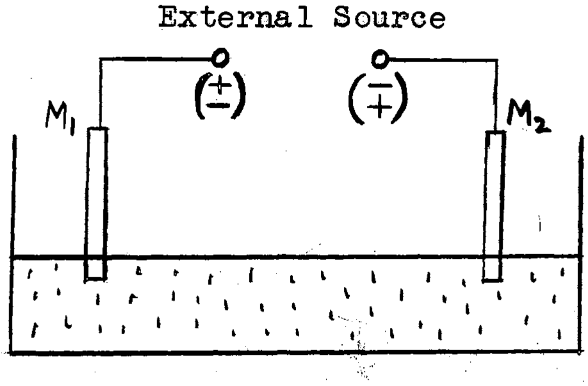

Figure 3. A Reversible Cell.

the polarity of the external source, as is apparent from Figure 3. This is the type of corrosion commonly called Electrolysis, or Corrosion from Stray Currents. It is associated with direct-current generating and distribution systems which utilize the earth as all or a part of the return conductor. The Stray Currents in returning to the generator may enter and leave such underground structures as water pipes and gas mains. Where the Stray Currents leave the structure to flow into the earth, by analogy to a simple cell, is an anodic area, and is subject to corrosion. This type of corrosion is primarily caused by the external source of current. There is some difference of opinion regarding corrosion from alternating current as compared with direct current.[7] Alternating-current corrosion is directly related to frequency. If the frequency is quite low, a few cycles per second or less,

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[7] Evans, p. 40.

the direct-current condition is approached which is the severe limiting case. The ordinary commercial power frequencies, fifty or sixty cycles per second, are believed to result in only 1 per cent of the corrosion caused by an equivalent direct current. But at the relatively high radio frequencies, it is also known that the ground terminal, such as a water pipe, of a radio receiving set exhibits considerable corrosion; the reason is unknown. The most obvious procedure for reducing corrosion from stray currents is the wrapping of the buried structure in an insulating material. Though this is obvious, it is not perfect. No wrapping is completely free from minute, pin-hole imperfections. Where the corrosive stray currents are distributed in space along a bare pipe, these same currents are concentrated in the imperfections of a wrapped pipe. This is actually a worse condition than results from no wrapping at all. By Faraday's Law, about 20 pounds of iron or steel are dissolved by one ampere in one year. If the current is confined to the small area of a pin-hole, the pipe is pitted completely through to its inner surface in a very short time, resulting in failure of the pipe. Wrapping is not a panacea for the ills of corrosion; more correctly, wrapping only makes more practical the electrical method of Cathodic protection, which is the subject of this thesis to be treated fully in later chapters. Some cooperation is necessary between the electrical generating companies who cause the stray currents and the water and gas companies whose pipelines suffer from the currents, as is often found between power and telephone companies in the matter of interference between transmission lines.

The simple cell shown in Figure 2 may be construed to represent a form of Natural Corrosion. There is no external source of current, but a flow of current exists in the closed circuit as a result of the dissimilarity of the two metal electrodes. The anodic electrode, in this example the zinc, corrodes where current leaves it to flow into the electrolyte. Instead of two distinct electrodes, as in Figure 2, minute local cells may exist on a single piece of metal in the earth as a result of the non-homogenous structure of the metal itself. One such cell is shown in Figure 4. The earth is the electrolyte, the metal itself is the metallic connecting link between anode and cathode to close the circuit, and corrosion occurs on the portion of the metal where current leaves it to enter the earth. Even if the metal were perfectly homogeneous, a local cell could exist because of non-homogeneity of the electrolyte connecting two portions of the same metal. Another cause of a local cell formation is

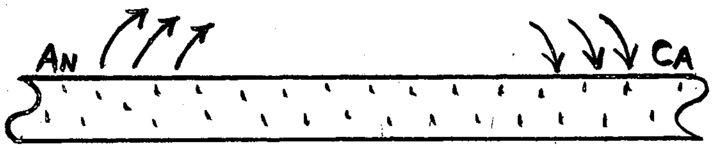

Figure 4. Local Corrosion.

the thermocouple effect: a difference of potential may exist between two points in the same metal because of a difference in temperature of the two points. Still another cause of local cells is stress differences within the same metal, which is a piezoelectric phenomena similar to the action of crystals used in electronic oscillators. Local cells may be formed as the result of potentials induced in the metal by changes in the magnetic field of the earth, or by magnetic storms. Thus, there are many different means of creating the local cells. However the cell may be caused, once it exists there is an accompanying electric current flow and the inevitable corrosion. Regardless of the mode of creation of the cell, the cell has four common parts: the corroding anode, the cathode, the electrolyte, and the metallic conductor connecting the anode to the cathode. The cell is a closed electric circuit.

Natural Corrosion, or corrosion from formation of natural local cells, can exist whether or not an external source of electrical energy is involved. It is found in isolated areas far from cities which have ground-return d.c. distribution systems or d.c. electric street railways. It is of particular concern to the petroleum industry, which lays buried pipelines in many places quite remote from stray-current sources. The author has frequently separated the metal connection between the casing and surface flow line at well-heads hundreds of miles from any external source of d.c. stray currents, and has measured through a low-resistance ammeter currents of 35 to 40 amperes flowing down to the well-casing. The corresponding measured potential difference between casing and flow line at the point of separation was only a few tenths of one volt. The ohmic resistances of both the metal and earth paths of current flow are very low. Such large destructive currents cause failure of casing in a very few years or even months. Wrapping of well-casing is impossible; Cathodic Protection is the only solution to elimination or reduction of casing corrosion, and this is also true in regard to the large oil storage tank bottoms which are always in contact with the earth. The metal rods in reinforced concrete are subject to corrosion from local cell action. The oxides that form on the surface of the rods increase the volume occupied by the rods which in turn increases internal stresses of the concrete to the point of failure. Wrapping of these rods would aid not at all since local cells are the corrosion source; only Cathodic Protection can prevent such corrosion.

It is quite possible that a new source of corrosion emfs has been discovered by research on pipeline pressure surges recently conducted by the Engineering Experiment Station, Oklahoma A and M College.[8] Generated potential differences due entirely to the flow of fluid within the pipe were detected and measured. In addition, measurable fluctuations of the generated potentials were attributed directly to the fluid pressure surges that result from pumping. Potential gradients of the order of several millivolts per inch were recorded,

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[8] J. R. Norton, "A Theoretical Study of The Electrokinetic Transducer" (unpublished M.S. thesis, Oklahoma A and M College, 1951).

which are high compared with those measured on empty pipe and casing. The very existence of these flow emfs implies that corrosion currents will flow as the result of fluid flow, and so may be expected in either pipelines or well-casing. Though the study which discovered the flow emfs was not concerned with corrosion, it is again mentioned that corrosion is caused by the emfs without regard to the mode of creation of the emfs.

The conditions in the field, where natural corrosion is found, are often quite different from those in a laboratory, where conditions may be controlled to a certain extent. It is obvious that buried metal structures in the field cannot be examined or observed physically by an investigator. It is for this reason that electrical measurements must be utilized and relied upon as the means of detection and measurement of corrosion activity underground. Corrosion engineering, much of which consists of electrical measurements, is not an exact science. Its development depends upon application of engineering principles based on the laws of physical science.

THE STATUS OF CORROSION ENGINEERING RESEARCH TODAY

The enormous cost of corrosion to industry, estimated at over five billion dollars yearly, has attracted the attention of many scientific and technical groups in the United States. The accepted electrochemical theory of corrosion was proposed[9] in 1903 by Dr. Willis R. Whitney, Vice-President and Director of Research for the General Electric Company for many years.

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[9] "The Corrosion of Iron," Journal of the American Chemical Society, XXV (1903), pp. 394-406.

Since that time, the investigation of corrosion has cut across the boundaries of many fields of science and engineering. At present, the American societies which have sections or committees devoted to corrosion are: The American Chemical Society, The American Gas Association, The American Petroleum Institute, The American Institute of Electrical Engineers, The American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, The American Society for Metals, The American Society for Testing Materials, The American Water Works Association, and The Electrochemical Society. The National Association of Corrosion Engineers, founded in 1944, publishes a monthly journal which, like the Association, is devoted entirely to corrosion engineering and research.

A stimulus to research in corrosion, and to an appreciation and understanding of corrosion problems, is the estimate that 20 per cent of the five billion dollar annual loss can be saved by research.

There seems to be a void between the electrochemical theory and the many different attempts to prevent corrosion. The vast number of applications of protection against corrosion has greatly exceeded the basic knowledge. At present, it is not precisely possible to predict accurately the quantitative degree of protection required for a proposed application. Nor is it exactly possible to state accurately the quantitative degree of protection actually furnished to a given application. Because electrical potential and current are so much an integral part of the corrosion mechanism, it would be useful to the engineer to base both the corrosion and the protection processes on familiar principles. Equivalent electrical circuits have long been used in the analysis of transformers and induction motors, and equivalent circuits have been adopted widely in the last decade as analogue representations of hydraulic, mechanical, and thermal systems. Representation of both the corrosion and the protection processes by equivalent circuits will aid in unifying the understanding of both, as well as providing a means of quantitative description and analysis.

Refinements and new developments in the methods of electrical measurements are constantly sought for use in corrosion research. Basic facsimile experiments utilizing small specimens have been recommended as a means of providing knowledge of a fundamental nature. Since these experiments are of an electrical character, electrical regulating-circuits should be developed as a first necessity in order to make the experiments possible. These facsimile experiments can be conducted in any given soil environment in order to determine the criteria for protection, in terms of critical potential, current-density, or both, for the particular locality.

Each of these topics will be considered in subsequent chapters of this thesis.

CHAPTER II

CATHODIC PROTECTION AGAINST CORROSION

ANALYTICAL EXPRESSION OF CATHODIC PROTECTION

The most extensive engineering means of diminishing electrochemical corrosion underground is the basic electrical method called Cathodic Protection. The protection is achieved when the underground structure is caused to become cathodic with respect to the surrounding earth. Since corrosion occurs at the points of the structure where current flows from the metal to the earth, thus constituting anodic points, it can be seen that a sufficiently large current supplied by an external d.c. source, which is connected to force the current through the earth and into the structure, could be applied to negate the free corrosion current. This qualitative description of cathodic protection will not serve as an accurate means of determining the magnitude of the protective current relative to the free corrosion current.

Cathodic protection can be recklessly applied without any knowledge of principles. This is the method of solving a difficult problem in a difficult manner by means of brute force. In contrast to this poor procedure is the method of science: to learn and apply principles if they are known, and to originate and develop principles if they are unknown. A great step forward in the development of cathodic protection was the original theory of cathodic protection in which it is shown that complete protection is attained if the local cell cathode potential is reduced by polarization from the applied current to a value equal to the local cell anode potential.[1] By a different line of reasoning, a second theory of cathodic protection[2] has been postulated which shows that complete protection may be achieved if the local cathode potential is reduced by the ohmic resistance voltage drop of the applied current at the surface of the protected metal to a value equal to the local anode potential. There seemed to be a great deal of difference between the two theories, so the authors of the first theory published another exposition[3] in which they imply that the theory of Ewing is only a part of their own polarization theory. No representation of cathodic protection in electrical circuit form is to be found in any of the three articles cited. The writer proposes: 1) to represent cathodic protection in circuit form, 2) to derive a general expression as the solution of a circuit representation from which the results of both Mears and Brown, and Ewing can be obtained, and 3) to extend the general theory by including the effect of resistivity of the earth, an important effect which has not been considered in the previous theories; the effect of the resistivity of the earth is shown quite clearly in the circuit

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[1] R. B. Mears and R. H. Brown, "A Theory of Cathodic Protection," Transactions of the Electrochemical Society, LXXIV (1938), pp. 519-531.

[2] S. P. Ewing, "Determination of Current Required for Cathodic Protection," Proceedings of The American Gas Association, 1940, pp. 613-622.

[3] R. B. Mears and R. H. Brown, "Cathodic Protection," Transactions of The Electrochemical Society, LXXXI (1942), pp. 455-481.

representation. The value of representing cathodic protection in circuit form lies in its familiarity to the electrical engineer who is accustomed to explanations of various phenomena by means of circuit theory and analysis. Without a sound knowledge of principles, the results of experimentation are incomprehensible. With the aid of principles new types of experimentation can be devised, and the results interpreted. The circuit representation of cathodic protection is referred to herein in terms of equivalent circuits. The equivalent circuits that are shown are exactly equivalent to the cathodic protection system; the only difference is that the distributed resistances of the earth are shown in the equivalent circuit in lumped form as resistors. Though the resistance of the earth is distributed, it is also both finite and determinate, and it can be found from direct measurement by a method presented in the next chapter.

It may seem, as a preliminary conclusion, that a protective current equal in magnitude and opposite in direction to the free corrosion current would result in zero current flow to or from the metal and, hence, no corrosion of the metal would occur. That the preceding statement is misleading and often erroneous may be shown with the aid of an equivalent electrical circuit to represent the local cell of corrosion.

The local cell is represented as the series connection of two half-cells, one for the potential difference at the anode-earth interface, and one for the cathode-earth interface difference of potential. The equivalent circuit is shown in Figure 5. The potentials E_c and E_a of the cathodic and anodic half-cells, respectively, are shown with polarities in series-opposition. This connection of the half-cells is necessary

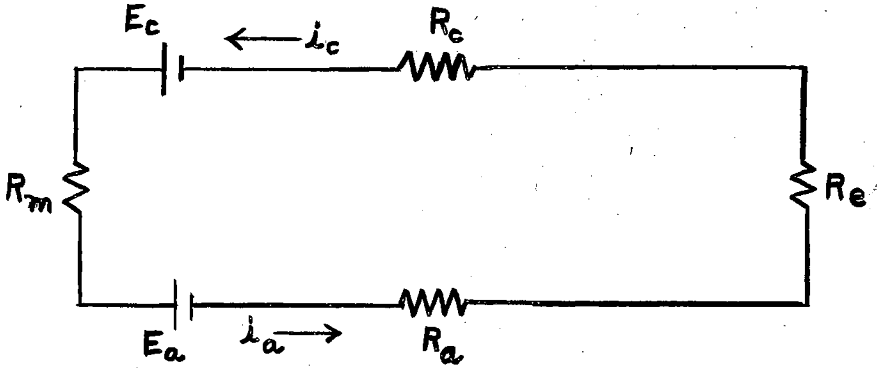

Figure 5. Equivalent Circuit of the Local Cell.

because of the negative algebraic sign of the anodic potential on the Hydrogen Potential Scale, Table I. The resistors R_c and R_a are the ohmic contact resistances of the cathodic and anodic surfaces at the metal-earth interfaces, respectively; R_m and R_e are the resistances of the metallic current path between the cathode and anode and of the earth current path between the two electrodes, respectively. As a first approximation, both R_m and R_e may be neglected; R_m is very small compared with the electrolytic resistances, and the earth itself is a very large parallel path for current flow compared with the surface areas of the cathode and anode. The simplified approximate equivalent circuit, omitting both R_m and R_e, is given in Figure 6.

The two currents, i_c and i_a, shown in Figure 6, are the currents flowing from the cathode and from the anode, respectively. The directions of current flow are conventional, considering again the algebraic sign of the anodic potential

E_a. The cathodic current i_c is shown flowing from the cathode to the metal which joins the cathode to the anode, and the anodic current is shown flowing from the anode to the earthen current path joining the anode to the cathode. Since the complete path for current flow is closed, it is obvious from inspection of this simple series circuit that the anode current is equal to the cathode current, or stated analytically,

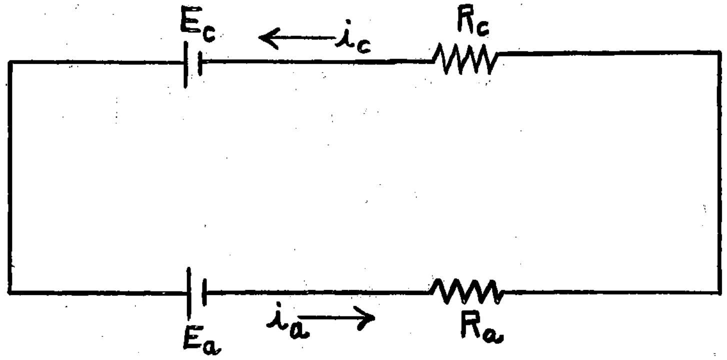

Figure 6. Simplified Equivalent Circuit.

$$i_a = i_c = i_f \tag{2-1}$$

where i_f is the free corrosion current of the local cell. Application of Kirchhoff's Law of voltage summation around the closed circuit yields the equation

$$E_c - E_a = i_c R_c + i_a R_a \tag{2-2}$$

By use of the relationship between currents given by equation (2-1), the voltage equation becomes

$$E_c - E_a = i_f (R_c + R_a) \tag{2-3}$$

or, in the equivalent form of Ohm's Law it is

$$i_f = \frac{E_c - E_a}{R_c + R_a} \tag{2-4}$$

Now, if a protective current is forced into the buried structure from an external d.c. source connected between the structure and an auxiliary ground anode, then the equivalent circuit must be altered to include the external source. The new equivalent circuit containing the external current source is given in Figure 7. E_{bb} is the external applied voltage,

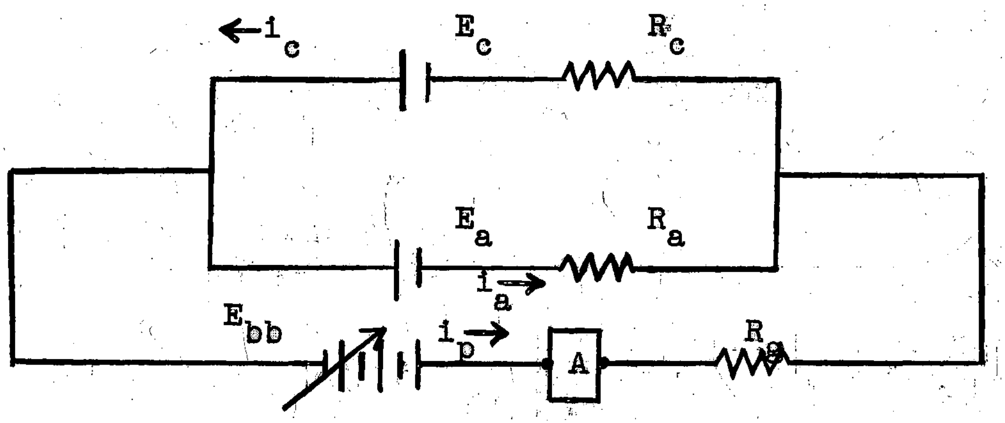

Figure 7. Equivalent Circuit with Protection Applied.

R_g is the resistance of the auxiliary anode to ground, i_p is the protective current, and A is the auxiliary anode.

A voltage summation equation can be written around the loop of the two parallel branches as

$$E_c - E_a = i_c R_c + i_a R_a \tag{2-5}$$

which is identical to equation (2-2). Kirchhoff's Law for the summation of currents at a junction gives the relation

$$i_c = i_p + i_a \tag{2-6}$$

Substitution of equation (2-6) into (2-5), in order to eliminate i_c, results in the new equation:

$$\begin{aligned} E_c - E_a &= (i_p + i_a)\, R_c + i_a R_a \\ &= i_p R_c + i_a\,(R_c + R_a) \end{aligned} \tag{2-7}$$

from which, by rearrangement of terms,

(2-8) $$\frac{E_c - E_a}{R_c + R_a} = i_p \frac{R_c}{R_c + R_a} + i_a$$

For complete protection, the local anode current i_a must be reduced to zero. Imposing the condition $i_a = 0$ upon equation (2-8),

(2-9) $$\frac{E_c - E_a}{R_c + R_a} = i_p \frac{R_c}{R_c + R_a}$$

The left side of equation (2-9) is recognized, from equation (2-4), as the free corrosion current of the local cell. Therefore, the preceding expression can be written as

(2-10) $$i_f = i_p \frac{R_c}{R_c + R_a}$$

which relates the free corrosion current to the protective current. Rearranging this equation,

(2-11) $$i_p = i_f \frac{R_c + R_a}{R_c} = i_f \left(1 + \frac{R_a}{R_c}\right)$$

Thus, only if the anode resistance R_a is very small compared to the cathode resistance R_c does equation (2-11) reduce to

(2-12) $$i_p = i_f (1 + 0) = i_f$$

which states that the protective current i_p is equal in magnitude to the free corrosion current i_f. The currents i_f and i_p flow in opposite directions, as has been indicated in Figure 7. In general, then, equation (2-11) shows that the protective current i_p may be equal to the free corrosion current, as given in equation (2-12), but if the anode resistance R_a is appreciable then i_p is always greater than i_f and may be much greater by its dependence upon the ratio of

R_a to R_c.

The measurable electrical quantity usually regarded as the dominant factor in electrochemical corrosion is the potential of the buried structure. The potential of an electrode is dependent upon the temperature of the electrode, its particular constituent materials, and the composition of the electrolyte with which it is in contact, as has been mentioned in Chapter I, but the potential is also dependent upon the surface density of the current flowing to or from the electrode.[4] In general, the electrode potential can be expressed as

$$E = F\ (T,\ M,\ C,\ J) \qquad (2\text{-}13)$$

in which the electrode potential E is a function of its temperature T, its materials of construction M, the electrolyte composition C, and the current density J on the surface of the electrode. For a given buried structure, the quantities C and M do not vary and T varies only slightly, so these can be taken as essentially constant in value. Under these conditions, the potential of the given electrode is a function of the surface current density; or

$$E = f\ (J) \qquad (2\text{-}14)$$

The surface current density J may be caused entirely by the free corrosion current, or it may be altered by controlled application of an external protective current. The open-circuit potentials of most metal electrode materials are known, some

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[4] A. Hickling, "Studies in Electrode Polarization", *Transactions of the Faraday Society*, XXXVIII (1942), p. 27.

of which have been given in Table I. With a current flow to or from the electrode, the closed-circuit potential differs from the open-circuit potential by the (IR) ohmic resistance voltage drop and by the polarization of the electrode caused by the current flow. Polarization itself was not mentioned in the preceding development of the conditions for cathodic protection. However, from the fact that current flows through the anodic and cathodic half-cells in both the freely corroding local cell and the cathodically-protected local cell, the potentials E_a and E_c are closed-circuit potentials——the actual potentials of the anode and cathode, respectively, while there is a flow of current. The potentials E_a and E_c, then, are not true open-circuit potentials, regarding open-circuit potentials as the values corresponding to no current flow.

It will be recalled from the discussion of polarization in Chapter I that this phenomenon is entirely caused by current flow. When there is no current flowing to or from a buried metal surface, the potential of the metal is a constant fixed value such as the values listed in Table I for various metals. Only when there is a current flow do the potentials change or deviate from the constant fixed values. The current in an electrolyte is a flow of both positive and negative ions, actually a flow of the matter or mass of which the metal electrodes are composed, as distinguished from the ordinary current flow in a metallic conductor which is a drift of free electrons from atom to atom of the conductor. As positive ions are deposited on the cathode surface, these ions form a sheath about the cathode which tends to become a more complete shield around the cathode as the magnitude of the current flow is increased. As the shield becomes more complete, the potential of the cathode becomes more the potential of the ion sheath than the potential of the metal of which the cathode is composed. In any electrolyte containing moisture, such as the earth, the positive ion is the hydrogen ion, which is lower on the Hydrogen Potential Scale than any of the cathodic metals (see Table I). Therefore, the cathode potential is reduced in the anodic (more negative) direction, but again only when there is an ion current flow. The reduction in the cathode potential is called polarization, and the magnitude of the potential reduction is called the polarization emf. Thus, the magnitude of the change or deviation in the constant fixed reference value of potential is the polarization emf. The equations containing polarization terms will be correlated with experimental electrical measurements in Chapter V in a quantitative manner which was previously unknown.

The changes in the open-circuit potentials of the anode and cathode caused by flow of current, which are the polarization voltages, depend upon the direction of current flow at the two electrode surfaces. The direction of the protective current flow has been indicated in Figure 7 to add to the cathodic current flow and to oppose the anodic current. Reversal of the direction of protective current flow is of no value since this would decrease the cathodic current, increase the anodic current, and the externally applied current would be destructive rather than protective. The externally applied current, therefore, will always be considered to flow as a protective current. With this customary current flow direction now established, it is possible to relate the open-circuit potentials to the closed-circuit potentials.

Denoting the cathodic polarization voltage as

(2-15) $$\Delta E_c = f_c\,(J_c),$$

since this is the deviation from the fixed reference value, where J_c is the cathodic surface current density

(2-16) $$J_c = \frac{i_c}{S_c}$$

and S_c is the surface area of the cathode. Then the anodic polarization voltage is expressed as

(2-17) $$\Delta E_a = f_a\,(J_a)$$

in which J_a is the anodic surface current density

(2-18) $$J_a = \frac{i_a}{S_a}$$

and S_a is the surface area of the anode. The current densities J_c and J_a are apparent values rather than actual values because the surface areas S_c and S_a are of necessity obtained from geometrical consideration when possible, whereas the surface areas are not smooth under a microscopic examination. The actual areas, then, are in general greater than the apparent areas, resulting in higher apparent current densities than the actual densities.

With the various currents flowing in the directions shown in Figure 7, it is possible to write[5]

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[5] The right members of equations (2-19) and (2-20) are equivalent to the polarization functions of Mears and Brown, loc. cit.

(2-19) $$E_c = E_{co} - \Delta E_c = E_{co} - f_c(J_c)$$

and

(2-20) $$E_a = E_{ao} + \Delta E_a = E_a + f_a(J_a)$$

because the cathodic current flow decreases the open-circuit cathode potential E_{co} by the amount of the polarization voltage ΔE_c, but the anode current flows from that electrode and the change in potential ΔE_a is in the opposite direction[6] in its effect upon the open-circuit anode potential E_{ao}. The quantities in equations (2-19) and (2-20) should be examined with due regard to the algebraic signs of the various component terms. With respect to the Hydrogen Scale of potential measurement, cathodic potentials are inherently positive and anodic potentials are negative. Primarily, the polarization voltages are chosen as functions of the electrode current densities, rather than selecting the actual potentials E_c and E_a as the functions, because this choice of notation in equations (2-19) and (2-20) indicates that the actual electrode potentials differ from the constant reference potentials E_{co} and E_{ao} only when current flows. Furthermore, the choice of algebraic signs indicates in which direction the actual potentials deviate from the reference values, since the polarization voltages are inherently positive.

Substitution of equations (2-19) and (2-20) into equation (2-5) yields an expression in terms of open-circuit potentials, polarization voltages, and current densities:

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[6] U. R. Evans, <u>Metallic Corrosion, Passivity, and Protection</u>, (London, 1946), p. 19.

$$(2\text{-}21) \qquad \begin{aligned} E_c - E_a &= E_{co} - E_{ao} - (\Delta E_c + \Delta E_a) \\ &= E_{co} - E_{ao} - f_c(J_c) + f_a(J_a) \\ &= i_c R_c + i_a R_a \end{aligned}$$

Equating the latter two forms of (2-21), eliminating E_c and E_a,

$$(2\text{-}22) \qquad E_{co} - E_{ao} = i_c R_c + f_c(J_c) + i_a R_a + f_a(J_a)$$

and the protective current i_p can be introduced by use of equation (2-6), eliminating i_c, giving

$$(2\text{-}23) \qquad \begin{aligned} E_{co} - E_{ao} &= (i_p + i_a) R_c + f_c(J_c) + i_a R_a + f_a(J_a) \\ &= i_p R_c + f_c(J_c) + i_a (R_c + R_a) + f_a(J_a) \end{aligned}$$

Again, for complete protection, the anodic current must be reduced to zero; also, the anodic polarization voltage function $f_a(J_a)$ must be zero, since the anodic current is zero. Inserting these conditions in equation (2-23), it becomes

$$(2\text{-}24) \qquad E_{co} - E_{ao} = i_p R_c + f_c(J_c)$$

or, equivalently,

$$(2\text{-}25) \qquad E_{ao} = E_{co} - f_c(J_c) - i_p R_c$$

Equation (2-25) is a quantitative statement to the effect that, for complete protection to be achieved, the open-circuit cathode potential E_{co} must be reduced by both cathodic polarization $f_c(J_c)$ and by ohmic resistance drop ($i_p R_c$) to the open-circuit anode potential E_{ao}. This statement also is indicative of a very important basic consequence of applying "cathodic protection": the potential of the "cathodically-protected" structure is actually forced to become <u>anodic</u> in order to achieve <u>cathodic</u> protection. The structure is cathodic because current is forced to flow from the earth to the structure, in the conventional sense; but as the cathodic protection current is increased, the potential of the structure becomes increasingly anodic. When the potential of the structure becomes sufficiently anodic, as indicated by equation (2-25), complete cathodic protection is realized. An understanding of the electrode potential phenomenon presented here is fundamental to comprehension of the essential principle of cathodic protection, though the textbook explanations tend to present and to dismiss the entire subject with the qualitative statement that an external d.c. source is connected to the structure in such a way that current is forced through the earth to the structure. It is obvious that cathodic protection is actually more scientifically precise than such a qualitative statement implies, and further that it is subject to explanation by quantitative methods of electrical circuit analysis.

Equation (2-25) is the general statement of complete cathodic protection including the effects of both polarization and ohmic resistance, as obtained by the author. It is the origin of two less general relations emphasizing polarization and ohmic resistance, individually, as the predominant factor. In case polarization of the cathode is impossible or is negligible, equation (2-25) reduces to

$$E_{ao} = E_{co} - i_p R_c \tag{2-26}$$

(2-26) states[7] that, for complete protection, the open-circuit

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[7] This is the theory of Ewing.

cathode potential E_{co} must be reduced by the ohmic resistance voltage drop (i_pR_c) to a value equal to the open-circuit anode potential E_{ao}. If, on the other hand, polarization of the cathode occurs and the ohmic resistance R_c of the cathode surface is negligible, equation (2-25) becomes

$$E_{ao} = E_{co} - f_c(J_c) \tag{2-27}$$

which shows that, for complete protection in the absence of ohmic cathode resistance, the cathode potential must be reduced by polarization to a value equal to the anode open-circuit potential E_{ao}. In other words, the cathode must be polarized to the anode open-circuit potential.[8] Both of these equations, (2-26) and (2-27), are to be interpreted physically as indications that it is the cathode potential which is altered by the application of cathodic protection, and that, in both cases, the <u>cathodic</u> potential is forced in the <u>anodic</u> direction. It cannot be overemphasized that the <u>cathodic</u> potential must be made sufficiently <u>anodic</u>, according to the conditions of equations (2-26) and (2-27), in order to achieve complete <u>cathodic</u> protection.

The paradox of forcing the potential of a structure in the anodic direction in order to cause the same structure to become cathodic is, like the apparent discrepancy regarding the direction of charge motion in the electrolyte discussed in Chapter I, the result of the commonly accepted usage of the words anode and cathode. The algebraic signs of anodic and cathodic potentials, referred to the Hydrogen Scale, are

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[8] This is the theory of Mears and Brown.

based upon the direction of flow of the conventional current in the circuit external to the electrolytic cell, and the conventional current is regarded as a flow of positive charge. Then the conventional current of positive charge must appear to flow from anode to cathode, from negative to positive, within the cell. Whether current is regarded conventionally as a flow of positive charge or is considered as a flow of negative charge or both types of charge are assumed to flow simultaneously, the (±) charge within the electrolyte will appear to flow toward the electrode with the same (±) sign. The confusion of the positive and negative signs is increased, perhaps, by the older usage in chemistry texts of a <u>positive</u> sign with <u>anodic</u> potentials and a <u>negative</u> sign with <u>cathodic</u> potentials. In this usage, the <u>positive</u> charge within the electrolyte appears to move toward the <u>negative</u> electrode, and vice versa, with the result that in the circuit external to the cell the positive charge appears to flow from the negative electrode, and vice versa. The different use of the (±) polarity signs by the chemist is probably the result of the chemist's primary interest in the phenomena of the electrolytic cell itself, whereas the engineer may be primarily concerned with the phenomena of the circuit external to the cell. The difference is apparently one of relative viewpoint, and is only the expression of an alternative concept of the same general physical action: motion of charge. The conventional engineering positive and negative signs for cathodic and anodic potentials, respectively, have been used consistently herein; these polarity signs are the standard notation of the current periodical literature.

EFFECT OF THE RESISTIVITY OF THE EARTH

If the local anode and cathode of the corrosion cell are so widely separated that the resistance of the earth to current flow cannot be neglected, the equivalent circuit must be altered. For the freely corroding cell, the effect of the resistivity of the earth is represented by an additional resistance in the circuit of Figure 8.

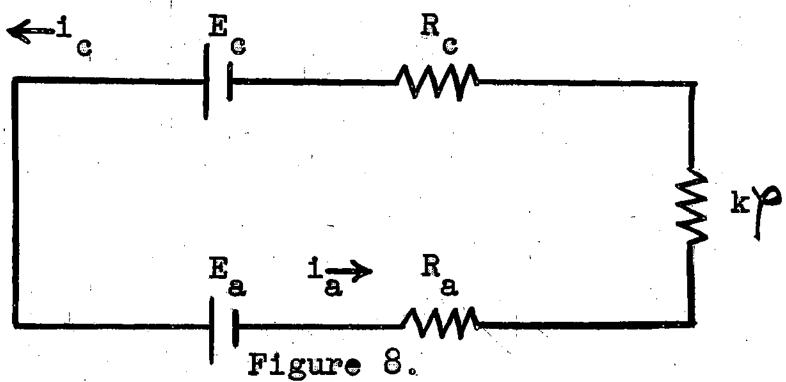

Figure 8.
Local Cell Equivalent Circuit, including Earth Resistivity.

The additional resistance $k\rho$ is the effect of the resistivity of the earth, where ρ is the resistivity of the earth and k is a proportionality factor[9]. Solution of this circuit gives the current and voltage equations

(2-28) $i_a = i_c = i_f$, the free corrosion current,

and

(2-29) $E_c - E_a = i_f\ (R_a + R_c + k\rho)$

Or, the free corrosion current is

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[9] k corresponds to the indeterminate ratio of length to cross-sectional area; see equation (1-4).

(2-30) $$i_f = \frac{E_c - E_a}{R_a + R_c + k\rho}$$

Application of an external protective current to the corrosion cell can be represented by expanding the equivalent circuit of Figure 8 to include the external d.c. source and auxiliary anode. The two resistances $a\rho$ and $c\rho$ are the two component parts of the earthen resistance $k\rho$, so that

(2-31) $$k\rho = a\rho + c\rho = (a + c)\rho$$

or

(2-32) $$k = a + c$$

where a and c are proportionality factors for the anode and cathode, respectively. Figure 9 shows the new circuit.

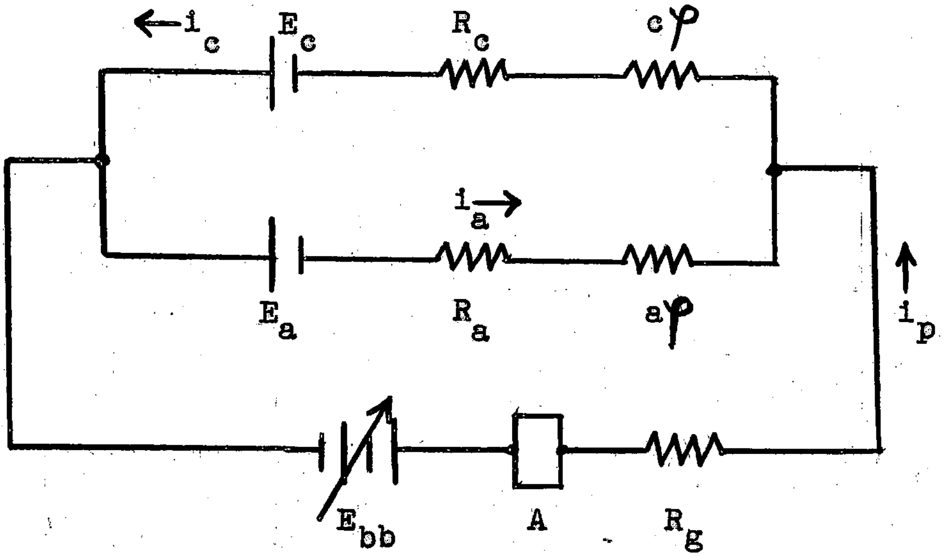

Figure 9.

Equivalent Circuit including Earth Resistivity, with Protection Applied.

For the closed loop of the two parallel circuits, the voltage summation equation is

(2-33) $$E_c - E_a = i_c (R_c + c\rho) + i_a (R_a + a\rho)$$

The current equilibrium equation for the entire equivalent circuit is

(2-34) $$i_c = i_p + i_a$$

Elimination of the current term i_c between equations (2-33) and (2-34) gives

(2-35) $$\begin{aligned} E_c - E_a &= (i_p + i_a)(R_c + c\varphi) + i_a\,(R_a + a\varphi) \\ &= i_p\,(R_c + c\varphi) + i_a\,(R_a + R_c + a\varphi + c\varphi) \\ &= i_p\,(R_c + c\varphi) + i_a\,(R_a + R_c + k\varphi) \end{aligned}$$

from which is obtained

(2-36) $$\frac{E_c - E_a}{R_a + R_c + k\varphi} = i_p\,\frac{R_c + c}{R_a + R_c + k\varphi} + i_a$$

Now the term on the left side of (2-36) is recognized as the free corrosion current of (2-30), and the result is

(2-37) $$i_f = i_p\,\frac{R_c + c\varphi}{R_a + R_c + k\varphi} + i_a$$

Imposing the condition for complete cathodic protection that the anodic current i_a becomes zero,

(2-38) $$i_f = i_p\,\frac{R_c + c\varphi}{R_a + R_c + k\varphi}$$

This is the equation relating the free corrosion current i_f to the applied protective current i_p when complete cathodic protection is achieved. This equation can be rewritten as

(2-39) $$\begin{aligned} i_p &= i_f\,\frac{R_a + R_c + k\varphi}{R_c + c\varphi} \\ &= i_f\,\frac{R_a + R_c + a\varphi + c\varphi}{R_c + c\varphi} = i_f\,\left(1 + \frac{R_a + a\varphi}{R_c + c\varphi}\right) \end{aligned}$$

Inspection of equation (2-39) reveals that the applied protective current i_p can never be less than the free corrosion current i_f, though i_p may be equal to i_f. Furthermore, i_p is in general greater than i_f by an amount depending upon the ratio of total resistance in the cathodic current path to total resistance in the anodic current path. The term "total resistance" includes electrode surface resistance plus the resistance of the earth in the electrode current path.

Polarization can be included in the equations by employing the method of a previous section. By introducing the polarization equations (2-19) and (2-20) into equation (2-35), there results

$$(E_{co} - \Delta E_c) - (E_{ao} + \Delta E_a) = i_p\,(R_c + c\rho) + (R_a + R_c + k\rho) \tag{2-40}$$

or, by rearranging the terms, and also from (2-15) and (2-17),

$$E_{co} - E_{ao} = i_p\,(R_c + c\rho) + f_c(J_c) + i_a\,(R_a + R_c + k\rho) + f_a(J_a) \tag{2-41}$$

Now, when complete protection is realized the anodic current i_a is zero; also, since i_a is zero, there is no polarization of the anode, hence $f_a(J_a) = 0$. So,

$$E_{co} - E_{ao} = i_p\,(R_c + c\rho) + f_c(J_c) \tag{2-42}$$

or, in a slightly different form,

$$E_{ao} = E_{co} - f_c(J_c) - i_p\,(R_c + c\rho) \tag{2-43}$$

Equation (2-43) is to be interpreted physically as a statement that the cathodic potential E_{co} must be polarized and further reduced by the ohmic voltage drop to a value equal to the open-circuit anodic potential E_{ao}. The open-circuit cathode potential E_{co} must be shifted in the anodic direction, i.e., the cathodic potential must become more negative. The author's usage of the terms cathodic and anodic, and the polarities associated with each, are in accordance with the notation employed in the current literature.

Typical approximate values[10] of the resistivity of a few types of soil are given in Table III. It will be noticed that, since the earth is an electrolyte, the resistivity is extremely large compared with the resistivities of the common metals. Resistivities of a few metals are given[11] in Table IV. The metal resistivities are from one-millionth to one-billionth the values of the earth resistivities. In addition to the variation of the resistivity of the earth with the particular type of soil, there is enormous variation of soil resistivity with moisture content and temperature[12]. In the range of temperature variation from a few degrees above freezing to summer soil temperatures, the variation of soil resistivity may be of the order of 100 to 1. Depending upon the moisture content of the same soil in different seasons of the year, the soil resistivity may vary more than 100 to 1.

As will be noticed from inspection of equation (2-38), the presence of the $k\rho$ term in the denominator shows that both the free corrosion current and the applied protective current are of smaller magnitude, because of the effect of the resistivity of the earth, than each current was previously

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[10] W. J. Creamer, *Elements of Electrical Engineering* (New York, 1948), p. 58.

[11] *Ibid.*, p. 323.

[12] B. McCollum and K. H. Logan, *Electrolysis Testing* (Washington, D.C., 1927), p. 56.

TABLE III

RESISTIVITIES OF THE EARTH

Element	Resistivity, ohm-centimeters
Dry River Sand	Very Large
Dry Earth	10^6 or greater
Fresh Water	10^4 to 10^6
Wet Sand	10^2 to 10^4
Wet Clay	10^2 to 10^4
Moist Earth	10^3 to 10^5
Sea Water	10^2

TABLE IV

RESISTIVITIES OF METALS

Material	Resistivity, ohm-centimeters, 20°C.
Aluminum	2.92×10^{-6}
Graphite	720×10^{-6}
Copper (annealed standard)	1.72×10^{-6}
German Silver	33.8×10^{-6}
Gold	2.44×10^{-6}
Iron (pure)	10.0×10^{-6}
Iron (hard cast)	$(75 \text{ to } 100) \times 10^{-6}$
Silver (pure)	1.64×10^{-6}
Steel (hard)	45.0×10^{-6}
Steel (soft)	11.8×10^{-6}

in equation (2-10). Physically it is reasonable that high soil resistivity results in high resistance to free corrosion current, and, therefore, both the free corrosion current and the applied protective current will be lower. This is an important effect to be considered which has not even been mentioned in the cited works of Mears and Brown, and Ewing. In fact, the resistivity of the earth, which can be obtained by direct measurement, is a simple method of determining the corrosive areas along a structure of extensive size such as a pipeline. The writer has observed that in low, moist areas where the soil resistivity is relatively small, corrosion is more severe. In the high, arid areas where the soil resistivity is relatively great, corrosion is less severe. Actual measurement of the soil resistivity along the pipeline right-of-way will indicate the places where corrosion is the worst, if leaks have not already been noticed, and these are the places where cathodic protection is necessary. The additional theory in this chapter, contributed by the author, on the effect of the resistivity of the earth is a useful means of explanation for the differing results obtained by investigators who measure similar structure potentials but find different amounts of corrosion in different soils.

It is usually fallacious to believe that the metal dissolved by the anodic current i_a is deposited on the cathode when the corrosion occurs with the earth as the electrolyte. Ordinarily, hydrogen is evolved at the cathode, and the dissolved metal from the anode remains in the earth. This is similar to the action of the zinc-copper cell in Figure 2, Chapter I. The resistance R_c, which has been defined as the ohmic resistance of the cathode surface, is composed primarily of a film of hydrogen ions that forms as a result of current flow from the electrolyte to the cathode. It has been noted by the writer many times that an applied protective current diminishes in magnitude as the elapsed time of application increases. As the film becomes more complete, cathodic polarization and ohmic resistance both become greater. Cathodic polarization decreases the voltage available for forcing a corrosion current to flow, and increased cathodic resistance also decreases the current flow in the manner shown by Ohm's Law. Because of the protective nature of the cathode film, it is better to apply an overly large protective current initially so as to form the film as quickly as possible. Then the current can be decreased later in order to effect a long-time economy in operating expense. The formation of the film results in the current necessary for protection being less after a period of application than it was at the beginning.

Several causes of the formation of local cells on a buried structure were given in Chapter I, among which is the variable nature of the constituents of both the structure and the earth. The local cells thus formed are of differing magnitudes in physical size and in electrical potential difference. There are a number of local cells, each with a local cathode and local anode, present upon a buried structure. As the anodic areas grow in size, so do the cathodic areas grow larger because of the evolution of hydrogen at these areas and the resulting film. Ultimately, an equilibrium condition is realized in which every different part of the surface is either anodic or cathodic, and the structure is then similar to a large local cell. The aim of cathodic protection is to transform the structure from the status of a cell with an anode and a cathode to the status of cathode in a cell composed of the structure and the auxilary anode. That cathodic protection actually does transform a structure with local cells into a structure which is itself a cathode will be shown in Chapter V.

CHAPTER III

MEASUREMENT OF POTENTIAL, CURRENT, AND RESISTIVITY

MEASUREMENT OF POTENTIAL

In Chapter II, it was mentioned that polarization changes both the potential and the resistance of an electrode. These two simultaneous effects may be visualized if it is recalled that a current flow in an electrolyte is a flow of ions, and that the ions form a sheath on and about the electrode surface. As the ion sheath becomes more nearly complete, the potential of the electrode becomes more nearly that of the ion sheath rather than that of the electrode material. Also, the effective area of the electrode is reduced by the ion sheath, so that the ohmic resistance is increased.

Experimental data must be utilized in order to determine the actual magnitude of the potential of a buried ferrous structure. The potentials listed in Table I, The Potential Series of the Metals, cannot be relied upon to furnish accurate values for a structure in the earth[1] because the Series is referred to a fixed set of standard conditions not obtainable in the field. However, the potential of a buried structure can be measured with the circuit arrangement used by the author shown in Figure 10. Electrical contact with the structure may be made with a sharpened iron or steel rod. The

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[1] F. L. LaQue and B. B. Knapp, "Planning and Interpreting Corrosion Tests", a paper presented to the Division of Petroleum Chemistry, American Chemical Society, September 11-15, 1944, New York, New York.

potential difference between the structure and the reference half-cell, represented schematically as

(3-a) structure | earth | solution | electrode

is equal to the reading of the potentiometer when there is no galvanometer deflection. Obviously, the measured potential is dependent upon the reference half-cell used. The use of the term "half-cell" is apparent from inspection of (3-a), in which the entire cell is composed of 1) the reference half-cell, and 2) the half-cell formed by the structure and the earth. The reference half-cell contains a metal electrode in contact with a specified solution. A reference half-cell found by the author to be very reliable in the reproducibility of its readings is the calomel half-cell, frequently called the calomel electrode. The calomel reference electrode (half-cell) consists[2] of pure mercury in contact with a paste of

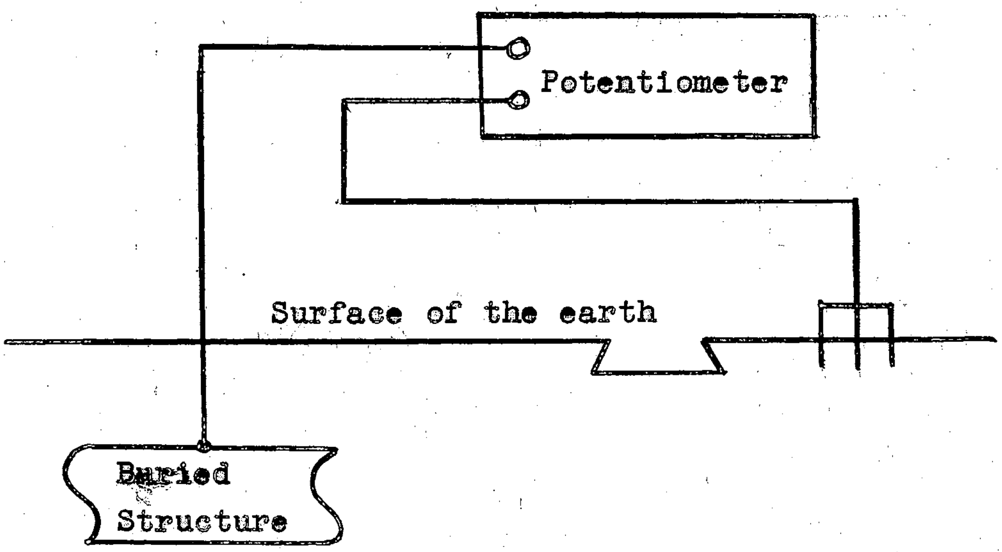

Figure 10. A Potential Measuring Circuit.

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[2] F. K. Harris, Electrical Measurements (New York, 1952), p. 192.

mercury and mercurous chloride (calomel), and a solution of saturated potassium chloride (KCl).

On the Hydrogen Scale, the potential of the saturated calomel electrode[3] is about +0.2801 volts. A potential measurement of the type shown in Figure 10, sometimes called the potential of the structure with respect to the ground, is a true open-circuit potential in the sense that there is no external source of current to complicate the measurement with polarization of the structure surface from the applied current. A rather arbitrary value of potential, -0.85 volts with respect to the saturated copper-copper sulphate reference electrode, has long been in use as a rule-of-thumb criterion in the determination of a suitable value of potential indicative of protection[4]. The value of -0.85 volts is equivalent to a value of about -0.78 volts with respect to the saturated calomel reference electrode[4]. That is, the saturated calomel electrode is about 0.07 volts negative to the copper-copper sulphate electrode, or the potential of the latter electrode is about +0.3501 volts on the Hydrogen Scale.

A connection between the rule-of-thumb potential criterion and the author's comments at the close of Chapter II concerning the importance of the resistivity of the earth is this: The writer has noticed that in the low, wet, most corrosive areas that the measured potential is often already more anodic

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[3] Ibid. p. 192.

[4] S. P. Ewing, "Potential Measurements for Determining Cathodic Protection Requirements," Corrosion, VII (1951), p. 411, 416.

(negative) than the -0.85 volts, or -0.78 volts, criterion for protection. Therefore, the structure should be adequately protected without cathodic protection; but, as has been mentioned, these are the most corrosive areas where the potential is found to be most anodic (negative). In the higher, dry, areas the potential is often measured to be less anodic, or more positive, than the rule-of-thumb criterion indicates for protection; but, again, these are the least corrosive areas though the arbitrary potential criterion would indicate the installation of cathodic protection as a necessity in these areas. A potential criterion is believed to be a possibility, but not a single fixed value indicative of adequate protection in any and all soil environments. The fallability of the single fixed potential criterion will be illustrated by experimental results in Chapter V.

If an external direct-current source and an auxiliary anode are provided for the purpose of cathodic protection, the circuit arrangement becomes that pictured in Figure 11. The protective currents, i, forced through the earth and into the structure are not confined to any particular path or paths in the earth itself, hence these currents enter the structure from many different directions. As indicated in Figure 11, some of the many currents introduce (IR) voltage drops in the earth between the structure and the reference electrode. The potential now measured by the potentiometer as existing between the structure and the reference electrode includes a resultant (IR) voltage drop in the earth itself. If the structure is small in size then the protective current is of small magnitude.

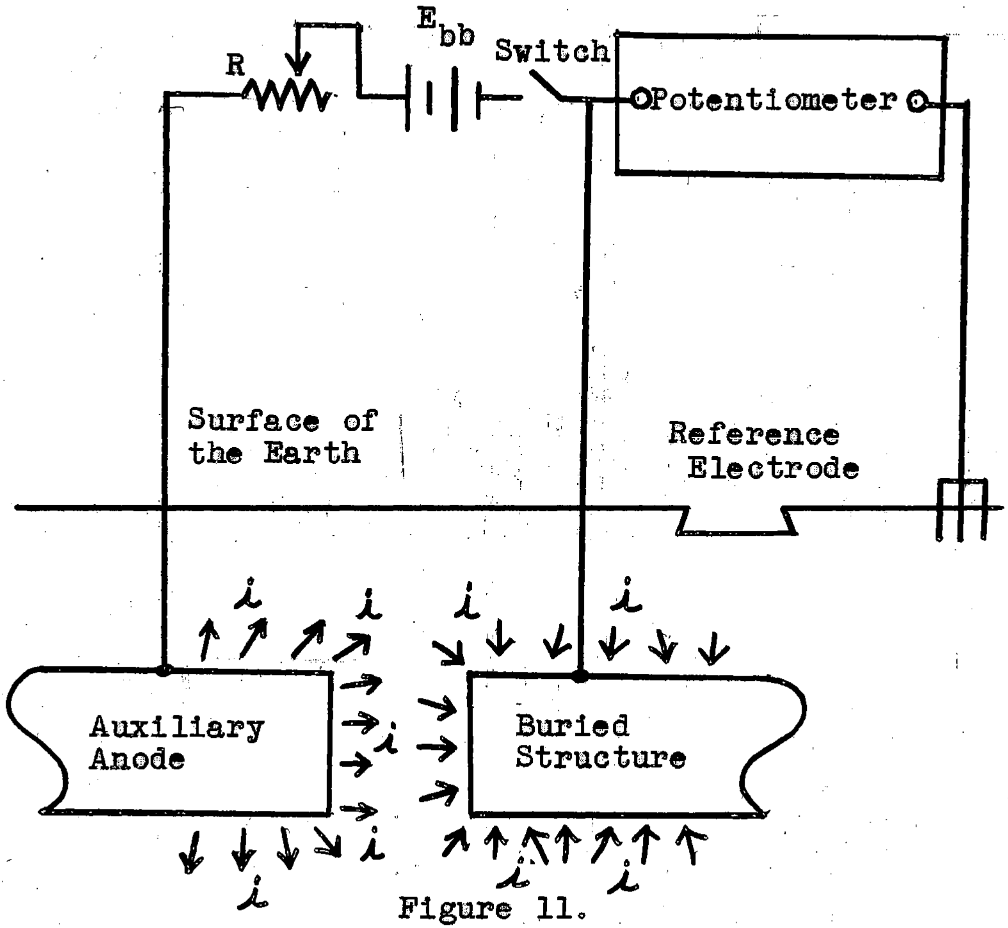

Figure 11.

A Potential Measuring Circuit, with Protection Applied.

In this case, the (IR) drop in the earth is almost completely negligible, and the measuring circuit of Figure 11 will indicate the true potential of the structure even though there is a current flow in the earth. Particularly is this true if the structure is a section of only one pipe-line, a small specimen, a short surface flow line, et cetera, in view of the fact that the physical size of the structure has a direct bearing on the magnitude of the applied current. If the structure is of great size, such as a network of surface flow lines, the junction of several pipelines, or a well-casing several thousand feet long, the magnitude of the applied current may be large enough to produce an appreciable (IR) drop in the earth between the reference electrode and the structure.

One method that has proved useful, after a considerable amount of manual practice, in obtaining true open-circuit potential readings on large extensive structures, as well as small ones, is to disconnect the source at the switch and quickly to balance the potentiometer[5]. This method was shown in the cited reference[5] to compare favorably in accuracy to the use of compensated-bridge methods of potential measurement reported by others[6]. The writer performed the experimental work described in the reference[6] jointly with its author.

The use of the term "true open-circuit potential" should be noted at this time. In Chapter II, the condition developed for complete cathodic protection in equation (2-25) indicated that the open-circuit cathode potential must be reduced by both cathodic polarization and ohmic resistance potential drop to a value equal to the open-circuit anode potential. Both of these potential drops are considered to occur on or at the surface of the metallic structure; this (IR) drop should not be confused with the (IR) drop in the earth itself which occurs external to the metal surface. It is the (IR) drop in the earth which sometimes obscures accurate measurement of both the true structure potential and the changes in this potential caused by the applied current. By disconnecting

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[5] Ibid. p. 418.
[6] Ibid. pp. 417-418.

the switch in Figure 11, the current is reduced to zero; therefore, the (IR) drop in the earth is zero. The potential measurement—if made quickly—indicates the effect of polarization on the structure potential, since several minutes are required for depolarization. A judicious setting of the potentiometer, for least effort in balancing the reading, is the result of some experience with this method.

An original compensated-bridge circuit which the writer aided in developing, under the direction of the author of the previously cited reference[6], is shown in Figure 12.

The bridge proper is composed of the one megohm resistor, which provides two of the arms, and of the earth itself which provides the other two arms. A basic difference between this bridge and the usual bridge composed entirely of passive circuit elements is that sources of voltage—active network elements—are present in the two half-cell electrodes and in the adjustment circuit directly on the left of the one megohm resistor.

In order to balance the bridge circuit, it is necessary to place Electrode 1 as far from the buried structure as is necessary to include as much of the effect of the structure as is desirable. Also, Electrode 2 should be set in closer proximity to the auxiliary anode so that sufficient difference of potential exists between the two electrodes for the balancing of the bridge. The proper placement of the two electrodes should be such that Electrode 1 is far enough away from the buried structure to include the effect of the structure, and that Electrode 2 is located between Electrode 1 and the

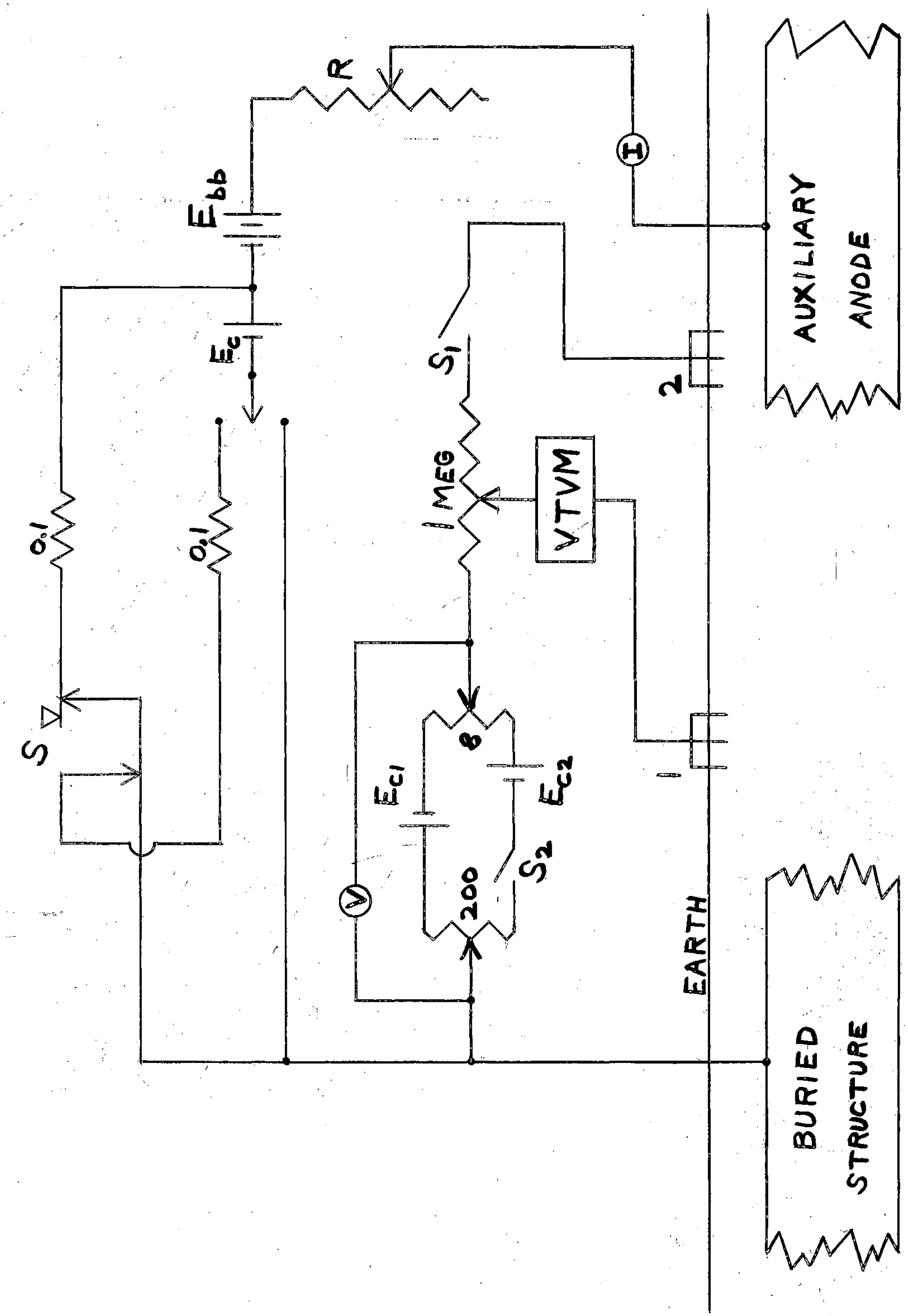


Figure 12. A Compensated-Bridge Potential Measuring Circuit.

auxiliary anode but near enough to the anode to ensure that voltage between the two electrodes is great enough for a balance of the bridge.

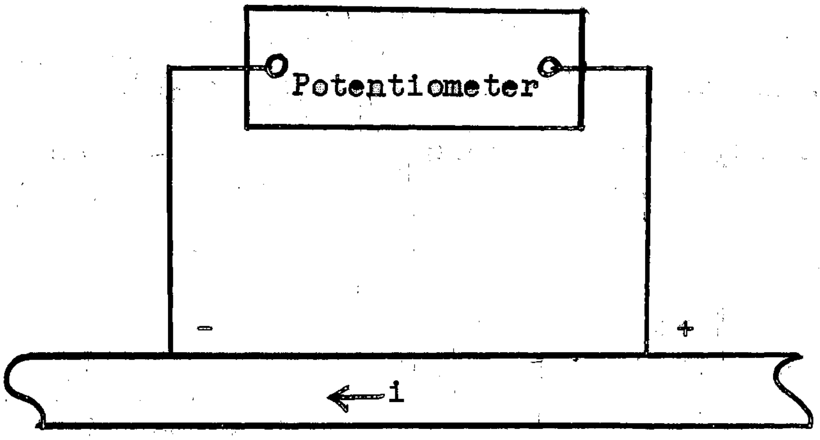
A true open-circuit potential measurement of the structure is obtained by opening both the auxiliary anode circuit and switch S_1, and then adjusting the two voltage-dividers until there is no deflection of the VTVM. This can be seen to be the equivalent of the previous potential measurement method, with the circuit of the two voltage-dividers replacing the potentiometer. The potential is indicated by voltmeter V. With the auxiliary anode circuit closed, so that a protective current is forced onto the structure, the (IR) drop in the earth is compensated by closing both switches S_1 and S_2, and then adjusting the movable contact on the megohm resistor until the deflection of the VTVM is unchanged when the switch in the anode circuit is depressed. The (IR) drop in the earth between the structure and the nearest electrode is then equal to the voltage between the movable contact and the structure appearing in the circuit containing the two voltage-dividers. Now, the two voltage-dividers are adjusted for a zero deflection on the VTVM, and the true potential is again indicated by V. The potential indicated by voltmeter V is, in both cases, the potential of the structure with respect to the near electrode.

E_{bb} is of the order of 6 to 12 volts d.c.; E_{c1} and E_{c2} are small dry cells. R is a variable rheostat used to adjust the magnitude of the applied protective current. VTVM is a high input-impedance vacuum-tube voltmeter serving as the bridge balance detector; it is not necessary that the voltmeter V be a vacuum-tube instrument.

This compensated-bridge is subject to several limitations. First, it cannot be used for measurements on small structures because the bridge itself may occupy a linear distance on the surface of the earth up to fifty feet; in other words, this bridge is not entirely contained within the confines of an instrument case. As has been previously mentioned, this bridge is for use with very large, extensive structures. This bridge is not automatic: each time the magnitude of the applied current is changed, the bridge must be balanced again by the operator. A stable balance of the bridge is sometimes difficult to attain. This circuit was developed especially for potential measurements on deep wells several thousand feet long.

MEASUREMENT OF CURRENT

The current flow in a horizontal structure, such as a pipeline, can be determined with the aid of the measurement arrangement developed by the author shown in Figure 13. Both the magnitude and polarity of the voltage drop in the pipe between the two steel probes can be determined from the potentiometer reading at balance. Since no current flows through the potentiometer when it is balanced, this is an accurate measurement of the overall voltage drop. The resistance of the pipe can be calculated from geometrical considerations, and the current can be found from Ohm's Law. The interpretation of the potentiometer reading depends somewhat upon the distance between the probes.



Buried Pipeline

Figure 13. A Current Measuring Circuit.

If the distance is relatively short, of the magnitude of a few feet, then the polarity as shown by the potentiometer is a reliable indication of the direction of current flow in the pipe. Carrying the analysis further, if several such measurements are obtained, each separated by a short distance, then a change of polarity will indicate where current is being exchanged between the pipe and the earth. For example, in Figure 14 (a) a change in polarity indicated by successive measurements shows that an area where current is being discharged from the pipe to the earth must be located between the two points of measurement. Thus, an anodic area can be detected and located. It is apparent now why the distance between the probes themselves should not be great: such an anodic area might be contained in the span of the probes, and would be obscured regardless of the polarity indicated. The situation as pictured in Figure 14 (b) is the reverse of (a). These two successive measurements indicate an area where

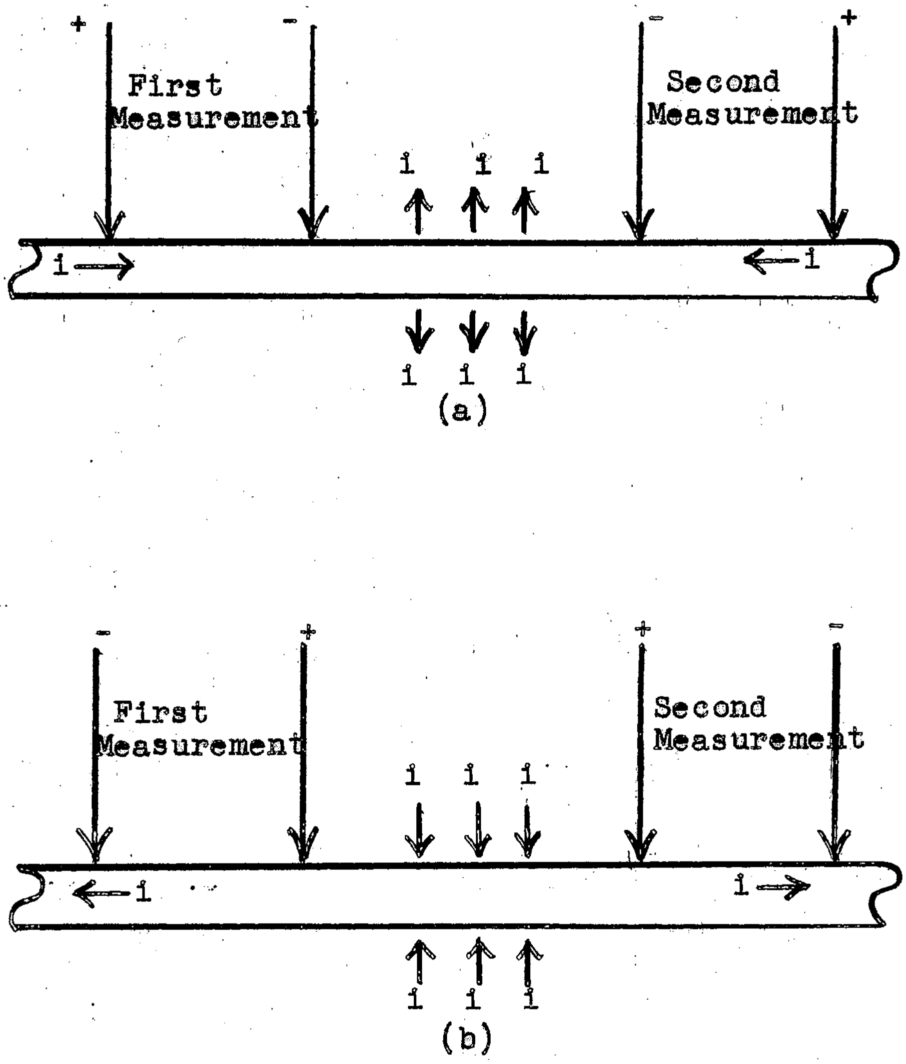


Figure 14. A Corrosion Locator Circuit.

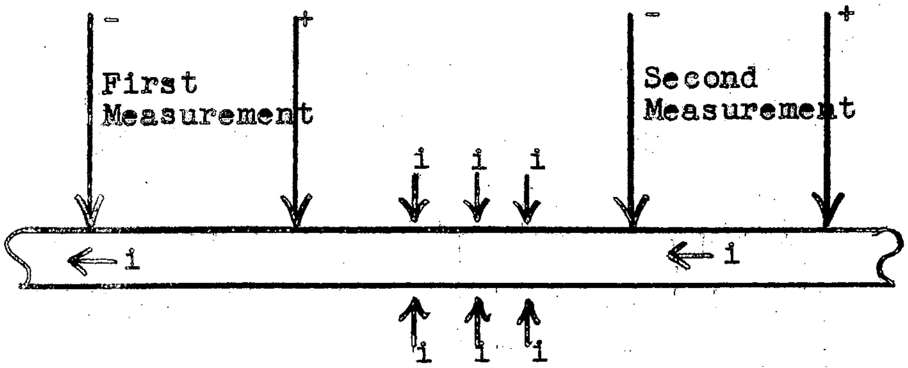


Figure 15. A Corrosion Locator Circuit.

current is entering the pipe, thus locating a cathodic area.

The disadvantage of this type of measurement lies in the physical difficulty inherent in making contact with the pipe each time the probes are moved. Along a pipeline of any length, the number of times the probes are moved would be large, as necessitated by accuracy.

If this disadvantage were not present, it would be possible to detect anodic and cathodic areas even though there is no reversal of polarity between successive points of measurement. This method of detection is illustrated with the aid of Figure 15. For example, if the current at the right end of the section of pipe is larger than the current, flowing in the same direction, at the left end, then the implication is that current is being discharged to the earth in the section between the two points of measurement. If the current at the left end is larger than the current at the right end, then current is flowing from the earth to the pipe (a cathodic area) in the section between the two successive points of measurements. Because of the presence of the earth between the potentiometer and the pipe, it is simply impossible to devise a means for making a continuous sliding contact between the probes and the pipe. For each successive measurement, the probes must be removed from the first position, and then placed in the second position again in contact with the external surface of the pipe.

For the horizontal pipeline, the measurements were of necessity made on the external surface of the structure. However, consideration of a vertical structure, such as an oil-well casing, indicates that measurements made on the external surface are virtually impossible. The alternative for the vertical structure is to make the potential measurements on the inside of the surface area. In Figure 16, the electrical probes are attached mechanically to a rigid body that can be moved up or down by means of the cable fastened at the top. Electrical connections are made from the two probes—themselves insulated from the body—to insulated conductors located inside the supporting cable. The calculation of the current flow, and the interpretation of the indicated polarities, is now the same as for the horizontal structure. Measurements made on the horizontal and vertical structures are wholly analogous, only the mode of obtaining the same information in the same general manner is different. Since the probes are not in contact with the earth, it is possible

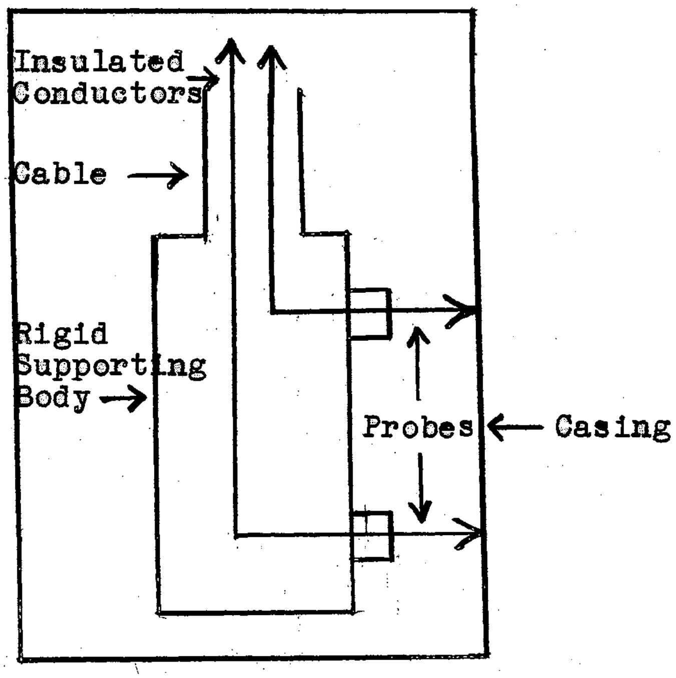


Figure 16. A Corrosion Locator Circuit.

to make a continuous sliding contact with the internal surface of the pipe. Any liquid present inside the pipe does not present the impossible barrier to motion of the probes, as contrasted with the solidity of the earth preventing motion of the probes on the external surface of the pipe. The depth of vertical pipe is, at most, several thousand feet; thus requiring a flexible cable, containing insulated conductors, of the same length as the pipe. To make a continuous sliding contact with the internal surface of a horizontal pipe, a method of projecting the cable through the pipe is necessary first; then the cable could pull the probes through the pipe. Unfortunately, the distance between points of entry on the horizontal line may be several miles, thereby requiring a cable of unreasonable length and weight. For the vertical line, the weight of the body, to which the probes are attached, is sufficient to move the body downward under the force of gravity. A continuous recording of 1) voltage drop between the probes, 2) the polarity of this voltage drop, and 3) the mean distance to the probes, could be utilized to great advantage in locating cathodic and anodic areas. Recordings made both before and after the application of cathodic protection could be compared in order to determine the effectiveness of the applied protective current in eliminating, or at least reducing, the corrosion of the anodic areas.

MEASUREMENT OF RESISTIVITY

The resistivity of the earth should be measured by alternating-current means, otherwise errors caused by polarization will be introduced through the usage of direct-current methods in accordance with the polarization theory presented in Chapter II. One commercial instrument is used almost universally for the measurement of ground-resistivity: the Megger, which is manufactured by the James G. Biddle Company of Philadelphia, Pennsylvania.

The Megger is a true ohmmeter in the sense that the instrument is capable of measuring resistance without requiring a definitely known potential or a calibrating adjustment each time a different resistance is measured. Contained within the instrument case of the Megger is a hand-crank d.c. generator, a current reverser, a potential rectifier, and a direct-reading scale mounted on a current coil and a potential coil. External to the instrument case are four steel pins used as ground electrodes and connected to four terminals on the case. Direct current generated by the hand-crank generator is passed through the current reverser converting the direct current to alternating current which is passed through the outermost two of the four steel pins arranged in a straight line on the surface of the earth. An alternating voltage drop is thus produced in the earth between the outermost two pins. The two inside pins are potential electrodes spaced apart by a specified distance. The alternating voltage drop produced in the earth between the two potential pins is connected in series with the potential rectifier which converts this a.c. voltage to d.c. voltage, and the d.c. voltage is applied to the potential coil. The current coil is in series with the hand-crank d.c. generator. The scale of the instrument indicates the quotient of the potential coil voltage divided by the current coil current. The scale is calibrated to read directly in resistivity units rather than resistance units; this is possible because of the specified spacing of the two steel-pin potential electrodes.

A slightly different Megger from that which has been explained may be used to measure directly the resistance-to-ground of a ground-electrode. With this second type of Megger, the ground electrode replaces one of the two outermost steel pins used with the first type. The resistance of the current path in the earth is then the resistance-to-ground of the ground-electrode. This type of Megger is calibrated to indicate directly in resistance units (ohms), rather than in the resistivity units (ohm-centimeters) of the first type of Megger. The mechanism of the Megger is essentially the same in both types of the instrument.

CHAPTER IV

METHODS OF CALCULATING GROUND-RESISTANCE OF ELECTRODES

The effect of the resistivity of the earth has been explained in the author's extension to the theory of cathodic protection, Chapter II, and a means of direct measurement of ground resistivity has been presented in the preceding chapter. It is the purpose of this chapter to examine critically the classical theoretical, or mathematical, method of calculating electrode ground-resistance, and further to develop a more general method of calculation which can be applied to electrode configurations that cannot be analyzed by the classical method. It will be recalled from Chapter II that the auxiliary anode resistance-to-ground is one of the component resistors of the equivalent circuits which represent cathodic protection.

Usually, cathodic protection is applied to a structure already in existence instead of instigating cathodic protection simultaneously with the establishment of the structure. The ohmic resistances of the cathodic and anodic areas are determined by the resistivity of the surrounding earth, and to some extent by the polarization of the areas. After a structure has been built, little can be done to alter the resistivity of the surroundings. However, when cathodic protection is applied, an auxiliary anode must be installed to propagate the protective current to the structure. Any ohmic ground-resistance associated with the auxiliary anode will result in an undesirable (I^2R) power loss. This loss not only adds unnecessarily to the cost of the protection but also this loss is dissipated as heat in the surrounding earth. The effect of the heat is to evaporate the moisture in the soil, which increases the resistivity and ground-resistance, and this then increases the loss for a given value of current; altogether, this is a deleterious cumulative effect which should be minimized.

So, it is necessary to know quantitatively the ground-resistance of an auxiliary anode, and also the factors upon which the resistance depends, in order to decrease this resistance effectively at the time of the installation of the auxiliary anode. Two methods are given in this Chapter for the calculation of ground-resistance.

THE CLASSICAL METHOD

The classical method of calculating the ground-resistance of electrodes of various shapes has been given by H. B. Dwight[1]. This method is based upon the fundamental equation

$$(4\text{-}1) \qquad R = \rho \frac{L}{A}$$

previously written as equation (1-4), Chapter I. Though the mathematical difficulties involved in the use of (4-1) may become complex, the broad generality of the classical method arises from the application of only (4-1). Theoretically, then, the ground-resistance of an electrode of any arbitrary shape, size, or form can be determined by calculation.

It is simple, from the mathematical standpoint, to con-

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[1] "Calculation of Resistances to Ground," Electrical Engineering, LV (1936), pp. 1319-1328.

sider first the calculation of the ground-resistance of a hemispherical electrode whose flat surface is coincident with the surface of the earth. This type of electrode is shown pictorially in Figure 17. Current leaving the electrode to enter the earth will flow radially with a uniform distribution. The radius of the electrode itself is r. At some variable radial distance x from the center of the hemisphere, the elemental resistance of the current path in the earth is

(4-2)
$$dR = \rho \frac{dx}{2\pi x^2}, \quad (A = 2\pi x^2,\ \ell = dx)$$

where ρ is the resistivity of the earth. The total resistance is found from summation of the elemental resistance by integration:

(4-3)
$$R = \int dR = \int_r^d \rho \frac{dx}{2\pi x^2}$$

where d is any particular fixed distance from the center of

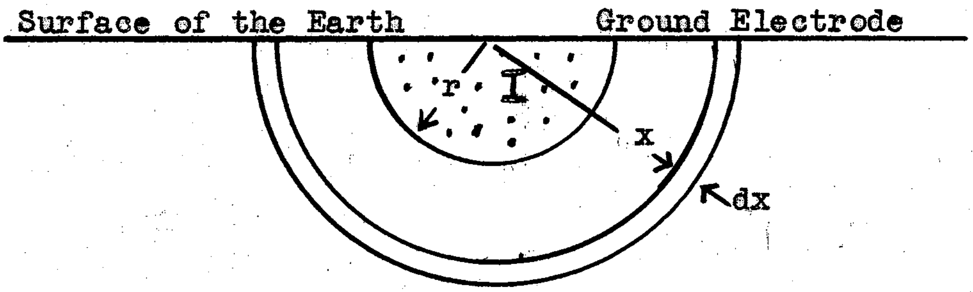


Figure 17. A Hemispherical Ground Electrode.

the hemisphere that is greater than the radius r. Performing the integration indicated in (4-3),

(4-4)
$$R = \frac{\rho}{2\pi}\left[-\frac{1}{x}\right]_r^d = \frac{\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{d}\right]$$

Since d is always greater than r, R is always positive as given by (4-4)——which is the only plausible physical meaning of R. It is common to speak of the ground-resistance of an electrode, though it is obvious from (4-4) that R is the resistance of the ground itself between r and d in the form of a hemispherical shell. The ground-resistance associated with this electrode depends upon the particular value of d. As d becomes larger compared with r, the effect of the $\frac{1}{d}$ term on R becomes less. The limiting condition is for d to become infinite; then

(4-5)
$$R_L = \frac{\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{d}\right] \text{ as } d \rightarrow \infty$$
$$= \frac{\rho}{2\pi r}$$

which is the maximum possible value of R. If d is 100 times as great as r,

(4-6)
$$R' = \frac{\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{100r}\right] = \frac{.99\rho}{2\pi r}$$

and the magnitude of R' relative to R_L is

(4-7)
$$\frac{R'}{R_L} = \frac{\frac{.99\rho}{2\pi r}}{\frac{\rho}{2\pi r}} = .99, \text{ or } 99 \text{ per cent}$$

So, the greater part of the ground resistance is located in the vicinity of the electrode.

Consideration of the analysis of the hemispherical electrode provides both familiarity with the method and an insight into the extension of the method to other electrodes of varied shape.

Calculation of the ground-resistance of a sphere is quite similar to the procedure for the hemisphere. The sphere, immersed in the earth, is shown in Figure 18. At a distance x from the center of the sphere, and external to the sphere, the spherical cross-sectional area through which current flows is

(4-8) $A = 4\pi x^2$

and the elemental resistance is

(4-9) $$dR = \rho \frac{dx}{4\pi x^2}$$

Integrating (4-9) to find the total resistance from the surface of the sphere out to any given radial distance d larger than r,

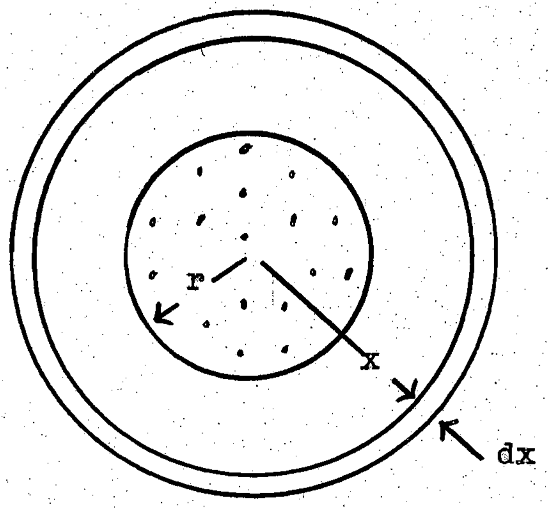


Figure 18. A Spherical Ground Electrode.

(4-10)
$$R = \int_r^d \rho \frac{dx}{4\pi x^2} = \frac{\rho}{4\pi}\left[\frac{-1}{x}\right]_r^d$$
$$= \frac{\rho}{4\pi}\left[\frac{1}{r} - \frac{1}{d}\right]$$

Comparison of (4-10) with (4-4) shows that the ground-resistance of the sphere is one-half that of the hemisphere. This can be interpreted physically by noting that the elemental resistance for the sphere consists of two like elemental resistances for the hemisphere in parallel.

The ground-resistance of a hollow, right circular cylinder will be calculated next. This is the geometrical shape of a length of ordinary pipe, as shown in Figure 19. For an axial length L, the cylindrical area of the current path is

(4-11) $$dA = 2\pi x L$$

and the elemental resistance is

(4-12) $$dR = \rho \frac{dx}{2\pi x L}$$

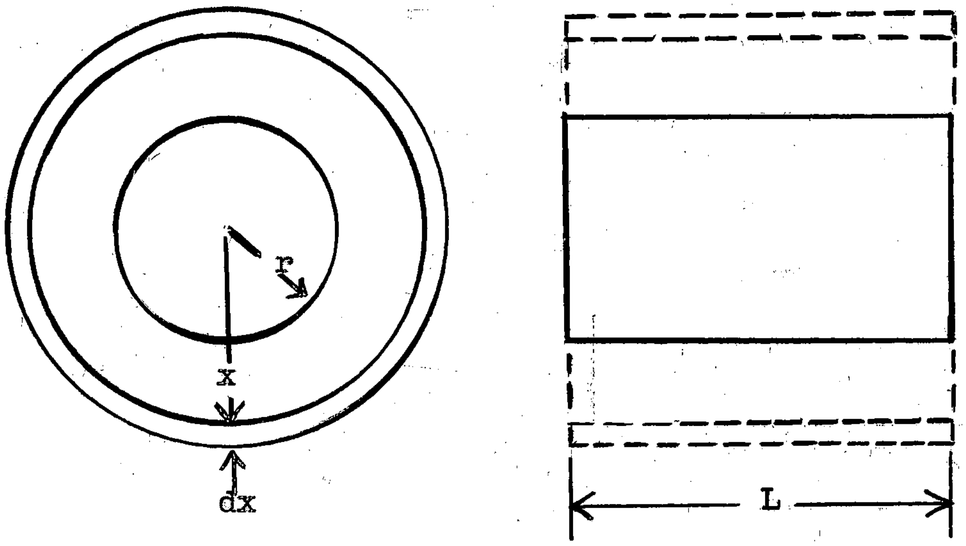


Figure 19. A Hollow Cylindrical Ground Electrode.

The total resistance of the ground out to a radial distance d is

(4-13)
$$R = \int_r^d \rho \frac{dx}{2\pi xL} = \frac{\rho}{2\pi L}\Big[\ln x\Big]_r^d$$
$$= \frac{\rho}{2\pi L}\Big[\ln d - \ln r\Big] = \frac{\rho}{2\pi L}\ln\frac{d}{r}$$

This calculation has neglected the possibility of current flow from the ends of the hollow cylinder because the cross-sectional area of the ends, being hollow, is extremely small compared with the curved surface area. As the length L is increased, the resistance R decreases in inverse proportion; physically, the unit lengths of L are in parallel for a radial current flow. Equation (4-13) may be compared with (4-4) and (4-10) for both of which the resistance approaches a limiting value as the radial distance d approached infinity. In (4-13), as d approaches infinity, the ground-resistance also approaches infinity.

A SUPPLEMENTARY, OR ALTERNATIVE, METHOD OF CALCULATING THE GROUND-RESISTANCE OF ELECTRODES, BASED UPON GAUSS' THEOREM

A second method of calculating ground-resistance, as developed by the author from the principles of the general electromagnetic field theory, will be presented now and will be shown to be applicable to a configuration impossible to analyze by the classical method.

Gauss' Theorem states that the net electric flux penetrating a surface which completely encloses a body of electric charge is equal to the net positive charge contained within the closed surface. There are several alternative mathematical expressions of this Theorem:

(4-15) $$\oint_S \overline{D} \cdot \overline{dS} = \int_V \overline{\overline{\nabla}} \cdot \overline{D}\, dV = \int_V \text{div}\, \overline{D}\, dV$$

This is the vector integral form in which $\overline{D}$ is the electric flux density, $\overline{dS}$ is the vector elemental surface area in the direction of the positive outward normal to the surface S, $\overline{\overline{\nabla}}$ is the vector partial derivative operator

(4-16) $$= \overline{i}\frac{\partial}{\partial x} + \overline{j}\frac{\partial}{\partial y} + \overline{k}\frac{\partial}{\partial z}$$

and dV is the elemental volume of the volume V completely enclosed by the surface S. The integral on the left side of (4-15) is a surface integral, and the circle indicates that the integration is over the <u>closed</u> surface S. The integral on the right side of (4-15) is a volume integral, for the volume V completely contained within the closed surface S.

Another form of this same theorem is

(4-17) $$\oint_S \overline{D} \circ \overline{dS} = \int_V P\, dV = Q$$

in which the integral on the right side contains P, the charge density (charge per unit volume).

Stated in terms of scalar quantities rather than vectors, Gauss' Theorem is

(4-18) $$\oint_S D_n\, dS = \psi = Q$$

where D_n is the component of $\overline{D}$ in the direction of the positive outward normal to the surface S, ψ is the electric flux passing outward through S, and Q is the net positive charge enclosed by S.

Now, the current flowing from any shape of electrode completely buried in the earth is equal to the summation of the current flowing normally outward through an arbitrary surface S which completely encloses the electrode. Such a configuration is shown in Figure 20, in which the shape of both the electrode and closed surface are entirely arbitrary so long as S completely encloses the electrode. Stated mathematically,

(4-19) $$I = \oint_S \overline{J} \cdot \overline{dS} = \oint_S J_n \, dS$$

where $\overline{J}$ is the vector current density, and J_n is the scalar component of the current density in the direction of the positive outward normal to the closed surface S.

The current density $\overline{J}$ is related to the electric field intensity $\overline{E}$ in a conducting medium by the microscopic form of Ohm's Law,

(4-20) $$\rho \overline{J} = \overline{E}$$

since the current is entirely a conduction current. Though media may be classified broadly as conductors or dielectrics,

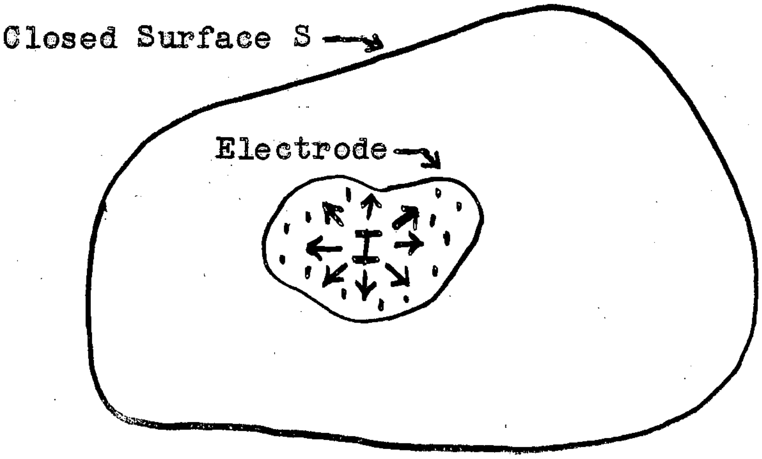


Figure 20. A Current Ground Electrode.

there is no sharp division of the two classes. Any medium has some of the properties of both classes, and these properties are the resistivity ρ and the dielectric constant ε . In particular, the earth has both of these properties. By Gauss' Theorem,

$$(4\text{-}21) \qquad \oint_S D_n \, dS = Q$$

and from the general Electromagnetic Field Equations,

$$(4\text{-}22) \qquad \bar{D} = \varepsilon \bar{E}$$

which implies that a component of $\bar{D}$ in any direction is equal to the permittivity ε times the component of $\bar{E}$ in the same direction. Therefore,

$$(4\text{-}23) \qquad D_n = \varepsilon E_n$$

and from (4-20), equating components only,

$$(4\text{-}24) \qquad \rho J_n = E_n$$

where J_n and E_n are components in the positive outward direction. Substituting (4-23) into (4-21),

$$(4\text{-}25) \qquad \oint_S \varepsilon E_n dS = Q$$

and then substituting (4-24) into (4-25),

$$(4\text{-}26) \qquad \oint_S \varepsilon \rho J_n \, dS = Q$$
$$= \varepsilon \rho \oint_S J_n \, dS = \varepsilon \rho I$$

according to equation (4-19). The basic relation for dielectric circuits is

$$(4\text{-}27) \qquad Q = CV$$

where C is the capacitance, and the basic relation for electric circuits is Ohm's Law:

$$(4\text{-}28) \qquad V = IR$$

Substituting (4-27) for Q, and (4-28) for I, into (4-26),

$$(4\text{-}29) \qquad CV = \varepsilon \rho \frac{V}{R}$$

or, alternatively,

$$R = \frac{\varepsilon \rho}{C} \qquad (4\text{-}30)$$

Equation (4-30) relates the electrical resistance R of the medium to the electrostatic capacitance of the medium. This equation can be used to determine R where it is more advantageous to calculate C directly rather than to calculate R directly from equation (4-1).

As an example of this method, and for comparison with the classical method, the ground-resistance of a spherical electrode will be found from the capacitance of the electrode. For the sphere, Figure 21, upon which is distributed a positive charge Q, the electric field intensity E at a radial distance x external to the sphere is

$$E = \frac{Q}{4\pi\varepsilon x^2} \qquad (4\text{-}31)$$

and the direction of E is positive outward from the center of the sphere in the direction of x. The potential difference between the surface of the charged sphere and a concentric

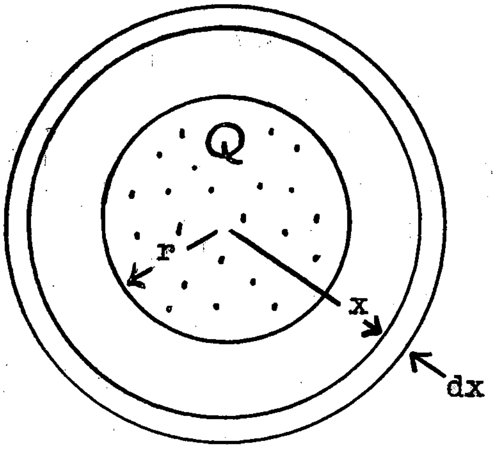


Figure 21. A Spherical Ground Electrode.

sphere of radius d is, by definition of potential difference in terms of the electric field intensity,

(4-32)
$$V = V_r - V_d = \int_r^d E\,dx = \int_r^d \frac{Q\,dx}{4\pi\varepsilon x^2}$$
$$= \frac{Q}{4\pi\varepsilon}\left[\frac{-1}{x}\right]_r^d = \frac{Q}{4\pi\varepsilon}\left[\frac{1}{r} - \frac{1}{d}\right]$$

From equation (4-27), the capacitance C found from (4-32) is

(4-33)
$$C = \frac{Q}{V} = \frac{4\pi\varepsilon}{\left[\frac{1}{r} - \frac{1}{d}\right]}$$

Now, the resistance R can be found by applying the basic relation (4-30) to (4-33):

(4-34)
$$R = \frac{\varepsilon\rho}{C} = \frac{\varepsilon\rho}{\frac{4\pi\varepsilon}{\left[\frac{1}{r} - \frac{1}{d}\right]}}$$
$$= \frac{\rho}{4\pi}\left[\frac{1}{r} - \frac{1}{d}\right]$$

The result of (4-34) is identically the same as the result of (4-10) which was calculated according to the classical method emphasizing only the variation of resistance with the length and cross-sectional area of the current path.

As a second example, the ground-resistance of the hollow cylindrical electrode, shown previously in Figure 22, will be calculated. For a charge Q, uniformly distributed over the surface of the cylinder, the symmetry of the figure shows that the electric flux lines are pointed outward in the radial direction. By Gauss' Theorem, the electric flux passing outward through the concentric cylindrical surface of radius x, which completely encloses the electrode, is

(4-35)
$$\Psi = D_n S = 2\pi x L D_n = Q$$

or, in a slightly different form,

(4-36) $$D_n = \frac{Q}{2\pi xL}$$

Substituting equation (4-23) into (4-36) gives

(4-37) $$E_n = \frac{Q}{2\pi\varepsilon xL}$$

The potential difference between the surface of the electrode and the surface of a concentric cylinder of radius d is

(4-38) $$V = V_r - V_d = \int_r^d E_n dx = \int_r^d \frac{Q\,dx}{2\pi\varepsilon xL}$$
$$= \frac{Q}{2\pi\varepsilon L}\Big[\ln x\Big]_r^d = \frac{Q}{2\pi\varepsilon L}\ln\frac{d}{r}$$

The capacitance, from (4-27), is

(4-39) $$C = \frac{2\pi\varepsilon L}{\ln\frac{d}{r}}$$

Applying the general relation between R and C given by (4-30), the ground-resistance is

(4-40) $$R = \frac{\varepsilon\rho}{C} = \frac{\varepsilon\rho}{\frac{2\pi\varepsilon L}{\ln\frac{d}{r}}} = \frac{\rho}{2\pi L}\ln\frac{d}{r}$$

A slight modifying assumption has been made throughout in obtaining the result of (4-40)—the ends have been neglected, so that all of the charge resides on the curved surface. This assumption is analogous to the one made concerning the flow of current from the ends when calculating the resistance by the classical method. The result of (4-40) is identical to the result of (4-13) obtained earlier.

A pointed comparison of the two methods can be made by consideration of the hemispherical electrode. The ground-resistance of this electrode was relatively simple to calculate by the classical method. It would be quite difficult, if not impossible, to calculate the resistance by the second method: primarily because of the non-uniformity of the charge distribution as the consequence of the lack of geometric symmetry, and also because of the difficulties presented by the location of the electrode in two different media, the earth and the air. The advantage offered by the classical method is obvious.

However, another comparison can be made which will illustrate the superiority of the second method for this particular case. Instead of a single ground electrode, consider two ground electrodes, one of which discharges current to the earth and the other receives the current from the earth. This arrangement is shown in Figure 22. Both of the electrodes are spheres, though of unequal radii, and the centers are separated a distance d. The solution of this problem by the first method is complicated by the lack of a single elemental resistance dR which includes the effect of both spheres simultaneously.

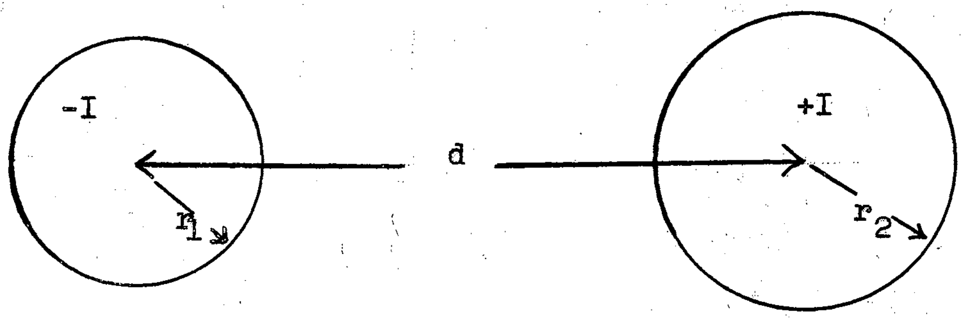


Figure 22. Two Spherical Ground Electrodes.

By the second method, the resistance is determined from the capacitance, which can be calculated.

The spheres are redrawn in Figure 23, one carrying a charge (+)Q and the other a charge (-)Q. The potential difference between the surfaces of the two spheres can be found by applying the basic definition of potential difference in the electrostatic field: the difference of potential between two points in the electrostatic field is the line integral of the electric field intensity between the two points. The value of the line integral must be independent of the particular path chosen, since the electrostatic field is conservative. The surface of each of the two spheres is an equipotential surface; therefore, the difference of potential calculated along any line joining the two surfaces has the same value. At a point at a distance x from the center of the larger sphere and lying on the line joining the centers of the spheres, the electric field intensity caused by the (+)Q charge is

$$E_1 = \frac{Q}{4\pi\varepsilon x^2} \tag{4-41}$$

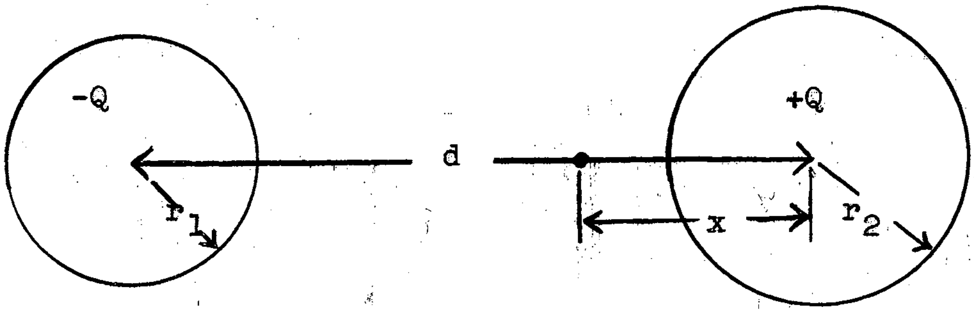


Figure 23. Two Spherical Ground Electrodes.

and is directed toward the center of the smaller sphere. The electric field intensity at the same point caused by the (-)Q charge is, similarly,

(4-42)
$$E_2 = \frac{-Q}{4\pi\varepsilon\,(d-x)^2}$$

but the minus sign indicates that this intensity is also directed toward the center of the smaller sphere. So, the total intensity at the point x is the vector sum of E_1 and E_2,

(4-43)
$$E = \frac{Q}{4\pi\varepsilon\,x^2} + \frac{Q}{4\pi\varepsilon\,(d-x)^2}$$

and is also directed toward the center of the smaller sphere. Then, the difference of potential between the surfaces of the spheres is

(4-44)
$$\begin{aligned} V &= \int_{r_2}^{d-r_1} E\,dx = \int_{r_2}^{d-r_1} \frac{Q}{4\pi\varepsilon}\left[\frac{1}{x^2} + \frac{1}{(d-x)^2}\right] dx \\ &= \frac{Q}{4\pi\varepsilon}\left[\frac{-1}{x} + \frac{1}{d-x}\right]_{r_2}^{d-r_1} \\ &= \frac{Q}{4\pi\varepsilon}\left[\frac{-1}{d-r_1} + \frac{1}{d-d+r_1} + \frac{1}{r_2} - \frac{1}{d-r_2}\right] \\ &= \frac{Q}{4\pi\varepsilon}\left[\frac{1}{r_1} + \frac{1}{r_2} - \frac{1}{d-r_1} - \frac{1}{d-r_2}\right] \end{aligned}$$

A close approximation to this result can be effected if the distance d is large compared with the two radii r_1 and r_2, in which case (4-44) simplifies to

(4-45)
$$V = \frac{Q}{4\pi\varepsilon}\left[\frac{1}{r_1} + \frac{1}{r_2} - \frac{2}{d}\right]$$

From equation (4-27), the capacitance is

(4-46)
$$C = \frac{Q}{V} = \frac{4\pi\varepsilon}{\left[\frac{1}{r_1} + \frac{1}{r_2} - \frac{2}{d}\right]}$$

Use of the basic relation (4-30) gives for the resistance:

$$(4\text{-}47) \qquad R = \frac{\varepsilon\rho}{C} = \frac{\varepsilon\rho}{\dfrac{4\pi\varepsilon}{\left[\dfrac{1}{r_1}+\dfrac{1}{r_2}-\dfrac{2}{d}\right]}} = \frac{\rho}{4\pi}\left[\frac{1}{r_1}+\frac{1}{r_2}-\frac{2}{d}\right]$$

The solution of this type of problem by the classical method is not readily feasible, if at all possible, because of the numerous paths in different directions for current flow from the larger sphere to the smaller. Use of the classical method demands the choice of a cross-sectional area (see equation (4-1)) such that the surface of A is everywhere perpendicular to the direction of current flow. What is implied but never mentioned in any use of the classical method is that it is always necessary to assume that current flows infinitely far along the lines of geometric symmetry of the electrode. Only simple geometric figures exhibiting symmetry can be analyzed in a strict sense by the classical method. Further, only a <u>single</u> electrode can be analyzed by the classical method. The fallacy of the classical method is that current propagated from a single electrode cannot possibly flow infinitely far along the lines of geometric symmetry but must eventually return to the source of current. The classical method gives good results if the ground-electrode and current source are widely separated because, as has been shown in equation (4-7) for the hemispherical electrode, nearly all of the resistance-to-ground is concentrated in the immediate vicinity of the electrode; but it has also been shown for a cylindrical electrode that the ground-resistance becomes infinitely great at an infinite distance from the electrode. For the electrode configuration of two spheres, shown in Figure 25, if the two spheres are close together then the current flow from one sphere to another is not along the lines of geometric symmetry—excepting the line joining the centers of the sphere—but the lines of current flow begin to curve immediately outside either electrode and are not straight radial lines extending to infinity. The concept of ground resistance of two electrodes close together is even meaningless from the point of view of the classical method, because actually both electrodes must be considered if they are close together. The lack of geometric symmetry of the current flow lines makes it impossible to apply the classical method to such a configuration as the two spheres unless they are assumed to be separated infinitely far apart, in which case the ground-resistance of the two spheres is simply the ordinary arithmetic sum of the two individual ground-resistances.

Each of the calculations of ground-resistance, for the various electrodes which have been considered, shows that the resistance is concentrated in the immediate vicinity of the electrode. Therefore, at the time of installation of the electrode, the ground-bed surrounding the electrode should be constructed of a low-resistivity substance. A ground-bed of coke is commonly used. Thorough wetting of the ground-bed after the ground-electrode has been encased will tend to improve the contact between the bed and electrode. The addition of common salt to the backfill soil is effective in reducing ground resistance.

The weakness inherent in mathematical calculations of resistance-to-ground is the necessity of considering electrode configurations with a high degree of geometric symmetry so that the calculations can actually be completed rather than only indicated. But this is true also of many applications of mathematics to practical problems. The resistance-to-ground of any ground-electrode can be measured directly with a Megger, as explained in the last section of the preceding chapter. The value of the mathematical calculations is in indicating which kind of ground-electrode may be expected to have a low resistance-to-ground, then the resistance can be verified by direct measurement on the particular electrode selected.

CHAPTER V

CURRENT—POTENTIAL CURVES

The potential of an unprotected buried structure is dependent upon the particular environment. Some variation in the potential is to be expected in dissimilar locations which differ greatly in the type of soil, moisture content, ambient temperature of the soil, et cetera. Though this apparent, overall, open-circuit potential of a particular structure cannot be estimated accurately from the Potential Series, it is a simple matter to determine this potential by a direct measurement. The method previously presented in Figure 10, Chapter III, will suffice for this potential measurement.

If protective current is applied to a buried metal structure, the potential of the structure should deviate from the open-circuit potential by the polarization emf caused by the current flow, according to the theory presented in Chapter II. The applied current immediately causes the structure potential to change, because of cathodic polarization, in the direction of more negative (anodic) values. In Figures 24 and 25 are shown numerical current-potential data obtained by the author from electrical measurements performed on six shallow (1500 feet) well-casings. The method of obtaining the measured potential was by interrupting the source of protective current and quickly balancing a potentiometer connected as shown in Figure 11, Chapter III, which method has been previously explained and compared with the compensated-bridge

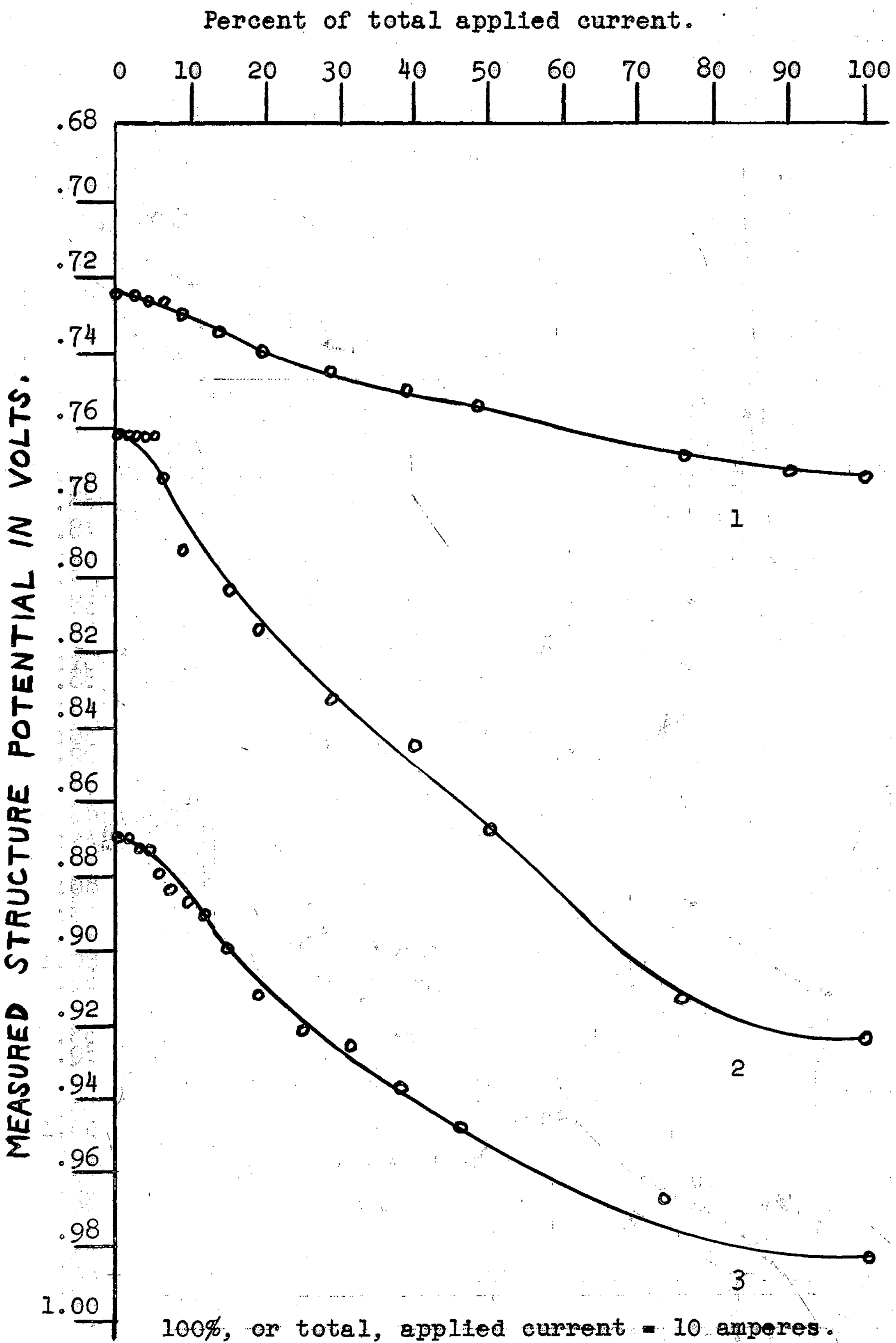
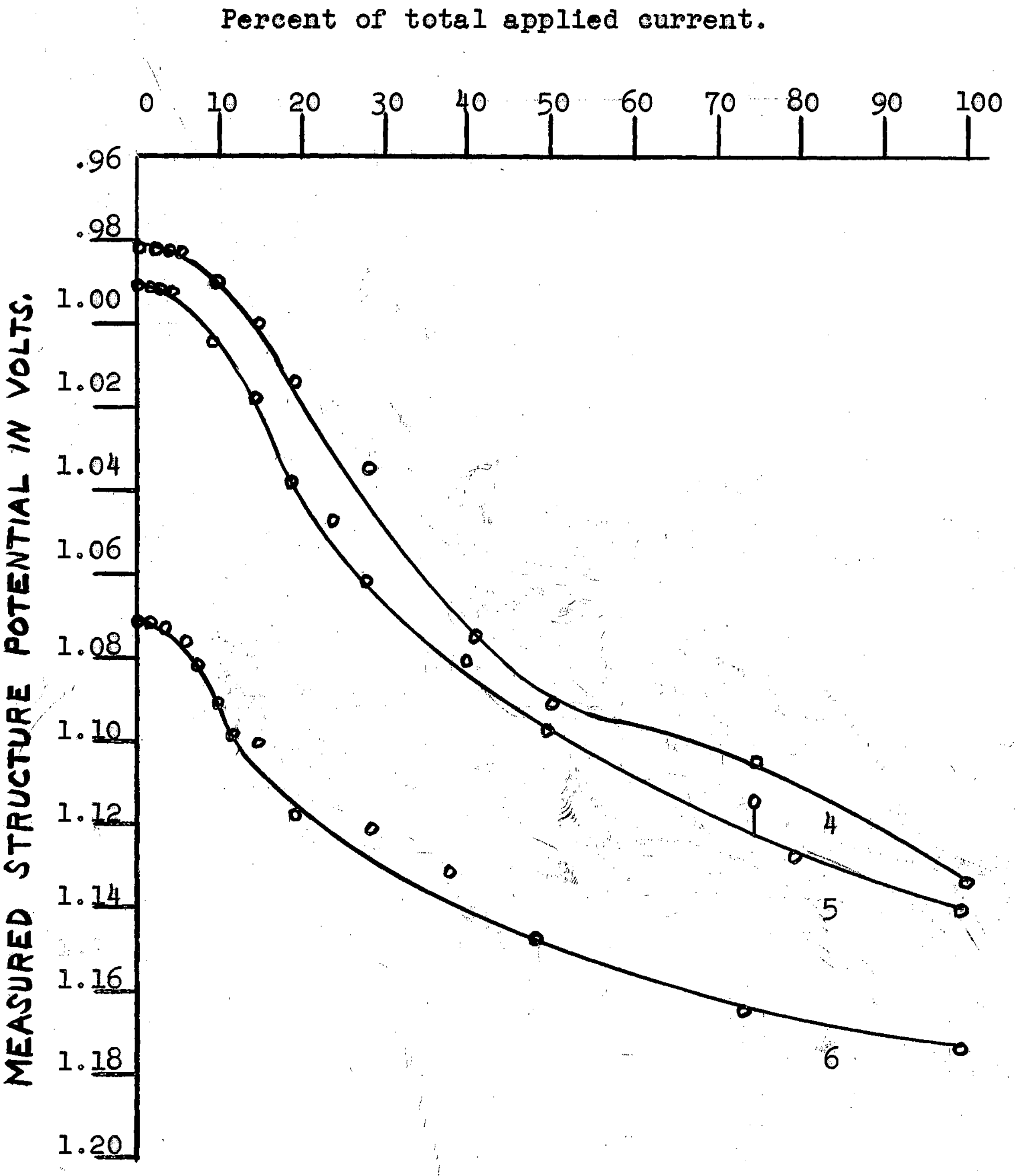


Figure 24. Current-Potential Curves.



100%, or total, applied current = 10 amperes.

Figure 25. Current-Potential Curves.

method in Chapter III. The wells from which the electrical measurements were obtained are in the St. Elmo Field of Illinois. The potentials were measured with respect to a saturated calomel reference half-cell, and it will be remembered from Chapter III that a buried structure which exhibits a potential of -0.78 volt with respect to this half-cell should be adequately protected according to the rule-of-thumb criterion explained in Chapter III.

The nearly identical specimens were buried in different localities, and the potentials with no current applied illustrate the effect of the various locations. The applied current (or current-density) was varied from zero to a maximum value considered to be greatly in excess of the value required for protection. The magnitude of the maximum current is the same for each specimen, 10 amperes, so the current scale is given as the percent of maximum in order that the abscissa be generally nondimensional and emphasize the shape of the curve rather than the magnitude of the current. Only the potential axes of the two figures are different; the current axes are the same. Different potential scales have been used so that the variation of potential of each particular specimen can be clearly shown.

As expected from the polarization theory presented in Chapter II, the potentials all change toward the anodic direction, though not by the same amount at each location. The potential of specimen 1 changed much less than any of the other five, and the potential did not quite reach the -0.78 volt value called for by the arbitrary standard—but the current-density was thought to be very much greater than necessary at the maximum. The potential of 2 changed much more than 1 for the same applied current. The potential variation of 3 is similar to that of 2, but it is still more anodic (negative). Specimens 4 and 5 were in the same location, and the curves of these two are only slightly different. Specimen 6 was in a different location, and the curve for it differs from the others and is more anodic (negative) than any of the others. The open-circuit potentials—that is, with no applied current—of 3,4,5, and 6 are all more negative than the arbitrary value of -0.78 volt with respect to a calomel electrode, which has been explained in Chapter III to be rigidly observed by many as an absolute protection criterion. Therefore, by this doubtful standard, all four of these specimens should be sufficiently protected without the application of a protective current. However, all six specimens were in the ground for some years before the potential-current measurements were made. Upon examination, 3, 4, 5, and 6 were all found to be pitted by corrosion, though the -0.78 volt criterion indicates adequate protection for these four. The open-circuit potentials of 1 and 2 were both less than -0.78 volt, and they were also pitted. From the evidence, the -0.78 volt criterion cannot be accepted as a fixed standard indicative of protection for any and all ferrous specimens. However, the numerical data for a particular specimen may be valuable in determining an adequate potential and current for any one specimen.

If the same numerical current-potential data for the six specimens are plotted on semi-logarithmic paper with potential on the linear scale and current on the logarithmic scale, certain similarities in all the data are more prominent. For relatively small values of current, the potential is approximately a straight line with an almost horizontal slope until a point is reached beyond which the points lie on and about a line of steeper slope. These data are shown in Figures 26 and 27. The potential scale is large, as it was on the ordinary coordinate paper, in order to show the data in great detail.

The shape of the various curves are all typical of a most important discovery by Dr. Scott P. Ewing[1]. In the reference cited[1], Dr. Ewing showed that current-potential curves of buried ferrous structures were all of a particular shape: the first portion of the curve is a nearly horizontal line at the value of the structure open-circuit potential, and the second part of the curve is another straight line of steeper negative slope (in semi-logarithmic coordinates). Also, the point of intersection of the two straight-line portions of a single current-potential curve was shown by experimental results in the reference work[1] to be the minimum value of current required for protection. This is a very powerful quantitative means for determining the proper magnitude of protective current for any type of buried structure. The numerical data for a single current-potential curve can be obtained by direct measurement, as has been explained, and a curve can be fitted to the numerical data by any of the conventional methods of curve-

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[1] S. P. Ewing, "Determination of Current Required for Cathodic Protection," <u>Proceedings of The American Gas Association</u>, 1940, p. 613.

Figure 26. Current-Potential Curves, Semi-Logarithmic

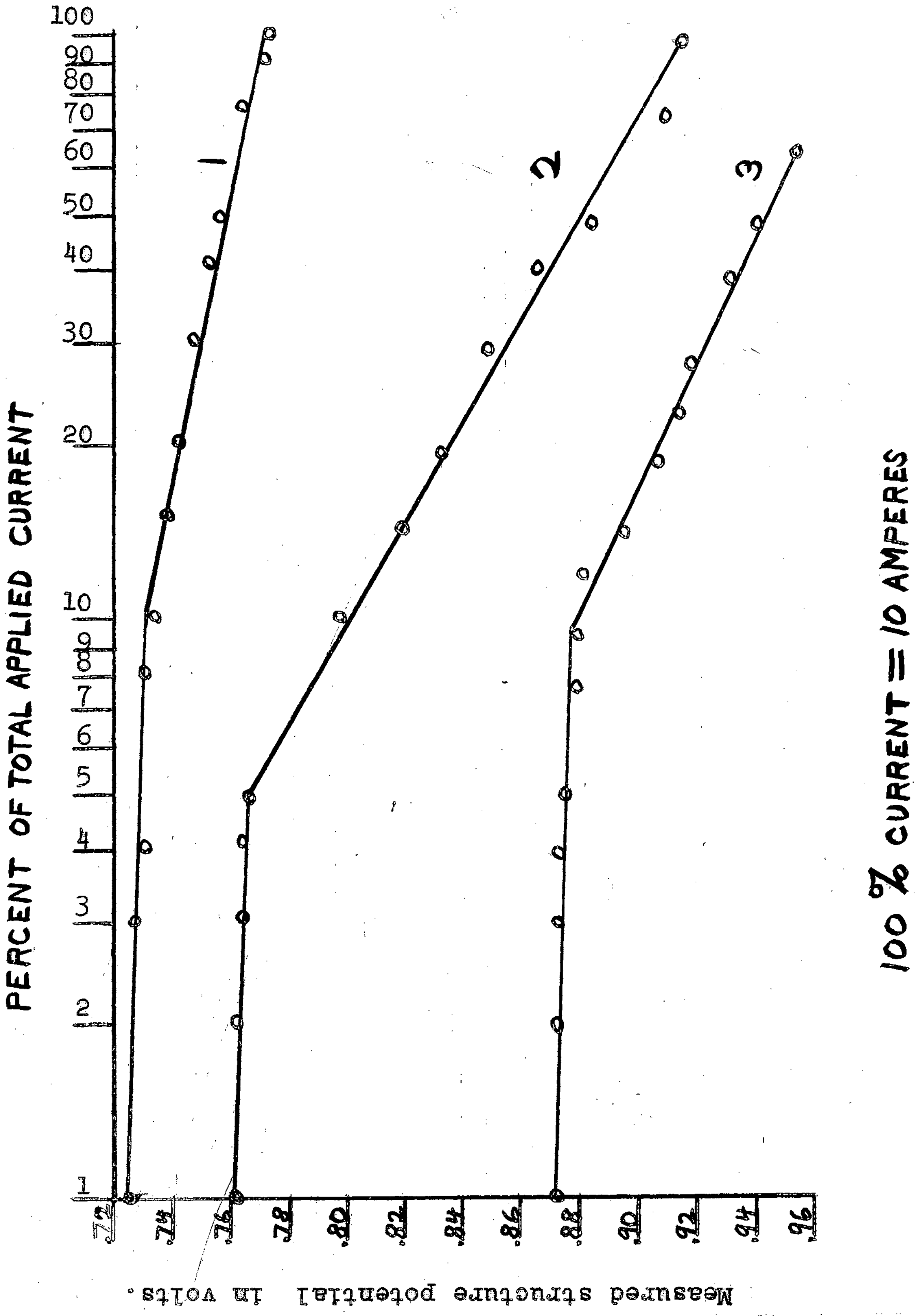
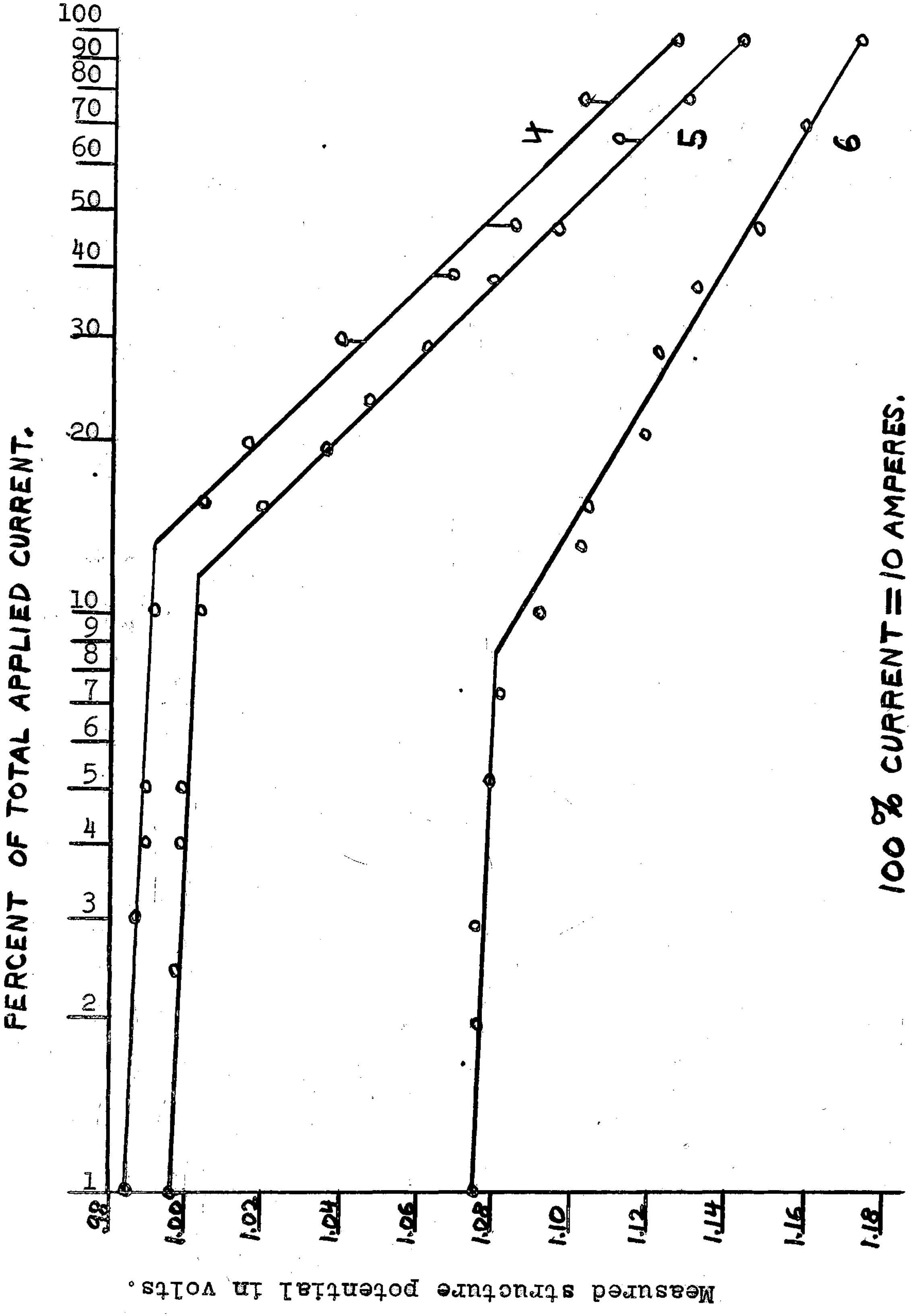


Figure 27. Current-Potential Curves, Semi-Logarithmic



fitting such as the standard statistical Method of Least Squares. The writer's experience with such curve-fitting has indicated that the curve so fitted is useful only for the one set of data for a single particular curve because of the inordinately large number of terms required to represent the peculiar shape of a single current-potential curve in semi-logarithmic coordinates. Further, the Method of Least Squares fails to emphasize the most important single point on the curve: the breakpoint. It would be valuable to fit a single empirical equation to the current-potential curve which would apply to all such curves, regardless of the height of the horizontal segment and the location of the breakpoint, and which would emphasize the breakpoint. Such an equation would make it possible to correlate all experimental results with the analytical theory of Chapter II. It will be recalled that much of the analytical theory of Chapter II was of necessity expressed in general functional notation, such as the $f_c(J_c)$ and $f_a(J_a)$ in equations (2-19) and (2-20), for the very simple reason that the exact functions were unknown. The theory of Chapter II and the experimental results of this chapter will be correlated by means of a single general empirical equation which the writer has developed. No such correlation has ever been made previously between theory and experimentation.

Assuming that the potential-current curve is composed of two straight-line segments, then the two lines will intersect in a single point. All six of the semi-logarithmic experimental curves are drawn in this manner. A curve composed of two straight-line segments which are non-collinear cannot be represented by a power series with an infinite number of terms nor by an algebraic polynomial with a finite number of terms, since functions so defined have continuous first derivatives. There is no derivative at the breakpoint, or intersection, of the two straight-line segments. It is possible to represent the curve by a Fourier Series on a specified interval, but a large number of terms are required and the terms are dependent upon the specified interval; a change in position of the breakpoint results in a new Series.

An analytical expression will be presented by the author which has been used in an entirely different form as an approximate representation of attenuation-frequency characteristics in servomechanism analysis. It was in the study of servomechanism analysis that the writer conceived the idea of the new equation as an exact expression for the type of curve now under consideration. The dependent variable, which is here potential, is regarded as a function of a complex variable in such a way that the function itself is always real. If the value of the function is plotted as the ordinate on semi-logarithmic paper versus the real independent variable as abscissa, the real part of the function is considered to represent the function over the first part of the entire interval, and the imaginary part of the function represents the function over the second part of the entire interval. This type of analytical expression is known as the "asympotic approximation"[2] when used to represent a continuous smooth curve. However, the

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[2] H. Chestnut and R. W. Mayer, Servomechanisms and Regulating System Design, (New York, 1951), pp. 302-310.

type of curve considered here is not a smooth continuous curve but is exactly the same shape as the "asympotic approximation" curve, and so can be represented exactly by an expression for the "approximate" curve.

The analytical expression developed by the author is written as

$$(5\text{-}1) \qquad E_s = -\left| -E_o + jm \log kI \right| , \quad (j = \sqrt{-1})$$

in which E_o is the open-circuit measured potential of the specimen (with no current applied), I is the applied current, k is an arbitrary constant, m is proportional to the slope of the inclined segment on semi-logarithmic paper, and E_s is the actual specimen potential (with current applied). In (5-1), it should be recognized that E_o is inherently negative by our means of measurement, m is positive though the inclined segment always has a negative slope, and both I and k are positive. The independent variable is the current I.

The horizontal segment of the curve is represented by the real part of the complex quantity,

$$(5\text{-}2) \qquad E_s = -\left| -E_o \right| = E_o$$

The inclined segment of the curve is represented by the imaginary part of the complex quantity,

$$(5\text{-}3) \qquad E_s = -\left| jm \log kI \right| = -m \log kI$$

The breakpoint in the curve occurs where the real part is equal to the imaginary part:

$$(5\text{-}4) \qquad -E_o = m \log kI$$

From equation (5-2), it can be seen that $E_s = E_o$ is the horizontal part of the curve. If equation (5-3) is expanded, (5-5) $$\begin{aligned} E_s &= -m \log kI = -m\ (\log I + \log k) \\ &= -m \log I - m \log k \\ &= (-m)\ X + C,\ (x = \log I),\ (C = -m \log k) \end{aligned}$$

then equation (5-5) is recognized as a straight-line on semilogarithmic paper since log I is the abscissa, (-m) is the slope, and C is an arbitrary constant. The particular base of logarithms used—excepting zero, unity, and negative numbers—is optional, though the base 10 has been used for convenience in plotting.

A correlation between experimental data and the theory of Chapter II can now be effected. Equation (2-19) of that chapter is rewritten for reference as equation (5-6):

(5-6) $$E_s = E_o - f_s(J_s)$$

The cathodic equation of Chapter II, equation (2-19), is used now because the protected structure is the cathode in a cell composed of: 1) the structure as cathode, 2) the earth as electrolyte, and 3) the auxiliary anode as anode. The subscripts of this chapter have been appropriately attached with E_s the specimen potential with current applied, E_o the open-circuit measured potential of the specimen with no current applied, both of which terms have been previously defined in connection with equation (5-1) of this chapter, and the term $f_s(J_s)$ written in general functional notation is the polarization emf. Now, by comparison of (5-6) with equations (5-1), (5-2), (5-3), (5-4), and (5-5), it is immediately discernible that:

(5-7) $$E_o = E_o$$

an identity, for the horizontal portion of the curve; and

(5-8) $$-f_s(J_s) = -m \log kI$$

or, in positive terms,

(5-9) $$f_s(J_s) = m \log kI$$

for the second portion of the curve, which is inclined at a negative slope. Equation (5-9) can be further written, by the use of the methods of Chapter II, since $f_s(J_s) = \Delta E_s$, as

(5-10) $$\Delta E_s = m \log kI = f_s(J_s) = f_s\left(\frac{I_s}{S_s}\right)$$

or, in equivalent exponential form as

(5-11) $$I = \frac{1}{k} 10^{\frac{\Delta E_s}{m}}$$

where ΔE_s is, again, the polarization emf. The very important result of (5-10) is that the polarization voltage $f_s(J_s) = \Delta E_s$, previously written in general functional notation is now completely described in analytical terms of a particular function: the polarization emf is a logarithmic function of the applied current, and the constants m and k can be easily fitted to any curve of similar shape. Regardless of the particular value of E_o or the location of the breakpoint for any curve of similar shape, the two constants m and k absolutely determine the curve. For example, using the experimental data of curve 2, Figure 26: $E_o = -0.760$ Volt, the breakpoint is at (.05) (10) = 0.5 ampere, and

$$m = \frac{.836 - .760}{\log 20 - \log 5} = \frac{.836 - .760}{\log \frac{20}{5}} = \frac{.076}{\log 4} = \frac{.076}{.6} = 0.127$$

all of which are determined directly from curve 2, and the value of k is calculated now from equation (5-4):

$$-(-0.760) = .127 \log 0.5k$$

$$0.760 = .127 \log k + .127 \log 0.5$$

$$= .127 \log k + (.127)(-.3)$$

$$= .127 \log k - .038$$

$$0.760 + .038 = 0.798 = .127 \log k$$

$$\log k = \frac{.798}{.127} = 6.28$$

$$k = 10^{6.28}$$

Now, the equation of curve 2 can be written quite compactly, from equation (5-1), as

$$E_s = -\left| 0.760 + j0.127 \log 10^{6.28} I \right|$$

which is a simply determined, easily readable expression in analytical form for the extremely nonlinear curve 2. A numerical check of the above empirical equation of curve 2 is provided by selecting a particular value of current from curve 2 and calculating the potential from the equation. Selecting the current at 20 per cent of maximum or (0.20) (10) = 2.0 amperes, the calculated potential is as follows: since the 2.0 ampere point selected is to the right of the breakpoint, equation (5-3) is used.

$$E_s = -m \log kI$$

$$= -0.127 \log (10^{6.28}) (2)$$

$$= -0.127 (6.28) - 0.127 (.3)$$

$$= -0.798 - .038$$

$$= -0.836 \text{ volt}$$

which is precisely the potential value on curve 2 corresponding to a current of 2 amperes. This value is as accurate, analytically, as the actual value read from curve 2.

The equations of the other experimental current-potential curves can be empirically derived in a similar manner.

No such powerful correlation between the theory of cathodic protection and the experimental results, as has been presented in full detail in this Chapter, has ever before been made. The polarization terms in the equations of Mears' and Browns theory, footnote references 1 and 3 in Chapter II, are in general functional notation because the particular functions were unknown; Ewing's theory did not contain polarization terms. Mears and Brown have used linear functions, but these are obviously poor approximations of the nonlinear characteristic curves.

Actual experimental curves may depart slightly from the ideal form, as shown by the curves of Figures 26 and 27, but the breakpoint can be used as a basic quantitative value of current which can be modified by an appropriate safety factor. This method of determining the value of protective current is seemingly opposed to the critical-potential criterion, since the breakpoint method is based upon the value of current at which the potential variation begins, while the critical-potential method consists of varying the potential until it assumes an arbitrary value. However, over a lengthy period of time, the value of current determined by the breakpoint method will cause the potential to change in the same direction as the potential variation of the critical-potential method. The single critical potential criterion has been shown in this Chapter to be unreliable, and it is scarcely logical anyway. The breakpoint method of the current-potential semilog curves is actually the only true quantitative criterion, but it has previously been entirely experimental.

Any particular potential criterion for a single environment could be tested as to reliability by maintaining the potential of a small specimen, buried in the environment, at the selected value. Similarly, the value of protective current, as determined from either 1) a current-potential curve of a small specimen buried in a given environment or 2) any arbitrary postulated value, could be tested by maintaining the particular current at its fixed value. Of primary importance, then, are methods of performing the potential and current criteria experiments. Original methods will be presented in the following chapter.

CHAPTER VI

ELECTRICAL METHODS OF PERFORMING BASIC EXPERIMENTAL RESEARCH STUDIES

EXPLANATION OF THE TWO TYPES OF BASIC EXPERIMENTS

In lieu of exact analytical methods for the prediction of protection requirements for varied environments, two types of basic experiments have been officially recommended by the Minimum Current Requirements Committee of the National Association of Corrosion Engineers. It is believed that a large number of experimental studies, conducted in a wide variety of environments, will add to the fundamental knowledge of both corrosion and protection phenomena. These experiments should also yield quantitative data for the predetermination of critical potentials and current-densities required for protection of structures, both existing and proposed, located in any of the various environments.

An exact description of methods of performing the two types of experiments has never been published. It was believed that individual investigators would devise a number of methods. The following methods and explanation of the two types of experiments are the writer's solution to the problem of methods. The experiments can be performed quite simply if the proper electrical circuits can be developed for use. No satisfactory circuits have been published for use in these experiments. In this chapter, original methods will be developed for the experimentation.

The first of the two experiments is a constant-current type. For a number of specimens buried in one particular place, it is desired to set the magnitude of the protective current (or current-density) applied to each specimen at a chosen fixed value which will remain essentially constant throughout the period of the experiment. Though the individual current applied to each specimen is constant, the several currents should differ from one another by increments of sufficient size to ensure that a wide current range is covered. Equal current increments would ordinarily be chosen for uniformity in the interpretation of the results. For example, with a set of five specimens each of which has an exposed surface area of one square foot, the individual currents might be fixed at 1, 2, 3, 4, and 5 milliamperes, respectively. For the same set of specimens, the currents may instead be set at 0.5, 2.0, 3.5, 5.0, 6.5 milliamperes, or possibly at 1, 4, 7, 10, 13 milliamperes, et cetera. Local conditions dictate the choice of current range to a large extent, involving the consideration of soil resistivity, moisture content, and other pertinent factors. The results of this type of experimentation should indicate the critical value of applied current (current-density) for protection of structures located in the same environment in which the experiment is conducted.

The second type of experiment is a constant polarization emf study. It has been shown previously that the initial overall potential of an unprotected structure is changed in the anodic (negative) direction by application of protective current, and that the change in potential (ΔE_c) is the cathodic polarization emf. Assuming that the initial open-circuit potential E_{co} of the unprotected structure is approximately constant, it can be seen from the equation,

$$(6\text{-}1) \qquad E_c = E_{co} - \Delta E_c = E_{co} - f_c(J_c)$$

which was developed in Chapter II as equation (2-19), that the potential E_c of the cathodically-protected structure can be set at a constant chosen value by setting the polarization emf ΔE_c at a constant value. As shown by equation (6-1), ΔE_c is a function of the cathodic current-density J_c, and J_c is dependent upon the applied protective current. Then, the actual potential E_c varies with the strength of the applied current. This E_c versus I_p variation has already been shown, in Chapter V, in graphical form for a typical group of specimens not all buried in the same location. With a group of specimens buried in the same locality, the measurable potential E_c of each specimen is to be set at a fixed predetermined value by adjusting the individual currents to the specimens. The fixed potentials of the several specimens should differ by appreciable increments, usually of equal magnitude, in order that a broad range of potential may be examined. Fixed potentials for a group of five specimens could be selected as -0.60, -0.70, -0.80, -0.90, and -1.00 volts, respectively, measured with respect to the saturated calomel electrode, so that the arbitrary critical potential, -0.78 volts, would be adequately bracketed on both sides. The choice of fixed potentials may be -0.70, -0.75, -0.80, -0.85, and -0.90 volts, respectively, et cetera. The particular potential range selected will be determined to some extent by the conditions of the particular environment. Each specimen-potential should remain essentially constant over the entire period of the experiment. Results of the potential studies should yield the critical potential of protection for a structure located in the specific environment of the experiment.

Steel pipe specimens are quite satisfactory for use in the two types of experiments because the ends can be sealed to eliminate the sharp corners and edges which make a uniform current-density a virtual impossibility. Equal protection of every unit area of the cathodic surface demands a uniform current-density, and, though this is rather an ideal condition, it should be attained as nearly as possible. Only one pitted hole is necessary to render a section of commercial pipeline undesirable for use, and a pipeline is only as strong as its weakest section.

The results of a polarization emf experiment in which the author participated[1] are indicative of the difficulties encountered in such a study. In Figure 28 are shown graphically the measured potentials, with respect to a saturated calomel cell, of three steel pipe specimens over a period of approximately three months. The potentials were measured by means of the circuit shown schematically in Figure 29. A potentiometer connected between the reference electrode and a particular specimen will read the approximate true open-

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[1] Scott P. Ewing, "Potential Measurements for Determining Cathodic Protection Requirements," Corrosion, VII (1951), pp. 410-422.

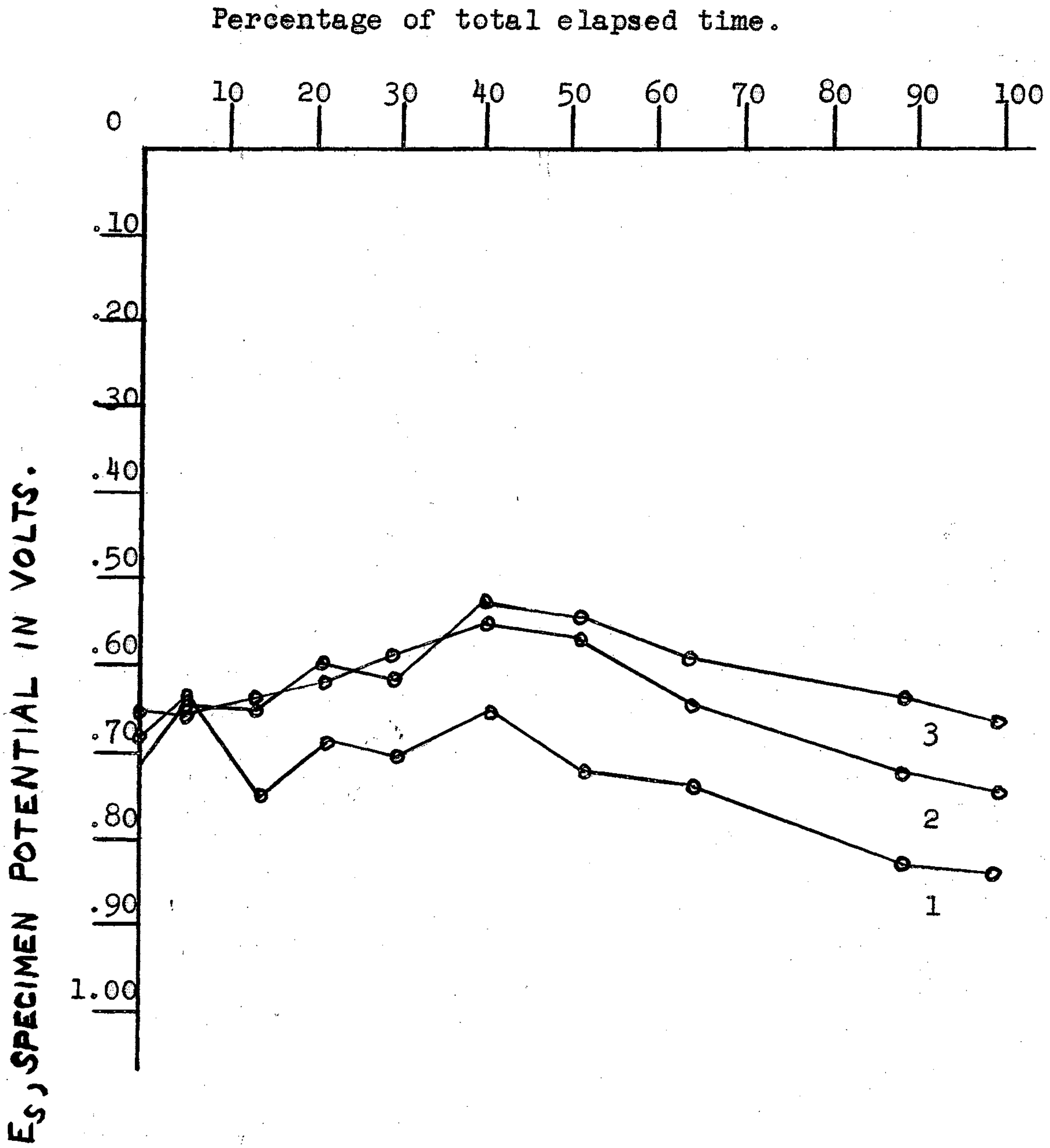

Figure 28. Potential-Time Curves.

circuit potential of the specimen if the switch S is opened and the potentiometer is quickly balanced—a matter of manual dexterity. Adjustments of currents to individual specimens are made by moving the clips attached to the wire resistor R. The currents to each specimen can be determined by measuring the voltage drop, with a potentiometer, across the precision resistors r (one ohm) in series with each specimen.

As Figure 28 shows, there is considerable variation in the measured potentials of the specimens between the times of making the measurements. In Figure 30, potential measurements of three similar specimens located in a fresh-water pond at a depth of 12 inches, whereas the first three specimens were placed in sandy loam at a depth of 12 inches, show the same unavoidable variations in potential with elapsed time. To correct these potential variations manually, a human operator would have to be capable of supplying continuous adjustments to the position of the clips. Continuous manual adjustments are not readily feasible over any considerable period of time; for this reason, it is highly desirable to develop automatic control circuits as a replacement for manual operations. The desired potentials at which specimens 1, 2, and 3 of Figure 28 were to be maintained constant are -1.00, -0.85, -0.80 volts, respectively. Specimens 1, 2, and 3 of Figure 30 were to be held at the constant potential values of -1.00, -0.85, -0.70 volts, respectively. The current applied to each specimen was varied manually only after each potential measurement and in the direction to increase or decrease the measured potential toward the constant specified value pre-

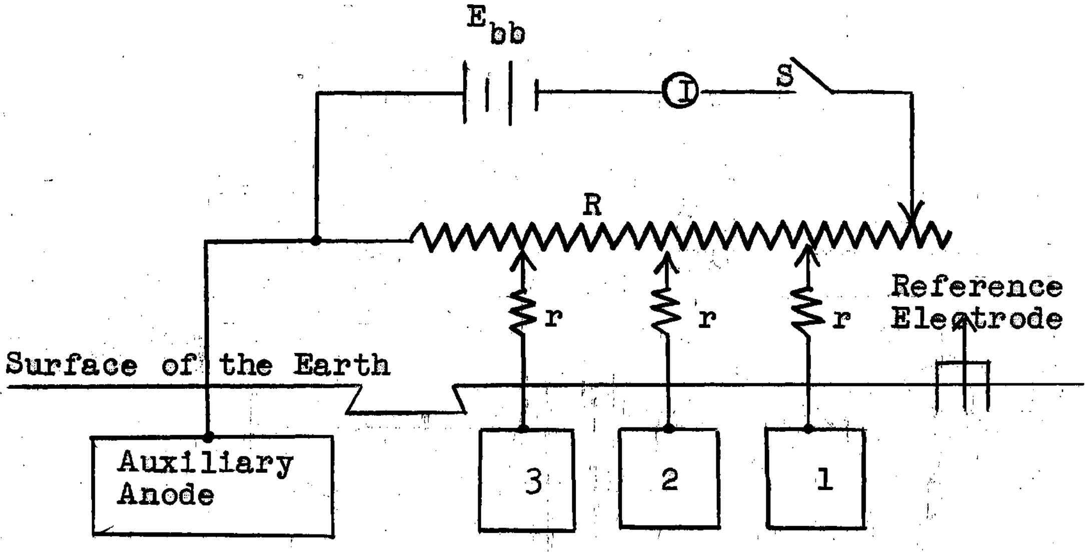

Figure 29. An Experimental Potential Circuit.

selected for each specimen.

METHODS OF PERFORMING THE TWO TYPES OF EXPERIMENTS

The results shown by both Figures 28 and 30 clearly illustrate the impossibility of maintaining the potential of a specimen at a fixed value by periodic manual changes in the applied current.

So far as can be ascertained, only one automatic potential-control circuit has been developed[2]. The circuit diagram appears in Figure 31. Tubes T_1 and T_2 are vacuum triodes; tube T_3 is a thyratron triode. The D.C. supply voltage is 200 volts; the A.C. supply is 25 volts. Resistor r is 5

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[2] A. Hickling, "Studies in Electrode Polarization", Transactions of The Faraday Society, XXXVIII (1942), pp. 27-33.

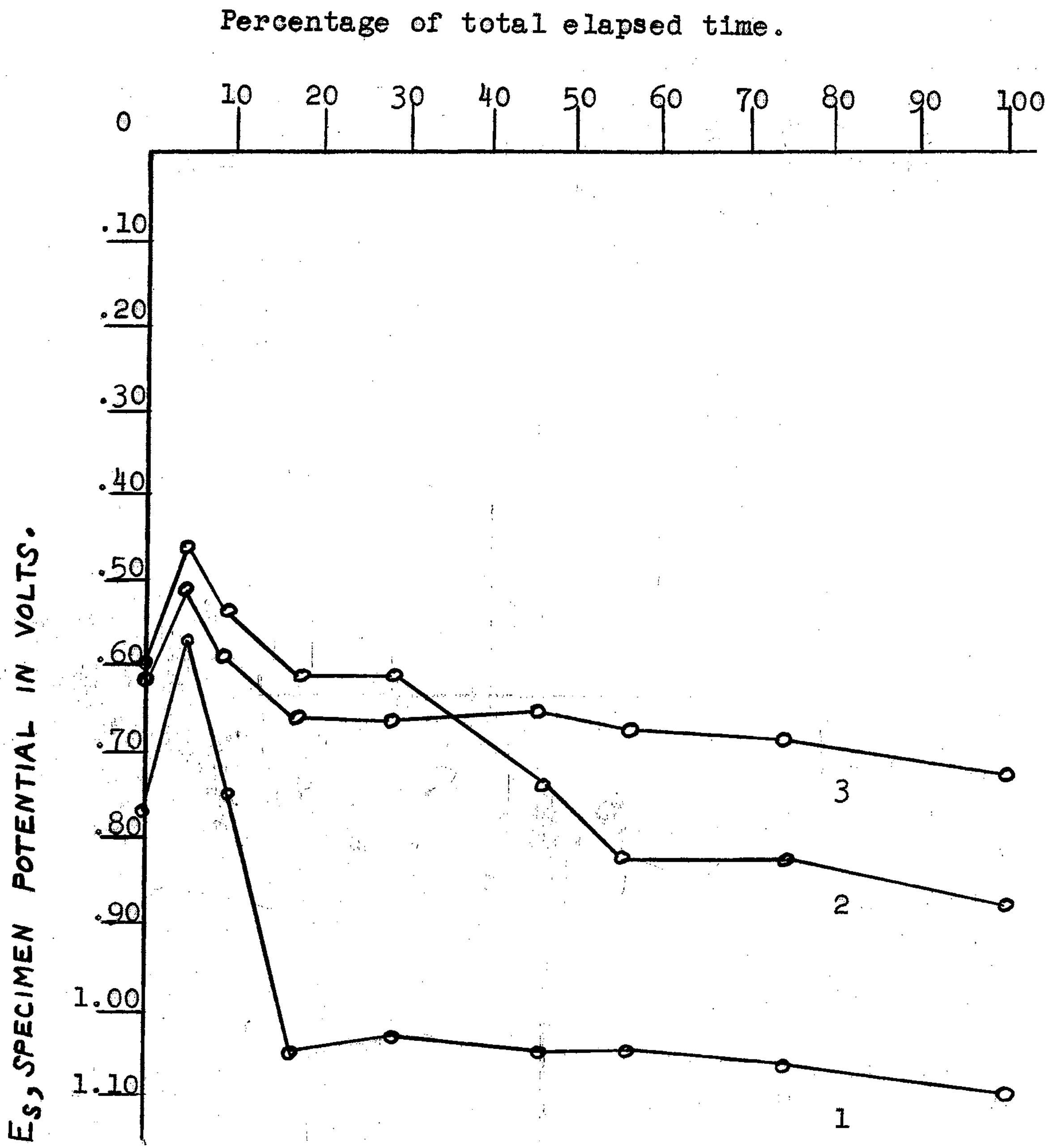

Figure 30. Potential-Time Curves.

megohms, r_3 is 100,000 ohms, r_1 is 5,000 ohms, r_2 is 300 ohms, and r_4 is 10,000 ohms. These values are quoted only to illustrate the relative sizes of the various components; all of the values, including batteries B_1 and B_2, depend upon the particular tubes used.

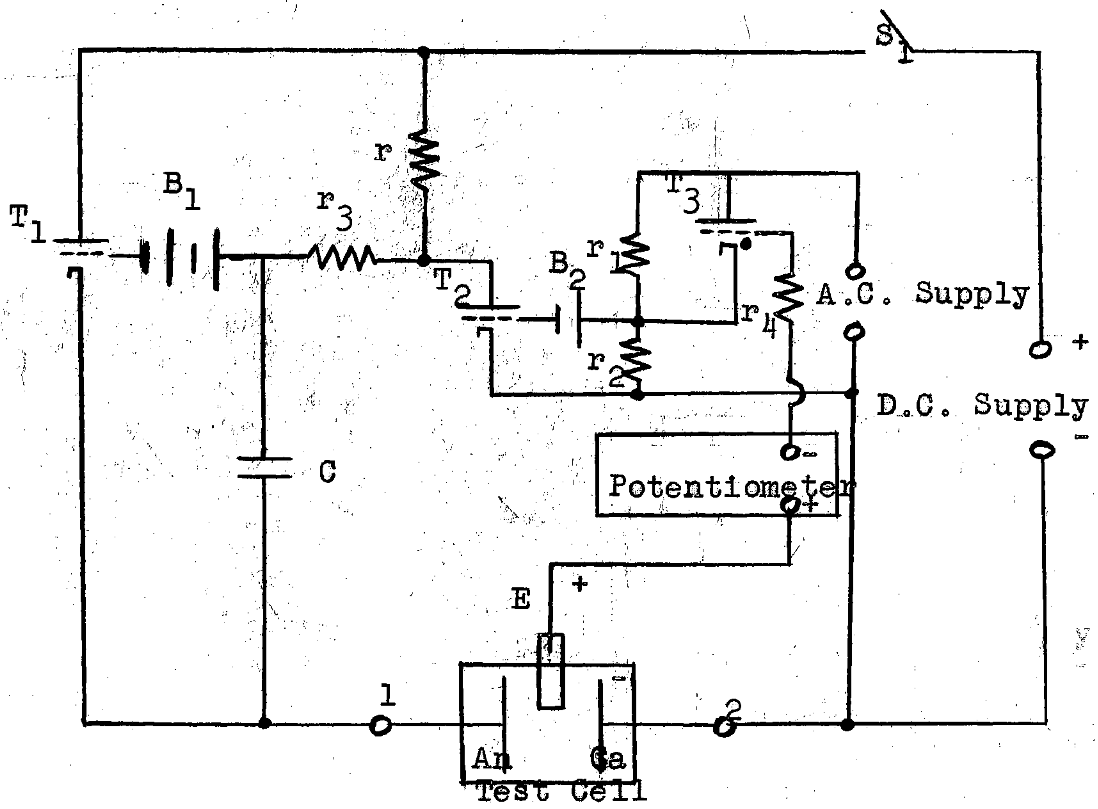

Figure 31. An Electronic Regulator.

When switch S_1 is closed, condenser C charges through resistors r and r_3, with the upper plate positive. The condenser voltage opposes the negative bias of B_1 on the grid of T_1, causing the plate current of T_1 to increase. The plate current of T_1 is also the current which flows through the test cell. The cathode Ca of the test cell tends to polarize because of the flow of current onto it, and the polarization increases as the current increases, thereby forcing the cathodic potential more and more in the (negative) anodic direction. The difference of potential between the cathode and the reference electrode E is connected in series with the reference potential standard furnished by the potentiometer and further to the grid of the thyratron T_3. When the cathodic potential is equal in magnitude and opposite in polarity, as shown, to the potentiometer voltage, then the thyratron is allowed to conduct. A part of the plate current of T_3 flows through r_2, from top to bottom, which voltage opposes the negative bias of B_2 on the grid of T_2. The decrease in grid bias on T_2 allows this tube to conduct, so condenser C can then discharge through T_2, which increases the grid bias on T_1 and decreases the plate current of T_1. Now, the polarization of the test cell cathode decreases, causing the cathode potential to rise momentarily in the (positive) cathodic direction which allows the potentiometer to cut-off the plate current of the thyratron. A complete cycle of operation has thus been described. This automatic regulatory circuit is in the on-off category, causing the cathodic potential to flucuate around the value of potential set on the potentiometer.

The Electronic Regulator of Figure 31 can be modified for use as an automatic current regulating circuit. A resistor is connected in series with the test cell, and the (IR) voltage drop across the resistor is held constant, thus holding the current itself constant. This modification is shown in Figure 32. Only one connection is changed: the lead from the reference electrode is disconnected and then placed at the left end of the series resistor r_5. Now the voltage across r_5 is

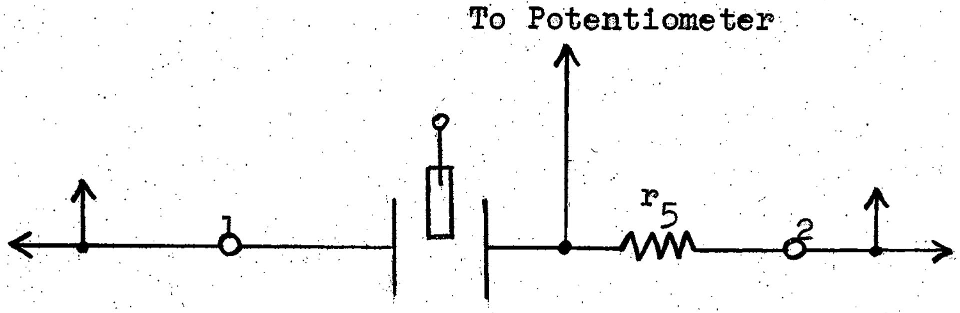

Figure 32. Modification of The Electronic Regulator.

in opposition to the potentiometer voltage, just as the reference-electrode voltage is connected in Figure 31. In the modified circuit, the test-cell cathode potential can be measured by connecting a second potentiometer between the reference electrode and the cathode, external to the cell. So, this Electronic Regulator is a dual-purpose circuit: though it is basically a potential regulator, it can be adapted to regulate either constant potential or constant-current.

The principal disadvantage of this Electronic Regulator is the erratic firing characteristic of the thyratron. The firing characteristic of a gas-filled triode changes appreciably from time to time for a given tube, and the characteristic curve for the same type of tube varies considerably among individual tubes. The inconsistent nature of the firing characteristic is the source of difficulty in firing the thyratron at the proper time when the test-cell cathode attains the desired pre-selected potential value.

A simple method of performing the constant-current experiment, through electronic means, is illustrated by Figure 33. It is well known that the plate current of a pentode is essentially constant over a wide range of plate voltage, for a fixed control-grid voltage. The D.C. Supply voltage is usually 200 to 300 volts. In series with the tube and D.C. supply is the test-cell whose difference of potential between Anode and Cathode is at most only a very few volts. Though the Anode-Cathode voltage of the test-cell may vary with the current through the cell, the range of the voltage variation is so small compared with the magnitude of the D.C. Supply voltage that the current is unaffected and remains constant in value. The desired value of constant-current is set by adjustment of the control-grid bias obtained from the variable resistor R. If it is necessary to observe the potential of the Cathode relative to a reference electrode, a potentiometer and electrode can be connected in the same manner that has

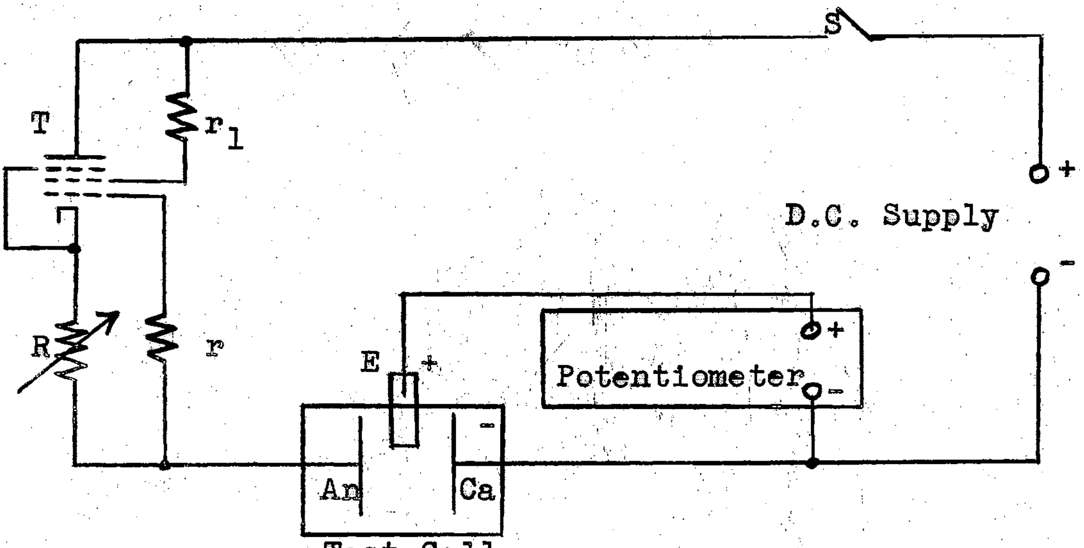

Figure 33. A Constant-Current Regulator

been previously given for Figure 32. The only limitations on the circuit of Figure 33 are: 1) the current-voltage characteristic of the tube should be flat, and 2) the tube should be capable of passing the desired value of current.

In Figure 34, curves of applied current versus elapsed time of current flow are shown. Values of the various circuit parameters used in the constant-current regulator of Figure 33 are listed directly above the curves. A test-cell was used consisting of two metal electrodes each with approximately 50 square inches of exposed surface area and an electrolyte of water. This test-cell should represent a more difficult situation than the same electrodes placed in the earth, since the resistivity of the water is higher than that of the earth. The current was measured by a milliammeter reading accurately to 0.05 milliampere. As the curves indicate, there was no measurable variation in the current over a period of several days. This regulator is as reliable as its constituent components. The curves are equivalent to current-densities of approximately 3, 9, and 15 milliamperes per square foot for curves 1, 2, and 3, respectively. These current-densities adequately bracket the range of most interest, and the curves imply that any value of current between the extreme values of 1.00 and 5.00 milliamperes may be expected to remain constant. If the self-bias provided by R is not adjustable to suit individual requirements, a separate voltage source can be used. Several individual circuits, each like that of Figure 33 can be operated in parallel from the same power supply, depending upon the current capacity of the supply. The usual power

Values of circuit components, for the current regulator of Fig. 33.

D.C. Supply——260 volts
250 volts
r_1——100,000 ohms
r——90,000 ohms
R——20,000 ohms
T——6SJ7

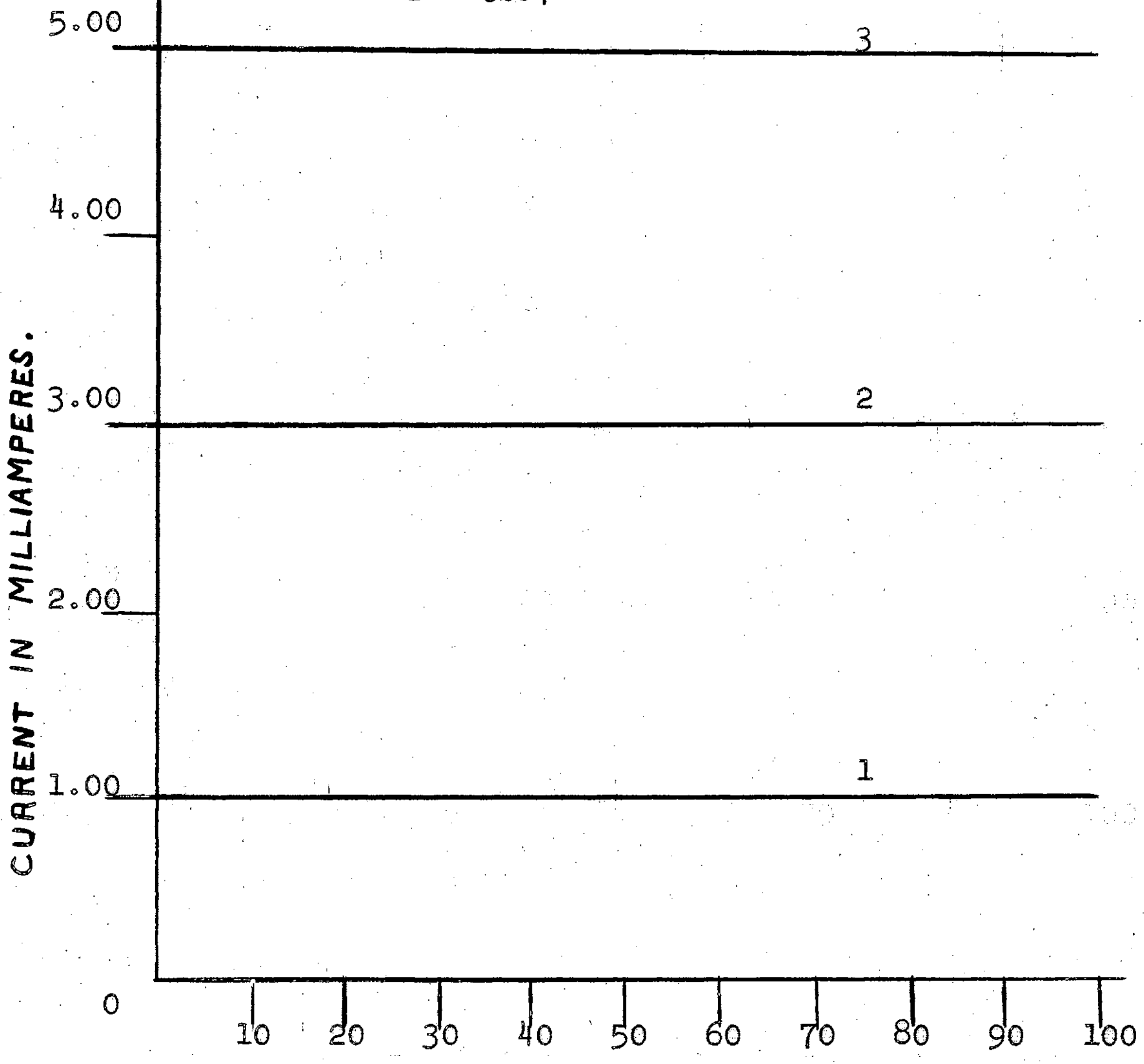

Figure 34. Current-Time Curves.

supply containing a type 80 rectifier tube or equivalent will easily provide current for six small specimens. A different type of pentode tube, such as the 6SK7, can be used instead of the 6SJ7 if more current is needed. Changes in current caused by both polarization emf and varying electrode resistance are effectively eliminated by this constant-current regulator.

A type of constant-potential experiment different from that previously explained can be performed with the circuit of Figure 33. In Figure 35 are shown curves representing the difference of potential between Anode and Cathode of the test cell, with the Anode positive, versus the applied current. These curves illustrate the nonlinear relationship between the difference of potential and the current, which is caused by both polarization and variable internal resistance of the cell. Three different sets of data are plotted in order to determine the ability to reproduce the same data. The differences in the three curves are within the range of possible experimental error. The points on the curves were obtained about three minutes apart, time enough for polarization to occur. The curves indicate that a fairly definite difference of potential exists for a given current; therefore, for a particular fixed value of current, a desired value of potential difference can be maintained almost constant. Holding the difference of potential constant, rather than the potential of either electrode with respect to a reference electrode, eliminates the necessity of measurement with respect to the arbitrary reference electrode. For this type of constant-

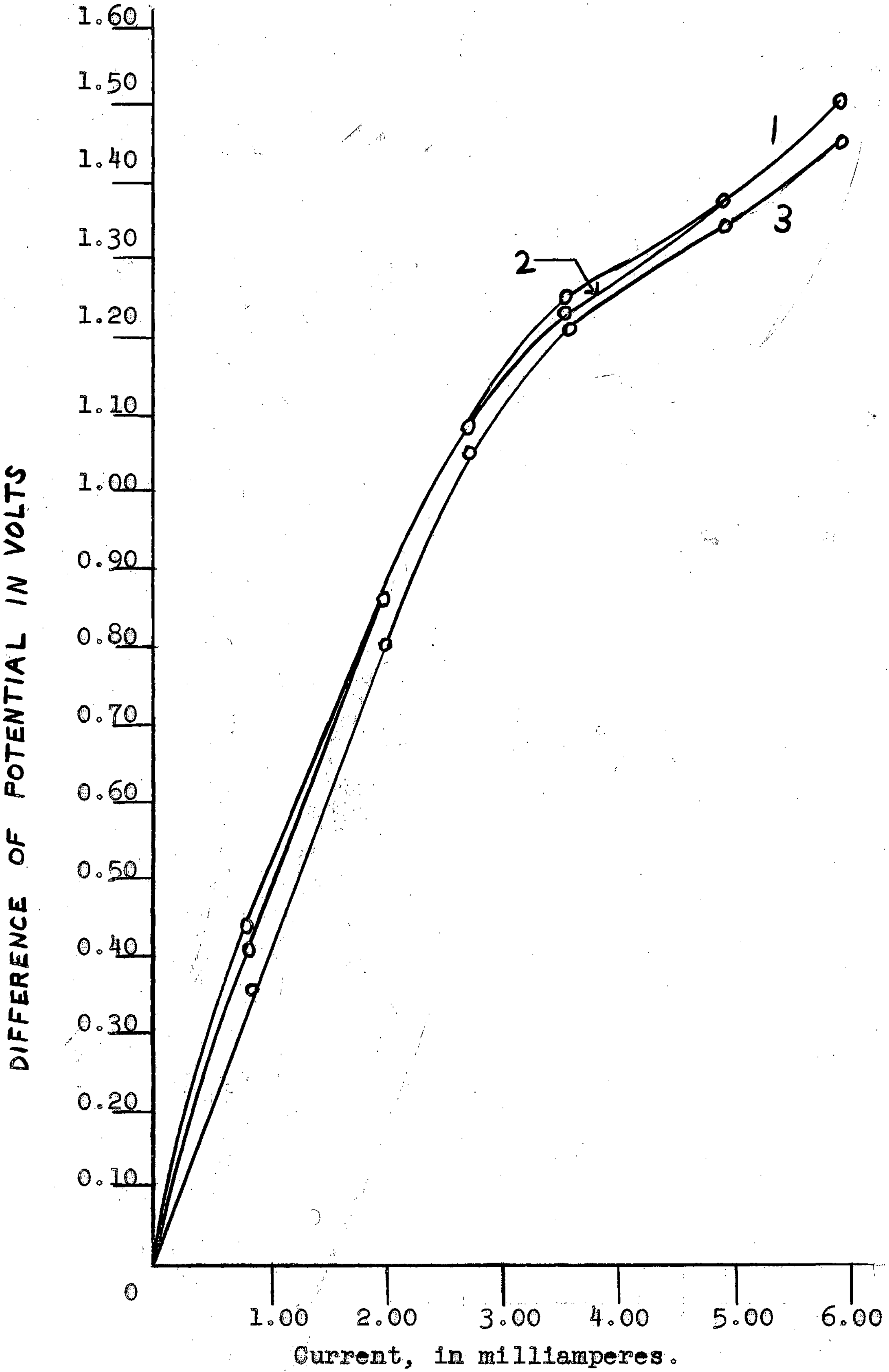

Figure 35. Test-Cell Difference of Potential versus Current.

potential experiment to be of value, the anode should be large enough compared with the cathode to ensure no polarization of the anode while effecting the desired polarization of the cathode. Thus, the constant-current regulator is also a dual-purpose circuit which 1) maintains the current at a definite fixed value, and 2) maintains a nearly definite fixed difference of potential for some corresponding value of current.

A better method of maintaining a desired difference of potential constant is shown in Figure 36. Two regulated d.c. power supplies are connected in series opposition through a voltage-divider R. If the voltage of power supply 2 is higher than that of supply 1, then the polarity of the voltage across R is as shown. With both supplies operating near their rated output voltages, the voltage across R will be very nearly

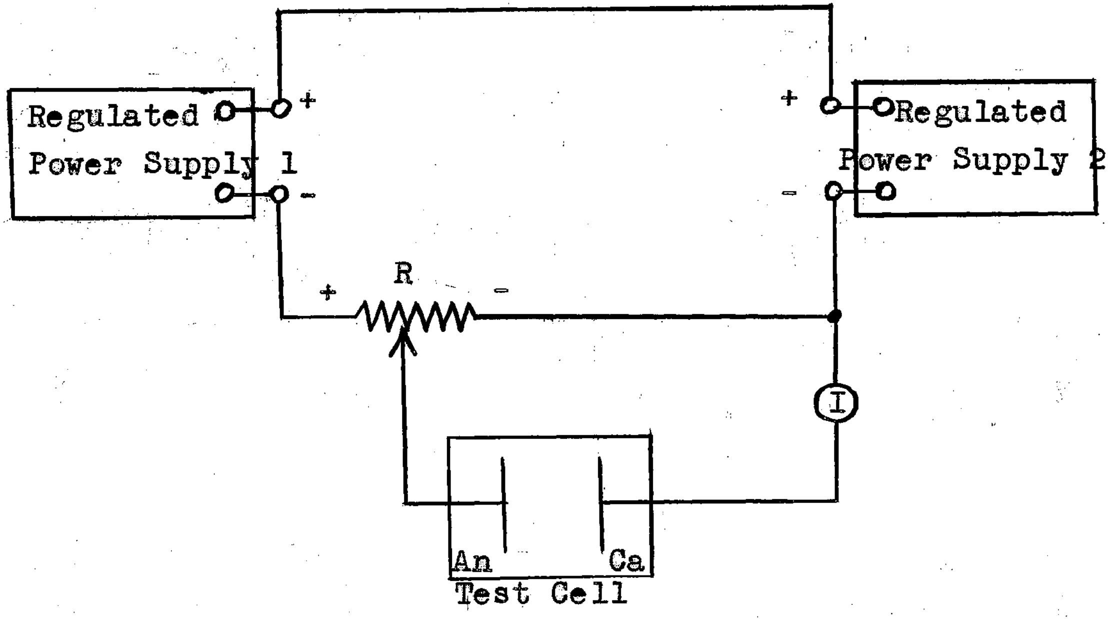

Figure 36. A Constant Difference of Potential Circuit.

constant. The desired difference of potential for the test cell is obtained by adjustment of the movable terminal on R, and this voltage will also be regulated to a constant value. Figure 37 shows the variation of three preselected values of difference of potential versus elapsed time of application. All of the voltages were constant over a period of several days, and the current measured at the same time as the voltage is slightly variable. The reliability of this circuit is determined by the dependability of the circuit components. The particular values of constant voltages are 0.50, 0.75, and 1.00 volt for curves E_1, E_2, and E_3, respectively, which correspond approximately to the same general range of interest as the constant-current curves of Figure 34. The voltage range of this method may be varied widely by relative adjustment of the two d.c. power supply output voltages as well as by varying R. The curves of Figure 37 were obtained with power supply 2 set at 260 volts, supply 1 at 245 volts, and the voltage across R was, of course, 15 volts with the polarity as marked on the figure. The particular value of R used was 2500 ohms. The values of current flowing through the test-cell are also plotted on Figure 42. The current I_1 corresponds to voltage E_1, I_2 to E_2, and I_3 to E_3. As the curves show, in spite of the variation in current caused by polarization and variable internal resistance of the test-cell, the potential across the cell is maintained constant in every case.

The reason for developing two new methods for performing a constant difference of potential experiment is that if an anode of large size relative to the size of the specimens is

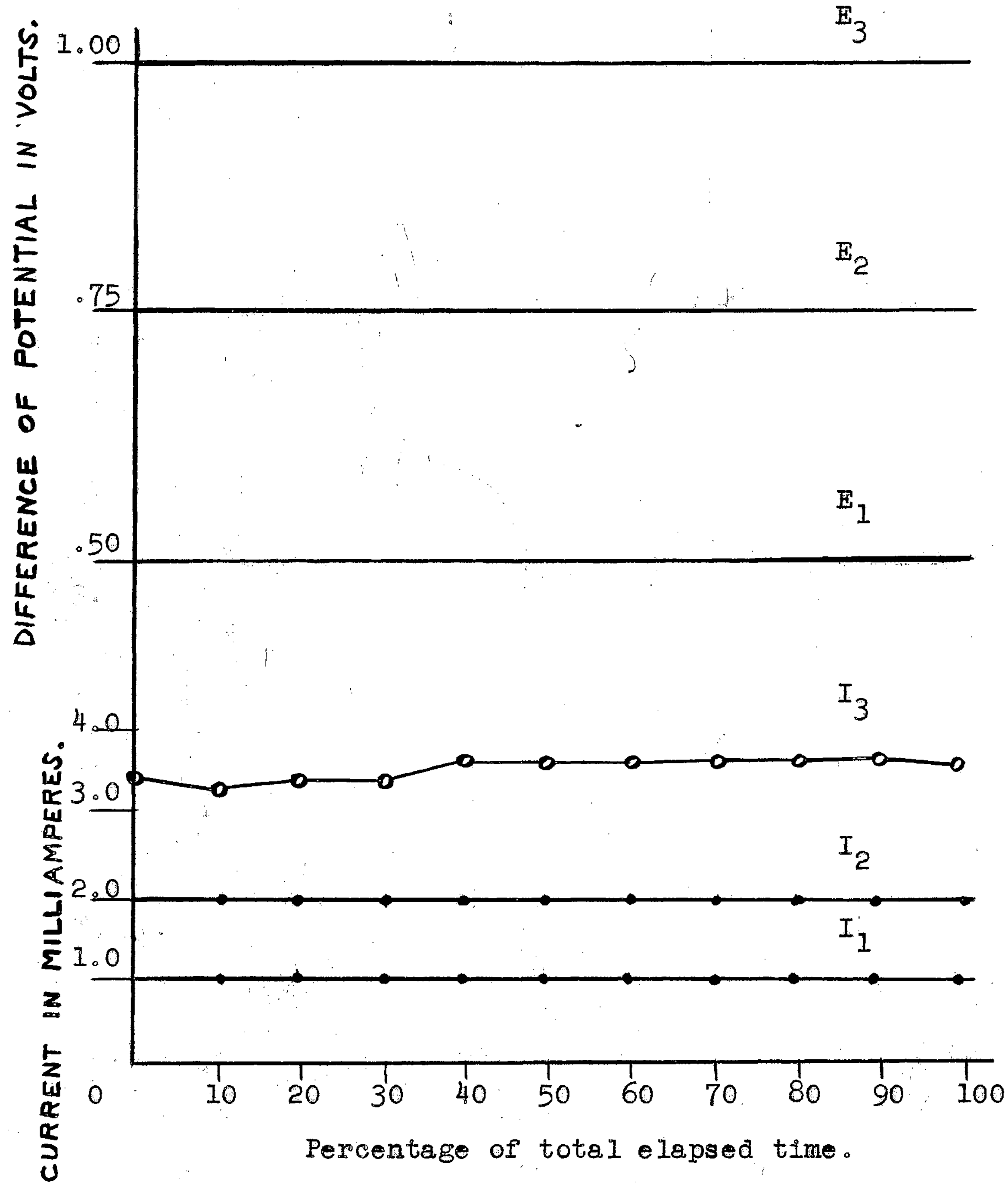

Figure 37. Regulated Potential Difference and Current, versus Elapsed Time.

used, then the anode will not polarize and the experiment is exactly the same as the first type of constant-potential experiment. That an electrode will not polarize if the current-density on the surface is small has been clearly shown by the horizontal portions of the semi-logarithmic current-potential curves of Chapter V. In these curves, the measured potential of the specimen tends to remain constant at the open-circuit potential value even after current has been applied until the breakpoint is reached. It is necessary only to use an anode large enough so that it is operated on the nearly horizontal part of its current-potential curve.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The representation of the cathodic protection mechanism by equivalent circuits is a valuable physical picture to the electrical engineer who by education and training visualizes many electrical phenomena in terms of circuit theory. The solutions of the equivalent circuits are interpreted as the quantitative principles of cathodic protection in mathematical form. The writer's extension to the fundamental theory of cathodic protection, consisting of the section of Chapter II entitled "Effect of the Resistivity of the Earth", was made possible by his representation of cathodic protection in equivalent circuit form. The validity of equivalent circuit representation is verified in Chapter II by the derivation of the previous theories of cathodic protection from the author's equivalent circuit form, first, before extending the theory to include the resistivity of the earth. The effect of the resistivity of the earth, as developed in the new extension to the older theories, is a means of explanation for the high corrosion rate found in low-resistivity soils and the low corrosion rate in high-resistivity soils though the measured potentials of structures in the two different types of soil may be of the same magnitude. The theory developed in Chapter II is later correlated with the experimental data, Chapter V, in the quantitative form of empirical, analytical equations; such a correlation has not been previously possible.

The methods for the measurement of potential and current presented in Chapter III have been explained in detail and shown to be applicable to many different types of structures. The author's method of measuring structure potentials has been compared with the methods of other investigators, in Chapter III, and has been found to be comparable in accuracy to any of the other methods. The arbitrary potential-criterion that is regarded by many as an absolute law for successful cathodic protection has been carefully explained, in the same chapter, for later comparison with experimental results in Chapter V.

Chapter IV is a consideration of one of the basic constituents of any cathodic protection system: the auxiliary anode, which propagates the applied protective current to the structure. The author's method of calculating electrode resistance-to-ground as derived from the electromagnetic field equations, Gauss' Theorem in particular, has been shown not only to supplement the classical method based upon summation of a geometric elemental resistance but, more important, to provide an alternative for electrode configurations to which the classical method cannot be applied. Further, a critical examination of the classical method is made which clearly enumerates the assumptions and limitations inherent in its application to any type of practical problem.

A potential criterion for a given environment is a strong possibility, but a single potential indicative of protection in any and all environments appears to be ridiculous. In particular, the experimental results in the form of Current-

Potential Curves, Chapter V, show conclusively that the arbitrary potential criterion of -0.85 volt is completely unreliable. This arbitrary critical potential of a buried structure, with respect to a copper-copper sulphate electrode, is a standard which has long been rigidly observed by many research personnel. The single empirical equation which has been fitted to the characteristic Current-Potential semi-logarithmic curves is a powerful, simple means of expressing the numerical data in exact analytical form. The theory of Chapter II has been correlated with the empirical equation representation of Current-Potential experimental data in Chapter V to yield a known analytical function, a logarithmic function, for the general functional notation employed in all previous theories. This correlation has never before been possible because of the extremely nonlinear form of the Current-Potential curves. The empirical equation representation can be adapted to <u>any</u> curve of the characteristic shape whereas any other known method would require an extensive set of calculations applicable <u>only</u> to a <u>single</u> such curve being considered. A complete example of the ease with which such curves may be fitted in equation form is given numerically in Chapter V.

A detailed explanation of types of fundamental research experimentation in cathodic protection is given in Chapter VI. Original methods which make possible the performance of such experimentation are given in the form of electronic circuits, complete with diagrams and test results. The dual-purpose electronic regulator containing three electron tubes was originally reported in the literature for use in laboratory investigations of electrode behavior; however, it is equally applicable to experimentation in the field, either constant-current or constant-potential. The electronic regulator utilizing a single tube has by demonstration proved to be ideally suited to constant-current experimentation, and slightly less reliable for constant difference of potential experimentation. The method for the latter type of experiment which contains two regulated electronic d.c. power supplies in series-opposition is quite precise and stable in operation. These circuits are believed to be adaptable to a wide range of application because of the proven reliability of the test results. The methods presented in this chapter should be of value to any research investigator of corrosion and cathodic protection phenomena.

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