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OAK RIDGE
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LOCKHEED MARTIN

ORNL/Sub/95-SR893/3

HVDC Power Transmission Electrode Siting and Design

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MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
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HVDC POWER TRANSMISSION
ELECTRODE SITING AND DESIGN

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EXECUTIVE SUMMARY

Introduction

A monopolar line configuration using earth as the return conductor is projected to reduce capital costs per megawatt as much as 20 % compared to a bipolar line. However, full time use of earth in this manner is prohibited by the National Electric Safety Code (NESC) due to the threat to human (and animal) safety in the form of step-and-touch voltages. Also, large direct currents (typically ranging in thousands of amperes) could be responsible for corrosion and other forms of "interference" to underground facilities; viz. pipes, cables, etc. Presumably, such problems would be virtually eliminated if the current could be forced to flow *only* deep inside the earth. This would require that the connection to "deep earth" be made with deep-earth electrodes. The statement of work for this project suggested that electrodes placed deeper than 100 feet (30 km) should satisfy this need, a notion that is not supported by practical experience. This research strives to shed light on the feasibility and practicality of using deep earth electrodes to permit their use for extended periods without adverse consequences.

This report begins with a review of the fundamentals associated with current conduction in earth, including the various techniques available for measuring the earth's electrical properties. The sources of existing data are discussed and some specific data for selected regions of the U.S. and Canada are reviewed as examples. Electrode technology and design issues are reviewed and recent experience gained by New England Power and Hydro-Quebec is discussed. The issues associated with direct current flowing in underground pipelines (and other facilities) are described and the present-day mitigation measures are evaluated. Suggestions are made for further R&D in the coordination of cathodic protection systems, an area that has evolved as an empirical, trial-and-error art more than a science.

Summary of Key Findings

There is substantial world-wide experience with both sea and land HVDC electrodes. The only full time monopolar-earth-return systems utilize sea (or beach) electrodes. Most land electrodes are of the shallow horizontal configuration, but some of the most recent ones in the U.S. employ vertical electrodes exceeding 100 feet in depth. The experimental deep electrode (550 meters) associated with the Baltic Cable HVDC link is the only electrode that is located directly in the transmission substation; all others are remote (7-95 km) from the HVDC station they serve. Although it is not located directly in the sea, the ground water in which the experimental electrode is suspended is brackish due to its proximity to the Baltic Sea; so in effect, it is equivalent to a beach or sea electrode.

The effectiveness of an inland ground electrode depends largely on the electrical properties of the local and regional geology. All existing ground electrodes, whether shallow or deep satisfy NESC step-and-touch voltage criteria in the locality of the electrode but may not perform alike relative to their interference with underground facilities. To illustrate this fact one need only consider the deepest ground electrode (116 meters) in North America, namely the Duncan site that serves the Radisson HVDC terminal on the Quebec-New England 2000 ampere line. Although very deep, the electrode is embedded in very high resistivity rock, so a significant part of the current remained shallow. Initially, about 10 % of the electrode current found its way into the parallel ac electric system through ac ground connections. The direct current caused half-cycle saturation of transformers which created harmonics to flow in the ac system, causing overheating of some equipment and missoperation of protective relaying. Hydro-Quebec added small series capacitors in key ac lines near the HVDC station to minimize the direct current in the ac circuits to tolerable levels. Short of placing the electrode into the earth's mantle (about 30,000 meters beneath the surface), going deep alone does not guarantee trouble-free performance.

Meanwhile, a properly-designed shallow electrode can perform with little interference if it is located in "good geology" and is remote from underground facilities. For example, the Nelson River HVDC link operated in monopolar-earth-return for about six months with no trouble. The electrodes for that system are deployed horizontally in a ring at 3 meters depth. Finding the "good geology" is key and accepting responsibility for mitigation of "stray current" effects on pipelines, etc. along the route is necessary.

Mitigation of "stray currents" in pipelines and underground cable systems is a mature technology, evolved largely for protection against naturally-occurring electrolytic corrosion and telluric currents caused by solar flare activity. Passive and active cathodic protection schemes are common on all pipelines. Active protection using small ac-dc converters are necessary on underground facilities exposed to highly variable "stray current" effects. In areas of congested underground facilities, interaction between cathodic protection systems, often attached to competing utilities' facilities, can create complex and imperfect protection. While the effects from HVDC ground currents might be swamped by telluric current effects during a solar storm event, the continuous presence of HVDC in full time earth return mode would require robust cathodic protection of numerous facilities in the HVDC path.

As always, economic considerations will prevail in choosing between monopolar-earth return and monopolar-metallic return operation. Because most of New England is high resistivity granite, New England Power chose to extend an electrode line 235 miles (386 km) to the existing and adequate Windsor electrode in Quebec rather than develop a new electrode for their Sandy Pond terminal in Massachusetts. The electrode line, also called a dedicated metallic return conductor - a third conductor on the HVDC line - cost less than the estimated cost of a new electrode.

Future Research

Currently available electrode materials and configuration designs have evolved from a mature cathodic protection industry and can serve the HVDC application for part-time (emergency conditions only) utilization as they are deployed today. This research did not determine whether or not today's materials and configurations are suitable for full time use at thousands of amperes - 8760 hours and 2000 amperes = 17.5 million ampere-hours per year or about twenty *tons* of electrode (anode) decay during each year! The life-cycle cost of a system would need to include provisions for annually replacing many electrode elements that are packed in coke-breeze located hundreds of feet down a one-foot diameter well. If full time monopolar-earth return operation is to be practical, for high rated

HVDC systems at least, research into 1) materials for longer lasting anodes and 2) into deep electrode configuration designs that will permit cost-effective means for replacement of depleted anode elements, might be suitable. Alternatively, research into more compact HVDC line designs incorporating a metallic return (perhaps using the static wire position) might prove fruitful. This approach could be economic for short distances whereas an expensive deep electrode may not be economic except for long lines.

Added research into using state-of-the-art network analysis computational techniques for designing and operating active cathodic protection systems in areas of complex underground facilities is recommended. Currently, the coordination between multiple systems is accomplished by technicians using trial-and-error methods. The equivalent of a power flow program is non-existent in the cathodic protection industry. More effective cathodic protection system designs might allow more and larger ground current sources (including HVDC) to be accommodated.

MONOPOLAR HVDC ELECTRODE SITING

1. INTRODUCTION

This study considers the geological-geophysical conditions relative to the installation of an earth ground return for monopolar HVDC transmission. There are a number of ground returns in operation world-wide, for the most part these are sea electrodes either directly immersed in the sea water or close enough to the sea to benefit from the high conductivity saltwater. For the purposes of this report, we have considered land sites only; while sea electrodes should be carefully installed, the technology is well known, considerable experience exists, site specific and regional geologic conditions are not nearly as relevant to successful siting.

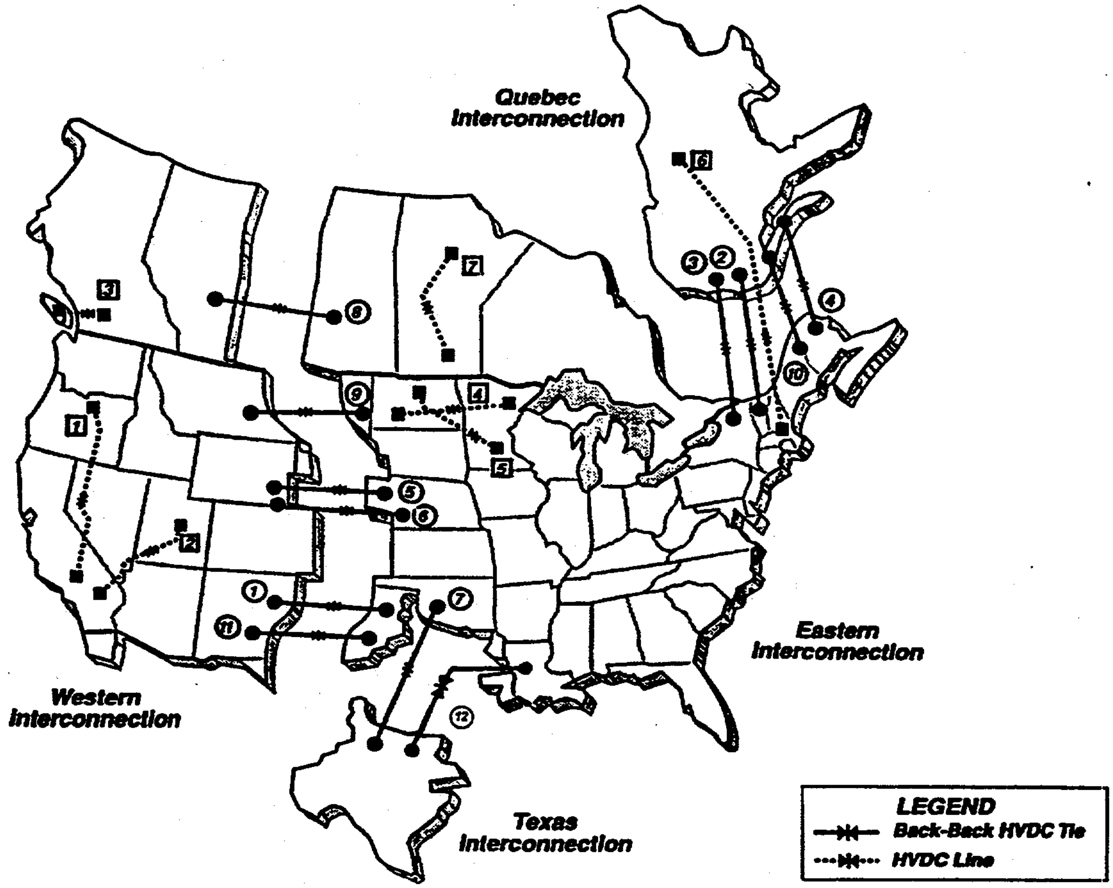
Shown on Figure 1.1 are the HVDC interconnections and transmission lines. Typical areas for the United States and Canada are discussed relative to their general geological conditions as it relates to earth conductivity. A substantial literature search of data bases consisting of the National Technical Information Service, Energy Science and Technology (DOE), and Georef (American Geological Institute) was made for appropriate information. More than 25,000 individual electrical surveys of some description were found that pertain to site specific and local areas. These studies involve mostly shallow penetration while for the purposes of this report we are mainly concerned with deep geological conditions. Such local studies however could be of use to an individual utility for assessment of near surface conditions if the site and survey coincide. Over 3,000 papers, articles and deeper electrical surveys were reviewed and used for the purposes of this report. These were in addition to appropriate text books and the data for the New England area that was assembled by New England Power Company for the Comerford, NH - Des Canton, Quebec, HVDC transmission line. Electrode installation descriptions for the Lisbon (Comerford) and Windsor (Des Canton) sites are taken mainly from individual electrical utility reports.

1.1 BACKGROUND

1.1.1 Potential Benefits of Monopolar-Earth-Return Operation

All long distance overhead-line HVDC systems in the North American continent operate normally in a bipolar mode, with earth return employed only when one pole is disabled for some reason. The allowable duration of earth-return operation is generally limited to short periods for emergencies and maintenance. This limit is intended to minimize interference (corrosion, etc.) with underground facilities such as pipelines, communications cables, power cables etc. Some HVDC lines have operated in earth-return for long periods of time without incident*, but such events are not allowed in the U.S.

* The Nelson River line located in Manitoba Canada operated in monopolar-earth-return mode for about six months due to the lack of a part, but no negative impacts were experienced. Extensive testing was done since two rail lines and a pipeline are in the vicinity of one electrode.



BACK - BACK HVDC TIE

1. Blackwater (200 MW)
2. Highgate (200 MW)
3. Chateauguay (1000 MW)
4. Eel River (320 MW)
5. Hamil (100 MW)
6. Virginia Smith (200 MW)
7. Oklaunion (200 MW)
8. McNeill (150 MW)
9. Miles City (200 MW)
10. Madawaska (350 MW)
11. Artesia (200 MW)
12. East Texas - Welsh (600 MW)

HVDC LONG DISTANCE TRANSMISSION SYSTEM

1. Pacific HVDC Intertie (3100 MW)
2. IPP (1920 MW)
3. Vancouver Island (682 MW)
4. CU (1000 MW)
5. Square Butte (500 MW)
6. Hydro Quebec - New England (2250 MW)
7. Nelson River (3668 MW)

Figure 1.1 North American HVDC Interconnections and HVDC Transmission Lines

Theoretically, a bipolar HVDC line is regarded as two circuits and should enjoy the same reliability as a double circuit ac line. That is, if one circuit fails, the remaining circuit can carry at least half of the initial power. To satisfy this reliability criterion without reservation would make a bipolar HVDC line (2 wires) equivalent to a double circuit ac line (6 wires), but with fewer conductors, lower losses and less expensive towers. However, without a return circuit available for extended periods, the bipolar HVDC does not strictly meet the two-circuit reliability criterion. The return circuit need only be available for single-pole operation long enough to repair the other pole line. However, most repair times exceed the limits (like 15 minutes in case of New England - Quebec 2,000 MW tie) agreed upon with affected pipeline (and other underground) utility operators.

Ideally, full time dc earth return currents would allow single-wire dc lines which could permit better utilization of some narrow transmission line rights-of-way (ROW). Numerous instances could arise where additional transmission capacity is needed on a tight corridor, but the expense of a bipolar installation is not justified. In such cases a single-wire monopolar line would be more desirable than a three wire ac circuit due to limited space. Line commutated and some - but not all - forced commutated converter technologies are suitable for earth-return operation.

Since such tight transmission corridors are most likely to occur in highly developed urban areas, the existing underground pipelines, cables, etc., would preclude collocation of dc earth-return currents on a full time basis today. The likelihood of prohibitive corrosion problems and dangerous step and touch potentials could be substantial in such a case. The National Electric Safety Code-NESC C2-1993, paragraphs 92, 215, 314, prohibits full time use of earth as a current carrying conductor for these reasons. Efforts to amend the NECS to allow such currents, provided the objectionable effects are mitigated, are on- going.

If the dc earth-return currents could be forced to penetrate deep into the earth and remain at depth, many of these objections to monopolar-earth-return operation could be eliminated. The electrode could be located in the same substation as the HVDC converter eliminating the need for a special electrode-line connecting the converter to a remote electrode site. Both the expense of the electrode-line and acquisition of ROW for that line and the electrode would be avoidable for perhaps a 20% reduction in the cost of an electrode facility. The risk of dc current flowing in underground cables, pipelines, electric utility transmission grounds, and a host of other surface or near-surface structures would be substantially lessened, although not eliminated altogether.

Substantial experience with successful "deep earth" electrodes will need to be documented before the NESC and the underground utility operators are likely to accept full time monopolar-earth-return operation of high current dc lines. Experience with full time sea-return operation is extensive around the world and should provide some guidance. Unbalanced currents associated with the New Zealand hybrid HVDC arrangement have caused earth currents that caused interference with underground facilities; conditions that have been documented and mitigated. The technology exists to mitigate such problems (see section 6 of this report) and, in time, more liberal use of earth-return for dc transmission could be justified.

This report documents the state-of-the-art in HVDC electrode siting and design and speculates on the prospects of successful use of deep-earth electrodes in the U.S. transmission systems. Present techniques for mitigating impacts of HVDC earth currents on underground facilities are described and the more promising areas for improving the technology are suggested. The report should provide future system planners with valuable insights into where, when and how monopolar-earth-return dc transmission can be employed to help meet the needs of their increasingly competitive industry.

1.1.2 Distribution of Current Between Two Electrodes

1.1.2.1 For Homogeneous Earth

It is important to understand how electrical current is conducted in the earth to understand the complexity of installing a successful ground electrode for distant transmission. Shown on Figure 1.2 is a cross section of the current flow lines and the orthogonal potentials for two current electrodes separated by a distance L in a homogeneous earth. The potential is zero halfway between the two current electrodes; the potential gradient is highest close to the electrodes and drops rapidly with distance away from the electrode. The symmetry of potentials between electrodes for a homogeneous earth is distorted by inhomogeneities such as lateral and vertical changes in the conductivity particularly if such changes exist near one of the electrodes. This is shown later in consideration of the New England-Quebec, HVDC line electrodes.

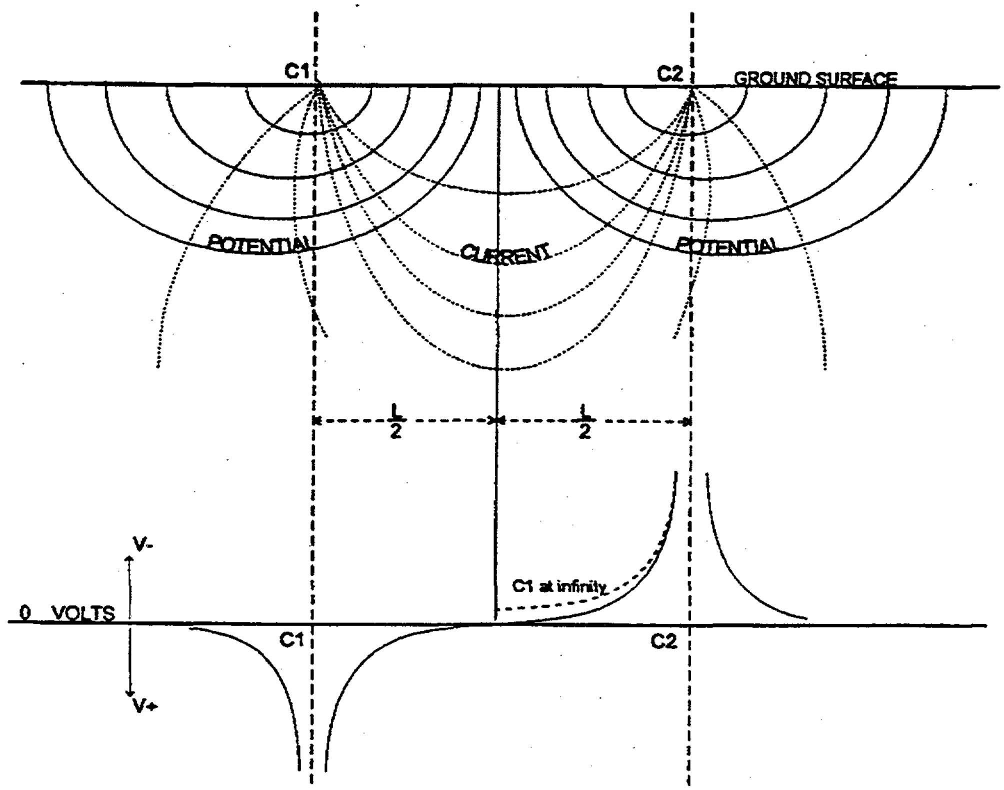
1.1.2.2 Two Layer Earth

Shown on Figure 1.3 is the fraction of current flow in the bottom layer for a two layer earth of resistivities ρ_0 for the top layer and ρ_1 for the bottom layer. Plotted on the abscissa is "k" the contrast of the resistivities. A perfect insulator is shown on the extreme left and perfect conductor on the right. The zero "k" line represents a homogeneous earth. The plane separating the two layers is chosen at three depths relative to the electrode separation L, at one-half (L/2), one third, (L/3) and at the full separation, (L).

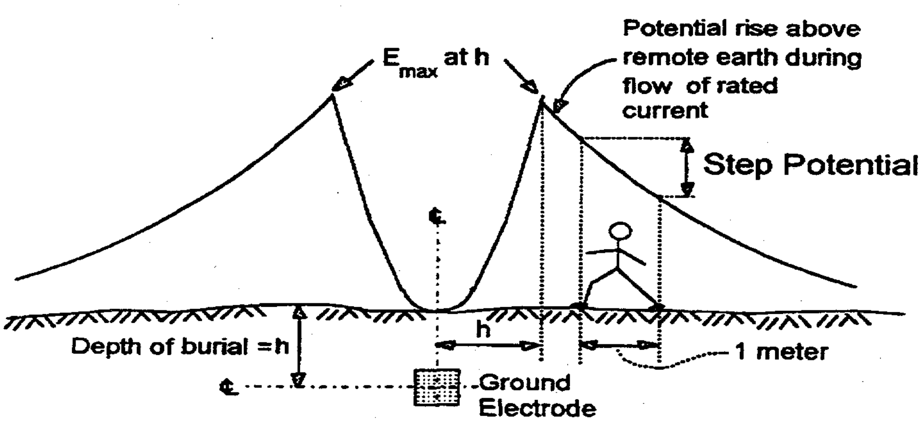
Shown on the ordinate is the ratio of the current flow in the bottom layer versus the total current flow. As might be expected, as the plane of separation between the two layers becomes shallower and/or the conductivity of the second layer increases, more current flows in the second layer; this is the desired condition for siting an electrode. For a homogeneous earth, 50% of the current flow is into the second layer at half the electrode separation.

1.2 EFFECTIVENESS OF DEEP ELECTRODE

There are two main reasons for the construction of a deep electrode: the reduction of near electrode step potentials (high voltage gradient) that could cause electrical interference and present dangerous potentials to humans and animals; a better connection to a deeper conductive layer.

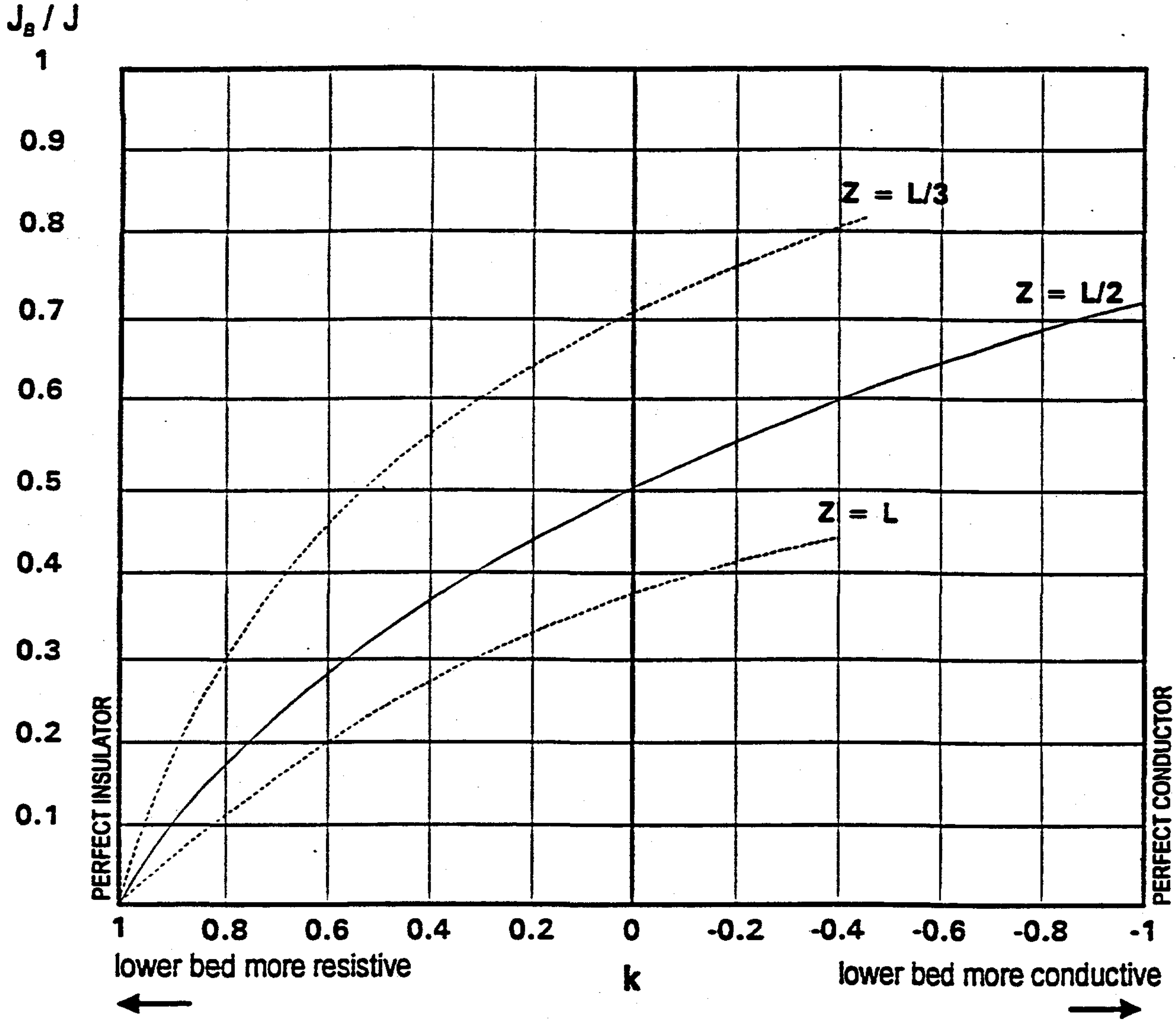


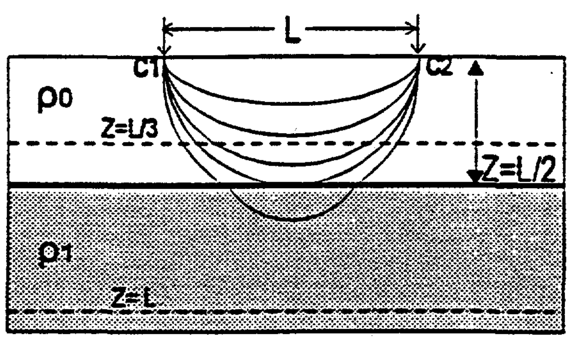
a) Current and Voltage Distribution for Two Current Electrodes
- Cross Section and Voltage Profile for Ideal Single-Layer Earth



b) Illustrative Definition of Step Potential

Figure 1.2 Current and Voltage Distribution for Two Current Electrodes, Step Potential





$$k = \frac{\rho_1 - \rho_0}{\rho_1 + \rho_0}$$

ρ_0 = resistivity of top layer

ρ_1 = resistivity of bottom layer

k = 0 for homogeneous earth

J_B = current flowing in the bottom layer

J = total current

L = electrode separation

Figure 1.3 Fractional Current Flow - Two Layer Earth

1.2.1 Step Potential

A step potential problem may exist at the boundaries of a very localized near surface conductive body or where the near surface materials are resistive. As seen in Figure 1.2, the potential gradient nearest the electrode is greatest and the potential is quickly reduced with increasing distances from the electrode. For a sub-surface electrode, the potential is not infinite above the electrode as implied by Figure 1.2A but reaches a maximum value at the electrode site as shown in Figure 1.2B. The peak potential (E_{max}) becomes less in magnitude the deeper the electrode is buried, although it appears further from the actual site. The step-potential problem is minimized by reducing E_{max} and "flattening" the profile.

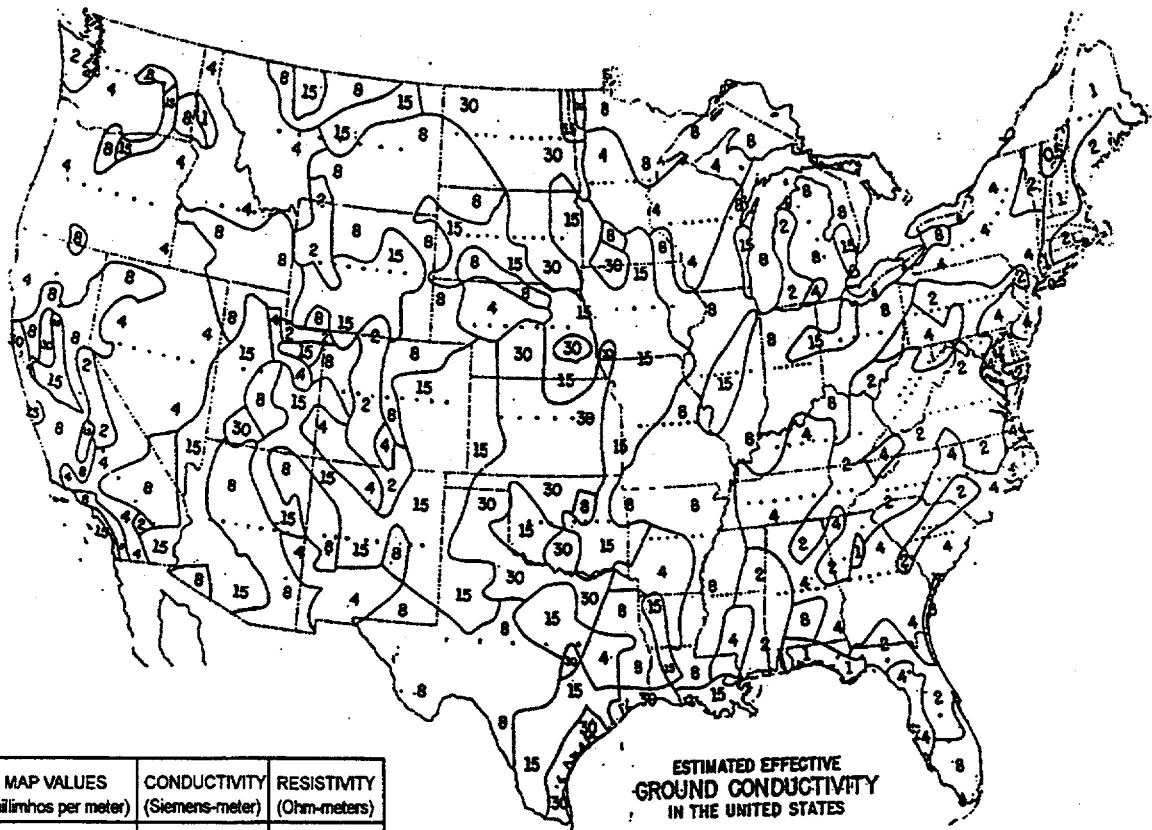
1.2.2 Connection to Earth

A second advantage of buried electrodes may be in the connection to earth. There are many cases where the top layer will have a higher resistivity than deeper layers In this case, the direct placement of the electrode into the conductive layer reduces the step potential effects at ground surface and direct connection to a layered conductor provides a much better chance for deeper conduction.

1.3 POTENTIAL FOR SITING IN THE UNITED STATES

The potential for siting a ground electrode in the United States depends on both regional and local earth conductivity conditions. Local conduction can be uniform or quite variable; Figure 1.4 is a map showing general U.S. shallow (mostly soils) conductivities prepared by the U.S. Department of Agriculture, (1954). The conductivity for sea water (not shown) is about 4 to 5 S/m (4,000 to 5,000 millimhos; a S/m (siemens/meter)= 1/ohm meter. This map is shown for a general impression only, in some of the more resistive zones designated with a value of 1 (1,000 ohm-m) very conductive soils can be found and conversely, although not as frequently, higher resistivities will be found in some of the more conductive zones (8-30). While local conductive soils (bogs, swamps etc.) may enhance electrode connection to the surrounding geology, it does not necessarily achieve deep conduction.

Shown on Figure 1.5 taken from Keller (1966) are the relative conductances of the near surface rocks (<10 km deep). These data were gathered from the grounding conditions for radio stations throughout the United States. While this map should not be used for siting, it accurately represents the broad conditions of the Midwest and parts of the West where the success of ground electrode siting is easier to predict. Areas that have moderate to high resistivities are discussed in more detail below.



MAP VALUES (millimhos per meter)	CONDUCTIVITY (Siemens-meter)	RESISTIVITY (Ohm-meters)
1	.001	1000
2	.002	500
8	.008	250
30	.030	33
5,000 (sea)	5	.02

Figure 1.4 Ground Surface Conductivity Map of The United States

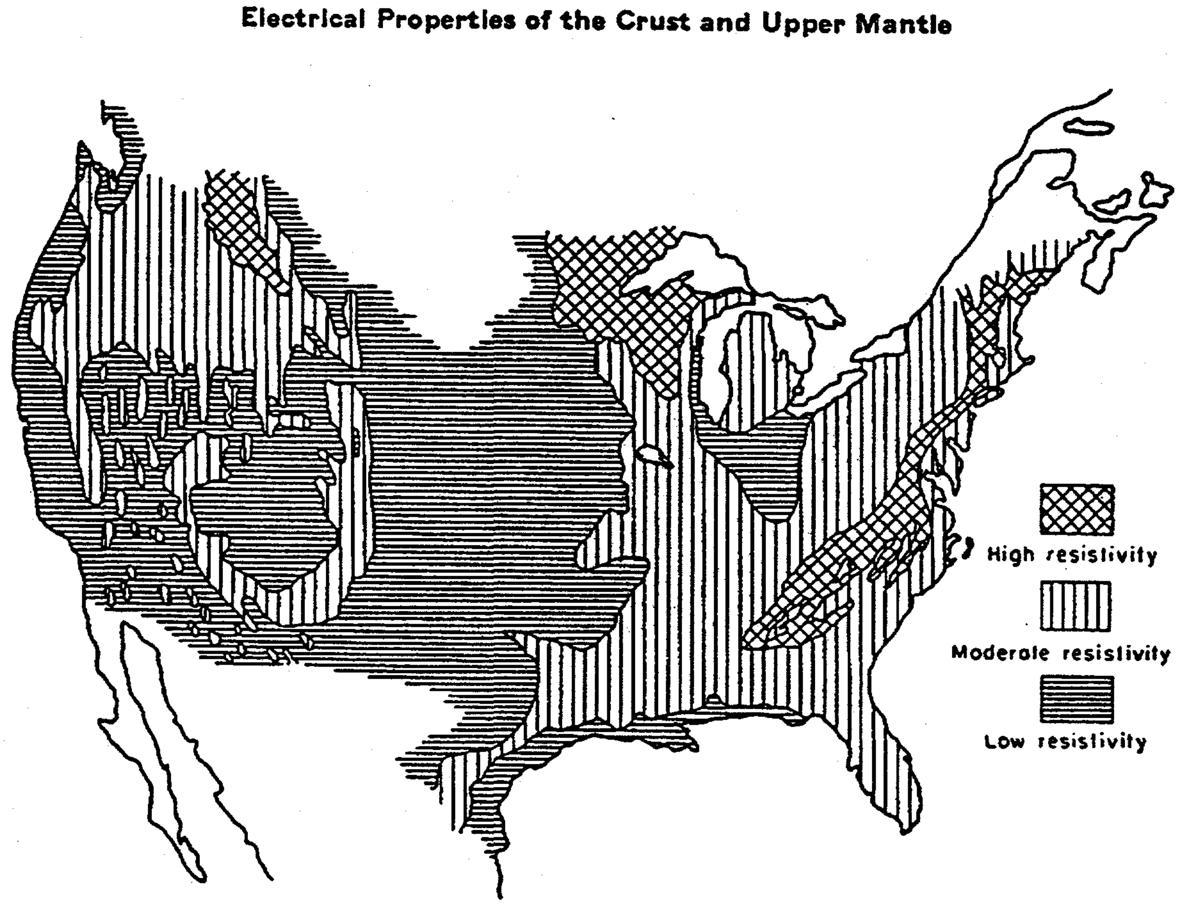


Figure 1.5 Surficial Bedrock Resistivity Map of The United States

2. ELECTRICAL PROPERTIES OF THE EARTH

There are several methods for exploring the earth by electrical means; these range in frequency from dc to low frequency ac (or commutated dc) galvanic measurements made by direct electrode contact with the earth to the higher frequency inductive measurements ranging from a few hertz to megahertz used in ground penetrating radar. The latter are used to assess local site conditions only. Our concern here is deep wide spread conduction associated with large electrode separations.

2.1 CONDUCTIVITY AND OTHER PARAMETERS

There are three electrical properties that describe the flow of electricity and associated magnetic fields for earth materials, the conductivity, the dielectric constant, and the permitivity. The permitivity is essentially that of air and does not generally enter into our considerations. The dielectric constant also does not significantly impact the lower frequency results as it would control high frequency ground penetrating radar for example. For our purposes, the conductivity (or its reciprocal resistivity) controls the flow of electricity and is our single parameter of concern.

2.2 CONTROLLING FACTORS FOR CONDUCTIVITY

2.2.1 Conductivity of Rocks

In general the resistivity of any dry rock material is very high since it is made up mainly of nonconducting elements and minerals. The conductivity of rocks is controlled by the amount of water present in their pores (sedimentary rock), fractures (sedimentary, igneous, metamorphic rocks), crystalline structures and boundaries.

Some rocks have inherently higher conductivities due to the presence of conductive minerals (magnetite, copper, tin, etc.) however the dispersed condition of these minerals rarely result in contact conduction between them except when the intervening spaces are "bridged" by the presence of water. Dispersed conductive minerals are generally associated with darker igneous and metamorphic rocks (gabbros, basalt, etc.) and some sedimentary rocks. In a resistive rock, less than one part in 1,000 (volume) of water will effect the conductivity value by (at least) an order of magnitude (10 times).

The resistivity of a material is a function of its resistance across a volume:

$$\rho = R\,A/L$$

Where ρ is the resistivity, R is the resistance, A is the cross sectional area, and L is the length of the specimen. The most common method for measuring the earth's resistivity is by injecting current to two current electrodes and measuring the voltage (potential) with two other electrodes in some predetermined electrode configuration; cross sectional area and length are determined by the electrode geometry used, this is treated in detail in the many text books on electrical prospecting (Telford et al 1990).

In terms of ohm's law the resistivity is expressed as:

$$\rho = E / J$$

Where the potential E is in volts/meter (m); and the current density J, is in amps/m^2; which results in units of ohm-meters for the resistivity ρ. The reciprocal of resistivity is conductivity expressed in siemens/m (formally mhos/m.) As has already been stated, water is the principal conducting agent in rocks, the resistivity of a material containing water can be expressed in terms of an empirical relationship called Archie's Law (Archie 1941) which was developed relative to the electric logging of wells:

$$\rho_b = a\rho_w \, \phi^{-m} \, S^{-n}$$

Where ρ_b is the bulk resistivity of the formation, ρ_w is the resistivity of the water, ϕ is the fractional pore volume, S is the fractional pore volume containing water, and a and $-m$ are rock formation parameters determined by a number of tests. Generally these values are: n= 2; ($1.3 \le m \le 2.5$); ($0.5 \le a \le 2.5$); ($0.1 \le \Phi \le 0.3$); in the case of igneous and many metamorphic rocks, the porosity is associated with fractures or intergranular spaces and as a consequence is usually much smaller.

The resistivity value for water ρ_w (ohm-meters) is largely dependent on its salinity content, typical values for water contained in earth materials are:

Igneous and metamorphic rock	0.5 - 90
sediments	1 - 80
sedimentary rocks	0.3 - 70
sedimentary rocks — oil bearing	0.03 - 10

Typical resistivity values for dry rocks exceed 10,000 ohm-meters. Conductive minerals such as the metals will make a difference in rock resistivity depending on how the minerals are dispersed and as previously mentioned, the presence of water.

The thermal gradient of the earth increases with depth and is sufficient at more than 30 km to cause at least partial melting; this condition also occurs for rocks very near surface where tectonic (structural deformation) forces are or have been recently active. Similar to the conduction when water is present, the conduction for rocks involved with melt or near melt conditions is mostly ionic although some electronic conduction can take place.

2.3 DISTRIBUTION OF ROCK CONDUCTIVITIES

Since the separation of the electrodes for DC current injection are conceived to be in the order of hundreds of kilometers, the current flow from such a separation can reach very great depths (Figure 1.3) although near surface conductors (natural or man-made) will impede this.

2.3.1 Versus Depth

In general, near surface rocks are more fractured and water filled than those deeper. As rock fractures close with depth, the water content is reduced and the conductivity drops. This variation of resistivity with depth is shown on Figure 2.1 (Keller 1968) which is drawn from a very limited data base but illustrates a general intermediate high resistivity layer particularly for older rocks. An increase in conductivity takes place at depths where partial melt occurs (>30 km). In general, the resistivity profile from earth's surface is:

0 - 10 km	10 - 2,500 ohm-m
10- 30 km	10,000 - 100,000 ohm-m;
> 30 km	10 to 100 ohm-m.

This oversimplifies actual condition for older geologies and the vertical profile differs substantially throughout the country. This general condition does caution that when the second layer is highly resistive it will result in higher potentials at distance from the electrodes (Figure 2.2).

The number of deep penetrating electrical surveys for the U.S. is not great, covering but a small part of the geography. For this reason, it would be beneficial if the electrical properties could be correlated to other geophysical data such as magnetic, gravity, seismic prospecting or earthquake recordings the combination of which reveal the crustal properties as well at the earths major mechanical boundaries such as the crust (6-30km thick), mantle, and core. There are abundant seismic survey and earthquake data which describe the vertical profile of the earth and magnetic and gravity data that help identify the rock lithologies. Correlations of the electrical data to the seismic data do not stand up well. This is not entirely surprising, since the seismic properties depend on the inherent mechanical properties, the moduli values, Young's, bulk, shear, as well as Poisson's Ratio and density of the host material whereas the electrical properties are controlled by the addition of water to the host material. At the near surface the electrical properties many times do correlate to the seismic properties because both are controlled, at least in part, by fracturing. The electrical properties correlate poorly with gravity data and even magnetic data; the latter, since the magnetic properties are driven by the content of magnetite which is mostly dispersed (discussed above).

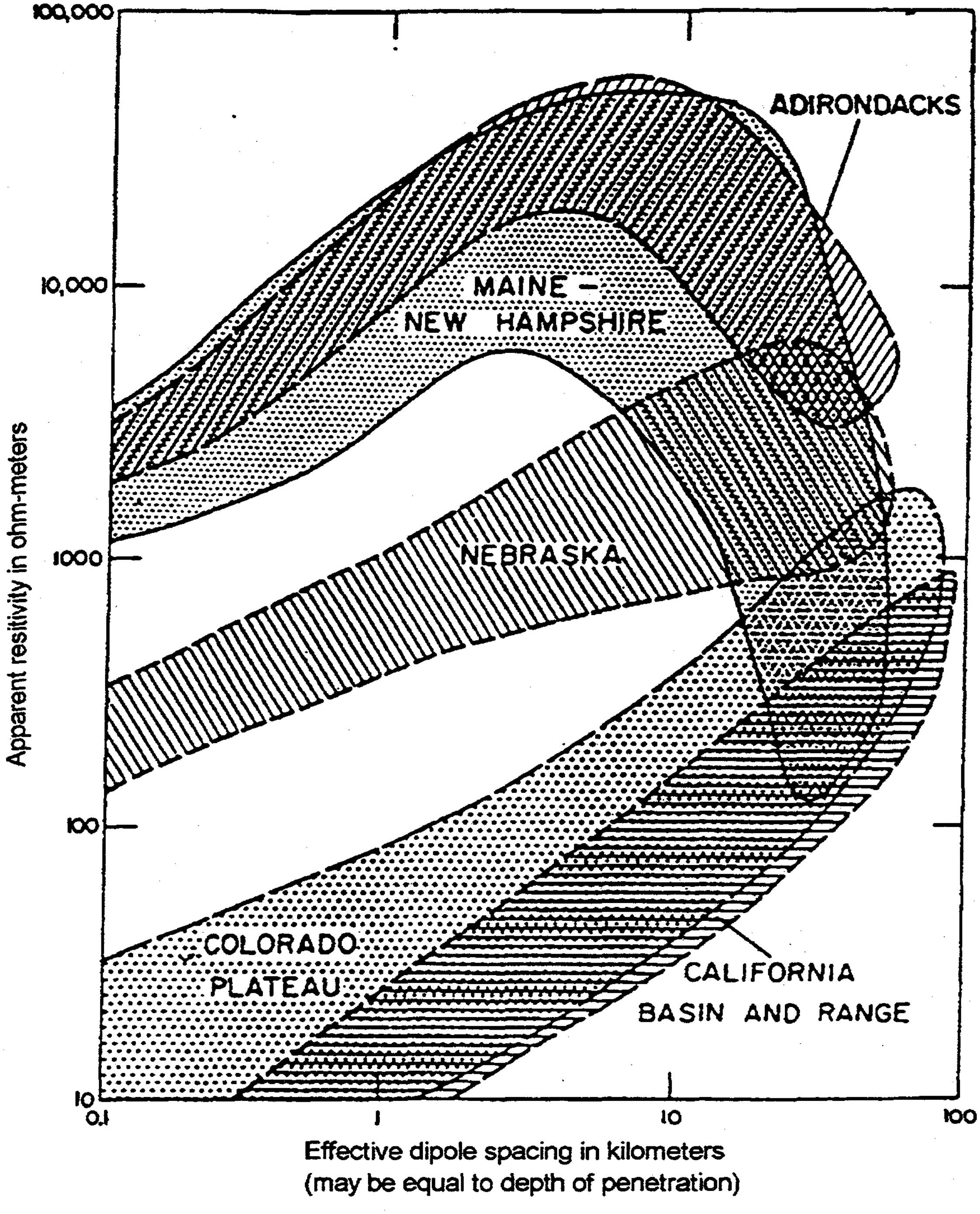


Figure 2.1 Vertical Profiles Four Regions of the United States (Keller, 1996)
Published by Society of Exploration Geophysics

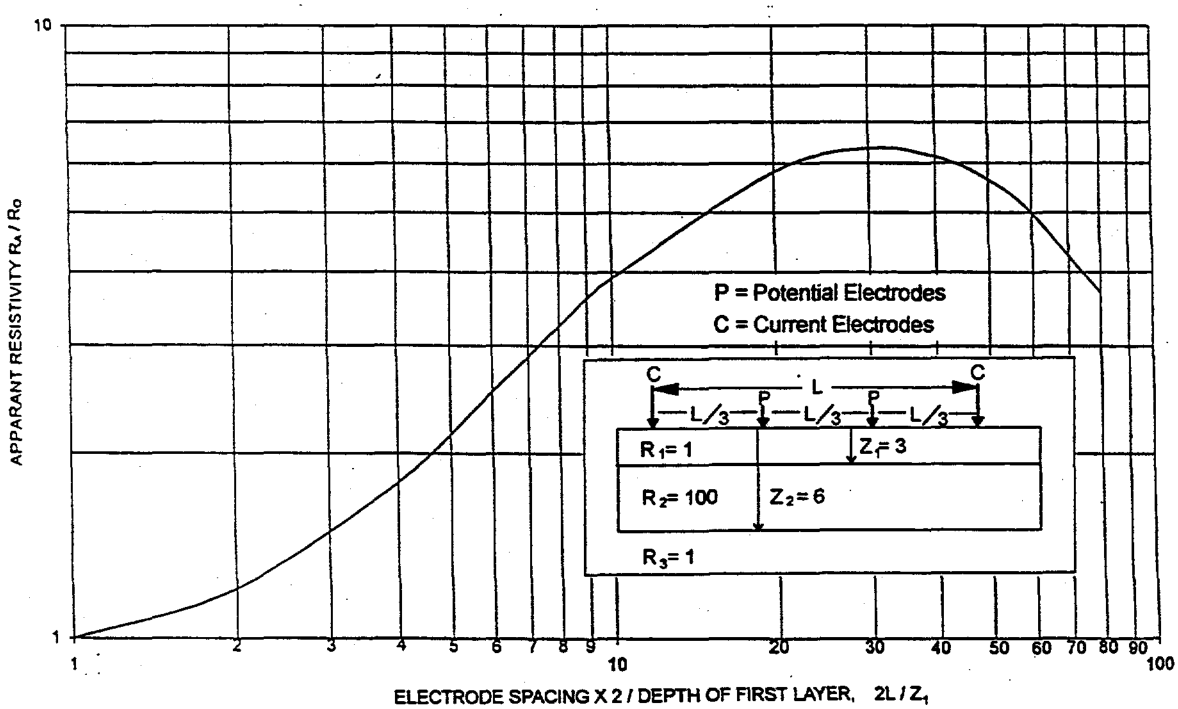


Figure 2.2 Three Layer Earth Resistivity Profile Low - High - Low

For the most part we are left with electrical surveys to describe the electrical properties of the earth and, in general the vertical conductivity profiles are poor. This is based on a number of factors, some of which are discussed under techniques below. Deep penetration requires significant averaging over long distances; the results of this averaging include any lateral effects such as the presence of conductive bodies not at depth, but at a horizontal distance. The presence of an ocean within the range of investigation will affect the results as will the presence of any other large scale conductive body. The more conductive the near surface body, the more concentrated will be the current in the body with less penetration to depth.

Prediction of the earths vertical profile in any region is highly uncertain because of the scarcity of deep penetration electrical surveys. While geological inference together with a few measurements can help to assess whether a ground electrode is feasible, it should be anticipated that at least some measurements will be required to confirm feasibility.

2.3.2 Versus Geology

While the correlation of the electrical properties of the earth are not well correlated to other geophysical data, the electrical properties can, many times, be reasonably correlated to geological data (see Archie's Law for formation factors above). A good correlation of the electrical conductivity to geological formations is quite beneficial because it allows the use of geological maps to extend our knowledge. This is also true for the vertical extent of the formation with the qualification that fractures control conductivity and fractures generally close with depth so the vertical profiles are not as easily predicted. Formational characteristics can change in a substantial manner laterally, but the formation conductivity is still a good indicator of its relative conductivity over a large volume.

Shown on Figure 2.3 are sedimentary basins whose depths are generally several kilometers and whose sediments are likely to have higher conductivities than the surrounding rock, based on their geology. This is roughly verified by Figure 1.5.

2.4 SPECIAL CONDITIONS

2.4.1 Shield Areas

Shield areas are areas of the world that have existed relatively undisturbed by active tectonic forces for millions of years. This is not to say that such areas are not deformed by previous orogenic forces it means that they have not been subjected to such forces for several million to billions of years, central Canada for example. They are composed of rocks that are highly resistive being relatively unfractured. While most shield areas are poor candidates for electrode siting, they can have zones rich in conductive minerals which in the presence of water make them conductive these are the exception and require exploration to find. As has been pointed out earlier, broad characterizations do not qualify or disqualify a site for potential ground conduction. The shield area of Canada would, in general, be classified as resistive and not a good candidate. However even these areas have anomalous conductors present which can be exploited; shown on Figure 2.4 is a conductive body which underlies the central plains of the U.S. and transect the shield area of Canada.

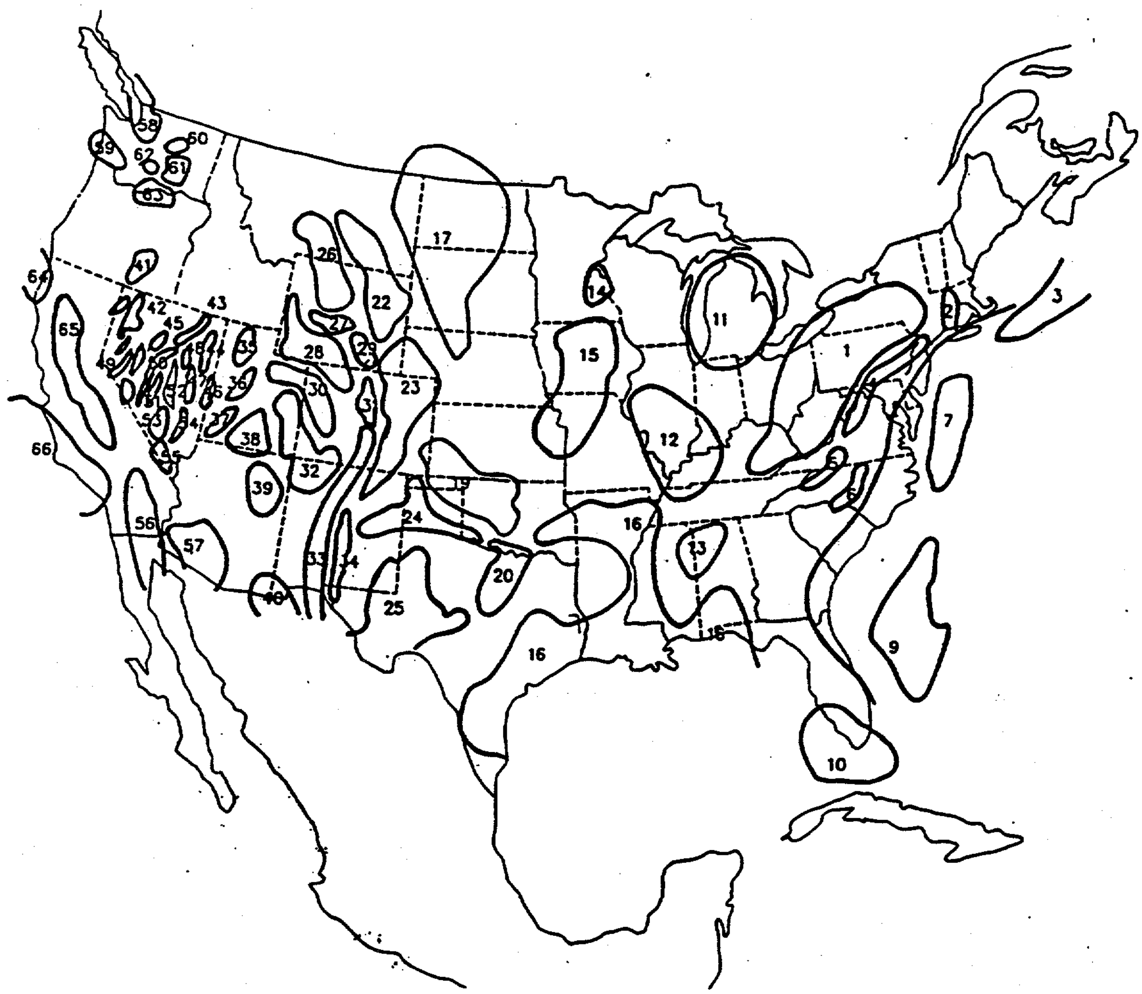
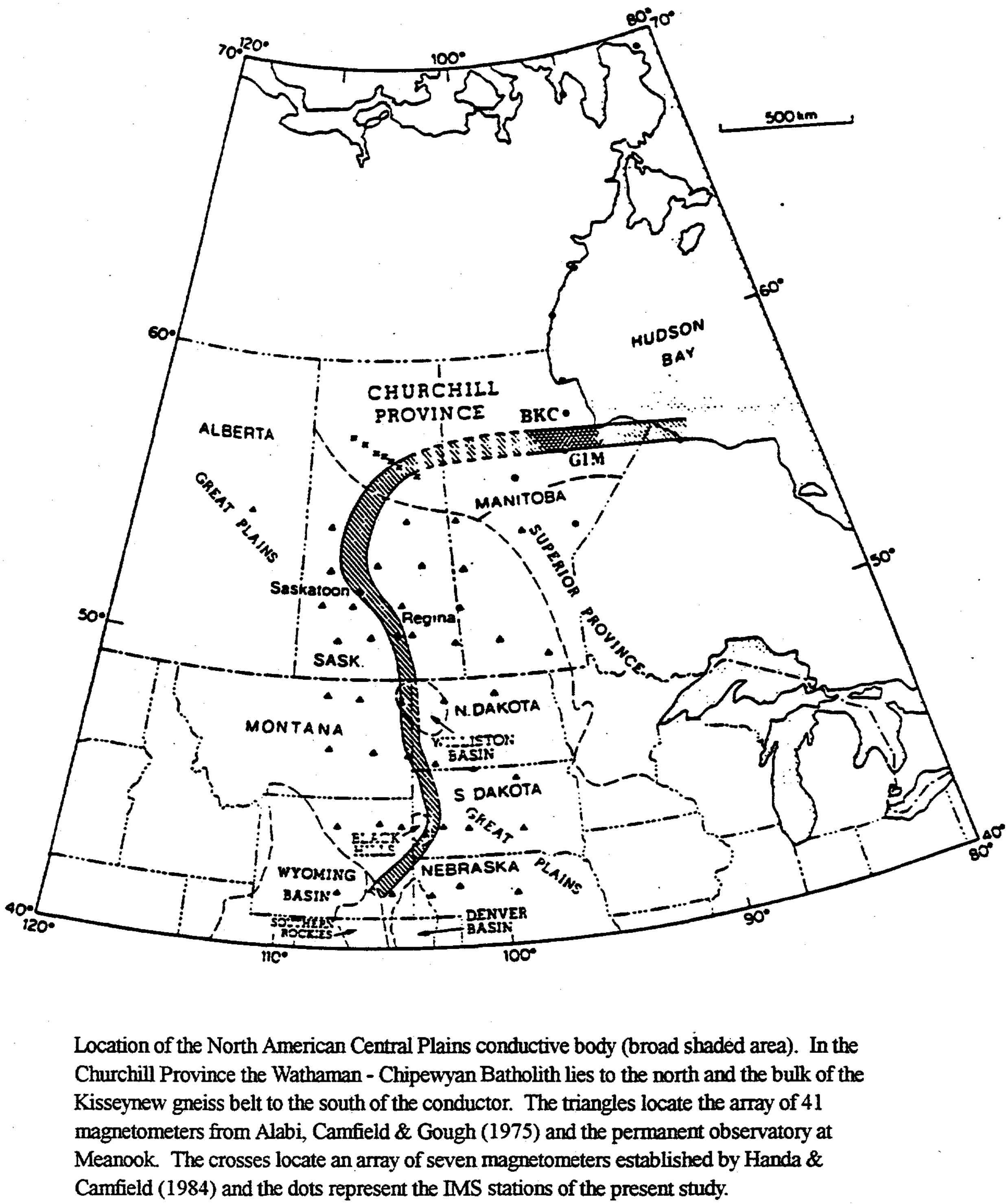


Figure 2.3 Basins of the United States Likely to Have Conductive Sediments (Keller, 1989) GSA, Memoir 172



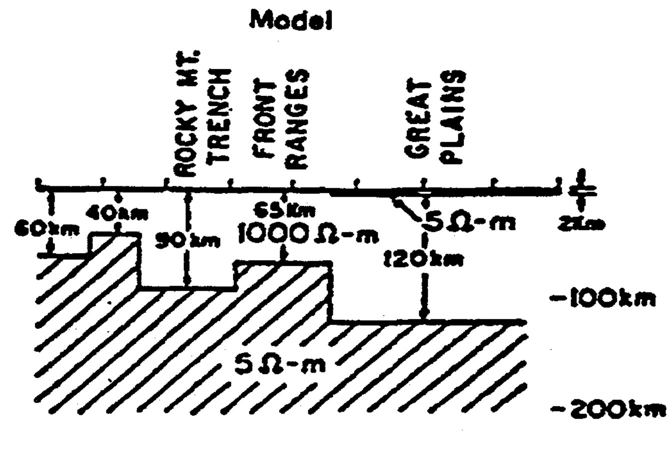
Location of the North American Central Plains conductive body (broad shaded area). In the Churchill Province the Wathaman - Chipewyan Batholith lies to the north and the bulk of the Kisseynew gneiss belt to the south of the conductor. The triangles locate the array of 41 magnetometers from Alabi, Camfield & Gough (1975) and the permanent observatory at Meanook. The crosses locate an array of seven magnetometers established by Handa & Camfield (1984) and the dots represent the IMS stations of the present study.

Figure 2.4 - North American Central Plains Conductive Body (Gupta et al 1985)

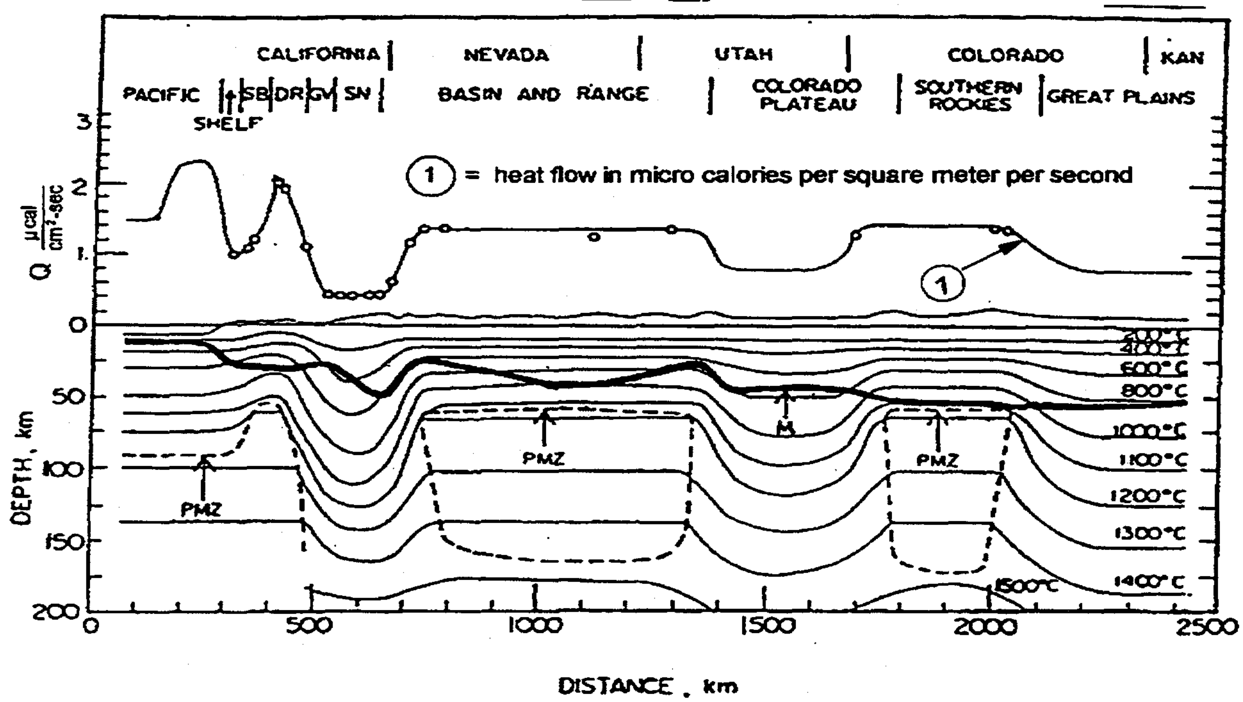
2.4.2 "Hot Spots"

Many areas underlying the Western US mountain ranges are underlain by melted or partially melted rocks which are relatively conductive. This is shown of Figure 2.5 which is a cross section from California to Kansas.

A conductive zone in a California area of partially melted rocks is shown on Figure 2.6. The latter exists close enough to the surface that a reasonable chance of connection to it could be made either by deep drilling or by finding the right surface geological formations or structures that would intersect it. These areas of melted or partially melted rocks present an opportunity because they could be used to produce electricity via geothermal power conversion and at the same time qualify as a good site for a HVDC ground electrode for transmission.

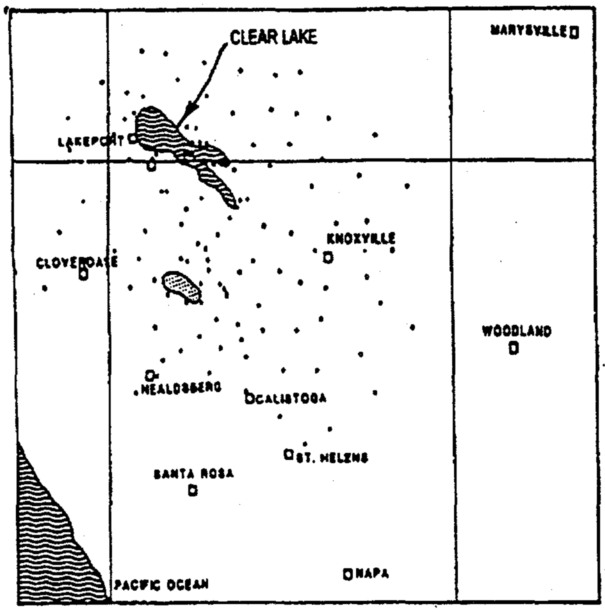


a) Physical Model

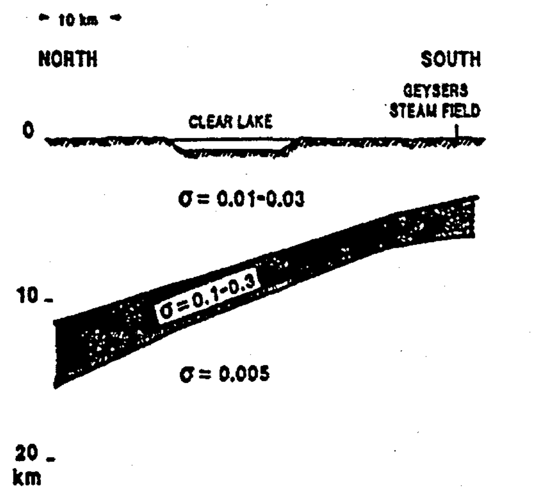


b) Heat and resistivity profiles

Figure 2.5 Cross Section Heat and Resistivity Profile, California to Kansas (Chaipayungpun, et al 1977 © 1977 American Geophysical Union (AGU) Geophysical Monograph #20.



Locations of MT soundings in northern California, in the vicinity of The Geysers Steam Field.



Electrical conductivity cross section through the Geysers area, California, based on one-dimensional inversions of MT soundings. The Steam Field is the dotted area south of Clear Lake.

Figure 2.6 Vertical Cross Section of Conductive Body Geysers Steam Field, Northern California (Keller, 1989) GSA Memoir 172

3. TECHNIQUES FOR MEASURING EARTH'S DEEP ELECTRICAL PROPERTIES

3.1 BACKGROUND

When two electrodes are placed in the ground the current distribution is three dimensional. The current distribution from a land electrode near the ocean will be largely effected by the proximity of the ocean with current flow in the saltwater similar to a conductor at depth. The potential distribution between the two electrodes, unless the geology both local and regional is very simple, will be very complex including lateral as well as vertical flow.

This is illustrated of Figure 3.1 (Bechtold et al 1967) where the current flow is estimated based on the outcropping of basement rocks which are assumed to be resistive. In fact this distribution of current does not account for the presence of partial melting of some of the basement rocks underlying the area shown; partial melting with a consequent better conductor will cause more current to flow at depth.

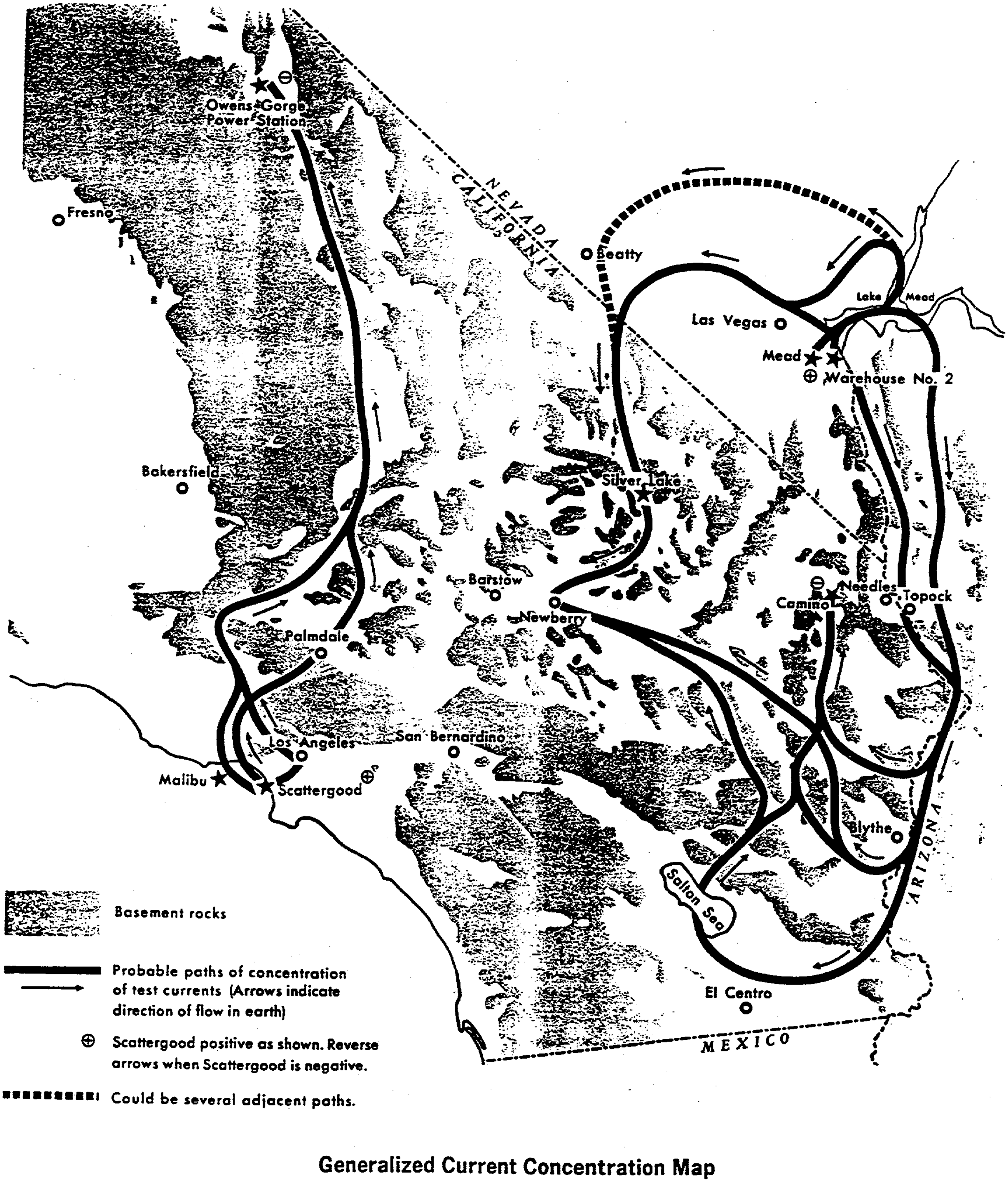
3.2 CURRENT INJECTION

The use of man-made current injection is a definitive method for establishing the potential electrical distribution between two HVDC ground electrodes; it involves the use of a DC generator unit at 100 amps or greater and a dedicated transmission line or hard wired electrodes. Current injection with sequential polarity switching uniquely identifies the injected current induced on pipe lines and other important utilities, establishes an electrical potential profile, determines the total resistance between the electrodes, and eliminates the uncertainty associated with estimations based on electrical conductivity modeling. The negative elements are the expense involved including the cost of renting or building a DC generator, dedicating a transmission line, and the number of personnel involved.

This method is usually used when the less definitive but far less costly methods, discussed below have established the potential for siting ground electrodes.

3.2.1 Electrode Separation and Current

The electrode separations should be in the order of the separation of those that will be permanently installed. However this may be difficult and a shorter interval may be have to be used. In this case, Figure 1.4 for a two layer earth can serve as a guide, note the differences in current flow between a conductive layer at the electrode separation at one at half the electrode separation and one at one third of the electrode separation. If a widespread conductive layer lies closer to the surface than one half the separation this will be readily evident when the potential profile is constructed between electrodes and this condition will also be evident on installed utilities. When conductive layers lie much closer to the surface than one half the electrode separation, they will dominate the flow of electrical current. Geological inference and limited testing prior to the current injection should have defined a rough vertical profile and this will provide information relative to the separation of electrodes for a current injection test.



Generalized Current Concentration Map

Test Currents

Figure 3.1 - California - Nevada Current Concentration Map (Bechtold , 1967)

The current required for injection will vary with the resistance of the ground between the two electrodes, generally at separations of 100 km or more current generation capabilities should be in the order of 100 amps based on experience.

3.2.2 Use of Transmission Lines or Hard Wire

For many of the HVDC ground electrodes installed in the past, transmission lines were taken out of service and used as the hard wire connection between test electrodes. This works well if the transmission line represents the site and regional conditions for the planned installed electrodes. The alternate to transmission line use for injection is hard wire installation which is usually economically prohibitive at the distances contemplated. When transmission lines cannot be used because they cannot be taken out of service or their geographical position doesn't represent the ground electrode geological-electrical path, then one or more of the methods described below will serve as a substitute although effects on utility lines will not be as well defined.

3.3 EARTH'S NATURAL CURRENTS

3.3.1 Brief Background

From center to surface, the earth consists of a solid inner core and liquid outer core, visco-elastic mantle, and a solid crust; these property differences in the presence of the earths rotation give rise to a magnetic and electrical field. The relationship of the solid earth to the magnetosphere and the ionosphere, and both of these with solar influx create a vastly complex interaction which produces both a longer term relatively stable as well as a highly variant eposodic electrical field in the earth. Solar influx causes magnetic storms that are well known to play havoc with electrical systems particularly in highly resistive environments such as shield areas mentioned above:

"Ionospheric electric currents, especially those strong currents that occur during magnetic storms, can have a number of impacts. The magnetic field produced by the currents induces additional electrical currents in the Earth that can flow through grounded electrical power grids and harm their transformers or trip circuit breakers,. On occasion, magnetic storms cause large-scale disruptions of power grids, as happened in Quebec on March 13, 1989" (Richmond 1996).

These induced currents, ordinary or associated with magnetic storms, provide an opportunity to determine the electrical properties of rocks by passive means.

3.3.2 Magneto telluric (MT) Measurements

The resistivity of the earth can be determined from the electrical field, E and the magnetic field, H (Telford et al 1990) by:

$$\rho = 0.2T \left|\frac{E}{H}\right|^2 \Omega m$$

Where ρ is the resistivity, E is the electrical field in volts per meter, and H is the magnetic field in gammas (nano Teslas); T is the period in seconds or inverse frequency. Simultaneous measurements of the electrical and magnetic field will determine the earth's resistivity. The system in its simplest state requires an electrical line(s) to measure the earth's potential (in one or more directions) and a coil to measure the induced magnetic field. The latter must be very stable because the magnetic field measured is in pico Teslas.

The penetration can be very great because the frequencies measured may be as low as 0.00001 Hz. (T=100,000 sec.). The attenuation (penetration) is commonly referred to in terms of the skin depth at which the signal is reduced to 1/e or to 37% of its strength. This is given by:

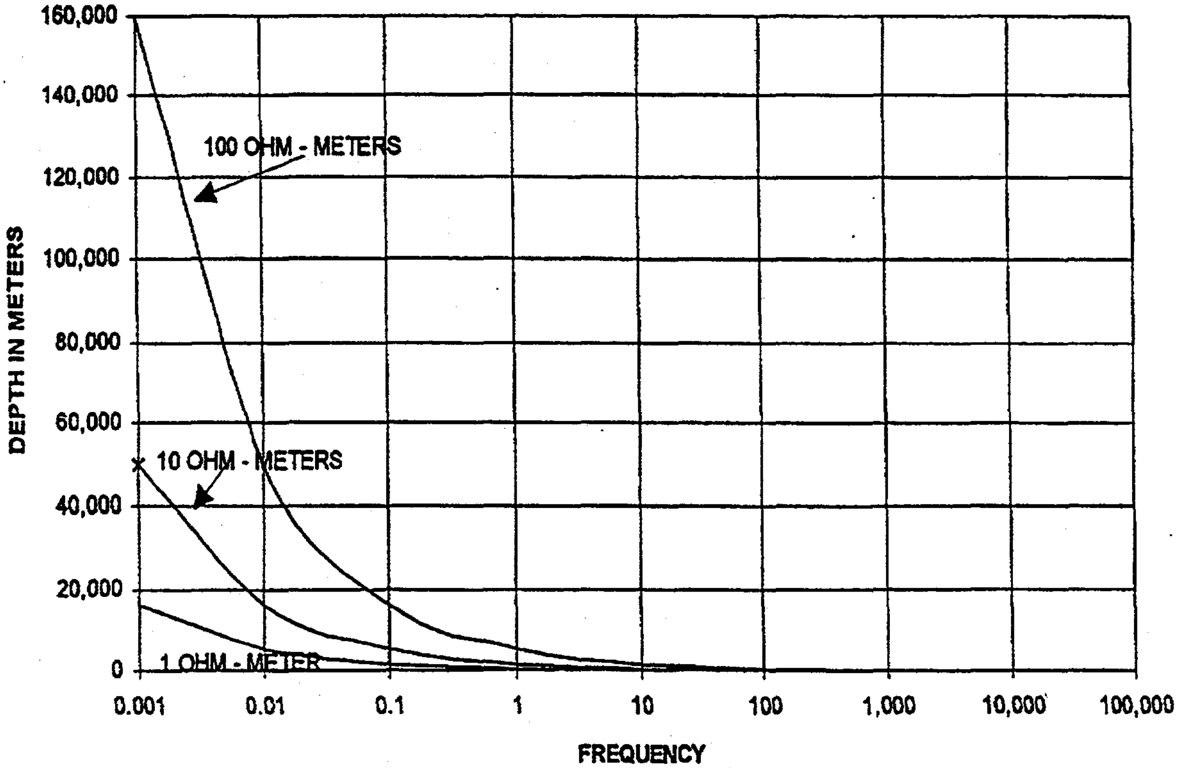
$$z = 500 \sqrt{(\rho/f)} \quad m$$

Where z is the skin depth in meters, ρ is the resistivity and f is the frequency (Telford et al 1990.) As can be seen on Figure 3.2, the penetration is limited by lower resistivities and or higher frequencies.

A plan map for an MT survey for eastern Colorado is shown on Figure 3.3 and the results of the survey with constructed vertical resistivity models is shown on Figure 3.4. The interpretation of the data is complex both in the reduction of the field data as well as the mathematical modeling of the number of layers, their thickness and resistivities. As discussed in section 4.2.1, the latter are not unique and the results can be equivalent for different layer resistivities and thicknesses. It is beneficial to have some way to constrain the model with other information such as the geologic, drill holes, seismic data etc.; horizontal conductors have to be accounted for. Although the cost for an MT survey is moderate its best use is subsequent to the identification of pre-selected locations to define the deep electrical resistivities.

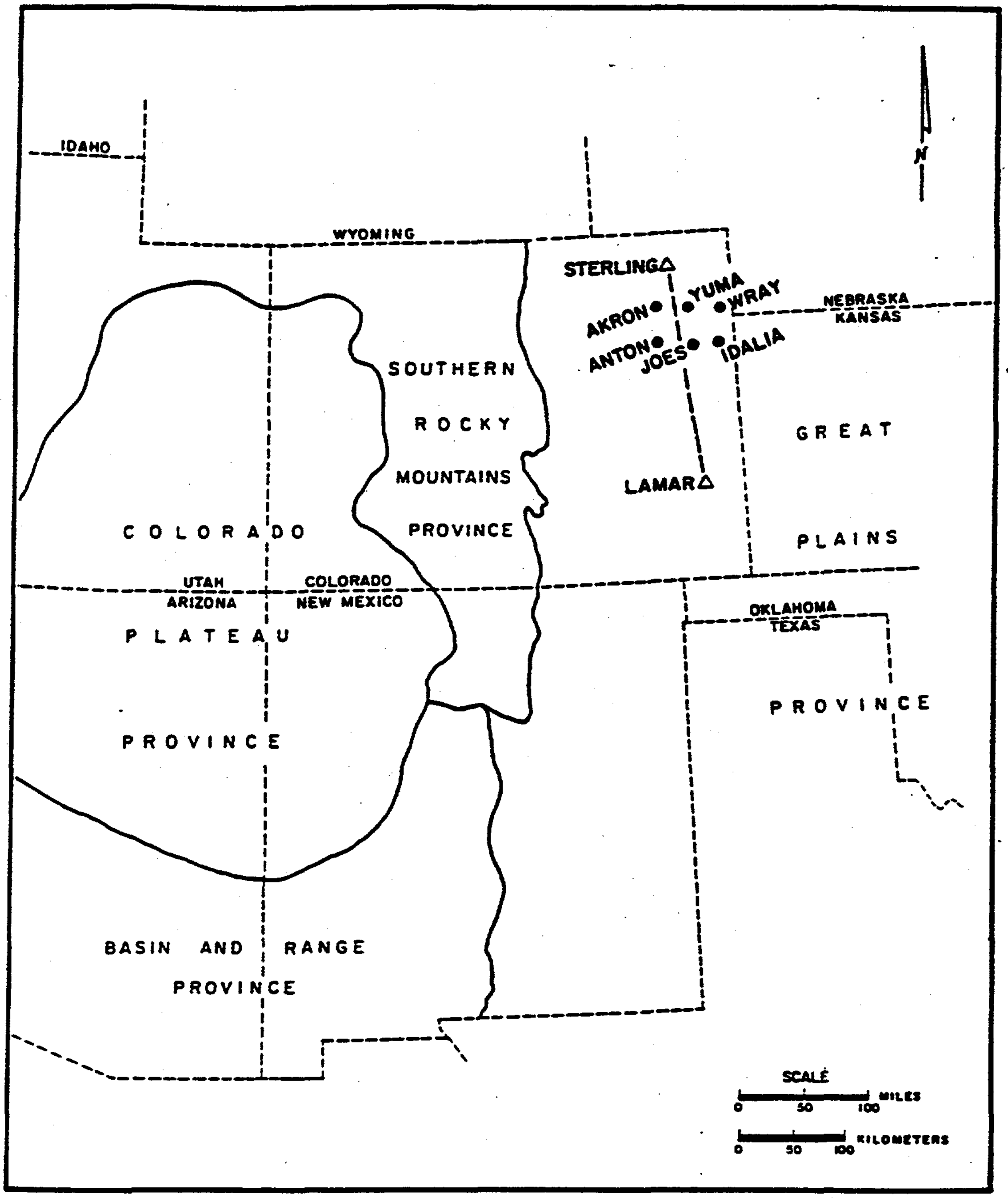
3.3.3 Magnetic Storms

Similar to MT surveys, a long line connecting two electrodes can be used to determine the earth's resistance. A spare wire on an existing transmission line or a hard wired line of electrodes will measure the earth's field. The line will generally be long enough that the earth's magnetic field variations during a magnetic storm can be taken from one of the existing government or university magnetic observatories. Time of the electrical and magnetic variations must be synchronized, so the varying field is measured at the same time. Generally this is done by accurate time determinations on both sets of data. It would be desirable to install a magnetometer(s) along with the electrical line for simultaneously time recording of both sets of data. Such an installation is modest in cost.



$SD = 500\sqrt{(\rho/f)}$

Figure 3.2 Skin Depth Versus Resistivity and Frequency



Map showing locations of six magnetotellric stations and Lamar-Sterling seismic refraction profile in the High Plaines of eastern Colorado.

Figure 3.3 - Magnetotelluric Survey Eastern Colorado Plan Map
(Chaipayungpun, et al 1977)
AGU Geophysical Monograph #20

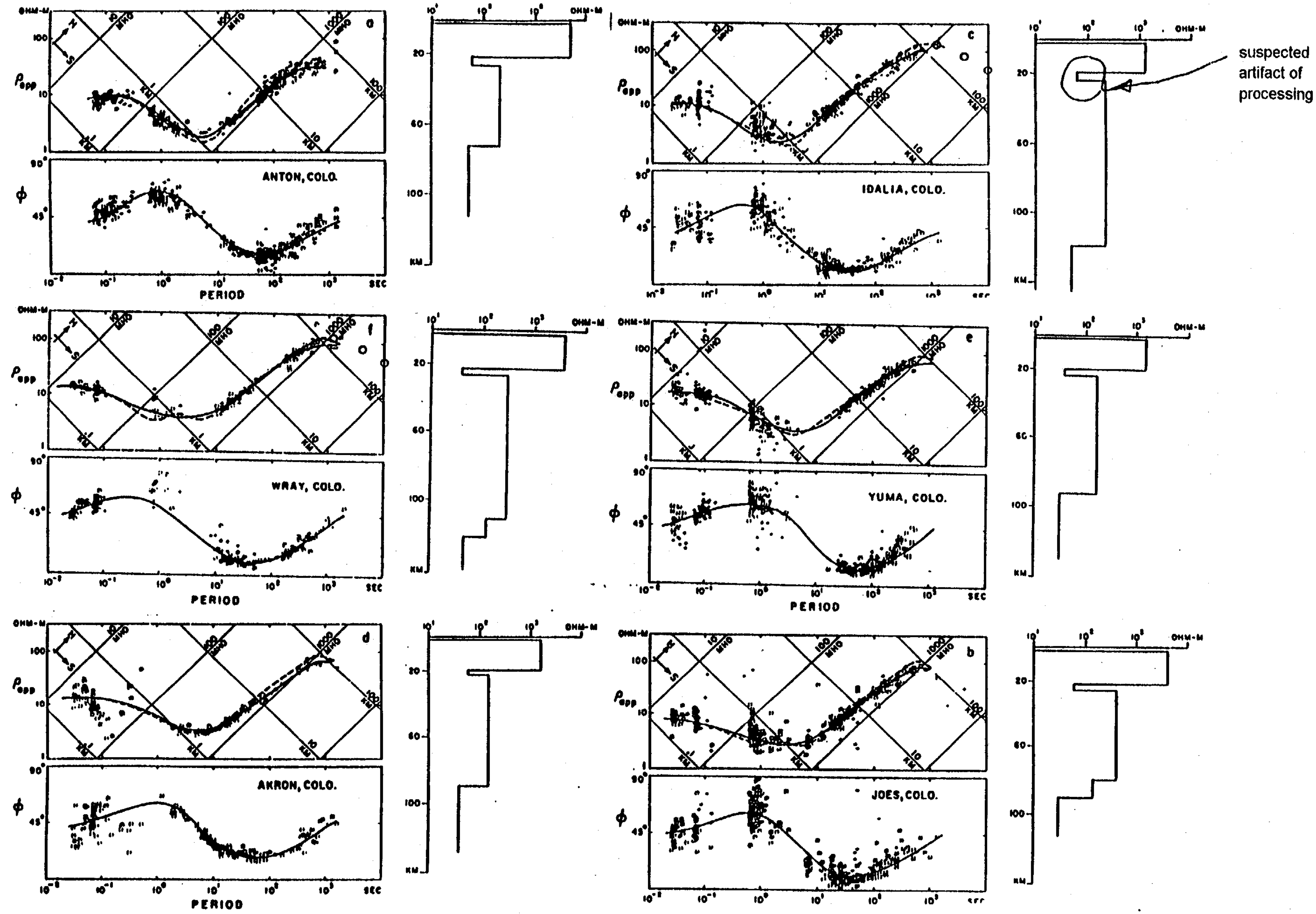


Figure 3.4 - Magnetotelluric Resitivity and Phase Plots and Interpreted Resistivity Vertical Cross Sections (Chaipayungpun et al 1985) AGU Geophysical Monograph # 20

Shown on Figure 3.5 are recordings by Hydro-Quebec for a magnetic storm; the recorded voltages are for a north-south 20 km long line and an east-west 5 kilometer line. The bottom trace is a record for the magnetic field variations. The record supplied by Hydro-Quebec was taken in the vicinity of LG-2 which is near Hudson Bay. A very rough approximation can be made of the resistivities involved from the trace. If we look at the largest excursion the period is about 180 seconds (taken from zero crossings) the north-south voltage is 85 x 10^6 micro volts; the magnetic field is about 350 gammas (nano-teslas). Using the formula given in section 3.3.2 above, the computed north-south resistivity is 5,000 ohm-m, and the east-west resistivity is 3,800 ohm-m. Using the skin-depth graph, Figure 2.4 the period of 180 seconds is a frequency of about 0.006 which has a penetration of about 115 kilometers. This is much deeper penetration than any of the electrical surveys taken at the site, even the Magneto telluric data. The surface resistivities are variable but in many cases exceed 15,000 ohm meters. Given that the magnetic storm data are penetrating much deeper, the very high surface resistivities are averaged into the deeper better conductors and the numbers cited are reasonable; however, there is little contribution of the deep conductors to current distribution from electrodes even at several hundred kilometers separation.

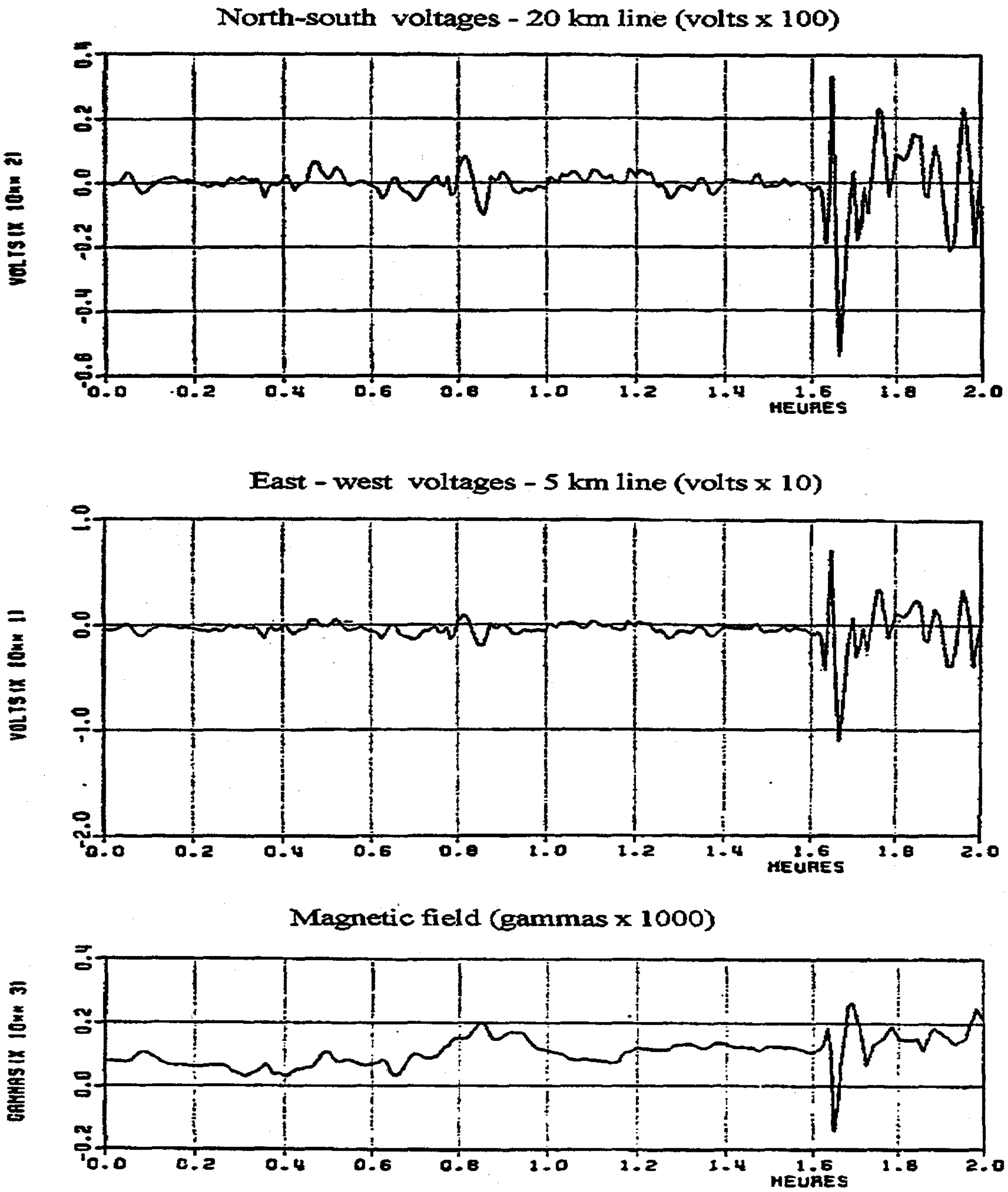


Figure 3.5 Magnetic Storms (Hydro Quebec 1981)

4. AVAILABLE DATA FOR SHALLOW AND DEEP CONDUCTION

There are existing data in the form of MT, DC galvanic, ground and airborne VLF (very low frequency), AFMAG (audio frequency magnetics), surveys that have been conducted for petroleum and mining purposes as well as university studies. Such studies are not prevalent however and the chances of finding one in the area of interest and with deep penetration is low. However if the geology is uniform and predictable over a large area and a study exists that defines the resistivity of the key formation(s), then it could be useful for an electrode installation. Several studies such as the Oregon to California intertie, or the New England Power- Hydro-Quebec current injection studies definitively assess regional conditions.

4.1 EXISTING DATA BASE

The purpose of this report is to point the reader to the type of resources that might be useful, it is not intended to serve as a bibliography.

4.1.1 Petroleum, Mineral, Electric Utility, Mining, Academic

With few exceptions when a petroleum or gas well is drilled an electrical "E" log is taken. The electric log can take many forms but generally is a log of the resistivity of the formations and fluids penetrated by the hole. There are hundreds of thousands of such holes which vary in penetration from a few thousand feet to 15,000 feet (4.5 km) or more in a few cases. Petroleum is usually associated with high sulfate water conditions which make the formations very conductive. The potential for using a petroleum basin for an electrode site should be quite good given that the corrosion problems imposed on existing wells are not severe or can be mitigated. The results of the electrical log survey are often available from the state geological survey or other agency that requires the industry to make such information available to the public after a certain amount of time. In addition, such information is usually available from the industry itself at reasonable cost. While the bulk of the petroleum data are in oil or gas producing environments these exist throughout a large part of the United States.

Known ground conditions at power plants, switch yards, and along transmission lines might be useful if tied to a geological formation whose resistivity can be determined. The latter have limited penetration and are not particularly useful for assessing deep conditions, their use would be in the correlation to determine geological formation resistivities for local siting.

Wide spread VLF data are beneficial, these have been taken mainly by the mining industry, but may exist for other purposes; environmental, ground water exploration etc. The VLF method utilizes a very low frequency radio transmission used by the US Navy for communication. A hand held portable meter weighing a few pounds is used. Penetration is limited but because it is simple to run, inexpensive, and quickly performed, it has good potential to determine formations resistivities and provide preliminary site information. AFMAG which is in the low frequency range of 1 to 1,000 Hz.

measures the magnetically induced field from world wide lightning strikes by airborne or ground surveys to determine the electrical resistivity of the ground. These data are generally used for mineral exploration. Penetration is rather shallow, a few meters to a few hundreds of meters they do allow a correlation of resistivity to various geological formations and a near surface value of the earth's resistivity. They could be useful in preliminary siting considerations.

4.1.2 Regional Conditions

4.1.2.1 Existing Data

As stated in the introduction to this report, there are several major geological reference data bases that can be accessed quickly and inexpensively to determine the availability of data for a particular area or region; these are listed in the reference section.

4.1.2.2 Correlation of Specific Measurements to Geology

If geological conditions are well known and detailed geological maps exist, these become the basis for preparing a conductivity map to determine the potential for shallow and deep conduction. The geology knowledge consists of both the rock types (petrology-chemistry) as well as the regional and local tectonics. Each important contributing rock formation (petrology) can be tested where it outcrops or existing data may be used; this allows a general correlation of resistivity to rock type which are generally wide spread. It is important to understand the tectonics both on the regional and local scale. The tectonics are the network of structural features faults, folds, shear zones, that have been imposed on the rock from mechanical forces. Many times faults will reach to great depths and can be conductive. Using the geology knowledge as a basis, electrical ground testing can be optimized.

4.2 TYPES OF REGIONAL GEOLOGICAL CONDITIONS

The earth, throughout its history of several billions of years continues to undergo significant changes. These changes occur in geologic time periods of many millions of years. The surface of the earth consists of a series of mobile plates (such as North America) that may be in collision (mountain creation), separation (rifting) or a combination thereof. These plate boundaries may be presently active or inactive; the interior of the plate may be stable and undisturbed for millions to billions of years (shield areas). In general, the rocks that constitute ancient mountains such as the Appalachians and beneath the Paleozoic (520 to 230 million years before present) sedimentary cover of the mid-continent, are cooler, less fractured and more resistive than those in more recent active regions where partial melt conditions may have produced more conductive rocks. Rift areas have deep sedimentary rocks whose composition may be favorable for the conduction of current flow, in addition, they may be underlain by partially melted conductive rocks. Mountainous areas have folded sedimentary rocks which may exist at high elevation but the better candidates are those in basins between the uplifted fold belts, these can be quite deep and conductive. The combination of ancestral mountainous areas covered by deep sedimentary rock characterize the Midwest where ancient mountains (over a billion years old) have been eroded to a level surface, subsided into an inland sea during the formation of the

Appalachian Mountains and covered with several thousands of feet of sediments (indurated to rock) whose lateral extent may be measured in hundreds of miles.

4.2.1 Deep Sedimentary Rock- Rocky Mountains-Kansas

An HVDC interconnection between Lamar, Co. And Garden City, KS has been discussed from time-to-time. The following information is pertinent to the specific area such a dc line would cross. Eastern Colorado is at the boundary of the eastern end of the Rocky Mountains underlain by deep sedimentary rocks extend into Kansas. Conduction between these two areas will depend principally on the conductivity of the sedimentary rocks. There are electrical surveys that penetrated several kilometers in the Eastern Colorado area that are indicative of rocks in the range of 200 to 1,000 ohm meters. These data provide some information but it is insufficient to define what the current distribution or the resistivity between the two area would be. Conductivity values of geological formations within the sedimentary section would be helpful in predicting the potential success of a HVDC ground electrode since the individual geological formations have sufficient lateral and vertical extent to control the current flow between the two areas.

The plan map for a magnetotelluric survey taken in Eastern Colorado is shown on Figure 3.3 and the results shown on Figure 3.4 as an average resistivity versus depth cross section plotted to the left of the phase MT data. This was discussed in section 3.3.2. The period and phase plots are combined with the interpreted vertical profiles of resistivity. The resistivity "low" shown at a 20 km depth is probably an artifact of the processing and the average resistivity of 200± ohm m without this zone is probably more representative. Exploration for a suitable electrode site in this area would include looking for a more conductive layer at the surface that might be continuous from two ground return electrodes or that might connect to the lower 200± ohm-m material below about 20 km.

Shown on the top of Figure 2.5 is a resistivity cross section taken across the northern Rocky Mountains in the vicinity of the Canadian border. The bottom cross section shows a temperature-heat flow cross section from California to Kansas. While these are widely separated, they show a general correlation between the heat flow highs and the resistivity. The top diagram depicts the resistivities to a 100 km depth. On the bottom diagram, PMZ is indicative of a partial melt zone and M designates the Mohorovicic discontinuity (seismic boundary) at the bottom of the crustal layer.

While these diagrams cannot be used for electrode siting, they present several conditions for potential electrode siting. If the deep 5 ohm meter material of the top diagram could be "connected to" then a deep electrode would be most efficient. Shown to the right on this top is a widely distributed 5 ohm meter shallow material (a few kilometers thick) that might provide a low resistance path between two electrodes without the need for very deep conduction.

If a reasonably conductive body of rock could be found that might make "connection" to lower conductive melted or partially melted material then an efficient ground return would be achieved. The resistivities for eastern Colorado are shown of Figure 3.4 where the profile from near surface to 20 kilometers is not encouraging showing resistivities of 1,000 ohm meters or more.

4.2.2 Tectonic Rift Areas Colorado- New Mexico

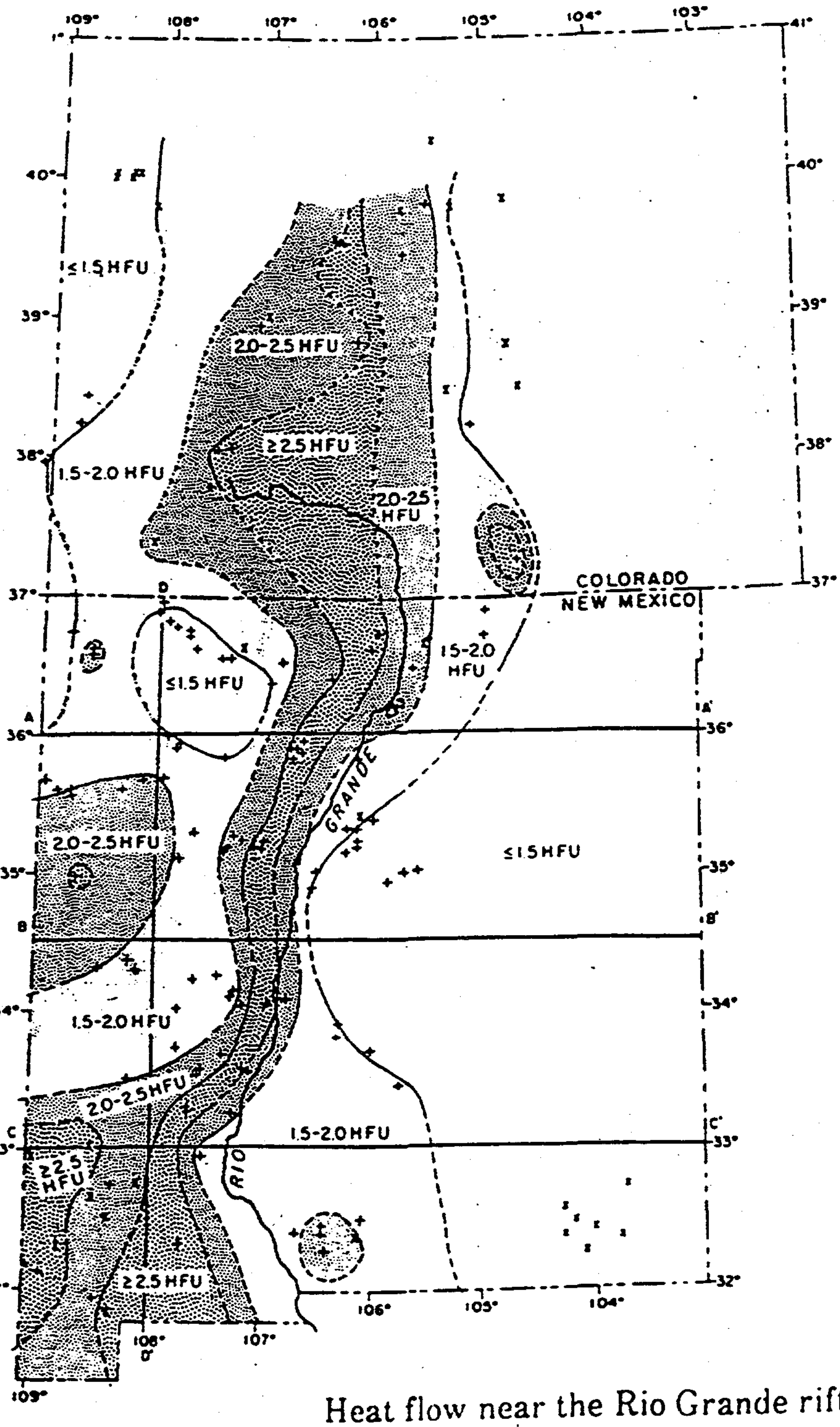
The RioGrande Rift Zone is an ancient rift zone which has retained relatively high heat flow as shown on Figure 4.1 (Reiter et al. 1975.) This is another area where a HVDC intertie might be considered since it holds the potential for conductance at depth. The problem is the same as discussed above, that is to find a connection between a near surface conductor to deeper conductive layers. This could be accomplished by a combination of geological inference and selected exploration.

4.2.3 Ancient Orogenic Belts - Appalachians New England, Quebec, Canada

The Appalachians extend from Alabama to Newfoundland and while region to region may differ in geological detail (which can be important to electrical conductivity) in general their core is characterized by massive igneous rocks that are no longer subject to the high temperatures associated with higher conductivity at depth. The first several kilometers are generally more fractured than the rock at depth and given that the surface rock can have conductive minerals, then relatively good conductors can be found at ground surface or within the reach of a drill hole. In general the rock at depths of 10 km to 30 km pose a problem in that they are (for the most part) highly resistive (>10,000 ohm-m). The success of a ground electrode in this region requires a geological formation(s) large enough to reduce potential gradients to an acceptable level and provide a sufficiently low resistivity to make a ground return feasible. There is the possibility that geological features such as regional faults may exist that have connection to deeper conductors. The discovery of such zones depends on a through knowledge of the geology, lithologies (rock types) and tectonics, and a good feel for their conductivities. Siting in the Appalachian environment is discussed below for the electrodes in Lisbon, NH and Windsor, PQ, section 5.8.1.

4.2 4 Features Cutting Across Regional Geologies

There are deep geological conditions favorable to conduction of currents that cross the boundaries of major geologic provinces such as described in section 2.4.1 above, and shown on Figure 2.4. This feature extends from Wyoming - Nebraska to Hudson Bay. Much of this feature transect the rocks of the Canadien Shield where relatively unfractured igneous-metamorphic rocks are highly resistive. The feature was defined by an installation of an array of magnetometers as shown. Undoubtedly more such features associated with buried ancestral geologies exist but are undiscovered. One of the problems associated with such a feature may be vertical connection since its depth could be several kilometers.



Heat flow near the Rio Grande rift

Figure 4.1 Rio Grande Rift Basin Heat Flow
(Reiter et al, 1975) GSA Bulletin 86

5 ELECTRODE CONSIDERATIONS

The experience with respect to electrodes cited in this section is drawn from the site and regional exploration, selection, testing, design input, and installation of a HVDC electrode in Comerford, NH., and DesCanton, Quebec in highly variable geologic conditions. In addition, there was direct involvement principally in the form of consultation for the electrode at Radisson Quebec. The conditions surrounding these sites were complex geologically and known to be mostly adverse in that they are in regions of highly resistive rocks.

5.1 ELECTRONIC VS ELECTROLYTIC CONDUCTION

5.1.1 Electronic to Electrolytic (electrode to earth)

Previous discussions have adequately discussed the fact that conduction in the earth is by electrolytic means. The ground water may be contained in a porous media in which the contact to water is effectively through the pore spaces. In porous media such as sands and sandstones the contact can be predicted from the porosity of the material; these media present a relatively uniform porosity contact along the electrode surface. The porosities for such materials could approach 30%. In the case of igneous or metamorphic rocks where the porosity is mainly in fractures, the contact with the electrode is not uniform but is concentrated in relatively small areas where the porosities are generally less than 5%.

5.1.2 Electrolytic (earth)

There are several consequences of electrolytic conduction that are not desirable:

- the conduction may involve current densities and potentials that will electroplate earth materials onto the electrode;
- resistive earth materials may be deposited on the electrode which could significantly increase its earth resistance;
- gassing may occur from the electro-chemical process that will increase the contact resistance and further raise the temperature at the electrode;
- heat generated by the conduction may reach temperatures that will evaporate away water, this will raise the resistivity;
- corrosion of metallic electrode elements may occur;
- existing utilities in the earth potentially suffer the same consequences as the ground electrode in that induced currents placed on them could corrode them;
- water content in the earth materials surrounding the electrode may change adversely.

5.2 ELECTRODE TYPES, CONFIGURATIONS

Ideally an electrode would conduct current to the ground uniformly without corroding and with minimum maintenance.

5.2.1 Environmental Considerations

In all cases, the electrode must be designed for the chosen site conditions to limit step potentials and avoid or minimize interference such as corrosion of underground structures.

Step potentials or gradients created in the near field of the electrode should follow standards that minimize:

- the effect on humans and animals;
- corrosion of any utilities or other important underground facilities and interference with communication lines.

These standards are fairly well known for switch yards, power plants etc.

The potentials created are a direct function of the amount of current and the resistivity of the materials surrounding the electrode. The local resistivity near the electrode is important however, a good conductor of limited extent no matter how low its resistivity, may not be sufficient to maintain low potentials. A local swamp or bog of even large extent (10's of miles) which rests on resistive rocks will produce unwanted effects in the earth materials at its boundaries. This is easily inferred from Figure 1.3, showing a two layer earth. Local conductors that are isolated pods in a resistive rock are not good electrode sites.

5.2.2 Sea or Shoreline, Shallow Earth, Deep Earth

Sea or shore electrodes are simple in a sense that they make contact to the earth through conductive sea water (4 S/m) which is a good conductor compared to normal earth materials. Installation of sea electrodes usually involves submerging the chosen electrode material directly in the sea water by laying it on the sea bed, or supporting it with a submerged structure. To restrict access by sea life and limit damage from anchors etc., the electrode may be enclosed within a cage or box on the seabed.

Shore electrodes are a form of shallow earth electrodes which is typically saturated with saline ground water or sea water most or all of the time so it attains its connection with remote earth through the sea water. Installation is relatively easy in that a linear or star configuration of electrodes are placed in ditches or other like construction. Sometimes they are placed in vertical holes as is the case of the experimental deep hole electrode [Karlsson, 1995] at the Swedish terminal of the Baltic Cable HVDC link. Many times the ditch or hole is filled with calcined fluid petroleum coke breeze powder that, under proper compaction, creates electronic conduction between itself and the electrode. This material is referred to as simply "coke breeze" throughout this report. Whatever material surrounds the electrodes, the final conduction to the earth is electrolytic and successful operation depends upon observing the same precautions of any earth electrode. That is, one must avoid excess current densities that could otherwise dry out the surrounding media or generate excess gasses that typically accompany electrolysis.

Shallow earth electrodes are placed in a ditch, surrounded by a compacted coke breeze filler and back filled as shown in Figure 5.1. Contact between the electrode elements and earth should be as uniform as possible to avoid non-uniform current sharing. For instance, whether the electrode be shallow earth, shoreline, or deep vertical construction, electrode elements in direct contact with water will carry more current initially than those that are only partially or not in contact with water. More corrosion or electroplating of earth materials will be experienced by those elements leading to eventual overloading of other elements as the current distribution between elements changes.

Deep earth electrodes (with a depth over 30 meters as defined in the RFP for this project) invariably are, or will be, vertical configurations. Such electrode structures are described in the next section. The term "deep earth" as it used in this context could be misleading since a connection to deep earth conduction is not guaranteed simply by sinking the electrode over 30 meters below the surface.

5.2.3 Horizontal (Linear, Ring, Star)

Horizontal electrodes are those set usually at or very near the ground surface. They take many forms, linear rings, stars, (see Figure 5.2 and Table 5.2.1) or some other horizontal configuration depending on the site conditions and the desired effect that is to be accomplished. In general these are put in a dug trench (Figure 5.1) below or in close proximity to the ground water table and the electrode(s) is surrounded by coke breeze. The size of the horizontal array is usually determined by the desired current densities and step potentials. The configuration may in part, be determined by the size of the tract of land involved although this is usually a secondary consideration.

Vertical arrays are those put in boreholes, their selection is usually determined by the geology, including ground water considerations and or land restrictions that might exist. A typical vertical arrangement would consist of several arrays of electrode elements suspended in wells and surrounded by a compacted coke breeze filler as illustrated in Figure 5.3. The dimensions given are for the Lisbon electrode associated with the Comerford HVDC terminal in northern New Hampshire. The wells and the number of elements per well will vary depending upon the geology and other characteristics of the site. The total contact area required to limit the current densities to acceptable levels for a given electrode current will dictate the number of electrode wells. A vertical array is discussed in detail for the Comerford electrode described in section 5.8 of this report.

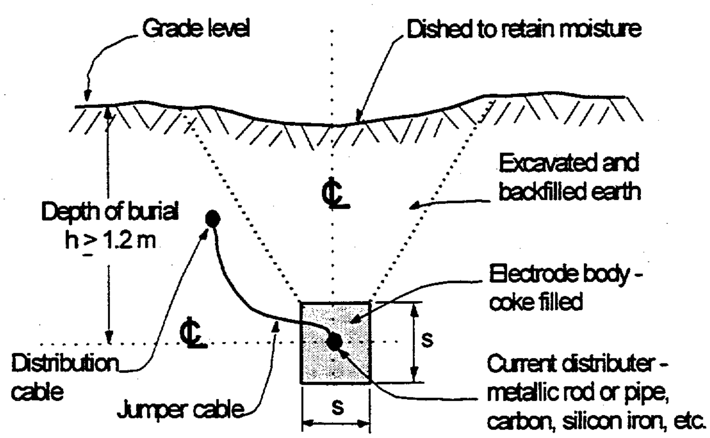


Figure 5.1 Shallow Earth Electrode - Cross Section
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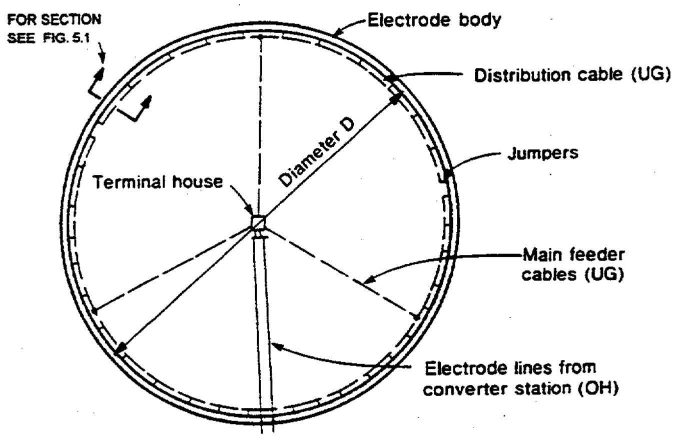
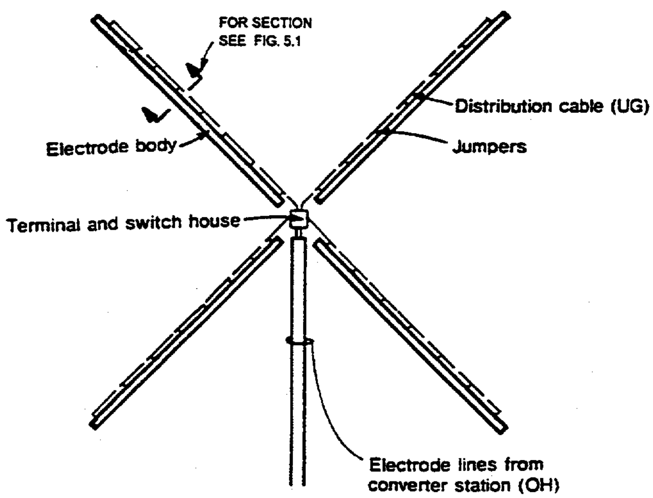
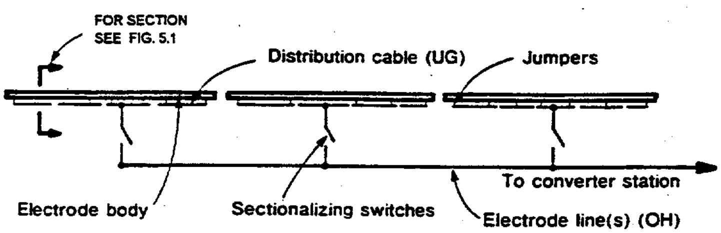


a) Typical Ring Array



b) Typical Star Arrangement



c) Linear Array

Figure 5.2 Various Horizontal Configurations

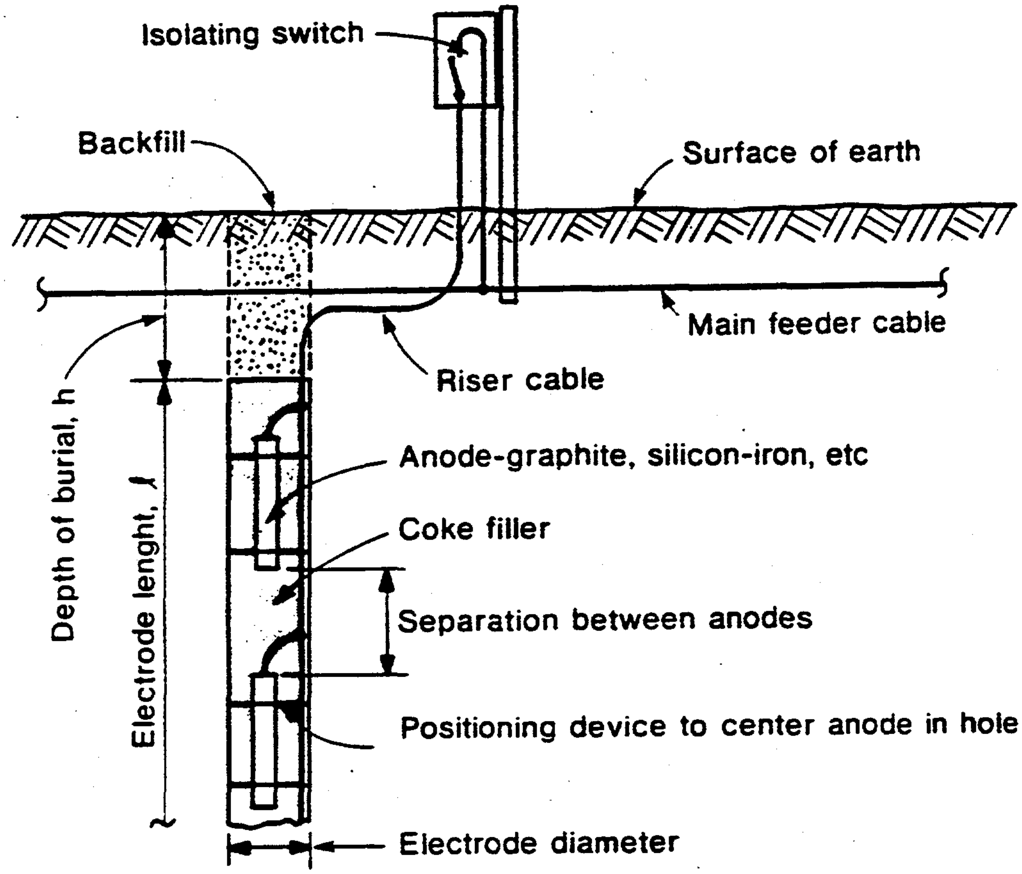


Figure 5.3 Typical Vertical Configuration
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5.2.4 Electrode Line

All but one existing land electrode installations are some distance from the HVDC converter stations they serve. The electrode is connected to the HVDC station through what is called its electrode line. As seen in Table 5.2.1 the electrode lines range in length from 7 km (Apollo station of Cahora Bassa) to 95 km for the Coyote electrode serving the Adelanto terminal of the Intermountain HVDC line outside Los Angeles. If the dedicated metallic return conductor between Sandy Pond and Des Cantons of the hydro-Quebec-New England Phase II line is considered an electrode line, it is longer still. The only exception is the experimental "deep hole" electrode on the Baltic Submarine Cable, which is located in the HVDC substation.

The reasons why the electrode is not typically collocated in the HVDC substation are clear when the potential field illustrations in Figure 1.2 are consulted. In addition to high step (and touch) potentials, the dc earth currents could interfere with the substation ground mat or find its way into the neutral connections of the ac system and cause a variety of problems (discussed in Section 6). The latter condition frustrated Hydro-Quebec's attempts to system test and operate the Radisson HVDC terminus of the Hydro-Quebec-New England Phase II 2,000 MW link for some time. This problem persisted even through the electrode was located 40 km from the HVDC terminal; the geological bedrock conditions are far from ideal in northern Quebec. The ultimate solution involved the installation of special series capacitors in the ac lines near the Radisson HVDC terminal, which minimized, but did not eliminate the dc currents in the ac system neutrals.

5.3 WIDE AREA (REGIONAL) AND SITE TESTING

Site selection for the placement of a ground electrode depends on a number of factors including such logistical considerations as the distance from the converter station but of most importance, the current load that the electrode must handle.

5.3.1 Area Influence from Current Injection vs Electrode Separation

The partition of current flow at depth relative to the electrode separation L (Figure 1.3) can be estimated if the conductivities for the geological conditions are known. Depths in an oil well field may approach 30,000 ft. (10 km); for an electrode separation of 600 miles this represents a boundary at about one tenth the electrode separation or L/10; for this condition, most of the flow of current will be in the lower layer(s). As illustrated on Figure 3.2, in a complex geology, there is a complex relationship to the distribution of conductivities. Estimates of the latter will have a good deal of uncertainty associated with any estimates from geological considerations even when supported with good conductivity information.

Table 5.2.1

Summary Data for Selected HVDC Electrodes

				*********************************	Electrode	Rated	**
Project Name	MW	KV	km	Location of Electrodes	type	Amps	Description of Electrodes
Gotland I	20	+/-100	96 sea	Near Vastervik term, Sweden	sea, anode	200	12 magnetite in graphite, hung on wood platform,shallow
				Near Visby term, Gotland	sea, cath		300m noninsul cu, seabed & buried on seashore
Volograd -	720	+/-400	470 OH	24 km from Volograd term	land,horiz	900	30 mm stl rod in coke, 2-sect loop 1200 m circumference
Donbass				32 km from Donbass term	land,horiz		30 mm stl rod in coke, 2-sect loop 1200 m circumference
New Zealand	600	+/-250	570 OH	25km from Haywards	sea/beach	1200	25 graphite eltrds ,118mmx1.5m, vert., grvl in concrete
(Original)			39 sea	Bog Roy, 8km from Benmore	land,horiz		6-40mm stl rods, 1.5m+ deep in coke, modified star
New Zealand	1240	+270/	same	same	sea/beach	2400	repl w/40 high silicon chromium iron, trenched into sea
(Hybrid upgrade)		-350		same	land		doubled size w/ branches, in low sulfer coke
Konti-Skan I	250	250	85-sea	30km from rect in Denmark	beach-anode	1000	25-2.4 m graphite, *initially* vert in pvc, pumped sea water
			95-OH	23 km from inv in Sweden	sea		300 m cu on sea bed 10 m deep, 3km off shore
SACOI	300	+/-200	121-sea	Sardinia coast 26km fr sta	sea-anode	1000	30 branches, platinum over titanium pipe, in bay
			292 OH	Isle Corsica, 9km from sta	land-an/cath		50 ferro-silicium-chrome electrodes, horiz, near sea
				Italy coast, 50 km from sta	sea-cathode		bare cu on blocks, 28m deep, 3km from shore
PNW-PSW tie	1440	+/-400	1362 OH	Rice Flats - 10km from Celilo	land,horiz	3000	3 part ring, 1030 m dia, HiSi iron in coke,1.5m deep
(initial rating)				1.6km at sea, 51km fr Sylmar	sea,linear		24 silicon-iron, horiz, 15 m dp off sea bed, in conc.encl.
Skagerrak	500	+/-250	113 OH	30km from Denmark station	land,horiz	1000	41 graphite-in-concr. rings, 2.5 m dia, 2m dp /coke
			127 sea	30km from Norway station	land,horiz		multiple graphite-in-wood rings, 2.5 m dia, 2m dp /coke
Square Butte	500	+/-250	749 OH	10km from rectifier at Center	land,horiz	1000	53-59mmx2.4m, HiSi in coke, 3m deep, on 26m dia ring
				37km from inverter at Arrowh'd	land,vert		210 HiSi, ibid, in holes 6 m deep, edges of 230 kV ROW
CU	1000	+/-400	710 OH	10km from rect at Coal Creek	land,vert	1250	18-300mm dia vert electrodes, 60 m deep in coke
				22km from inv at Dickinson	land,vert		18-300mm dia vert electrodes, 60 m deep in coke
Cahora Bassa	1920	+/-533	1360 OH	15km from Songo rect sta	land,vert	1800	5 graphite, 100mm x 60m, graphite powder 60m deep
				7 km from Apollo Inv sta	land,vert		4 graphite, 300mm dia, in bitumen/graphite, 130 m deep
Nelson River	1620	+/-450	892 OH	11 km from Radison Rect	Land,horiz	1800	Steel rods in 381 m dia ring, in coke 3m deep
Bipole 1				22 km from Dorsey Inv	land,horiz		Steel rods in 305 m dia ring, in coke 3m deep
Nelson River	1800	+/-500	930 OH	11 km from Radison Rect	Land,horiz	2000	Steel rods in a 2nd - outer- ring, 548 m dia, in coke
Bipole 2				22 km from Dorsey Inv	land,horiz		Same electrode as for BP 1
Intermountain	1920	+/-500	785 OH	Sevier-48 km from rect, DeltaU	land,vert,deep	1920	60 wells in ring-10 seg x 6 wells x 11 HiSiCr anods; 87m
Power Project				Coyote-95 km from Adelanto	land,vert,deep		60 wells in ring-10 seg x 6 wells x 11 HiSiCr anods; 71m
GeSha China	1200	+/-500	1044 OH	32 km from Nan-Qiao term	land, horiz	1200	Similar to Nan Qiao end? Did it fail too?
				38 km from Gezhouba term	land, horiz		840 m carb stl rod in coke, along Yangtze-failed 228Ayrs
HQ-NE Phase I	690	+/-450	172 OH	Windsor - 9 km to Des Cantons	land,horiz	800	4x19 segmt ring 600m dia, 2.75m deep in coke
				Lisbon - 18 km from Comerford	Land,vert		54 HiSiCr elctrds/coke, in 6 wells on 70m circ, 70 m dp
HQ-NE Phase II	2000	+/-450	1500 OH	Duncan Lk-40 km So./Radisson	land, vert	2900	9 eltrds in coke-well 116m dp - eltrds optimally spaced
				DMR Sandy Pd to Windsor	land, horiz		
Vancouver Isl	682	+260/	28 sea	Sansum,17.6km from V.I. term	sea, anode	1700	28 graphite, 2.4mx1.6cm, shallow @ shore line
		-280		Boundary Bay 5.8 km fr Arnott	land, cathode		46 silicon iron, linear, in coke , 1.2m dp, shore / dike
Baltic Cable	600	450	12 OH	23km from Swedish term	sea	1364	precious oxide/titanium mesh, seabed 700m from shore
			250 sea	20km from German term	sea		precious oxide/titanium mesh, on seabed 12m deep
Baltic Test				On site at Sweden terminal	Deep land	350	Same mtl, 45 m x 70 mm, 550 m deep, w/salt water
Deep Electrode							

5.3.2 Geological Influence Shallow and Deep

At electrode separations of 3 to 6 times the depth of the crust (Figure 5.4) or 90 to 200 km (55 to 125 miles) there would be significant flow of current in the upper mantle (bottom of the crust) if the earth were homogenous. The higher the resistivity in the 10 km to 30 km depth range, the greater will be the concentrations of current flow in the near surface rocks.

The first step in the process of determining the regional distribution of conductors (and non-conductors) should be consideration of existing geological conditions and the correlation of resistivity or conductivity values to the regional geological conditions. The starting point is gaining a good understanding of the total geology of the region including the lithologies (rock types) and the tectonics (faults, and other dominant features imposed by ancestral stress regimes.) Many times faults, folds etc., reach great depths (greater than 30 km), and tend to be more fractured and water laden than the host rock. In addition, they are many times altered by the intrusion of hydrothermal fluids which can emplace conductive minerals.

In a simple geological environment with flat lying strata such as exists in the Midwest for example, the conductivities near the earth's surface (0 - 6,000 ft 2 km or more) can be extrapolated for many miles (laterally) and if both electrodes are underlain by the same conditions then the conductivity between them should be reasonably predictable. Unfortunately, the resistivities are generally higher as we fetch deeper in the crust until they become more conductive below the crust at depths in the order of 30 km (Midwest) or more. If the surface layers are conductive and wide spread the three dimensional lateral effect will lower the potential gradients significantly, possible to an acceptable level, even in the presence of a underlying highly resistivity layer.

In many cases it will not be possible to estimate the conductivities at depths of 10 to 30 kilometers from known geological conditions, in this case there may exist geophysical data as discussed in section 3 to determine mid and lower crustal conductivities.

5.3.3 Gross Conductivities From Geological Inference

Geological maps exist for the entire United States generally in reasonably good detail. These maps were prepared by various sources such as state geological surveys, the United States Geological Survey, and universities, independently or with state or federal support. In addition there exist many geophysical surveys, airborne and ground magnetic, conductivity, radioactivity as well as ground seismic, gravity, deeper electrical conductivity etc. All of these resources can be used to define the geology in an area and ideally to construct a three dimensional picture of the earth's conductivity.

The idea is to begin with the larger picture of the region and to eliminate areas that are not candidates for local siting and where deeper conduction is not favorable. Based on the construction of the conductivity-geological map then the next step in the process of defining those areas of potential interest is with a few simple inexpensive field tests to confirm the constructed conductivity map (see 5.3.4 below.) This step- by- step process is more important in those areas that are complex geologically. Candidate surface rocks must have sufficient lateral and vertical extent.

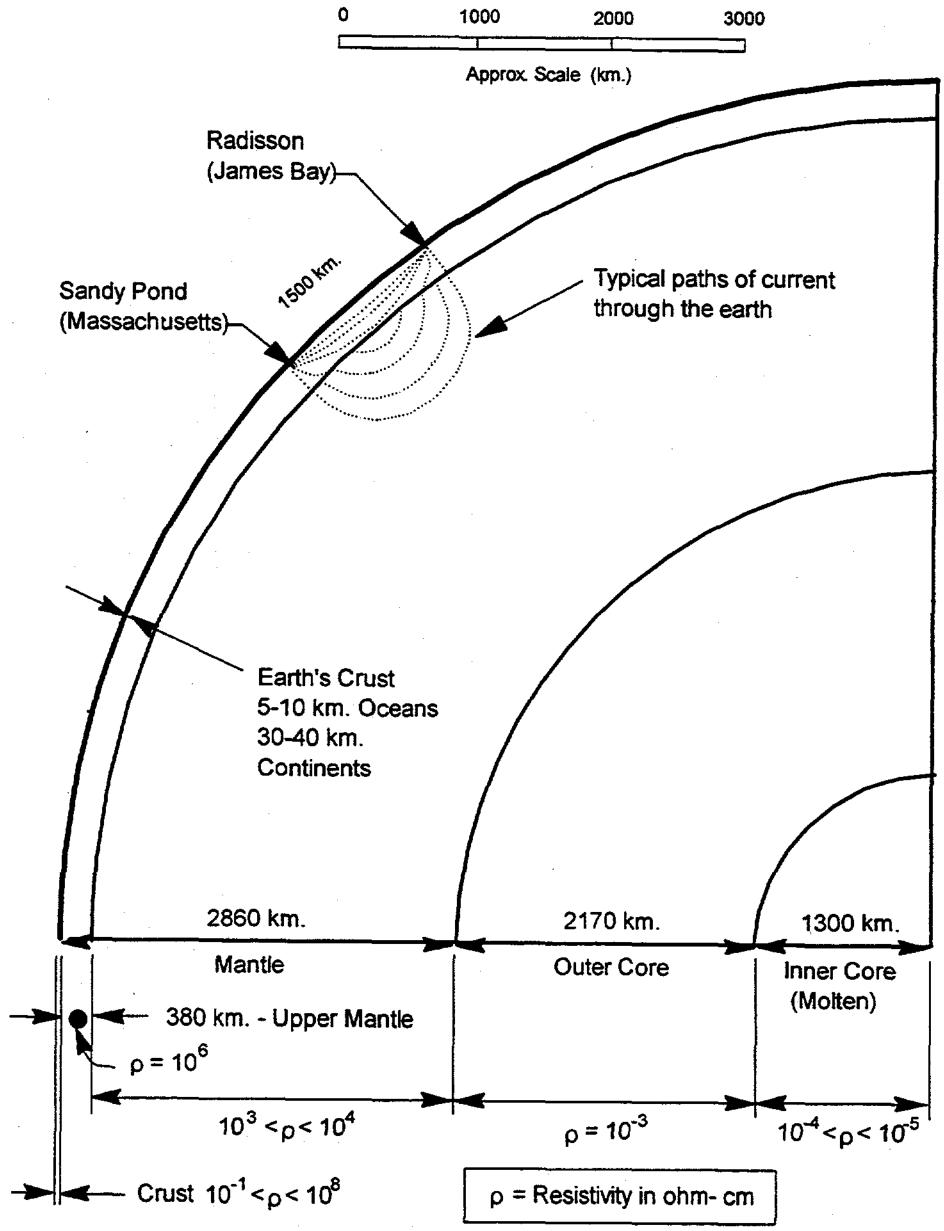


Figure 5.4 Earth's Layers and Resistivities

The constructed map will serve to assess whether or not certain techniques will be successful; if for example, the map shows a number of conductive rock outcroppings interspersed with resistive rocks; determining the deep conductivity by MT methods may not be possible.

5.3.4 Types of Tests

The intent of this section, as has been the rest of the report, is to provide background information to the reader, not a tutorial on testing methods; these are well described in various texts such as Telford et al (1995), Keller et al (1966)

5.3.4.1 Testing Specific Geological Formations

Enough tests should be made, such that the formation variations can be established. The latter may not provide accurate resistivity values at depth because fracturing at the surface may be greater. If the initial tests prove that the formation is a candidate for electrode placement then selected areas may be further tested using deeper penetration methods.

In some cases, where exploration for oil and/or gas exist, sufficient data may be available to establish formation resistivities. There are many surveys, ground and airborne, that will yield the resistivity of the surface layer and searching for these is worthwhile. Generalized maps such as Figures 1.4 and 1.5 are for background information, not specific use.

5.3.4.2 Shallow Penetration Methods to Determine Specific Resistivities

There are a number of methods to determine the resistivity which have various accuracies, ranging from high for the direct methods such as galvanic, to moderate, or low for the electromagnetic methods which rely on induction. The electromagnetic methods may be time or frequency dependent, ground transported or airborne, the latter mostly associated with mining exploration.

The VLF method, previously discussed, is selected for a brief description because it is inexpensive, readily available, easy to use and can be performed by someone with little or no experience, and the data interpretation is straightforward. The VLF measures a radio signal from one or more of a number of transmitter stations (Cutler, ME, Annapolis, MD, Boulder, CO, Seattle, WA, Hawaii.) installed for marine navigation. The signal is in the range of 15 to 25 kHz. Two or more of these stations can be received anywhere in the U.S.

Two mutually perpendicular coils are used to measure the tilt angle and quadrature phase of the signal by rotating the coils to a minimum or null position. The phase angle (lag) between the electrical and magnetic fields depends on the resistivity of the earth materials under the measurement point. Near surface conductors will dominate the signal so that if measurements on a rock formation are desired, the soil cover should be much more resistive than the rock (not the usual case) or measurements should be made on rock outcroppings. If one wants to follow the strike of the formation the azimuth may be such that the incoming signal is weak and another station should be used.

This method is useful for determining the relative formation(s) resistivity to be superimposed on a geological map to create a regional and site conductivity map. The map becomes the basis for deep testing or injection and together with the site specific data, becomes the basis for an electrode design.

5.3.5 Cooperation With Utility Owners (Pipe Lines etc.)

If current injection is to be performed, cooperation with the utility owners is important. In the case of a major utility with long oil or gas lines for example it is important that they be consulted prior to the injection so that their personnel can make any measurements relative to their facilities. The conductivity between the two electrodes, the amount of current and the distance to the underground facility determine the injection affect on the utility. High ground conductivity, long distance and moderate currents all are favorable for minimum influence on the utility. At some point along the electrode path, the background of the earth's natural currents will equal or exceed the injected current (usually 40 to 100 km). This point should be established from the conductivity map and some simple modeling before current injection. During injection, polarity switching can be performed for unique identification of the current source at the utility.

In the case of local utilities, water lines, local gas lines, etc. the owner may require some education on the part of the electric utility that is to perform current injection. The utility doing the testing would be wise to hire a consultant to look after the interests of the local utilities likely to be impacted.

5.4 ON-SITE TESTING

The complexity of the geological conditions (conductivities) along with the amount of urban development that could be effected by corrosion or interference, determine the on-site testing. Two site phases are usually involved those made before the installation of the electrode and used for design and those post electrode installation for confirmation. A third and final phase, conducted some time after commissioning is also recommended.

5.4.1 Local Resistivity (1km)

The geology in the vicinity of the site may consist of simple flat lying layers with predictable conductivity values that are adequate for the installation of an electrode at or near ground surface. In this case, a few measurements using one of the conventional galvanic methods (see section 2.2.1.) are made with the electrode separation expanded until the desired depth of penetration is achieved. The distribution of current in a cross section of earth is a continuous smooth function, the depth of penetration relative to the electrode separation depends on layer thickness and resistivity see Figure 2.2. Interpretation is by modeling, where the field results are compared to a theoretical construction based on a number of layers, their thicknesses and resistivities. Since there are equivocal solutions for various layer and resistivity combinations the knowledge of the interpreter is very important as is constraining information from other types of data.

The principal purpose of the on site measurements is the design of the electrode to achieve the best earth contact which includes the lowest step potentials and local interference. The materials that the electrode will be placed in should be measured carefully under several conditions. It has been abundantly stated elsewhere that near surface highly conductive materials overlying a resistive rock are not sufficient for a good electrode site. The material into which the electrode will be placed is critical. Remembering that the conduction in the earth is electrolytic, the conductivity of the "connecting" material, soil or rock, should be measured under a variety of moisture conditions. If the material is saturated and will remain saturated throughout the year and throughout a severe drought period, then a few measurements will surface. However if moisture conditions will change during the operation of the electrode, then the range of conditions should be measured for electrode design input in actual or simulated moisture conditions.

If a vertical electrode is being considered then it is important to know the conductivity in the vertical direction. This is most accurate when done with boreholes in the initial phase of on-site testing along with careful surface testing.

5.4.2 Safety-Step Potentials V/m levels.

Step potentials should be made after the installation of the electrode. The purpose of the on-site testing before the electrode installation is to provide information so that the electrode is designed to minimize the step potentials and interference. It is possible to gain a good grasp on the final potential gradients by knowing the lateral and vertical resistivities. Most formations including soils (although less so than rock) are anisotropic in three orthogonal directions, along strike, (the trend of the formation), perpendicular to strike, and in the thickness direction (vertically for a horizontal formation); these differences in the resistivity values will be reflected in the step potentials.

Subsequent to the installation of the electrodes, step potentials are best made at current levels above those used for the measurement of the resistivities. A few amps (50±) is usually sufficient to allow the measurements to be carried out to a kilometer or more away from the electrode.

5.4.3 Cooperation With Local Utilities

This subject was covered in section 5.3.5. It is worthy of note that in many urban areas, particularly those with electrical transit buses or subways, ground returns of hundreds of amps are used and these will generally be well above those currents caused by HVDC ground electrodes. Local utilities in such areas should be aware of the corrosion and interference from these sources. Additional mitigation, or readjustment of existing systems, could be necessary.

5.5 ELECTRODE DESIGN AND INSTALLATION

The design of the electrode system is highly individual depending on the local geology, site conditions and potential for affecting any surrounding facilities etc.

5.5.1 Electrode Materials Considerations

Extensive literature exists for the design of electrode systems ranging from a corrosion proof installation to those that are more prone to corrosion and will be replaced on some schedule. Special coated metals exist that corrode very slowly and yet provide conduction to the ground. The most common electrode system consists of a number of commercially available electrode elements that are placed in a coke breeze powder to minimize corrosion; the use of coke breeze is discussed further in the next section and in section 5.8.

The final decision relative to electrode materials is probably best made on an economic basis comparing maintenance and replacement of a simple electrode system subject to corrosion versus a more exotic protected coated metal system that is not as susceptible to corrosion and requires little attention. An electrode system that makes non-uniform contact with the ground water will have higher current densities at those points that are in good contact with consequent adverse results already cited.

5.5.2 Electrode-Embedment Materials-Earth

It is common practice to embed the electrode system in a coke breeze powder, that under proper compaction, will act as an electronic conductor. The coke breeze effects a uniform material around the electrode and apparently reduces corrosion. However the coke breeze makes contact with water, and the uniformity of the contact is critical; elements subject to high current density create a problem, coke breeze or not.

5.5.3 Provisions for Monitoring-Repair-Contingency Planning

Monitoring of the electrode potential as well as temperature and perhaps current for each element of the electrode should detect any significant changes in current conduction that could adversely effect the system. High current at certain elements can cause an increase in the temperature at that point by either or both of two methods: the formation of gas bubbles that cling to the coke or directly to the electrode and the adverse deposition of resistive materials (silica for example) on the anode.

Corrosion of the electrode system or elements may require that the system be refurbished from time to time in which case consideration should be given in the design and installation phase to making it easy to access and repair the electrode.

If under certain conditions of extreme drought the water table at the site is lowered or the materials which surround the electrode become dry then the system may have to be taken out of service. Preferably, the system should be placed in an area where the water table will not drop below the electrode contact. If there is a question then creation of an emergency water pond on site may be advisable Care should be taken such that future activities by man will not draw down the water table to the point where the electrode elements (coke breeze, etc.) may be exposed to dry surroundings.

5.6 MONITORING

Monitoring can be local only or remote; generally the information is not critical so that the data readout can be made as desired. Data recorders may be used for continuous monitoring for interrogation on a periodic basis or the data can be hard wired back to a manned point.

5.6.1 Conductivity to a Reference Point, Temperature

The single most important measurement is the conductivity to the ground measured by the potential from the electrode elements to a standard reference point. An unusual change in potential is indicative of a site change either in the electrode system or in earth conditions. It may be that such changes (within a tolerable level) are due to external events such as rain or a drop in the water table; correlation to ordinary weather changes will build up an experience base. Temperature rises and voltage rises are important; failures of past electrodes have been associated with high current densities, gas generation, and or plating of resistive materials on the anode. All such occurrences lead to thermal run-away with potentially destructive results.

5.6.2 Monitoring-Continuous or Periodic

Unless there is some site peculiarity , continuous monitoring is probably not necessary. The exception being that if there is a potential or temperature rise that does not return to normal, then “run away” (high resistance and temperature rise) is possible and this can happen rather quickly.

5.6.3 Magnetic Storms On-site; Remote

The advent of a magnetic storm can produce a positive or negative current flow relative to the electrode and knowledge relative to the influence on the electrode will be beneficial both for the electrode system as well as general knowledge for the electrical grid. Monitoring during magnetic storms should be continuous; however, continuous monitoring can take place after a threshold trip level signals the advent of a magnetic storm. The site may be equipped with SUNBURST monitors described later in section 6.

5.6.4 Local Utility Conditions

Conditions relative to the current flow on local utilities, particularly in an urban area, may depend largely on current flow induced by sources other than an electrode system. Under such circumstances monitoring the potential on the local utility system will require a distinctive signature from the injected current. Again, the SUNBURST system was developed for this purpose.

5.7 OPERATION & MAINTENANCE ISSUES

5.7.1 Expected Routine Maintenance Based on 5.4 and 5.5

During the installation of the ground electrode system certain unusual conditions may exist that would require maintenance. For a vertical (borehole) electrode, maintenance of good electrode-ground contact may be impaired by "plating" of resistive elements silica etc, on the rock wall (see below section 5.8.) This resistive coating can be removed by steel brushing the rock walls, in addition the electrode elements may stand a cleaning. If coke breeze has been added to the borehole, then this must be removed and consideration of this eventually in the design and installation could save a lot of work. In the case of a linear electrode, provision should be made for the removal of coke breeze and excavation of the electrode elements for repair or replacement.

5.7.2 Potential Problems and Provisions for Solution

Should the earth materials that make contact with the electrode dry out this will create a serious situation and will be cause to shut down. For electrode sites that could encounter this, as previously stated, an on-site water supply could be treated as an emergency supply or it could be constantly fed to the electrode for ground water recharge to insure uniform electrode element contact with the earth. Also in the installation, fine materials that might migrate to the electrode and change the porosity should be removed. Such materials in contact with the electrode or the coke breeze might be less porous and less conductive.

The electrode system, whether in coke breeze or direct contact with the earth, can produce gassing at relatively low current densities. Some of the small bubbles created are very difficult to remove, clinging hard to the surrounding materials and causing an increase in resistivity with a consequent rise in temperature which causes a further increase in bubble production. It is important that the potential and the temperature be monitored to detect such a condition. The removal of such gas bubbles may be difficult, successful venting will depending on the bubble size and surface cohesion to the material in which they are entrapped. Generally, it is best to prevent gas bubbles from forming since they are near-impossible to remove later. Compaction of coke breeze helps and perhaps periodic compaction of the coke breeze for shallow ditch electrodes would be beneficial.

5.8 EXAMPLES

5.8.1 Lisbon NH (Comerford)

The town in which the Comerford HVDC station's electrode site exists is Lisbon, NH; the converter station is in the adjoining town of Monroe. The electrode link is for an HVDC line to Des Cantons (Sherbrook) Quebec. The geologic setting of the site is in the northern Appalachians in a tightly folded sequence of rocks that have been subjected to several geological episodes. The formations are mostly resistive with interbedded conductive formations constituting but a small volume of the total rock. The effort to find a suitable conductor was extensive. It included assembling geological, geophysical, and water well data, and resistivity field testing, current injection, laboratory testing for electrode and coke breeze behavior with the rock for a vertical electrode design, and on site testing pre and post installation. In fact, two sites were identified, Lowell NH and Lisbon NH; the Lisbon site was closer to the Comerford HVDC terminal, requiring only 18 km of electrode line.

In deeply soil covered candidate areas, river valleys for example, galvanic (hard electrode earth contact) methods using one or more of several electrode configurations were used. For those candidate areas where the rock was outcropping or near outcropping VLF or one of the inductive methods was used as a reconnaissance method to measure formation resistivities; if required, this was followed by a galvanic survey. The following is a very brief synopsis of the studies.

Exploration to find suitable sites consisted of assembling basic data including a detailed geological map in the area of interest. While the existing base maps were excellent, they were checked in critical areas by ground inspection and adjustments where made where needed. Next the geological formations were assigned conductivity values based on petrographic knowledge, drill hole information, particularly bedrock water production, and a few existing geophysical measurements on the same or similar formations. The geological formation resistivities are shown on Figure 5.5, a local geological map surrounding the Lisbon site showing the conductive Littleton Formation (filled in gray.) The selected formation is surrounded by high resistivity rocks. The section A-A' identified on the plan map is shown on Figure 5.6. Much of the rock is granite, or highly metamorphosed granite-like with very high resistivities (5,000 ohm m or higher). Conductive formations were not extensive in the horizontal direction and their extent in the vertical direction was largely unknown.

The Littleton formation in which the electrode resides is basically an argillite (sedimentary high clay content rock) with dispersed graphite and pyrite. It is relatively conductive 0.5 to 0.005 siemans (2 to 200 ohm meters). The surface outcrop (fig 22) of the conductive Littleton Formation is about 15 miles (24 km) long and about 4 miles (6 km) wide, not a great extent. The key question relative to the formation being a suitable conductor for the 800 amps of phase 1 and 2,000 amps of phase 2, was the potential for its intersection with other conductive formations and its connection with conductive rocks at depth. The eastern border of the Littleton Formation terminates against the Ammonoosic Fault a major deep seated fault with some conductivity near the surface which could be associated with the emplacement of hydrothermal fluid deposits.

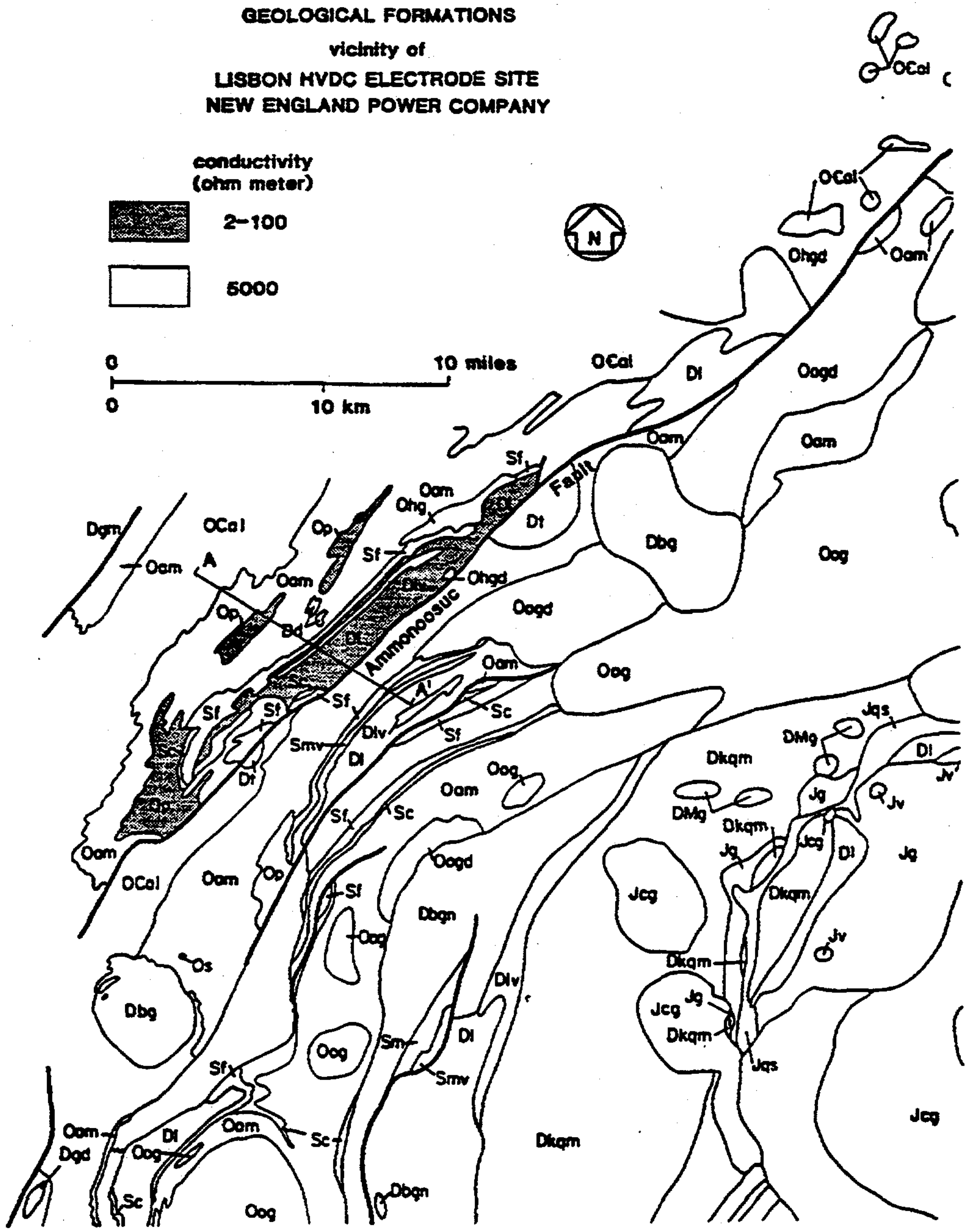


Figure 5.5 Geology - Resistivity Map, Lisbon, New Hampshire Electrode Site
(Serving the Comerford HVDC Station in Monroe, NH)
New England Power Service Company, 1984

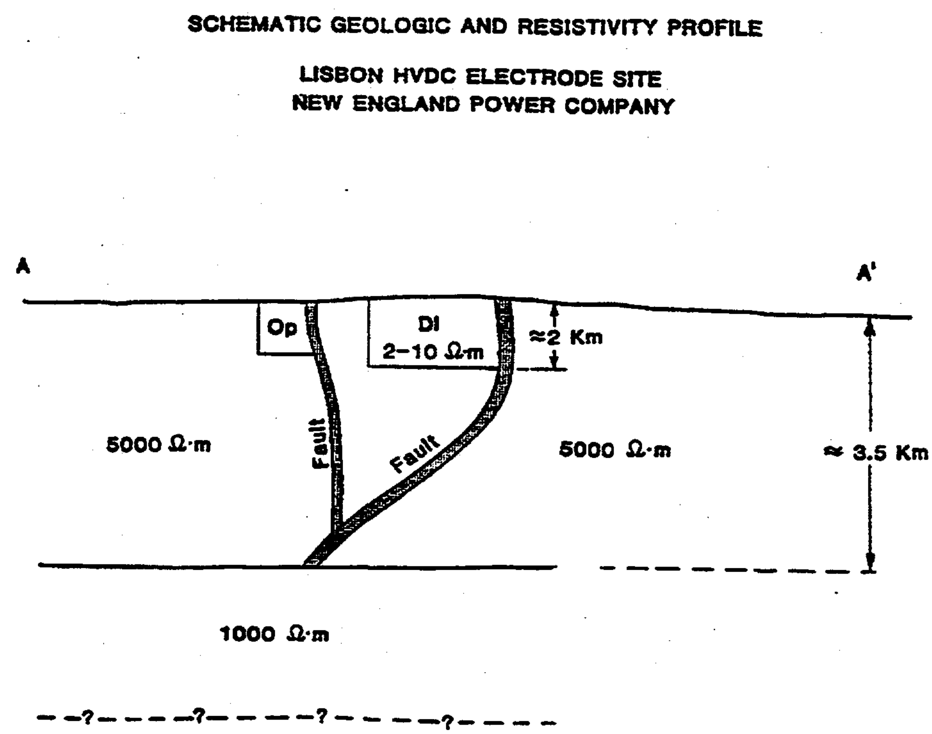


Figure 5.6 Cross Section A-A' From Figure 5.1. Showing the Ammonoosuc Fault New England Power Service Company, 1984

A suggested cross section for the fault is shown on Figure 5.6. Should either one or both of the vertical fault splays have conductive materials extending to the mantle, then excellent conduction was assured. The conductive portion of the fault is shown terminating at 3.5 kilometers although its depth was unknown. The conductive formations at the surface Op and Dl are shown to be about 2 km thick based on the best geological/geophysical inference that could be drawn. The 1,000 ohm m material shown at depth is extrapolated from formation values determined in southern NH by a Magneto telluric study of deep electrical conductivity using telephone lines and natural currents. (Kasameyer 1974.) Deep exploration methods to determine the vertical extent would have yielded equivocal results so they were not used. While the installation of a long line to monitor natural earth currents, particularly magnetic storms may have been successful in determining the conductivity to depth, the effect of current injection on major and local utility lines would not have been obtained and time did not allow it. It was decided to inject current using transmission lines.

The current injection was at approximately 125 amps. Similar testing was performed at the Windsor, Quebec electrode site for the Des Cantons terminal. The potential profile between these two electrodes developed from the injection testing is shown on Figure 5.7 As can be seen from this plot, the voltage gradients are not indicative of a deep earth connect at the Lisbon electrode. (See Figure 1.2a with C_1 remove to infinity.) The surface potentials resulting from current injection, shown on Figure 5.8, indicate the horizontal extent of the Littleton Formation and the relationship of the potentials to a major pipe line.

The limited rock conductor at Lisbon is manifest on Figures 5.7 and 5.8, the latter by the gradual reduction outside the influence of the Littleton formation where the potential remains flat and above the 16 volts representative of the mid- point voltage for a homogeneous earth. Clearly the electrode at Windsor is in a larger conductor that has much greater volume as illustrated on Figure 5.9 which shows the horizontal extent of the of the conductive rocks at the surface, principally the Magog formation of sedimentary rocks.

A major pipe line that runs from Portland ME to Montreal Quebec is shown on Figure 5.8 and 5.9. This line was monitored during the injection tests for which polarity switching of the input current allowed unquestioned recognition of the current on the pipe line. Mitigative measures for the pipe line were required. Local utility lines, in the town of Littleton NH crossed the boundaries of the Littleton formation where the potential gradients associated with the more resistivity boundary rocks exists. In this case they were effectively grounded at the Littleton formation, and the resistivity map, along with the current magnitude provides the information for mitigation if appropriate. The non-uniform distribution of ground resistivities creates high current densities at particular utility locations. Most of the utilities are buried in soils the bulk of which are derived from glacial action constituted mostly of damp silt, clay, sand admixtures with resistivities ranging from 300 ohm-m to about 1,500 ohm-m. Many times, however, clean dry sands and rock conditions are encountered which have resistivities of 5,000 ohm-m or higher; so that utility - ground contact is highly variable creating high current densities along the utilities at some locations.

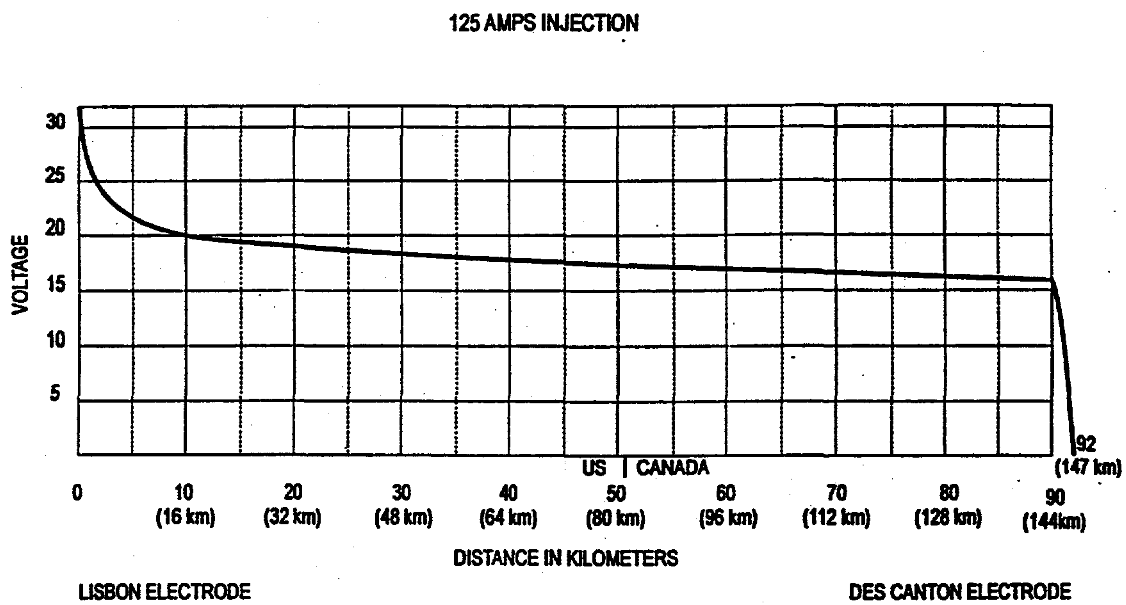


Figure 5.7 - Voltage Profile - New England to Quebec. 125 Amps. Injection

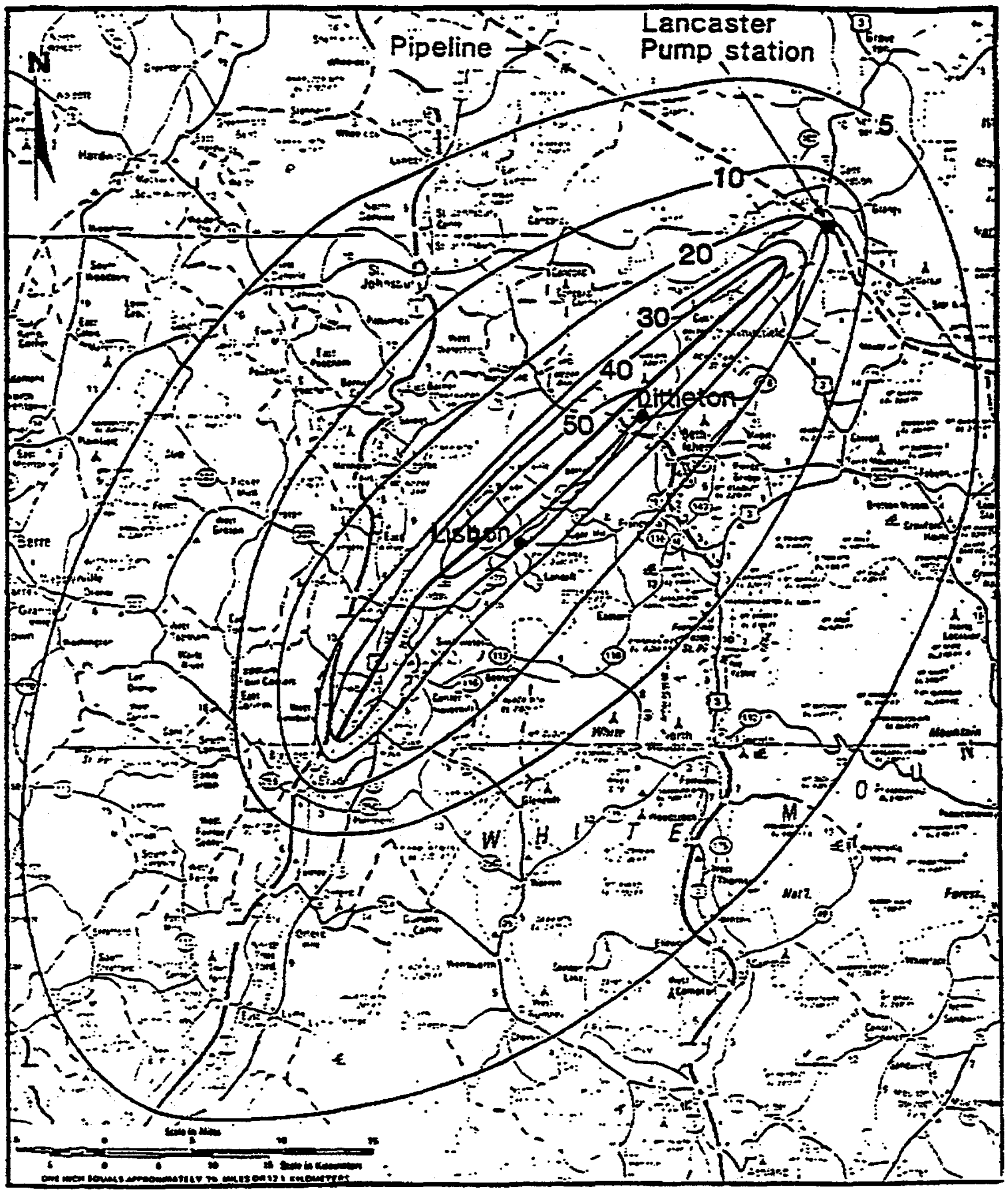


Figure 5.8 Contours of the Potential Distribution Based on Current Injection of 850 Amps, Lisbon Electrode - New England Power Service Company, 1984

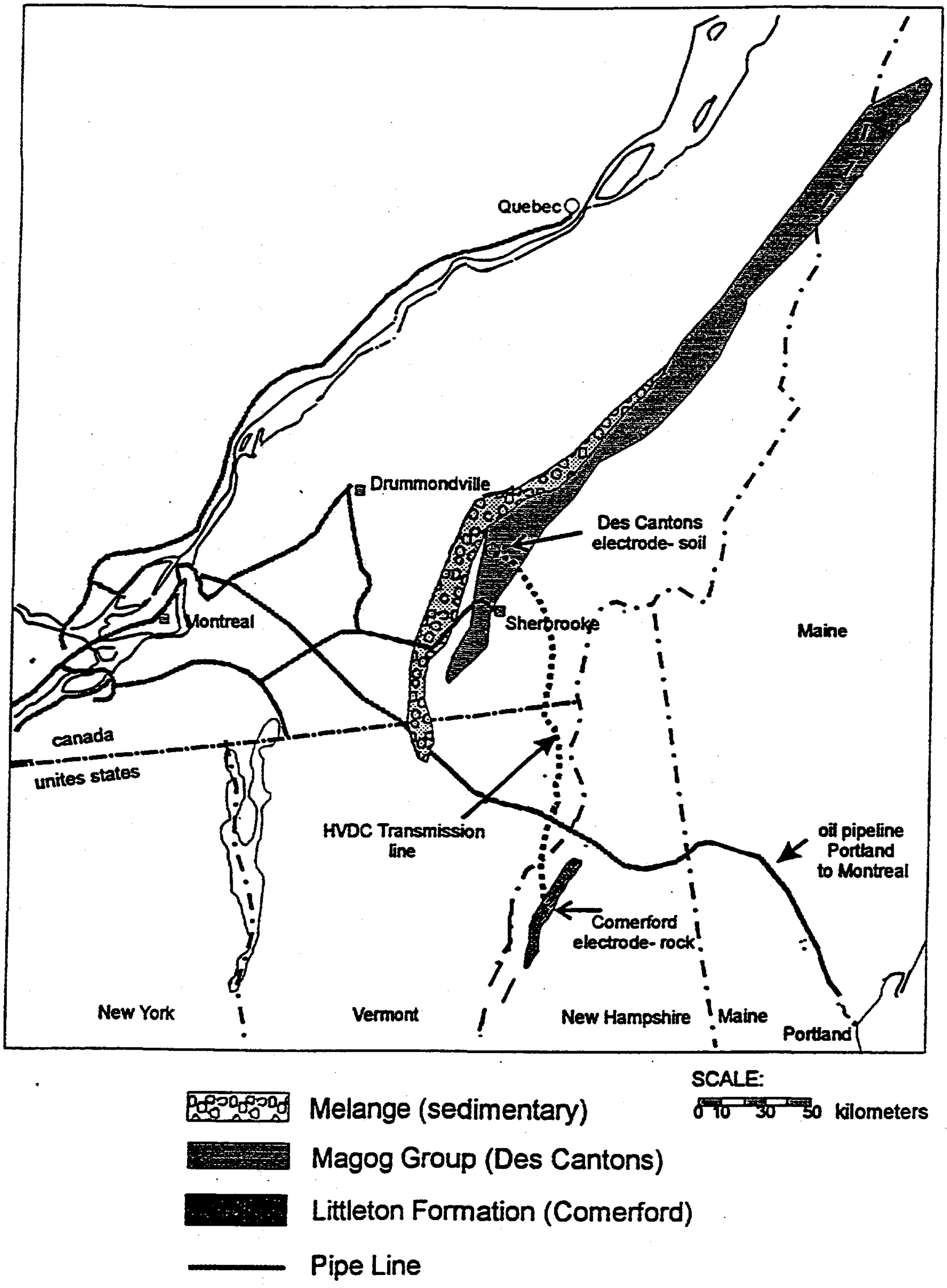


Figure 5.9 Relative Size of Conductive Rock Formations for the Lisbon (Comerford) New Hampshire and the Windsor (Des Cantons) Quebec Electrode Sites

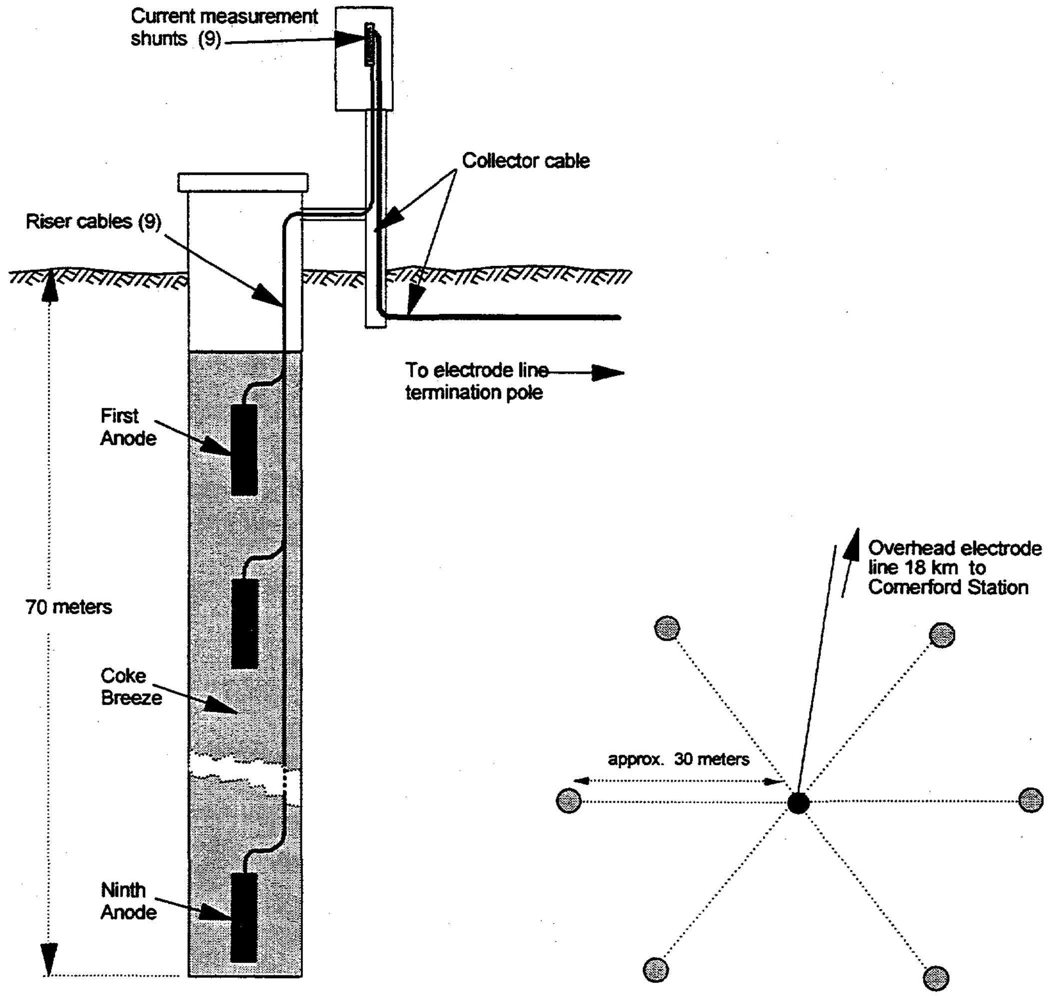
A vertical rock-well electrode was selected for the electrode design. During the exploration phase it was recognized that the conductive rock would have highly variable conductivities at dimensions of a few inches or less. This is due to the fact that the water in the formation is contained in the rock fractures which are a millimeter or so to a few centimeters wide. These highly variant conditions are not noticed when electrodes are placed a few meters apart. The electrode design called for six 12 inch (25 cm) diameter boreholes approximately 70 m deep with a fixed interval between the electrode elements. The six wells were arranged in a circle as shown in Figure 5.10. The resistivity profile (saw toothed curve), the average resistivity profile relative to the electrode elements for one of the six wells (rectangular histogram), and the electrode elements are shown on Figure 5.11.

It was decided that the annulus between the electrode and the borehole wall would be filled with coke breeze. A specimen of surface rock about 2 ft (60 cm) cubed of the Littleton Formation was selected for laboratory studies; a 3" (7.6 cm) diameter hole was drilled through it for electrode-borehole simulation.

The resistivity of the electrode-coke breeze-rock connection in a 3" diameter hole in the rock specimen with pressure of 0, 6, and 12 psi (pounds per square inch) was determined. The effect of compaction of the coke breeze was to decrease the electrode-coke-rock resistivity from about 10 ohm-m for zero pressure to about 6 ohm-m for 6 psi. For the coke alone, the reduction was from about 0.3 ohm-m at 0 confining pressure to 0.01 ohm-m for 6 psi; increasing the pressure to 12 psi dropped the resistivity of the coke to 0.007 ohm-m. Pressures beyond the 6 psi did not significantly reduce the resistivity. Most importantly, with zero confining pressure there was significant gassing (hydrogen) at the coke-rock interface. Short term gassing was not evident at 6 psi compression on the coke. Test current densities were about 100 amps/m^2 at the steel rod electrode and 20 amps/m^2 at the rock interface. The very small bubbles created by the electro-chemical process clung tenaciously to the rock face and also to the coke breeze.

Saturating the coke breeze with site ground water did not decrease its resistivity, in fact, it raised it slightly, the resistivity of the ground water is higher than that of the coke. There was a systematic resistivity increase in the laboratory test specimen from about 4 ohm-m to about 20 ohm-m in a period of about 4 months which remains unexplained but could be due to specimen drying out combined with gas entrapment or changes in chemical composition along the small conductive rock fractures. It is doubtful that the mass of in-situ rock would act in like manner because: the "dry" specimen conductivity values duplicated the in-situ values, the specimen was subjected to rather high current densities during the experiments, the small specimen size exposed to the air does not represent in-situ conditions, and the connection of the cathode to the specimen was through a painted conductive patch that showed signs of deterioration.

The current injection tests demonstrated that the Ammonoosic Fault does not have connection to depth and that the combination of geological inference and geophysical testing (shallow) predicted accurately the dimensions of the conductive formation including its depth of 2 km.



a) Typical electrode well, with 9 Durichlor - high silicon cast iron Chromiuim alloy - electrodes

b) Site plan with six wells arranged in circle connected to Comerford HVDC terminal by electrode (distribution class) line.

Figure 5.10 Lisbon Vertical Electrode Design dimensions, etc.
New England Power Service Company, 1984

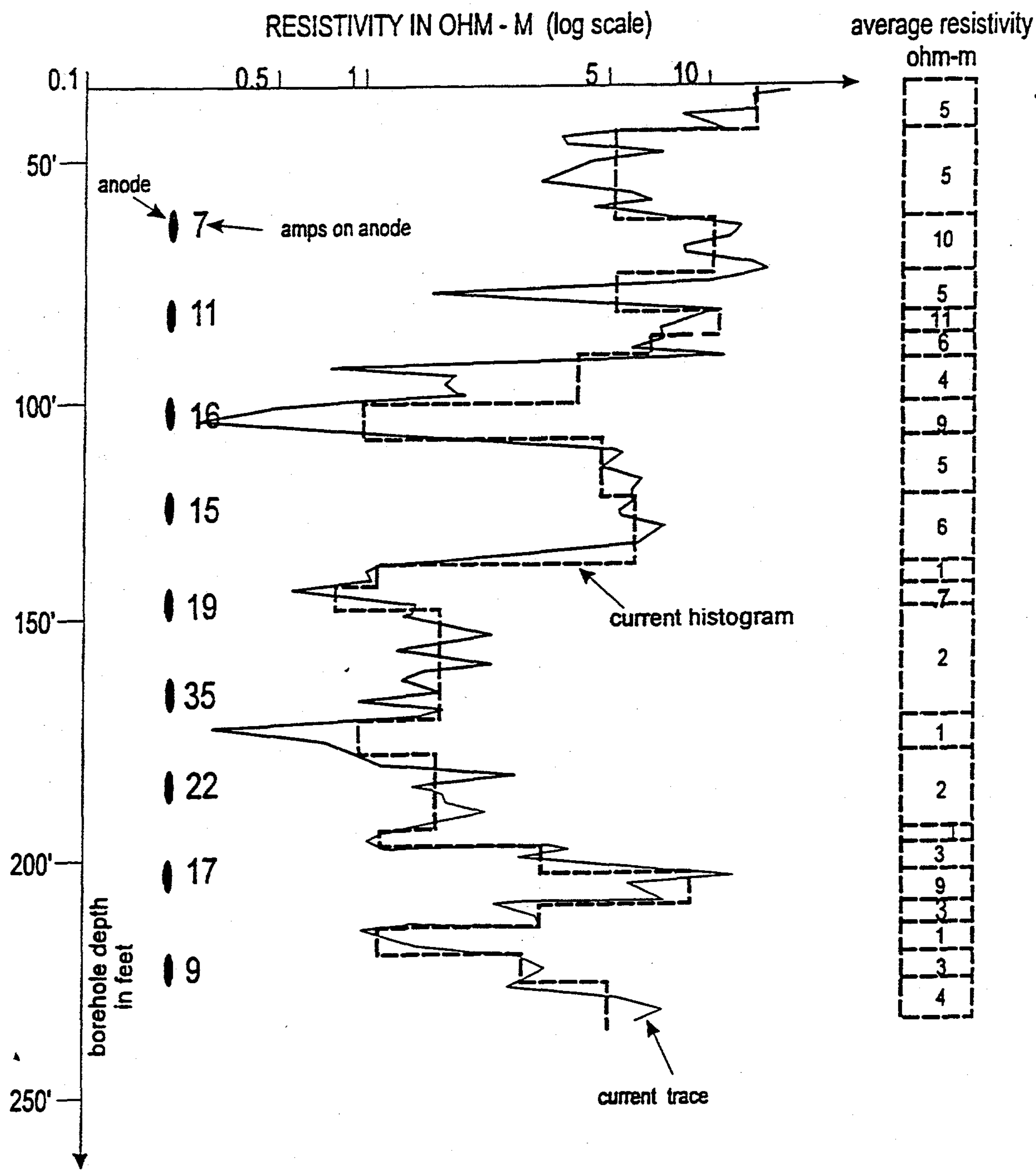


Figure 5.11 Borehole Resistivity Profile. Lisbon, New Hampshire (Comerford Electrode) New England Power Service Company, 1984

In summary while the electrode is suitable for current injection (at some level) the following negative aspects are noted: The electrode was placed in a limited conductor which elevated the potentials at some distance from the site and required mitigation relative to underground utilities.

Gassing and electroplating occurred with the current injection. Either of these conditions could produce an undesirable increase in resistivity and consequent increase in temperature which could dry out the various ground connections (fractures, mineralized zones, etc.)

Periodic maintenance relative to the gassing or electro-plating would be based on the electrode element to ground resistance as measured by potentials or current flows in each element.

5.8.2 Windsor (Des Cantons) PQ, Canada

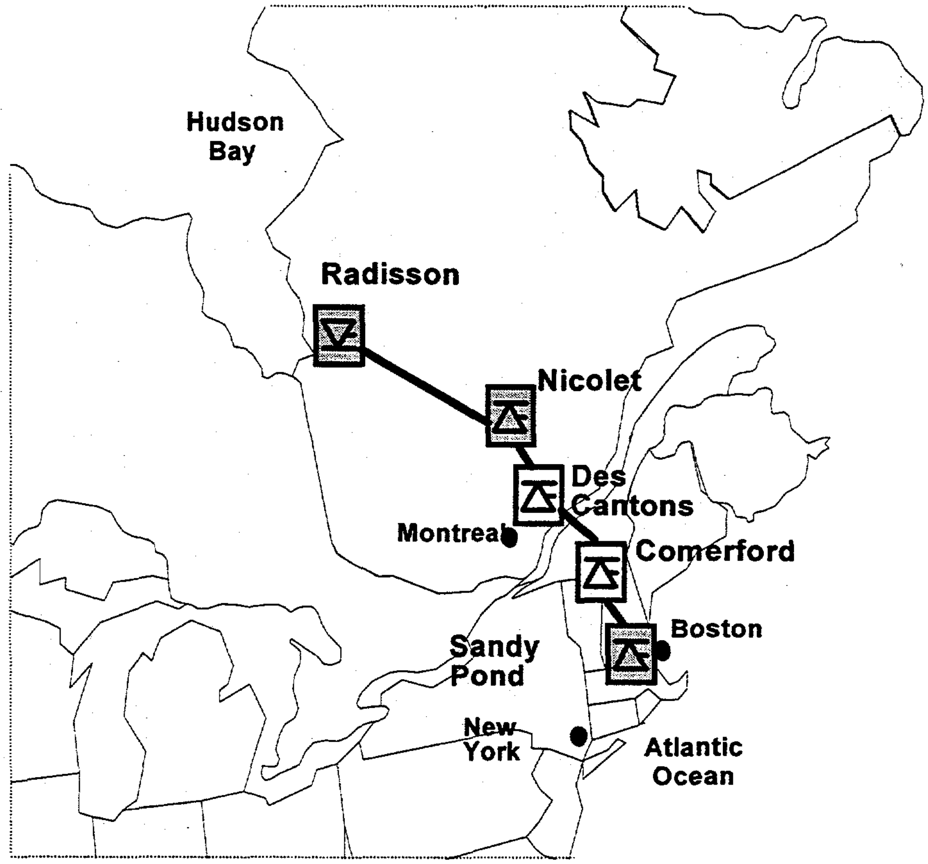
Exploration of this consisted of assessing the geology and a few field tests to confirm the lithological-conductivity relationship. The site has been discussed previously, and the geological setting is shown on Figure 5.8. The rock at the site is relatively close to ground surface, the site area is large and there exists a large swamp area within the ground water table which appears to be stable. A surface electrode was chosen for this site. The installation was straight forward; a circular ditch was excavated, the electrode elements installed and the ditch was backfilled with coke breeze.

The major difference of this electrode and the Lisbon electrode is the size of the conductive formations. The major consideration for this site would be a lowering of the water table that might cause loss of ground connection with the electrode. It is understood that potentials as well as current and temperature are monitored for the electrode; so that a change in soil water content would be noted well in advance of a significant increase in ground resistivity.

The superiority of the Windsor electrode compared to Lisbon made it the obvious choice for grounding the Phase II terminals at Nicolet (Quebec) and Sandy Pond (US). A dedicated metallic return (DMR) conductor, in the form of a third wire on the dc line connects the Sandy Pond 2,000 MW HVDC terminal to the electrode at Windsor. The Lisbon electrode, like the Comerford and Des Cantons HVDC terminals, are used only for back-up to the Sandy Pond-Nicolet international connection (**Figure 5.12**).

5.8.3 Duncan Lake (Radisson) PQ, Canada

This electrode site is placed in a localized conductor surrounded by highly resistive rocks of the Canadien Shield the average resistivity away from the conductor generally being in the order 10,000 ohm-m or greater. While James Bay is relatively close, this could not be used because of environmental reasons. Again, like Lisbon NH the conductive body is of limited extent although both the host rock and the relatively conductive rock chosen for the electrode site are more resistive. This ground return caused problems in that the high resistivity rocks have caused high current flow into the ac system some 40 km away. While MT surveys were run at the site, penetration to depth indicated highly resistive rocks the limited lateral (~ 2km x 20 km) and vertical (~ 2km) dimensions of the conductive rock formation prevented accurate modeling of the depth profile because of its lateral effect.



The figure shows the complete multiterminal Quebec - New England Phase II, 2000 MW +/- 450 kV HVDC Line with terminals at Radisson, Nicolet and Sandy Pond operating normally. Comerford and Des Cantons operate only when the other terminals are unavailable which is very rare.

Figure 5.12 Sandy Pond - Nicolet 450 kV DC Line

The problems that resistive rocks have caused on the ac systems could not be remedied at the electrode as the highly resistive rocks cannot be avoided within a relatively large radius of the site (40-100 km). The HVDC return currents were minimized in the ac system by adding series capacitors in key ac lines around the Radisson HVDC terminal. Most of the direct current was blocked by the capacitors and the residue is tolerable.

6. CORROSION EFFECTS AND MITIGATION APPROACHES

6.1 OVERVIEW

This report section provides a survey of the effects of stray current interference such as operational disruptions and plant damage due to corrosion upon underground facilities . Existing stray current detection, measurement and monitoring methods, and presently used mitigation measures are also reviewed. Speculation as to the most productive direction for future monitoring and mitigation advancements is presented.

The effects and mitigation of stray dc and very low frequency stray current interference have been a subject of scientific and engineering study for over a century. Hence, a body of knowledge exists that can be extremely useful in assessing and solving interference problems associated with the use of monopolar or unbalanced bipolar HVDC transmission systems. Specifically, effects and their amelioration are reviewed for HVDC transmission systems, dc rail transit systems, and cathodic protection systems since they represent the preponderance of interference sources. Even though it may appear that these sources are quite different, it will be found that a substantial similarity exists relative to interference effects upon buried structures located within their influence. Likewise, mitigation approaches applied for each of these sources are quite similar.

Based upon this observation, not all possible interference sources, e.g., mining operations, have been explicitly reviewed. However, the effects, monitoring and mitigation of such other possible interference sources closely parallel those presented for the specific systems reviewed.

6.1.1 Corrosion Mechanisms

6.1.1.1 Galvanic Corrosion

Corrosion is a natural occurring electrochemical process existing in nature, wherein a material deteriorates as a result of its reaction to its environment. The term can be applied to many materials, but in this section metal corrosion is primarily considered. Most metals exist in their native state as an ore, that is, impure. In order to be used the metal is extracted, refined and alloyed, and thus is put into a relatively pure state. Corrosion is basically the return of the metal to its native state, generally by the formation of oxides.

A metal will corrode if it is physically in contact with an electrically conducting electrolyte which is ionized. For example, in the case of underground iron/steel structures considered here, in the usually present soil moisture, the water molecules (H_2O) are broken down into positively charged hydrogen ions ($H+$) and negatively charged hydroxyl ions ($OH-$). Due to inhomogeneities in the metal, certain areas on the metal surface will exhibit a more negative electrical contact potential to the electrolyte (anodes), and others will be less negative (cathodes). Because of the potential difference, a current will flow in the soil from the anode to the cathode (ionic conduction), and to complete the circuit, from the cathode to the anode within the metal (electron flow).

The chemical reactions involved with this current flow are diagrammed in Figure 6.1. In particular,

- At the anode, with the electrons flowing in the metal towards the cathode, positively charged iron atoms remain which at the metal interface combine with the negatively charged hydroxyl ions to form ferrous hydroxide [$Fe(OH)_2$]. In time, with additional chemical reactions, hydroxide [$Fe2(OH)_3$] which is common rust will be formed.
- At the cathode, the negatively charged electrons arriving from the anode will combine at the metal soil interface with the positively charged hydrogen ions to form hydrogen gas (H_2).
- When the hydrogen ions are converted to hydrogen gas at the cathode, a surplus of hydroxyl ions may exist at the anode which increases the alkalinity in these regions.

In summary the metal corrodes or rusts, i.e., is consumed where current enters the electrolyte (soil). The regions receiving current do not corrode except for certain amphoteric metals such as aluminum or lead which will corrode if the received current is excessive. For iron the consumption rate is approximately 20 pounds per year for one ampere of dc current flow. Other metals are consumed at different rates as shown in the Table contained in Section 6.2.3.1.

The discussion has considered the self corrosion of a single metal. If two dissimilar metals are electrically coupled together so that current can flow between them and they are both immersed in an electrolyte, corrosion of one of the metals will occur. This is due to a potential difference that normally will exist between them. The magnitude of this potential and which of the metals will corrode will be dependent upon their relative position in what is known as the electromotive force series. This emf series characterizes the natural potential a metal assumes when immersed in an electrolyte consisting of its own salts. Typical metal potentials measured in neutral soils with respect to a copper-copper sulfate reference cell are given in Table 6.1. Figure 6.2 illustrates the details of a typical cell.

Table 6.1
Typical Metal Interface Potentials in Soils

Metal	Potential volts
Magnesium alloy	-1.75
Zinc	-1.1
Aluminum alloy	-1.05
Mild steel	-0.2 to -0.8
Lead	-0.5
Copper, brass	-0.2

When coupled together the more negative potential metal (anode) will discharge current to the less negative metal (cathode), thus causing the anodic metal to corrode. The combination of an anode and a cathode gives rise to what is commonly called a corrosion cell.

Cathode

$$4H^{+} + O_2 + 4e^{-} \rightarrow 2H_2O$$

$$2H^{+} + 2e^{-} \rightarrow H_2$$

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$$

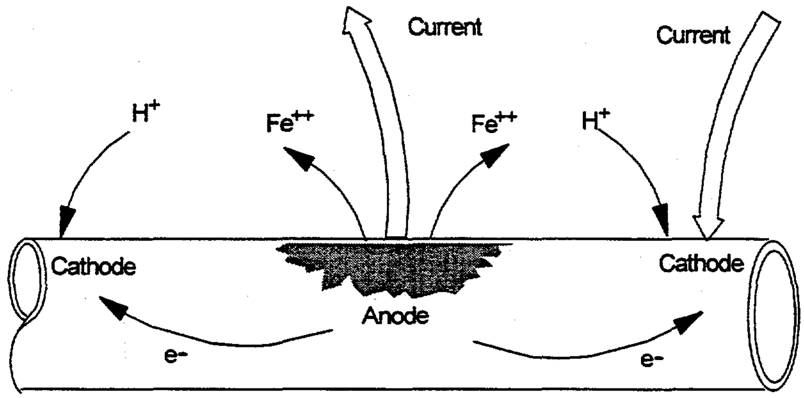
Electrolyte

$$Fe^{++} + 2OH^{-} \rightarrow Fe(OH)_2$$

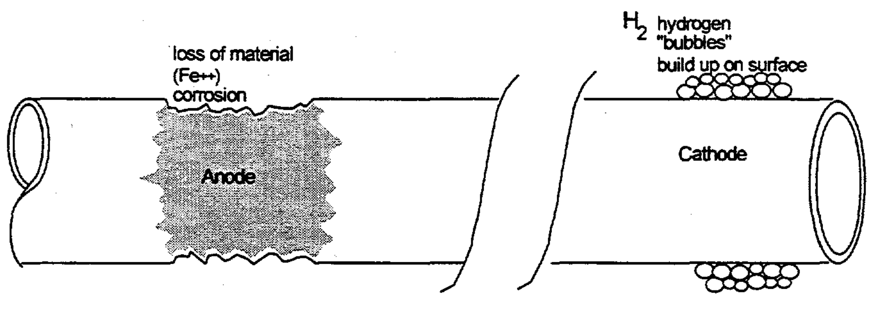
$$2Fe(OH)_2 + H_2O + \tfrac{1}{2}O_2 \rightarrow 2Fe(OH)_3$$

Anode

$$Fe \rightarrow Fe^{++} + 2e^{-}$$

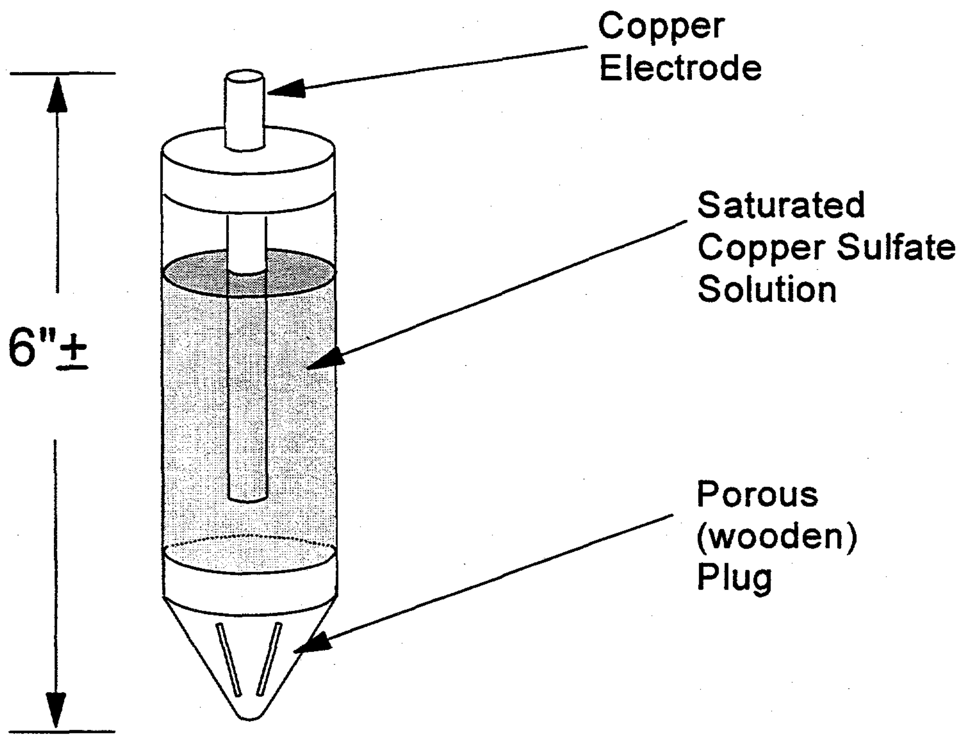


a) current flow causes electrolytic action

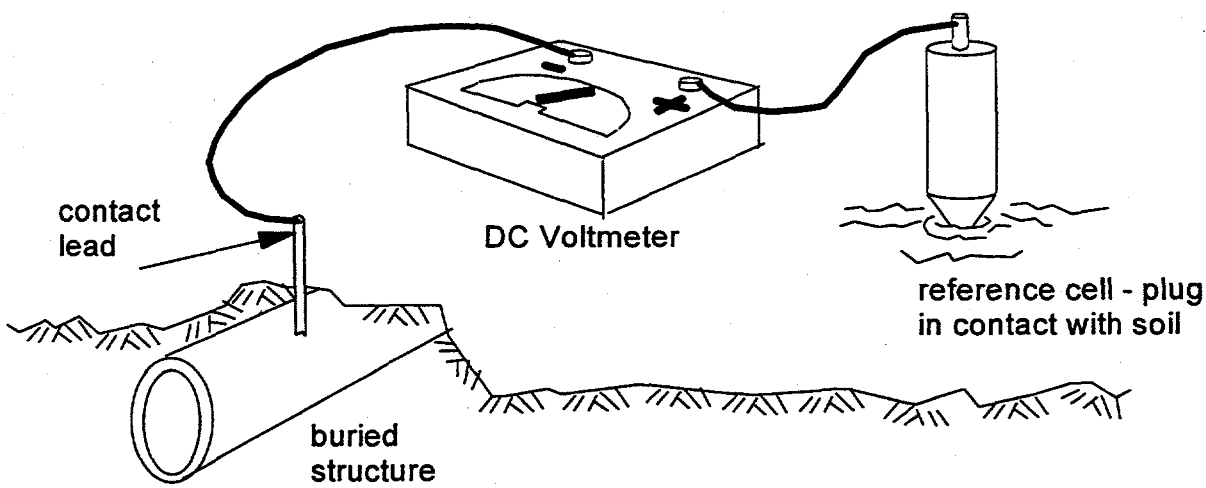


b) Resulting corrosion and polarization

Figure 6.1 - Basic Corrosion Mechanism



a) Cell Detail



b) Structure-to-soil potential measurement

Figure 6.2 - Reference Cell Measurement

6.1.1.2 Polarization

The corrosion rate of the metal is proportional to the current leaving the surface which in turn is inversely dependent upon the resistance of the electrical circuit in the corrosion cell. This resistance is made up of ohmic resistances such as the resistance of the metallic path between the anode and the cathode, the external resistance through the electrolyte, and the resistance of any coatings or corrosion products built up on the metal surface. The hydrogen film built up on the surface of the cathode may be considered as an insulating layer which also adds resistance to the circuit. This film is called a polarization film and as it builds up upon the cathode surface, it limits the flow of current because of the voltage drop developed across it. The polarity of this (polarization) potential is opposite to that of the net driving potential between the anodic and cathode which caused the current to flow initially. As the film thickness increases, the net circuit (corrosion) current becomes essentially zero, and it is stated that the cathode has been polarized to the open circuit potential of the anode.

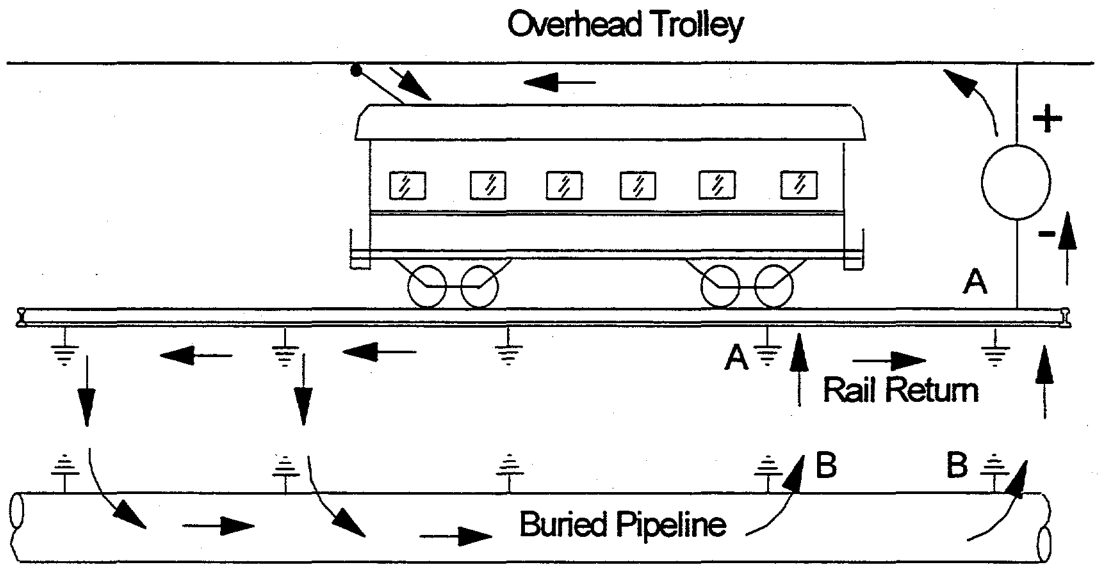
6.1.1.3 Stray Current Corrosion

It has shown that corrosion is a chemical process involving the flow of electrical current from the surface of the metal into the electrolyte caused by galvanic potential differences. Similarly, corrosion can be initiated by other factors such as an electrical current induced into the structure, flowing along the structure, and then leaving the structure and discharging into the electrolyte. As in the galvanic situation, corrosion also occurs at the location of current discharge into the electrolyte. The externally induced current may be caused by either of two mechanisms.

The first mechanism is direct (stray) current conduction through the electrolyte to the affected structure. A typical example of this type of current coupling could be the case of an extended structure, such as a buried pipeline, paralleling a dc rapid transit system rail carrying the return current to the local substation as shown in Figure 6.3. If the alternative current return path through the pipeline offers a lower or comparable resistance, current could leave the rail at the location of the traction motor, enter the pipeline through the common electrolyte (soil), flow along on the pipe to some point in the vicinity of the local substation and return back to the transit rail.

The second coupling mechanism results from the potential gradient developed in the electrolyte (soil) when current discharges through an earthed electrode such as in the case of a dc transmission system. Referring to Figure 6.4, if an extended structure such as a buried pipeline is situated in the electrode gradient, a portion of the current flowing through the electrolyte is transferred unto the pipeline. That is, the component of the electric field that is parallel to the pipeline drives a current unto the pipe at the location closest to the dc electrode. The induced current flows from that location along the pipe in both directions and eventually leaves the structure at more distant locations. Again, corrosion will occur in the regions of current discharge.

This latter mechanism is of principal concern in this report. However, the former is also addressed for completeness in that monitoring and mitigation techniques developed for this interference mode will also have applicability to the reduction and elimination of interference experienced by structures from dc transmission lines utilizing ground return electrodes.



Stray current interference of dc railway with buried pipeline illustrated. Bonding between points A and B is required to reduce corrosion problems at current drainage point.

Figure 6.3 - Typical Transit System Interference

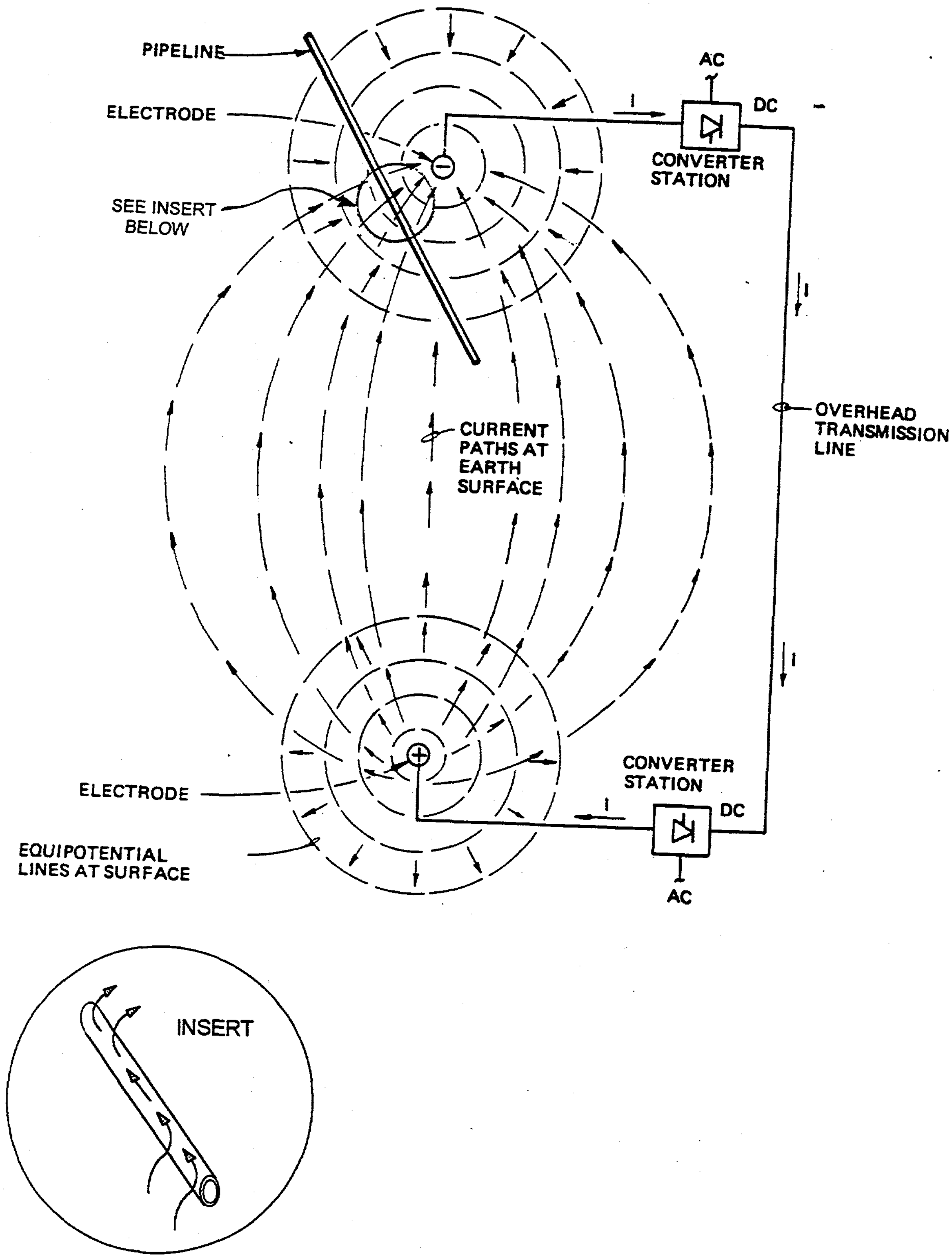


Figure 6.4 - Interference mechanism of DC line on Buried Pipeline
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HVDC Ground Electrode Design. Reprinted with Permission

6.1.1.4 Cathodic Protection

Both galvanic and stray current caused corrosion are the result of current entering the electrolyte at the anodic regions existing on the structure. At the cathodic regions where current flows unto the structure from the electrolyte corrosion does not occur. Hence, it appears logical to accept that if all the exposed surface area were made to collect current, corrosion of the structure would be essentially eliminated. Cathodic protection is a means by which this condition is forced. Direct current from an external source is made to flow unto the structure until all of the surface area is collecting current, thus becoming cathodic and overpowering the current discharge of the previously anodic areas. To accomplish this the driving potential of the cathodic protection system must be adjusted to be greater than that of the corrosion cells being suppressed.

The cathodic protection system may consist of either buried galvanic anodes, e.g., magnesium or zinc, connected to the structure or an impressed dc current source, e.g., a rectifier whose negative lead (often called the negative drain) is attached to the structure and whose positive terminal is connected to a ground bed. Cathodic protection is one of the principal techniques for the mitigation of dc current interference. However, as discussed later, cathodic protection systems can themselves be sources of interference if designed and implemented improperly.

6.1.2 Affected Structures

HVDC transmission lines injecting current into the soil through their ground electrode(s) are a source of stray current interference. Any buried electrically conducted structure can be affected by stray current with the current entering and exiting at one or more locations. Typical structures which may be affected are,

- Telecommunication and CATV cables
- Coaxial and fiber optic cables
- Concentric cable neutrals
- Structure reinforcing bars
- Metallic support hardware
- Grounding systems
- Power system tower footings
- Water, sewer, or communication systems
- Buried pipelines

6.2 INTERFERENCE CURRENT SOURCES

6.2.1 Collocated DC Transmission Lines

In this section a review of the interference problems which may be caused by dc transmission lines. The coupling to and the corrosion mechanisms affecting nearby underground systems and objects is reviewed. Monitoring and mitigation methods relative to dc transmission line caused stray currents are discussed in Sections 6.3 and 6.4, respectively.

6.2.1.1 Overview

HVDC transmission lines are a cause of ground current injection when operated in the monopolar or unbalanced bipolar modes. Monopolar mode transmission lines inject the total load current into the ground electrode one hundred per cent of the time. Bipolar transmission lines inject only the instantaneous unbalanced component of the load current into the ground one hundred per cent of the time, but inject the load current into the soil for only short periods when the line is operated in a monopolar fashion during emergencies. Disruptive effects to equipments are generally proportional to the instantaneous injected current. However, corrosion effects are proportional to the time integration of the injected current. For example, corrosion of a steel structure progresses at the rate of 20 pounds metal loss per amp-year of interference current leaving the structure, i.e., one amp of current for ten years is equivalent to ten amps of current for one year.

The ground injected load current causes a ground potential rise at the electrode. That is, the current causes a voltage drop in the earth from the electrode to remote earth. An opposite polarity voltage variation exists at the other electrode. The potential gradient at any location is the summation of the voltage variations from each of the electrodes. In the vicinity of the electrodes, the shape of the equipotential lines is electrode geometry dependent. As the radial distance from an electrode increases, for example, exceeding twenty to thirty times the largest electrode dimension, the equipotential lines would be circular if the earth were homogeneous both radially and with depth. See Figure 1.2 in Section 1.0. In this case the potential and its gradient, i.e., the electric field, at a location could be easily and relatively accurately calculated. However, the earth is highly non homogeneous with soil conductivity variations in both the horizontal and vertical directions. For example, soil variations occur horizontally, and the earth is multi-layered vertically, i.e., with an outer and inner crust, a mantle and outer and inner cores, each having its own range of conductivity. For relatively close electrodes on the order of a few tens of kilometers separation, the radial flow of current between the electrodes will be heavily influenced by soil conductivity changes in the near surface and upper crust regions. In contrast for widely spaced electrodes on the order of several thousand kilometers, the current flow will tend to seek the more highly conductive regions of the earth's mantle and outer core regions. Hence, due to the inhomogeneity of the soil and the preferred path variability, the calculation of the potential gradient, i.e., the electric field at a particular near surface location is usually difficult and relatively inaccurate. Therefore, resort must usually be made to direct measurement for obtaining a reasonably accurate characterization of the electric field existing at a structure.

The spatial electric field developed as a result of the flow of current into the system electrodes, and therefore, into the earth is an important factor in determining the disruptive and corrosive effects to an object or structure attributable to the collocated dc transmission line. The extent of such effects is dependent upon the magnitude and direction of the electric field at the location of each collocated buried facility. Affected facilities and systems can include telecommunication and CATV cable, electric power transmission facilities such as cables, tower footings, and transformers, buried pipelines, and railroad tracks and signaling and communication systems.

6.2.1.2 Electric Field Coupling

Disruptive and corrosive effects upon buried objects and structures are a consequence of their lying within the electric field produced by the electrode current passing through the earth. At any location the electric field is equal to the product of the current density (amperes/meter^2) flowing past that point and the medium's resistivity (ohm-meters). The resistivity is the reciprocal of the medium's conductivity. For example, if a small isolated metallic object is placed within the field, the current density induced upon the surface of the object is approximately three times that of the current density flowing externally through the electrolyte. This is a consequence of the concentration of the electric field at the object causing the effective cross-sectional capture area of the object to be somewhat larger than its actual physical area. Current will enter one side of the object and leave off the other side, thus producing an anodic region causing corrosion of the metal.

For extended conducting objects such as pipelines, cable metallic sheaths, etc., coupling to the structure is effected by the component of the electric field parallel to the structure. If the structure changes direction, the effective electric field coupling component will likewise change direction. The parallel or longitudinal component of the field along the structure will cause current flow along the structure with current entering the structure at one or more locations and eventually leaving to return to remote earth at other locations. For complicated structure geometry or where a number of structures are electrically connected, there may be multiple points of current entry and discharge. Each point of current discharge is a candidate location for corrosion on the structure. On long structures traversing the electric field for extensive distances, the current flowing upon the structure will be proportional to the incident electric field. Portions of the structure will be cathodic with others anodic. For example, a pipeline traversing an anodic electrode field, i.e., the electrode is injecting current into the soil, will be cathodic for a region about the closest point of approach to the electrode. At greater distances along the pipeline in either direction from the closest point of approach the pipe will be anodic.

In general, dc currents may be coupled unto a variety of objects such as grounding electrode systems, steel reinforcing bars, etc. As an example of coupling, cable shields are normally grounded at multiple locations. If a dc gradient exists between grounding points, current will be picked up and will flow along the cable shield. When the current find a low resistance return path it will leave the cable shield resulting in an anodic condition at that location. By the same mechanism, stray dc current can also be coupled into electric power transmission and distribution systems. Ground rods and grids, bare concentric cable neutrals, pipe type cables and other metallic conductors and support hardware associated with the power system are subject to the pickup and eventual discharge of stray dc currents. Figure 6.5 illustrates a hypothetical situation of current pickup and discharge from transformer grounded Y-connections.

6.2.1.3 Corrosion and Disruptive Effects

At the locations of current pickup, the structure or object's potential with respect to local earth is generally shifted more negative resulting in a possibly detrimental environment. For example, if a lead sheathed cable potential is made more negative than 1500 mV with respect to a Copper / Copper-Sulfate reference electrode, the alkalinity generated at the surface may be sufficient to cause the sheath to dissolve. The aluminum outer conductor of coaxial cables can suffer dissolution in the alkaline environment caused by highly negative structure to soil potentials. Buried optical fiber cables can experience high transmission losses due to the migration of hydrogen into the cable; the hydrogen being formed at the cable surface by the cathodic reaction occurring at locations of dc current pickup. For submarine fiber optic cables lying in deep water the partial pressure of the hydrogen in the cable increases to the level where the signal loss becomes excessive rendering the cable useless. The negative shift in a pipeline's potential at the point of current pickup, if excessive, can cause hydrogen embrittlement in high strength steels. Disbonding of the pipe coating at these points can also occur due to hydrogen evolution at the surface of the pipe.

Stray dc current picked up by the grounding systems and neutral conductors of electric power transmission and distribution systems can cause saturation of the systems' transformers. The dc flowing through the transformer windings can distort the normal magnetic flux in the core causing harmonic generation, excessive magnetizing currents, and overheating. In regions where the earth surface potential gradient due to the electrode current is large, dc current pickup may occur at local power system towers and carried on overhead grounded shield wires to more distant towers where current discharge will occur.

Under adverse situations such as close proximity to the dc electrode, the possibility of disruption to railroad signaling devices exists. Generally, the effect is mitigated due to sectionalization of the railroad track which limits the current pickup, and the fact that dc signaling systems employing relays require significant current flow for energization. More recent and advanced signaling systems are ac operated, and therefore, have a relatively high level of immunity to dc stray currents.

Corrosion of buried or underwater structures in contact with an electrolyte, e.g., soil or water, will occur at the locations of current discharge. For steel structures the loss of metal is approximately 20 pounds per ampere-year of current discharge. This loss is particularly serious for coated structures such as pipelines due to the current discharge being concentrated at small imperfections in the coating, as illustrated in Figure 6.6, thus leading to a rapid thinning of the metal. That is, the small area of the opening to the electrolyte, leads to a high current density discharge at the metal surface. Structures situated in the dc electrode's gradient which may corrode due to current discharge can include, but not necessarily be limited to,

- Telecommunication and CATV cables
- Coaxial and fiber optic cables
- Concentric cable neutrals
- Steel reinforcing bars
- Metallic support hardware
- Grounding systems
- Power system tower footings
- Water, sewer, or communications systems
- Buried pipelines

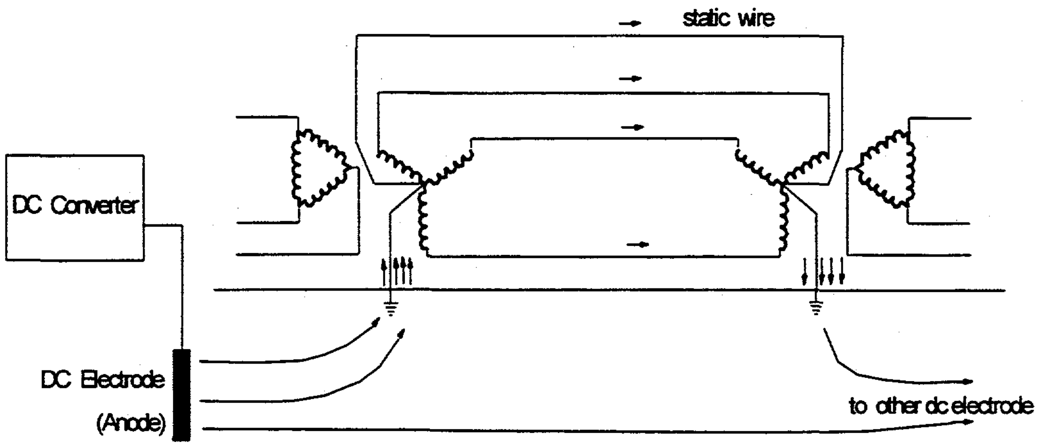


Figure 6.5 - Illustration of power system Interference

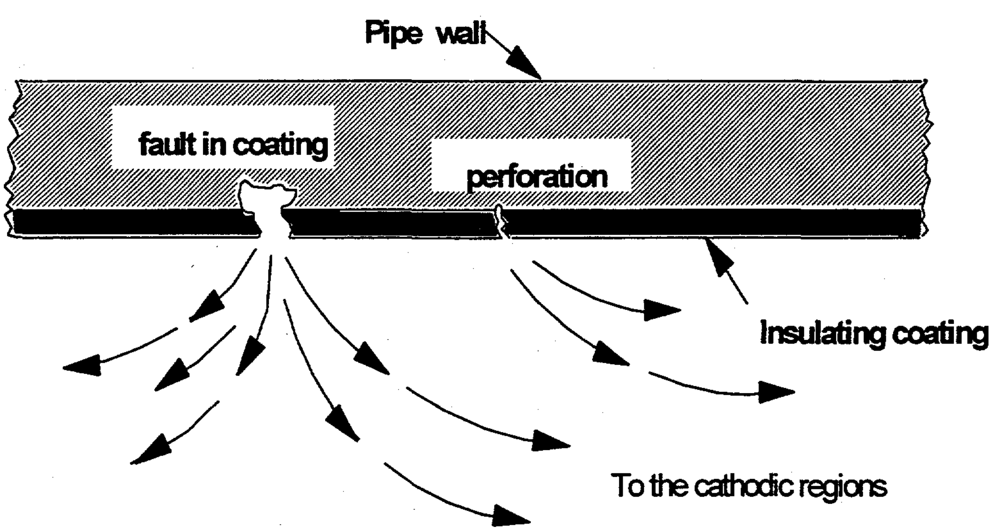


Figure 6.6 - Corrosion at Coating Imperfections

6.2.2 Geomagnetically Induced Currents

Geomagnetically induced earth currents are also known as tellurics. These currents are a consequence of a sun emitted solar wind consisting of a rarefied plasma of protons and electrons interacting with the earth's magnetic field. Three types of solar phenomena, i.e., solar flares, coronal holes, and disappearing filaments can cause fluctuations in the solar wind. The fluctuations interacting with the earth's magnetic field cause auroral currents or electrojets which, in turn, cause a time variation in the strength of the field. These time variations in the magnetic field result in earth surface currents which can cause interference in the operation of various systems that are either buried in the earth such as pipelines or coupled to through associated grounding systems to such facilities as electric power transmission and distribution systems.

6.2.2.1 Overview

Magnetic field variations caused by the auroral currents are usually called magnetic storms. During the magnetic storm period, the induced currents cause earth surface potentials (ESP) to be generated which can reach values up to 10 V/km or more depending upon storm severity and the earth's conductivity. Typical induction mechanisms are illustrated in Figure 6.7. For example, considering buried pipeline networks, ESP can induce currents in the pipelines in much the same manner as the potential gradients from a dc transmission system electrode. Although telluric currents can increase the likelihood of corrosion in pipelines, the most serious effect is that monitoring methods relating to cathodic protection are upset and in some instances rendered unusable. As for HVDC transmission line coupling, electric power system interference enters through the grounding electrodes. The currents induced into the power system are effectively quasi-direct currents which can cause severe disturbances in the system operation, especially when flowing through transformer windings.

Telluric currents vary in frequency from approximately 2.5 MHz to 100 MHz. The corresponding oscillatory periods are 400 sec. to 10 sec. These oscillations undergo intensity amplitude modulation ranging from a fraction of an hour to eleven years, i.e., the sunspot cycle. For the longer period components it is many times assumed that the effects of this natural interference on systems is similar to that observed in response to potential gradients produced by dc transmission system electrode currents. In estimating the impact of dc transmission lines upon collocated facilities, parallels have been drawn in a number of studies between the effects of the naturally occurring telluric currents and the interference levels caused by dc power transmission. That is, if estimated effects due to dc transmission line stray currents are less than or equal to that imposed by the natural telluric currents, it is assumed that the dc power line interference levels are acceptable.

Several analytical approaches have been used to calculate the earth surface potential. None of the approaches are exact. Each is based upon invoking certain approximations such as, for example, assuming that the earth is homogenous with a constant conductivity. One approach to modeling the auroral electrojet is to assume it is a line current source flowing from east to west at altitude of about 120 km above the earth's surface. Another analytical model used is to assume the magnetic field source to be a propagating vertically downward plane wave with the magnetic field lying horizontally in the east-west direction and the electric field horizontal and perpendicular to the magnetic field. Each model has its limitations in modeling the auroral source realistically. In general, the plane wave model gives as an upper bound solution for the geomagnetically induced ESP. The line current source assumption results in a lower bound solution. Calculated ESP levels are in the range of approximately 10 V/km and 1 V/km for the respective models. These values are within the ranges measured in practice in the east-west direction. Calculated ESP values in the north-south direction are somewhat lower, i.e., on the order of eighty per cent of the east-west values.

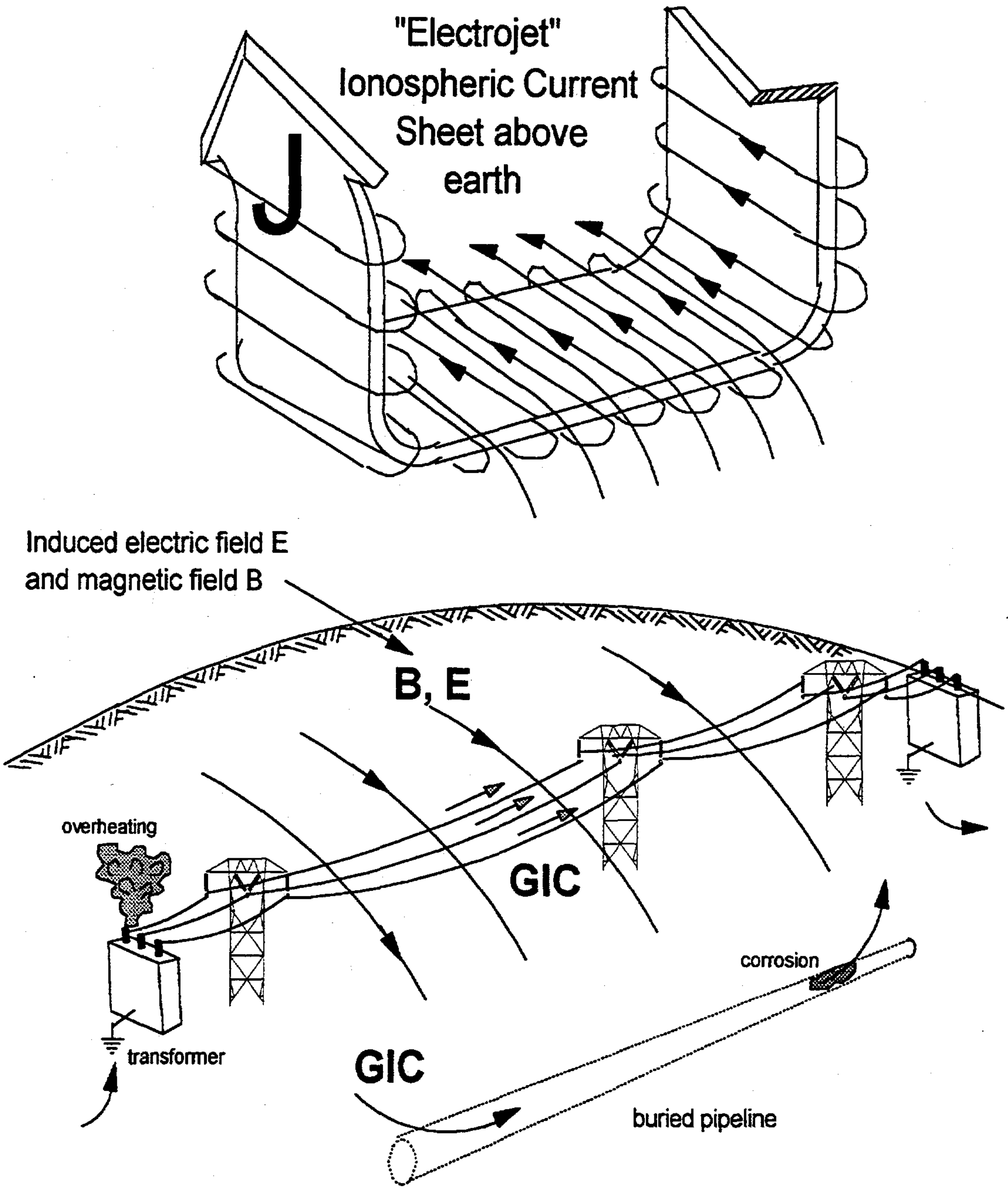


Figure 6.7 - Geomagnetic Induced Currents (GIC) flow in power lines, causing transformer saturation and overheating, flow pipelines causing corrosion, and interfere with communications (not shown).

To obtain a comparison between the naturally caused ESP and the potential gradient produced by a dc transmission system electrode, it may be noted that for a 2000 amp dc current flowing in 100 ohm-meter resistivity soil, the potential gradient at 1.78 km from the electrode is equal to 10 V/km. That is, voltage gradients produced by dc transmission electrodes are typically less in magnitude than those naturally occurring in nature. However, the differences in their respective durations can affect the nature and severity of the effects produced on buried facilities.

6.2.2.2 Telluric Current Coupling to Electric Power Systems

As for HVDC transmission lines, coupling to extended facilities such as cables, and pipelines is determined by the electric field components parallel to the system metallic conductor(s). For an electric power system, geomagnetically induced telluric currents are coupled into the system by the ESP difference existing between system grounding points. For a given value of ESP, the current flowing into the system is determined by system topology and component impedance. Using available electric network theory, coupled current levels into most facilities can be calculated by straightforward, but not necessarily simple numerical methods.

For example, modeling of the electric power system to determine the induced currents requires modeling of the overhead conductors including the static wires and their earth return path, and the tower grounding system. The section of overhead conductors between any two adjacent towers is modeled as one component, while each tower with its grounding electrode(s) is modeled as a second component. Each of the components is modeled by an equivalent and frequency dependent admittance matrix and equivalent current sources. A Norton equivalent circuit is constructed by transforming the differential voltage and current equations for each overhead conductor section into a set of decoupled equations. A specific analytical solution is computed for the decoupled equation set by using the voltages and currents at the line ends as boundary conditions. A tower model is developed where the admittance of the tower and the grounding system at any frequency is computed from the tower step voltage response.

The final model combines the equivalent circuits of each conductor section and the associated tower grounding systems, and the substation grounding and transformer winding resistances. The calculated system induced currents are found to be a function of the primary field ESP, and the neutral system, transformer and transmission line resistances. For typical geomagnetic storm conditions, induced voltage levels are system component and configuration dependent. However, typical calculated induced current levels may range from tens to several hundreds of amps in earthing and transmission line conductors. For example, currents of over 100 A have been measured in transformer neutral leads.

6.2.2.3 Corrosion and Disruptive Effects

Electric Power Systems

Due to the geomagnetically induced system currents being sporadic and temporary in nature, corrosion which is a relatively long term process is of secondary importance in power systems. Disruptive effects to the system are, however, of prime importance and consideration.

Almost all of the power system equipment, operation, and protection problems resulting from the induced currents are due to two effects. These are the half-cycle saturation of power transformers and the half-cycle saturation of current transformers used with protective relay systems. Of the two, the former is far more serious. During normal transformer operation, there is a nearly linear relationship between the input and output voltages and currents. However, in the presence of dc or near dc current, the magnetic circuit of the transformer steel core is biased in such a way that extremely nonlinear operation or saturation occurs during one half of the ac cycle.

This half cycle saturation leads to the following problems.

- A transformer suffers high values of exciting current with overheating and increased winding losses.
- The transformer generates harmonics which can overload capacitor banks and cause misoperation of protective relays.
- A large increase in inductive reactive power is drawn by the transformer.
- Stray flux leakage effects occur which can result in localized heating of the transformer.

The increased reactive power requirements stress the voltage regulation capabilities of the power system. The generated harmonic currents upset relay and protective systems .The consequence of these incurred problems is that unstable system operation may occur, possibly causing the tripping of key lines, which in the extreme case may lead to shut down of the power transmission system as occurred in Quebec in March 1989.

Buried Pipelines

Telluric currents are of concern to pipeline engineers because of the possibility of their contributing to corrosion of the pipeline. Their very low frequency of oscillation makes them appear essentially as a dc current source except for the eventual current direction for fifty per cent of the time. They may also affect electronic equipment connected to the pipeline, and, of course, make cathodic protection level monitoring and measurement difficult and sometimes impossible. Most researchers appear to have the belief that their contribution to corrosion is small. However, it has been more recently reported (Martin, 1993) in a pipeline measurement program using buried electrical resistance corrosion measurement probes that the inability of the existing cathodic protection system to fully respond to the time varying telluric currents resulted in a significant rate of corrosion remaining on the pipeline. For example, a corrosion rate of 38 micrometers per year was reported at one location which would lead to a ten per cent loss in pipe wall thickness in 14 years.

The induction of telluric currents into an extended conductor such as a pipeline is proportional to the solar storm generated electric field component parallel to the pipe. In areas near a coastline, due to the abrupt change in conductivity between the sea and the land, charge accumulation will occur on the coastline land mass in order to satisfy the equation of electrical continuity for current flow across the land-sea boundary. This can give rise to conducted current flow to a pipeline near the coastline in addition to the induction current produced by the parallel electric field component.

For given excitation sources, the induced current flow in a pipeline segment can be calculated exactly using a variation of the computational methods developed by the electric power industry for determining induction levels into their system. Unfortunately, the pipeline community, in general, has not taken advantage of such methods in evaluating the effects of telluric currents upon their pipeline systems, and for developing monitoring and mitigative measures. Their approach to evaluating effects and instituting corrective measures has been largely empirical. Education of the pipeline community to include such additional resources such as computer modeling and simulation into their mitigation application procedures could lead to the inclusion of more effective measures.

Two approaches can be taken to estimate the level of corrosion caused by the telluric currents. The first is to monitor the pipe-to-soil dc protection potential which is nominally held in the vicinity of 0.85 volts negative with respect to the electrolyte, e.g., the local soil. If the telluric current drives the pipe more positive, it can be assumed that some level of corrosion is being introduced. The second approach is to calculate the current leaving the pipe and estimating the current density at a "typical" holiday. The first method is quite definitive. The second is more difficult to assess since the size of a "typical" holiday is generally unknown. External coupons, i.e., a small piece, usually a few square inches in size, of bare metal with the same metallurgical characteristics as the pipe steel connected to the pipe whose current is monitored can yield some measure of the possible current density at the pipe coating imperfections. The problem here is that the relative size of the coating imperfections to the external test coupon is unknown.

For a pipeline section insulated from the remainder of the pipeline by electrical insulators at each end and lying in an external electric field parallel to the pipe, the telluric current will enter at one end and leave at the other. The entering current will force the pipe-to-soil potential more negative while at the opposite end the current leaving the pipe will produce an anodic condition causing the pipe voltage to become more positive. If a long pipeline is segmented by electrical insulators, these same characteristics are typical of each segment. For short insulated sections, e.g., on the order of 10 km or less, the pipeline voltage shift at the end terminals will be equal to $\pm E*L/2$, where E is the parallel incident geomagnetically induced electric field, and L is the length of the pipe section. For long length sections, i.e., on the order of 100 km or larger, the terminal voltage shifts will be equal to $\pm E/\gamma$ where γ is the dc propagation constant of the pipeline. For the usual range of pipeline propagation constants, the voltage shift may range from volts to tens of volts. These ranges of voltage shift are approximate since polarization effects have not been considered.

6.2.3 Stray Current Interference

Stray current interference can originate from a number of sources. For example, dc transit systems, mining operations, and cathodic protection systems may be sources of interference. In general, measures to reduce or eliminate stray current effects are similar and relatively independent of the source of the current. Hence, discussions of mitigative measures in the following sections will have considerable similarities independent of the source type or characteristics.

The following two sections review dc interference to underground structures from two of the most common sources, namely, rail transit systems and cathodic protection systems.

6.2.3.1 Rail Transit Systems

Stray currents from dc transit systems have been encountered since the turn of the century. One of the basic problems is that the transit systems are operational in high density urban areas, both in population and in other utility presence. Stray current interference originates from the common use of the running rails for the negative traction current return to the substation. Originally common practice dictated that the rails be solidly grounded. Due to the resistance in the rails, a voltage drop is developed in the rails as soon as the train motor is energized. This voltage existing along the rails causes a potential gradient in the earth which causes current to be conducted to any parallel electrical conductor. This conducted current is stray interference, and the mechanism for introducing it into other conductors/systems is not unlike that which occurs for conductors under the influence of dc transmission line electrode currents.

In an attempt to reduce stray current levels, and hence interference, newer transit systems were built with the running rails reasonably well insulated from earth. This practice reduced stray interference problems considerably. However, depending upon the level of the isolation between the rails and earth, a potential difference existed between the transit vehicle and the earth which could be a hazard to passengers. In order to limit this potential to a safe value, the rectifier negative lead is grounded to earth through a diode which conducts when the potential between the rectifier negative bus and the station structure reaches a preset safe threshold value.

In order to limit stray current interference still further, the more recent transit systems have the running rails extremely well isolated from earth electrically. In this system, the diode is absent and the substation rectifier negative bus and the connected rails are left electrically floating. Personnel safety is assured by designing the transit system with such parameters that under no circumstances will unsafe potentials, i.e.," the platform potential" appear between the grounded substation structures and the rectifier negative bus. Such design is computer aided and made prior to the construction of the system.

In general, transit system design has been recently directed towards electrical isolation of the complete system in order to reduce the prospects for stray current interference to collocated utilities, other systems, and structures.

Coupling to Structures and other Systems

Buried pipelines and metallic sheath cables are prime candidates for receptors of stray currents. The running rails with a high but finite resistance to earth will leak current to earth causing potential gradients in the adjoining electrolyte. A structure located in the electrolyte and within the gradient field may experience current pickup and discharge. The amount of current leakage into the earth and the resulting gradients are a function of the magnitude of the propulsion current, transit system design characteristics such as the substation spacing, location and grounding method, and the track impedance parameters. The stray current coupling mechanism to a foreign structure or system for the rail transit line is much the same as for dc transmission lines except that the transit line is generally an extended current source while the latter is essentially a point source.

Generally the presence of stray currents may be identified at the structure by observing fluctuations in the structure-to-electrolyte potentials. At the location where the current enters the structure the potential becomes more negative. At areas of current discharge, the potential is depressed, i.e., made less negative. When dynamically varying stray current is present, areas of pickup and discharge may change position along the structure and sometimes reverse. Discharge regions are usually more localized than pickup areas, and are located in the vicinity of the substation or other facilities, which are bonded to the rails or the negative bus, and carry a portion of the returning traction current.

Stray Current Effects

At the locations of stray current entry into the structure or system, the equivalent of added cathodic protection is obtained due to the increase in the negative potential. However, care must be taken to ensure that a state of overprotection does not occur, i.e., excessive hydrogen may be generated at the surface causing the local environment to become alkaline. For coated structures this can lead to disbonding and general degradation of the coating. Structural failure resulting from hydrogen embrittlement is a concern for many metals including highly stressed steel. Amphoteric metals such as aluminum and lead can incur dissolution in the resulting alkaline environment.

At the current discharge points a state of underprotection exists. Bare structures can experience corrosion over large as well as localized areas. Coated structures even though they are carrying significantly less current may exhibit large corrosion rates due to the fact that current is leaving the structure through small imperfections (holidays) in the coating, thus leading to very high local current densities. The amount of metal removed from a structure due to corrosion is dependent upon the metal, its purity and the chemical composition of the electrolyte. Approximate metal loss for common metals is given in the following table.

Table 6.2
Stray Current Metal Loss

Metal	Metal Loss per Ampere Year	
	Pounds	Kilograms
Iron, steel	20	9
Zinc	24.5	11
Magnesium	19.1	8.7
Lead	74.5	33.9
Aluminum	6.5	3
Copper	45	20.5

The typical impact of stray currents upon various utilities and structures is discussed below.

Cables. For buried bare lead sheathed cables, current pick up and discharge can occur almost anywhere depending upon the location of the stray current sources relative to the cable. The most serious situation is encountered when the pickup area is very wide resulting in a large current flowing unto the cable, and the discharge area is small. The resulting corrosion penetration rate is dependent upon the amount of current discharged, the discharge area, and the time over which the process takes place. As discussed previously, lead sheaths may undergo alkaline dissolution that can result in metal perforations. If the cable to electrolyte potential is more negative than -1.5 volts relative to a standard $Cu/CuSO_4$ reference cell, further examination and possible rectification of the situation may be necessary. Stray current corrosion can occur when the cable is connected to a central ground due to stray current picked up on other facilities connected to the same grounding point.

Pipe-type cables are high voltage power transmission cables that carry power into and within large metropolitan regions. Because of the density of utilities in these areas they may parallel dc transit rails, and hence, pick up stray current and act as alternative return paths to the system substation. The amount of current pickup is dependent upon the coating quality and the method of pipe grounding used at the power substation.

Overhead Transmission Lines. The power system overhead shield conductors are multiply grounded at generally every tower or pole. As in the case for a collocated dc transmission system stray currents can be picked up on nearby pole grounds, tower legs or other in ground hardware and discharged at remote grounding points thus leading to corrosion in these areas.

Pipelines. Parallel pipelines will also pickup stray current the amount of which is dependent upon the quality of the coating. As for cables, cathodic overprotection can occur at points of pickup with corrosion taking place at locations of current discharge. Electrically discontinuous pipe such as cast iron, ductile iron and prestressed or reinforced concrete is especially vulnerable to corrosion due to current leaving the pipe at every unbonded joint.

Other Structures. Other buried structures such as reinforced concrete foundations, caissons, retaining walls, pilings, etc. may also be subjected to stray current corrosion. Corrosion of reinforcing steel can lead to spalling and general deterioration of the concrete.

6.2.4 Cathodic Protection System Interference

Generally cathodic protection is viewed as a means for providing corrosion protection to underground structures and systems. However, where multiple closely spaced systems exist, it is possible to have mutual interference develop between systems and on facilities protected by them. Even with only a single rectifier it is possible to develop a stray current condition if a mix of protected and unprotected underground structures exist in close proximity.

6.2.4.1 Cathodic Protection Fundamentals

Corrosion is an electrochemical process which attempts to return a relatively pure metal to its native state, i.e., cause oxidation which is characteristic of rusting or corrosion. There are two basic mechanisms that contribute to the corrosion process. These are galvanic corrosion and electrolytic or stray current corrosion. Galvanic corrosion generally results from potential differences between electrically connected dissimilar metals that are immersed in a common electrolyte causing a current flow between them. However, galvanic corrosion can also occur on a single metal immersed in a conducting electrolyte due to dissimilar electrochemically related conditions existing along the surface of the metal. Electrolytic corrosion results from electrical current existing in the electrolyte from another source which enters a metallic conductor at one location, travels along the conductor and leaves at another location. Both forms of corrosion are similar in that current flow through the conducting electrolyte is involved. The region where the current leaves the metal and enters the electrolyte is called the anode and this region is the area of the metal subject to corrosion. The region where the current enters the metal from the electrolyte is called the cathode. For coated pipes, cables, etc., disbonding of the coating may occur in this region.

a)

b)

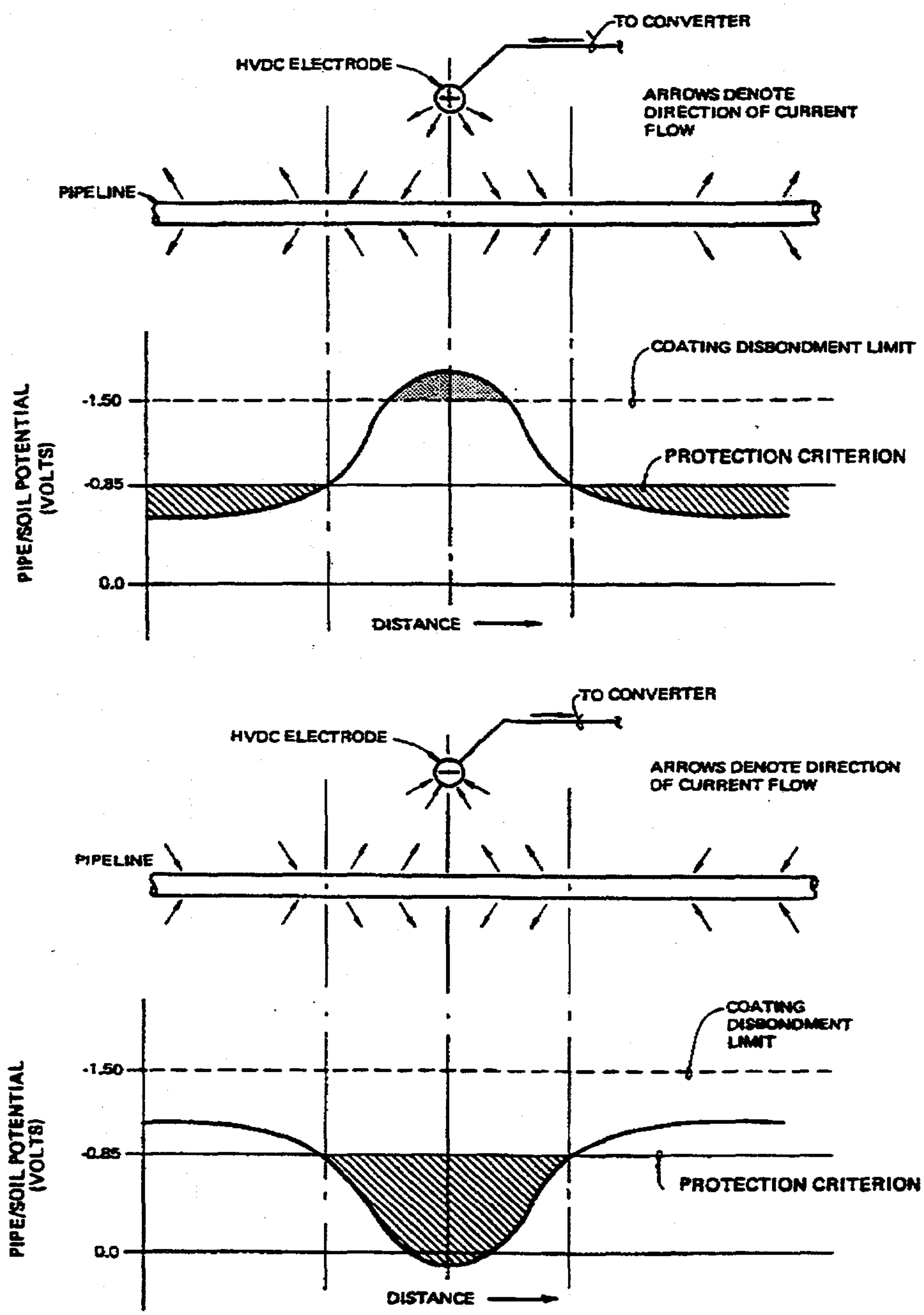
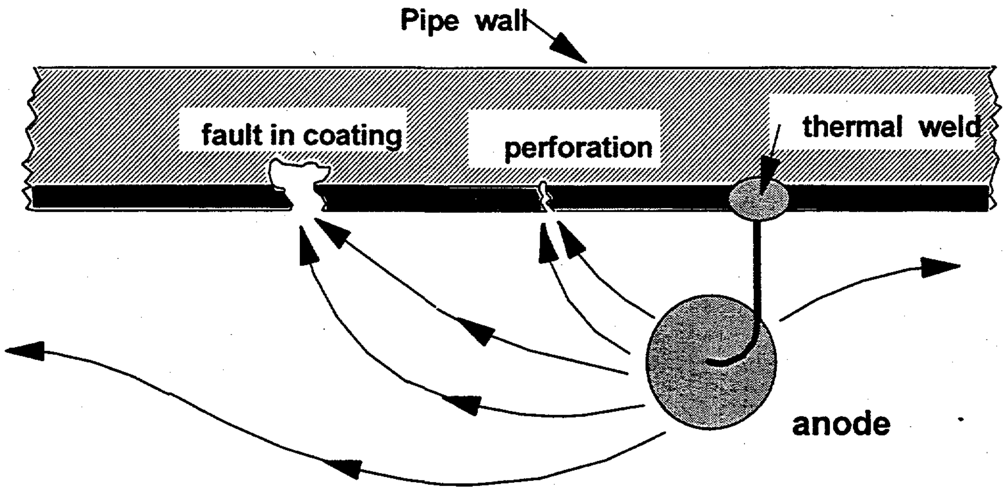
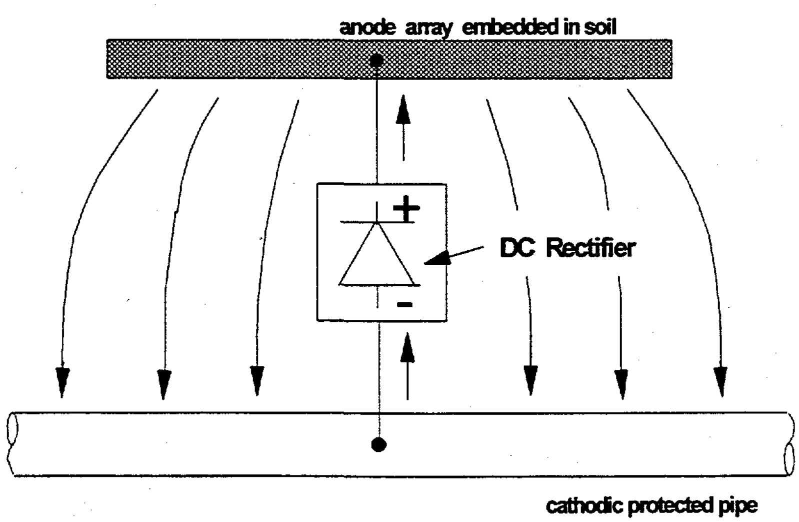


Figure 6.8 Induction Effects on Buried Pipeline
a) When HVDC Electrode is anode (positive)
b) When HVDC Electrode is cathode (negative)



a) Galvanic anodic protection



b) Impressed Current Protection

Figure 6.9 Cathodic Protection Schemes

As a practical illustration of these corrosion mechanisms, Figure 6.8 diagrams these effects for the situation where a buried pipeline traverses a HVDC electrode. In Figure 6.8a, for the electrode positive, overprotection and possible coating disbondment may occur in the cathodic region developed in the neighborhood of the electrode. Figure 6.8b diagrams the converse situation and illustrates the anodic condition developed on the pipeline in the region closest to the electrode.

Since electrical current leaving the metal constitutes a portion of the corrosion process, it follows that an externally generated dc current directed into the metal will lower the rate of corrosion by reducing the net current leaving the metal. This is the basis for the application of cathodic protection (c.p.). As shown in Figure 6.9, there are two basic methods for applying cathodic protection to a structure. In the first method, a ground bed connected to the positive terminal of an external dc power source injects the protection current into the electrolyte. The negative terminal of the dc source is connected to the protected structure. Current flow from the anodes through the electrolyte and into the surface of the structure under protection completes the circuit. A rectifier is usually used to produce the dc current. This type of protection system is known as an impressed current system. An alternative method is the use of a galvanic anode such as zinc or magnesium to provide the dc current to the protected structure. The difference in galvanic potentials between the anode and the structure drives the protection current through the electrolyte. The galvanic anodes are immersed in the electrolyte and are connected directly to the protected structure.

When the structure is unprotected the current leaving the structure at the anodic sites constitutes the corrosion process. The structure is considered protected when the cathodic protection current increases the potentials at the cathodes, i.e., polarizes the cathodes to the open circuit potentials of the anodes. When this occurs the current leaving the structure will be essentially zero.

In the case of stray current corrosion the anodic current leaving the structure will return to the source of the current. As for galvanic corrosion the effect of the applied cathodic protection current is to reduce the net anodic current to essentially zero.

6.2.4.2 C.P. System Generated Interference Mechanisms

Interference problems arise most often with the use of impressed current cathodic protection systems. This is due to the higher current output of such systems and placement of the anode ground bed farther from the protected structure in order to achieve a more uniform current distribution. Cathodic protection interference is defined as the undesired current discharge from a structure due to the cathodic protection applied to another structure. Two types of interference can be defined, that is, anodic and cathodic.

Anodic interference occurs when direct current enters the electrolyte by means of a impressed current system anode. As current flows radially away from the anode, a potential gradient is set up in the electrolyte with the region closest to the anode more positive. If a foreign structure, for example, a pipeline passes through this region, current will enter the structure in the vicinity of the anode and subsequently discharge at more distant locations. This mechanism is identical to that occurring when extended structures are in the potential gradient field of a dc power transmission line ground electrode, for example, as was shown in Figure 6.8a. Cathodic interference occurs when a poorly coated or bare structure is being protected. The protection current entering the structure lowers the electrolyte potential in the vicinity. When a foreign structure crosses and extends beyond the depressed potential region, current will discharge from that structure with resultant corrosion damage. This mechanism is illustrated in Figure 6.10.

The presence of multiple relatively closely space cathodic protection systems protecting well casings in oil production or natural gas storage fields can lead to mutual interference. In severe cases this can lead to insufficient cathodic protection at the greater depths on some wells. Another interference situation can exist when the number of field rectifiers is reduced and multiple well are protected by a single rectifier. Due to the well casings being almost always bare, the protection current requirements are high. Hence, the potential gradients at the anode bed are large. If one or more of the closest wells lie in this gradient, the vertical component of the gradient can be sufficiently large so as to produce an anodic region in the lower part of the casing. That is, even though the upper portion of the casing(s) is protected, the lower portion will experience a current reversal and actually discharge current thus resulting in corrosion damage.

6.3 INTERFERENCE MEASUREMENT AND MONITORING

6.3.1 Presently Used

6.3.1.1 DC Transmission Lines

Due to the non-homogeneity of the soil, it is difficult to model the earth's resistivity and its layering. Hence, the electric field produced by the electrode current at a given location cannot generally be calculated with a high degree of accuracy. Therefore, recourse must be made to the use of soil injected current tests to define the effects of the exciting field at a buried structure. Measured data includes initial protection levels, pipe-to-soil potential shifts, induced structure currents, and earth potential gradients. Usually agreements are reached between utility and HVDC system operators regarding the content and conduct of injected current tests. If a local electrolysis coordinating committee is available, their assistance is also requested. Current injection tests and measurements are made in three phases. The first phase consists of the initial current injection tests. The second phase consists of a commissioning test. A final check out phase completes the tests and measurements.

<u>Testing</u>

The initial current injection tests consist of the following components.

- Direct current is injected into the ground at the HVDC electrodes. Measurements of potential shifts, induced currents and potential gradients are taken. For a monopolar system, the current injected is a small fraction of the rated system current. With a bipolar system, the current injected may be as high as 25 per cent of the anticipated maximum current.

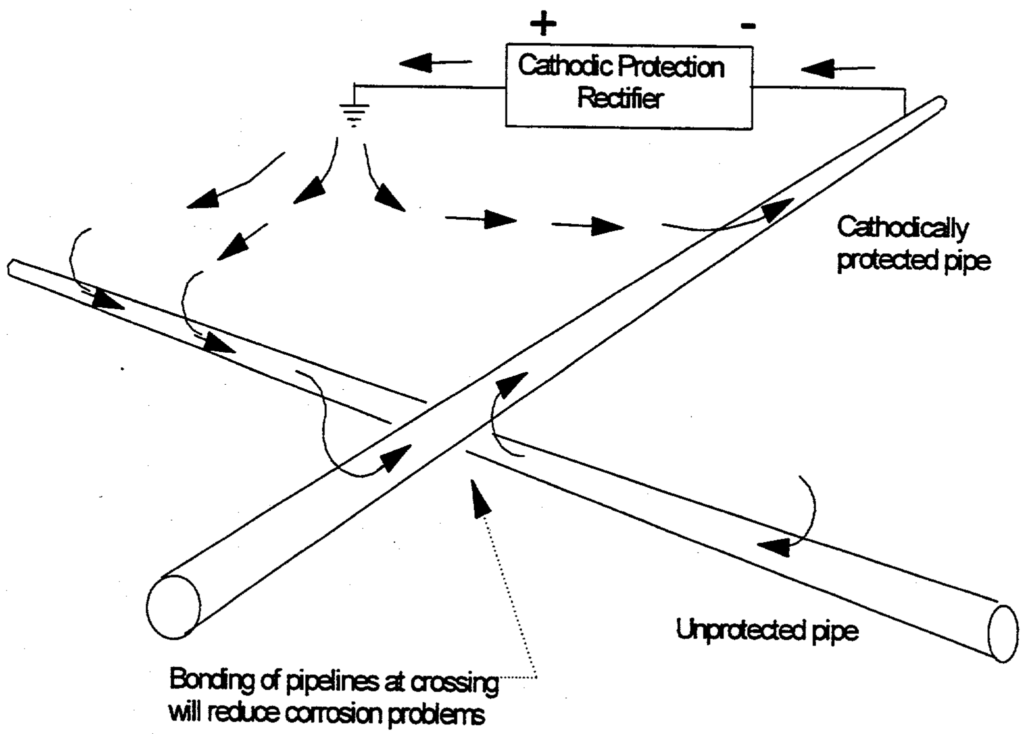


Figure 6.10 Interference caused by cathodic protection on unprotected pipeline.

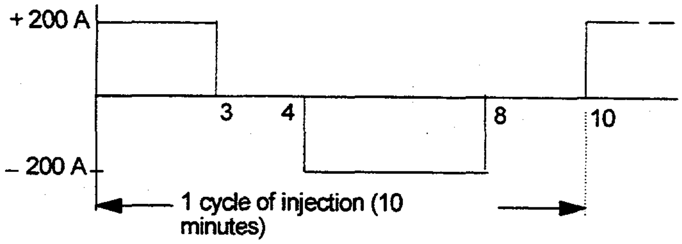
- The injection tests are repeated at designated intervals so that underground facility operators may have sufficient time to make measurements in different locations as necessary. For bipolar system testing, the tests are conducted with the polarity of the injected current periodically reversed in order to simulate effects produced by either current polarity. A typical electrode test current is shown in Figure 6.11a. The corresponding pipe-to-soil measured potential variations are diagrammed in Figure 6.11b. To allow for complete measurements on complex and extensive structures, e.g., measurements may need to be carried out over a number of days.
- Communication lines are established between the field crews making the measurements and the HVDC system operator.
- Measurements are made of the structure-to-soil potentials including potential shifts, induced current levels, and soil potential gradients.
- Data gathered is analyzed and mitigation systems are analyzed and implemented.

Post commissioning tests are made after the dc transmission system is put into operation. The same test protocol is generally used as that for the current injection tests. Data is taken to evaluate the effectiveness of the emplaced mitigation system. Any necessary changes to the system are made. The third and final check out testing is usually made some months later in order to verify the effectiveness of the modified mitigation system. The test format is similar to that used for the post commissioning tests.

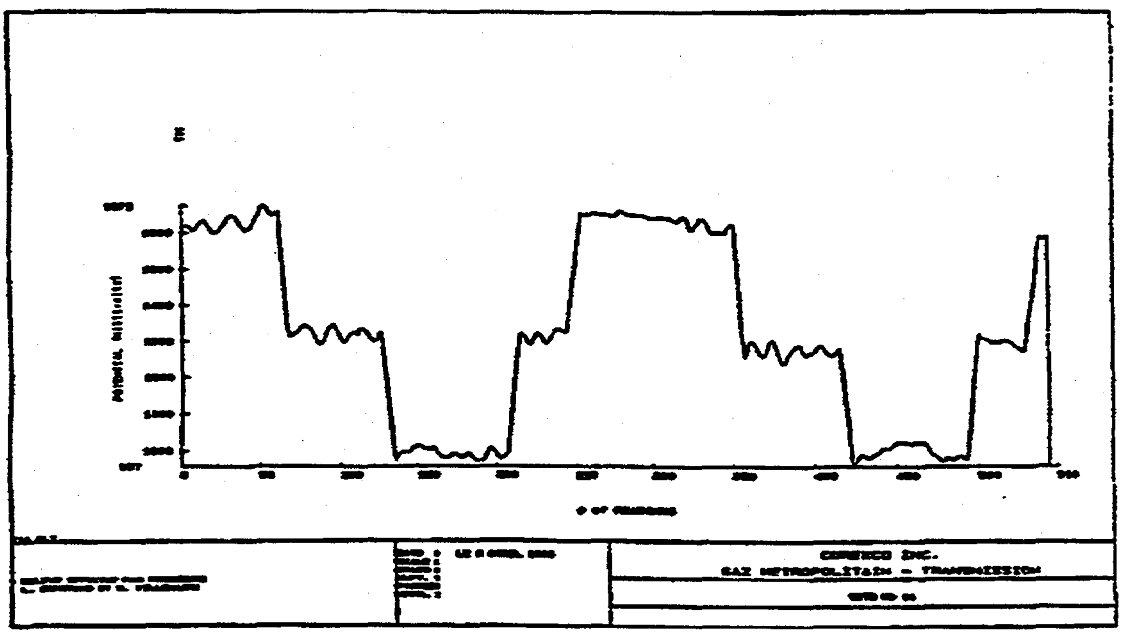
The planning of a field test involves the consideration of the following factors.

- The locations of all test stations, insulated flanges and couplings, resistance bonds, etc., are noted. Additional test stations may be installed as considered necessary.
- A sufficient number of four wire IR (voltage drop in the pipe steel over a measured span length caused by the induced current, I flowing through the pipe resistance, R) measurement test stations are installed along the structure so as to enable induced current flow to be measured.
- A mutually agreed upon test schedule is established with a timing schedule that will allow adequate time for testing on the affected structures. Flexibility must be available which will allow more detailed testing in areas where there is current discharge from a structure.
- Scheduled measurements should include structure-to-electrolyte potentials and potential shifts, current flow upon the structure, and soil potential gradients.
- Adequate measurement equipment such as voltmeters, recorders, reference cells, data loggers, etc., must be available. Provision for communications between all parties involved in the testing must also be made.
- Upon test completion, all data should be analyzed and summarized. It should be made available to all test participants and other interested parties.

Based upon test results final adjustments to the mitigation system are made. Permanent reference electrodes are installed to allow monitoring of structure potentials and soil potential gradients. Four wire IR drop leads are installed at the structure where necessary to allow current monitoring.



a) Typical test current waveform



B) Variation of pipe-to-soil voltage during injection test

Figure 6.11 Variation of the pipe-to-soil potential during an injection test (Dutil, 1995).

Monitoring

As long as the HVDC system is in operation, its effects upon buried structures are monitored. This is necessary because system parameters may change for both the HVDC system and the underground utilities. Monitoring functions may include,

- Periodic testing
- Reviews of historical data
- Remote monitoring of system functions, and
- Scheduled communications between the HVDC utility underground structure operators.

Testing includes monitoring of structure current, structure-to-electrolyte potentials, and earth conducted currents. Any degradation in performance is corrected by adjusting or modifying the mitigation system. Testing is performed whenever any modifications to the HVDC system are made or if temporary changes are made in operating current levels. It is necessary that operators of the underground utilities be informed of such changes in a timely manner so that appropriate action may be taken.

For coated underground structures under cathodic protection such as pipelines, annual review of the cathodic protection records is beneficial to ensure that the protection levels remain adequate as the coating deteriorates with age or by possible overvoltages applied to the system during abnormal operation of the HVDC transmission system.

Monitoring of electric power systems and underground facilities for reasons other than assessing dc electrode current effects is widespread and growing. Existing and new technologies employed for those applications can be utilized for dc earth return current investigations, as appropriate. Some of these monitoring techniques are discussed next.

6.3.1.2 Geomagnetically Induced Currents

Electric Power Systems

To collect data concerning the impact of GIC on the power system, the Electric Power Research Institute (EPRI) has established a monitoring network called SUNBURST. Utilities located in regions with a high likelihood of GIC activity are primary members of the network. EPRI has developed a electronics monitoring package that participating utilities can use to collect transformer and substation GIC data. The measurements typically consist of the simultaneous ac and dc measurement of transformer phase and neutral currents. From these data correlation between the existence of GIC source currents and transformer harmonic currents can be established. The data is sufficiently precise so as to determine if a transformer is saturating, and hence, generating harmonics or if it is just passing the harmonic currents. If the harmonics are created within the transformer, the severity of the geomagnetic storm can be estimated from the data. Monitoring sites can also install local fluxgate magnetometers to directly measure the changes in the external magnetic field. At some sites the GIC in capacitor bank neutrals, reactors and filters are also monitored. These data enhance the capabilities to evaluate the impact of GIC upon the operation of the power system. Some utilities although not directly attached to the SUNBURST network have also installed GIC recorders in their transformer neutrals. A number of utilities also monitor related effects such as transformer gassing, transformer reactive power, and tertiary harmonic currents.

A single monitoring system can accommodate data input from up to 120 analog signals. Digital signal processing capabilities are available with on-line Fast Fourier Transforms (FFT) providing frequency decomposition of input waveforms. Magnitudes and phases of waveform harmonics obtained from the FFT enable the recognition of geomagnetically induced events. Real and reactive power in the system components can be calculated from the complex FFT coefficients for voltage and current. At each waveform frequency component the complex product of voltage and conjugate current is formed. Summation of these products over frequency provides real and reactive components of the power. Sequence components of voltage and currents can also be computed from the FFT coefficients, and then used to obtain complex power. In this manner, voltage and current data can be processed to determine transformer real and reactive losses resulting from the geomagnetic event. Correlation of these results with measured variations in the external magnetic field have proven to be only fair. Hence, while these data provide knowledge of the effects of the GIC on power system components, their effectiveness in predicting or providing advance warning of geomagnetic events is questionable.

Buried Structures - Pipelines

Buried structures under cathodic protection usually have test stations placed every one to two km for the purpose of monitoring the structure-to-electrolyte potential. These stations simultaneously provide the means for measurement of the potential shift caused by the flow of telluric currents to and from the structure. In addition, four wire potential/current drops may be installed along the structure to monitor the current flowing in the structure. Ancillary data is sometimes obtained from buried coupons_ attached to the structure by means of a test lead which may be disconnected at will. During normal operation, an "instant off" coupon potential may be obtained which is indicative of the polarization level of the structure. When investigating the effects of telluric currents upon the structure, information may be gained by monitoring the current flow to and from the coupon as well as the polarization shift of the coupon. Electrical resistance probes have been used on occasion by some operators. Reported results from some sources indicate that under some circumstances significant corrosion levels may be caused by telluric currents, although generally, tellurics are considered a nuisance only relative to accurate measurement of structure electrolyte-to-soil potentials. Affected system data is obtained by manually read voltmeters or automatically by recording instruments. Sophisticated instrumentation as developed by the electric power industry for monitoring effects to their systems does not appear to be used as prevalently by the underground utility operators.

Pipeline corrosion engineers utilize the close interval pipe-to-soil potential survey to assess the adequacy of the applied cathodic protection. Being an extended structure the pipe potentials readings are affected by telluric currents for locations in the northern and southernmost latitudes where magnetic storm activity is the greatest. Therefore, pipeline engineers have devised data processing schemes for the purpose of eliminating telluric current effects from the pipe potential readings. For example, a two reference cell method uses one reference cell to acquire time varying pipe-to-soil potentials at a fixed location while the second cell is moved along the pipeline to obtain potentials which are both time varying and position dependent. The time varying potential deviations from a datum obtained from the first cell are subtracted from the second cell readings to obtain "telluric free" data. When using this technique two sources of error exist. First, an accurate baseline must be established at the stationary location during a period when telluric activity is absent, and second, the correction factors obtained from the stationary cell must be timed accurately with the moving cell readings. Another method for correcting telluric contaminated structure-to-electrolyte potential data has been to measure the geomagnetically induced electric field component parallel to the pipeline. A correction factor to the measured structure potential is derived on the basis of the determined electric field value and the length of the survey trailing wire. The use of this technique has been reported for a pipeline survey made in the North Sea.

Recently a "telluric null" data processing technique has been evolved for use on the Trans Alaska Pipeline System (TAPS). The method involves the simultaneous measurement of pipe-to-soil potentials and the current flowing in the pipeline over a period of time. The pipe current consists of a dc component and non-zero frequency telluric components. By using a data averaging procedure the telluric component can be isolated. It has been found that this current component has a linear dependence with the pipe-to-soil potential. Performing a linear regression between the telluric current and the potential yields a regression line slope and an intercept value corresponding to zero telluric current. This intercept value is the pipe potential for zero telluric current flowing. In essence, the effects of the telluric current have been "nulled out". The linear relationship between the pipe-to-soil potential and the telluric current is derived at a number of stationary locations along the pipeline. It is then possible to account for telluric effects occurring on close interval potential surveys. This is accomplished by simultaneously measuring pipe potentials at a stationary electrode where the telluric nulled data was obtained and from a moving reference cell used while making a close interval survey. The difference between the pipe-to-soil potential measured at the stationary electrode and the calculated telluric null potential is used to correct the measured close interval survey potentials.

6.3.1.3 DC Transit Systems

The investigation for stray current interference generally consists of structure-to-electrolyte potential readings over a period of time. In dynamically changing situations recording voltmeters are usually used for data gathering. Measurements may also be taken between the affected structure, the rails and the system negative bus. Voltage drop measurements along the affected structure are useful in determining the direction and level of current flowing along the structure. The test period usually extends over a 24 hour weekday in order to document the system peak and off-peak load variations. Tests used to identify stray currents and their sources are,

- Structure-to-electrolyte potential. Readings that fluctuated, are more positive or negative than normal usually are indicators of stray current activity on the structure.
- Correlation monitoring. Structure-to-electrolyte and structure-to-negative bus or rail potentials are measured simultaneously and analyzed for correlation properties. Existing correlation in the monitored potential fluctuations aids in identifying the stray current sources.

- Beta Surveys. A beta survey consists of identifying locations of maximum current discharge from the structure based upon examining the slopes of the correlation curves. The value of the slope of the beta curve is a parameter that determines the drainage bond resistance if such is used.
- Electrolyte current surveys. The magnitude and direction of currents in the electrolyte may be measured by the use of balanced reference cells and a voltmeter. This survey is useful in locating the stray current sources and the current discharge points on the structure.
- Line current surveys. This survey measures the flow of current along the structure. It is useful for pinpointing the locations of current pickup and discharge along the structure.

6.3.1.4 Cathodic Protection Systems

Stray current problems encountered with cathodic protection systems are detected and monitored in much the same way as for other stray currents. For example, the measurements and procedures used for transit system stray current detection are used with some adaptation to fit the situation.

The majority of measurements made on cathodically protected structures involve obtaining the structure-to-electrolyte potentials. These potentials are useful in that both the adequacy of the cathodic protection may be estimated as well as stray current interference conditions detected.

One of the problems with the measurement is that it will be electrolyte IR drop contaminated. In order to obtain a true measure of the structure state of protection or polarization level, the IR drop should be estimated or accounted for in some manner. In order to obtain accurate measurements one or more of the following procedures may be used.

- Measure the structure-to-electrolyte potential with the reference cell close to but not in contact with the structure surface.
- Measure potentials at several locations along the structure and compare measurements to determine if any one measurement may be contaminated by the gradient from a nearby but unknown anode.
- Estimate the IR drop in the reading by measuring the structure-to-electrolyte potential as a function of decreasing distance to the structure. Measurements should be made on both sides of the structure. Extrapolate the results to zero distance using an appropriate formula.
- Interrupt the cathodic protection current as another means of effectively removing the electrolyte IR drop. An optimum time window after the instant of current interruption exists for the best measurement. This window excludes the inductive voltage spike present immediately after current interruption, but should also be small enough so as not to allow the structure to depolarize significantly. Errors in this measurement may still be present, however, due to other rectifier currents, the presence of uninterruptable galvanic anodes, long line structure currents set up by widely separated galvanic cells, and telluric currents.

There are several criteria used to determine if the structure cathodic protection levels are adequate. For example, two of the most commonly used are,

- Negative 0.85 volt. This criterion requires a negative voltage of at least 0.85 volt measured between the structure surface and a saturated copper-copper sulfate reference cell contacting the electrolyte. Determination of this voltage can be made with the cathodic protection current applied, and hence, the measurement contains some unknown level of IR drop. When making the measurement, the reference electrode is placed as close to the structure as possible.
- 100 mV negative polarization shift. This criterion requires "a minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a stable reference electrode contacting the electrolyte. The polarization voltage shift is determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage change after the immediate shift shall be used as the base reading from which to measure polarization decay."

If neither of the above or other applicable protection criteria are not met the logical premise is to assume that the cathodic protection system design should be reviewed. C.P. system design considerations are beyond the scope of this document. However, if protection criteria are not met only on an intermittent or fluctuating basis, stray current interference should be suspected and appropriate measurements instituted for detection and identification of the source(s).

6.3.2 Future Possibilities

Techniques for the measurement and monitoring of stray current interference are well documented and not unduly complex. In fact much of the data gathering and analysis is accomplished at the technical specialist level.

As electronics and computer technology improve, it will be possible to obtain more precise measurements with higher sampling rates and store larger records containing real time data. More sophisticated data processing capabilities such as spectral analysis, e.g., FFT and statistical estimation for time series is also available allowing real time data manipulation on site using notebook computers. A good example of presently available measurement and monitoring capabilities is the instrumentation developed for the SUNBURST network developed for obtaining data on GIC and their interference mechanisms. The same or similar technology could be used or adapted to satisfy other measurement protocols.

Present measurement and monitoring methods relative to corrosion and interference control, for example, are used for determining if a problem exists, identifying the problem, and collecting the data necessary for implementing mitigation. Data processing and interpretation methods do not fully utilize state-of-the-art capabilities. Most design is done by "cut and try" in the field. Although the technology for a more refined approach to corrosion problem identification and mitigation exists presently, its use has not become standard practice in the dc and very low frequency interference control community.

Sophisticated electrical network modeling and analysis computer programs are readily available at the present time. With the use of such programs many interference problems could be modeled and characterized electrically. The interference source characteristics and the interfered structure response could be modeled to yield a more comprehensive understanding of the problem. This, in turn, would allow more refined data gathering protocols to be defined and mitigative measures to be modeled and exercised, and thusly, their effectiveness determined. With such capabilities, improved mitigation approaches could be identified and designed. It is believed that such an approach would advance interference control methodology. Hence, it is recommended as a future development effort.

6.4 MITIGATION APPROACHES

6.4.1 Presently Available

6.4.1.1 DC Transmission Lines

Mitigation for HVDC earth currents starts with the design of the HVDC system. The ground electrodes are placed, if possible, in remote areas, in high conductivity soil, and are designed so as to have the lowest resistance to remote earth. Except for submarine cable systems, mostly in northern Europe, all HVDC transmission lines operate today in monopolar earth-return only for emergencies, and then only for short periods, e.g., approximately 15 minutes. Most of the time they operate bipolar with minimal unbalance current in the earth.

<u>Buried Structures - Pipelines</u>

For extended structures such as pipelines, the insertion of insulated flanges to make the line electrically discontinuous is a common form of mitigation. For an isolated pipe section of length, L the end voltages are of the order of $\pm$ E*L /2, where E is the component of the HVDC system electrode electric field (potential gradient) parallel to the pipeline. Hence, by breaking up the pipe into smaller sections, the maximum voltage can be bounded. The disadvantage to this approach is that the addition of each insulated flange creates an end condition where the voltage peaks at $\pm$ E*L /2 and current either enters or discharges from the pipe on either side of the flange. Attempts to limit the current flow through the coating at the pipe section ends, and thus reduce the corrosion in these areas are sometimes made by connecting galvanic anodes at these locations. Although intuitively comforting, due to other considerations, these anodes can prove to be ineffective under certain conditions. Depending upon the polarity of the HVDC electrode, the galvanic anode may collect current which is an undesirable situation. To preclude such an event diodes are sometimes placed in series with the anodes.

The most common mitigation for pipelines is the use of one or more controlled rectifiers to supply the cathodic protection and interference compensation currents. These rectifiers respond to changes in the pipe-to-soil potential measured between the pipe and a nearby permanent reference electrode. They adjust their current output level in such a manner as to keep the pipe-to-soil potential as constant as possible. If the pipe-to-soil potential is allowed to become more positive than -0.85 volt the possibility of pipe steel corrosion develops. On the other hand, if the potential becomes more negative than approximately -1.5 volt the coating may be damaged and possibly disbonded from the pipe (see Figure 6.8a). For these reasons there is a need to maintain the pipe-to-soil potential within this range. For a pipeline passing through the gradient of a HVDC electrode that is positive, i.e., current leaving the electrode, the pipeline section nearest the electrode will collect current and its potential will become more negative. At greater distances the pipe will discharge current and the pipe potential will become more positive. Controlled constant potential rectifiers placed in these outer regions will have the property of increasing the cathodic protection levels in these areas. However, if the HVDC electrode is negative the pipe section closest to the electrode will discharge current causing its potential increase in the positive direction. For this condition the pipe may incur corrosion in this region. One or more appropriately sized rectifiers placed in this region should return the pipe potentials into the desired range.

Signal and communication cables can also pickup stray current. The pickup and flow of current is generally managed through selective sectionalization of the cable shield wire and grounding by means of galvanic anodes.

Electric Power Systems

Electric utilities located in the vicinity of the ground electrode will also experience a pickup due to the potential gradient surrounding the electrode. Current can enter and leave the system at grounding points for the shield wires and the distribution system neutral. Customer grounding systems and anchor rods are also sources and discharge points for stray current. Current introduced into the system is carried along overhead shield wires, and phase and neutral conductors. It may pass through transformers, voltage regulators, and other electrical equipment. Mitigation approaches are the insertion of insulators into anchor leads and inline capacitors into phase conductors. The separation of customer grounding systems from the distribution neutral can also aid in mitigation. Other mitigation approaches are similar to those used for suppression of geomagnetically induced current effects. These approaches are discussed in the following section.

6.4.1.2 Geomagnetically Induced Currents

Electric Power System

Primary access of geomagnetically induced currents into power systems is through grounded neutral leads of wye-connected transformers and capacitor banks. In order to provide mitigation, research investigations have been directed towards consideration of both passive and active devices.

An active device once under serious consideration was a method for injecting counterposing currents into a particular transformer so as to null out its GIC current. Two approaches were investigated. The first consisted of a controlled dc circuit in a special purpose winding on the transformer core. The other approach used a controlled dc current in the tertiary winding. For either approach the objective was to produce a counter-MMF that would cancel the MMF produced by the GIC in the main windings. Research conducted by the Electric Power Research Institute concluded that, in general, such active devices are not a practical solution to the GIC induced half cycle saturation problem.

Passive devices for mitigation use the approach of blocking the flow of GIC on either the transmission system or through a specific transformer. Transmission line series capacitors may be used to impede the flow of GIC on the phase conductors. (This approach can also be used to block interference currents produced by HVDC systems.) The use of ordinary series capacitors is costly, but they have the compensating economic advantage of simultaneously providing line impedance compensation which may increase power transfer limits. Special low impedance low cost series capacitors have been developed for the express purpose of providing GIC mitigation. Although economically attractive, these lower cost capacitors do not provide line impedance compensation.

Recent research has been concerned with devices for blocking GIC that can be installed in the neutral to ground connection of a transformer. The objective is to block the quasi-dc GIC while maintaining a low impedance path for 60 Hz. The research was successful with the development of a device using capacitors and appropriate bypass circuitry. Careful application of blocking capacitors in the neutral connection must be made lest safe operation of the system be compromised. Concepts being investigated in current research depend upon quick bypass of the capacitors to limit transformer neutral and capacitor voltages. Alternative methods using metal-oxide varistor banks to achieve the same result have also been investigated.

In addition to hardware mitigation devices, guidelines for operation during electromagnetic disturbances have been developed by many power system operators. To some extent these may be considered as "soft" approaches to mitigation. For example, typical courses of action may be,

- Discontinue maintenance work and restore out of service transmission lines to service.
- Maintain the system voltage within an acceptable range.
- Reduce the loading on critical transmission lines to 90% or less of their normal rating.
- Reduce the use of system operations that are dependent upon shunt capacitor banks and static var compensators.
- Dispatch generation to manage system voltage, tie line loading, and to distribute operating reserves.
- Bring equipment on line that will provide controllable reactive power reserves.
- Communicate and coordinate these actions with adjacent control areas.

Important to operators for the orderly implementation of these procedures is an advance notice of impending GIC. Unfortunately geomagnetic disturbances can occur without warning necessitating immediate action. Hence, the implementation of one or more of the above actions can in some situations present a conflict with utility practices required to procure a secure system operating environment.

Buried Structures - Pipelines

Overall, mitigation techniques used for alleviating dc transmission line interference are also applicable to GIC mitigation. The range of frequencies associated with each are approximately the same, i.e., zero for the former and from zero to a few Hertz for the latter. One basic difference between the two is that occasions of GIC are unpredictable and unannounced, while in most cases planned abnormal operation of the HVDC system is communicated to the underground utility operators. Unplanned HVDC transmission line operation in the earth return mode is generally limited in time (typically 15 minutes) after which the line must be switched out of the ground current mode or shut down. Mitigation for tellurics must accommodate current reversals at the structure much the same as for bipolar HVDC system caused interference.

The sporadically occurring positive GIC caused pipe potential excursions and the fact that the GIC contains frequency components other than zero minimizes long term corrosion problems. During the GIC period, however, the instantaneous corrosion rate is not necessarily insignificant. Generally the most aggravating problem encountered by underground utility operators is the error introduced into structure-to-electrolyte measurements by the GIC fluctuations. Hence, mitigative techniques instituted by affected structure operators are usually first, operational procedure modification, and second hardware implementation. For example, typical utility actions are to:

- Perform potential surveys only in the absence of geomagnetic activity,
- If surveys are carried out during period of GIC, devise a measurement technique that will allow data correction for telluric induced voltage gradients,
- Install insulating joints to break the structure into shorter lengths,
- Install automatically controlled constant potential rectifiers along the structure as needed.

6.4.1.3 DC Transit Systems

Following any changes in substation loading, transit system operations or in the adjoining underground utilities, the appropriate local electrolysis coordinating committee should be notified. This allows all affected parties to conduct tests and formulate planning for making modifications to their respective systems, if necessary. Based upon test results, if added mitigation is deemed necessary, the several approaches are usually considered. Typically these are, drainage bonds, reverse current switches, cathodic protection, and structure sectionalization.

Drainage Bonds. Drainage bonds provide conductive paths for stray current to return to its source without causing corrosion to the affected structure. One end of the bond is connected to the affected structure at the point of current discharge. The other end is connected to the negative return path to the substation. Generally an adjustable resistance is used in series with the bond to limit the current drained to the proper value where corrosion is suppressed at the drainage point without adversely affecting the structure-to-electrolyte potential. Proper adjustment of bonds is difficult if multiple drainage points exist along the structure.

For older transit systems where the rails were not insulated, the use of drainage bonds from each affected structure back to the rails was frequent and common. The disadvantage of that mitigation method was that as each structure bond was added, the rail resistance to remote earth was decreased, thus increasing the available stray current. For modern transit systems where the running rails are essentially insulated from the earth, drainage bonds are seldom used and only as a last resort.

Reverse Current Switches. Reverse current switches are placed in series with drainage bonds so as to allow current to drain from the interfered structure through the switch and back to the transit system negative bus. It, however, prevents current flow in the opposite direction, i.e., into the structure. Such a reverse current flow could occur under certain transit system operational conditions, but is prevented by the switch. Allowing the reverse current flow to proceed would be deleterious to the structure in that additional sites of current drainage would be set up elsewhere on the structure. Several types of switches are in use. Among them are solid state switches such as silicon diodes, or selenium rectifier stacks, and electromechanical contactors.

Cathodic Protection. Cathodic protection can be used to suppress the effects of stray current. It is the preferred method of mitigation in situations where the use of drainage bonds is not feasible. Either galvanic anodes or impressed current cathodic protection systems may be used. As for HVDC transmission line mitigation, potential controlled rectifiers may be required.

Structure Sectionalization. On extended structures such as pipelines, sectionalization of the structure by means of insulated flanges, for example, will serve to limit the current flow on the structure. Again, the disadvantage of sectionalization is that current discharge regions are set up at each electrical discontinuity, i.e., insulator. Other considerations reviewed in the previous report section discussing mitigation for HVDC electric power transmission lines also apply here.

6.4.1.4 Cathodic Protection Systems

Interference from cathodic protection systems or mutual interference from multiple systems can be found by procedures similar to that used for detecting stray currents from foreign sources. Hence, in general, the mitigation techniques discussed above apply. One advantage when dealing with cathodic protection system interference is that the cathodic protection system adjustment, design, and placement is to a reasonable extent controllable by the corrosion engineer. Generally interference from a cathodic protection system is constant in value, thus making the measurements and adjustments easier than when dealing with foreign stray currents. In addition, the rectifier can be interrupted upon command, an option which allows identification of currents from the c.p. system to be made. In difficult mitigation system interference situations, one option exists which is not available when dealing with foreign sources of stray interference, and that is, to also protect the interfered structure by the interfering c.p. system. However, in practice this not necessarily always a viable option.

In summary, there are several basic approaches to solving cathodic protection interference problems. These are; (1) design the c.p. system(s) so as to minimize the exposure of foreign structures, (2) use resistance bonding as necessary to allow a metallic drainage for current picked up by a foreign structure, (3) use auxiliary drainage such as galvanic anodes at the affected structure to afford alternative paths for current leaving the structure, (4) make large objects discontinuous by the use of insulating flanges, insulators, etc., and (5) use insulation where possible, such as the installation of insulated cables, coating for pipelines, insulation for foundations and footings, insulation of overhead shield wires at particular towers, and sectioning of guy wires by insulators at electric power system poles and towers.

6.4.2 Future Approaches

The basic mitigation approaches discussed previously such as, e.g., structure sectionalization, bonding, auxiliary drainage, etc. are well known and have been in use for decades. The implementation of these techniques and the resulting mitigation strategy and system design are generally dependent upon the expertise of the designer. The final adjustment of the mitigation system is most often made on site because many variables are involved in the design which can not be easily accounted for during the design process. The present state-of-the-art does not give the corrosion engineer sophisticated tools for use in the design process which leads to unduly complex, and in many cases, inefficient designs. As an example take the case of a long extended structure such as a pipeline and with a complex geometry situated in the potential gradient field of an electrode. From field tests the corrosion/interference engineer can identify the locations of current discharge from the structure. Controlled constant potential rectifiers may then be installed at these locations to reverse the current flow from the structure. These in turn may cause new locations of current discharge to develop which will necessitate additional rectifier installations, and so forth. Computer modeling of the interference and the structure as electrical sources and passive networks, respectively, could lead to enhancement of the design process and reduce the "cut and try" procedures presently necessary.

The increasing availability and decreasing costs of computer resources allows computational methods to be used in the design procedure. For example, in the design of cathodic protection systems, especially for off shore oil well platforms, numerical simulation techniques have been developed for determining the polarization behavior and the final protection levels achievable for these geometrically complex structures. Applicable numerical techniques are the finite difference, and the finite element and the boundary element methods. The former is applicable to a simple geometry, while the latter are applicable to more complex structures. Exercise of these methods for cathodic protection system design has shown them to be viable and has resulted in more optimum designs. One of the principal advantages to such simulations is that once set up, subsequent design changes can be quickly evaluated. These modeling techniques are presently used for the specific purpose of determining cathodic protection current distribution and polarization levels along the structure.

Similar approaches have not as yet been evolved or found widespread usage for the design of interference mitigation. As discussed in Section 6.3.2, the technology is available that could be gathered and focused towards the solution of interference problems by computer simulation. For example, interference currents modeling could be added to above models together with controlled rectifier system response simulation to evaluate mitigation effectiveness. Use of modern control theory employing fuzzy logic principles for real time rectifier current output adjustment could result in more effective mitigation system designs. With the ability to view and understand the effects of both design and initial parameter changes upon the results almost instantaneously, it is logical to assume that in time new mitigation approaches would be conceived. It is recommended that computer simulation and modeling of mitigation methods as applied to dc interference problems be pursued in order to place current design practices on a more sound analytical footing.

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