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Mutual Design Considerations for Overhead AC Transmission Lines and Gas Transmission Pipelines
Volume 2: Prediction and Mitigation Procedures

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Volume 1: Engineering Analysis
Volume 2: Prediction and Mitigation Procedures

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ABSTRACT

As a result of a program jointly funded by the Electric Power Research Institute (EPRI) and the Pipeline Research Committee (PRC) of the American Gas Association (A.G.A.), known data has been consolidated and a systematic investigation has been made into the mutual effects of ac electric power transmission lines (power lines) and natural gas transmission pipelines (pipelines) jointly sharing rights-of-way. The results presented are of use to both the electric power and natural gas transmission industries for addressing problems arising from a mutual coexistence. Program objectives were:

1. to consolidate known data concerning mutual effects arising from power lines and pipelines sharing a common right-of-way;
2. to develop a unified and systematic method for predicting electromagnetically induced voltages and currents on pipelines; and
3. to investigate mitigation techniques to minimize interference effects upon pipeline and component reliability and personnel safety.

In the fulfillment of these objectives, new techniques for coupling prediction and pipeline mitigation have been developed and other available data has been collected and summarized.

The overall objective of the program was to develop a reference book which concisely presented the coupling prediction and mitigation information derived in a manner useful to both power and pipeline industry users in the design, construction and operation of their respective systems.

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The authors also wish to thank the chairman of the EPRI/A.G.A. Steering Committee, Mr. R. E. Hodge, Natural Gas Pipeline Company of America; vice chairman, Mr. R. E. Kennon, EPRI; and other committee members, for their invaluable guidance throughout the program.

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project was a joint effort by the Pipeline Research Committee of the A.G.A. and EPRI to develop analytical techniques for determining the induced potential on pipelines that parallel electric transmission lines. This is an area of interest to both electrical system and pipeline operators.

The purpose of this project was to develop analytical methods for prediction and mitigation of voltages induced on pipelines by nearby ac transmission lines. Verification by actual tests was necessary. Further, analyses of ac corrosion effects, personnel safety and pipeline component reliability were sought.

PROJECT OBJECTIVES

The contractor was asked to first assess commonly used methods to compute induced voltages and to determine their accuracy and applicability. This was necessary since considerable literature plainly states that calculations of pipeline voltages are often different by a factor of 10 from measured voltages. The next step was to develop valid analytical techniques that could be verified by both theory and field tests. In a follow-on effort IITRI engineers were asked to develop simplified methods of computing induced voltages that could be executed on a programmable hand calculator. Then mitigation techniques were to be developed.

CONCLUSIONS AND RECOMMENDATIONS

The contractor did develop the required analytical techniques, which are reasonable and supported by field test results. New mitigation methods were then developed and old ones evaluated for their effectiveness. All of the mathematical analyses were to be compared with several sets of data from field tests. The accounts of these tests are well documented in this report.

The theoretical considerations are discussed in Volume 1 of this report. Included are discussions on prediction, mitigation, personnel safety and pipeline susceptibility. In Volume 2 techniques for performing the necessary calculations are presented without proof or discussion. It is anticipated that Volume 2 will be useful as a workbook.

It was especially gratifying for those participating in the project to work in the atmosphere of cooperation that existed between the two sponsors.

Richard E. Kennon, Program Manager
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FOREWORD

This two volume reference book is a result of a program jointly funded by the Electric Power Research Institute (EPRI) and the Pipeline Research Committee (PRC) of the American Gas Association (A.G.A.). This program has consolidated known data and has made a systematic investigation into the mutual effects of ac electric power transmission lines (power lines) and natural gas transmission pipelines (pipelines) jointly sharing rights-of-way. The results presented here are of use to both the electric power and natural gas transmission industries for addressing problems arising from a mutual coexistence. Program objectives were:

1. to consolidate known data concerning mutual effects arising from power lines and pipelines sharing a common right-of-way.
2. to develop a unified and systematic method for predicting electromagnetically induced voltages and currents on pipelines; and
3. to investigate mitigation techniques to minimize interference effects upon pipeline and component reliability and personnel safety.

In the fulfillment of these objectives, new techniques for interference prediction and mitigation have been developed and other available data has been collected and summarized. The work performed during the program is presented in detail in Volume 1 of this book.

The overall objective of the program was to develop a reference book to present the information and the methodologies derived in a manner useful to both power and pipeline industry users in the design, construction and operation of their respective systems.

In compiling this book, advantage was taken of the knowledge available and applicable information has been categorized and summarized for inclusion into this book. However, in certain areas, existing gaps in knowledge became apparent, and original research was conducted to advance the state-of-the-art. From this work, several significant accomplishments have resulted which have been verified by field tests.

- A method for the prediction of electromagnetically coupled pipeline voltages and currents has been developed.
- Instrumentation has been developed for direct measurement of the longitudinal electric field from a power line.
- Techniques for the mitigation of induced interference on pipeline systems have been investigated and design procedures for the optimum implementation of these techniques have been developed.

The book consists of two volumes. Volume 1 contains detailed engineering analyses encompassing the areas of:

- Interference Level Prediction
- Susceptibility Evaluation
- Mitigation Techniques
- Measurement Procedures

A complete summary of Volume 1 is presented in Volume 1.

Volume 2 is a much synopsized version of Volume 1. The intent of the second volume is to provide the user with a procedures manual which will allow him to determine interference levels and estimate mitigation design requirements in the field. Hence, the material presented in this volume is restricted to coverage of objective 2 and a part of objective 3. More specifically, the following areas are covered:

1. Procedures for calculation of electrostatically and electromagnetically induced voltages and currents are presented in a concise manner. Even though similar material exists in Volume 1, the presentation here allows for more rapid access.
2. Discussion of mitigation procedures has been restricted to basically the use of grounding techniques. The reason for this approach is that the user in the field is generally faced with an "after the fact" situation. Other mitigation techniques such as pipeline and power line design modification are normally instituted during the planning stages of a project.

Liberal use of hand calculator programs, developed specifically for this book, is suggested to ease computational complexity. Since the underlying theory is not presented in this volume, it would be expected that the user have some familiarity with the contents of Volume 1 in order to answer questions of procedures applicability to the more difficult systems interaction situations.

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Section 1

PREDICTION OF INDUCED PIPELINE VOLTAGE-ELECTROMAGNETIC COUPLING

INTRODUCTION

Induced ac voltages and currents on buried pipelines are caused by electromagnetic coupling between the power line and the pipeline(s). Calculation of induced ac levels is basically a two-step procedure: (1) calculate the longitudinal electric field existing at the pipeline of interest taking into account all current carrying conductors on the right-of-way, i.e., power line phase wires, shield wires, other pipelines, etc.; and (2) given the longitudinal electric field at the pipe and the electrical parameters of the pipeline, determine the voltage (current) profile.

In this reference book, the procedure outlined for calculating an ac interference profile makes liberal use of TI-59 hand calculator programs (c.f., Appendix A) to expedite computations. Some minimal facility with the use of complex numbers will most probably be required; however, in addition, determination of pipeline voltages and currents will require familiarity with the application of the Thevenin equivalent circuit.

CALCULATION OF THE LONGITUDINAL ELECTRIC FIELD

Generally, on a right-of-way (ROW), the principal conductors are the overhead phase wires carrying (assumed) known load currents, power line shield wires carrying induced currents (if they are grounded at more than one point) and some number of pipelines. Depending upon the exact configuration, the calculation procedure varies somewhat, and hence the proper procedure for a given situation is best explained by example. Hence, a number of cases will be explained.

Case 1. Single Pipeline-Single Point Grounded Shield Wires

For this situation, the shield wires do not carry induced currents and the electric field at the pipeline is due to the currents in the phase wires only. The calculation procedure is as follows:

- From the ROW geometry determine the heights of each conductor, both power line and pipeline (the height is considered negative for a buried pipeline, and the geometric mean height is used for power line conductors), and the lateral separations of each phase line to the pipeline position. Use program CARSON to find the mutual impedances between each wire and the pipeline. (Note: In the application of this program and others, ancillary data such as, for example, ground resistivity, may be required. Such requirements will not be specifically pointed out here, but will be obvious upon review of program instructions in Appendix A.)

- Given the magnitude and phase of the currents carried by each conductor, use program FIELD to calculate the phase and magnitude of the electric field at the pipeline location.

This procedure is applicable to any number of current carrying conductors on the ROW. An illustrative application of this procedure is contained in Appendix B (Mojave Desert case history).

Case 2. Multiple Pipelines-Single Point Grounded Shield Wires

For this situation, mutual coupling effects between the pipelines will affect the ac currents (and voltages) in each of the pipes. Hence, the unknown currents in all pipes must be solved for concurrently, by means of a set of simultaneous equations. The program CURRENTS performs this function, and the calculator has sufficient capacity to accommodate up to five pipelines on the ROW. Prediction of the ac interference level is accomplished as follows:

- Using program CARSON, find the mutual impedances between each phase wire and pipeline, and between each pipeline.

- Using program PIPE, determine the propagation constant, γ, and the characteristic impedance, Z_0 for each pipeline. Calculate the self-impedance, $Z_{C_iC_i}$ of each pipeline which is equal to γ times Z_0.

- Input the phase wire currents, and the mutual and self impedance matrices into the program CURRENTS. The solution yields the induced currents in each pipeline. The program assumes pipeline parallelism for distances, ℓ, such that $\gamma\ell >> 1$. (Situations where this condition is not satisfied are discussed later.)

- The driving source electric field for any pipeline is then calculated by multiplying the pipeline current as determined by the program CURRENTS by the negative of the pipeline self impedance, $Z_{C_iC_i}$.

Case 3. Single Pipeline-Multiple Point Grounded Shield Wires

For this case, it is necessary to determine the currents flowing in the shield wires since, generally, they contribute significantly to the electric field at the pipeline. Calculation of the electric field at the pipeline proceeds as follows:

- Using the program CARSON determine the mutual impedances between (1) each phase wire and shield wire, (2) between each phase wire and the pipeline, (3) between each of the shield wires, and (4) between each shield wire and the pipeline.
- Using the program SHIELD determine the self impedance of each shield wire.
- From the program PIPE determine the self impedance (= γZ_0) of the pipeline.
- Enter into the program CURRENTS, the phase wire currents, and the mutual and self impedances. The program output will yield the shield wire and pipeline currents.
- Multiply the pipe current by the negative of the pipe self impedance to obtain the external source longitudinal electric field driving the pipeline.

Due to the limited capacity of the calculator, the maximum number of multiple grounded shield wires that can be accommodated is four. The procedure for more than four shield wires existing on a ROW is covered next.

Case 4. Single Pipeline-More Than Four Multiple Grounded Shield Wires

In this situation, the usual ROW placement of shield wires is one or two on each transmission tower which also will usually carry one or two three-phase electrical circuits. Although there exists mutual coupling between any set of shield wires, all phase wires and all other shield wires on the ROW, the principal contribution to the shield wires' induced currents is from the phase wires carried on the same tower.

Hence, for a ROW containing many circuits with multiple-grounded shield wires, the following procedure, which yields an approximate solution, may be used.

- Consider one tower at a time. Use program CARSON to find the mutual impedances between the phase wires on the tower and each shield wire and the shield wires themselves.

- Use program SHIELD to calculate the self impedances of the shield wires.

- Use program CURRENTS to determine the shield wire currents assuming that the only excitation currents are from those phase lines carried on the same tower.

- Repeat the procedure for each of the other towers.

- Once all the shield wire currents have been determined, use program CARSON to find the mutual impedance between each phase wire and the pipeline, and each shield wire and the pipeline.

- Use program FIELD to directly compute the longitudinal electric field at the pipeline. Take into account all phase and shield wire currents.

Using this approximate procedure, the error in the calculated electric field should be reasonably small for a pipeline situated within a few hundred feet of the nearest transmission tower. The error would increase with an increase in distance between the towers and the pipeline.

Case 5. Multiple Pipelines and Shield Wires

When the total number of unknown currents is less than or equal to five (capacity) limit of the calculator program) their solution may be obtained from the program CURRENTS for any arbitrary apportionment between pipeline and shield wire currents. For a large number of unknown currents, the approximation procedure outlined for Case 4 should be followed. That is:

- Solve for the shield wire currents, using the program CURRENTS, on a single tower-by-tower basis. (This will also require use of programs CARSON and SHIELD to obtain required mutual and self impedances).

- Assuming the shield wire currents so obtained to be known pipeline driving sources, use program CURRENTS to solve for unknown currents in up to a maximum of five pipelines sharing a single ROW (after determining the appropriate self and mutual impedances).

- Calculate the driving electric field for any of the pipelines by multiplying its current by the negative of its self impedance.

Case 6. Short Length Pipeline Exposures

Case 5 considers multiple pipelines on the same ROW. However, pipeline current solutions obtained by use of the program CURRENTS are correct only for all pipeline exposure distances, L, being quite long, generally where $\gamma\ell >> 1$ for each pipeline. This condition may be met by all the pipelines, in which case the previous solution (Case 5) is exact, or it may be met by only some or possibly none of the pipelines. For these latter two situations, modification of the pipeline mutual and self impedances is required when inputting these quantities into the program CURRENTS (c.f., Appendix D, Volume 1). The modifications necessary for a correct solution from the program CURRENTS are as follows:

- For any pipeline that satisfies the condition, $\gamma\ell < 1$, input a modified self impedance into the program CURRENTS, that is $Z_{ii} \rightarrow Z_{ii} \div (\gamma\ell/2)$.
- Modify the mutual impedances between a long pipeline (A) and a short pipeline (B) as follows: $Z_{AB} \rightarrow Z_{AB}\left(\frac{\gamma_A\gamma_B}{\gamma_A+\gamma_B}\right)\frac{\ell}{2}$ where ℓ is the length of the short pipeline, but $Z_{BA} \rightarrow Z_{BA}$.
- For two short pipelines, (A) and (B),

$$Z_{AB} \rightarrow Z_{AB}\left(\frac{\gamma_B}{\gamma_A+\gamma_B}\right), \text{ and}$$

$$Z_{BA} \rightarrow Z_{BA}\left(\frac{\gamma_A}{\gamma_A+\gamma_B}\right)$$

- The driving source electric field for each pipeline is then the pipe current solution obtained times the negative of its <u>modified</u> self impedance.

EXAMPLES OF ELECTRIC FIELD CALCULATION

Five case histories are presented in Appendix B as illustrative examples of the procedures just described. These are in order of presentation.

- Southern California Gas Company Line 235, Needles, California.
- Northern Illinois Gas Company 36-inch Aux Sable pipeline, Aurora, Illinois.
- Consumers Power Company Line 1800, Kalamazoo, Michigan.
- Texas Gas Transmission Corporation, Memphis, Tennessee.
- Consumers Power Company, Karn-Weadock Line, Bay City, Michigan.

Review of these case histories is advisable. The Southern California Gas Company example exemplifies the simplest application of the theory (Case 1), namely, a single pipeline and a single power line with single point grounded shield wires. Consumers Power Company Line 1800 represents the next level of complexity with a double circuit vertical geometry and a pair of multiple grounded shield wires on the same tower sharing the ROW with a single pipeline (c.f., Case 3). The Northern Illinois Aux Sable line represents additional complexity with multiple circuits on the ROW and the pipeline meandering along the ROW changing position relative to the electrical circuits. Such changing geometry requires a new electric field prediction to be made for each new change in pipeline geometry or power line tower configuration.

The Texas Gas Transmission Corporation, Memphis ROW contains multiple electric circuits and pipelines and, in addition, short exposure lengths. This case history represents the most complex ROW reviewed here. A reasonably exact solution for the electric field would require, because of the number of unknown currents, first, an approximate solution for the shield wire currents on a tower-by-tower basis, and then use of modified self and input impedances in the CURRENTS program (c.f., Cases 5 and 6). However, because the pipelines are relatively widely spaced along the width of the ROW, and somewhat separated by intervening power transmission circuits, it was assumed that each pipeline was primarily driven by its adjoining electric power circuits only. This assumption allowed considerable simplification of the problem with the electric field at each pipeline calculated by use of the programs CARSON and FIELD (c.f., Case 1). In essence, the mutual impedance between pipelines was disregarded, but the solution thusly obtained is reasonably accurate because of the short electric field exposure distances for the pipelines.

The Consumers Power Company Karn-Weadock Pipeline, Bay City, Michigan case history illustrates a direct measurement of the electric field in lieu of prediction by calculation. This procedure is attractive in a situation where the power line already exists on a ROW and a prediction of induced voltage for a future pipeline is desired. The direct measurement technique is discussed in the following subsection.

DIRECT ELECTRIC FIELD MEASUREMENT

Because of the presence of the vertical electric field in the vicinity of power lines, direct measurement of the longitudinal field requires specialized instrumentation. Such instrumentation using commercially available voltmeters, but a unique shielding and grounding arrangement, is described in Appendix C. This instrumentation is capable of measuring not only the magnitude of the electric field, but also the relative phase which, as shown in the following subsection, is necessary to accurately predict the induced voltage on a pipeline subject to different value electric fields because of physical or electrical ROW discontinuities.

The Consumers Power Company case history for the Karn-Weadock, Bay City, Michigan pipeline illustrates use of the instrumentation to measure the electric field directly and then uses these measurements for prediction of the pipeline induced voltage.

CALCULATION OF INDUCED PIPELINE VOLTAGES

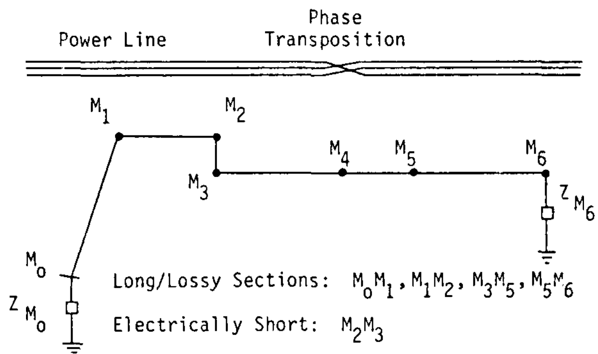
The theory developed depends upon recognition of the fact that induced voltage peaks will occur at points of electrical or physical discontinuity along the ROW (which result in variations in either the longitudinal electric field magnitude or phase or both) and that the induced voltages decay exponentially on either side of a discontinuity.

Node Analysis of Arbitrary Pipeline/Power Line Collocations

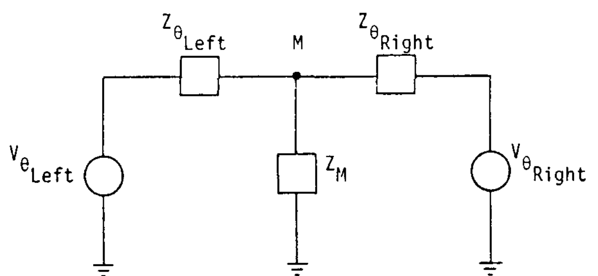
This section presents a computation method for the peak induced voltages at a discontinuity on a buried pipeline having multiple sections with differing orientations with respect to an adjacent power line, or subject to pronounced variations of the driving field due to power line discontinuities. The method is based upon Thevenin decomposition procedures, leading to a node voltage analysis at pipeline or inducing field discontinuities.

Figure 1-1a illustrates the connection of several arbitrary pipeline sections adjacent to a power line with an electrical discontinuity (phase transposition). The peak induced voltages are computed by introducing a Thevenin observation plane at each junction, M, between dissimilar pipeline sections or at discontinuities of the driving field, as illustrated in Figure 1-1b. This placement of the Thevenin plane is based upon Volume 1 analyses which showed the generation of exponential pipeline voltage peaks at all non-zero impedance terminations of a long/lossy pipe section.

In Figure 1-1, $V_{\theta_{left}}$ and $Z_{\theta_{left}}$ denotes the Thevenin source voltage and impedance, respectively, for the pipeline seen to the left of the observation point. Similarly, $V_{\theta_{right}}$ and $Z_{\theta_{right}}$ denote the Thevenin equivalent circuit of the pipeline to the right of the observation point. Z_M denotes the mitigating grounding impedance (if any) at M. The use of mitigating impedances will be discussed in the following section. For the present, Z_M may be considered as infinite. If the V_θ's and Z_θ's are known quantities, the voltage at point "M" on the pipeline may be determined by use of the TI-59 hand calculator program NODE (c.f., Appendix A). This program also solves for the pipeline current at point "M".



(a) Locations of Thevenin Observation Planes



(b) Connected Thevenin Circuits for the Induced Voltage Peak at Observation Plane M

Figure 1-1. Peak-Voltage Analysis of a General Multi-Section Pipeline

Illustrative examples of points of discontinuity, as shown in Figure 1-1, where voltage peaks will be in evidence are:

1. Junction between a long/lossy parallel section and a long/lossy non-parallel section (point M_1);
2. Junction between two long/lossy parallel sections having different separations from the power line (points M_2 and M_3);
3. Adjacent to a power line phase transposition or a substation where phasing is altered in some way (point M_4);
4. Junction between two long/lossy sections of differing electrical characteristics, for example, at a high resistivity soil - low resistivity soil transposition (point M_5);
5. Impedance termination (insulator or ground bed) of a long/lossy section (point M_6).
6. Crossings between power and pipelines (although not specifically drawn in Figure 1-1).

Points M_1, M_2, M_3, and M_6 are illustrative of pipeline orientation or termination discontinuities; point M_4 is illustrative of a discontinuity of the driving field; and point M_5 is illustrative of a discontinuity of the pipeline electrical characteristics. The magnitude of the voltage peak at any of these points is computed simply by applying program NODE at the discontinuity to the Thevenin equivalent circuits for the pipeline sections on either side. In this way, the use of a single program along with a collection of Thevenin equivalent pipeline circuits, is sufficient to estimate the voltage peaks on an arbitrary multi-section, buried pipeline.

Derivation of Thevenin Equivalent Circuits

Before the Thevenin circuit can be derived the pipeline electrical parameters, γ, the propagation constant, and Z_0, the characteristic impedance must be known. These may be determined by the calculator program PIPE listed in Appendix A. Necessary inputs to the program PIPE are ROW and pipeline quantities such as burial depth, pipe diameter, pipe thickness and coating conductivity. These factors are usually approximately known. However, in the application of the program PIPE, parameters of the steel itself, such as permeability and resistivity, must be inputted but, in general, may be unknown. In general, the values of these parameters can vary widely, but variations in their values do not impact the overall voltage prediction accuracy to any significant extent. Hence, it is permissible to use nominal values for these quantities and still make accurate predictions for the voltage level induced. Moreover, to further simplify the Thevenin equivalent circuit derivation at this point, pipeline electrical parameters have been derived using nominal steel parameter values in the program PIPE for various sizes of pipelines, etc., and the results have been plotted in Appendix D. Hence, these graphs may be used to determine the γ and Z_0 values required as inputs to the program THEVENIN.

The program THEVENIN is described in Appendix A, and is used to find the Thevenin equivalent circuit parameters, V_θ and Z_θ looking to both directions from a discontinuity. The reader is cautioned that determination of the Thevenin equivalent circuit at an arbitrary point on a pipeline cannot be generally carried out in a single step since the far end terminating impedance, Z_L, and voltage, V_L (c.f., Figure A-5), are usually unknown. The procedure to follow is tc start from a point of the pipeline where V_L and Z_L are known and derive these quantities at the point of interest by repeated derivation of Thevenin equivalent circuits in tandem.

For example, if the "right" equivalent circuit at point M_4 were desired, one would, in general, have to start the derivation at point M_6. Here referring to Figure A-5, $V_L = 0$, and $Z_L \approx Z_{M6}$. Application of the program THEVENIN for the distance between points five and six yields a Thevenin "right" equivalent circuit at point 5, of $V_{\theta 5}$ and $Z_{\theta 5}$. These quantities then become the far end terminating parameters, V_L and Z_L for the second equivalent circuit derived for the distance between points four and five. The solution obtained for this circuit by exercise of program THEVENIN will be the desired quantities $V_{\theta 4}$ and $Z_{\theta 4}$.

Case History Examples

The simplest application of Thevenin equivalent circuit derivation, once the longitudinal electric source field is known, is for the Southern California Line 235. The principal characteristic of this example is that the pipeline length may be considered "long" to either side of most encountered discontinuities on the ROW and, hence, for each equivalent circuit, $Z_L = Z_\theta = Z_0$, the characteristic impedance of the pipeline.

The Consumer Power Company Kalamazoo Line 1800 example is more complex and representative of a pipeline terminated in end impedances not equal to each other and also not equal to the pipeline characteristic impedance. The Karn-Weadock, Bay

City line is illustrative of the repeated tandem derivation and application of the Thevenin circuit discussed in the previous subsection.

The Texas Gas Transmission Corporation Memphis ROW is illustrative of the Thevenin equivalent circuit concept for multiple pipelines on a ROW which are multiply electrically connected and bonded to each other at several points.

SUMMARY: ELECTROMAGNETIC COUPLING

Prediction of the electromagnetically induced voltages and currents on a pipeline can be made accurately using a two-step procedure, i.e.,

- Determine the longitudinal electric field at the pipeline either by calculation - use programs CARSON and FIELD for a single unknown current, or - use programs CARSON and CURRENTS for multiple unknown current carrying conductors/pipelines on the ROW, or
- Directly measure the electric field using the instrumentation described in Appendix C.

Once the electric field is found, use of the Thevenin equivalent circuit concept allows prediction of induced pipeline voltages and currents by the following procedure.

- At the point of interest on the pipeline, find the Thevenin equivalent circuit parameters using the program THEVENIN for both directions up and down the pipeline from that point, and
- Apply the program NODE to the Thevenin circuits at the point to compute the induced voltage and current.

In the application of these procedures, certain caveats not readily apparent from the theory, but found to exist in practice should be observed.

- Prediction of the electric field at greater distances from the power line requires knowledge of the ground resistivity at deeper depths to maintain prediction accuracy. However, reasonable prediction accuracy has been maintained out to distances of 100 meters from the power line, using a ground resistivity averaged over 3 to 5 meter depths.
- If a pipeline interference level prediction is to be made on the basis of an actual electric field measurement, make the measurement at a point along the span between towers where the height of the phase wires is equal to the geometric mean of the phase wire heights at the tower and at midspan, i.e., the square root of the product of both heights.
- One of the principal factors in determining the average induced voltage levels on a pipeline is its coating conductivity (c.f.,

Appendix D). Hence, an estimate or range of coating conductance is usually required.

- It should be recognized that the voltage induced on a pipeline is proportional to the current carried by the phase wires. However, due to current unbalances between the phase wires, large temporal variations in the induced voltage levels may be experienced for relatively small variations in one or more phase line currents (c.f., Appendices B and C of Volume 1).

Section 2

MITIGATION OF ELECTROMAGNETICALLY COUPLED PIPELINE VOLTAGES

INTRODUCTION

Various mitigation techniques can be employed to reduce 60 Hz ac electromagnetic coupling to a pipeline system consisting of arbitrary buried and above-ground sections. These techniques include:

1. Design of a joint pipeline/power line corridor for minimum electromagnetic coupling including optimum phase sequencing of power line conductors;
2. Pipeline grounding methods;
3. Use of screening conductors;
4. Use of insulating devices; and
5. Use of pipeline extensions.

Of the above techniques, the first was recently derived from the basic theory of Section 3, Volume 1. The remaining techniques have been employed in the past, but evidently not optimally. This section will discuss optimization of pipeline grounding methods for achieving mitigation. Restriction of the present discussion to this simple method is consistent with the intended use of this volume, i.e., as a field reference book. The other techniques are discussed in detail in Section 8 of Volume 1, and are considered to have basic applicability more so in design and planning stages for joint occupancy of a ROW.

PIPELINE GROUNDING METHODS

As shown in Figure 2-1, the pipeline and personnel hazards due to electromagnetic coupling to buried pipeline can be mitigated by grounding the pipe using either independent ground beds, distributed anodes, or horizontal ground wires, and by installing ground mats at points of possible human contact. Basic considerations for the application of these techniques are now summarized.

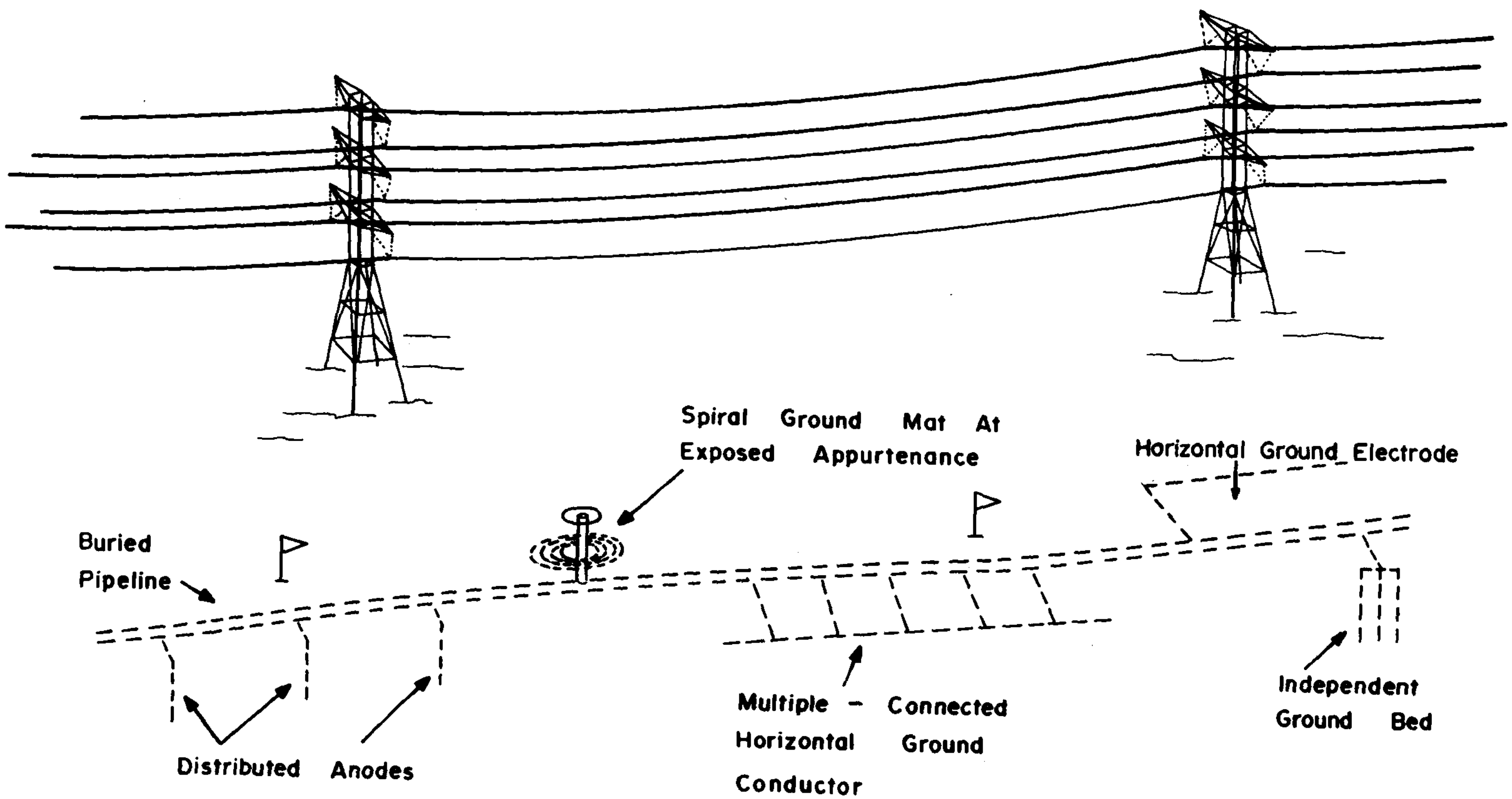


Fig. 2-1 APPLICATION OF GROUNDING TECHNIQUES FOR MITIGATION OF ELECTROMAGNETIC COUPLING TO A BURIED PIPELINE

Grounding Requirements

The most effective location for a grounding installation on a buried pipeline is at a point where the induced voltage is maximum. A good ground established at such a point serves to null the local exponential voltage distribution. However, the mitigating effects of this ground installation are negligible at an adjacent voltage peak located more than 2/Real(γ) m away, where γ is the propagation constant of a buried pipeline. Therefore, a ground should be established at each induced voltage maximum.

To effectively reduce the induced ac potential on a long buried pipeline of characteristic impedance, Z_o, by connecting the mitigating grounding impedance, Z_m, the condition

$$|Z_m| < |Z_o| \simeq 2 \text{ ohms} \tag{2-1a}$$

must be achieved. Grounding impedances exceeding $|Z_o|$ are essentially useless for mitigation in this case. Grounding impedances much less than $|Z_o|$ reduce the local pipeline voltage by

$$\% \text{ reduction} = 100 \left(1 - \left|\frac{Z_m}{Z_o}\right|\right) \quad . \tag{2-1b}$$

The grounding requirement of Eq. 2-1a is much more demanding than that for mitigation of electrostatic coupling to an above-ground pipeline. The combination of possibly high values of pipe source voltage, V, and low values of pipe source impedance, Z_o, serves to create severe shock hazards. Using the equivalent circuit of Figure 2-2, the shock current, I_w, through the worker can be shown to equal

$$I_w = \frac{V_\theta}{Z_o + Z_w \left(1 + \frac{Z_o}{Z_m}\right)} \tag{2-2}$$

where Z_w is the impedance of the current path through the worker. Mitigation of I_w requires values of Z_m significantly less than Z_o. This is in contrast to the mitigation requirement which states that Z_m need only be less than Z_w for mitigation of electrostatic shock hazards for the above-ground pipelines.

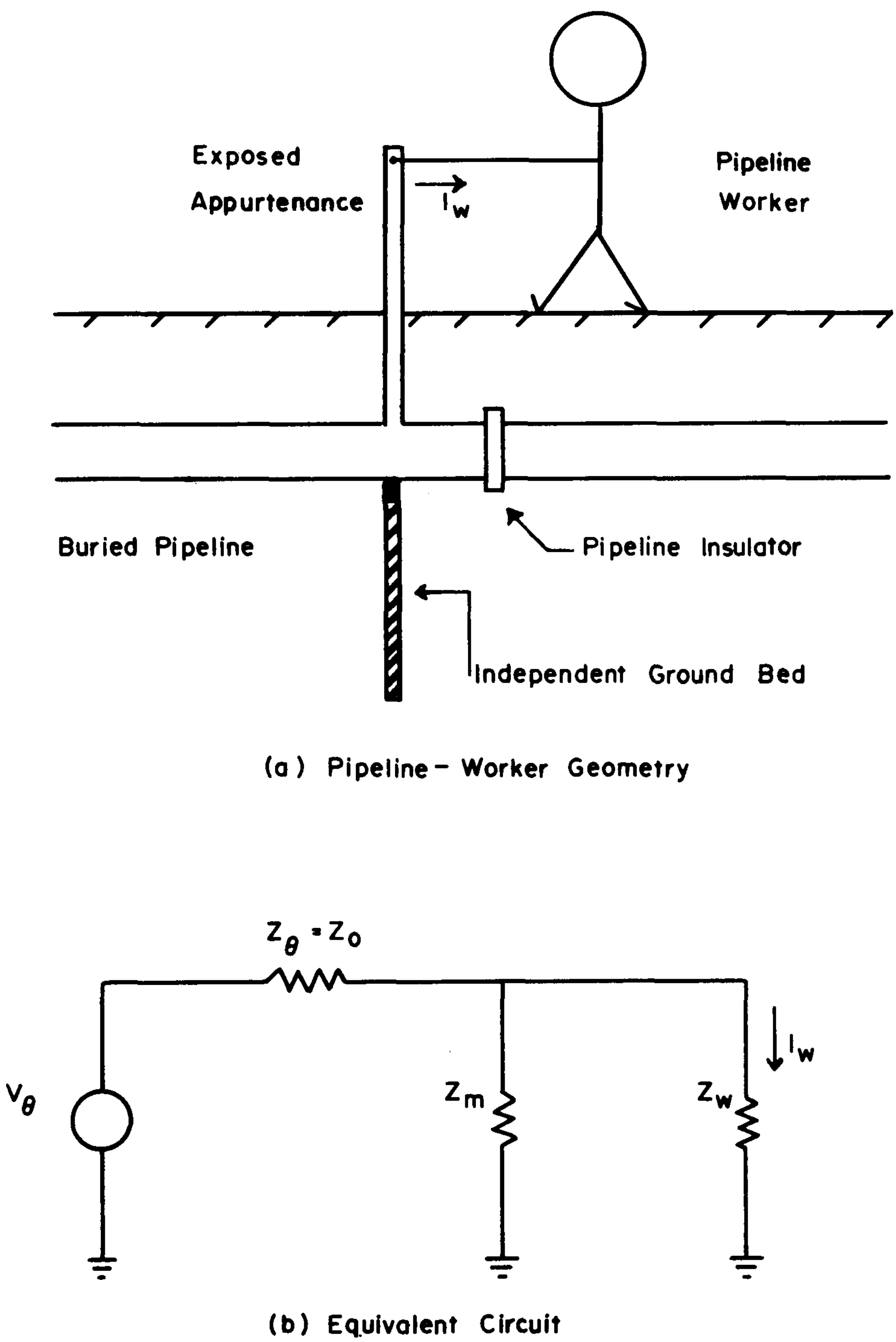


Fig. 2-2. MITIGATION OF EM SHOCK HAZARDS BY PIPELINE GROUNDING

Two general types of independent grounding systems, namely vertical anodes and horizontal conductors (including casings), have found extensive use in realizing the low impedance grounds required for mitigation of electromagnetic coupling to buried pipelines. In addition, ground mats have been used to protect personnel at exposed pipeline appurtenances. The following subsections summarize the characteristics of the various low impedance grounding systems, and briefly review the use of grounding mats.

Vertical Anodes

A vertical anode grounding system can be realized with either a single deep anode, several connected anodes, or a continuous system of distributed anodes connected along the pipeline. Single and multiple connected anodes are discussed separately in the following subsections. The effect of a continuously distributed system is the most difficult to predict theoretically, but it can be accounted for approximately by assuming that the resistance of each anode to remote earth is in parallel with the pipeline coating resistance to remote earth. Hence, the effect of such a grounding system can be accounted for by calculating a new effective resistivity for the pipeline coating (c.f., Eq. 2-8).

Single Anode. A vertical ground rod and its surrounding earth form a lossy transmission line characterized by the propagation factor, γ_{rod}, and the characteristic impedance, $Z_{o_{rod}}$. The ac ground impedance, Z_{rod}, is simply the input impedance of this lossy transmission line. It is incorrect to assume that Z_{rod} is equal to the dc grounding resistance, R_{rod}. As will be shown below, the transmission line characteristics of a vertical ground rod significantly affect its performance.

For a vertical ground rod with radius a, the propagation factor is given by

$$\gamma_{rod} = \sqrt{j\omega\mu_o(\sigma + j\omega\varepsilon)} \ \ m^{-1}$$

$$\simeq 0.0154\cdot(1+j)\cdot\sqrt{\sigma}\ m^{-1}, \text{ at 60 Hz} \qquad (2\text{-}3)$$

where $\omega = 2\pi f$; $\mu_o = 4\pi 10^{-7}$ H/m; σ = soil conductivity in mhos/m; ε = soil permittivity in F/m; and $\sigma >> \omega\varepsilon$ is assumed. The characteristic impedance is given by

$$Z_{o_{rod}} = \frac{1}{2\pi}\sqrt{\frac{\omega\mu_o}{2\sigma}}\left[(1 + j)\cdot \ln\left(\frac{1.12}{a\sqrt{\omega\mu_o\sigma}}\right) + (1 - j)\cdot\frac{\pi}{4}\right] \text{ohms}$$

$$= \frac{2.44\cdot 10^{-3}}{\sqrt{\sigma}}\left[(1 + j)\cdot \ln\left(\frac{51.6}{a\sqrt{\sigma}}\right) + (1 - j)\frac{\pi}{4}\right] \text{ ohms at 60 Hz} \quad (2\text{-}4)$$

The ac grounding impedance of a single, electrically short vertical ground rod of radius a, and length L, is given by

$$Z_{rod} = Z_{o_{rod}} \coth(\gamma_{rod} L) \simeq Z_{o_{rod}}/\gamma_{rod}L \text{ ohms}$$

$$\simeq \frac{0.159}{\sigma L}\left[\ln\left(\frac{51.6}{a\sqrt{\sigma}}\right) - j\frac{\pi}{4}\right] \text{ ohms at 60 Hz} \quad (2\text{-}5)$$

where

$$a \ll L \ll \delta = \sqrt{\frac{2}{\omega\mu_o\delta}} = \frac{64.9}{a\sqrt{\sigma}} \text{ m = soil electrical skin depth} \quad (2\text{-}6)$$

The ln term of Eq. 2-5 is usually of the order of 10, so that Z_{ac} is almost a pure resistance. For comparison, the dc resistance of the same ground rod is given by

$$R_{rod} = \frac{0.159}{\sigma L}\left[\ln\left(\frac{4L}{a}\right) - 1\right] \text{ ohms} \quad (2\text{-}7)$$

Equation 2-5 yields values of Z_{rod} significantly higher than the values of R_{rod} obtained from Eq. 2-7.

Example. Compute the 60 Hz ac grounding impedance of a 6-foot long, 1-inch diameter, vertical ground rod installed in soil having a resistivity equal to 100 ohm-m. Also, compute the dc resistance of this ground rod.

Solution. First, convert all quantities to the proper metric units.

L = 6 feet = 1.83 m

a = 0.5 inch = 0.0127 m

σ = 1/(100 ohm-m) = 0.010 mhos/m

From Eq. 2-5 we compute

$$Z_{rod} \simeq \frac{0.159}{(0.010)(1.83)} \left[\ln \left(\frac{51.6}{0.0127\sqrt{0.010}} \right) - j\frac{\pi}{4} \right] \text{ ohms}$$

$$8.69\ (10.6 - j\,0.785) \text{ ohms}$$

$$(92.1 - j\,6.8) \text{ ohms.}$$

From Eq. 2-7 we compute

$$R_{rod} = \frac{0.159}{(0.01)(1.83)} \left[\ln \left(\frac{(4)(1.83)}{0.0127} \right) - 1 \right]$$

$$= 8.69\ (6.36 - 1) = 46.6 \text{ ohms.}$$

$|Z_{rod}|$ is seen to equal 2.0 times R_{rod}.

Multiple Vertical Anodes. The use of a single deep anode may be uneconomical in regions where the earth conductivity is low and buried rock strata make deep drilling difficult. In such cases, the use of multiple, short, distributed magnesium or zinc cathodic protection anodes may be indicated.

A. For vertical anodes grouped together in a distinct bed (arranged on a straight line or circle) with the spacing between the rods equal to the length of the rods, the net ac grounding impedance is approximated by the following table (established for dc resistance).

No. of Rods in Bed	Approximate Net ac Grounding Z
1	Z_{rod}
2	$0.58 \times Z_{rod}$
4	$0.36 \times Z_{rod}$
8	$0.20 \times Z_{rod}$
10	$0.16 \times Z_{rod}$
20	$0.09 \times Z_{rod}$
50	$0.04 \times Z_{rod}$

B. For vertical anodes distributed uniformly along a short ($<$ 300 m) stretch of a buried pipeline, the ac grounding impedance is simply the grounding impedance of one anode divided by the total number of anodes.

C. For vertical anodes distributed uniformly along a length (> 3 km) stretch of buried pipeline, Eq. 2-1b does not precisely describe the mitigation effect. Wave propagation effects within the grounded section must be taken into account. The value of the propagation constant, γ_m, of the pipeline section with anodes is estimated as

$$\gamma_m \simeq \gamma \sqrt{\frac{Y + Y_m}{Y}} \qquad (2\text{-}8a)$$

where γ and Y are the propagation constant and admittance to remote earth, respectively, of the pipeline section before mitigation, and Y_m is the mitigating admittance per km provided by the distributed anodes. The reduction in voltage is estimated as

$$\%\ \text{reduction} \simeq 100 \left(1 - \left|\frac{\gamma}{\gamma_m}\right|\right) \qquad (2\text{-}8b)$$

$$\simeq 100 \left(1 - \frac{1}{\sqrt{1 + \frac{Y_m}{Y}}}\right)$$

Equation 2-8b indicates that appreciable mitigation is obtained for this case only if the net mitigating admittance per km is much greater than Y, which is of the order of 0.1 mhos/km for a typical, moderately well insulated, buried pipeline.

Example: Vertical anodes with an ac grounding impedance of 50 ohms are installed at regular intervals of 20 m along a buried pipeline having a Y value of 0.1 mhos/km. Estimate the resulting mitigation.

Solution: Each anode presents an ac grounding admittance of 1/50 mhos. At a spacing of 20 m between anodes, there are a total of 50 anodes per km. Thus,

$$Y_m = 50 \frac{\text{anodes}}{\text{km}} \cdot \frac{1}{50} \frac{\text{mho}}{\text{anode}} = 1 \frac{\text{mho}}{\text{km}} .$$

Using Eq. 2-8b, the percent mitigation is estimated as

$$\%\ \text{reduction} \simeq 100 \left(1 - \frac{1}{\sqrt{1 + 1/0.1}}\right)$$

$$= 100 \left(1 - \frac{1}{\sqrt{11}}\right) \simeq 70\%$$

Horizontal Conductors

A horizontal ground wire and its surrounding earth form a lossy transmission line characterized by the propagation factor, γ_{wire}, and the characteristic impedance, $Z_{o,wire}$. The ac grounding impedance, Z_{wire}, is simply the input impedance of this lossy transmission line. It is incorrect to assume that Z_{wire} is equal to the dc grounding resistance, R_{wire}. As will be shown below, the transmission line characteristics of a horizontal grounding wire significantly affects its performance.

Further, horizontal ground conductors can be subject to the same driving electric field generated by the adjacent power line as the pipeline is exposed to. Therefore, ground wires can develop appreciable terminal voltages which must be accounted for in computations of the expected mitigation. Additional factors involve the effects of resistive and inductive coupling between long ground wires and the nearby pipeline. All of these factors are highly dependent upon the specific orientation of the ground wire relative to the power line and the pipeline. Reference will be made to Figure 2-3 which shows four common types of horizontal ground wire installations, and to Figure 2-4, which shows the electrical equivalent circuit for each type of installation.*

Mitigation Wire Perpendicular to the Pipeline. This ground wire configuration, denoted as A in Figure 2-3, is the simplest to analyze because the perpendicular configuration serves to minimize inductive and conductive coupling between the wire, pipeline, and power line. In this configuration, the wire acts only as the grounding impedance, Z_{wire}, for the pipeline, as shown in Figure 2-4b. The overall mitigation effect is computed in three steps.

1. Use the calculator program WIRE to determine the propagation constant, γ_{wire}, and characteristic impedance, $Z_{o,wire}$. This program is suitable for wires of arbitrary electrical conductivity and permeability, and diameters up to one inch, for the full range of possible earth resistivities.

*The design procedures for the different types of mitigation wires considered here were developed from field tests made in December 1977 on the Southern California Gas Company Line 235 extending from Needles to Newberry, California. Detailed test procedures and data reduction are presented in Appendix E of Volume 1.

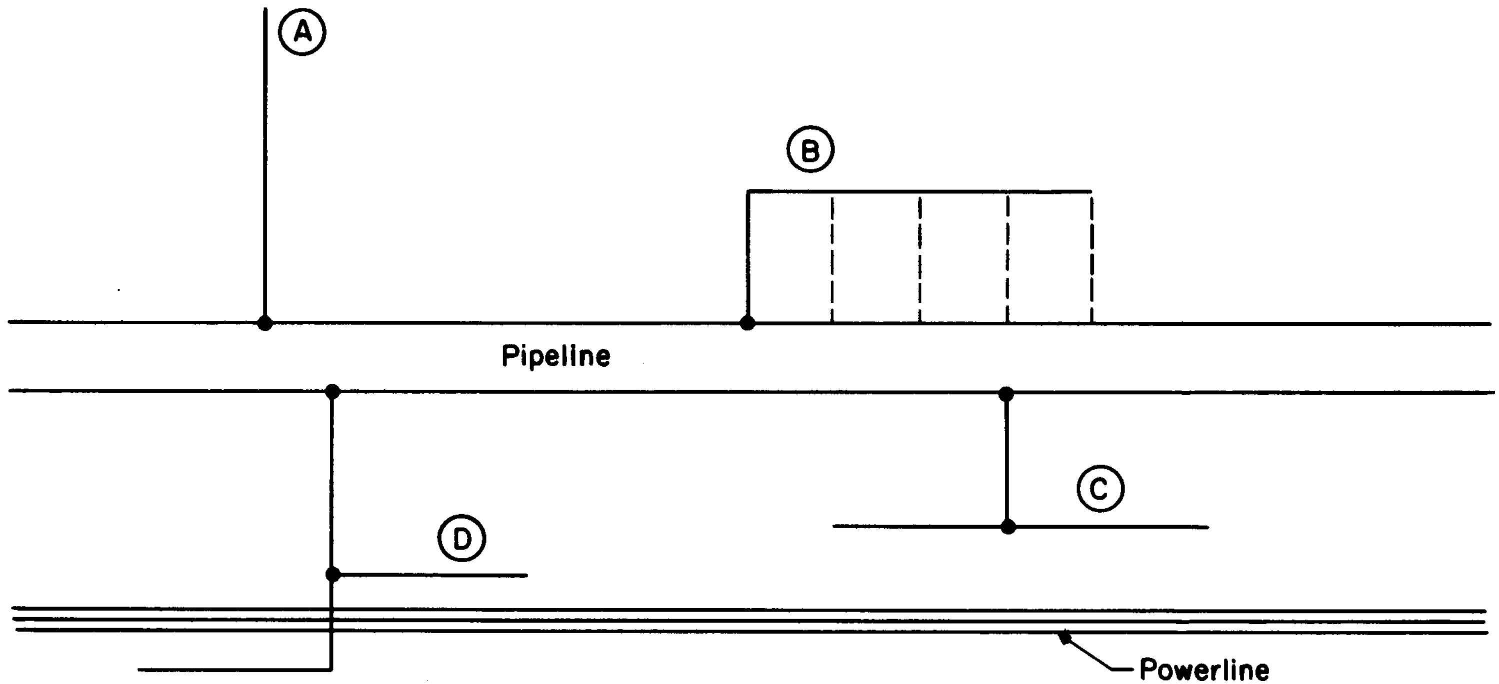


Fig. 2-3. TYPES OF HORIZONTAL GROUND CONDUCTOR INSTALLATIONS

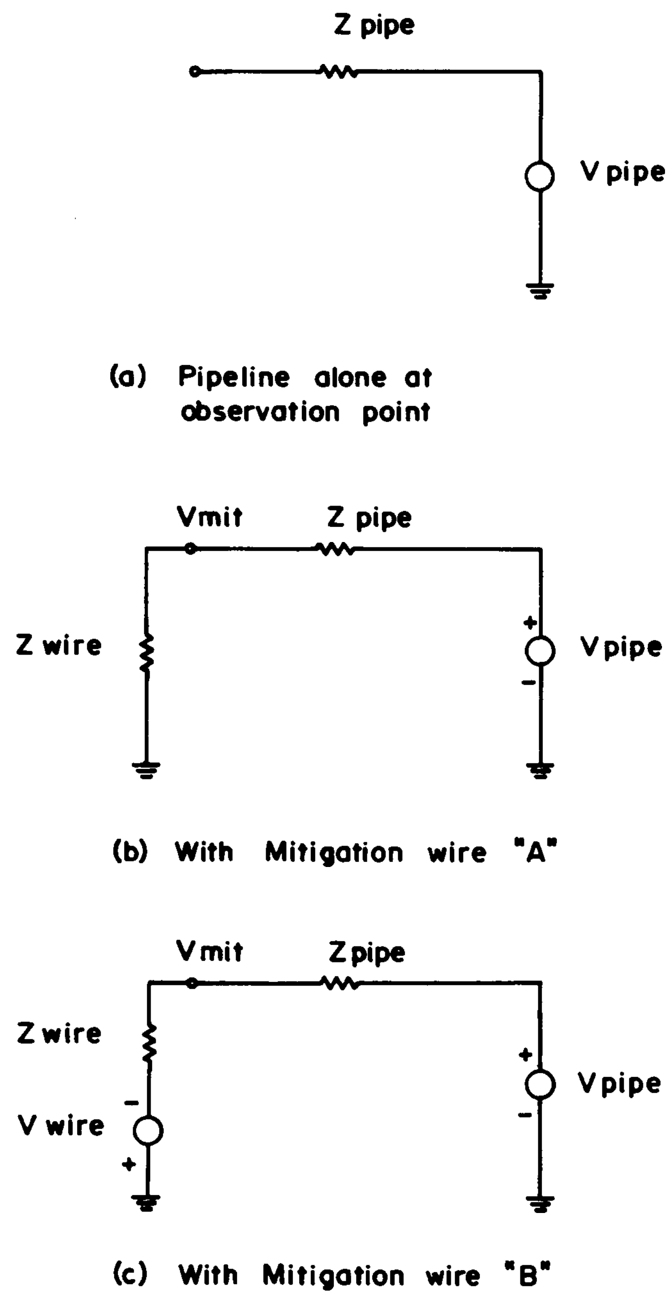
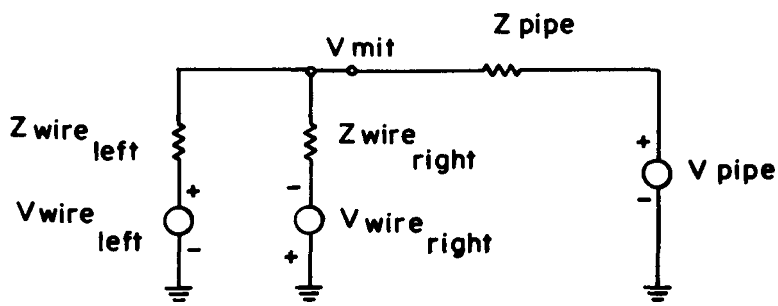
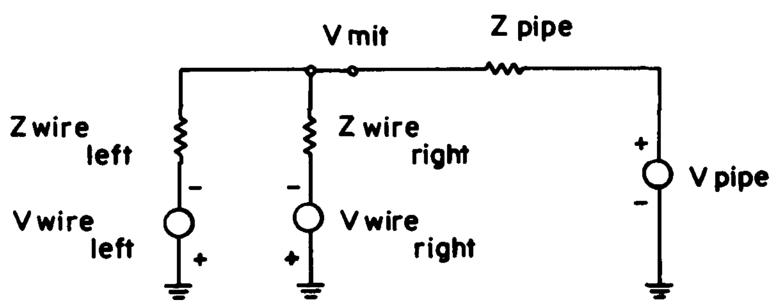


Fig. 2-4 HORIZONTAL GROUND WIRE EQUIVALENT CIRCUITS



(d) With Mitigation wire "C"



(e) With Mitigation wire "D"

Fig. 2-4 (Cont.) HORIZONTAL GROUND WIRE EQUIVALENT CIRCUITS

2. Apply the calculator program THEVENIN to determine Z_{wire} by using γ_{wire} and $Z_{o,wire}$ as data inputs. This program is suitable for wires of arbitrary length and having arbitrary far-end impedance loads.

3. Determine V_{pipe} and Z_{pipe}. This procedure is outlined in Section 1. It involves use of programs: CARSON; SHIELD, if applicable; PIPE; either CURRENTS or FIELD, depending upon the ROW configuration; and THEVENIN.

4. Apply the calculator program NODE to determine the unknown node voltage, V_{mit}, of Figure 2-5. Here, Z_{wire}, Z_{pipe}, and V_{pipe} are used as data inputs. This gives the value of the pipeline voltage after connection of the horizontal ground wire.

Ground Wire Transmission Line Properties - Example. Figure 2-5 illustrates the importance of accounting for the transmission line properties of a ground wire when determining its mitigation effectiveness. Here, the straight line plots the dc resistance of an experimental wire installed at the Mojave test site, as computed using the most common dc grounding formula,

$$R = \frac{\rho}{\pi \ell} \left(\ln \left(\frac{2\ell}{a} \right) - 1 \right) \tag{2-9}$$

where ρ = ground resistivity; ℓ = length of wire; and a = radius of wire. The curve plots the values of Z_{wire}, obtained using the programs WIRE and THEVENIN. Finally, the solid squares represent values of grounding impedance actually measured during the field test. It is seen that the measured results agree extremely well with the predicted results using the calculator programs which predict a leveling off of the grounding impedance at $Z_{o,wire}$ as the wire length exceeds 1/Real (γ_{wire}). Hence, for a given grounding installation, there is an optimum length (in the vicinity of the knee of the curve) where the mitigation-efficiency/cost ratio is greatest. Thus, indiscriminately lengthening a perpendicular ground wire may not necessarily be cost effective. This is in sharp contrast to results implied by the dc grounding resistance formula, which is evidently useful only for small-to-moderate conductor lengths.

End-Connected Parallel Ground Wire. This ground wire configuration, denoted as B in Figure 2-3, requires additional analysis steps to account for the effects of voltage build-up on the ground wire due to its parallelism with the power line and mutual coupling between the pipeline and the ground wire.

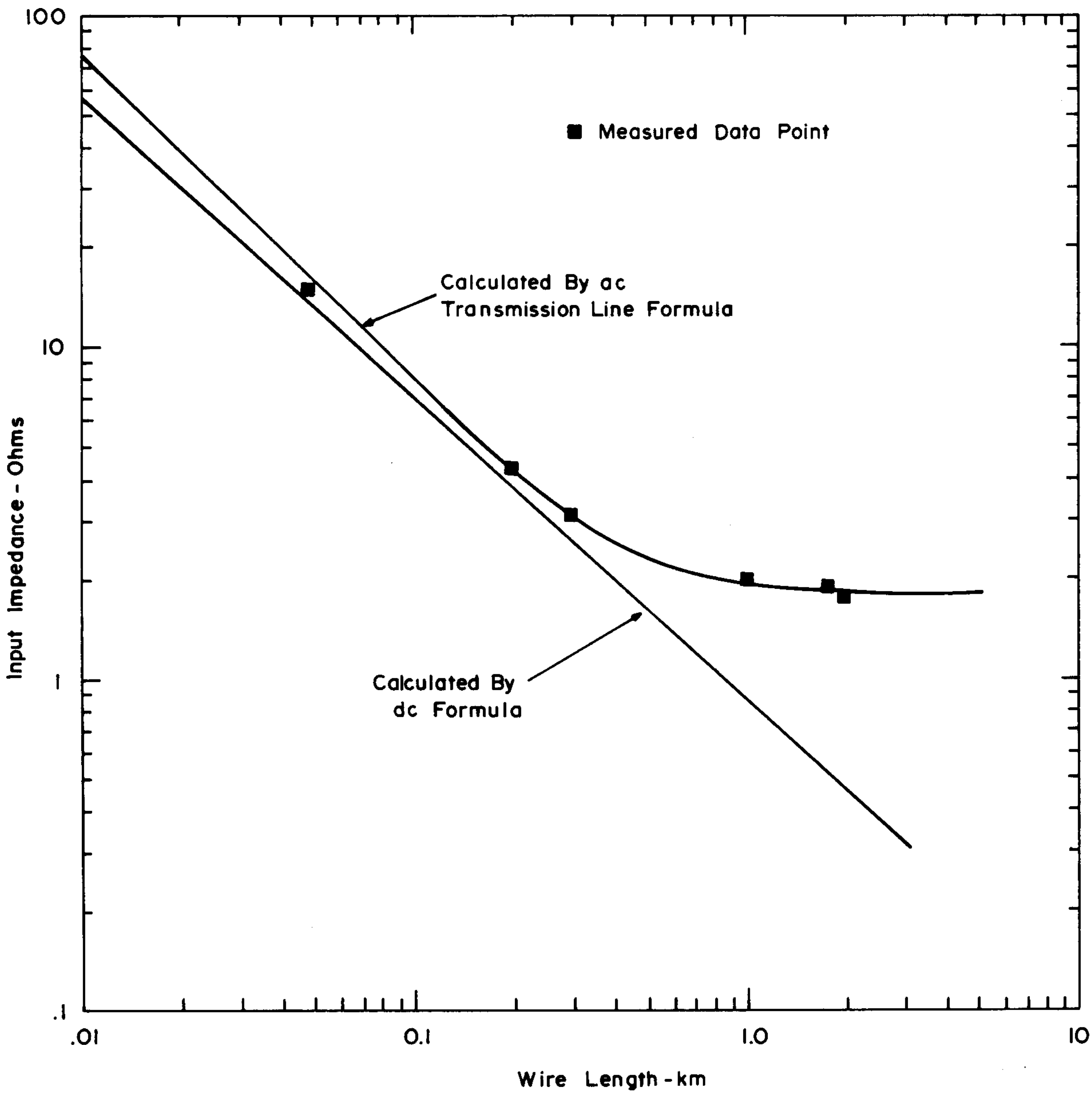


Fig. 2-5. GROUNDING IMPEDANCE OF HORIZONTAL WIRE

In this configuration, the wire acts as both the grounding impedance, Z_{wire}, and the voltage source, V_{wire}, as shown in Figure 2-4c. The overall mitigation effect is computed by the following procedure:

1. Apply the calculator program CARSON to determine the mutual impedances between the power line phase conductors and each passive-multiple-grounded conductor sharing the right-of-way, including the pipeline to be mitigated and the ground wire. Repeat the procedure to determine the mutual impedances between all passive, multiple-grounded conductors on the right-of-way.

2. Apply the calculator program CURRENTS to determine the maximum currents within the pipeline to be mitigated and other passive conductors of the right-of-way under the influence of the power line, the ground wire, and each other.

3. Apply the calculator program FIELD to determine the driving electric field at the ground wire location. This program forms and then sums (current) x (mutual impedance) products determined using the data inputs of Steps 1 and 2. Contributors to this field include the power line phase conductors and all other conductors on the right-of-way.

4. Apply the calculator program WIRE to determine the propagation constant and characteristic impedance of the ground wire.

5. Apply the calculator program THEVENIN to determine Z_{wire} and V_{wire} using the results of Steps 3 and 4 as data inputs.

6. Apply the calculator program PIPE to determine the characteristic impedance and propagation constant of the pipeline.

7. Apply the calculator program THEVENIN to determine V_{pipe} and Z_{pipe} using the results of Steps 3 and 6 as data inputs.

8. Apply the calculator program NODE to determine V_{mit} of Figure 2-4c. Here, Z_{wire}, V_{wire}, Z_{pipe}, and V_{pipe} are used as data inputs.

For best results with this ground wire configuration, the phase of V_{wire} should equal that of $V_{pipe} + 180^{o}$ in order to achieve a voltage cancellation effect at V_{mit}. This is illustrated in Figure 2-4c by the choice of signs of the V_{wire} and V_{pipe} voltage sources. In the ideal case, $V_{wire}/Z_{wire} = -V_{pipe}/Z_{pipe}$, so that $V_{mit} = 0$. The wire impedance and voltage properties can be adjusted by choosing the wire length and separation from the power line. However, this usually does not give enough adjustment range to attain the ideal case. Additional adjustment can be realized by either a continuous or lumped inductive loading of the ground wire to alter its transmission line characteristics. Program WIRE is structured to permit data input of the average added inductive resistance per kilometer due to inductive loading to allow rapid calculation of the new wire propagation constant and characteristic impedance. Then, program THEVENIN can be used to compute the new V_{wire}/Z_{wire} ratio.

The chief effect of connecting a long, parallel ground wire and an adjacent pipeline with multiple ties (indicated by the dashed lines of the "B" configuration of Figure 2-3) is the reduction of the effective V_{wire} and Z_{wire}, in a manner discussed below. This can be useful under conditions where voltage cancellation at V_{mit} is not deemed important. If such ties are used, they should be spaced no closer than $1/\mathrm{Real}(\gamma_{wire})$ for maximum effect at minimum cost.

Center-Connected Parallel Ground Wire. This ground wire configuration, denoted as C in Figure 2-3 is aimed at achieving minimum values of V_{wire} and Z_{wire} for any given length of wire. Its performance is most easily understood by examining the equivalent mitigation circuit shown in Figure 2-4d. From this figure, it is seen that the center connection caused the effective V_{wire} to equal zero because of the bucking effect of $V_{wire,\ left}$ and $V_{wire,\ right}$. Further, the effective Z_{wire} is seen to equal the parallel combination of $Z_{wire,left}$ and $Z_{wire,right}$. This value is always less than the grounding impedance for the wire when used in an end-connected manner for mitigation because of the leveling off of the impedance curve with length. (In effect, two short wires give a lower grounding impedance than one long wire having the combined length of the short wires).

The mitigation effect of this ground wire configuration can be computed by applying program WIRE to determine γ_{wire} and $Z_{o,wire}$; then applying THEVENIN to determine $Z_{wire,left}$ and $Z_{wire,right}$; the application of CARSON, CURRENTS or FIELD, and THEVENIN to find V_{pipe} and Z_{pipe}; and finally applying NODE. In applying NODE, the voltage sources $V_{wire,left}$ and $V_{wire,right}$ need not be known specifically because of their self-cancelling effect, so that a value of zero volts can be assumed for both. Thus, in many respects, calculation of the mitigation effectiveness of a center-connected parallel ground wire is the same as for the perpendicular ground wire.

Back-to-Back Parallel Ground Wire.* This ground configuration, denoted as D in Figure 2-3, is aimed at achieving simultaneously a maximum value of V_{wire} and a

*Best applicability for mitigation of the effects of power lines having a combination of configurations and phase sequences which yield an electric field phase difference of approximately 180^{o} from one side of the power line to the other.

minimum value of Z_{wire} for a given length of wire. This is made possible by moving one ground wire leg to the opposite side of a horizontal configuration power line, so that the fields driving the two legs are equal in magnitude but 180^0 out of phase. Thus, as shown in Figure 2-4e, $V_{wire,left}$ and $V_{wire,right}$ reinforce each other instead of bucking, allowing a maximum cancellation effect at V_{mit}. Similar to the center-connected parallel ground wire, the effective Z_{wire} is seen to equal the parallel combination of $Z_{wire,left}$ and $Z_{wire,right}$.

The mitigation effect of this ground wire configuration can be computed by treating the left and right halves of the ground wire as two distinct end-connected parallel ground wires, and combining the results for $V_{wire,left}$, $Z_{wire,left}$ and $V_{wire,right}$, $Z_{wire,right}$ using program NODE.

Example. An example of the design calculations for a back-to-back mitigation wire arrangement is presented here. This design was originally proposed for installation on the Southern California Gas Company Line 235 for mitigation of the voltage peak at Milepost 101.7. A more detailed analysis of this mitigation wire design concept is given in Appendix E, Volume 1. The physical installation of the wire is shown in Figure 2-6. The design computations involve the following steps.

Computation of Z_{pipe} and V_{pipe}. The first part of this analysis requires computation of the Thevenin equivalent source impedance, Z_{pipe}, and source voltage, V_{pipe}, of the pipeline at Milepost 101.7. The computation involves the following steps:

a. Assumption of a 700 kΩ-ft^2 pipe coating resistivity, a 40 kΩ-cm earth resistivity, and a 700 ampere balanced power line current loading;

b. Use of the computer program CARSON to calculate the electric field at the pipeline as being equal to 14 volts/km at a phase of -122.6^0 relative to the power line currents; Details of this calculation are given in the Mojave Desert case history (c.f., Appendix B)

c. Interpolation of the graphs of Figure D-6 (Appendix D) to obtain the pipeline propagation constant equal to (0.115 + j0.096) km^{-1}.

d. Computation of V_{pipe} as

$$V_{pipe} = \frac{-0.5 \times 14.0\underline{/-122.6^0}}{(0.115 + j\,0.096)} = 46.7\ \underline{/17.6^0}\ \text{volts}$$

using Eq. 3-18a (Volume 1) and the condition that $Z_1 = Z_0$.

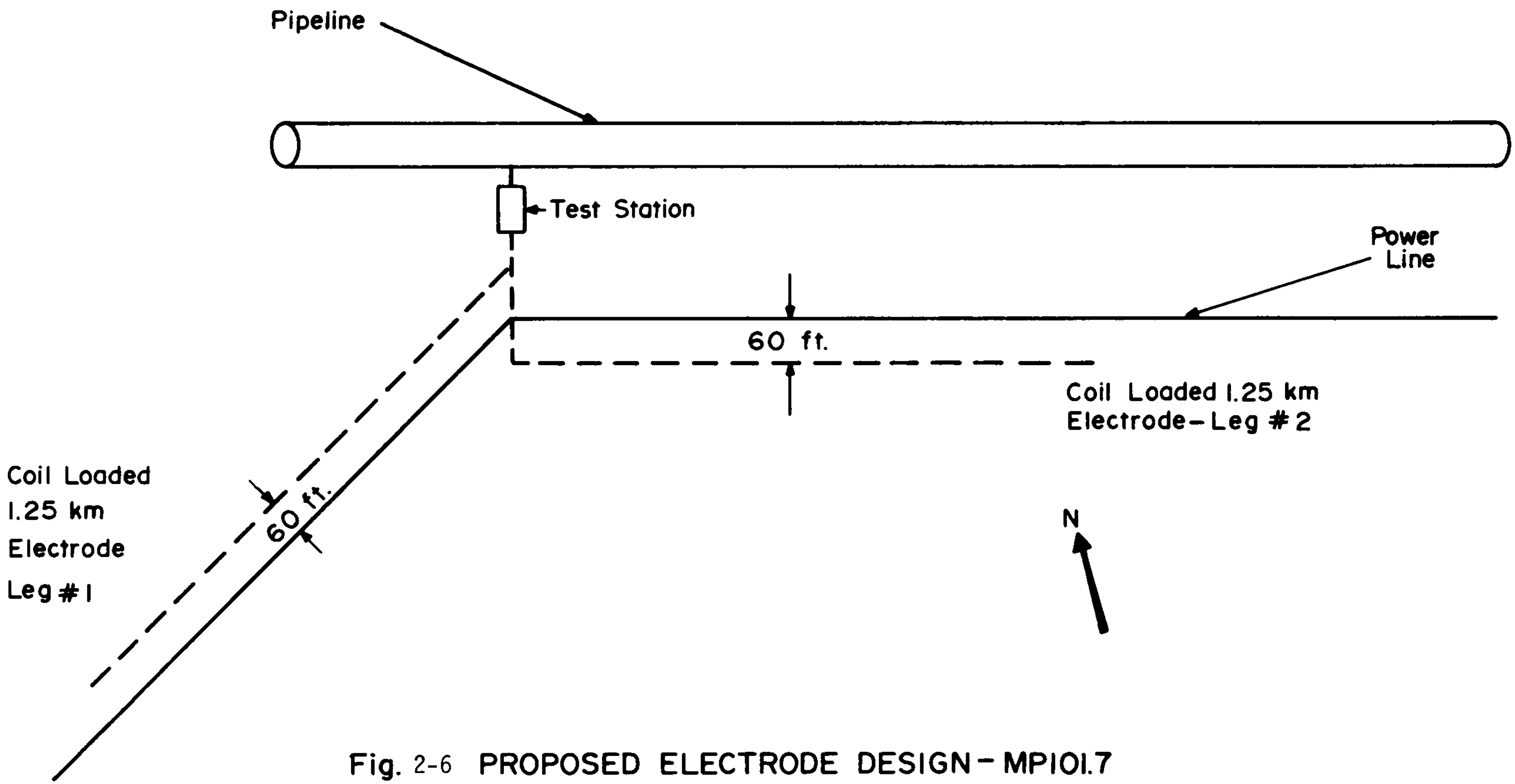


Fig. 2-6 PROPOSED ELECTRODE DESIGN - MP101.7

e. Interpolation of the graphs of Figure D-14 (Appendix D) to obtain the pipeline characteristic impedance, Z_o, equal to $(2.9 + j\,2.4)\,\Omega$;

f. Computation of $Z_{pipe} = 0.5\ Z_o$, or

$$Z_{pipe} = 0.5(2.9 + j\,2.4) = (1.45 + j\,1.2)\,\Omega = 1.88\underline{/39.6^o}\ \Omega.$$

The pipeline section to the west of Milepost 101.7 is assumed to be sufficiently far from the power line so that it experiences little or no induced voltage pick-up. This pipeline section thus serves as a characteristic impedance load for the section to the right of Milepost 101.7, which is influenced by the power line. Therefore, a multiplying factor of 0.5 is introduced into the calculations for V_{pipe} (Step d) and Z_{pipe} (Step f) to take into account the loading effect of the west section upon both the Thevenin source voltage and source impedance as seen looking to the east.

Computation of Z_{wire} and V_{wire}. This part of the analysis computes the Thevenin equivalent source impedance, Z_{wire}, and source voltage, V_{wire} of the mitigating wire. The computation involves the following steps:

a. Assumption of a wire burial depth of one foot, a 40 kΩ-cm soil resistivity at the wire and a 700 ampere balanced power line current loading;

b. Use of the CARSON program applying the exact Carson's infinite series to calculate the electric field at the wire as being equal to 29.2 volts/km at a phase of -121.5^o relative to the power line currents.

c. Use of the program WIRE to obtain the propagation constant of the mitigating wire, equal to $(1.137 + j\ 1.022)\ km^{-1}$ and the wire characteristic impedance, equal to $(1.122 + j\ 0.816)\ \Omega$. Calculations were made for a 0.372-inch diameter bare aluminum wire loaded at the rate of 1.5 Ω-km.

d. Use of the THEVENIN program to obtain $Z_{wire} = 1.259\underline{/32.3^o}$, and $V_{wire} = 16.7\underline{/-173.3^o}$ volts.

In this analysis, the entire length of the mitigating wire is assumed to be influenced by a constant power line field of 29.2 volts/km.

Computation of V_{mit}. This part of the analysis is the computation of the voltage at Milepost 101.7 after mitigation, V_{mit}. This computation involves simply joining the two Thevenin equivalent circuits for the pipeline and mitigation wire, respectively, and solving a single node equation (the program NODE may be used here) for the voltage at the junction. The equation which the program NODE solves is,

$$V_{mit} = \frac{V_{wire} \times Z_{pipe} + V_{pipe} \times Z_{wire}}{Z_{pipe} + Z_{wire}}$$

$$= \frac{(16.7\underline{/-137.3^o})(1.88\underline{/39.6^o}) + (46.7\underline{/17.6^o})(1.259\underline{/32.3^o})}{(1.88\underline{/39.6^o} + 1.259\underline{/32.3^o})}$$

$$= 11.6\underline{/-14.2^o} \text{ volts.}$$

Computation of V_{mit} - Complete System. In this computation, the values of V_{pipe} and Z_{pipe} remain unchanged. The individual wires comprising each leg of the mitigation system are located in a mirror image configuration about the power line structure. The electric fields driving the respective wires, therefore, are 180° out of phase. However, because the direction of the wires from the point of pipe connection, relative to the power line electric fields, differ by 180°, the induced voltages in each leg are identical. Therefore, the open circuit Thevenin voltage for both wires connected together is equal to V_{wire} as derived previously. However, relative to earth, the input impedances of the wires are in parallel after connection, and Z_{wire} for the complete system is one half of the previous value, or $0.630\underline{/32.3^o}$. The mitigated value for the complete system then becomes

$$V_{mit} = \frac{(16.7\underline{/-137.3^o})(1.88\underline{/39.6^o}) + (46.7\underline{/17.6^o})(.63\underline{/32.3^o})}{1.88\underline{/39.6^o} + .63\underline{/32.3^o}}$$

$$= 6.8\underline{/-68.1^o} \text{ volts.}$$

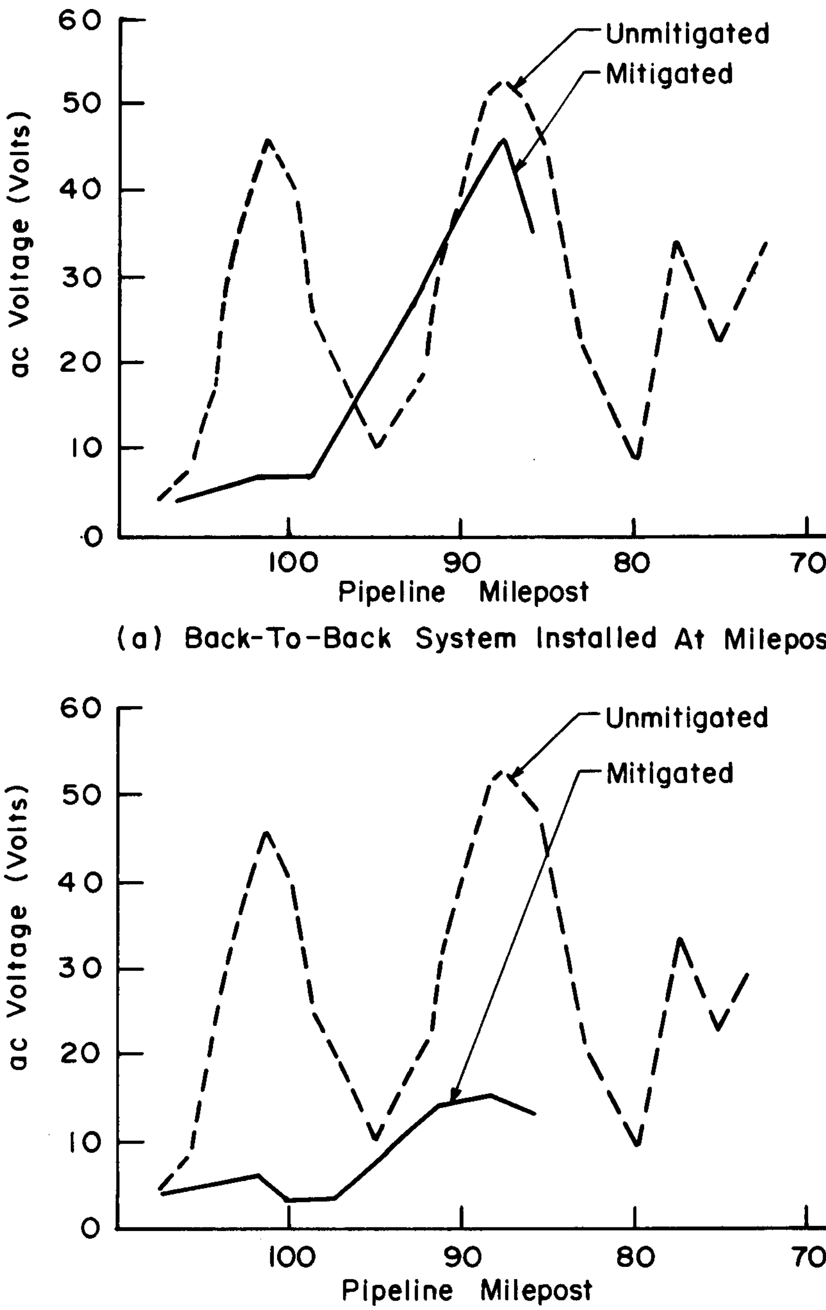
Complete Pipeline Mitigation - Example. The previous discussions were directed toward considering each mitigation wire individually and, hence, mitigation at a single point on the pipeline. In general, due to multiple physical or electrical discontinuities along the right-of-way, a pipeline will develop a number of induced voltage peaks. Installation of a single mitigation wire may reduce the local pipeline voltage but leave the other peaks unaffected. In fact, slight increases of the pipeline voltage may be caused a few miles from the grounding point due to the discontinuity of the corridor geometry introduced by the ground wire itself. However, as discussed below, experimental results show that complete pipeline mitigation is possible by mitigating successive voltage peaks individually.

An assessment of the possibility of complete pipeline mitigation, obtained by direct measurements at the Mojave test site, is summarized in Figure 2-7. The upper graph shows the mitigation obtained by installing a 2.25 km (7400 ft) total length, back-to-back parallel ground wire at Milepost 101.7. The wire was stranded aluminum, 9.4 mm (0.37 in.) diameter, and buried at a depth of 30 cm (1 ft) along two paths parallel to the power line and 18.3 m (60 ft) to either side of the power line center phase. From the figure, it is seen that the original voltage peak at Milepost 101.7 of nearly 50 volts was reduced by about 90% by installing this ground wire, representing a virtually complete mitigation. In fact, some mitigation was recorded at Milepost 89. However, although not necessarily serious, an increase in the induced voltage was measured in the region between the two peaks. This is reminiscent of the balloon effect -- i.e., "squeeze" the pipeline voltage at one point and it enlarges somewhat at other points.

The lower graph of Figure 2-7 shows the extra mitigation obtained by installing an additional 0.8 km (2600 ft) total length, center-connected parallel ground wire at Milepost 89. This wire was solid aluminum, 3.0 mm (0.12 in) diameter, and buried at a depth of 5 cm (2 in.) along a path parallel to the power line and 30 m (100 ft) from the center phase. From the figure, it is seen that the combined mitigation system at Mileposts 101.7 and 89 succeeded in pipeline voltage reduction not only at the peaks, but at intermediate locations as well. Hence, it has been demonstrated that by a reasonable placement of mitigation wires at points of corridor discontinuity, long lengths of pipeline can be mitigated effectively.

Cathodic Protection Requirements

Design of grounding arrangements for pipeline mitigation of induced voltage has been discussed. However, in general, the majority of pipelines are cathodically protected against corrosion by application of a dc bias voltage of the proper



(a) Back-To-Back System Installed At Milepost 101.7

(b) Additional Center-Connected System Installed At Milepost 89

Fig. 2-7. EXPERIMENTAL MITIGATION OF THE MOJAVE PIPELINE

polarity. In applying the pipeline grounding techniques discussed, provision must be made so as not to negate this desired protection. Suitable procedures that can be implemented are among the following.

- The use of ground wire materials which are anodic with respect to steel, e.g., zinc, magnesium ribbon, etc.
- The use of a blocking capacitor in series with the grounding electrode. The impedance of the capacitor must be kept low relative to the input resistance of the ground wire.
- The use of a polarization cell in series with the grounding wire. A low ac cell impedance is easily achievable, but the cell electrolyte will require periodic maintenance.

Section 3

PREDICTION OF ELECTROSTATICALLY COUPLED PIPELINE VOLTAGES

INTRODUCTION

The voltage gradient method for predicting the voltages and shock currents electrostatically induced by power lines on nearby above-ground pipelines is summarized. This method develops approximations for the variation of the electrostatic field with distance from the power line, and uses them to obtain an estimate of the pipeline induction effects. This approach is useful for many different power line configurations and is suitable for hand calculation.

VOLTAGE GRADIENT METHOD

It is useful to interpret the electrostatic coupling problem in circuit form, i.e., to reduce what is really a problem in electrostatic field theory to one of network solution. Figure 3-1 illustrates this interpretation for a pipeline parallel to an arbitrary configuration of N power line phase conductors and shield wires. In this figure, C'_{mn} is the capacitance/meter between the mth and nth conductors in the presence of the other N-1 conductors. The pipeline is considered as the N+1 conductor at a height of H_{N+1}, and a capacitance to ground of $C'_{N+1,N+1}$. It will exhibit a voltage of V_{N+1} with respect to ground and a steady state current flow of I_{N+1} amperes to ground.

Because the pipeline is much closer to the ground than to any of the other conductors,

$$C'_{N+1,N+1} \gg C'_{n,N+1} \qquad n = 1, 2, \ldots, N. \tag{3-1a}$$

Therefore, the capacitive reactance of the pipeline to ground is much less than the capacitive reactances of any of the other conductors to the pipeline. Using simple voltage divider arguments, it can be shown that

$$|V_{N+1}| \ll |V_n|, \; n \varepsilon \{n_p\} = \text{subscripts of the phase conductors.} \tag{3-1b}$$

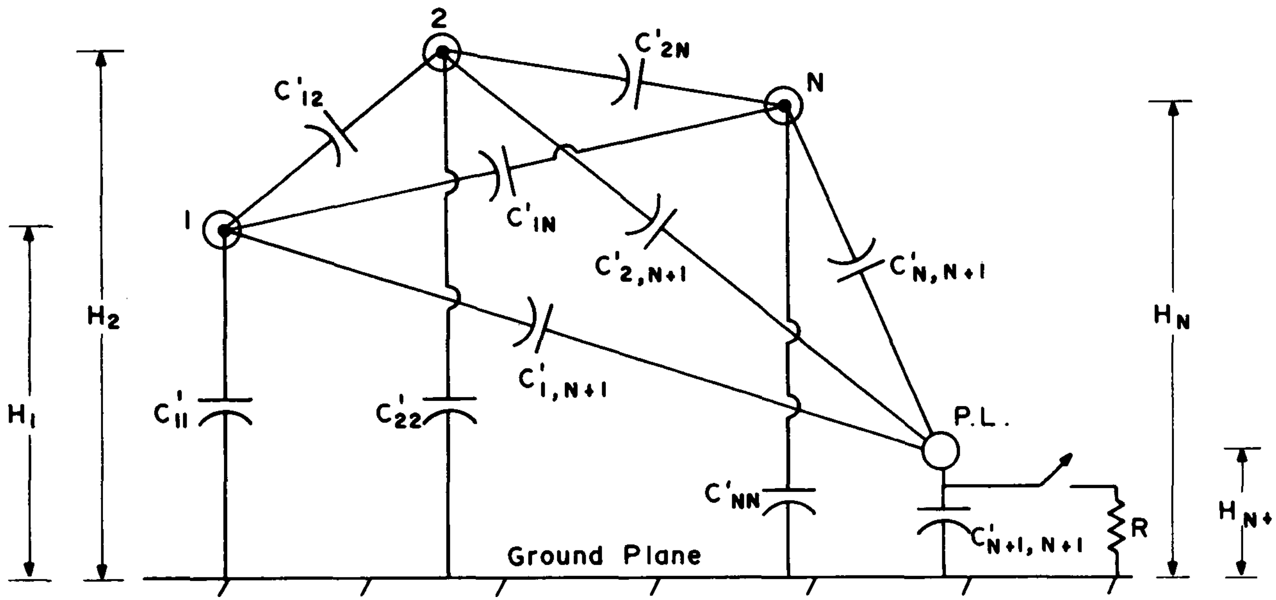


Fig 3-1. EQUIVALENT CIRCUIT FOR THE STUDY OF ELECTROSTATIC INDUCTION ON A PARALLEL PIPELINE BY N PHASE CONDUCTORS AND GROUND WIRES

However, the value of V_{N+1} can still be high enough to present a potential hazard. For example, as shown in Figure 3-1, where the pipeline is suddenly grounded through R, the body resistance of a pipeline worker. This grounding results in two electric shock hazards for the worker. First, the energy stored in the pipeline capacitance-to-ground, W_{max}, is discharged through his body in a pulse, and secondly, a steady state current, $I_{max} = |I_{N+1}|$ flows through his body, assuming that contact with the pipeline is maintained.

Application of the voltage gradient method is simple relative to other calculation techniques. Its simplicity is a result of the following approximations which have been found to be reasonable

$$V_{N+1} \simeq E_{N+1} H_{N+1} \text{ volts; } C'_{N+1,N+1} \simeq C_{N+1,N+1} \tag{3-2}$$

where V_{N+1} is the voltage induced on the pipeline, E_{N+1} is the ground level transverse voltage gradient (in volts/meter) at the pipeline location without the pipeline present, and $C_{N+1,N+1}$ is the pipeline capacitance to ground in the absence of the other conductors. Subject to these assumptions, the stored energy and current discharged from the pipeline are:

$$W_{max} \simeq \ell C_{N+1,N+1} |E_{N+1} H_{N+1}|^2 \text{ joules} \tag{3-3a}$$

$$I_{max} \simeq \omega \ell C_{N+1,N+1} |E_{N+1} H_{N+1}| \text{ amperes} \tag{3-3b}$$

where

$$C_{N+1,N+1} = \frac{2\pi\varepsilon_o}{\ln (4H_{N+1}/d_{N+1})} \text{ farads/m.} \tag{3-3c}$$

and

ε_o = free space permittivity = 8.85×10^{-12} F/m

ω = $2\pi(60) = 377 \text{ sec}^{-1}$,

ℓ = pipeline length, meters, and

d_{N+1} = pipeline diameter, meters.

The problem of estimating the pipeline voltage and the maximum shock energy and current is thus reduced to one of estimating the unperturbed transverse voltage gradient, E_{N+1}, at the pipeline.

NOTE: The unperturbed transverse voltage gradient, discussed in this section is <u>not</u> the same as the undisturbed longitudinal electric field discussed in Section 1 for electromagnetic coupling. The transverse voltage gradient results from the potential of the power line conductors with respect to ground; the longitudinal electric field results from the current flow through the power line conductors.

Estimate of the Peak Voltage Gradient

A graphical method for the computation of E_{pk}, the peak value of E_{N+1} within the power line right-of-way has been developed. This method is applicable to single and double circuits with either flat, delta, or vertical configurations of the phase conductors. The required data include the line-to-line voltage, the circular diameter of a conductor bundle, the phase conductor height and spacing, and the phase sequence for the case of double circuits. The required graphical aids for several single-circuit cases are depicted in Figure 3-2.

To illustrate this approach, consider the computation of E_{pk} for a power line with the following characteristics:

1. Single circuit, flat configuration
2. Line-to-line voltage: $V_{LL} = 500$ kV
3. Bundle data: $d_{bundle} = 0.46$ m
   $d_{subcon.} = 0.043$ m
   $k = 2$
4. Phase-to-phase spacing: $S = 10.67$ m
5. Height of phase conductors: $H = 10.67$ m

The equivalent diameter of a bundle conductor must be calculated. The appropriate formula is

$$d_{eq} = d_{bundle}\left(\frac{kd_{subcon.}}{d_{bundle}}\right)^{1/k} \text{ m}, \qquad (3\text{-}4)$$

where d_{bundle} is the bundle circular diameter; $d_{subcon.}$ is the subconductor diameter; and k is the number of bundle subconductors.

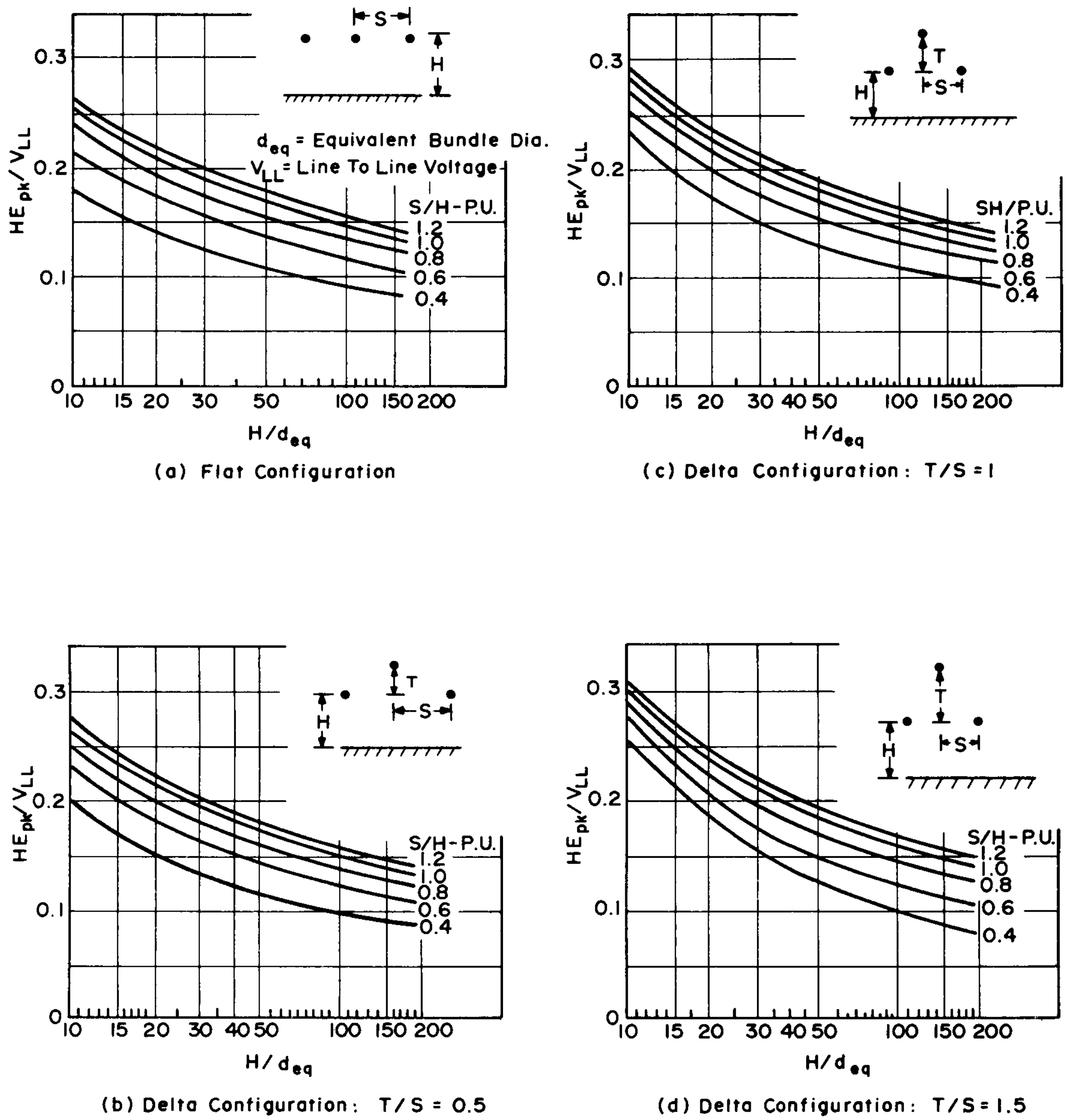


Fig. 3-2. GRAPHICAL AIDS FOR THE COMPUTATION OF E_{pk}

Using Eq. 3-4, the equivalent bundle diameter, d_{eq} is

$$d_{eq} \simeq 0.46\left(\frac{2 \times 0.043}{0.46}\right)^{1/2} = 0.199 \text{ m}$$

Two additional parameters must be calculated:

$$\frac{H}{d_{eq}} = \frac{10.67}{0.199} = 53.6$$

$$\frac{S}{H} = \frac{10.67}{10.67} = 1.0$$

where H and S are defined graphically in Figure 3-2 for several power line configurations.

Next, use Figure 3-2a, the graphical aid for the single circuit, flat configuration case. Enter the graph at the abscissa value $H/d_{eq} = 53.6$, and intersect the curve having the parameter S/H = 1.0 at the ordinate value of $H \cdot E_{pk}/V_{LL} \simeq 0.17$. Then,

$$E_{pk} \simeq \frac{0.17\ V_{LL}}{H} = \frac{0.17 \times 500}{10.67} = 8.0 \text{ kV/m}$$

The peak voltage gradient usually appears almost directly beneath the outer phase conductor for a flat configuration. This method yields information only about this worst-case pipeline position. Extension of this method will now be made to describe the variation of E_{N+1} with distance from the power line.

Estimate of the Variation of the Voltage Gradient with Distance

Straight-Line Approximation (Zone Diagram Method). A simple method to estimate the variation of E_{N+1} with distance from the power line has been developed. This method uses straight lines to approximate the exactly computed curves of E_{N+1} vs. distance for single circuit, flat configuration power lines. The formulae for the straight lines are simple enough to be hand calculable, and yet accurate enough to be highly useful. The required data include the line-to-line voltage and the height and spacing of the phase conductors.

To illustrate this approach, Figure 3-3 depicts a straight-line approximation, or zone diagram, for the variation of E_{N+1} near the 500 kV power line used in the previous example. The exactly computed values of E_{N+1} are bounded by the zone perimeter, which is defined in the general case by:

$$E_{pk} = K_1 V_{LL} V_{pu} \sqrt{S}\, H^{-K_2} \quad \text{kV/m} \qquad (3\text{-}5a)$$

$$E_{co} = K_3 V_{pu} \text{ kV/m} \qquad (3\text{-}5b)$$

$$D_{co} = K_4 S + K_5 \text{ m} \qquad (3\text{-}5c)$$

$$\beta = K_6 H^{-2} \text{ kV/m}^2 \qquad (3\text{-}5d)$$

where

E_{pk} = peak voltage gradient

E_{co} = cut-off voltage gradient

D_{co} = cut-off distance

β = zone slope

V_{LL} = line-to-line voltage (kV)

V_{pu} = per unit operating voltage of line (kV/kV)

S = phase-to-phase spacing (m)

H = phase conductor height (m)

K_1-K_6 = multiplying factors having the following dependence on V_{LL}:

V_{LL}	K_1	K_2	K_3	K_4	K_5	K_6
345	0.255	1.692	0.89	2.055	12.21	23.34
500	0.307	1.742	1.18	1.604	17.89	37.04
765	0.308	1.682	2.00	1.491	20.20	72.98
1100	0.253	1.588	3.35	1.640	17.01	115.57

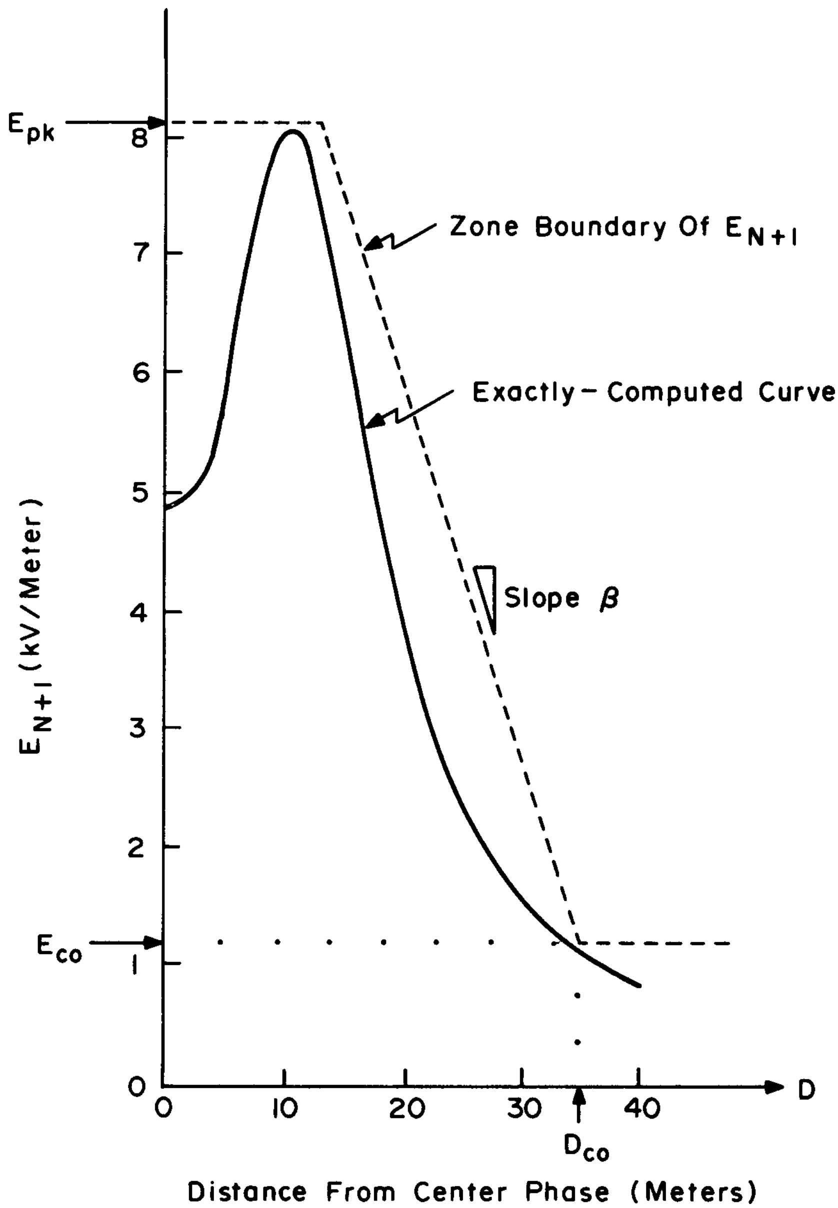


Fig. 3-3. ZONE DIAGRAM FOR A 500 kV, SINGLE-CIRCUIT, FLAT-CONFIGURATION POWER LINE

For the specific case of Figure 3-3, Eq. 3-5 yields,

$$E_{pk} = (0.307)(500)(1.0)(\sqrt{10.67})(10.67)^{-1.742} = 8.11 \text{ kV/m}$$

$$E_{co} = (1.18)(1.0) = 1.18 \text{ kV/m}$$

$$D_{co} = (1.604)(10.67) + 17.89 = 35.00 \text{ m}$$

$$\beta = (37.04)/(10.67)^2 = 0.32 \text{ kV/m}^2.$$

The value of E_{pk} calculated here differs from that obtained using the previous more simple approach by only about 2 percent, which is considered satisfactory. However, in addition to E_{pk}, we now have a useful estimate of the drop-off of E_{N+1} from E_{pk} as the distance to the power line increases up to D_{co}. Beyond D_{co}, the upper bound for E_{N+1} is simply E_{co}, which is independent of phase spacing and conductor height.

Cut-Off Zone Gradient Approximation. The zone defined by $D \geq D_{co}$, $E_{N+1} \leq E_{co}$, yields an upper bound for E_{N+1} that has no dependence on distance. However, as seen in Figure 3-3, the exactly computed curve for E_{N+1} continues to decrease in amplitude as D increases beyond D_{co}. A more useful bound for this case is

$$E_{N+1} \leq E_{co} \left(\frac{D_{co}}{D}\right)^2 , \; D \geq D_{co} \tag{3-6}$$

which represents the drop-off of the gradient for a single phase conductor above ground.

Extension to Different Single and Double Circuit Conductor Configurations. Extension of the zone approach to delta, inverted delta, and single circuit vertical configurations, and to center line symmetrical and center point symmetrical double circuit configurations is shown in Figure 3-4. The recommended procedure is as follows:

1. Determine V_{LL}, V_{pu}, S, and H for the power line configuration of interest, with S and H defined for the configuration as in Figure 3-4.

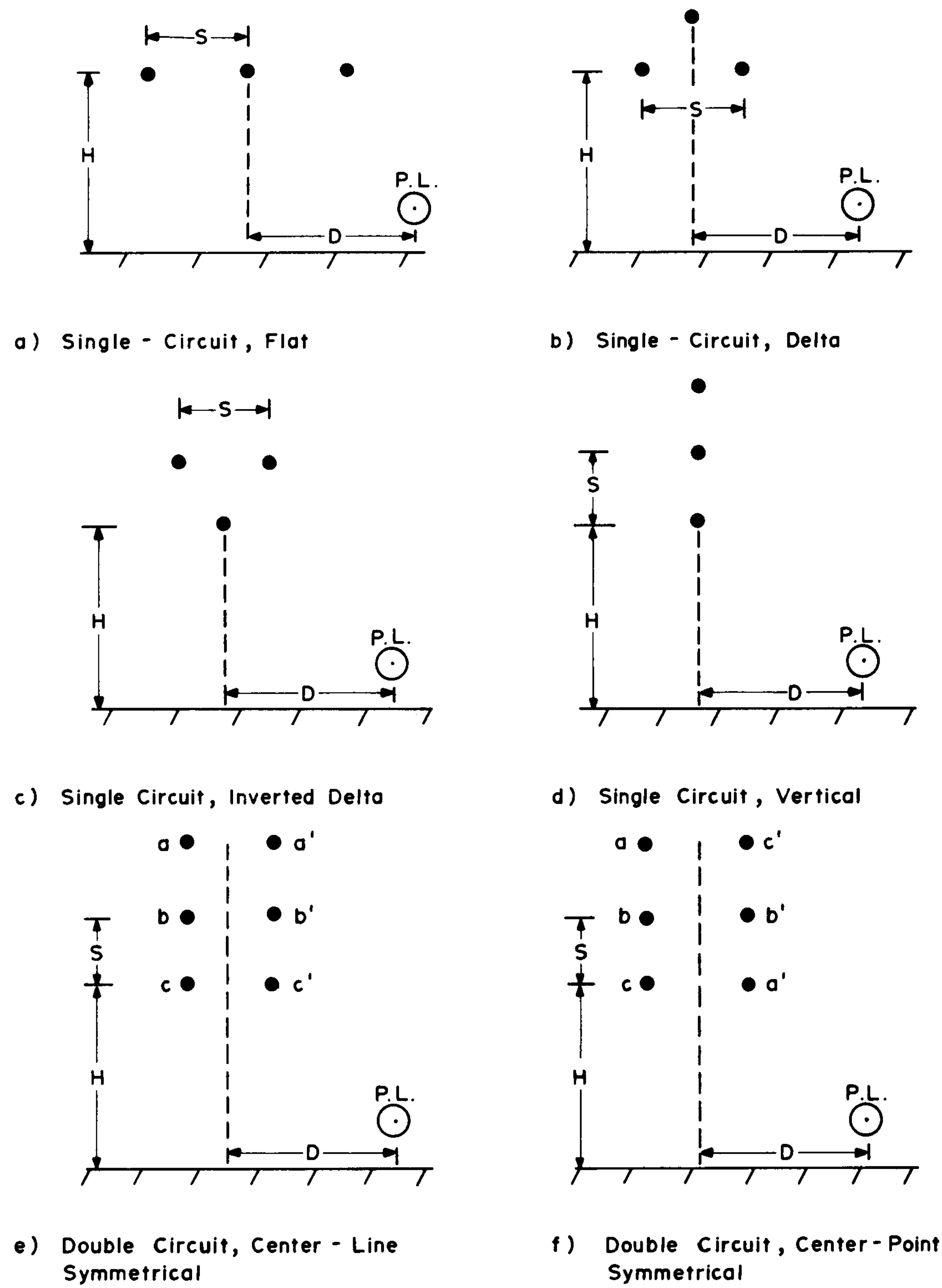


Fig. 3-4. LINE CONFIGURATIONS FOR THE EXTENDED ZONE METHOD

2. Determine E_{pk}, E_{co}, D_{co} and β, using Eq. 3-5 and the parameters of Step 1 above.

3. For the configuration desired, multiply the values determined in Step 2 by the following factors:

	Phase Conductor Configuration	Multiplying Factors for E_{pk}	E_{co}	D_{co}	β
(a)	Single circuit, flat	1.0	1.0	1.0	1.0
(b)	Single circuit, delta	0.9	0.8	0.8	0.93
(c)	Single circuit, inverted delta	0.9	0.78	0.5	1.15
(d)	Single circuit, vertical	1.0	0.4	0.6	1.03
(e)	Double circuit, center line symmetrical	1.3	0.5	0.8	1.3
(f)	Double circuit, center point symmetrical	0.84	0.5	0.75	1.0

In this manner, the significantly different voltage gradient profiles of six power line configurations can be estimated by a single, hand calculable method.

Extension to the Non-Parallel Pipeline Case. If the pipeline is built in different sections or if it is not parallel to the power line, computations should be made for each section, accounting also for the phase of the ground voltage gradient. This phase accounting requirement greatly complicates the computation procedure because no zone diagrams for the phase of the gradient are available. Therefore, the profile of gradient phase along the pipeline must be obtained by use of a relatively complex formula. Details of the computational procedure are given in Section 4 of Volume I.

SUMMARY

This section has summarized an available analytical method for predicting the voltage and shock currents electrostatically induced by ac power lines on nearby above-ground pipelines. The voltage gradient method reviewed allows accurate approximation of the electrostatically induced pipeline voltage and current, and is computationally simple. Here, the transverse voltage gradient at the pipeline location is determined either for the worst-case coupling condition, or as a function of pipeline separation from the adjacent power line. Pipeline shock hazards are then related to the transverse voltage gradient. The most important feature of this approach is the use of simple, hand-calculable approximation methods for the variation of the voltage gradient with distance from many typical power line phase conductor configurations, including flat, delta, inverted delta, and vertical single-circuit lines, and center-line and center-point symmetrical double-circuit lines. With the voltage gradient known at a given distance from the power line, the electrostatically induced voltage on the pipeline is then simply equal to the gradient value multiplied by the height of the pipeline above ground (c.f., eq. 3-2).

For the situation where a power line(s) exists on a ROW, a prediction of induced voltage levels may be based upon actual measurement of the voltage gradient. Methods and instrumentation are available for such measurements (1).

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1. Electrostatic and Electromagnetic Effects of Ultrahigh-Voltage Transmission Lines. Palo Alto, California: Electric Power Research Institute, June 1978. EL-802.

Section 4

MITIGATION OF ELECTROSTATICALLY COUPLED PIPELINE VOLTAGES

REVIEW OF THE CONSEQUENCES OF ELECTROSTATIC COUPLING

During the construction of a pipeline, it is possible that long sections of pipe may rest above the ground surface. If the pipe is located near a high voltage power line, it can assume a large voltage to ground. The voltage is due to the capacitances between the power line conductors and the pipe, and between the pipe and ground, which form a capacitive voltage divider. A pipeline worker accidentally grounding the pipe through his body faces two hazards.

1. The energy stored in the pipeline capacitance to ground is discharged through the body of the worker in the form of an exponentially decaying pulse. If there is sufficient stored energy, this discharge can be painful or even fatal. Additional hazard arises from the possible ignition of volatile liquids, such as gasoline, stored near the point of discharge.

2. If contact with the pipe is not broken, a steady-state current flows through the body of the worker. If the current is large enough, injury or death can result.

MITIGATION OF ELECTROSTATIC COUPLING

Spacing of the Pipeline from the Power Line

Where possible, electrostatic coupling of a power line to an adjacent aboveground pipeline can be mitigated simply by locating the pipeline as far as possible from the affecting power line. As shown in Section 3, the intensity of electrostatic coupling is directly dependent upon the magnitude of the transverse electric field generated by the power line. The method presented can be used for estimating the variation of this electric field with distance from the power line. It uses straight lines to approximate the exactly computed curves of transverse electric field vs. distance from several common phase conductor configurations. These straight lines represent upper bounds for the expected electric field, and thus, can be used to estimate the worst-case electrostatic coupling at each distance from the power line.

From Figure 3-2 it is seen that electrostatic coupling decreases markedly past the cut-off distance, D_{co}, falling off approximately as the inverse square of the separation. Thus, if possible, it is desirable to maintain a separation of at least D_{co} between a power line and an above-ground pipeline to achieve a significant reduction of the level of electrostatic coupling.

Pipeline Grounding

As shown in Figure 4-1, the hazards due to ac coupling to an above-ground pipeline can be mitigated by grounding long pipe sections using independent ground beds, and by installing ground mats at points of possible human contact with the pipe. Basic considerations for the application of these techniques are now summarized.

Independent Ground Beds. Mitigation of the electrostatic discharge pulse through a pipeline worker touching an above-ground pipeline can be achieved by grounding the pipeline through an impedance, Z_m, having a much smaller magnitude than that of Z_{pg}, the impedance of the pipeline-to-ground capacitance. As shown in Figure 4-2, mitigation of this hazard requires that $|Z_m|$ be much less than $|Z_w|$, the impedance of the current path through the body of the pipeline worker. In this way, Z_m can divert most of the shock current sourced by the high impedance, Z_{pg}, away from the worker in a current divider action. The required value of Z_m is given by

$$Z_m = \frac{I_w}{I_{max} - I_w} Z_w \qquad (4\text{-}1a)$$

where I_{max} is the maximum steady state current available from the pipe, and I_w is the maximum permissible steady state current through the worker.

To estimate the value of Z_m needed to mitigate the worst case, I_w is taken as the current level, 9 mA at which 0.5% of the men tested cannot achieve let-go, and Z_w is taken as the wet skin body impedance, 1500 ohms, resulting in

$$Z_m \text{ (worst case)} \simeq \frac{13{,}500}{I_{max}} \text{ ohms} \qquad (4\text{-}1b)$$

where I_{max} is given in mA and is assumed to be much greater than I_w (worst case) = 9 mA.

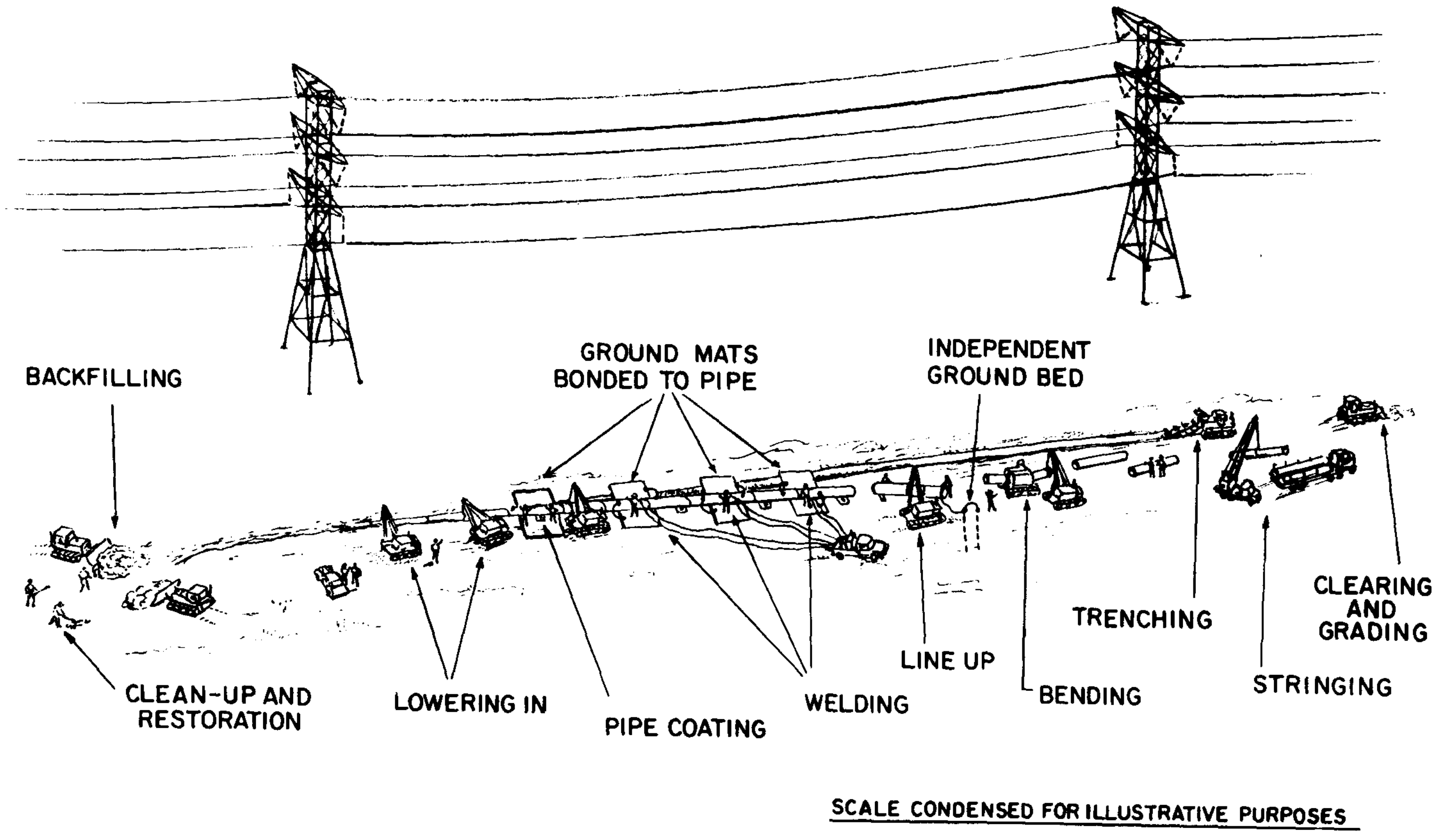
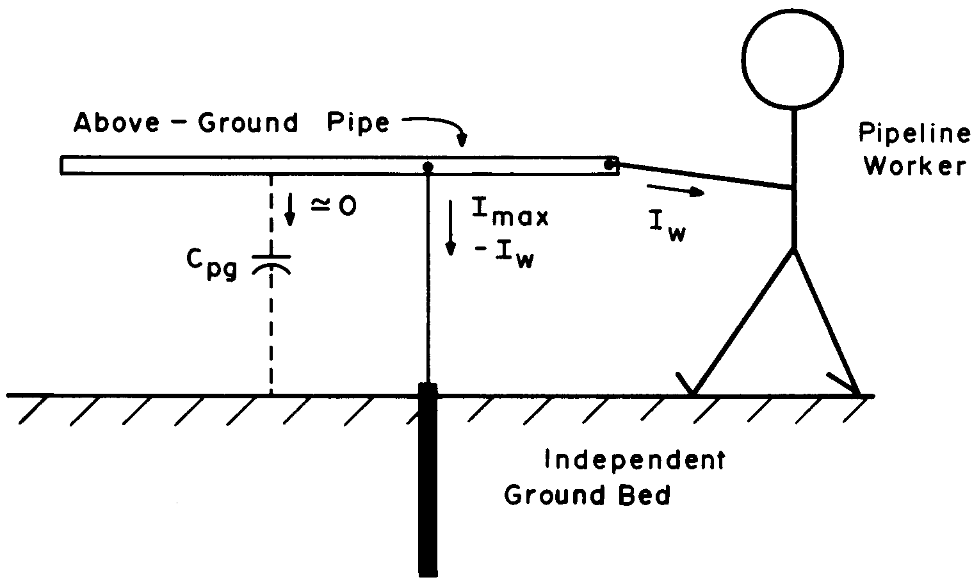
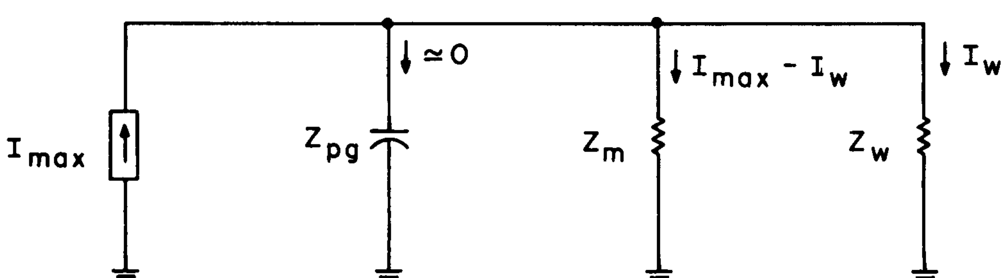


Fig. 4-1. APPLICATION OF GROUNDING TECHNIQUES FOR MITIGATION OF ELECTROSTATIC COUPLING TO A TYPICAL PIPELINE UNDER CONSTRUCTION



(a) Pipeline Worker Geometry



(b) Equivalent Circuit

Fig. 4-2. MITIGATION OF ES SHOCK HAZARDS BY PIPELINE GROUNDING

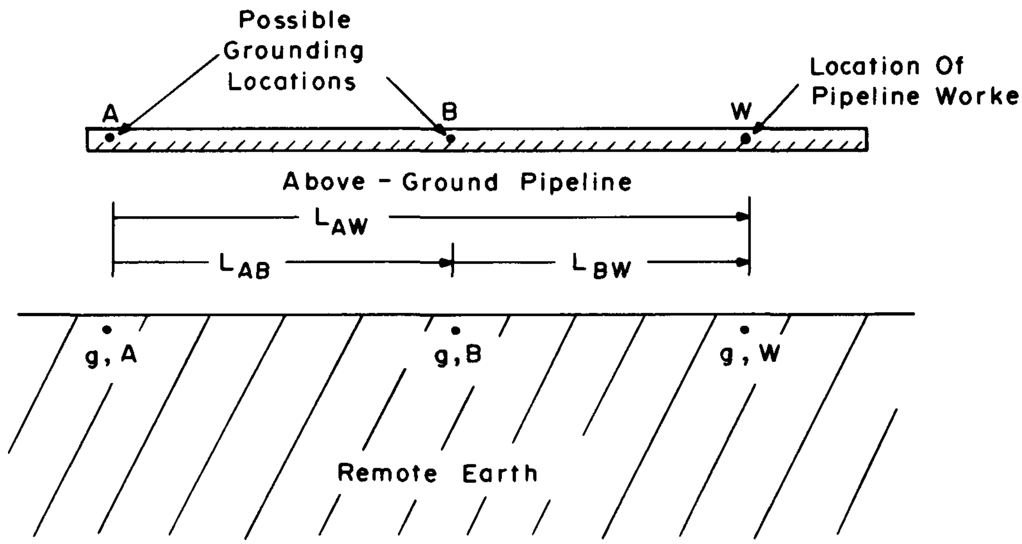
Z_m can be realized by installing one or more vertical or horizontal grounding conductors, forming a ground bed independent of the power line ground, as discussed in Section 2. Formulas are presented there which allow calculation of grounding impedances.

The installation of independent ground beds for mitigation of electrostatic coupling can lead to the inadvertent generation of pipeline voltage hazards due to electromagnetic and ground current coupling. This possibility is illustrated in Figure 4-3. After grounding the pipe at point A with impedance $Z_{m,A}$, an electric shock hazard at point W exists due to the inductively-coupled voltage, $E_o L_{AW}$, developed along the length of pipe between the ground and the worker. Addition of a ground at the intermediate point, B, serves to reduce (but not eliminate) this hazard.

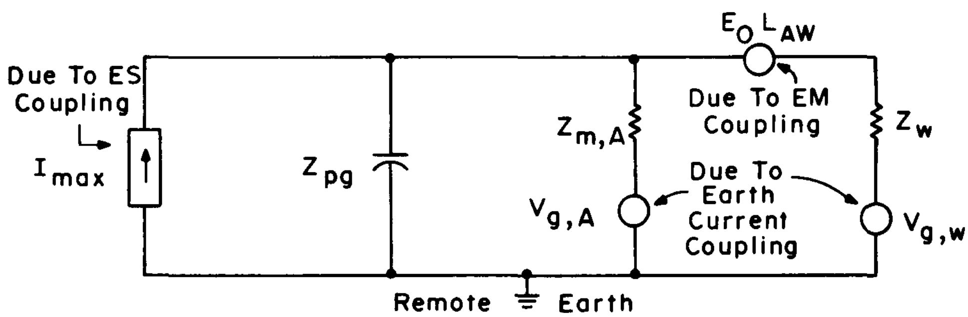
Further, grounding the pipe at point A or B can lead to elevation of the pipe potential if the ground systems are subject to earth current flow. Here, the earth current results in the ground systems being raised to the potentials $V_{g,A}$ and $V_{g,B}$, respectively. Additional hazard exists if the worker stands in an earth current area and is himself elevated to the potential $V_{g,W}$ relative to remote earth, and likely, the pipe. Earth potentials can range above 100 volts for representative values of ground resistivity, earth current magnitude, and distance from the current grounding area.

Problems associated with installing independent ground beds can be mitigated or avoided by proper positioning of the beds relative to the power line, as illustrated in Figure 4-4. The goal of this positioning is to minimize the earth potential at the location of each ground bed, and the electromagnetically-induced pipeline voltage between adjacent ground beds.

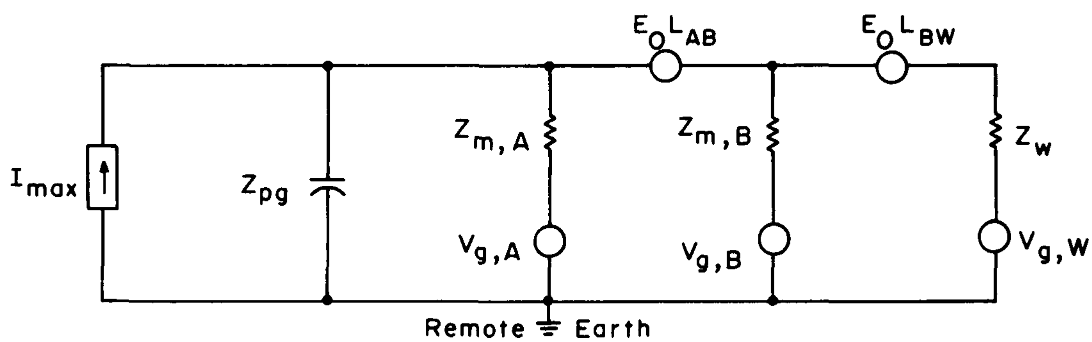
Inadvertent ground current coupling can be minimized by installing the ground beds outside the zone of hazardous earth potentials occurring during power line faults. The boundary of this zone is a function of the fault current capacity of the power line, the nature of the power line grounding system (structure footings and/or counterpoise), and the earth resistivity. The variations of earth potential with distance from the fault point is discussed later in this section. In general, ground beds should be installed midway between power line structures and as far as practicable from the power line. In this way, the earth potential at each ground bed is low at all times, and a worker contacting the pipe during a ground



(a) Pipeline - Worker Geometry



(b) Equivalent Circuit After Grounding Point "A"



(c) Equivalent Circuit After Grounding Points "A" And "B"

Fig. 4-3. INADVERTENT GENERATION OF MULTI-MODE COUPLING BY PIPELINE GROUNDING

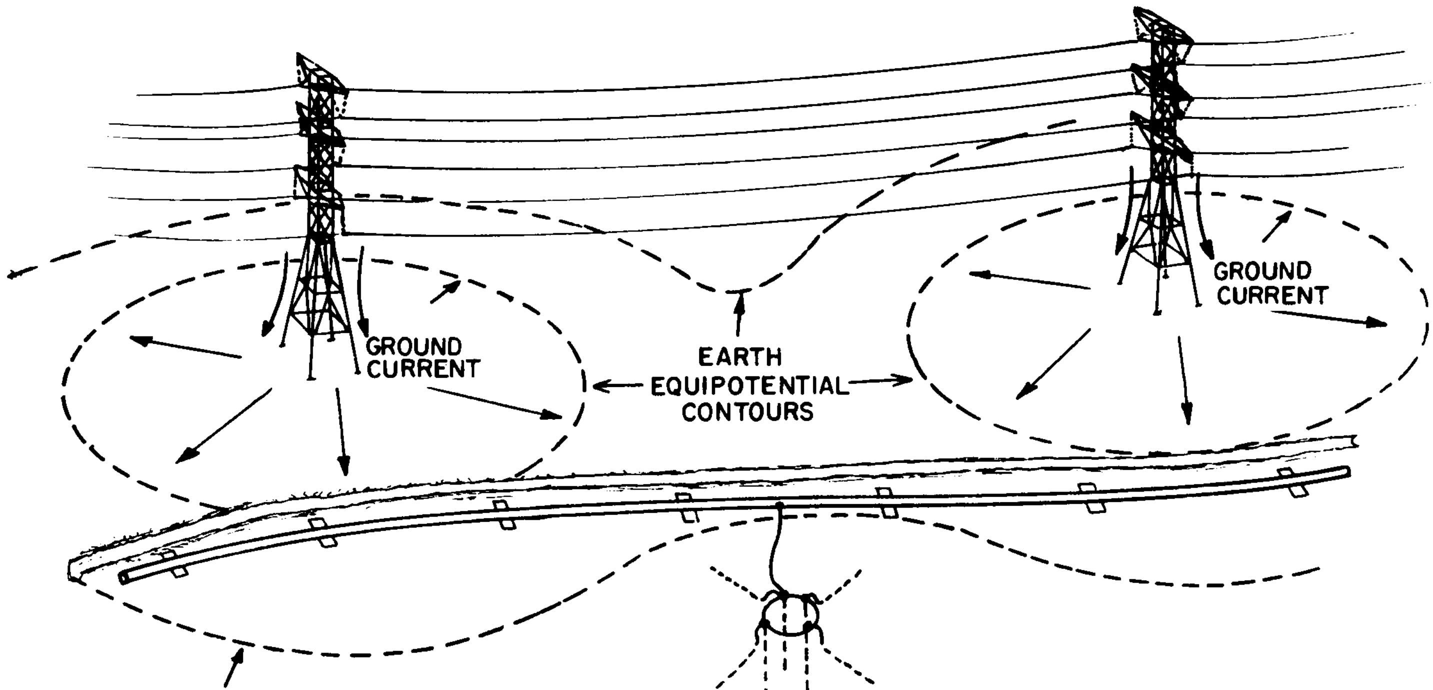


Fig 4-4. PLACEMENT OF INDEPENDENT GROUND BEDS FOR MITIGATION OF INADVERTENT MULTI - MODE COUPLING TO AN ABOVE-GROUND PIPELINE

current condition can be endangered only if his local earth potential is high, i.e., if he is located in a ground current area. Because most of the above-ground pipeline is probably outside of ground current areas, such a placement of ground beds provides for the protection of the maximum number of pipeline personnel.

Inadvertent electromagnetic coupling can be reduced by installing the ground beds at intervals of the power line span length. By selecting an ac impedance value of about 30 ohms for each bed, a net pipe leakage resistance to remote earth of about 10 ohms/km is achieved, which is comparable to the leakage resistance of a well-insulated buried pipeline. In effect, the periodic grounding, or impedance loading of an above-ground pipe results in an inductive coupling problem similar to that which would exist if the same pipe section were buried.

Mitigation is completed by installing a low impedance ground at each end of the pipe to reduce the voltage peaks which result there. The ac impedance of these pipe-end ground beds should be 2 ohms or less to achieve an effective overall potential reduction.

Ground Mats. Mitigation of multi-mode coupling to a pipeline under construction can be realized easily and effectively by installing ground mats at all worker locations. These mats, bonded to the pipe, serve to reduce touch and step voltages in areas where persons can come in contact with the pipe. These mats can be portable steel mesh grids laid on the ground at welding positions, and connected with a cable to the pipe. At permanent exposed pipeline appurtenances, such as valves, metallic vents, and corrosion control test points, ground mats can be constructed of strip galvanic anode material buried in a spiral pattern just below the surface and connected to the pipeline electrically. By using galvanic anode material, such mats reinforce any cathodic protection systems on the pipeline rather than contribute to the pipeline corrosion problem, as would be the case if copper grounding were used.

With mats so installed and connected, the earth contacted by the mat is at virtually the same potential as the pipe. In this way, a worker touching the pipe is assured that the potential appearing between his hands and feet is only that which is developed across the metal of the mat, regardless of the mode of ac interference affecting the pipe. This effective shunting of the worker by a metal conductor provides protection for very severe cases of coupling, such as occur during lightning strikes and faults. It is especially useful for pipes subject to simultaneous interference by electrostatic, electromagnetic, and earth-current coupling.

Ground mats should be designed large enough to cover the entire area on which persons can stand while either touching the pipe or contacting it with metal tools or equipment. Each mat should be bonded to the pipe at more than one point to provide protection against mechanical or electrical failure of one bond. Step potentials at the edges of each mat can be mitigated by providing a layer of clean, well-drained gravel beneath the mat and extending the gravel beyond the perimeter of the mat. This serves to reduce the conductivity of the material beneath the mat, and to provide a buffer zone between the earth and the ground mat.

Appendix A

INSTRUCTIONS FOR USE OF THE TEXAS INSTRUMENTS MODEL TI-59 HAND CALCULATOR PROGRAMS

INTRODUCTION

This appendix discusses eight programs for the Texas Instruments Model TI-59 programmable hand calculator that are used to implement the analytical methods of this book. These programs allow the simple and rapid computation of pipeline electrical parameters, driving fields, and induced voltages by applying sophisticated numerical techniques that would normally require a large-scale computer. Essentially no manipulation of complex numbers is required by the user, greatly reducing the possibility of error.

The eight programs are as follows:

1. Program CARSON. This program computes the mutual impedance between parallel earth-return conductors using Carson's infinite series (c.f., A-3).

2. Program CURRENTS. This program computes the currents in earth-return conductors adjacent to a power line that can influence the driving field at the pipeline of interest (c.f., A-6).

3. Program PIPE. This program computes the propagation constant and characteristic impedance of a buried pipeline having arbitrary characteristics (c.f., A-10).

4. Program WIRE. This program computes the propagation constant and characteristic impedance of a horizontal buried ground wire having arbitrary characteristics (c.f., A-13).

5. Program THEVENIN. This program computes the Thevenin equivalent circuit for the terminal behavior of an earth-return conductor parallel to a power line (c.f., A-16).

6. Program NODE. This program computes the node (pipeline) voltage and branch (pipeline) current for three Thevenin equivalent circuits connected at one common point (c.f., A-19).

7. Program FIELD. This program computes the driving field at an earth-return conductor, given a knowledge of the currents in adjacent earth-return conductors and the mutual impedance between each adjacent conductor and the conductor of interest (c.f., A-23).

8. Program SHIELD. This program computes the series impedance of a power line shield wire for use in Program CURRENTS (c.f., A-26).

All program descriptions include specific instructions for usage. It is assumed that the programs will be available on magnetic cards recorded prior to use in the field.

Examples of practical applications of these programs are given in the case histories reviewed in Appendix B.

Program CARSON

Program CARSON computes the mutual impedance between adjacent, parallel, earth-return conductors using Carson's infinite series. This program can be used in the field to determine Carson mutual impedances to better than 0.1 percent accuracy, regardless of earth resistivity conditions, conductor configuration (either aerial or buried), and conductor separation. This program, documented using Figure A-1 and Table A-1 computes and sums as many terms of the Carson series as is required to achieve the desired accuracy. The program can be permanently recorded on two magnetic cards.

Figure A-1 details the conductor geometry assumed for this program and defines the essential data parameters keyed in by the user. Table A-1 provides a step-by-step instruction procedure for the use of the program.

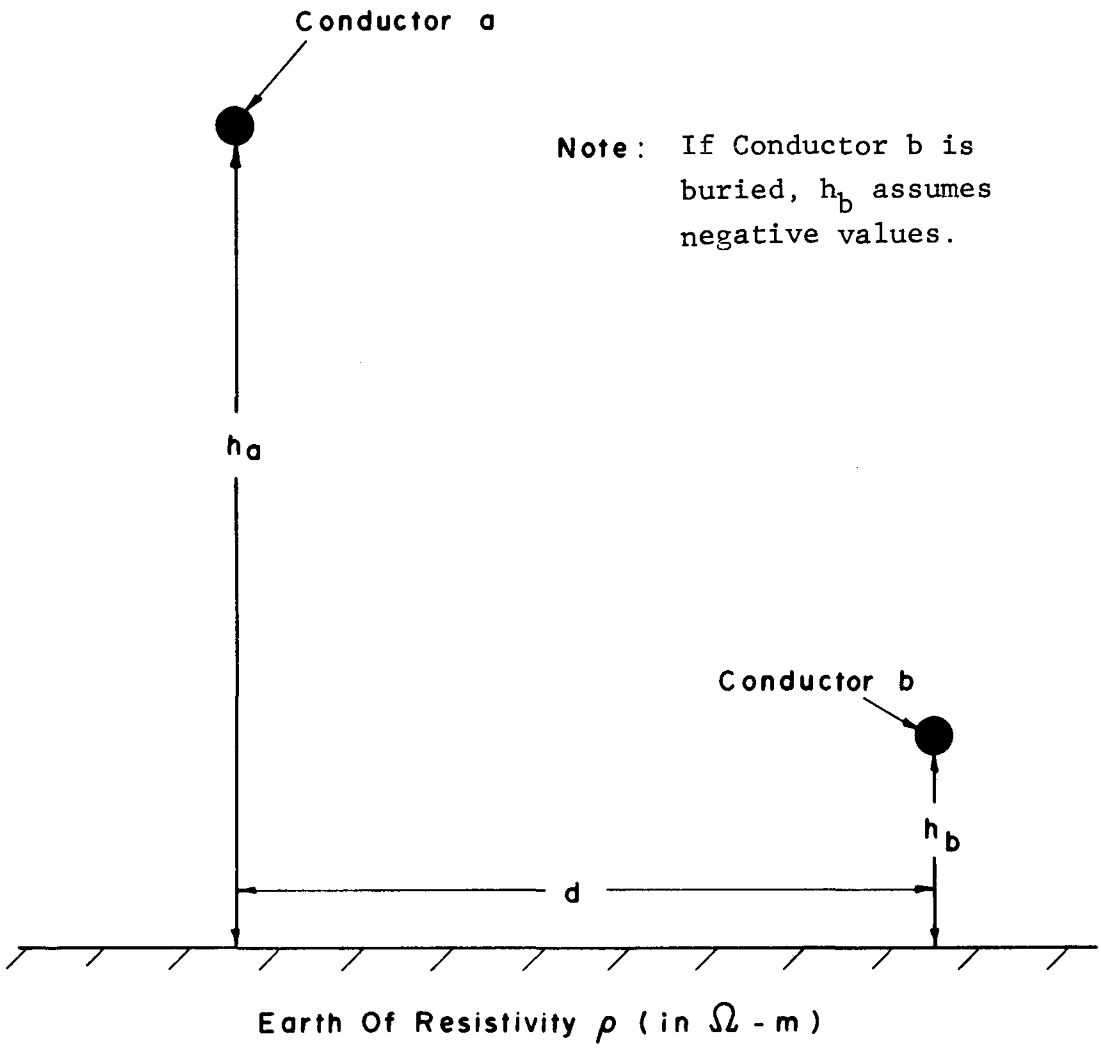


Figure A-1. Conductor Geometry for Program CARSON

Table A-1

INSTRUCTIONS FOR PROGRAM CARSON

1. Press CLR. Then, press 3 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.
   Press 2. Then, insert bank #2 into the card reader.
   Press 3. Then, insert bank #3 into the card reader.

3. Key ρ (in ohm-meters) into the display. Then, press A.
   Key h_a (in feet) into the display. Then, press B.
   Key h_b (in feet) into the display. Then, press C.
   Key d (in feet) into the display. Then, press D.

4. Press E. Then, wait for the display to unblank. The waiting time ranges from 24 seconds to 104 seconds, depending upon the number of Carson's series terms computed. The display then shows $|Z_{ab}|$ in ohms/km.

5. Press x⇄t to display $\angle Z_{ab}$ in degrees.

   NOTE: If the PC-100A printer is used, $|Z_{ab}|$ and $\angle Z_{ab}$ will be printed out automatically and labelled as "ZMAG" and "ZPHA", respectively. The solution will further be labelled "SERIES solution" or "ASYMPTOTIC SOLUTION" depending upon the computation method employed by the calculator.

6. If Z_{ab} is desired for different values of either ρ, h_a, h_b, or d, simply return to Step 3 and key in the appropriate values (in any order). Then, do Steps 4 and 5.

Program CURRENTS

Program CURRENTS computes the currents in earth return conductors adjacent and parallel to a multiple phase power line. These conductors may be either above or below ground level. Representative types are power line shield wires, fence wires, telephone wires, railroad tracks, or buried pipelines of sufficient length to significantly modify the total parallel electric field influencing the pipeline of interest. Since these earth return conductors affect each other as well as being affected by the power line, the solution is obtained by solving a set of simultaneous equations describing the mutual interactions. The calculator processes a system as complex as five unknown earth return conductors adjacent to 25 power line phase conductors, yielding both the magnitude and phase of each unknown current. The program allows the specification of a desired current magnitude accuracy, ΔI. The calculator continues computations until either this accuracy criterion is fulfilled for each of the unknown currents, or until ten iterations have been completed. The program can be permanently recorded on one magnetic card.

Figure A-2 details the conductor geometry assumed for the program and defines the essential data parameters keyed in by the user. Here, phase conductor currents are assumed to be known and unaffected by the adjacent conductor currents. Carson mutual impedances are assumed to have been computed previously using Program CARSON, already presented. Conductor self impedances are required to be inputted into the program and are found as follows.

The self impedance per kilometer of an above-ground conductor is given by Program SHIELD, to be discussed later in this appendix. The self impedance per kilometer of a buried conductor is obtained by using either Program PIPE or Program WIRE, also discussed later. Table A-2 provides a step-by-step instruction procedure for the use of the program.

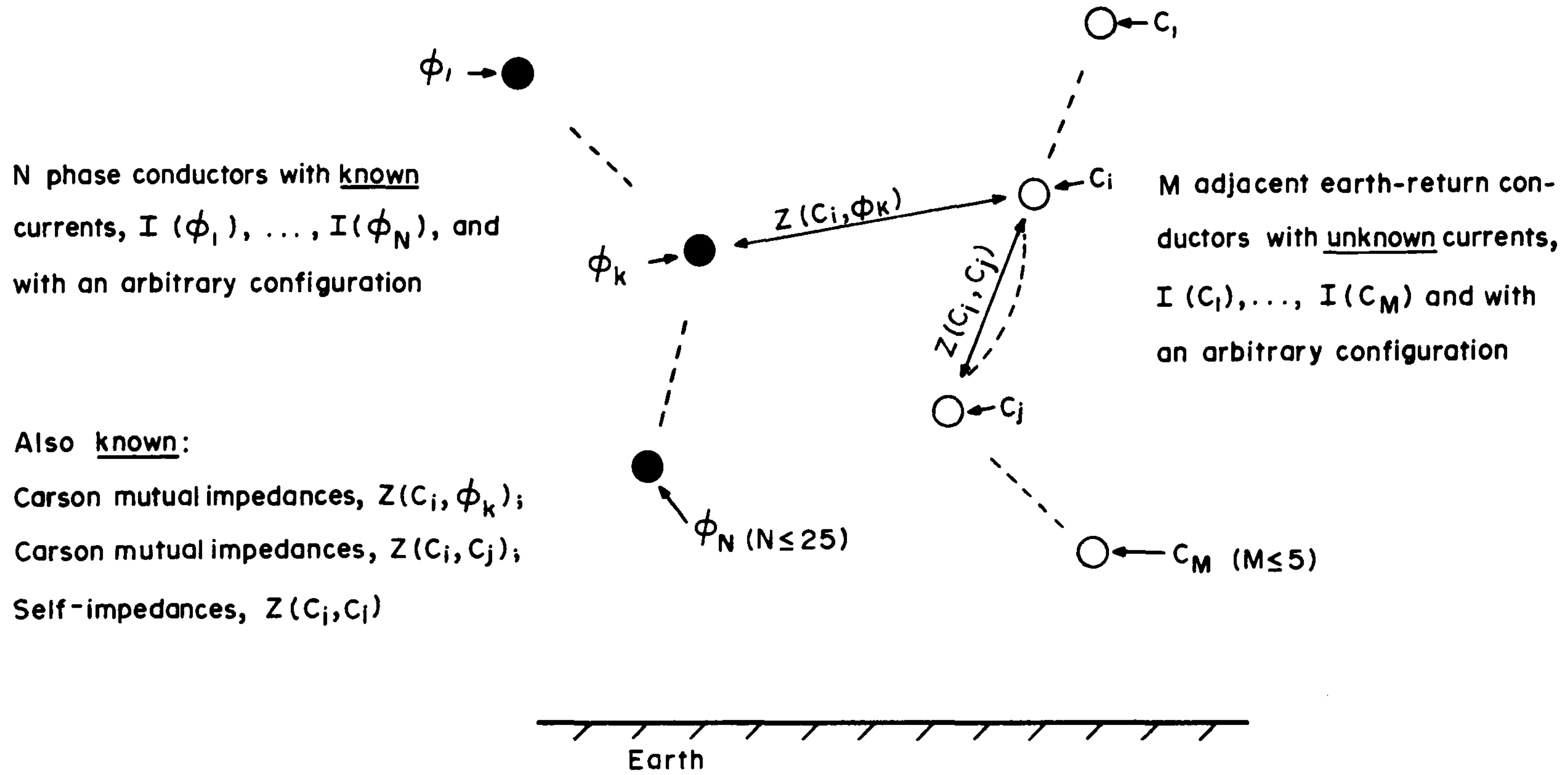


Figure A-2. Conductor Geometry for Program CURRENTS

Table A-2

INSTRUCTIONS FOR PROGRAM CURRENTS

1. Press CLR. Then, press 9 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.

3. Key N (an integer from 1 to 25) into the display. Then, press A.
Key M (an integer from 1 to 5) into the display. Then, press R/S.
Key ΔI (in amperes) into the display. Then, press R/S.

   NOTE: To limit the program running time but yet achieve good accuracy, choose ΔI to be about 0.1% of the typical phase conductor current.

4. Key $|I(\emptyset_1)|$ (in amperes) into the display. Then, press B.
Key $\angle I(\emptyset_1)$ (in degrees) into the display. Then, press R/S.
Repeat the preceding two steps for each of the other phase conductor currents, $I(\emptyset_2)$ ..., $I(\emptyset_N)$.

5. Key $|Z(C_1,\emptyset_1)|$ (in ohms/km) into the display. Then, press C.
Key $\angle Z(C_1,\emptyset_1)$ (in degrees) into the display. Then, press R/S.
Repeat the preceding two steps for $Z(C_1,\emptyset_2)$, ..., $Z(C_1,\emptyset_N)$.
Repeat the preceding three steps for each of the other earth return conductors, C_2, ..., C_M.

6. Key in the mutual impedance matrix of the system of earth-return conductors, in the following way:

Key in ↓ Press ↓ Key in ↓ Press ↓ ... etc.

$$|Z_{C_1C_1}|\ (D)\ \angle Z_{C_1C_1}\ (R/S) \rightarrow |Z_{C_1C_2}|\ (D)\ \angle Z_{C_1C_2}\ (R/S) \cdots |Z_{C_1C_M}|\ (D)\ \angle Z_{C_1C_M}\ (R/S)$$

$$|Z_{C_2C_1}|\ (D)\ \angle Z_{C_2C_1}\ (R/S) \rightarrow |Z_{C_2C_2}|\ (D)\ \angle Z_{C_2C_2}\ (R/S) \cdots |Z_{C_2C_M}|\ (D)\ \angle Z_{C_2C_M}\ (R/S)$$

etc. ...

$$|Z_{C_MC_1}|\ (D)\ \angle Z_{C_MC_1}\ (R/S) \rightarrow |Z_{C_MC_2}|\ (D)\ \angle Z_{C_MC_2}\ (R/S) \cdots |Z_{C_MC_M}|\ (D)\ \angle Z_{C_MC_M}\ (R/S)$$

Here, $Z_{C_iC_j}$ for $i \neq j$ is the Carson mutual impedance between earth-return conductors C_i and C_j. For $i = j$, $Z_{C_iC_i}$ is the series self impedance of earth-return conductor C_i. All magnitudes are in ohms/km; all phase angles are in degrees.

Table A-2 (Continued)

INSTRUCTIONS FOR PROGRAM CURRENTS

7. Press E and wait 15 seconds for the display to unblank.

8. Press CLR. Then, press 1 and insert bank #1' into the card reader.

9. Press A. Then, wait for the display to unblank. The waiting time ranges from 2 minutes to 15 minutes, depending upon the number of adjacent earth-return conductors computed. When the display unblanks, the presence of a 1 indicates that the problem has been solved with the specified accuracy, ΔI; a 0 indicates that the algorithm did not converge to within the accuracy bound.

10. To display the currents of the earth return conductors, perform the following operations.

Press	Display
RCL 80	$\|I(C_1)\|$ (amps)
RCL 85	$\angle I(C_1)$ (degrees)
RCL 81	$\|I(C_2)\|$ (amps)
RCL 86	$\angle I(C_2)$ (degrees)
	⋮
RCL 84	$\|I(C_5)\|$ (amps)
RCL 89	$\angle I(C_5)$ (degrees

Program PIPE

Program PIPE computes the propagation constant, γ, the induced voltage constant, $1/|\gamma|$, and the characteristic impedance, Z_0, of a buried pipeline having arbitrary characteristics. This program accurately accounts for the following pipeline or soil variables: pipe burial depth, pipe diameter, pipe wall thickness, pipe steel relative permeability, pipe steel resistivity, pipe coating resistivity, and earth resistivity. The pipe self-impedance can then be calculated by forming the product γZ_0.

Figure A-3 details the pipeline geometry assumed for this program and defines the essential data parameters keyed in by the user. Table A-3 provides a step-by-step instruction procedure for the use of the program.

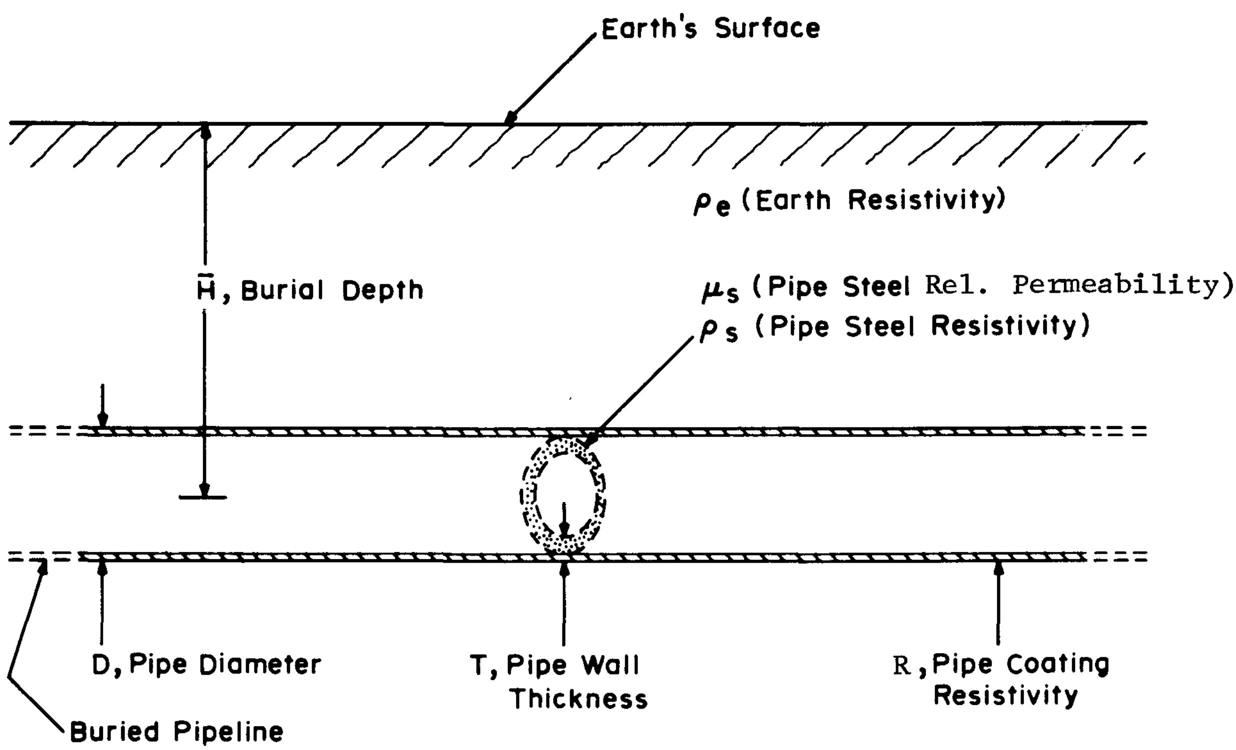


Figure A-3. Pipeline/Earth Geometry for Program PIPE

Table A-3

INSTRUCTIONS FOR PROGRAM PIPE

1. Press CLR. Then, press 3 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.
   Press 2. Then, insert bank #2 into the card reader.
   Press 3. Then, insert bank #3 into the card reader.

3. Press A.

4. Key $\overline{H}$ (in inches) into the display. Then, Press B.
   Key D (in inches) into the display. Then, press B.
   Key T (in inches) into the display. Then, press B.
   Key ρ_e (in ohm-meters) into the display. Then, press B.
   Key μ_s (dimensionless) into the display. Then, press B.
   Key ρ_s (in microohm-meters) into the display. Then, press B.
   Key R (in kiloohm-ft^2) into the display. Then, press B.

5. Press C. Wait 34 seconds for the display to unblank. The displayed number is the first iteration estimate of the exact value of Real(γ) in nepers/km. To display the first-iteration estimate of Im(γ) in radians/km, press x⇄t.

6. Press D. Wait 22 seconds for the display to unblank. The displayed number is the second-iteration estimate of Real(γ). Press x⇄t to display the second-iteration estimate of Im(γ).

7. Repeat Step 6 until two successive values of Real(γ) are identical. The final values of Real(γ) and Im(γ) are the exact values desired.

8. Press R/S to display $1/|\gamma|$.

9. Press R/S. Wait 4 seconds for the display to unblank. The displayed number is Real(Z_0) in ohms. Press x⇄t to display Im(Z_0) in ohms.

10. To compute γ, $1/|\gamma|$, and Z_0 for a different pipe, return to Step 3.

NOTE: If the PC-100A printer is used, each iteration's results for Real(γ) and Im(γ) will be printed out automatically and labeled as "GAMR" and "GAMI", respectively. Further, the quantity $1/|\gamma|$ will be printed out and labeled as "INVG". Finally, the quantities Real(Z_0) and Im(Z_0) will be printed out and labeled as "ZOR" and "ZOI", respectively.

Program WIRE

Program WIRE computes the propagation constant, γ, the induced voltage constant, $1/|\gamma|$, and the characteristic impedance, Z_0, of a bare horizontal, buried ground wire having arbitrary characteristics. This program accurately accounts for the following wire or soil variables: wire burial depth, wire diameter, wire relative permeability, wire resistivity, wire series inductive and resistive loading, and earth resistivity. The wire self-impedance may then be calculated by forming the product γZ_0.

Figure A-4 details the ground wire geometry assumed for this program and defines the essential data parameters keyed in by the user. Table A-4 provides a step-by-step instruction procedure for the use of the program.

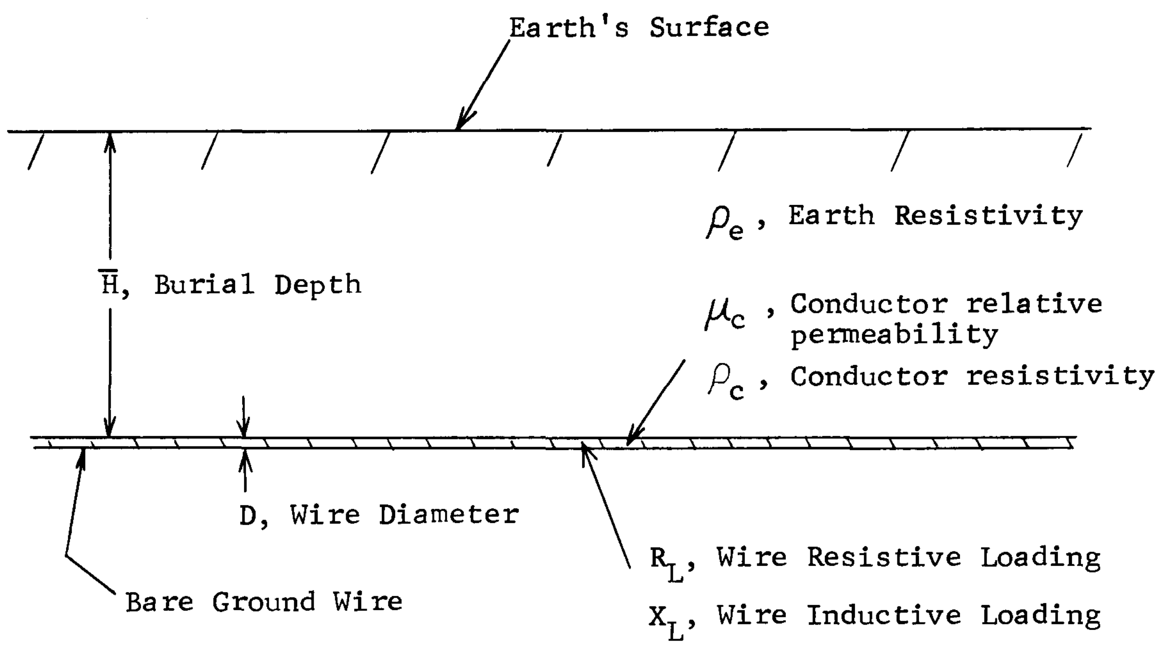


Figure A-4. Ground Wire/Earth Geometry for Program WIRE

Table A-4

INSTRUCTIONS FOR PROGRAM WIRE

1. Press CLR. Then, press 3 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.
   Press 2. Then, insert bank #2 into the card reader.
   Press 3. Then, insert bank #3 into the card reader.

3. Press A.

4. Key $\overline{H}$ (in inches) into the display. Then, press B.
   Key D (in inches) into the display ($D \leq 1"$). Then, press B.
   Key ρ_e (in ohm-meters) into the display. Then, press B.
   Key μ_C (dimensionless) into the display. Then, press B.
   Key ρ_C (in microohm-meters) into the display. Then, press B.
   Key R_L (in ohms/meter) into the display. Then, press B.
   Key X_L (in ohms/meter) into the display. Then, press B.

   NOTE: R_L and X_L equal zero for a ground wire with no artificial series inductive loading.

5. Press C. Wait 28 seconds for the display to unblank. The displayed number is the first-iteration estimate of the exact value of Real(γ) in nepers/km. To display the first-iteration estimate of Im(γ) in radians/km, press x⇄t.

6. Press D. Wait 22 seconds for the display to unblank. The displayed number is the second-iteration estimate of Real(γ). Press x⇄t to display the second-iteration estimate of Im(γ).

7. Repeat Step 6 until two successive values of Real(γ) are identical. The final values of Real(γ) and Im(γ) are the exact values desired.

8. Press R/S to display $1/|\gamma|$.

9. Press R/S. Wait 4 seconds for the display to unblank. The displayed number is Real(Z_o) in ohms. Press x⇄t to display Im(Z_o) in ohms.

10. To compute γ, $1/|\gamma|$, and Z_o for a different wire, return to Step 3.

    NOTE: If the PC-100A printer is used, each iteration's results for Real(γ) and Im(γ) will be printed out automatically and labeled as "GAMR" and "GAMI", respectively. Further, the quantity $1/|\gamma|$ will be printed out and labeled as "INVG". Finally, the quantities Real(Z_o) and Im(Z_o) will be printed out and labeled as "ZOR" and "ZOI", respectively.

Program THEVENIN

Program THEVENIN computes the Thevenin equivalent circuit for the terminal behavior of an arbitrary pipeline or ground wire parallel to a power line. The nature of the conductor is specified for the program simply by inputting the conductor's propagation constant, γ, and characteristic impedance, Z_0, determined using either Program PIPE or Program WIRE. The quantities V_L and Z_L are determined by the geometry and characteristics of the pipeline network. Usually, in finding the pipeline voltage at a given location, several iterations of the THEVENIN program are necessary to transform remote impedance terminations and voltage pickup along the pipeline into the local Thevenin equivalent circuit. Generally, the V_θ and Z_θ found from exercising the program will become the V_L and Z_L for a successive iteration. The program can be permanently recorded on one magnetic card.

Figure A-5 details the geometry of the earth return conductor assumed for this program and defines the essential data parameters keyed in by the user. Table A-5 provides a step-by-step instruction procedure for the use of the program.

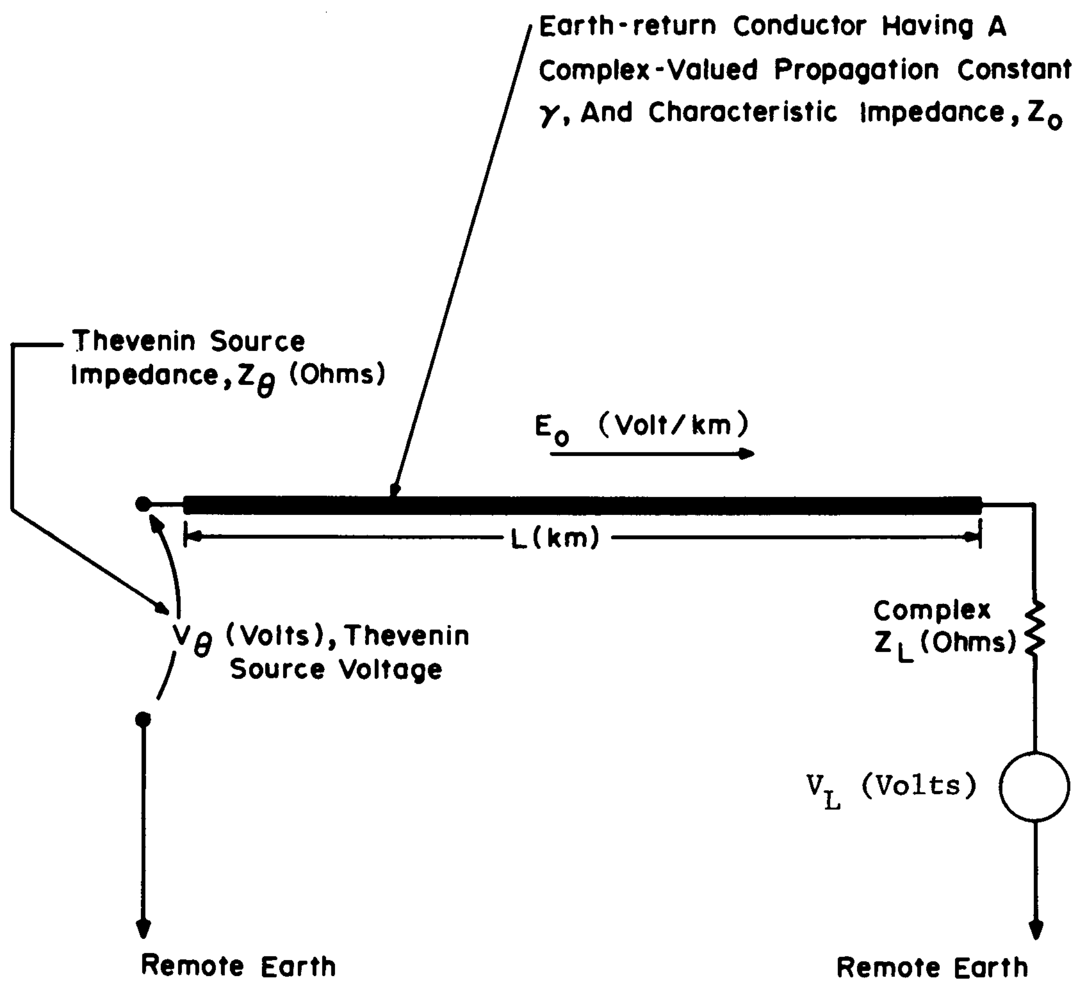


Figure A-5. Conductor Geometry for Program THEVENIN

Table A-5

INSTRUCTIONS FOR PROGRAM THEVENIN

1. Press CLR. Then, press 3 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.
   Press 2. Then, insert bank #2 into the card reader.

3. Press A.

4. Key Real(γ) (in nepers/km) into the display. Then, press B.
   Key Im(γ) (in radians/km) into the display. Then, press B.
   Key Real(Z_0) (in ohms) into the display. Then, press B.
   Key Im(Z_0) (in ohms) into the display. Then, press B.
   Key $|V_L|$ (in volts) into the display. Then, press B.
   Key $\angle V_L$ (in degrees) into the display. Then, press B.
   Key $|Z_L|$ (in ohms) into the display. Then, press B.
   Key $\angle Z_L$ (in degrees) into the display. Then, press B.
   Key $|E_0|$ (in volts/km) into the display. Then, press B.
   Key $\angle E_0$ (in degrees) into the display. Then, press B.

5. Key L (in km) into the display. Then, press C and wait 17 seconds for the display to unblank. The display then shows $|Z_\theta|$ in ohms. To then display $\angle Z_\theta$ in degrees, press $x \rightleftarrows t$.

6. Press R/S and wait 9 seconds for the display to unblank. The display then shows $|V_\theta|$ in volts. To then display $\angle V_\theta$ in degrees, press $x \rightleftarrows t$.

7. If results are desired for a different value of L, simply repeat Steps 5 and 6. Otherwise, begin at Step 3.

   NOTE: If the PC-100A printer is used, $|Z_\theta|$ and $\angle Z_\theta$ will be printed out automatically and labeled as "ZMAG" and "ZPHA", respectively. Further, $|V_\theta|$ and $\angle V_\theta$ will be printed out and labeled as "VMAG" and "VPHA", respectively.

Program NODE

This program computes the node voltage and branch currents for three Thevenin equivalent circuits connected together at a common point. The circuit geometry is shown in Figure A-6. This program is the last one usually used when computing the pipeline voltage at a specified location. When doing so the procedure is to first find the Thevenin equivalent circuits looking in both directions from the location. Then, as shown in Figure A-6, V_1 and Z_1 represent the Thevenin equivalent circuit parameters to one side of the location of voltage computation, and V_3 and Z_3 likewise represent the circuit parameters looking in the other direction. V_2 and Z_2 represent the Thevenin parameters for a mitigation grounding wire if connected at this point. If none exists, then Z_2 should be entered into the program as a large number, say 10,000 or more ohms, in order to obtain a correct result. It should be noted that while instruction 5 computes the pipeline voltage at the desired location, the succeeding instructions allow for calculation of the pipe and grounding wire currents at the same site.

A step-by-step instruction procedure is detailed in Table A-6. The program can be permanently recorded on one magnetic card.

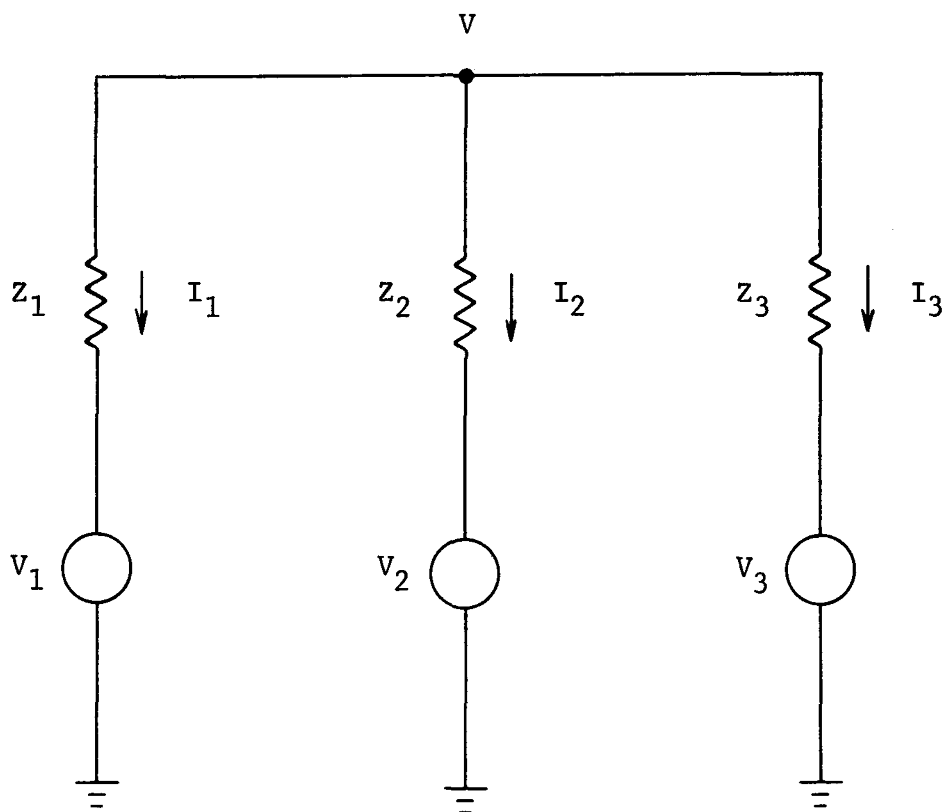


Figure A-6. Circuit Geometry for Program NODE

Table A-6

INSTRUCTIONS FOR PROGRAM NODE

1. Press CLR. Then, press 3 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.
   Press 2. Then, insert bank #2 into the card reader.

3. Press A.

4. Key $|V_1|$ (in volts) into the display. Then, press B.
   Key $\angle V_1$ (in degrees) into the display. Then, press B.
   Key $|Z_1|$ (in ohms) into the display. Then, press B.
   Key $\angle Z_1$ (in degrees) into the display. Then, press B.
   Key $|V_2|$ (in volts) into the display. Then, press B.
   Key $\angle V_2$ (in degrees) into the display. Then, press B.
   Key $|Z_2|$ (in ohms) into the display. Then, press B.
   Key $\angle Z_2$ (in degrees) into the display. Then, press B.
   Key $|V_3|$ (in volts) into the display. Then, press B.
   Key $\angle V_3$ (in degrees) into the display. Then, press B.
   Key $|Z_3|$ (in ohms) into the display. Then, press B.
   Key $\angle Z_3$ (in degrees) into the display. Then, press B.

5. Press C. Wait 16 seconds for the display to unblank. The display then shows $|V|$ in volts. Press x⇄t to display $\angle V$ in degrees.

6. Press R/S. Wait 8 seconds for the display to unblank. The display then shows $|I_1|$ in amps. Press x⇄t to display $\angle I_1$ in degrees.

7. Press R/S. Wait 6 seconds for the display to unblank. The display then shows $|I_2|$ in amps. Press x⇄t to display $\angle I_2$ in degrees.

8. Press R/S. Wait 6 seconds for the display to unblank. The display then shows $|I_3|$ in amps. Press x⇄t to display $\angle I_3$ in degrees.

9. To compute V, I_1, I_2, and I_3 for a different set of Thevenin circuits, return to Step 3.

   NOTE: If the PC-100A printer is used, all answers are printed out automatically and labeled as follows:

Quantity	Label
$\|V\|$	VMAG
$\angle V$	VPHA
$\|I_1\|$	|I1|

Table A-6 (Continued)

INSTRUCTIONS FOR PROGRAM NODE

Quantity	Label
$\angle I_1$	/I1
$\|I_2\|$	|I2|
$\angle I_2$	/I2
$\|I_3\|$	|I3|
$\angle I_3$	/I3

Program FIELD

This program derives the driving electric field at a location due to any number of parallel, current-carrying conductors, assuming that the currents and Carson mutual impedances are known. The conductor geometry is shown in Figure A-7.

Table A-7 is a step-by-step instruction procedure for the use of this program. One magnetic card is required for recording this program.

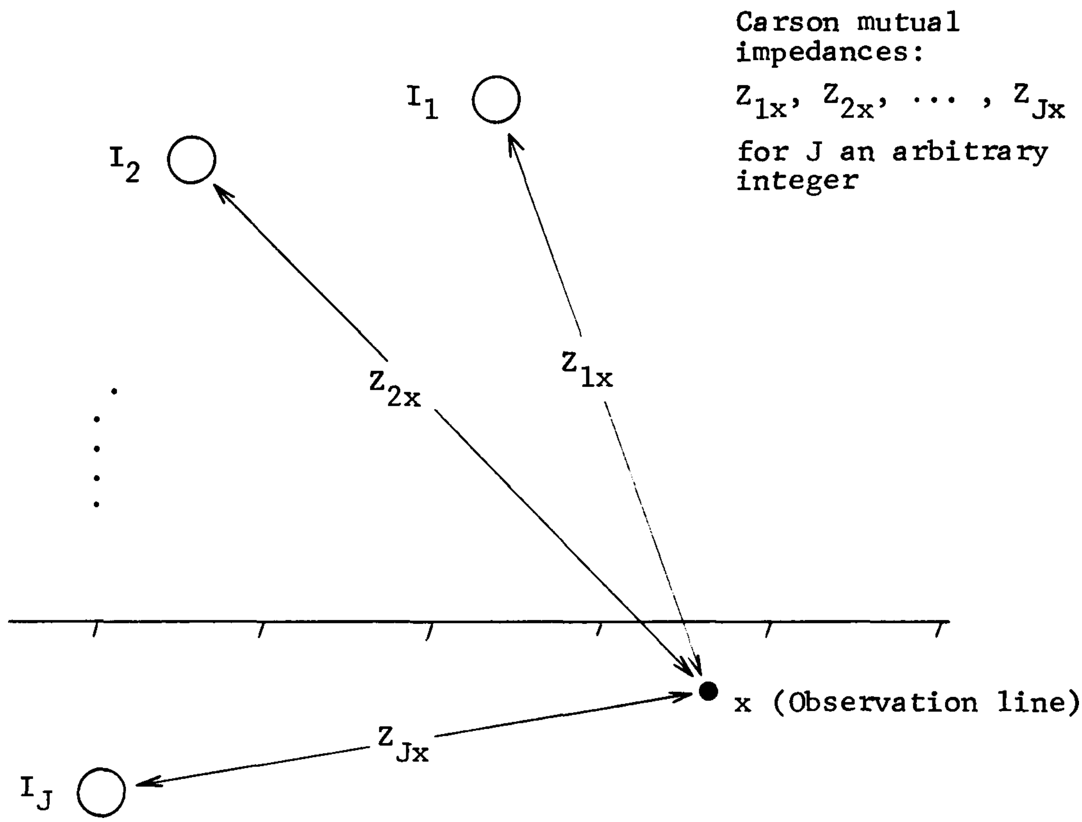


Figure A-7. Conductor Geometry for Program FIELD

Table A-7

INSTRUCTIONS FOR PROGRAM FIELD

1. Press CLR. Then, press 6 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.

3. Press A.

4. Key $|I_1|$ (in amps) into the display. Then, press B.

5. Key $\angle I_1$ (in degrees) into the display. Then, press C.

6. Key $|Z_{1x}|$ (in ohms/km) into the display. Then, press D.

7. Key $\angle Z_{1x}$ (in degrees) into the display. Then, press E. Wait 5 seconds for the display to unblank. The displayed number is $|E_x|$ in volts/km, the magnitude of the total driving electric field at x. Press x⇄t to display $\angle E_x$ in degrees.

8. If the field contribution due to another current-carrying conductor is to be summed, repeat Steps 4, 5, 6, and 7 for the new conductor. The display will always show the running total at the end of Step 7.

9. If an entirely different conductor configuration is to be considered, return to Step 3.

   NOTE: If the PC-100A printer is used, $|E_x|$ and $\angle E_x$ will be printed out automatically and labeled as "EMAG" and "EPHA", respectively.

Program SHIELD

This program computes the series self-impedance of a power line shield wire. Table A-8 is a step-by-step instruction procedure for the use of this program. One magnetic card is needed for recording this program.

Table A-8

INSTRUCTIONS FOR PROGRAM SHIELD

1. Press CLR. Then, press 6 Op 17.

2. Press 1. Then, insert bank #1 into the card reader.

3. Press A.

4. Key R, the series dc resistance of the shield wire (in ohms/mile) into the display. Then, press B.

   Key D, the diameter of the shield wire (in inches) into the display. Then, press B.

   Key ρ_e, the earth resistivity (in ohm-meters) into the display. Then, press B.

5. Press C. Wait 5 seconds for the display to unblank. The display then shows $|Z_s|$, the magnitude of the shield wire self impedance (in ohms/km). Press x⇄t to display $\angle Z_s$ in degrees.

6. For a different shield wire, return to Step 3.

   NOTE: If the PC-100A printer is used, $|Z_s|$ and $\angle Z_s$ will be printed out automatically and labeled as "ZMAG" and "ZPHA", respectively.

APPENDIX B

CASE HISTORIES OF PIPELINE INDUCED VOLTAGE PREDICTIONS

INTRODUCTION

Five "case histories" of voltage prediction are presented here. The situations analyzed are varied and thus provide a diverse set of illustrative examples. In studying the examples, particular attention should be taken as to the approach to the problem, the use of the hand calculator programs and, in particular, the use of the Thevenin equivalent circuit concept.

A listing of the examples in the order they are presented and the principal points of theory or prediction methodology they demonstrate is as follows:

- Southern California Gas Company Line 235, Mojave Desert, Needles, California. This case history vividly shows the appearance of voltage peaks at the locations predicted, i.e., points of physical or electrical discontinuity. It also illustrates the simplicity of the prediction methodology when successive points of discontinuity are sufficiently separated so as to provide electrical isolation. For such a situation, simple calculations are sufficient and use of the hand calculator programs is not required.

- Northern Illinois Gas Company, Aurora, Illinois. The treatment for this pipeline is essentially non-mathematical. The ROW is relatively complex and the desire here was to illustrate the methodology to be used for identifying the critical points of voltage induction by inspection.

- Consumers Power Company Line 1800, Kalamazoo, Michigan. The mathematical/hand calculator oriented approach is used here to derive the pipeline voltage profile. The ROW configuration is relatively simple, thus providing a good first introduction to obtaining mathematical solutions. This case illustrates how to take into account end terminations of the pipeline and evaluate their effects.

- Texas Gas Transmission Corporation, Memphis, Tennessee. This case history of voltage prediction is possibly the most complicated of the set presented in that four gas pipelines are collocated with several power circuits. The analysis becomes difficult because of electrical interties between the pipelines at several locations. The solution illustrates repeated use of the Thevenin equivalent circuit concept to produce successive simplifications of the problem.

- Consumers Power Company Karn-Weadock Line, Bay City, Michigan. The solution of the induced voltage prediction problem for this crude oil pipeline is obtained by an approach utilizing field measured data as much as possible in contrast to the purely analytical solutions presented for the previous case histories.

Voltage Prediction
Southern California Gas Company Line 235, Needles, California

This case history vividly shows the appearance of voltage peaks at the locations predicted, i.e., points of physical or electrical discontinuity. It also illustrates the simplicity of the prediction methodology when successive points of discontinuity are sufficiently separated so as to provide electrical isolation. For such a situation, simple hand calculations are sufficient and use of the hand calculator programs is not required.

Corridor Description. The Southern California Edison 500 kV electric power transmission line meets the Southern California Gas Company 34-inch diameter gas pipeline at pipeline milepost 47 (47 miles west of Needles, California) and leaves it at milepost 101.7, as shown in Figure B-1. The power line has a horizontal configuration with a full clockwise (phase-sense) transposition at milepost 68 and single-point-grounded lightning shield wires. During the test period, an average loading of 700 amperes was reported for each phase conductor. No other power lines, pipelines, or long conductors share the right-of-way.

Measurements performed during the tests indicated an average earth resistivity of 400 ohm-meter. Based upon furnished data, a value of 700 $k\Omega\text{-}ft^2$ was assumed as the average pipeline coating resistivity. Using these values as data input for the pipeline parameter graphs of Appendix D, the pipeline propagation constant, γ, was obtained as $(0.115 + j\ 0.096)\ km^{-1} = 0.15\underline{/40^o}\ km^{-1}$; and the pipeline characteristic impedance, Z_o, was obtained as $2.9 + j\ 2.4)$ ohms $= 3.4\underline{/40^o}$ ohms. Alternatively, the program PIPE may be used to find these parameters more accurately.

Voltage Peak Locations and Magnitudes. The node analysis presented in Volume 1 predicts the appearance of separably calculable pipeline voltage peaks at all discontinuities of a pipeline-power line geometry spaced by more than $2/Real(\gamma)$ meters along the pipeline. Using the value of γ obtained for the pipeline, all geometry discontinuities spaced by more than (2/0.115) km = 17.4 km ≈ 10 miles can be assumed to be locations of separable induced voltage peaks. These discontinuities include:

1. Milepost 101.7 (near end of pipeline approach section);
2. Milepost 89 (separation change);
3. Milepost 78 (separation change);

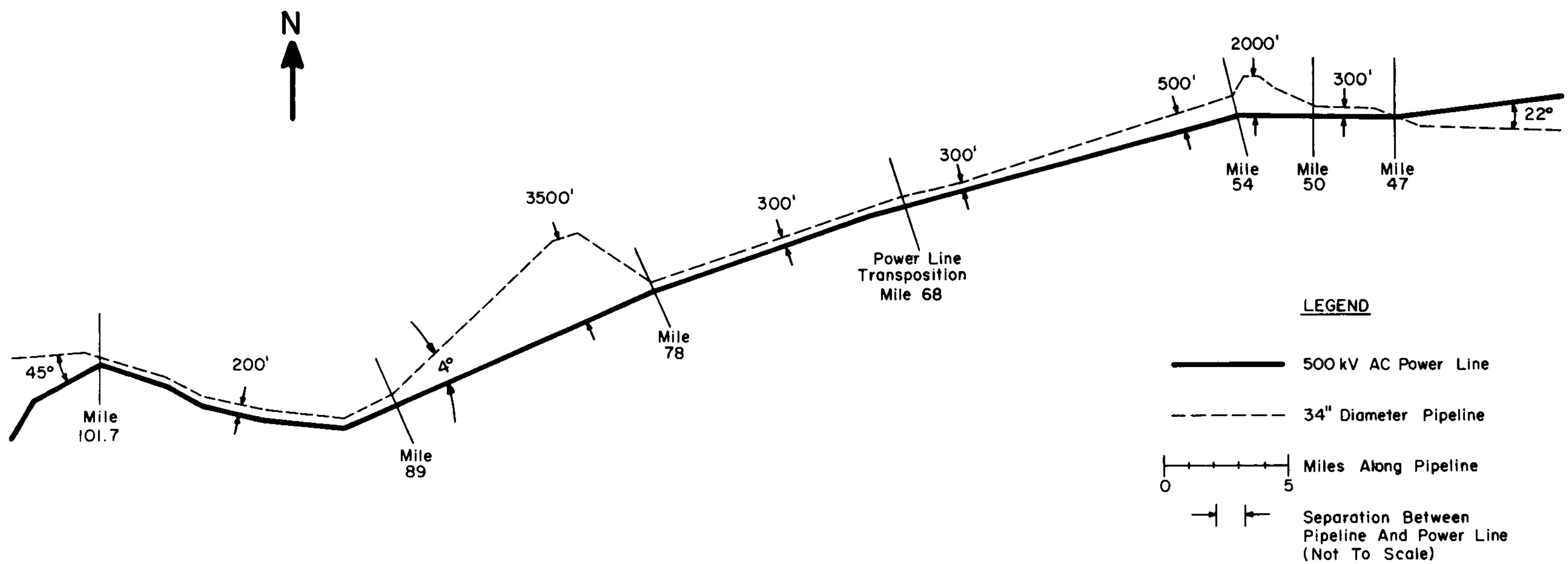


Fig. B-1 MOJAVE DESERT PIPELINE—POWER LINE GEOMETRY

4. Milepost 68 (power line phase transposition);

5. Milepost 54 (separation change); and

6. Milepost 47 (near end of pipeline departure section).

The voltages at these points of electrical discontinuity were predicted by application of Eq. 3-21 (Volume 1) to the Thevenin equivalent pipeline circuits derived for either direction from each of the points. The pipeline characteristics, γ and Z_0, were assumed constant with position along the pipeline, causing each Thevenin source impedance to be fixed at Z_0 (due to the long/lossy nature of the adjacent pipe sections). Further, Z_M was assumed to equal infinity at each Thevenin plane because no ac mitigating grounds were connected at the time to the pipeline, thus simplifying the equation to

$$V(M) = \frac{V_{\theta_{left}} + V_{\theta_{right}}}{2} \qquad \text{(B-1)}$$

To illustrate this approach, the predicted voltage peaks are calculated using Eq. B-1. Tables B-1 and B-2 list the results. The predicted electric fields were based on the following power line geometry:

1. The geometric mean height of the phase conductor equal to 60 feet;

2. Distance between phase wires equal to 32 feet; and

3. Horizontal circuit configuration.

At a given distance measured from the center phase wire, insertion of the appropriate distances into the program CARSON yielded the mutual impedances between each phase conductor and the pipeline (burial depth equal to three feet). The following phase currents were then assumed:

1. Phase wire closest to pipeline: $I = 700\angle{+120^\circ}$ amperes

2. Center phase wire: $I = 700\angle{-120^\circ}$ amperes

3. Farthest phase wire: $I = 700\angle{0^\circ}$ amperes

Program FIELD was then used to calculate the electric field using the above currents and the mutual impedances found by Program CARSON.

Table B-1

LONGITUDINAL ELECTRIC FIELD MAGNITUDE*

Distance from Center Phase (feet)	Predicted Field (volts/km)	Measured Field (volts/km)
0	10.2	10.4
20	18.3	14.3
40	27.3	24.5
60	29.0	27.0
80	27.2	22.2
100	24.2	22.2
200	14.0	14.0
300	9.5	8.5
600	4.8	4.0
1000	2.9	1.6
5000	0.4	-
10,000	0.1	-

Table B-2

ELECTRIC FIELD PHASE**

	West of Transposition	East of Transposition
North of power line	-120°	0°
South of power line	$+60^{\circ}$	180°

*For the balance current case, $|E_x|$ was found to be the same for equal distances both north and south of the power line and also on both sides of the power line transposition.

**Table B-2 lists the predicted phase of E_x at distances between 60 feet and 2000 feet from the power line. The phase tended to remain relatively constant at the tabulated values except for rapid variations directly under the power line. The current in the southernmost phase wire, I_A, serves as the phase reference ($\phi=0^{\circ}$).

It was not possible to measure the absolute values of the electric field phase relative to the reference phase current, I_A. However, phase measurements relative to two ground locations were possible, and hence differences of the absolute values listed in Table B-2 were measurable. For example, confirmation of the phase reversal occurring on opposite sides of the power line was readily obtained.

Milepost 101.7. A voltage peak occurs here because of a corridor geometric discontinuity, namely, the convergence of the pipeline and power line at an angle of 45° to a separation of 200 feet (0.06 km). Based upon a predicted longitudinal electric field of $14.0\underline{/-120^\circ}$ V/km at this separation, apply Eqs. 3-20 and 3-18 (Volume 1) to compute the two Thevenin voltage sources.

Looking to the west:

$$V_{\theta_{west}} \simeq \frac{14\underline{/-120^\circ} \times (0.3 - 0.06)}{4 \times \tan 45^\circ} = 0.8\underline{/-120^\circ} \text{ volts}$$

Looking to the east:

$$V_{\theta_{east}} = \frac{-14\underline{/-120^\circ}}{0.15\underline{/40^\circ}} = 93.3\underline{/20^\circ} \text{ volts}$$

Combining the Thevenin equivalent circuits by using Eq. B-1

$$|V(101.7)| = 0.5 \times |(0.8\underline{/-120^\circ} + 93.3\underline{/20^\circ})| = 46.3 \text{ volts}$$

The actual measured pipeline voltage at this point was 46 volts.

Milepost 89. A voltage peak occurs here because of a corridor geometric discontinuity, namely, the divergence of the pipeline and power line at an angle of about 4° from a separation of 150 feet (0.046 km) to a separation of 3500 feet (1.07 km). Based upon a predicted electric field of $18.0\underline{/-120^\circ}$ V/km at the 150-foot separation, Eqs. 3-18 and 3-20 (Volume 1) are similarly applied to compute the Thevenin voltage sources.

Looking to the west:

$$V_{\theta_{west}} = \frac{18\underline{/-120^\circ}}{0.15\underline{/40^\circ}} = 120.0\underline{/-160^\circ} \text{ volts}$$

Looking to the east:

$$V_{\theta_{east}} \simeq \frac{-18\underline{/-120^\circ} \times (0.3 - 0.046)}{4 \times \tan 4^\circ} = 16.3\underline{/60^\circ} \text{ volts}$$

Combining the Thevenin equivalent circuits:

$$|V(89)| = 0.5 \times |(120\underline{/-160^\circ} + 16.3\underline{/60^\circ})| = 54.0 \text{ volts}$$

The actual measured pipeline voltage at this point was 53 volts.

Milepost 78. A voltage peak occurs here because of a corridor geometric discontinuity, namely, the convergence of the pipeline and power line at an angle of about 19° from a separation of 3500 feet (1.07 km) to a separation of 300 feet (0.092 km). Based upon a predicted electric field of $9.5\angle{-120^\circ}$ V/km at the 300-foot separation, Eqs. 3-18 and 3-20 (Volume 1) are again used to compute the Thevenin voltage sources.

Looking to the west:

$$V_{\theta_{west}} \simeq \frac{9.5\angle{-120^\circ} \times (0.3 - 0.092)}{4 \times \tan 19^\circ} = 1.4\angle{-120^\circ} \text{ volts}$$

Looking to the east:

$$V_{\theta_{east}} = \frac{-9.5\angle{-120^\circ}}{0.15\angle{40^\circ}} = 63.3\angle{20^\circ} \text{ volts}$$

Combining the Thevenin equivalent circuits:

$$|V(78)| = 0.5 \times |(1.4\angle{-120^\circ} + 63.3\angle{20^\circ})| = 31.1 \text{ volts}$$

The actual measured pipeline voltage at this point was 34 volts.

Milepost 68. A voltage peak occurs here because of a corridor electrical discontinuity, namely, the power line transposition at a constant separation of 300 feet (0.092 km). Based upon a predicted electric field of $9.5\angle{-120^\circ}$ V/km at the 300-foot separation to the west of the transposition, and a predicted field of $9.5\angle{0^\circ}$ V/km at the 300-foot separation to the east of the transposition, application of Eq. 3-18 (Volume 1) yields the Thevenin voltage sources.

Looking to the west:

$$V_{\theta_{west}} = \frac{9.5\angle{-120^\circ}}{0.15\angle{40^\circ}} = 63.3\angle{-160^\circ} \text{ volts}$$

Looking to the east:

$$V_{\theta_{east}} = \frac{-9.5\angle{0^\circ}}{0.15\angle{40^\circ}} = 63.3\angle{140^\circ} \text{ volts}$$

Combining the Thevenin equivalent circuits:

$$|V(68)| = 0.5 \times |(63.3\angle{-160^\circ} + 63.3\angle{140^\circ})| = 54.8 \text{ volts}$$

The actual measured pipeline voltage at this point was 54 volts.

Milepost 54. A voltage peak occurs here because of a corridor geometric discontinuity, namely, the divergence of the pipeline and power line from a separation of 500 feet (0.15 km) to an average separation of about 1200 feet (0.37 km). Based upon a predicted electric field of $5.8\underline{/0^\circ}$ V/km at the 500-foot separation, and a predicted field of $2.4\underline{/0^\circ}$ V/km at the 1200-foot separation, again applying Eq. 3-18 (Volume 1), yields:

Looking to the west:

$$V_{\theta_{west}} = \frac{5.8\underline{/0^\circ}}{0.15\underline{/40^\circ}} = 38.7\underline{/-40^\circ} \text{ volts}$$

Looking to the east:

$$V_{\theta_{east}} = \frac{-2.4\underline{/0^\circ}}{0.15\underline{/40^\circ}} = 16.0\underline{/140^\circ} \text{ volts}$$

Combining the Thevenin equivalent circuits:

$$|V(54)| = 0.5 \times |(38.7\underline{/-40^\circ} + 16.0\underline{/140^\circ})| = 11.4 \text{ volts}$$

The actual measured pipeline voltage at this point was 11 volts.

Milepost 47. A voltage peak occurs here because of a corridor geometric discontinuity, namely, the divergence of the pipeline and power line at an angle of 22° from a separation of 300 feet (0.092 km). Based upon a predicted electric field of $9.5\underline{/0^\circ}$ V/km at this separation, Eqs. 3-18 and 3-20 (Volume 1) give:

Looking to the west:

$$V_{\theta_{west}} = \frac{9.5\underline{/0^\circ}}{0.15\underline{/40^\circ}} = 63.3\underline{/-40^\circ} \text{ volts}$$

Looking to the east:

$$V_{\theta_{east}} = \frac{-9.5\underline{/0^\circ} \times (0.3 - 0.092)}{4 \times \tan 22^\circ} = 1.2\underline{/180^\circ} \text{ volts}$$

Combining the Thevenin equivalent circuits:

$$|V(47)| = 0.5 \times |(63.3\underline{/-40^\circ} + 1.2\underline{/180^\circ})| = 31.2 \text{ volts}$$

The actual measured pipeline voltage at this point was 25 volts.

Figure B-2 plots both the measured ac voltage profile of the Mojave pipeline and the predicted voltage peaks. The solid curve represents voltages measured during the field test; the dashed curve is a set of data (normalized to 700 amperes power line current) obtained by a Southern California Gas Company survey. From this figure, it is apparent that the prediction method succeeded in locating and quantizing each of the pipeline voltage peaks with an error of less than ± 20%. In a dense urban environment, the prediction calculations would become more complex, as shown in the following case histories, but would still be within the scope of the distributed source theory and the programmable calculator programs.

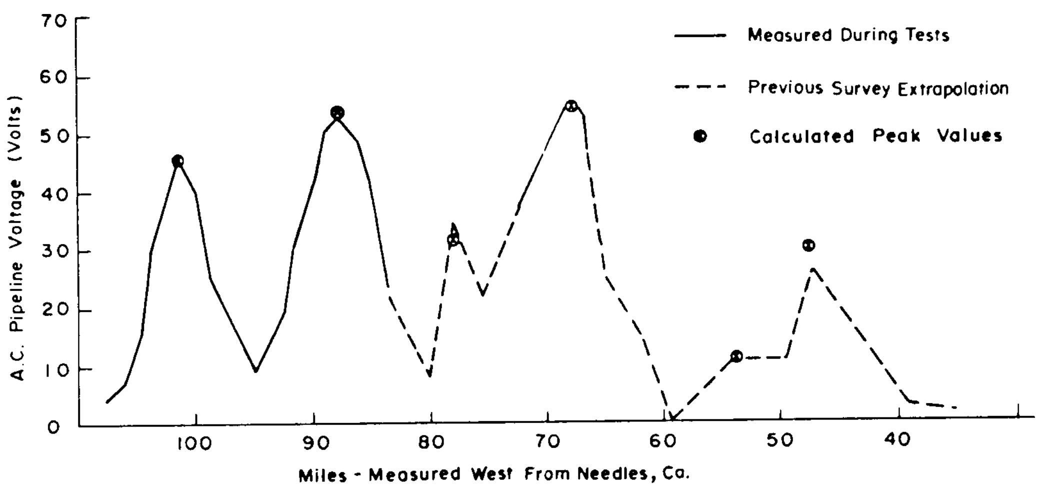


Figure B-2. Mojave Desert Pipeline Voltage Profile

Induced Voltage Prediction
Northern Illinois Gas 36-Inch Aux Sable Pipeline, Aurora, Illinois

Introduction. The treatment for this pipeline is essentially non-mathematical. The ROW is relatively complex and the desire here was to illustrate the methodology to be used for identifying the critical points of voltage induction by inspection. Induced voltage predictions for the 36-inch Aux Sable line have been made and the resulting voltage profile presented in Figure B-5. The voltage predictions have been made on the basis of longitudinal electric field measurements along the pipeline route in combination with an analytical model to obtain worst case estimates. The following discusses field measurements and subsequent electric field calculations, both of which are plotted in Figure B-4. Rationale for derivation of the voltage profile is also presented.

The pipeline section under consideration extends in a north-south direction for a distance of approximately thirty miles. It leaves a synthetic gas plant (electrically terminated in an insulator) at Station #00+00 and proceeds northward to a valve site at Station #1661+00 where it likewise is terminated in an insulator. The principal characteristics of the ROW profile are diagrammed in Figure B-3.

It enters the Commonwealth Edison ROW at Station #62+100, where it encounters four 345 kV vertical circuits and one 138 kV horizontal circuit as shown. In the region from Station #167+70 to Station #740+54, a ten-inch diameter hydrocarbon pipeline joins the ROW moving from one side of the ROW to the other and back again, as shown. At Station #740+54, the two east towers and the ten-inch hydrocarbon pipeline leave the ROW, and the Aux Sable pipeline crosses the ROW to within thirty feet of the remaining westernmost tower. At Station #903+65, two vertical 138 kV circuits enter the ROW. At Station #1046+50, the pipeline crosses to between the two towers and a 34-inch Lakehead pipeline is encountered, which leaves the ROW at approximately Station #1540+85.

Inspection of Figure B-3 shows several electrical/physical discontinuities, thus leading to the prediction of a like number of voltage peaks on the pipeline.

Measured Longitudinal Electric Field. Measurement of the magnitude of the longitudinal electric field existing along the pipeline route was made at the following stations: 73+00, 114+20, 178+50, 335+00, 506+30, 640+00, 761+00, 836+50, 845+00, 960+00, 1118+48, 1123+00, 1302+00, 1488+00, 1606+60. The data are plotted in Figure B-4.

Data were obtained with a HP3581A electronically tuned voltmeter which measured the voltage drop in a 15-meter horizontal probe wire laid along the ROW and grounded at both ends to a depth of approximately 18 inches. Electric field strength was calculated by dividing the measured voltage by the length of the probe wire.

Inspection of Figure B-4 shows the field extant at approximately Station 62+00, where the pipeline enters the Edison ROW. The field strength rises sharply at approximately Station 500+00. This rise is primarily due to the reduction in separation between the pipeline and the overhead transmission lines at this point. The electric field drops to a much lower value at Station 640+00 because of the

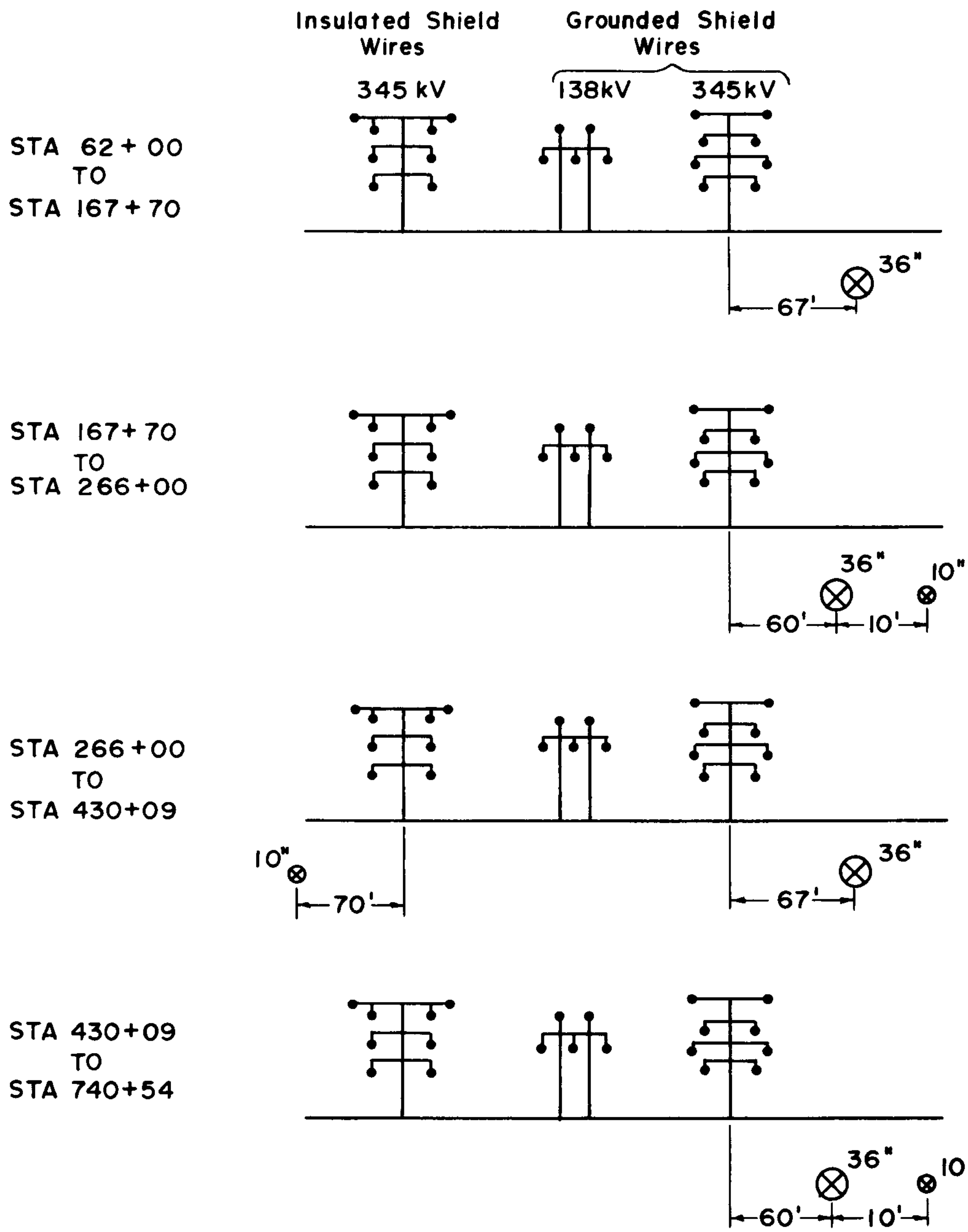


Fig. B-3 PROFILE LOOKING NORTH

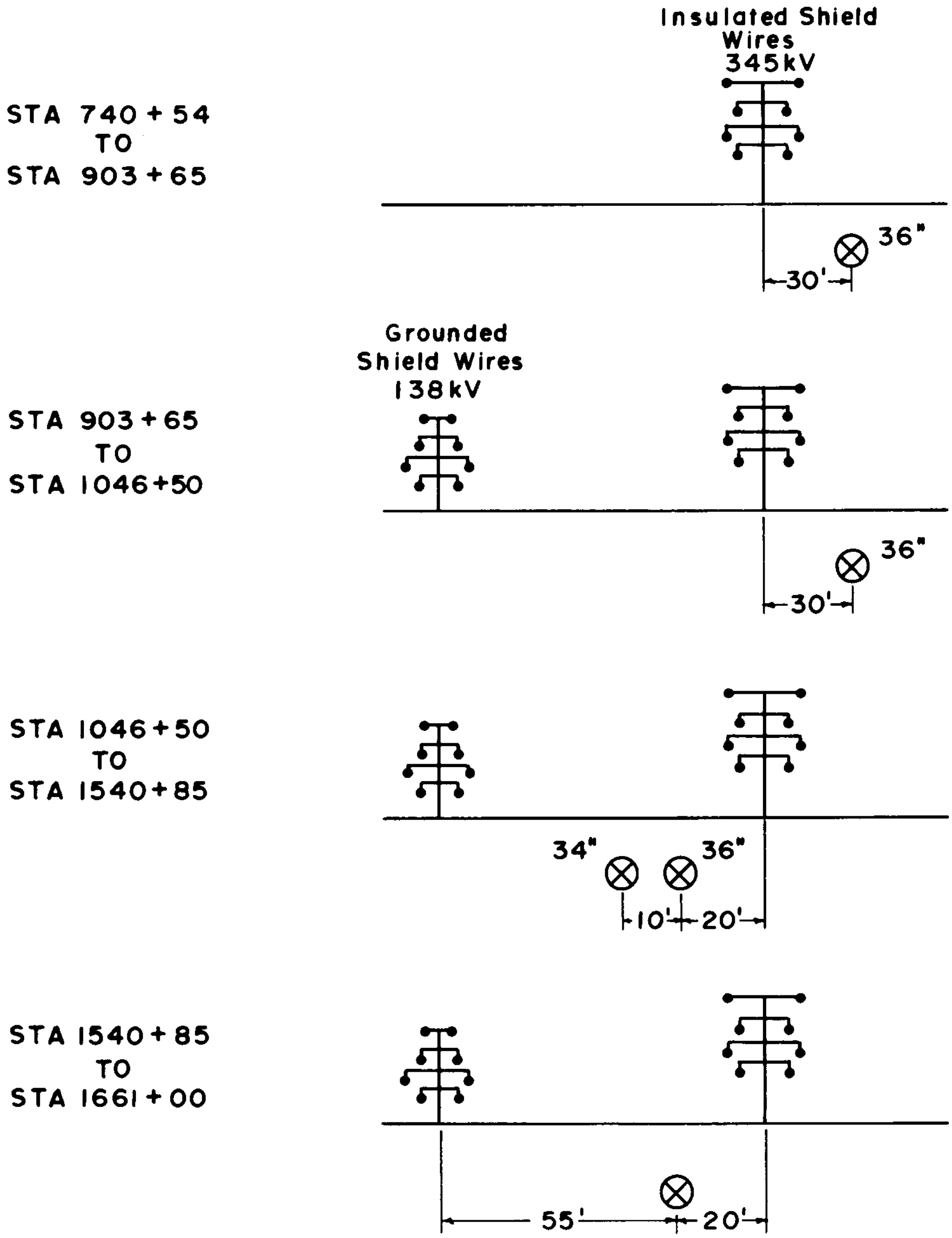


Fig. B-3 (cont.) PROFILE LOOKING NORTH

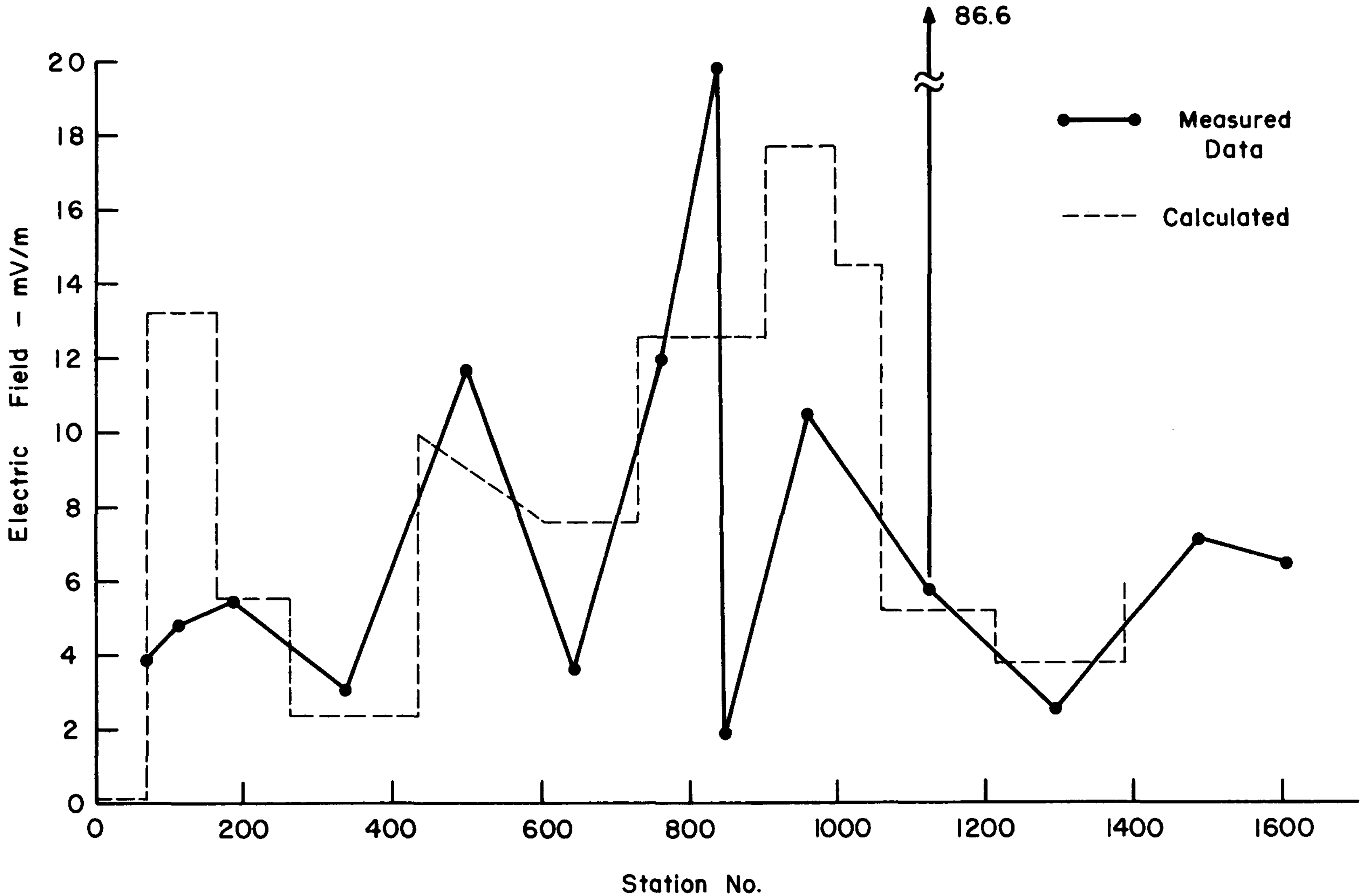


Fig. B-4 36" AUX SABLE HORIZONTAL ELECTRIC FIELD PROFILE ten-inch hydrocarbon pipeline which leaves the ROW at Station 740+00. (A similar drop at Station 334+00 is attributable to the particular power line current unbalances at the time of the measurement.)

Measurements made at Stations 836+50 and 845+00 show a ten-to-one variation in less than 1000 feet which can be attributable only to localized interference. These measurements were made in proximity to the village of Plainfield pumping station and possibly suffer interference from stray underground pipe currents. Although these electric fields were in existence at the time of measurement, because of their localized nature, their effect upon the resulting pipeline voltage would be small.

An extremely high electric field, again of a localized nature, was noted at Station 1118+48. This field appears to be introduced by electric currents leaking off of a grounded pipeline casing at this location. Apparently, the 34-inch Lakehead pipeline sharing the Edison ROW is capacitively connected to the road crossing casing at this point. To determine the effects of this current leakage induced electric field in detail would have required a more extensive set of measurements in this area. However, it appears that because of the localized nature of this electric field discontinuity, its effects upon the overall pipeline voltage profile will be superseded by higher magnitude effects arising from the electric field discontinuity appearing at Station 1050+00. Hence, additional measurements in this location would not be considered cost effective.

The electric field experiences a strength reduction in the vicinity of Station 1302+00 because of a phase transposition on a 138-kV circuit in this area. The electric field from this location to the insulator at Station 1618 is difficult to measure with certainty because of the junction of many electrical transmission circuits at Station 1606+00.

Computed Electric Field. In the interest of economy, magnitude only electric field data were measured. In order not to predict unduly pessimistic induced voltage levels on the pipeline, a knowledge of the phase of the electric field is necessary. Hence, computations of the electric field expected along the ROW were made using values for the electric transmission line phase currents existing at the time measurements were made. These currents were monitored and recorded by Commonwealth Edison on an hourly basis.

The calculations were made by the use of Carson's mutual impedance formulas and the electric field contributions from the individual power line circuits were vectorially added for the specific locations at which measurements were made along the ROW. A plot of the calculated magnitude for the electric field is also made in Figure B-4 for comparison with the measured data. Except for a few points which will be individually discussed, the calculated and measured values generally agree. The shapes of the curves, however, are different. The measured data points were arbitrarily connected by straight lines. However, calculated data points were joined by step functions. The reason for this is that along the ROW if the pipeline-power line physical geometry or electrical coupling remains constant, then the electric field also is constant. However, locations of electrical or physical discontinuity cause a relatively sudden change in the electric field, as shown by the step function variations in Figure B-4. The approximate locations of the significant discontinuities are:

Station No.	Discontinuity
62+00	36-inch Aux Sable pipeline enters Edison ROW
167+00	10-inch Hydrocarbon pipeline enters ROW
270+00	10-inch Hydrocarbon line crosses to far end of ROW
430+00	10-inch Hydrocarbon line crosses ROW, separation of 36-inch pipe from Edison tower reduced to 30 feet
740+00	Three electrical circuits leave the ROW
900+00	Two 138-kV circuits enter the ROW
990+00	Transposition of phases on 138-kV circuit
1060+00	34-inch Lakehead pipeline enters ROW: Aux Sable pipeline crosses to center of ROW
1220+00	138-kV circuit phase transposition
1390+00	138-kV circuit phase transposition
1618+00	Pipeline insulator.

The first and largest deviation in calculated electric field magnitude relative to the measured value occurs between stations 62+00 and 167+00. The reason for this deviation is that the calculation of the electric field is critically dependent upon knowing the exact value of the electric circuit currents. Because of the vectorial nature of the electric field, calculation of its magnitude at times involves the subtraction of two nearly equal large numbers and, hence, a small error in one number can result in a much larger variation in the result. Recognition of this fact and knowledge of the physical processes involved allows compensation to be made, thus minimizing errors in subsequent voltage computations. In general, heretofore, this effect has not been appreciated, thus leading to apparent inconsistencies in the functional relationships between the sources of the induced field, that is, the electric circuit's phase currents and the resulting pipeline voltages. This effect does not negate the theory, but yields an explanation for observed variations. Progressing along the ROW, the one exception to the step function discontinuity rule is found in the Station 430+00-600+00 region. Here, the electric field strength diminishes in roughly linear fashion to a low in the Station 600+00-730+00 region. This gradual reduction is a result of induced current in the ten-inch hydrocarbon pipeline lying along the ROW. It shows that multiple pipelines on the same ROW will, in general, cause a weakening of the electric field at the other pipelines and, thus, effect a reduction in the induced pipeline voltage. The plot for the calculated field shows that the extreme variations experienced between Stations 836+00 and 845+00 cannot be accounted for on the basis of purely inductive effects. Hence, it is believed that these variations are local effects due to the Plainfield Village pumping station and, as such, do not impact the voltage calculations to a significant extent. The difference between the calculated and measured electric field values in the region Stations 900+00-990+00 can be accounted for again by small variations in one or more of the power line currents, and this deviation does not significantly impact the induced voltage predictions.

Since differences in the computed and measured electric field magnitudes can be accounted for, it is believed that calculated electric field phase information is reasonably correct. Hence, the voltage profile discussed in the following subsection was based on the joint use of measured magnitude data and calculated phase information.

Voltage Profile from Measured Data. A pipeline voltage profile determined from the measured magnitude data and calculated phase is plotted as the dashed curve in Figure B-5. Inspection of the plot shows that peaks of induced voltage appear at locations corresponding to power line-pipeline discontinuities with an exponential decay betweek peaks. If the discontinuities are reasonably separated, the voltage peak is approximately equal to

NOTE: Profiles Are Drawn For A Pipe Coating Resistance Of 100,000 ohms-ft^2 For 200,000 ohms-ft^2 Coating Resistance Multiply Voltages By 1.5 .

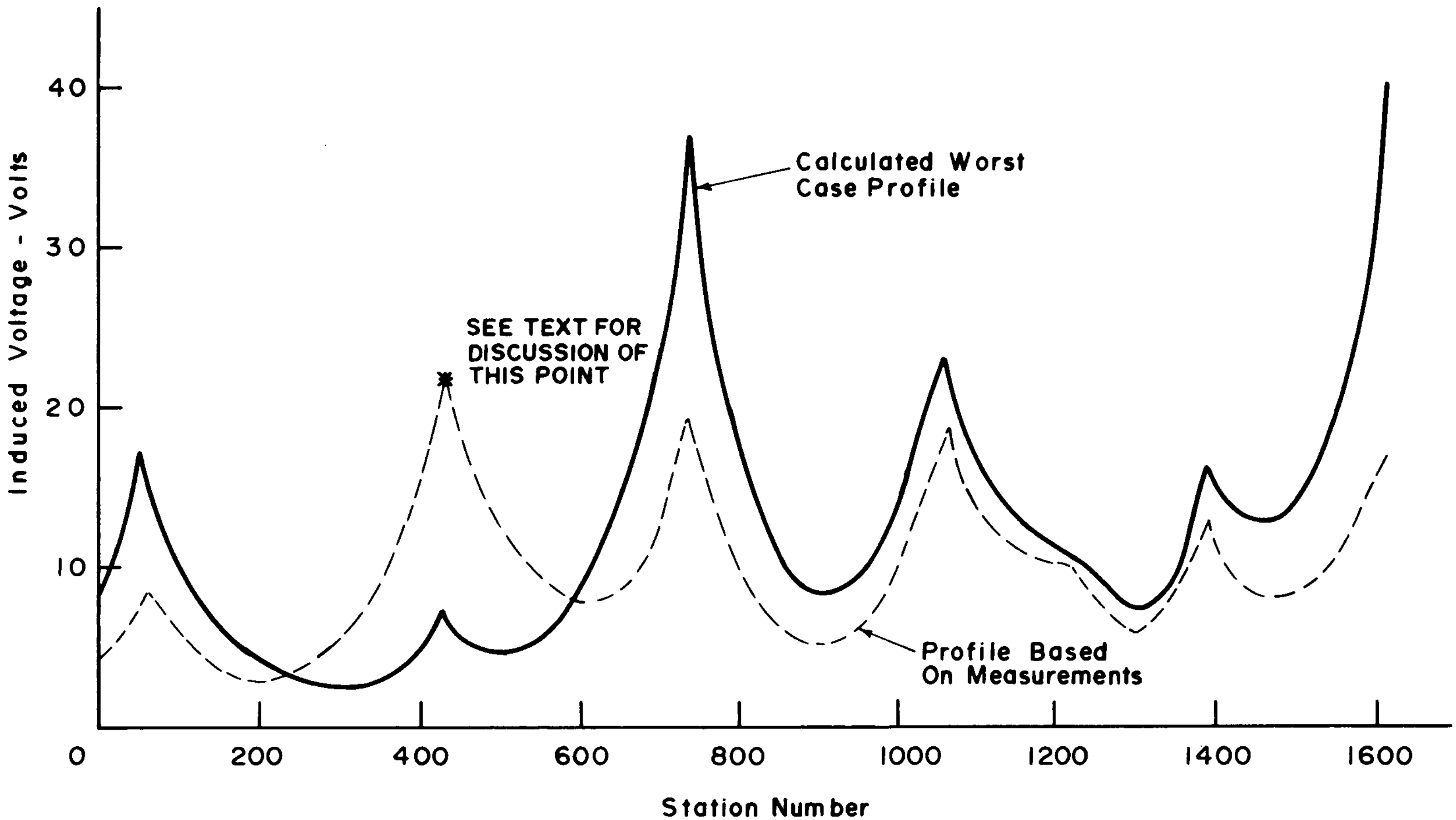


Fig. B-5. 36" AUX SABLE LINE VOLTAGE PROFILE

$$V_{peak} = \frac{E_1 - E_2}{2\gamma} \qquad \text{(B-2)}$$

where E_1 and E_2 are, respectively, the vector electric fields on either side of the discontinuity, and γ is the pipeline propagation constant which is a function of pipe steel parameters, pipe diameter, ground resistivity and especially of pipe coating conductivity. Since E_1 and E_2 are vectors, their difference angle is of extreme importance. For example, if it approaches zero, the resultant field will be the difference of the two, thus resulting in a relatively low voltage at the discontinuity. This point is exemplified at Station 900 since even though it is a location of a discontinuity, the resultant voltage is low. However, when the fields differ in angle by 180 degrees, then their effects are additive, thus causing high induced voltages such as at Station 740.

Insulators appearing at the ends of the pipeline act as severe electrical discontinuities and the voltage peak at an insulator may be approximated by

$$V_{ins} \simeq \frac{E}{\gamma} \qquad \text{(B-3)}$$

where E is the electric field in the vicinity of the insulating junction.

The predicted voltage plot of Figure B-5 covers the ROW from Station 00 to Station 1618+00, which represents the region of highest induced voltages for the pipeline.

Pipeline Propagation Constant. The previous calculations show that the induced voltage peaks are an inverse function of the pipeline propagation constant, the value of which is extremely sensitive to pipeline coating resistance. The curve of Figure B-5 is based on a value of $|\gamma| = 0.37\ km^{-1}$, which conforms to a pipeline coating resistance of 100,000 $ohms\text{-}ft^2$ for the pipe diameter and average soil conditions. Although higher resistances are desirable when considering cathodic protection requirements, they cause an increase in the induced pipeline voltage. For example, a coating resistance of 200,000 $ohm\text{-}ft^2$ would result in a value of $|\gamma| = 0.25$, and thusly increase predicted voltage levels in Figure B-5 by 48%; 300,000 $ohms\text{-}ft^2$ would result in a value of $|\gamma| = 0.21\ km^{-1}$, causing an increase in predicted voltage levels of 76%.

The coating resistivity after construction is completed is difficult to predict. For example, it has been reported that a coating with an average measured resistivity after burial of 200,000 ohms-ft^2 in moderately conductive soil was found to exhibit a high value of as much as 1,135,000 ohms-ft^2 and a low value of 10,000 ohms-ft^2 over a short section.

"Worst Case" Voltage Profile. A pipeline situated on a ROW with electrical circuits is in a constantly changing electromagnetic environment. Hence, depending upon the loading of the power lines, the degree of load unbalance, etc., the pipeline voltage at a given location will vary in time, and significant changes can occur in a time frame of hours or less. The profile determined from the measured data nearly approximates the pipeline voltage which would have existed at the time of electric field measurement. Some differences will exist because logistics force measurements to be made over a period of time greater than the period of "electrical stationarity" of the power line phase currents. An instantaneous "snapshot" of the electric field over the complete line length would provide the necessary information for an exact profile determination. However, compensation of data obtained in time sequence is possible.

It must be recognized that a dynamic situation exists on the ROW as regards electromagnetic induction. Measurements made in a relatively short time frame constitute only a single sampling of a time varying process; i.e., the voltage profile can vary in time. Hence, to account for these variations, a "worst case" profile has been computed for the condition of average load currents on the electrical circuits carried on the ROW, but where peak unbalances in phase load currents for a given circuit of up to $\pm$ 5% may be expected. (Such unbalanced conditions generally are the principal cause of pipeline voltage fluctuations.)

Applying a probability model for the induction phenomena to this situation results in the solid curve profile plotted in Figure B-5. Since this curve more nearly represents worst case conditions, it can be expected to always lie above the dashed curve representing conditions at the time of measurement. One exception to this rule is found at Station 430+00 and vicinity. Here, the "worst case" computed curve lies below the voltage peak calculated from measured data. Detailed analytical investigation of the electrical characteristics of the discontinuity at this location has shown that the peak calculated from the measured data is incorrect and appears because of a relatively significant change in power line current between the times the electric field was measured at locations south and north of Station 430+00, respectively.

Voltage Profile
Consumer Power Company, Kalamazoo Line 1800 Pipeline, Kalamazoo, Michigan.

Introduction. The mathematical/hand calculator oriented approach is used here to derive the pipeline voltage profile. The ROW configuration is relatively simple, thus providing a good first introduction to obtaining mathematical solutions. This case illustrates how to take into account end terminations of the pipeline and evaluate their effects. Line 1800 is a 20-inch-diameter gas transmission pipeline located north of Kalamazoo, Michigan. It runs approximately south to north for a distance of 31.1 km, starting at the Plainwell valve site and terminating at the 30th Street valve site at the north end. It parallels two 345 kV, three-phase circuits for a distance of 27.1 km, starting at a distance of 3.0 km north of the Plainwell valve site and ending at approximately 1 km south of the 30th Street valve site. For the region of parallelism, the average ROW profile is shown in Figure B-6.

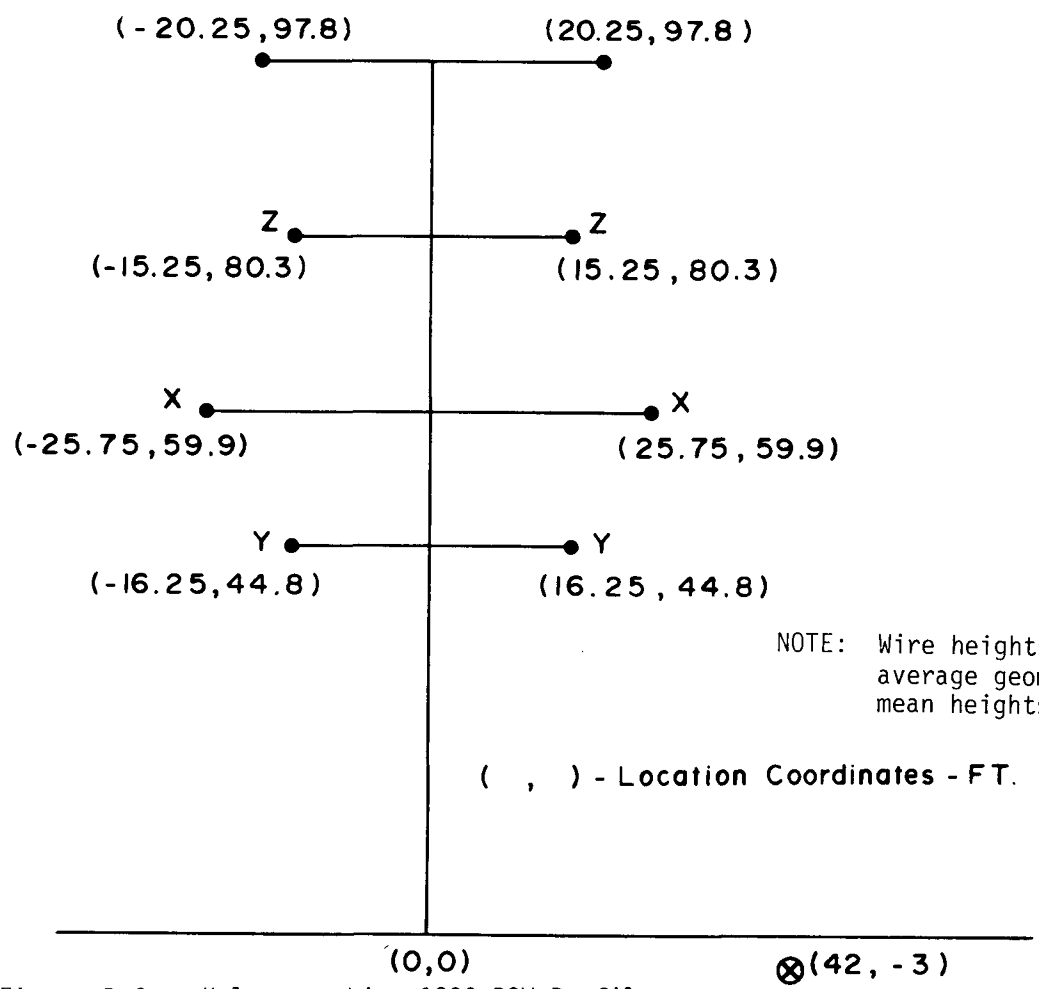


Figure B-6. Kalamazoo Line 1800 ROW Profile Facing North

An ac pipeline voltage survey was made along this ROW at a time when the currents in the electric circuits were being monitored. Based upon the developed prediction theory, a voltage profile was calculated. The calculated and measured profiles are plotted in Figure B-7 and, as shown, good agreement between both plots exists.

The pipeline is terminated at both ends in insulators with grounding cells across the insulators. At the time of the survey, it appeared that the grounding cell at the 30th Street valve site was partially shorted since bonding across the insulator did not cause a significant redistribution in pipe voltage and current. Hence, the pipeline at this location was electrically connected to a 24-inch pipeline (which, in turn, was electrically bonded to another 16-inch pipeline).

At the Plainwell valve site, a relatively good grounding system exists to the south of the pipeline insulator which is formed by the electrical connection of a 12-inch pipeline, several ground rods at the valve site, and a tie-in to the electrical power system neutral at this point. With the grounding cell connected across the insulator, which is normal operation, the pipeline is well grounded at the south end, and hence, mitigates ac induction at this end. The grounding cell at this end was fairly well dried out, and hence, the pipeline experiences relatively high voltage levels at the valve site if this bond is removed.

Inspection of Figure B-7 shows the voltage reduction experienced by bonding across the insulator and achieving pipeline grounding at this point. Experimental and calculated profiles agree excellently. At several points along the pipeline, magnesium anodes have been installed, but were disconnected while measurements were being made. To test the effect of such anodes on the reduction of induced ac voltages, measurements were also taken with a mag anode connected at 112th Street ($\simeq$ 5 km north of Plainwell valve). A single anode will provide an ac voltage reduction only at or near the point of connection, and the resulting calculated and measured voltage levels are plotted as the diamond-shaped points in the figure. In general, if voltage mitigation by means of mag anodes was desired over a large distance, placement of successive anodes at distances much less than γ^{-1}, the pipeline propagation constant, would be necessary. This procedure would effect the equivalent of a pipe coating of lower resistivity and, hence, uniformly reduce the voltage along the complete length of the pipeline.

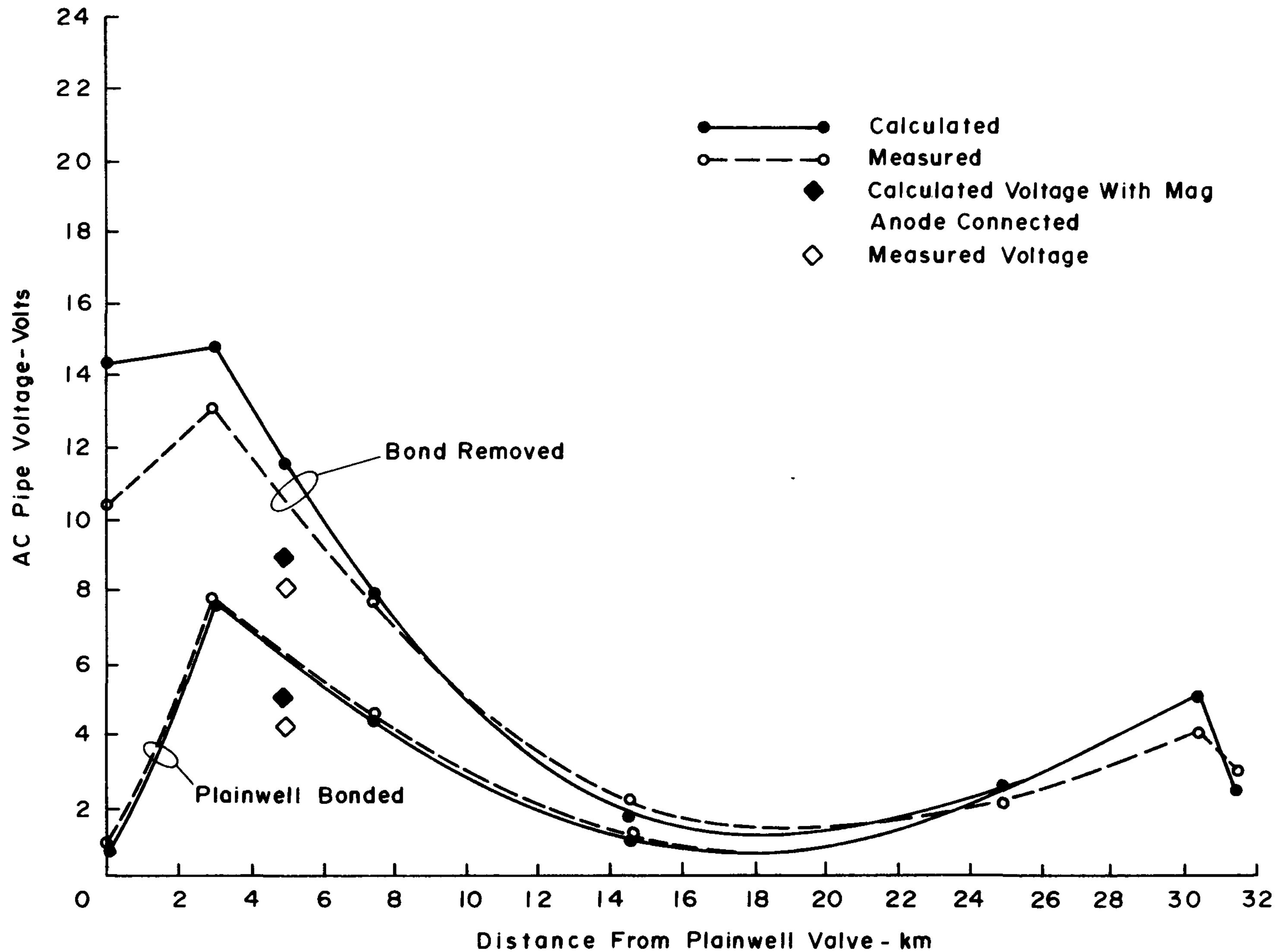


Fig. B-7. LINE 1800 VOLTAGE PROFILE

With the bond removed at Plainwell, the induced voltage levels at the north end are not affected due to the attenuation of the pipeline. They rise, however, at the south end due to the severe discontinuity the insulator presents to the pipe. Inspection of the plots shows a deviation between measured and calculated values at or near the Plainwell valve site. The discrepancy can be accounted for, however, by the fact that for the calculations a perfect insulator was assumed (infinite resistance), but obviously some leakage did occur across the existing ground cell which resulted in measured voltages being somewhat smaller than the calculated values.

The results plotted in Figure B-7 verify the developed prediction technique. Details of the calculations are described in the following sections.

Electric Field Calculation. The first step in predicting the voltage developed on the pipeline is to determine the longitudinal electric field driving the pipeline. The procedure is as follows:

1. From Figure B-6, determine the distances (using geometric mean height of the conductors) from each of the six phase line conductors to the shield wires and the pipeline. Also determine the distance between each shield wire and the pipeline.

2. Using the mutual impedance program CARSON developed for the TI-59 programmable calculator, determine the mutual impedances between the phase conductors, the shield wires and the pipeline. (An average ground resistivity of 400 ohms-meter is assumed.)

3. From available programs, calculate the self impedances of the shield wires (c.f., program SHIELD) and the pipeline (c.f., program PIPE) calculated self impedances are: shield wire, $Z = 2.05\underline{/29.2^o}$ ohms/km; pipeline, $Z = 0.596\underline{/77.6^o}$ ohms/km. (The shield wire dc resistance was assumed to be 1.727×10^{-3} ohms/m. The radius of the shield wire is 4.978×10^{-3} m. The pipeline self impedance is obtained by multiplying γ and Z_0 together. These latter parameters were obtained by means of program PIPE, with the following input parameters: (1) pipe burial depth - 36 inches, (2) pipe thickness - 0.32 inch, (3) ground resistivity - 400 ohm-m, (4) pipe steel relative permeability - 300, (5) pipe steel resistivity - 0.17 $\mu\Omega$-m, (6) pipe diameter - 20 inches, (7) coating resistivity - 300,000 ohms-ft^2. With these input parameters, calculated pipeline parameters were: $\gamma = 0.1397 + j\ 0.1129$ km^{-1} and $Z_0 = 2.593 + j\ 2.075$ ohms.)

4. Input the mutual and self impedances into the TI-59 program CURRENTS and for an assumed set of power line currents determine the pipeline current. Multiplication of the pipeline current and self impedance yields the driving electric field at the pipeline. Calculations were made assuming 50 amperes load in each phase conductor (phasing sequence X, Y, Z: CCW). The hand calculator program CURRENTS yields

a pipe current of $6.43\underline{/128.9^{o}}$ amperes, and hence, a source field of $E_0 = 3.83\underline{/26.5^{o}}$ volts/km.* This value is obtained by multiplying the negative of the pipe current times the pipe self impedance.

Pipeline Load Impedances

Plainwell Valve Site. Due to the fact that a complex grounding system exists at the valve site, e.g., ground rods, pipelines, and a tie-in to the electrical distribution system neutral, the grounding impedance was measured rather than calculated. With a bond across the insulator, a value of 0.15 ohm was measured. This measurement was made with a voltmeter and ammeter and, hence, the grounding impedance phase was not directly measurable. It was estimated to be in the vicinity of zero degrees, i.e., primarily resistive, and subsequent calculations made using this assumption yielded calculated voltage profiles commensurate with measured values. The estimate was based on prior field experience which has indicated that the impedance of short ground rods, lossy conductors and so forth, tends to be primarily resistive. The ground bed at this valve site is a composite of such grounds. With the bond removed, an infinite load impedance was assumed, which the plots of Figure B-7 show as being slightly in error; i.e., some leakage existed through the nominally dry grounding cell.

Thirtieth Street Valve Site. The valve at this site is physically connected to a 24-inch pipeline having a poorer coating ($\approx$ 100,000 ohms-ft^2) and this pipeline, in turn, is electrically bonded to a 16-inch pipeline with a coating resistivity of about the same magnitude. Hence, the load impedance seen by the pipeline with a shorted insulator at the valve site will be one-half of the parallel combination of the 16-inch and 24-inch pipeline characteristic impedances. This value was calculated to be $0.506\underline{/38.4^{o}}$ ohms, and was found by the following procedure. When

*Loading on these circuits varied considerably during the course of the measurements due to changes in current levels, line unbalances, and even in change of direction of power flow for one of the circuits relative to the other. For the variations observed within a 24-hour period, the pipe induced voltage could change by factors of three to four higher or lower than the calculations presented here.

an electrical bond is made to a pipeline extending for a significant distance to either side of the bond, the input impedance into the bond is equal to one-half of the pipeline characteristic impedances. By bonding to two pipelines, the impedances looking into each of the pipe bonds are in parallel. Hence, the effective impedance as seen by the 20-inch pipeline is the product of each external pipeline bond impedance divided by their sum.

Equivalent Circuit Derivation. At each location along the pipeline for which a voltage prediction is desired, Thevenin equivalent electric network circuits must be derived looking in both directions along the pipeline from that location. These equivalent circuits may then be combined as discussed in the following section, to determine the voltage at that point.

To elucidate the procedure, a sample calculation for a point approximately 7.2 km north of the Plainwell valve site (115th Street) will be made. (It will be assumed that the bond across the Plainwell insulator is removed.)

Equivalent circuit derivation is accomplished through repeated use of program THEVENIN, as follows.

To the North. The 30th Street valve site is approximately 23.9 km away from the location. However, the pipeline follows the electric transmission for the first 22.9 km. Hence:

1. Find the input impedance to the pipeline at a point 1 km south of the 30th Street valve. With the load impedance of $0.506/\underline{38.4^{\circ}}$ at the valve site, the input impedance is calculated as $3.32/\underline{38.7^{\circ}}$ ohms.

2. This calculated impedance is then used as the load impedance for the 22.9 km pipeline length. As previously determined, the driving electric field is $3.83/\underline{26.5^{\circ}}$ volts/km, and using these parameters in the THEVENIN program yields an equivalent circuit consisting of a voltage generator of $22.1/\underline{-191.2}$ volts in series with an impedance of $3.32/\underline{38.7}$ ohms.

To the South. The infinite impedance at the Plainwell valve site transforms through the use of Program THEVENIN to an impedance of $6.23/\underline{5.14^{\circ}}$ at a point 3.0 km north of Plainwell (location where the pipeline first contacts the power line). This impedance is then used as the load impedance for the 4.4 km of pipeline extending from the point of first contact to 115th Street. Using the previously calculated field of $E_0 = 3.83\underline{/26.5} + 180^{\circ}$ results in an equivalent circuit generator of $11.5\underline{/19.9^{\circ}}$ volts in series with $3.23\underline{/24.6^{\circ}}$ ohms using the THEVENIN program.

Pipeline Voltage Calculation. The pipeline voltage at this location is calculated by combining the two equivalent circuits and calculating the resulting voltage at the point of connection. To effect this solution easily, the hand calculator program NODE is used. Inputting the equivalent circuit parameters into the program yields a pipe voltage of $8.0\underline{/130.4^{\circ}}$ volts and a pipe current of $5.0\underline{/147.6^{\circ}}$ amperes.

The Program NODE also has the added capability of solving for the resulting voltage with either a mitigation (ground) wire or anode connected to the pipeline at the location. (When a ground or mitigation wire is not used, the impedance $|Z_2|$ must be set to a high value for the program to yield a correct result. A value of 10,000 or higher should be sufficient.)

Voltage Prediction
Texas Gas Transmission Corporation, Memphis, Tennessee

Introduction. This case history of voltage prediction is possibly the most complicated of the set presented, in that four gas pipelines are collocated with several power circuits. The analysis becomes difficult because of electrical interties between the pipelines at several locations. The solution illustrates repeated use of the Thevenin equivalent circuit concept to produce successive simplifications of the problem. Near the city of Memphis, Tennessee, the Texas Gas Transmission Corporation and the Memphis Gas, Light and Water Company share a common right-of-way for a distance of approximately 1.9 km. Four pipelines and the two existing power lines (three circuits) share the right-of-way. An additional power line with two vertical circuits is planned for the near future on the west side of the right-of-way, as shown in Figure B-8. In this section, the right-of-way lies in an almost north-south direction, from Highway 72 on the north end (Station #254+1377) to Messick Road on the South (Station #253+984).

A study of the impact the new circuits will make on the induced pipeline voltage distributions for both the steady state and transient conditions has been made.

Predicted Voltage Levels. Tabulated results of the steady state analyses and the transient analyses made in the following subsections are summarized here.

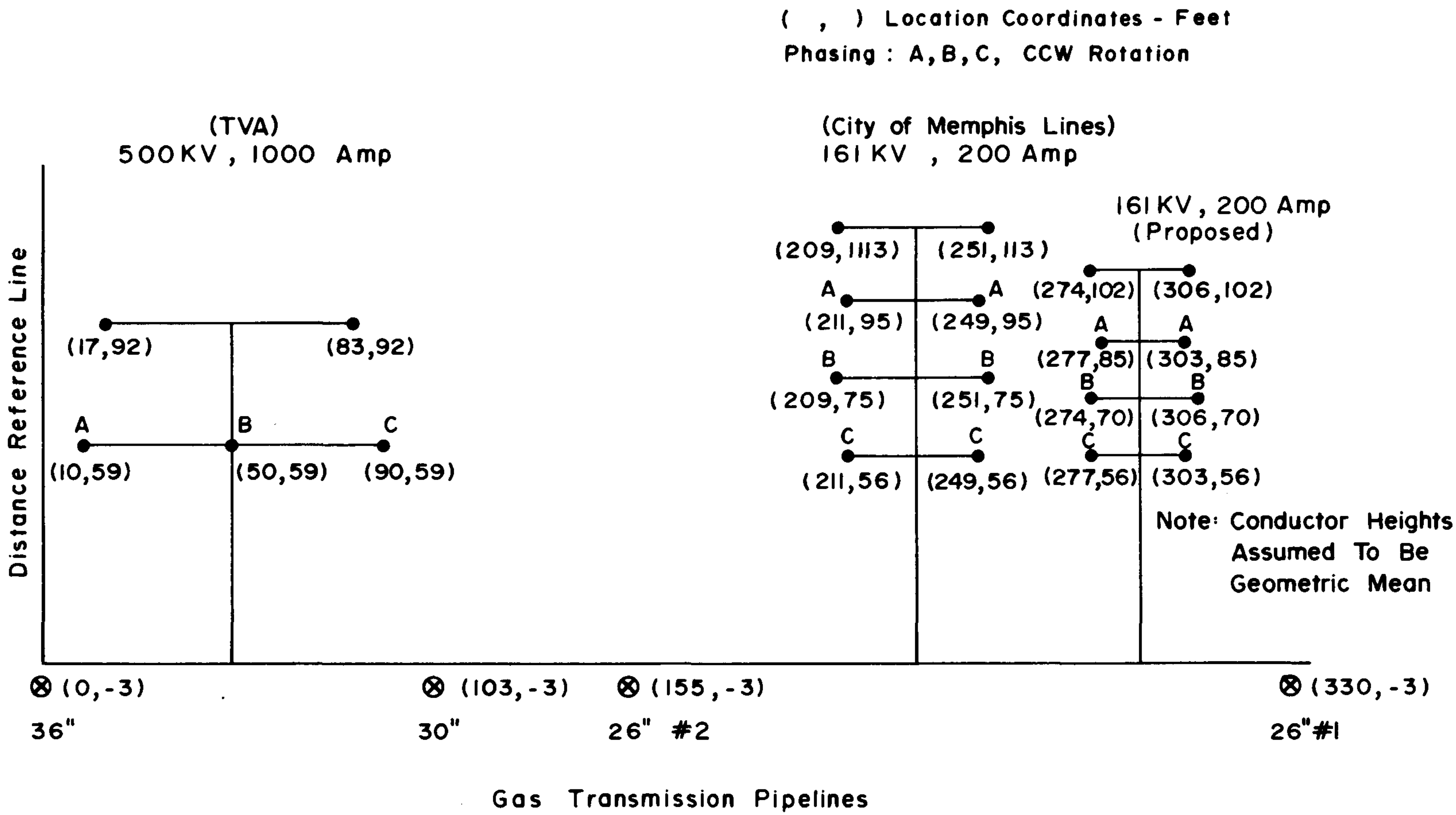


Fig. B-8. AVERAGE RIGHT OF WAY PROFILE

Steady State. Calculations for the peak voltages which occur at the north and south ends of the parallel exposure were made for the following conditions:

1. for the existing circuits (fully loaded, i.e., 1000 amperes for the 500 kV circuit and 200 amperes each for the 161 kV circuits) with the cathodic protection (C.P.) bond wire connecting all four pipelines at Poplar Pike - both connected and disconnected, and

2. for the fully loaded existing circuits plus the proposed circuits loaded to 200 amperes each (Tables B-3 and B-4).

Transient Voltage Levels. For a single phase line to ground fault, the worst case voltage stress across the pipeline coating is estimated at 6748 volts. Simultaneously, the pipe steel will rise to a level of 109 volts for the duration of the fault.

A station fault will cause an induced voltage to occur on all conductors along the right-of-way, i.e., phase wires, shield wires and pipelines. Due to the large number of conductors, an exact solution for the induced voltage level on any one conductor is not possible with the presently available hand calculator program. A worst case analysis, for example, gives 665 volts on the 26-inch - #1 pipeline, but in practice it would be expected that the actual voltage level would be a small fraction of this value.

Summary of Results. A comparison of Tables B-3 and B-4 shows that the addition of the proposed two circuits on the right-of-way primarily affects the voltage levels on the 26-inch - #1 pipeline. The voltage levels are increased from 19 to 27 volts at the south end of the exposure, Messick Road, and from 15 to 20 volts at the north end at Highway 72 (CP bond connected). It should be noted, however, that these are not the highest voltage levels that can be experienced on the right-of-way. Even with the existing circuits only in operation, a 1000 ampere loading on the 500 kV TVA line could induce higher levels on the 30-inch and 36-inch lines (c.f., Messick Road).

The worst situation transient problem occurs with a single phase tower fault in which a voltage stress of approximately 6700 volts is induced across the pipe coating.

Table B-3

VOLTAGE LEVELS - EXISTING CIRCUITS

	Messick Road		Highway 72	
Pipeline	CP Bond In	Bond Out	CP Bond In	Bond Out
26" - #1	19 V	20 V	15 V	20 V
26" - #2	36	33	19	36
30"	29	29	19	27
36"	38	29	6	27

Table B-4

VOLTAGE LEVELS WITH PROPOSED CIRCUITS

	Messick Road		Highway 72	
Pipeline	CP Bond In	Bond Out	CP Bond In	Bond Out
26" - #1	27 V	26 V	20 V	26 V
26" - #2	39	36	25	36
30"	29	29	20	27
36"	38	29	5	27

Steady State Voltage Prediction. The analytical approach to the problem is generally dictated by the number of pipelines, the electrical bonds between them, and the number of electrical circuits and associated unknown shield wire currents. Referring to Figure B-8, the right-of-way consists of (after installation of the proposed tower) 15 phase current carrying conductors, 6 shield wires, and 4 pipelines carrying unknown currents. In addition, as shown in Figure B-9, the following electrical bonds exist between the pipelines:

- 26-inch - #1 and 26-inch - #2 are electrically tied together at approximately 2.15 km south of Messick Road (south end of parallel exposure).

- All four pipelines are tied together at a distance of 8.3 km south of Messick Road.

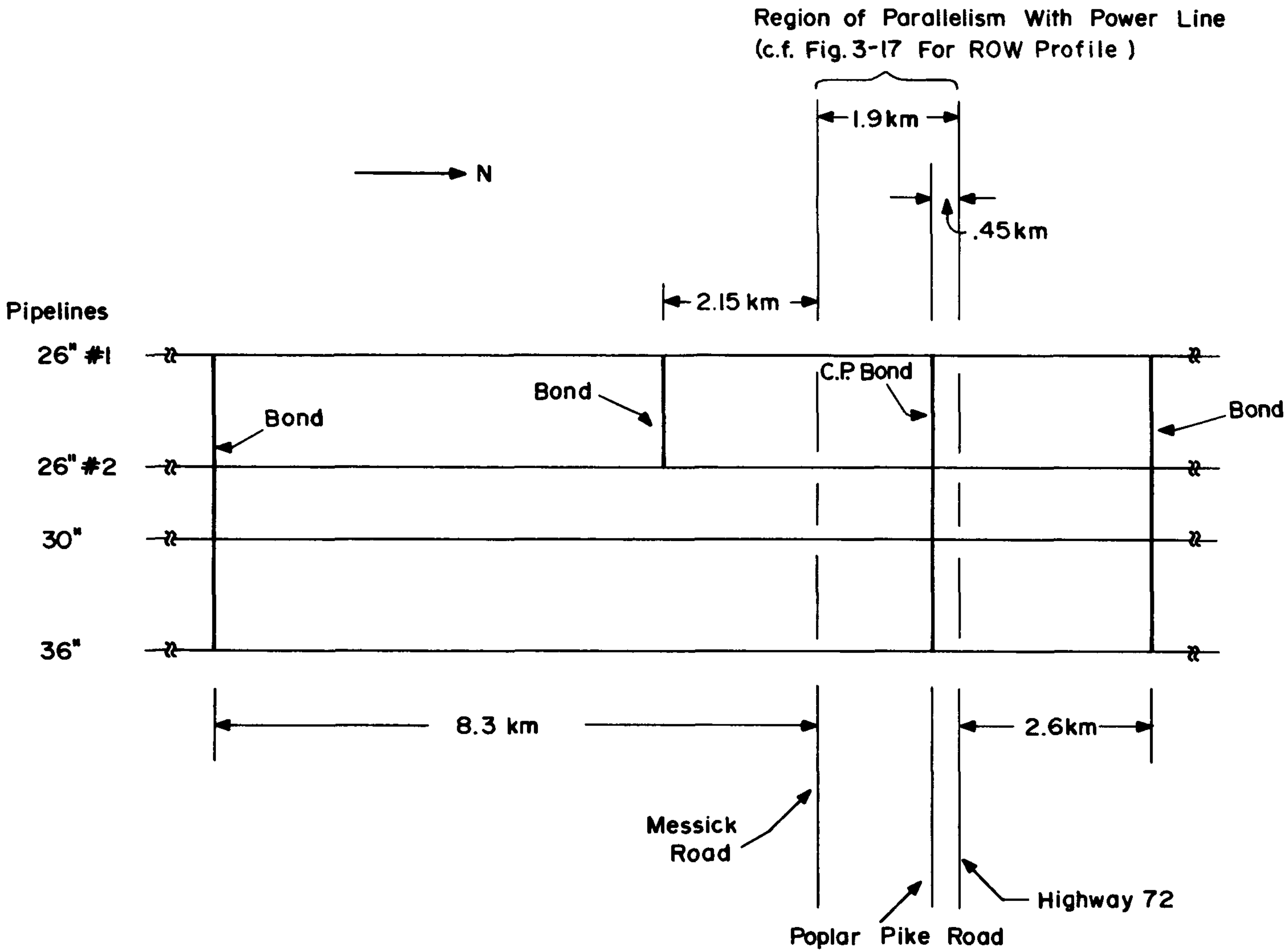


Fig. B-9 ELECTRICAL BONDS BETWEEN PIPELINES

- All four pipelines are tied together at a distance 2.6 km north of Highway 72 (north end of parallel exposure).
- A (removable) cathodic protection bond is made to all the pipelines at Poplar Pike, a distance 0.45 km south of Highway 72.

A rigorous solution to the voltage prediction problem for this right-of-way requires the simultaneous solution of equations for the ten unknown currents; this is complicated by the fact that not only does inductive coupling occur between the pipelines, but also direct coupling, as exemplified by the existing cross ties and bond wires. Cost effectiveness requires simplification of the problem, but in a proper manner so as not to compromise the solution. The approach used may be outlined as follows. Program CURRENTS can solve for unknown currents in up to five conductors in the presence of up to 25 known current-carrying conductors. In order not to exceed the program's capability, the following sub-set problems were solved:

1. The shield wire currents (4) for the 161 kV circuits were obtained by solving simultaneous equations, taking into account only the 12-phase wires on the two towers. The rationale behind this approximation is that these shield wires are primarily driven by their own phase wires, and hence, neglecting the other conductors (including the pipelines) will not materially affect the solution.
2. Assuming that the 500 kV phase wires were the prime driving sources for the shield wires mounted on the same tower, a solution for these shield wire currents was then obtained.

The solutions thusly obtained for the six shield wire currents reduce the number of unknowns to four (the pipeline currents), thus allowing the use of program CURRENTS directly for their solution. (Since the parallel exposure length is quite small, it would be necessary to input a modified set of mutual and self impedances into the program, which is discussed in Appendix D, Volume 1).

However, an alternative approach was used, namely considering each pipeline individually, calculating the electric field, and hence, the voltage at each pipeline ignoring mutual coupling effects between the pipes themselves. The reason for this approach was that the pipeline(s) response to an individual electric circuit was desired and proved simpler than successively re-inputting the calculator program parameters. Generally, neglect of the mutual impedances between pipelines would lead to relatively large errors in the predicted voltage level. In the present situation this is allowable because (1) the short exposure length limits the individual pipe currents so that the electric fields produced by them are relatively small, and (2) because of like phasing for the electrical circuits, the electric field from the power lines is relatively large, thus tending to mask the pipeline current contributions.

With the cathodic protection bond wires opened at Poplar Pike, calculation of the voltage profiles on each of the pipelines is relatively simple. Picking a point of observation (generally, the north or south end exposure points since peak voltages occur at these points), the equivalent circuit approach was used with numerical calculations made by means of the THEVENIN program. The principal point to keep in mind is that since the pipelines are tied together both north and south of the parallel exposure, they are not terminated in their characteristic impedances, and the effective end loadings must be determined.

For the case where the cathodic protection bonds are connected at Poplar Pike, the equivalent circuit voltage calculations become more difficult because this is a location along the parallel exposure. The procedure here is to find the Thevenin circuit for each pipeline to the north and south of Poplar Pike and parallel-connect all eight circuits. A Thevenin equivalent generator may then be derived, i.e., the connected bond(s) voltage at Poplar Pike. The peak voltages for each of the pipelines may then be calculated, e.g., from the south end of the exposure looking north or the north end looking south, with the transmission line(s) terminated in the Poplar Pike Thevenin equivalent generator.

The intermediate calculations are discussed in the following subsections.

Pipe Parameter Calculations. Averaged pipe parameters were obtained assuming a ground resistivity of 5000 ohm-cm and coating resistivities for all pipes of 100,000 ohms-ft^2. The propagation constant and characteristic impedance for each pipe was determined as,

$$\gamma = .26 + j.20 = .328\underline{/37.6^{\circ}}\ \text{km}^{-1}$$

$$Z_0 = 1.2 + j\,1 = 1.56\underline{/39.8}\ \text{ohms}$$

Even though the pipes varied in diameter, the same parameters were assumed for all the pipes, since possibly unknown variations in the above resistivities could supercede variations caused by the differences in the diameters.

Shield Wire Current Calculations. Using the approximate method outlined previously, the shield wire currents were calculated on the basis of 1000-ampere phase currents in the 500 kV circuit and 200 ampere currents in the four remaining 161 kV circuits (all circuits delivering power south). The Carson mutual impedance was calculated between each phase wire and shield wire using the program CARSON. Solution of the simultaneous equations for the unknown currents was made by the program CURRENTS. Results are:

500 kV Circuit*

East Shield Wire: $I = 27.7\underline{/214.4^{\circ}}$ amperes

West Shield Wire: $I = 29.1\underline{/48.26^{\circ}}$ amperes

East (existing) 161 kV Tower**

East Shield Wire: $I = 13.4\underline{/190.8^{\circ}}$ amperes

West Shield Wire: $I = 18.0\underline{/194.9^{\circ}}$ amperes

West (proposed) 161 kV Tower***

East Shield Wire: $I = 9.6\underline{/207.2^{\circ}}$ amperes

West Shield Wire: $I = 6.8\underline{/202.7^{\circ}}$ amperes

Electric Field Calculations. The voltage appearing on any of the pipelines is proportional to the driving electric field impinging upon the pipeline. For calculating the electric field, the program CARSON was used to find the mutual impedance between each pipe and all of the phase and shield wires. Because of the short exposure length of the pipelines to the power lines, mutual coupling effects between the pipelines themselves were ignored.

Calculated shield wire self impedance:

* $2.11\underline{/25.6^{\circ}}$ ohms/km (wire resistance = 1.85×10^{-3} ohms/m; wire radius = $.44 \times 10^{-2}$ m)

** $1.373\underline{/40.6^{\circ}}$ ohms/km (wire resistance = 0.984×10^{-3} ohms/m; wire radius = $.55 \times 10^{-2}$ m)

***$2.38\underline{/22.4^{\circ}}$ ohms/km (wire resistnace = 2.14×10^{-3} ohms/m; wire radius = $.44 \times 10^{-2}$ m).

26-inch - #1 Pipeline. The electric field calculations for the phase current loading given in Figure B-8 yield the following:

Partial electric field due to existing 161 kV circuit = $10.7\underline{/254.9^{o}}$ V/km.

Partial electric field due to proposed 161 kV circuit = $10.8\underline{/245.5^{o}}$ V/km.

Partial electric field due to existing 500 kV circuit = $18.4\underline{/231.7^{o}}$ V/km.

Total electric field at pipeline = $39\underline{/243^{o}}$.

Hence, addition of the proposed 161 kV circuits to the ROW will increase the steady state voltage at the pipeline by approximately one-third when the other circuits are fully loaded.

26-inch - #2 Pipeline.

Partial field due to existing 161 kV circuit	= $12.5\underline{/252.5^{o}}$ V/km.
Partial field due to proposed 161 kV circuit	= $4.54\underline{/274.4^{o}}$ V/km.
Partial field due to existing 500 kV circuit	= $37.7\underline{/234.1^{o}}$ V/km.
Total field at pipeline	= $53.5\underline{/241.5^{o}}$ V/km.

30-inch Pipeline.

Electric field due to 500 kV circuit = $38\underline{/240.7^{o}}$ V/km.

Electric field from other lines small.

36-inch Pipeline

Electric field due to 500 kV circuit = $35.7\underline{/56.9^{o}}$ V/km

Electric field from other lines small.

Voltage Calculations (Cathodic Protection Bond at Piplar Pike Disconnected)

30-Inch/36-Inch Pipelines (Messick Road). The voltage calculations for either pipeline are almost identical and will be made for one of the pipelines only (30"). Due to all the pipelines being tied together at 2.6 km north of Highway 72, the load impedance for the pipeline seen at this point is $Z_0/7$. Using program THEVENIN, this load impedance transforms into an impedance of $1.29\underline{/59^{o}}$ ohms at Highway 72. In turn, for 1.9 km of pipe, this impedance is changed to a value of $1.614\underline{/47.9^{o}}$ ohms at Messick Road. The Thevenin open circuit voltage at this point is found to be $58.8\underline{/48.2^{o}}$ volts.

The program THEVENIN is used many times in this book and was used in deriving the above equivalent circuit parameters. In order to keep the case histories from becoming unduly lengthy, details of each calculation are generally not given. However, as an illustrative example for aiding reader comprehension, the steps leading to the above equivalent circuit are presented here.

Two iterations of the program THEVENIN are required to arrive at the result:

1. Find input impedance at Highway 72 looking to the north.

   THEVENIN program inputs:

   $\mathrm{Real}(\gamma)$ = 0.26

   $\mathrm{Im}(\gamma)$ = 0.20

   $\mathrm{Real}(Z_o)$ = 1.20

   $I_m(Z_o)$ = 1.0

   $|V_L|$ = 0 (power lines not parallel to pipeline at 2.6 km north of Highway 72)

   $\angle V_L$ = 0

   $|Z_L|$ = 1.56 ÷ 7 = .223 (with four pipelines tied together the input impedance looking to the north at 2.6 km north of Highway 72 is $Z_o/7$, i.e., seven pipe characteristic impedances in parallel)

   $\angle Z_L$ = 39.8^o

   $|E_o|$ = 0

   $\angle E_o$ = 0

   L = 2.6 km

Exercise of program THEVENIN yields a Thevenin voltage generator of $0\angle 0^o$ and a Thevenin impedance of $1.29\angle 59^o$ ohms. These quantities become V_L and Z_L for the next iteration.

2. Find the Thevenin equivalent circuit looking to the north at Messick Road. THEVENIN program inputs

$Real(\gamma) = 0.26$

$I_m(\gamma) = 0.20$

$Real(Z_o) = 1.20$

$Im(Z_o) = 1.0$

$|V_L| = 0$

$\underline{/V_L} = 0$

$|Z_L| = 1.29$

$\underline{/Z_L} = 59^o$

$|E_o| = 38$ (electric field at 30" pipeline)

$\underline{/E_o} = 240.7^o$

$L = 1.9$ km

Exercise of program THEVENIN yields the Thevenin voltage of $58.8\underline{/48.2^o}$ volts and the Thevenin impedance of $1.614\underline{/47.9^o}$ ohms given previously.

The actual pipeline voltage at Messick Road is the open circuit Thevenin voltage corrected for the voltage division occurring between the pipe impedance ($1.614\underline{/47.9^o}$) seen looking to the north of Messick Road and the impedance looking to the south ($1.59\underline{/39.6^o}$). The latter impedance is obtained by calculating the input impedance of the pipe with a load of $Z_o/7$ at a distance of 8.3 km. The resulting calculated voltage is $29.3\underline{/44^o}$ volts.

At the north end of the exposure, Highway 72, the voltage division impedances are different, i.e., $1.29\underline{/59^o}$ to the north and $1.59\underline{/39.6^o}$ to the south, yielding a computed voltage of approximately 26.7 volts.

26-Inch - #2 Pipeline. This pipeline is tied to 26-inch - #1 at approximately 2.15 km south of Messick Road and to the other three lines at 2.6 km north of Highway 72. Such interconnection will tend to equalize the peak voltages appearing at both ends of the parallel exposure.

To compute the voltage at Messick Road, i.e., south end of the exposure, the following procedure is used:

> Assume a load resistance of $Z_0/3$ at the tie-in point south of Messick Road. The THEVENIN program transforms this impedance to $1.26\underline{/54.1^\circ}$ at Messick Road. In like manner, as for the 30 and 36-inch pipelines, the pipeline input impedance is calculated at $1.614\underline{/47.9^\circ}$ ohms, with an open circuit voltage generator $82.9\underline{/49^\circ}$ volts. Calculating the voltage division due to the two impedances yields $36.4\underline{/52.5^\circ}$ volts. The voltage at the north end of the exposure will be approximately the same.

26-Inch - #1 Pipeline. Because of the identical cross ties, the impedance transformations are the same as for the 26-inch - #2 pipeline. The electric field is less at this pipeline, resulting in a peak voltage at both ends of approximately (39/53.5)36.4 - 26.5 volts.

Voltages (Cathodic Protection Bond Connected). The cathodic protection bond, when connected, electrically ties all four pipelines together at Poplar Pike, and thus causes a voltage and current redistribution among the pipelines. In order to calculate the peak voltages on the individual pipelines, the following procedure must be used:

1. Calculate a Thevenin equivalent circuit for each pipeline looking to the north and to the south of Poplar Pike, eight total, and connect them in parallel using the program THEVENIN.
2. Recalculate a new Thevenin equivalent circuit for the above. This circuit then acts as the load for each of the pipelines using program THEVENIN.
3. Using the modified input parameters and the THEVENIN program, calculate the voltage at the north or south terminal exposure points.

A rigorous calculation for the above is rather elaborate. However, the procedure may be simplified as follows:

1. Assume that all lengths of pipeline have an input impedance equal to their characteristic impedance. This yields a Thevenin equivalent circuit impedance of $Z_0/8$.
2. With equal impedance in each leg, the voltage at Poplar Pike may be found by weighted averaging of the electric fields at the pipelines. Hence,

$$V = \frac{1}{8} \sum_{i=1}^{4} E_{o_i} \left(1.2\underline{/-7.8^o} + .425\underline{/177.5^o}\right) \qquad \text{(B-4)}$$

where

> $1.2\underline{/-7.8^o}$ is the Thevenin equivalent generator voltage produced in a pipeline length of 1.45 km (distance to Messick Road from Poplar Pike) for a driving electric field at the pipeline of $1\underline{/0^o}$ volt/km; $0.425\underline{/179.5^o}$ is the open circuit voltage generator for a pipeline length of 0.45 km (distance to Highway 72) for a driving electric field of $1\underline{/0^o}$ volt/km; and E_{o_i} is the electric field at the ith pipeline.

Solution of the previous equation yields a bond wire voltage of $9.2\underline{/233.2^o}$ volts for the case where the proposed circuits are in operation. For the circuits existing presently on the right-of-way, the bond voltage level is $7.7\underline{/232.8^o}$ when all circuits are fully loaded.

Using the THEVENIN program, the voltage levels at both ends of the exposure were calculated for each pipeline for the electrical circuits existing at present and also for the future case where the additional tower is placed on the right-of-way. The program yielded the Thevenin resistance and the open circuit voltages for each of the pipes and terminal points. The pipeline voltage was then computed assuming voltage division through the following terminating impedances:

26" - #1 26" - #2	$1.26\underline{/54.1^o}$ ohms at south end
30" 36"	$1.59\underline{/39.6^o}$ ohms at south end
26" - #1 26" - #2 30" 36"	$1.29\underline{/59^o}$ ohms at north end.

These computed results have been tabulated in Tables B-3 and B-4.

<u>Transient Voltages</u>. Due to right-of-way restrictions, the distance between the power line structure footings and 26-inch - #1 pipeline become small at several locations with a minimum separation of 16 feet. The magnitudes of the transient voltages induced by conductive and inductive coupling are considered in this section.

Conductive Coupling. A phase-to-ground fault at a tower in close proximity to the pipeline will cause a voltage gradient in the ground which will stress the pipeline coating.

Data provided by Memphis Light, Gas and Water indicate a tower to ground resistance of 3 ohms and a single phase-to-ground fault current of 10,988 amperes. Because of the grounded shield wires, the fault current will be divided between the tower and the shield wires. The impedance to earth as seen from the faulted tower is

$$
\begin{aligned}
Z_e &\simeq .5\sqrt{R_T\ Z_S} \\
&= .5\sqrt{3 \times 0.4} \\
&= .55\ \Omega
\end{aligned}
\tag{B-5}
$$

where

R_T is the tower to ground resistance, (3Ω), and

Z_S is the series impedance of the shield wires to the next tower - estimated at .4 Ω.

Because of the current division, the actual current flowing through the tower ground is

$$I_T = \frac{Z_e}{R_T} \cdot I_F = \frac{.55}{3} \cdot 10988 = 2014 \text{ amperes.} \tag{B-6}$$

Using a dc approximation for the current distribution in the earth, the voltage appearing at the pipeline coating is

$$V_C = \frac{I_T \rho}{8\pi} \sum_{i=1}^{4} \frac{1}{d_i} \tag{B-7}$$

where

ρ is the ground resistivity, and

d_i is the distance of each of the tower legs to the pipeline.

A worst case ground resistivity of 17,500 Ω-cm will be assumed. (This value was measured near Poplar Pike at a depth of 2'7".) The calculated voltage at the pipe coating is,

$$V_C = \frac{2014}{8\pi}(175)(.489) = 6857 \text{ volts.}$$

Due to conductive current leakage onto the pipe, the local potential of the pipe steel will also rise, and may be calculated by the following formula:

$$V_S = \frac{\gamma \rho I_T}{8\pi} \sum_{i=1}^{4} [\gamma d_i - \ln \gamma d_i + 0.116] \tag{B-8}$$

where

γ = $(.26 + j\ .20)\ 10^{-3}\ m^{-1}$, the pipeline propagation constant.

Assuming the worst case ground resistivity then yields

$$V_S = (.328)\frac{(10^{-3})(175)(2014)}{8\pi}[23.8]^*$$

$$= 109 \text{ volts.}$$

The calculated voltage stress across the pipeline coating is 6857 - 109 = 6748 volts.

Inductive Coupling of Transients. A single phase fault at a substation represents the worst case. Data supplied give 2635 amperes as the worst case current in one phase wire along the right-of-way. The worst case condition of induced voltage on the pipeline would occur if only the faulted phase conductor (the one closest to the pipeline) and a single pipeline were present on the right-of-way. For this situation, a worst case transient voltage of 665 volts could occur at the 26-inch - #1 pipeline (assuming coupling of all high frequency components to be the same as the 60 Hz component). However, due to the multiplicity of other conductors, i.e., phase wires, shield wires, pipelines on the right-of-way, induced current division between conductors will cause the actual induced voltage at any one conductor to be a small fraction of the calculated worst case voltage.

---

*d_1 = 4.88 m, d_2 = 12.13 m, d_3 = 7.81 m, d_4 = 13.6 m.

Voltage Prediction
Consumers Power Company Karn-Weadock Line, Bay City, Michigan

Introduction. The solution of the induced voltage prediction problem for this crude oil pipeline is obtained by an approach utilizing field measured data as much as possible in contrast to the purely analytical solutions presented for the previous case histories. This 16" pipeline runs north and south approximately 10.6 km from the Karn-Weadock power plants on the north end to a tap site and tank farm on the south end. It is terminated in an insulator and high resistance grounding cell on the north end ($Z_0 \to \infty$) and an insulator and a low impedance grounding cell at the south end. The principal right-of-way (ROW) characteristics are diagrammed in Figure B-10.

The pipeline shares the ROW with six 3ϕ circuits. Starting from the west there are two 138 kV horizontal circuits, each on an H-frame. Next, there are two vertical circuits carried on a single tower with the west circuit at 46 kV and the east circuit at 138 kV. The easternmost tower on the ROW carries two vertical 138 kV circuits. The pipeline ROW may be conveniently divided into five regions on the basis of the principal interaction characteristics with the electric power lines. These are as follows:

Region 1: In this region, the pipeline lies on the west end of the ROW. The distance to the nearest structure varies, however, and is equal to 70 feet in 1a; 190 feet in 1b, and approximately 380 feet in 1c. The extent of each region with distances measured from the north terminus are as shown in Figure B-10.

2: The pipeline crosses over to the east side of the ROW and hence is subject to a completely different excitation field.

3: The pipeline remains in the same position, but the 46 kV circuit (second tower from right) leaves the ROW. The excitation to the pipeline is only slightly changed because of "shielding" of the pipeline by the circuits on the east tower.

4: The pipeline moves to the center of the ROW, i.e., between the horizontal and vertical circuits. It experiences a relatively large change in source driving field at this point.

5: The pipeline remains in the same position, but the easternmost tower leaves the ROW. The excitation to the pipeline is modified, but not significantly, due to "shielding" by the single circuit remaining on the tower to the east. (This condition prevails because the two circuits on the east tower

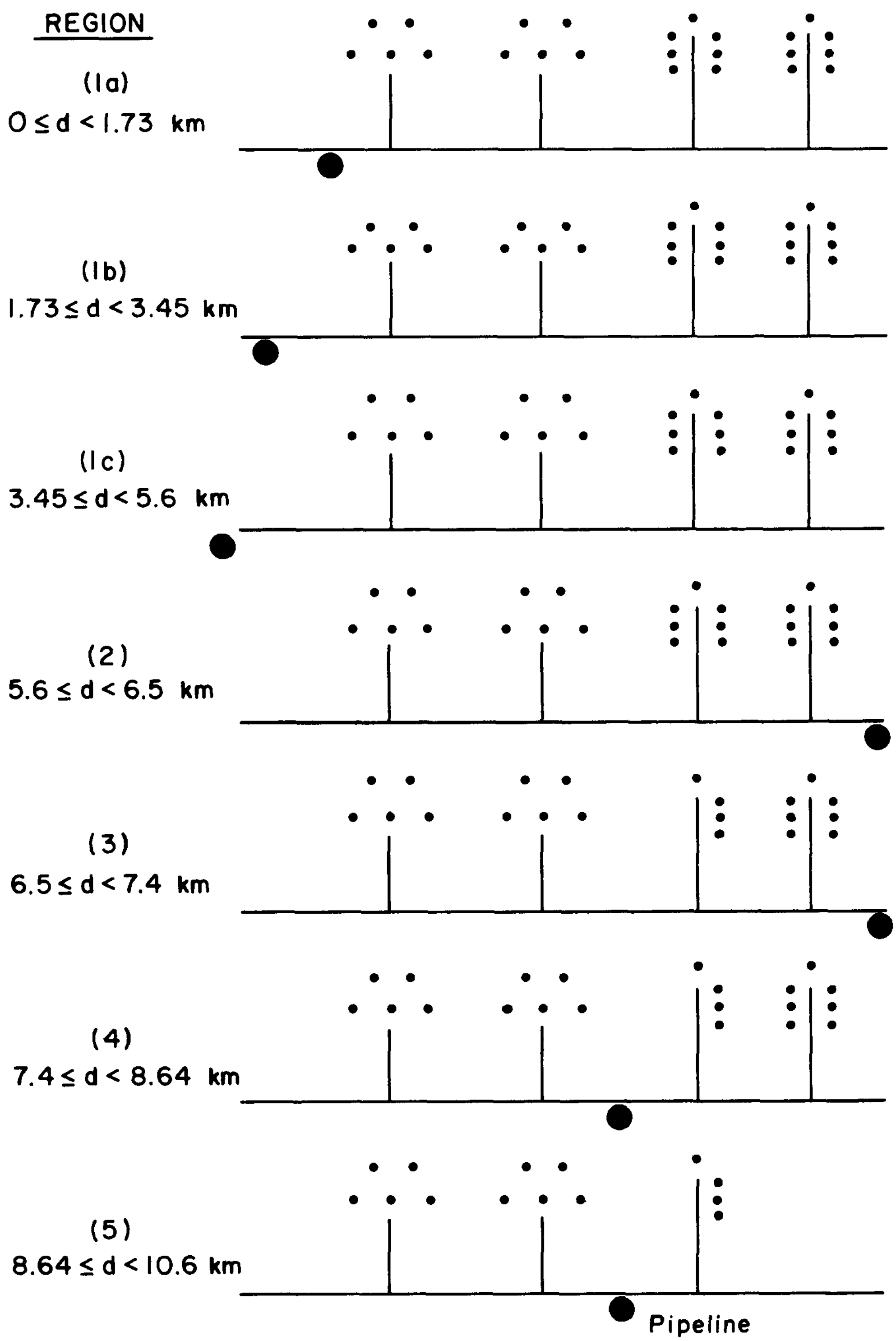


Fig. B-10. BAY CITY ROW PROFILE LOOKING NORTH in Region 4 are phased in partial opposition and, hence their contribution to the total electric field at the pipeline is small compared to that produced by the single circuit on the adjoining tower.)

Pipeline Voltage Prediction Approach. A purely analytical approach to the prediction of the pipeline voltage profile is primarily a two step process: (1) calculate the driving source electric field at the pipeline; and (2) using Thevenin equivalent circuits derived from the program THEVENIN, compute the voltage profile on a point-by-point basis. This procedure was followed, for example, in the Texas Gas Transmission Corporation (Memphis, Tennessee) and the Consumer Power Company (Kalamazoo, Michigan) case histories. For the situation where an existing ROW does not have all the electric power circuits installed, for example, and the effect of future circuits needs to be determined, then this purely analytical approach is necessary. However, in the present situation, where the power lines are already installed on the ROW, a measurement approach to obtaining the free field (Step 1) is possible and, especially in this case, desirable. The reason for this is that the ROW illustrated in Figure B-10 is quite complicated. For example, up to 18 phase lines and six shield wires may exist on the ROW. In addition, although not shown in the figure, there is another 16-inch pipeline sharing the ROW. Hence, there are eight unknown current-carrying conductors on the ROW which require a simultaneous solution for the unknown currents. This exceeds the capacity of the existing program CURRENTS; but as discussed in the Texas Gas Transmission Corporation case history, this limitation may be eliminated by solving for the shield wire currents on an individual piece-meal basis. However, as shown in Figure B-10, seven regions are distinguishable, thus requiring as many sets of calculations; and in addition, the phase line currents must be reasonably well known for all conductors in order to proceed with the calculations. Hence, the necessary calculations to typify this ROW are many and, at best, tedious.

An alternate and very viable approach to determine the driving electric field for the pipeline is by direct measurement, using the electric field magnitude and phase instrumentation developed during the program. An attractive feature of this approach is that knowledge of the phase line current values is not necessary. In using this approach, however, the following considerations apply:

1. The voltage profile calculated using this approach may not be as accurate as when using the calculative procedure. The reason for this is that it may take a better part of a day to make all of the measurements; and because line currents are dynamically varying, the measurements may not be completely consistent with each other. However, it appears in general that the resulting errors are at acceptable levels (c.f., Figure B-11).

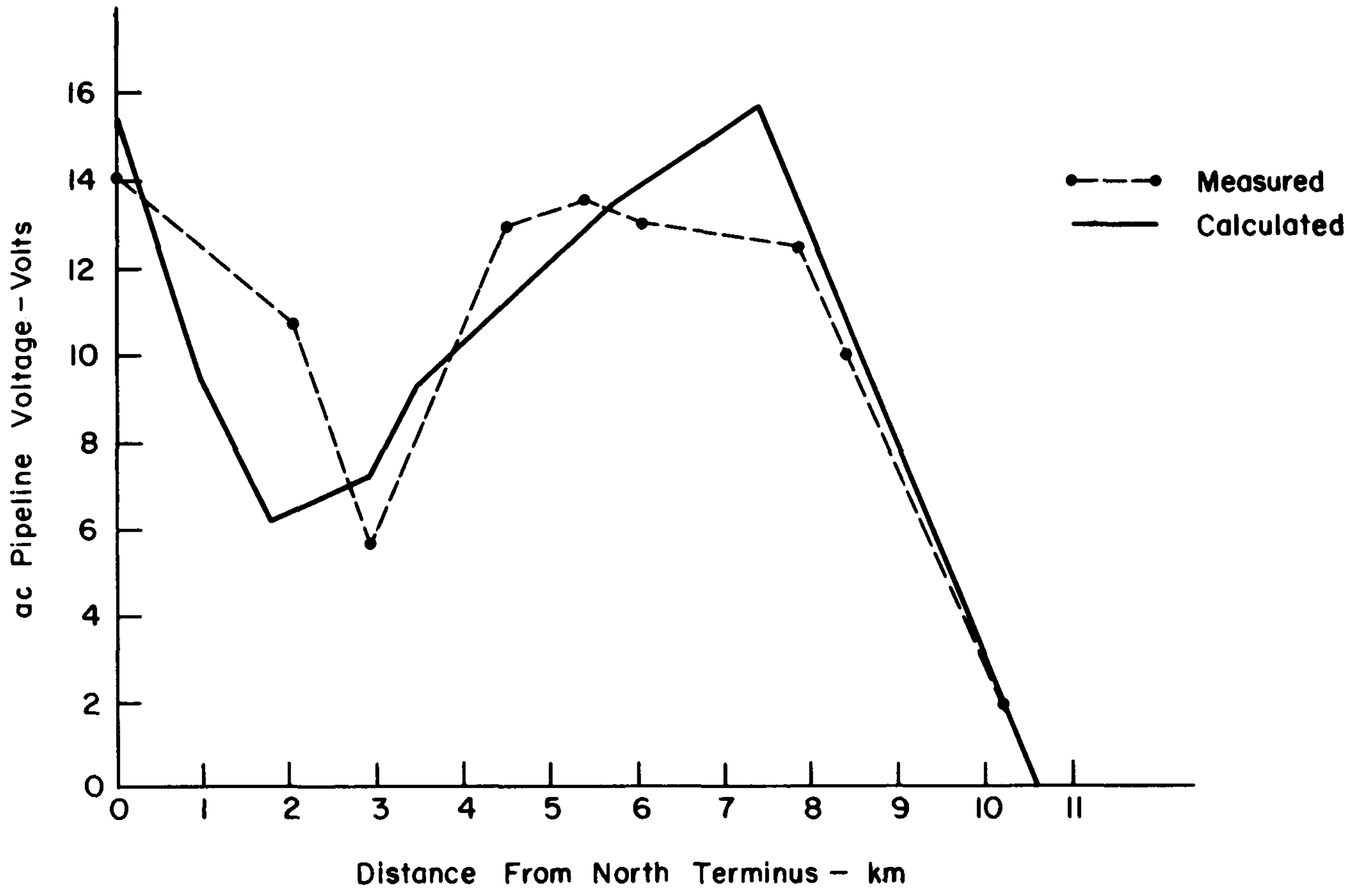


Fig. B-11. PIPELINE VOLTAGE PROFILE

2. It is necessary to measure the pipeline driving electric field for each location of the pipeline relative to the power lines. However, the measurements cannot be made in the vicinity of the pipeline itself since the pipeline current will perturb the measurements. Hence, the following procedure or a conceptually similar one may be used. For example, to obtain an approximation to the pipeline driving electric field in regions 1a, 1b and 1c, measure the electric field at the same distances from the power lines in region 2, since the pipeline has crossed over to the opposite side of the ROW. Likewise, the driving electric field for the pipeline in region 2 can be approximated by measurements at the same location relative to the power lines in any of the sub-regions of region 1. Similar considerations hold for the other regions.

3. A common phase reference must be established between all the electric field measurements made in the different regions. This is best accomplished by locating the equipment reference probe at the same location relative to the power lines in each of the regions that measurements are made. Two requirements must be made in choosing the reference probe location: (1) the electric field at the reference probe must be approximately the same, i.e., at least the closest power line circuits must be the same for all regions, and (2) the pipeline cannot be buried at this location in any of the regions. Reference to Figure B-10 shows that a location between the two westernmost structures will satisfy these requirements. In making the electric field measurements, the phase of each measured field is known relative to the reference probe and, hence, relative to any other measured electric field anywhere on the ROW. Arbitrarily, any one of the measured fields (or the field at the reference probe) may be assigned as the zero phase reference and all other electric field phases adjusted in a corresponding manner.

4. This measurement procedure is reasonably accurate (as in the situation here) if the presence of the subject pipeline on the ROW does not significantly alter the currents in other conductors situated on the ROW.

Measured Electric Source Fields. After adjusting the measured phase of the electric fields so as to be commensurable with a single phase reference common to all regions, the values shown in Table B-5 were obtained. (Note: The measured field magnitudes are not modified in any way.)

Pipeline Parameters. Knowledge of the pipeline parameters, γ, the propagation constant and Z_0, the characteristic impedance, are necessary in order to calculate the voltage profile. This, in turn, requires knowledge of the coating resistivity which, at best, can only be estimated. An additional complication exists for this line in that during construction, 17-pound magnesium anodes were installed every one-quarter mile and are inaccessible for measurement. (With such a close separation, the magnesium anodes in the aggregate act as a continuous holiday and, hence, basically lower the average resistivity of the pipe coating.)

Table B-5

ELECTRIC FIELD MEASUREMENTS

Region		Electric Field (volts/km)
1a	$0 \leq d < 1.73$ km	$7.0\underline{/10^o}$
1b	$1.73 \leq d < 3.45$ km	$4.0\underline{/\ 0^o}$
1c	$3.45 \leq d < 5.6$ km	$1.2\underline{/-10^o}$
2	$5.6 \leq d < 6.5$ km	$2.3\underline{/65^o}$
3	$6.5 \leq d < 7.7$ km	$\simeq 2.3\underline{/65^o}$
4	$7.4 \leq d < 8.64$ km	$7.0\underline{/178^o}$
5	$8.64 \leq d < 10.6$ km	$\simeq 7.0\underline{/178^o}$

This problem of establishing the pipeline parameters was solved practically in the following manner. At a point (far enough from either end so as to establish the characteristic impedance level) on the pipeline where a casing existed, the pipeline was shorted to the casing and the drop in the induced voltage level measured along with the resistance of the casing to remote earth. For example, it was found that for a casing of 1.3 ohms resistance, the pipeline voltage was reduced to one-half. This established the pipeline characteristic impedance as being approximately 2.6 ohms.

Using the hand calculator program PIPE, several trial runs were made with different assumed values of coating resistivity. It was found that a coating resistivity of about 200,000 ohms-ft^2 yielded a reasonably close approximation to the measured pipeline impedance. Substituting this value back into the program resulted in the following estimates for the pipeline parameters:

$$\gamma = 0.1473 + j\,0.1084 = 0.183\underline{/36.3^o}\ \text{km}^{-1}$$

$$Z_o = 2.151 + j\,1.586 = 2.67\underline{/36.3^o}\ \text{ohms.}$$

Voltage Calculations. Using the established pipeline parameters and the measured value of the source electric field, the induced voltage was calculated on a point-by-point basis, and the results are plotted in Figure B-11. A sample point calculation is given below for a distance of 5.6 km south of the north terminus.

Sample Voltage Calculation. As a first step, it is necessary to determine the Thevenin equivalent circuits to either side of the location. Considering first the equivalent circuit looking to the north, the following procedure is used.

1. Assume $Z_L = \infty$, because of the insulator at the north end of the pipeline. Using the program THEVENIN, find the equivalent circuit (to the north) at a distance of 1.73 km. Using the electric field appropriate to region 1a yields a solution for the open circuit voltage and Thevenin impedance as, $V_{OC} = 6.04\underline{/189.5^o}$ volts and $Z_{TH} = 8.53\underline{/1.79^o}$ ohms, respectively.

2. Using the quantities V_{OC} and Z_{TH} above for the load, program THEVENIN is used to find the equivalent circuit into the pipeline at the distance of 3.45 km. Using the driving source field appropriate to region 1b yields, $V_{OC} = 8.09\underline{/181.7^o}$ volts, and $Z_{TH} = 4.44\underline{/6.81^o}$ ohms.

3. Using the values of V_{OC} and Z_{TH} calculated in (2) as the load termination, calculate the input equivalent circuit at a distance of 5.6 km. Using the driving source field appropriate to region 1c yields the (north) Thevenin equivalent circuit of $V_{oc} = 6.84\underline{/173.3^o}$ volts and $Z_{TH} = 3.04\underline{/15.8^o}$ ohms.

To complete the prediction, the Thevenin equivalent circuit looking to the south at the point 5.6 km must now be calculated. The procedure is as follows:

1. Assume a very low terminating impedance at the south end, i.e., $Z_L \simeq 0$. Calculate the input impedance to the pipeline (to the south) at a distance of 3.2 km from the south end (or 7.4 km from the north end). Using the driving source field common to both regions 4 and 5 yields, $V_{oc} = 21.5\underline{/172.1^o}$ volts, and $Z_{TH} = 1.50\underline{/66.8^o}$ ohms.

2. Using these computed values as the new load termination, the (south) input equivalent circuit for the pipeline is calculated at 5.6 km. The driving source field appropriate to regions 2 and 3 is used, yielding values of $V_{oc} = 19.0\underline{/148.8^o}$ volts and $Z_{TH} = 2.17\underline{/59.5^o}$ ohms.

3. Using the north and south equivalent circuits just derived, the program NODE results in a predicted voltage of 13.4 volts.

Similar equivalent circuit calculations for other distances were made and the predicted voltage profile for the pipeline is plotted in Figure B-11.

Critique. Comparison of the measured and predicted values of the pipeline voltage shows a very good agreement, in general. The largest discrepancy lies in the region of from 1.5 to 2.5 km, and is presumed to occur because of a possible error in the electric field phase differential between one or more regions. Such a result is not surprising since it took the better part of the day to make the electric field measurements; and because of the time-varying power line currents, all the measurements were not necessarily commensurable.

A second deviation between the calculated and measured curves occurs at 7.4 km. Here, theory indicates the occurrence of a peak, but unfortunately, a measurement was not made close enough to the vicinity of the predicted peak to enable verification of its value. However, immediate data points on either side of the indicated peak exhibit excellent agreement with predicted values.

In summary, this case history, as presented, illustrates a field measurement oriented approach to the prediction of pipeline voltages. It is particularly useful, as in this case, where the interaction geometry between multiple power line circuits and the subject pipeline is varying, thus requiring many sets of calculations to be made if a purely analytical approach were used. Its principal benefits are that power line currents do not have to be known, and the interaction of other conductors such as other buried pipelines is automatically taken into account. The basic disadvantage to the method is that prediction errors can creep in because of changing power line currents while measurements are being made. However, as the results of this case history indicate, the prediction accuracy obtained is still at an acceptable level.

Appendix C

MEASUREMENT OF THE LONGITUDINAL ELECTRIC FIELD

INTRODUCTION

As shown in Section 1, the prediction of the inductive interference to a pipeline caused by a nearby power line requires knowledge of $E_x(s)$, the driving electric field along and parallel to the path of the pipeline. This appendix discusses a technique for an approximate* measurement of E_x along the path. For all cases where E_x is not constant with position along the pipeline, knowledge of the phase as well as the magnitude of E_x is required for evaluation of the inductive coupling to the pipeline using the computational procedures of Section 1.

The measurement is conceptually based upon use of a probe wire technique. However, when such a technique is used in the vicinity of a power line, stray coupling from the line's electrostatic field will introduce a significant measurement error. Necessary modifications to make this type of measurement accurately are discussed in this appendix. The resulting instrumentation described has been field tested, but is not presently available as an off-the-shelf item.

INSTRUMENTATION

Basic Probe Wire Technique

Probe wire techniques have previously been used to determine the magnitude of the longitudinal mutual impedance between a power line and a telephone circuit. This measurement is equivalent to determining $|E_x|$ due to the power line at the location of the telephone line. Therefore, the details of the probe wire technique are of relevance to the pipeline interference problem.

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*The electric field measured along the ROW with the pipeline absent is the "undisturbed" electric field. Once a pipeline is buried, it will carry an induced current which will cause a change in the induced currents flowing in other grounded conductors. The resultant electric field at the location of the pipeline is thusly modified and in actuality is the "driving" field for the pipeline. Voltage predictions based on "undisturbed" field measurements are generally of acceptable accuracy.

As shown in Figure C-1a, the probe wire is simply an insulated wire laid on the earth parallel to the proposed or mirror-image pipeline path and grounded at both ends with driven, vertical rods. The open-circuit voltage, V_{oc}, developed by the probe wire is sensed by a high-input-impedance, frequency-selective voltmeter placed between one ground rod and the end of the wire. Assuming no ground potential rise due to earth currents, no effects due to transverse electric fields (electrostatic coupling), and a short enough probe wire length, L, (30 meters or less) so that E_x is approximately constant over the length of the probe wire, V_{oc} can be determined by solving the equivalent circuit of Figure C-1b. Equating voltage drops around the single loop of the circuit yields

$$V_{oc} = I_v(Z_{g_1} + Z_{g_2}) - E_x L \tag{C-1a}$$

where I_v is the input current drawn by the voltmeter, and Z_{g_1} and Z_{g_2} are the earthing impedances of ground rods #1 and #2, respectively. For $I_v \simeq 0$, Eq. C-1a reduces to

$$V_{oc} \simeq -E_x L \tag{C-1b}$$

and therefore,

$$E_x \simeq -V_{oc}/L. \tag{C-1c}$$

The use of a standard voltmeter with no phase reference implies that only the magnitude of V_{oc} is sensed. Hence, only the magnitude of E_x is obtained:

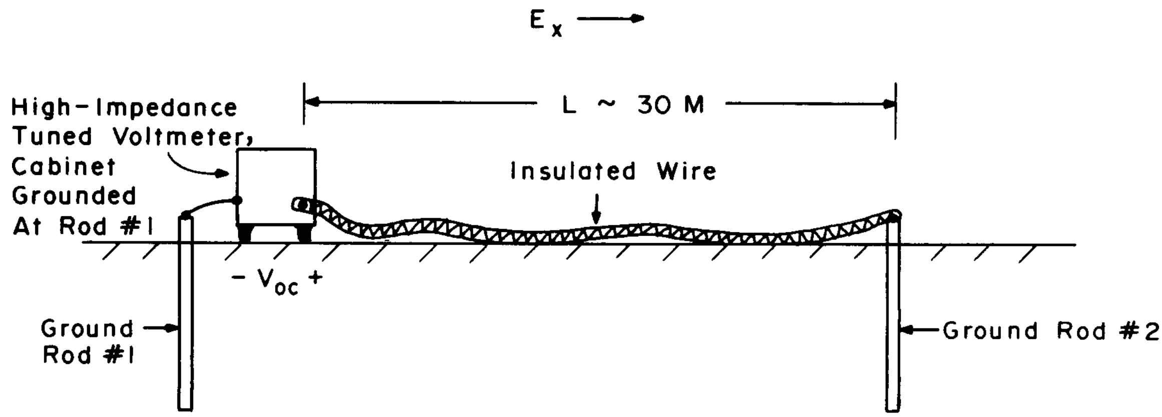
$$|E_x| \simeq |V_{oc}|/L. \tag{C-1d}$$

Problems With the Basic Probe Wire Technique

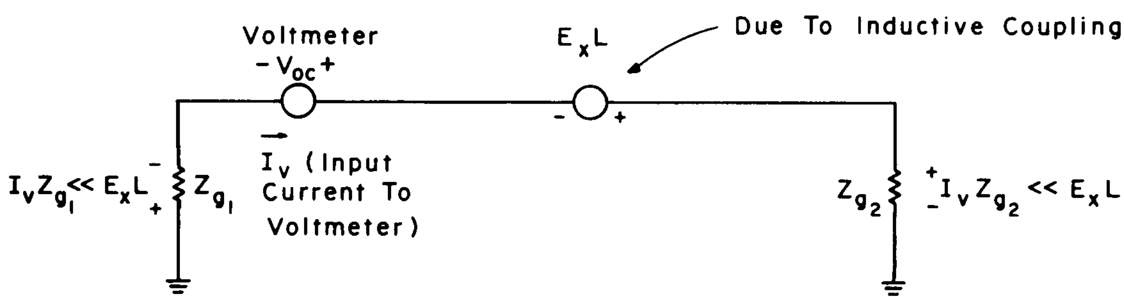
Measurement Error Due to Electrostatic Coupling. Electrostatic coupling to the probe wire can cause the voltmeter to sense a value of V_{oc} that is not due solely to E_x. As shown in Figure C-1c, the effect of electrostatic coupling can be modeled by introducing a probe wire current source, I_{max}, and capacitance-to-ground, C_g, in parallel with Z_{g_2}. Using Eq. 4-9 of Section 4, Volume 1:

$$C_g = \frac{2\pi\varepsilon_o}{\ell n(4H/d)} \cdot L \text{ Farads} \tag{C-2a}$$

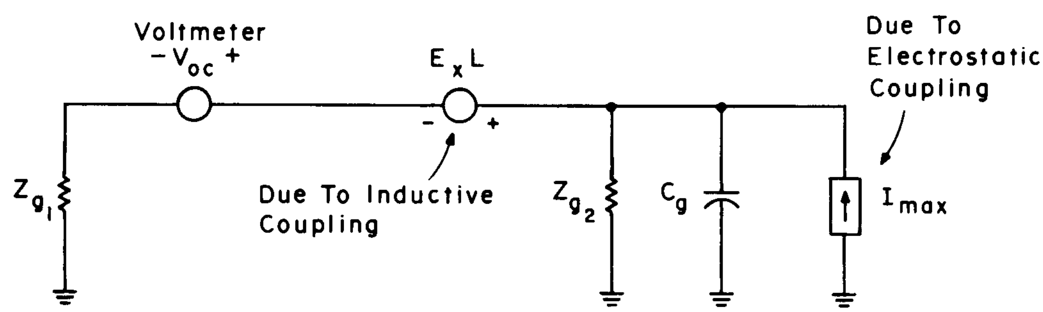
$$I_{max} = 2\pi f C_g \cdot E_t \cdot H \text{ amps} \tag{C-2b}$$



(a) Test Set-up



(b) Equivalent Circuit For Ideal Case



(c) Equivalent Circuit Assuming Electrostatic Coupling To Probe Wire

Fig. C-1. BASIC PROBE WIRE TECHNIQUE

where H is the height of the probe wire above the effective earth plane, d is the diameter of the probe wire, and E_t is the transverse electric field at the probe wire. Assuming that H/d = 1,

$$C_g = 40 \cdot L \text{ pF}; \tag{C-3a}$$

$$X_{C_g} = 1/(2\pi \cdot 60 \cdot C_g) = 66/L \text{ M}\Omega \tag{C-3b}$$

$$I_{max} = 1.5 \cdot 10^{-8} \cdot L \cdot E_t \cdot H \text{ amps.} \tag{C-3c}$$

From Eq. C-3, it is seen that the reactance of the probe wire capacitance-to-ground, X_{C_g}, is much larger than easily realizable values of ground impedance, Z_g. Therefore, virtually all of I_{max} flows through Z_{g_2}, yielding an electrostatic interference voltage of $I_{max} Z_{g_2}$. The ratio of the desired to undesired components of V_{oc} is simply

$$\frac{V_{inductive}}{V_{electrostatic}} = \frac{E_x L}{1.5 \cdot 10^{-8} \, L \, E_t \, H \, Z_{g_2}} = \frac{6.7 \cdot 10^7 (E_x/E_t)}{H \, Z_{g_2}} \tag{C-4}$$

The "signal-to-noise" ratio of Eq. C-4 is seen to be a function of the ratio of longitudinal to transverse electric fields, the height of the probe wire above ground, and the grounding impedance of the probe wire. This ratio is independent of the length of the probe wire. For a typical case near a high voltage ac power line, $E_x/E_t = 10^{-6}$, $H_{effective} = 10^{-2}$ m, and Z_g = 100 ohms, yielding a signal-to-noise ratio of about 70. This ratio can be degraded in cases of low-conductivity soil, where $H_{effective}$ and Z_g are increased above these nominal values.

Lack of E_x Phase Information. The E_x phase information necessary for the analyses of Section 1 is not provided by the basic probe wire technique, which measures only the magnitude of E_x, as shown in Eq. C-1d. Because the phase of E_x is a function of separation from the interfering power line and earth conductivity, it cannot be assumed to be constant over the length of the pipeline.

Instrumentation Developed for Electric Field Measurement: System Description. Because of the problems associated with the basic probe wire concept, an instrumentation system was developed for longitudinal electric field measurement since off-the-shelf equipment was not available.

Figure C-2 shows an electrical schematic diagram of the measurement system. It consists of two long wire probes, ℓ_1 and ℓ_2, each grounded at the far end. A high impedance (grounded) voltmeter is put in series with each wire. The ground rod impedances to remote earth are shown in the diagram as Z_g. Lengths ℓ_1 and ℓ_2 are not critical and typically 15 meters has been used. In normal operation of the system when mapping the electric field, line ℓ_1 is run at ground surface level parallel to and several hundred feet from the line. The voltage induced in this line is used as a phase reference for the electric field measurements made subsequently on both sides of the power line. The reference voltage under the line is monitored continuously by either Hewlett-Packard HP3581 or HP403 voltmeters (2). This allows a continuous check on variations in power line loading which will bias the readings. When using the HP403 voltmeter, because of its wide bandwidth, a RC filter is connected in series with the meter to eliminate AM broadcast station and other interference.

The filter is a five-section RC low pass filter with the gain characteristics shown in Figure C-3. Replicates of this filter are also used at both voltage input terminals to the HP3575 Gain-Phase Meter. The filter has a loss of 10 dB at 60 Hertz, which has been found to be acceptable. The measured attenuation at 1 kHz is 66 dB and the response rolls off at 100 dB per decade at higher frequencies.

When making voltage measurements, the field probe, ℓ_2, is set at the desired (variable) distance from the power line and the earth current induced voltage $E_{x2}\ell_2$, read as V_B on the HP3575 Gain Phase Meter. The reference voltage, V_R, is carried by a two-conductor shielded twisted pair cable, through an isolation transformer and filter to the reference channel (A) input of the Gain-Phase Meter. The transformer is required in order to isolate the earth grounds associated with the probes, ℓ_1 and ℓ_2, respectively. Without this isolation, cross coupling between the two probes would occur, thus giving erroneous readings. Another advantage to use of the isolation transformer is that extraneous common mode interfering signals coupled into the twisted pair line are cancelled by the differential input presented by the transformer.

Data obtained from the Gain Phase Meter are: (1) the voltage, V_A, which is approximately equal to V_R and, hence, proportional to the magnitude of the electric field at the reference location $|E_{x1}|$; (2) the voltage, V_B, which is proportional to the remote electric field magnitude, $|E_{x2}|$; and (3) the phase angle between the electric fields, E_{x1} and E_{x2}.

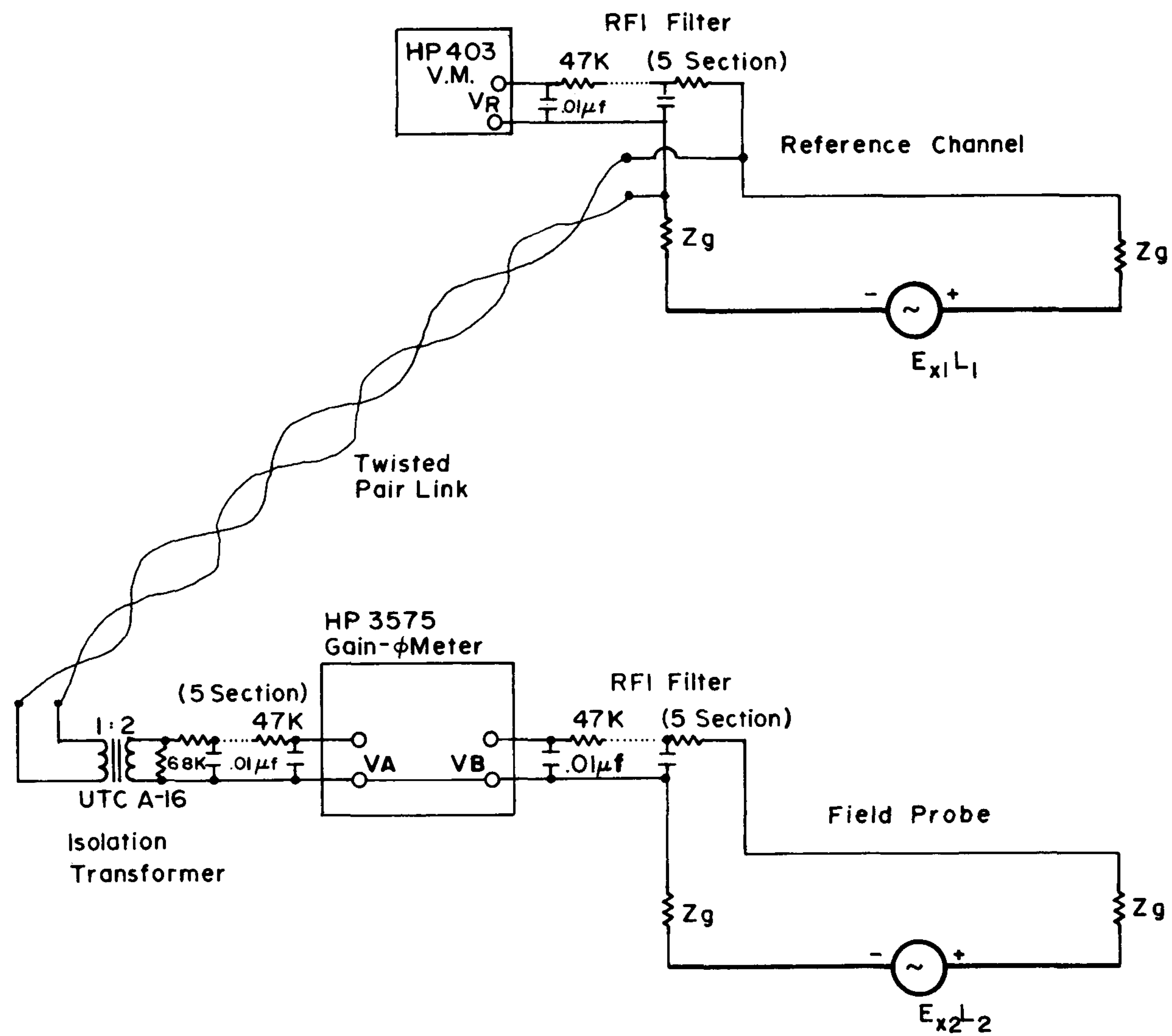


Fig. C-2. E-FIELD GAIN-PHASE MEASUREMENT - ELECTRICAL SCHEMATIC

The preceding discussion outlines the operation of the measurement system. In concept it is simple but, unfortunately, much more difficult to implement in practice, due to the fact that these measurements are being made in the presence of a much larger vertical electric field. For example, a typical longitudinal E-field amplitude may be on the order of 5 mV/m, while the vertical field at the same point may be 5 kV/m, a million times stronger. Hence, in order to obtain meaningful measurements, a carefully planned shielding arrangement is necessary.

Practical Difficulties. In making either one of the probe measurements, the following circuit parameter values are representative:

E_x = longitudinal electric field - 5 mV/m

ℓ = probe wire length - 15 m

Z_g = ground rod impedance - 500 ohms

R_V = voltmeter resistance - 1 megohm.

For these values, the current induced in the probe wire is

$$I_L = \frac{E_x \cdot L}{R_V + 2\, Z_g} \simeq 0.075\ \mu A \qquad \text{(C-5)}$$

The probe wire will also have a current coupled into it through the electrostatic vertical E field as calculated by the following equation.

$$I_{max} = 2\pi f \cdot C_g \cdot E_t \cdot H \quad \text{amps}$$

where

f = 60 Hz

E_t = electrostatic field strength - V/m

H = height of probe wire above ground - m

C_g = capacitance of probe wire to ground - F

= $40 \times 10^{-12} \cdot L$ Farads (for a wire of length L on the ground)

Representative values are as follows:

C_g = 6×10^{-10} F

E_t = 5 kV/m

H = 10^{-3} m.

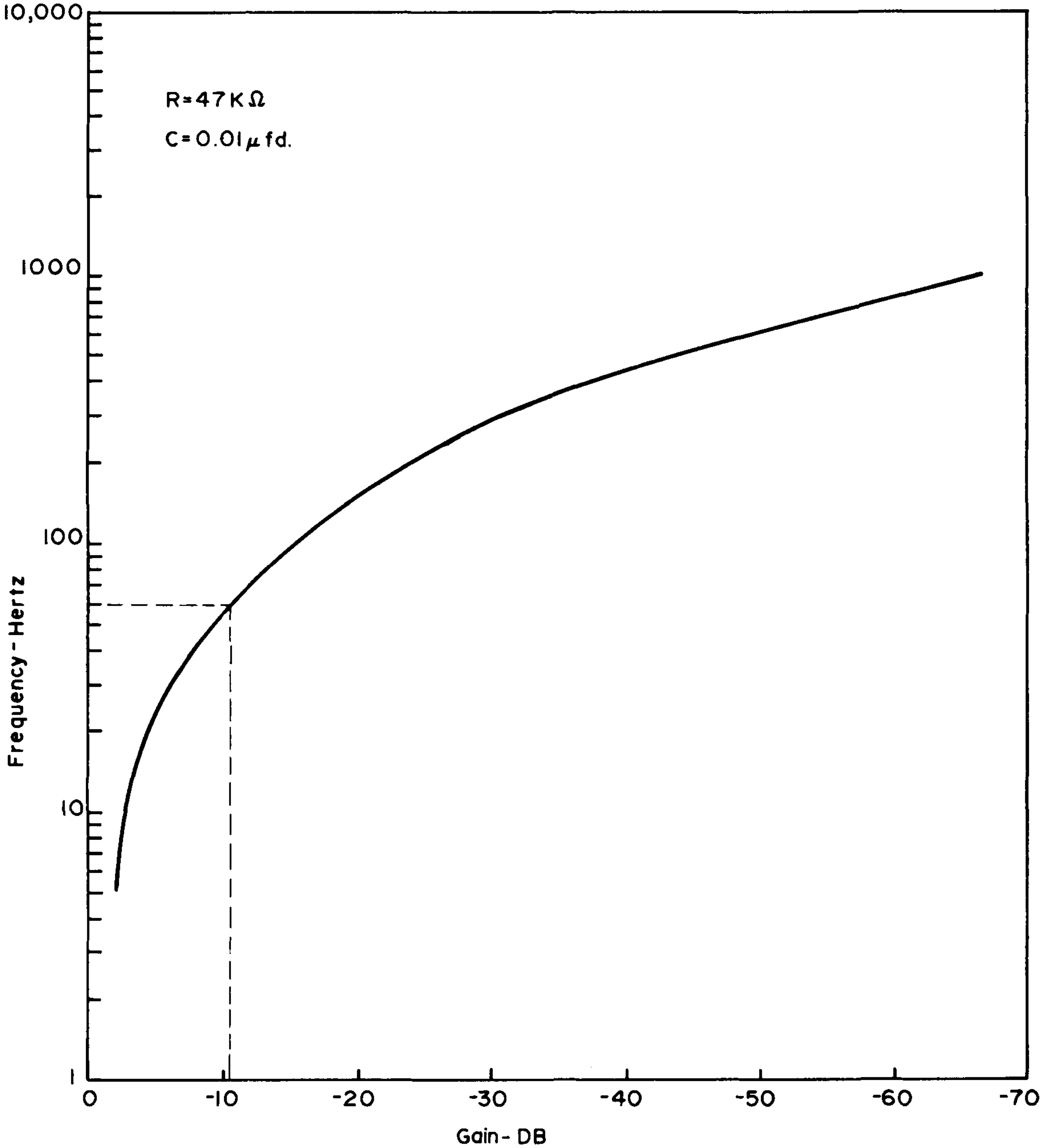


Fig. C-3. GAIN OF FIVE SECTION RFI FILTER

Hence

$$I_{max} = 1.13\ \mu A.$$

The ratio of I_{max} to I_L is 15. Hence, the voltmeter reading, which is proportional to the current flowing in the probe wire, will be proportional to the electrostatic electric field rather than the desired longitudinal field. In order to obtain an accurate longitudinal field reading, the current, I_{max}, must be reduced by a factor of at least 100 to possibly 1000 or more, which implies a shielding requirement of 40 to 60 dB.

The probe wire is not the only source of unwanted electrostatic field pickup. Other paths of ingress are (1) the voltmeter case, (2) connecting wires to ground rods, and (3) the twisted wire pair linking the reference and data channels. System shielding required to circumvent this extraneous pickup problem is discussed in the next section.

System Shielding. Electrostatic shielding for the measurement system is outlined schematically in Figures C-4 through C-6. Figures C-4 and C-5 show alternative reference channel configurations for use with the data channel shown in Figure C-6. Choice of either the HP3581 or HP403 arrangement is primarily dictated by voltmeter availability, but the HP3581 is preferred because of its phase locked loop and narrow tunable bandpass.

The success of the measurement system lies primarily in following religiously the following grounding and shielding rules:

1. The remote end (away from voltmeters) of a probe wire must be grounded with no other shield or ground at that point.

2. At the near end (at voltmeter connection) of the probe, the negative side of the voltmeter (and usually its case also due to internal connections) must also be grounded in a singular manner.

3. Considering the reference channel, a shielded wire (coax) is used for the probe wire and the shield must be connected to the metal box shielding the voltmeter. In turn, the shield for the twisted pair link between the reference and data channels must also be connected to this box. The box physically contains the voltmeter and filter, if used, and acts as an electrostatic shield for the voltmeter. However, the voltmeter must be electrically insulated from the box.

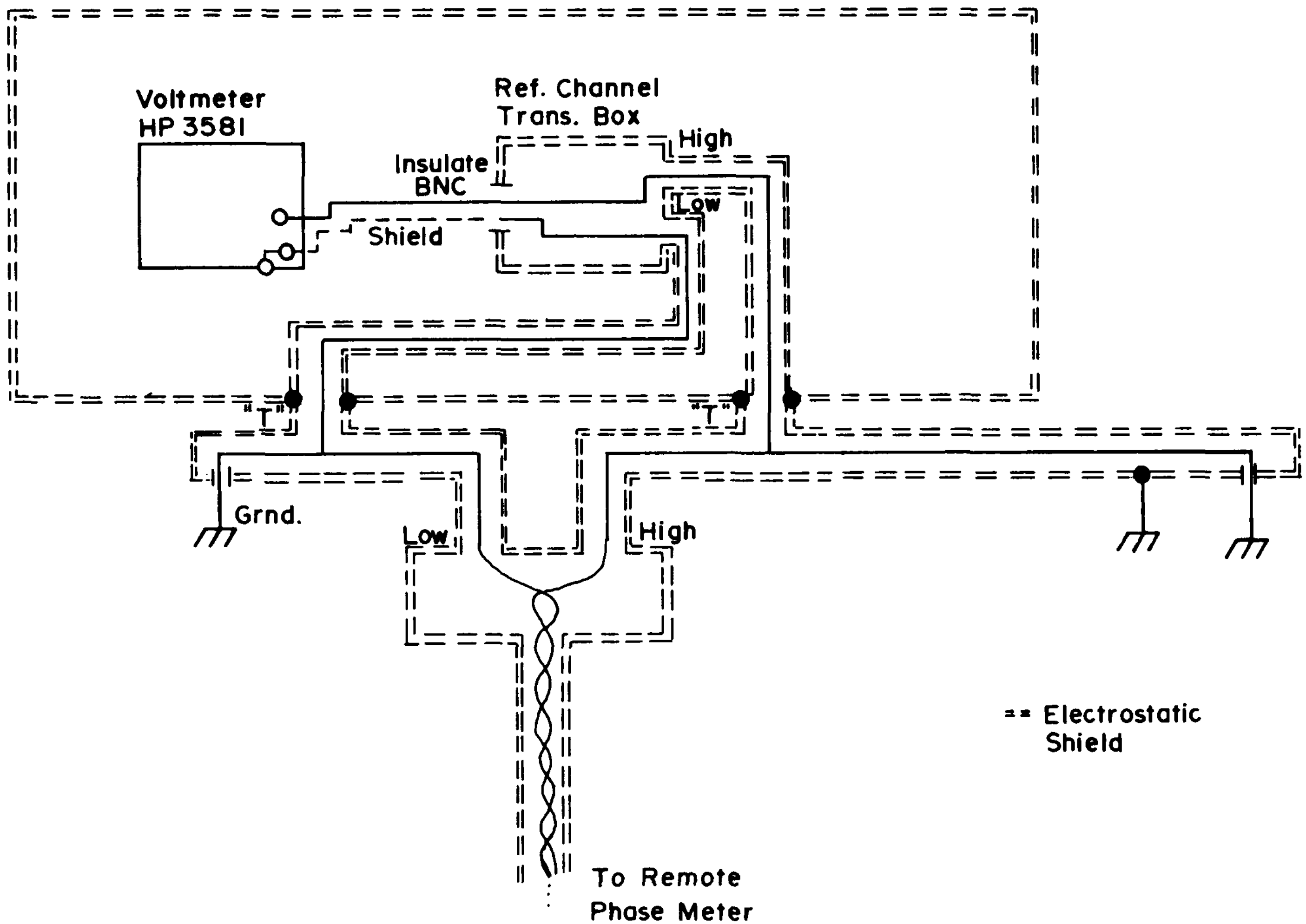


Fig. C-4. REFERENCE PROBE-HP3581 ARRANGEMENT

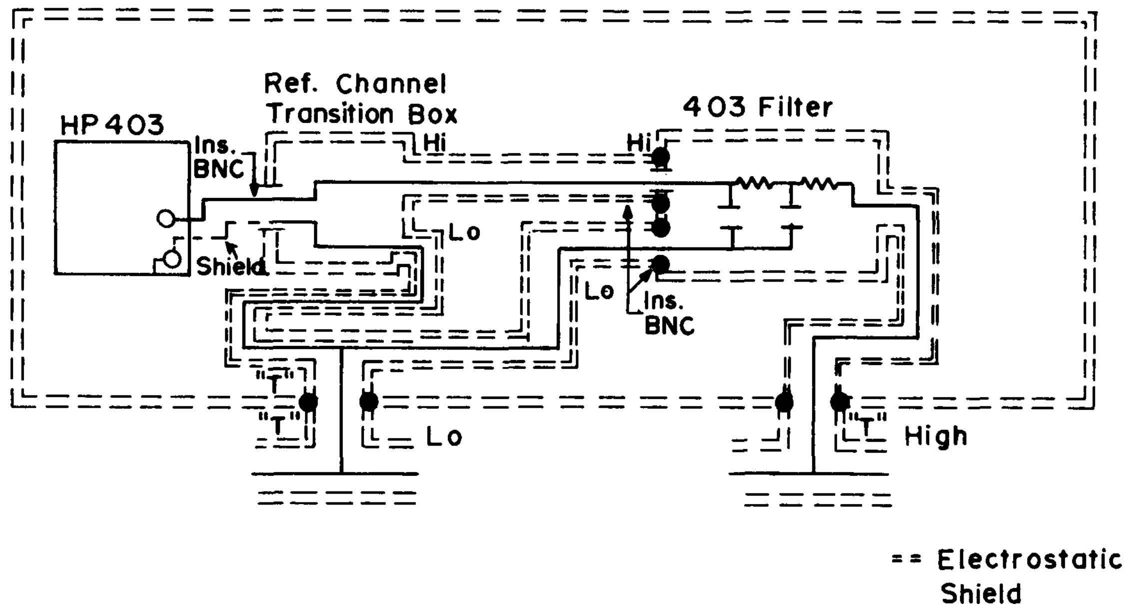


Fig. C-5. REFERENCE PROBE- ALTERNATE ARRANGEMENT ;HP403 VOLTMETER

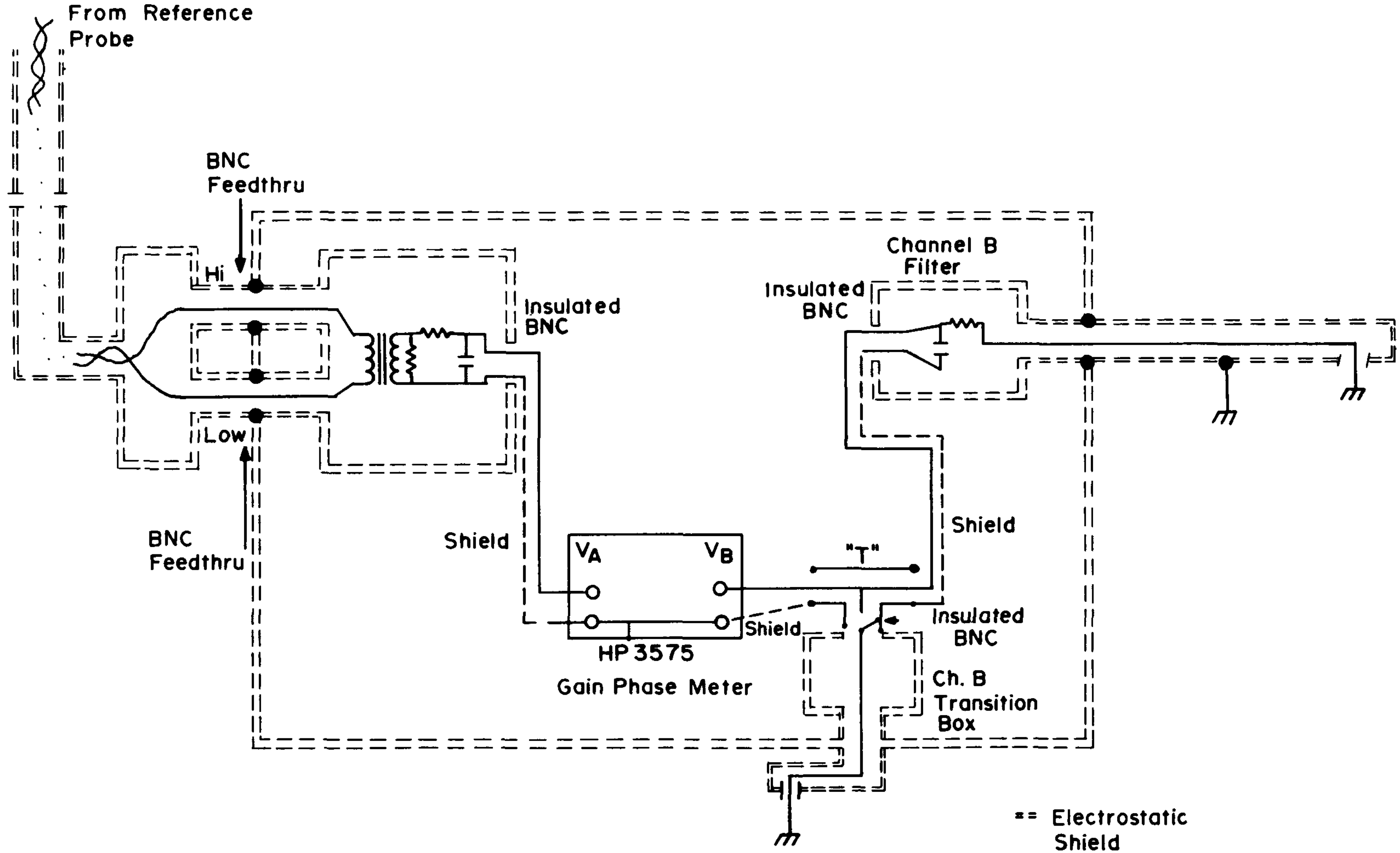


Fig. C-6. PHASE MEASUREMENT METER BOX

4. This electrically connected combination of reference probe shield, voltmeter shield box and twisted pair shield must be grounded at a single point separate from the voltmeter case and probe grounds. A convenient grounding point has been found to be the probe wire shield at approximately its mid-point.

These rules are exemplified by the arrangements shown in Figures C-4 and C-5. In Figure C-6, which outlines the data channel configuration, identically the same grounding rules are followed. However, in order not to couple the electrostatic grounding systems of the two channels, it is necessary to break and separate the shield of the twisted pair link connecting the two channels. A convenient point has been found to be roughly at the mid-point and a shield separation of approximately a quarter of an inch is sufficient to eliminate the possibility of inadvertently shorting the two ends of the separated shield.

In summary, four separate grounding systems are used:

- The reference channel probe-voltmeter combination
- The reference channel electrostatic shield
- The data channel probe-voltmeter combination
- The data channel electrostatic shield.

To implement these grounding arrangements simultaneously using standard coaxial cable and connectors requires that at times a single ground connection run may be alternately carried on either a coaxial cable shield or on the cable center wire. As shown in the accompanying figures, special boxes have been fabricated to accomplish the required transitions.

Appendix D

PIPELINE ELECTRICAL PARAMETERS

INTRODUCTION

The voltage/current prediction techniques discussed in the text, especially for the steady-state induction on a buried pipeline, are based upon the treatment of the pipeline as a lossy transmission line. Hence, its terminal behavior can be characterized from knowledge of its characteristic impedance, Z_0, and propagation constant, γ.

In this appendix, computer generated graphs are presented from which nominal values of these parameters may readily be obtained for most pipelines of interest. For situations where more accuracy is desired, the hand calculator program, PIPE, (c.f., Appendix A) is available.

DETERMINATION OF THE TRANSMISSION LINE PARAMETERS OF A BURIED PIPELINE

The pipeline parameters, Z_0 (characteristic impedance), and γ (propagation constant) are required for use in the hand calculator programs discussed in the text.

Hand calculator Program PIPE (c.f., Appendix A) computes these parameters for specific pipeline cases. However, to allow the user to obtain approximate data at a glance for a pipeline having nominal parameters, this appendix now presents graphical results for γ and Z_0. The following assumptions were made in developing these data:

1. The soil permittivity, ε, is equal to $3\varepsilon_0$, where ε_0 is the permittivity of free space.

2. The steel used for the pipeline has an average resistivity, ρ_S, equal to $1.7 \cdot 10^{-7}$ ohm-m, and an average permeability, μ_S, equal to 300 μ_0, where μ_0 is the permeability of free space. The usual pipe steel, depending upon chemical composition, may have a resistivity of from 15 to 20 $\mu\Omega$-cm, and depending upon magnetizing force a relative permeability of several hundred to a thousand or more. The nominal values used here are sufficiently accurate for present purposes, i.e., prediction of pipeline induced voltage levels.

3. The pipeline wall thickness t, varies with the pipeline diameter, D as

$$t = 0.132\ D^{0.421}$$

where t and D are in inches.

4. The pipeline internal impedance, $Z_i = R_i + jX_i$, is given as a function of ρ_s, μ_s, t, and D by the following expression

$$R_i = \frac{R_s}{(2\pi)(0.0127D)} \cdot \left[\frac{\sinh(t_n) + \sin(t_n)}{\cosh(t_n) - \cos(t_n)}\right]$$

$$X_i = \frac{R_s}{(2\pi)(0.0127D)} \cdot \left[\frac{\sinh(t_n) - \sin(t_n)}{\cosh(t_n) - \cos(t_n)}\right]$$

where

$$R_s = \sqrt{\pi \cdot 60\ \text{Hz} \cdot \mu_s \cdot \rho_s}$$

and

$$t_n = 0.0508 \cdot \frac{t \cdot R_s}{\rho_s}$$

5. $\bar{h}$ = 1 meter.

The first assumption is completely non-critical because $\omega\varepsilon < 0.0001\ \sigma$ at 60 Hz for all values of σ considered and for all possible values of ε. The second, third, and fourth assumptions apply to the pipe steel skin depth and its effect upon Z_i. Assumption 2 assigns average values of resistivity and permeability to the pipe steel. Assumption 3 assigns pipe wall thicknesses based upon an exponential curve fit to available data for standard pipe. Assumption 4 takes Z_i to be the unit length impedance of a thin walled tubular conductor where the wall thickness is comparable to the electromagnetic skin depth. For practical purposes, the results are relatively insensitive to the exact values chosen for wall thickness and burial depth.

Real and Imaginary Parts of γ

Figures D-1 through D-8 graph the results obtained in the computer solution for the following soil resistivities: 1 kΩ-cm; 2 kΩ-cm; 4 kΩ-cm; 10 kΩ-cm; 20 kΩ-cm; 40 kΩ-cm; 100 kΩ-cm; and 200 kΩ-cm. Each figure plots Real(γ) and Im(γ) as a

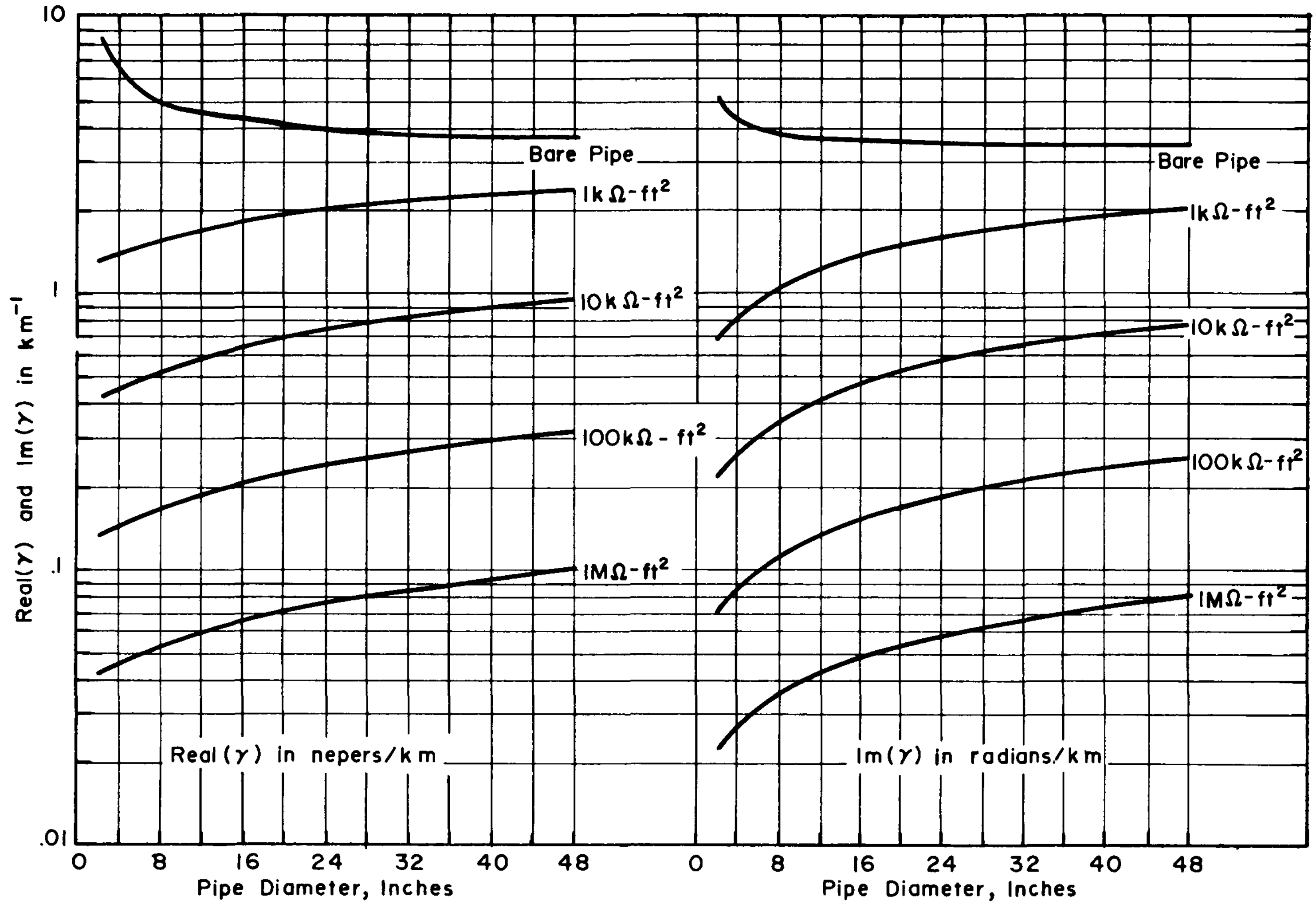


Fig. D-1 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR $\rho = 1k\Omega$-cm ($\sigma = 0.1$ mho/m) SOIL

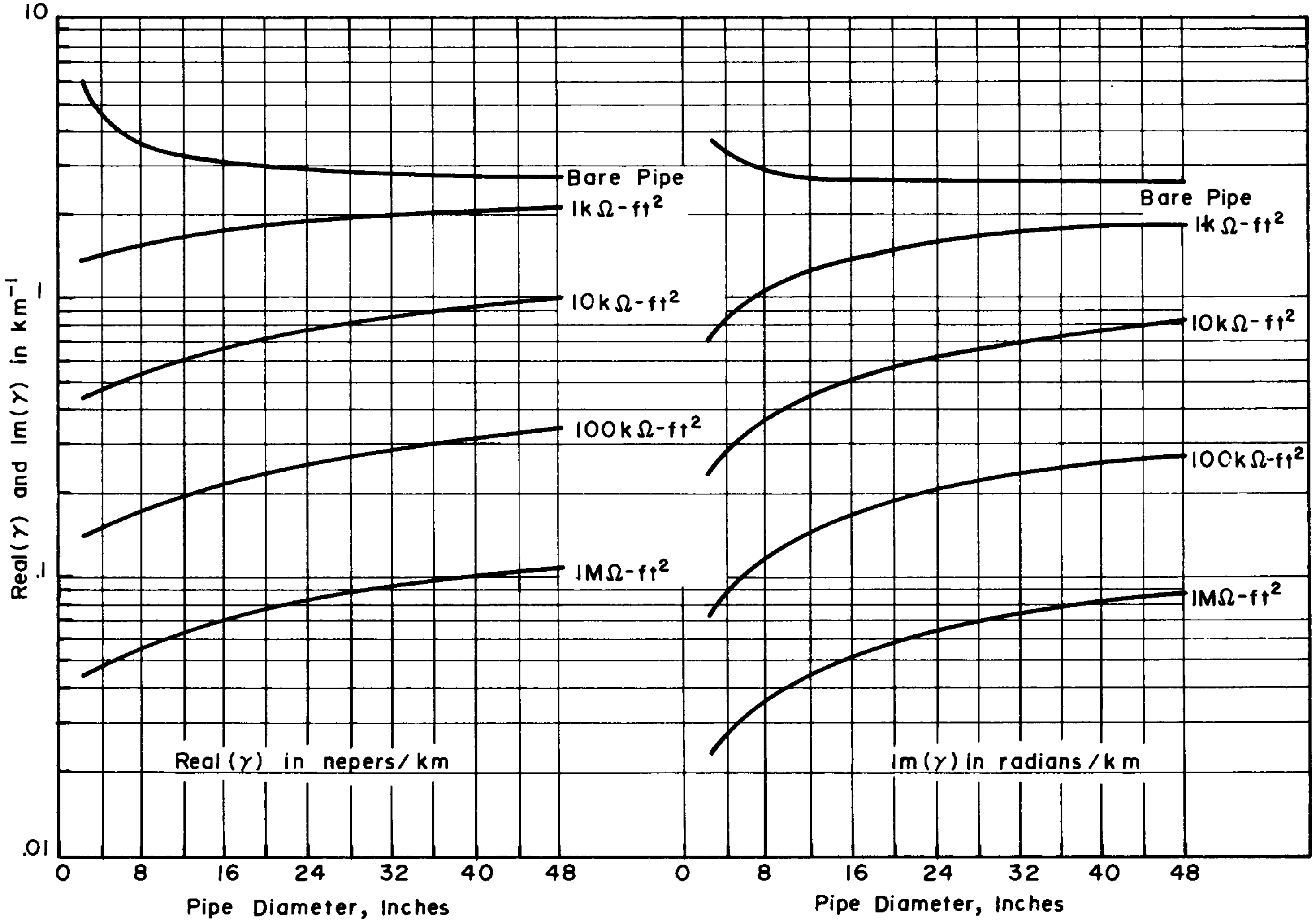


Fig. D-2 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR $\rho = 2k\ \Omega$-cm ($\sigma = 0.05$ mho/m) SOIL

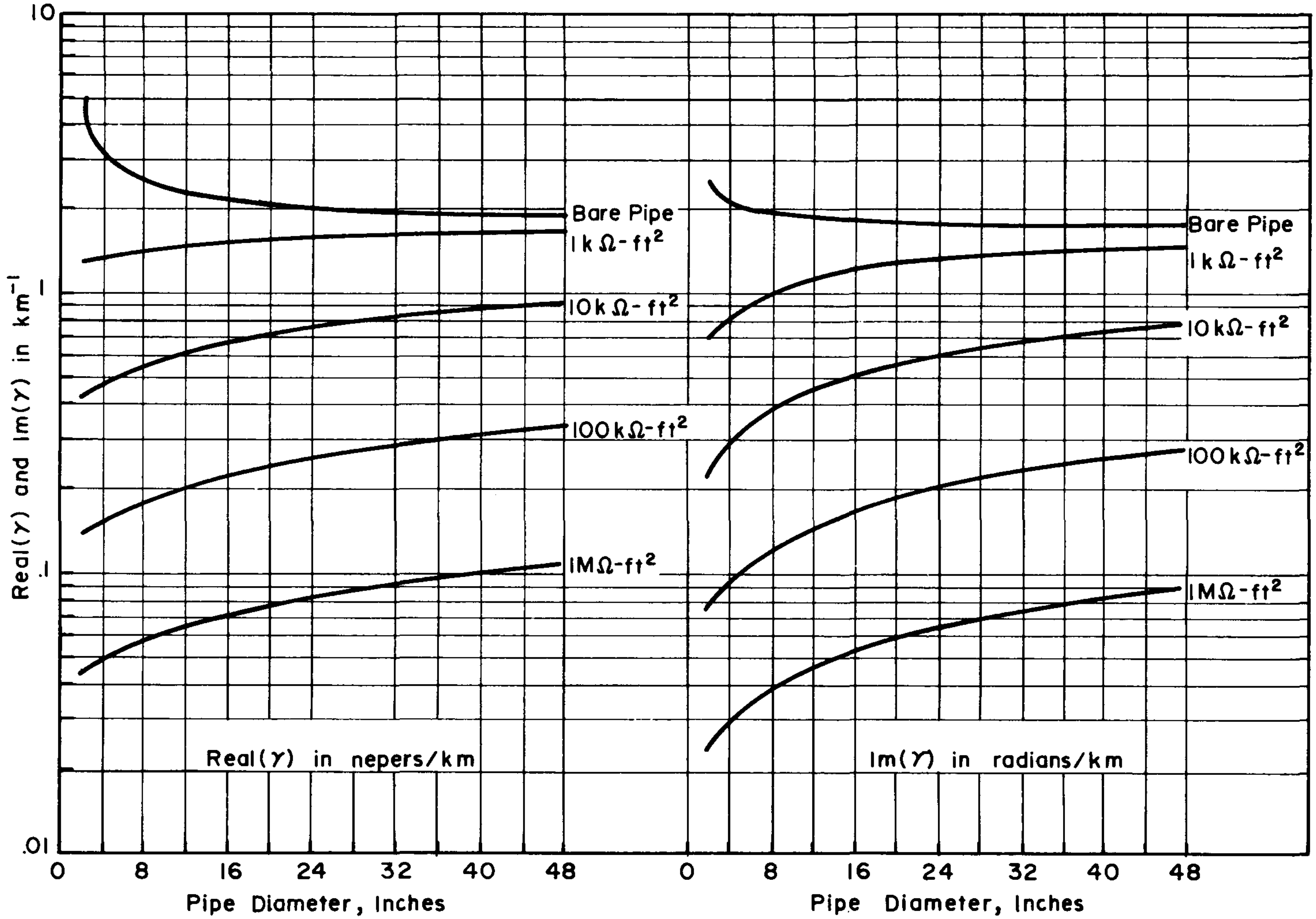


Fig. D-3 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR $\rho = 4\,k\Omega$-cm ($\sigma = 0.025$ mho/m) SOIL

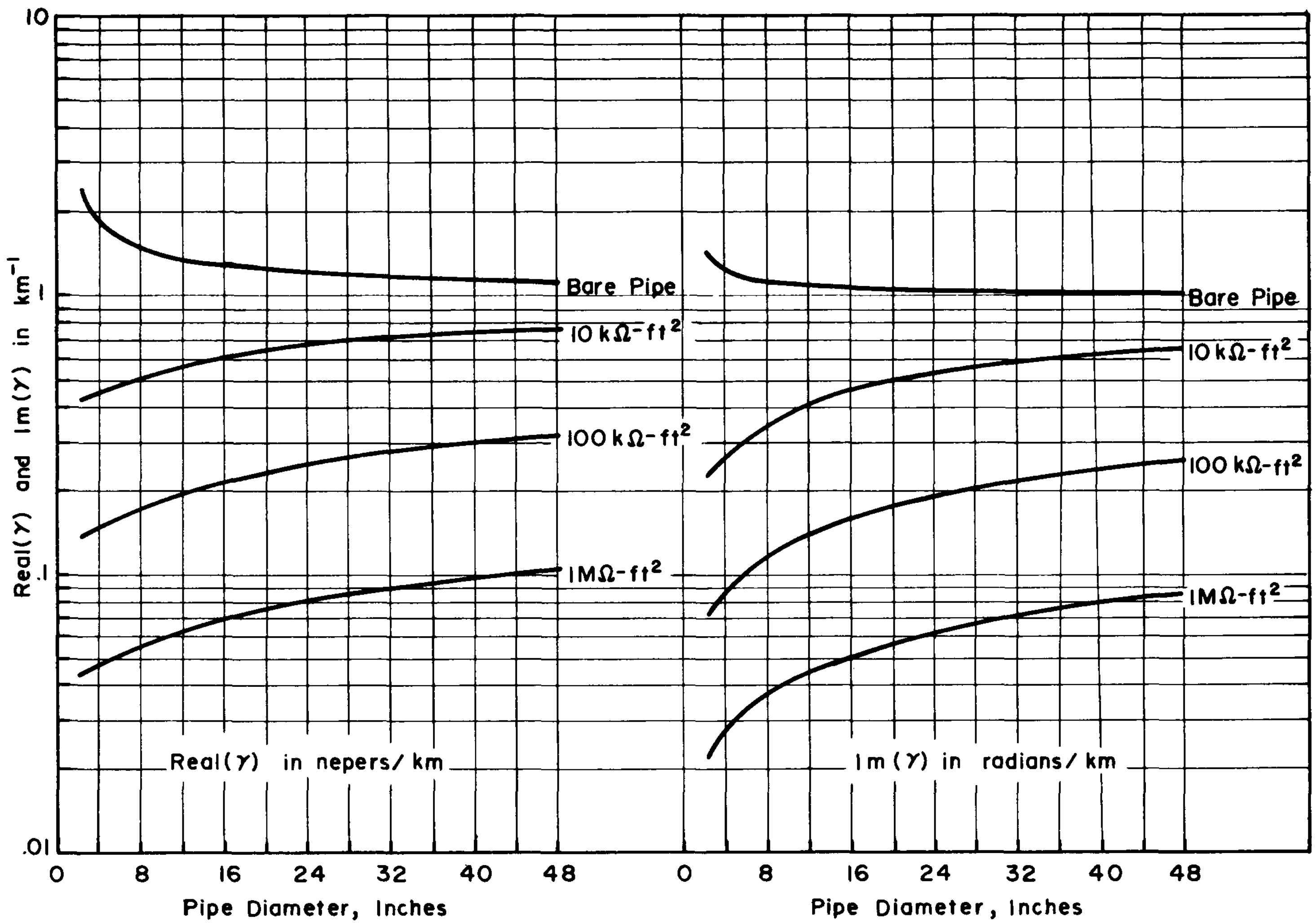


Fig. D-4 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR ρ = 10 kΩ-cm (σ = 0.01 mho/m) SOIL

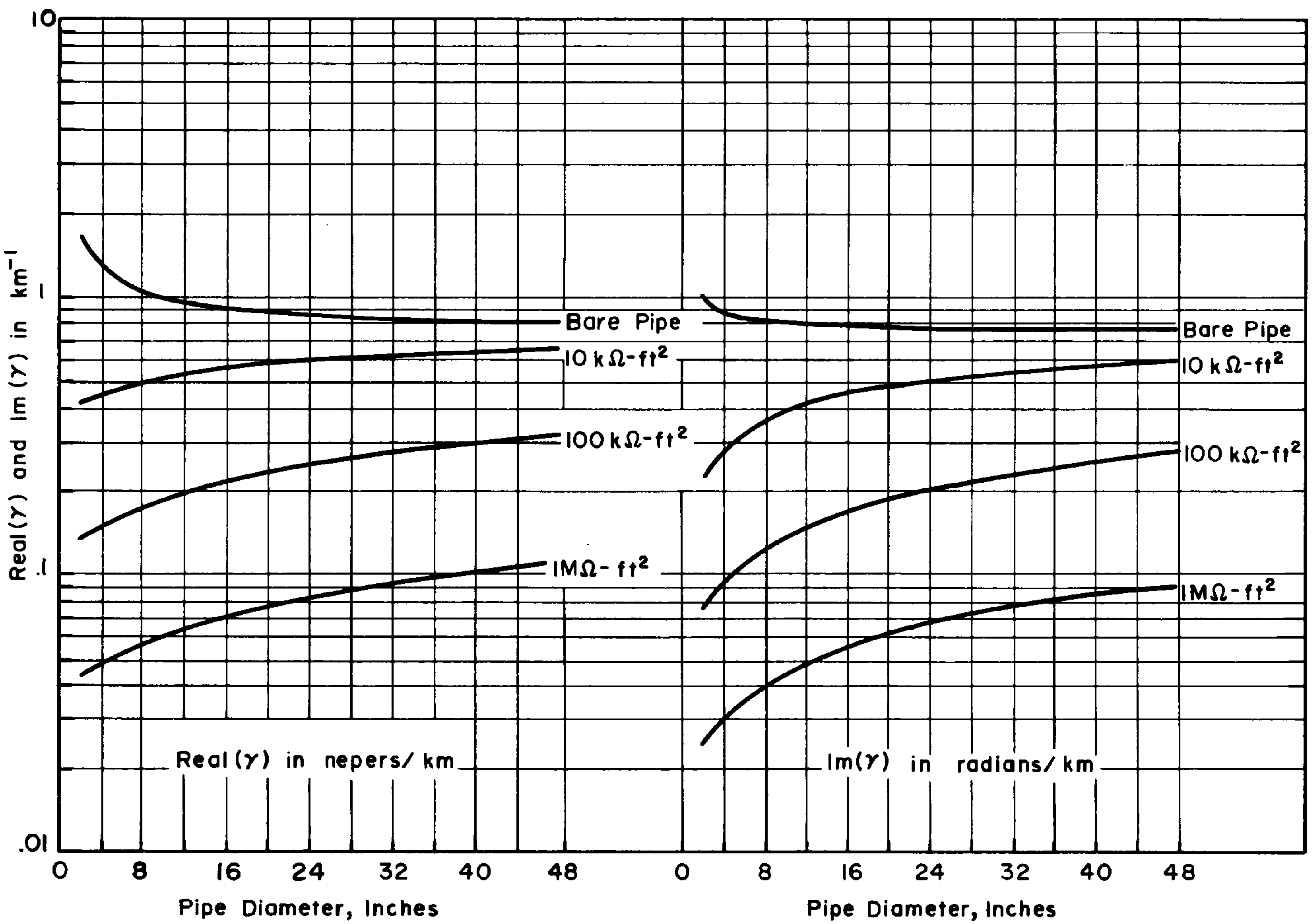


Fig. D-5 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR $\rho = 20\ k\Omega$-cm ($\sigma = 0.005$ mho/m) SOIL

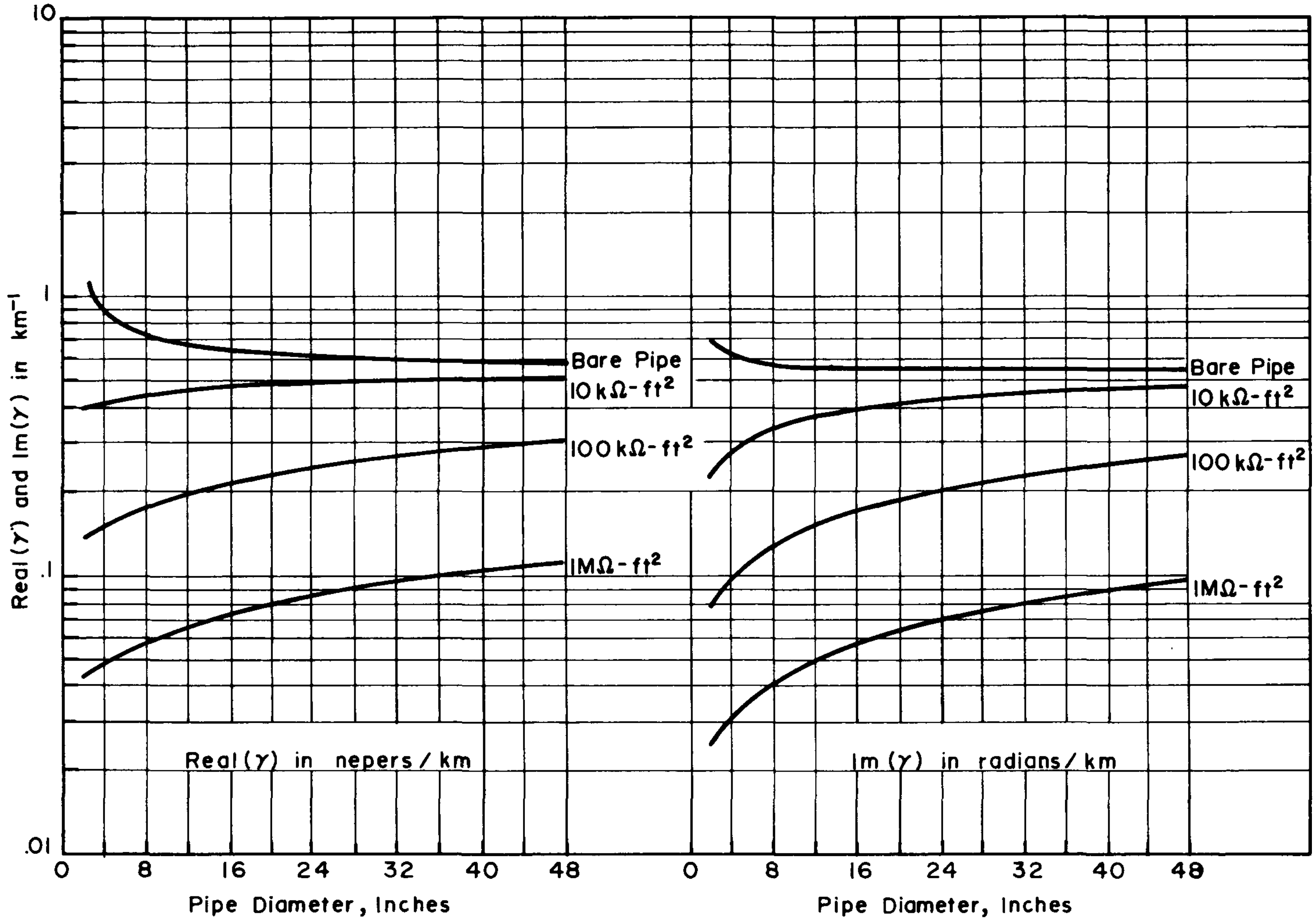


Fig. D-6 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR $\rho = 40\ k\Omega$-cm ($\sigma = 0.0025$ mho/m) SOIL

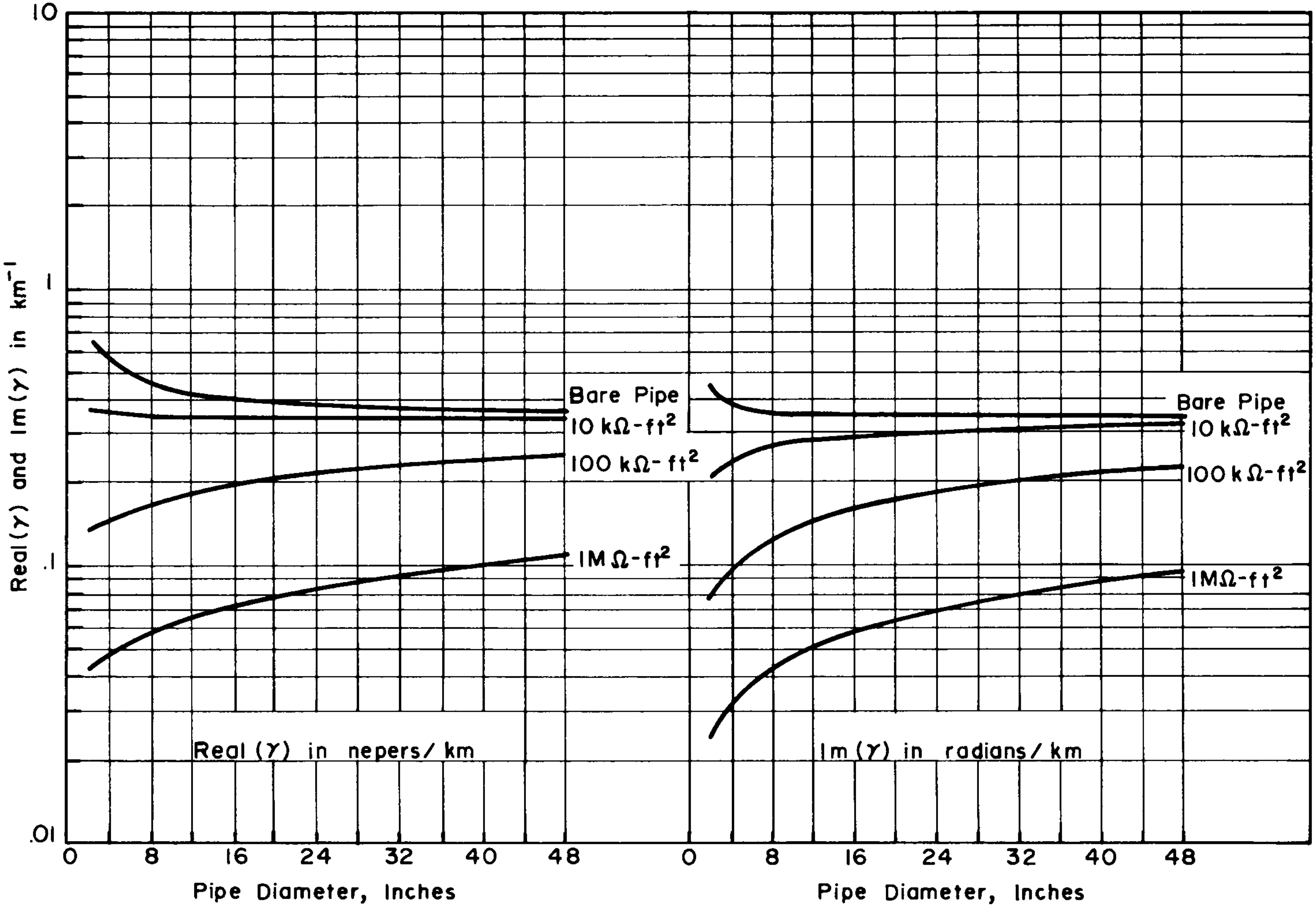


Fig. D-7 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR ρ=100 kΩ-cm (σ=0.001 mho/m) SOIL

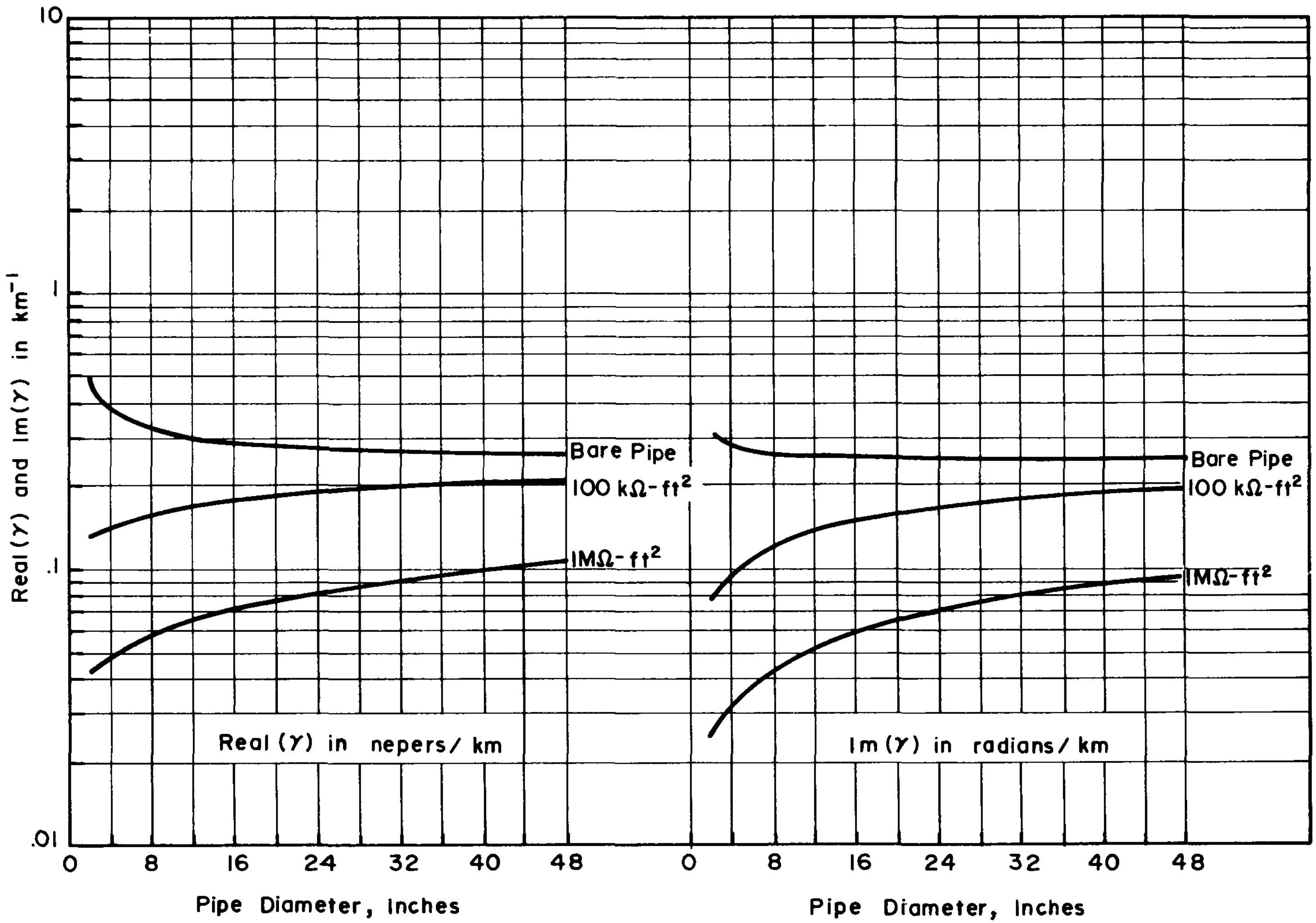


Fig. D-8 BURIED PIPELINE PROPAGATION CONSTANT, γ, FOR ρ=200kΩ-cm (σ=0.0005mho/m) SOIL function of pipe diameter from 2 inches to 48 inches for pipe coating resistivities of zero (bare pipe), 1 $k\Omega\text{-}ft^2$, 10 $k\Omega\text{-}ft^2$, 100 $k\Omega\text{-}ft^2$, and 1 $M\Omega\text{-}ft^2$.

The figures indicate that the principal effect of the pipe coating is to decrease both Real(γ) and Im(γ) from the bare pipe values at any particular pipe diameter. As expected, well coated pipes having coating resistivities exceeding 100 $k\Omega\text{-}ft^2$ have values of Real(γ) and Im(γ) virtually unaffected by the resistivity of the surrounding soil. On the other hand, bare or poorly coated pipes have values of γ that can vary by as much as ten to one, depending upon the soil resistivity.

Example D-1: The propagation constant of 0.508 m (20 inch) diameter pipeline having a coating resistance of $5 \cdot 10^4$ ohms-ft^2 and buried in $2 \cdot 10^4$ ohm-cm soil, is to be estimated.

Solution: The soil conductivity is simply $\sigma = 1/(2 \cdot 10^4 \text{ ohm-cm}) = 0.005$ mho/m. Figure D-5 is seen to give graphs of the real and imaginary parts of the propagation constant for this soil conductivity. In Figure D-5, the curves for a coating resistance of 50 $k\Omega\text{-}ft^2$ are interpolated. At a pipe diameter of 20 inches, the following propagation constant value is read off from the curves

$$\gamma \simeq 0.27 + j\,0.24 \text{ km}^{-1}$$

$$\equiv \alpha + j\beta \,.$$

Buried Pipeline Characteristic Impedance, Z_0

Figures D-9 to D-16 graph the corresponding results for Z_0, for the same set of soil resistivities and pipe coating resistivities used in the previous graphs for the propagation constant.

The figures indicate that the principal effect of the pipe coating is to increase both Real$|Z_0|$ and Im(Z_0) from the bare pipe values at any particular pipe diameter. Well coated pipes having coating resistivities exceeding 100 $k\Omega\text{-}ft^2$ have values of Z_0 virtually unaffected by the resistivity of the surrounding soil. On the other hand, poorly coated pipes have values of Z_0 that can vary by as much as ten to one, depending upon the soil resistivity.

Example D-2: The characteristic impedance of the buried pipeline of Example D-1 is to be estimated.

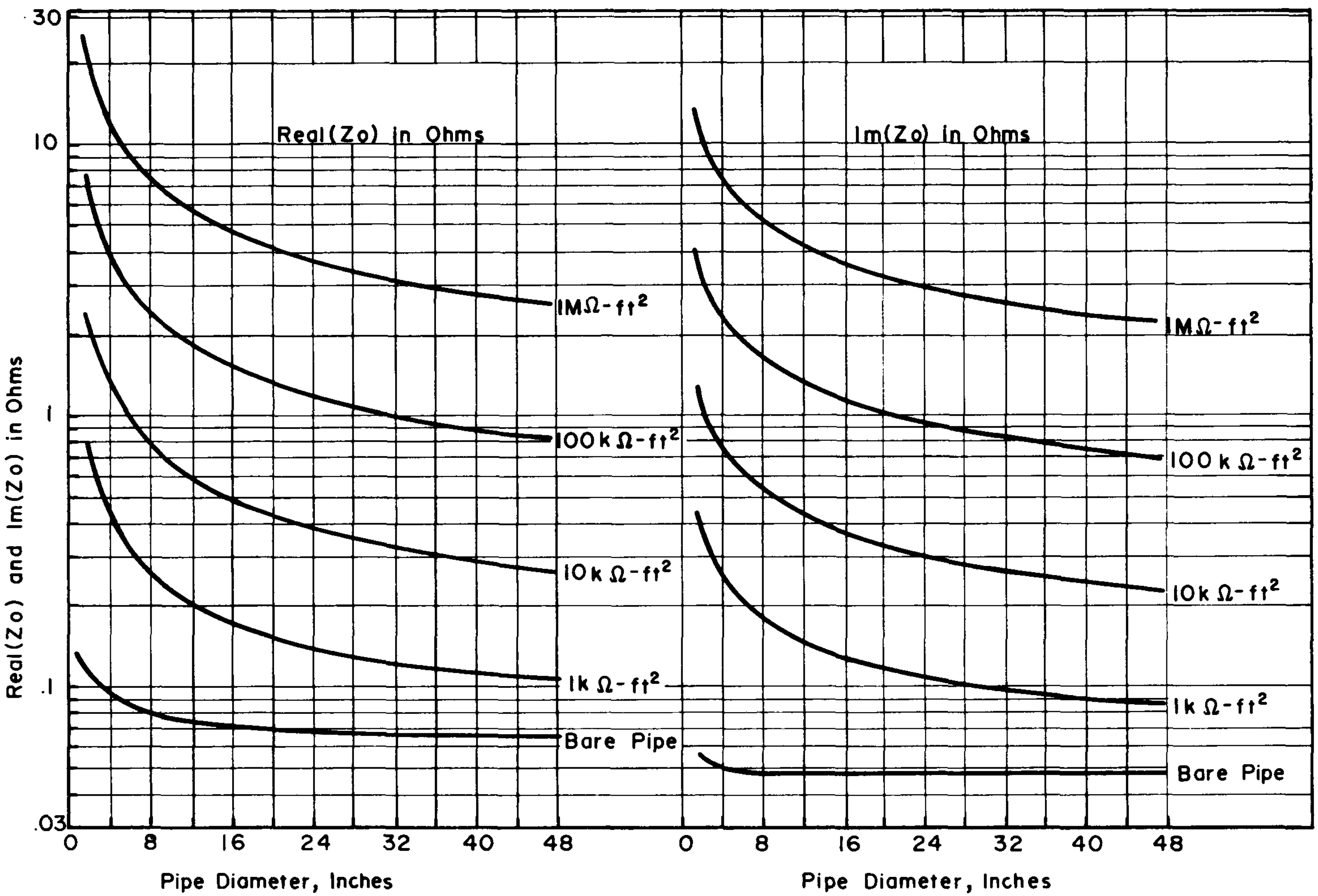


Fig. D-9 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_o, FOR $\rho = 1\,k\Omega\text{-cm}$ ($\sigma = 0.1$ mho/m) SOIL

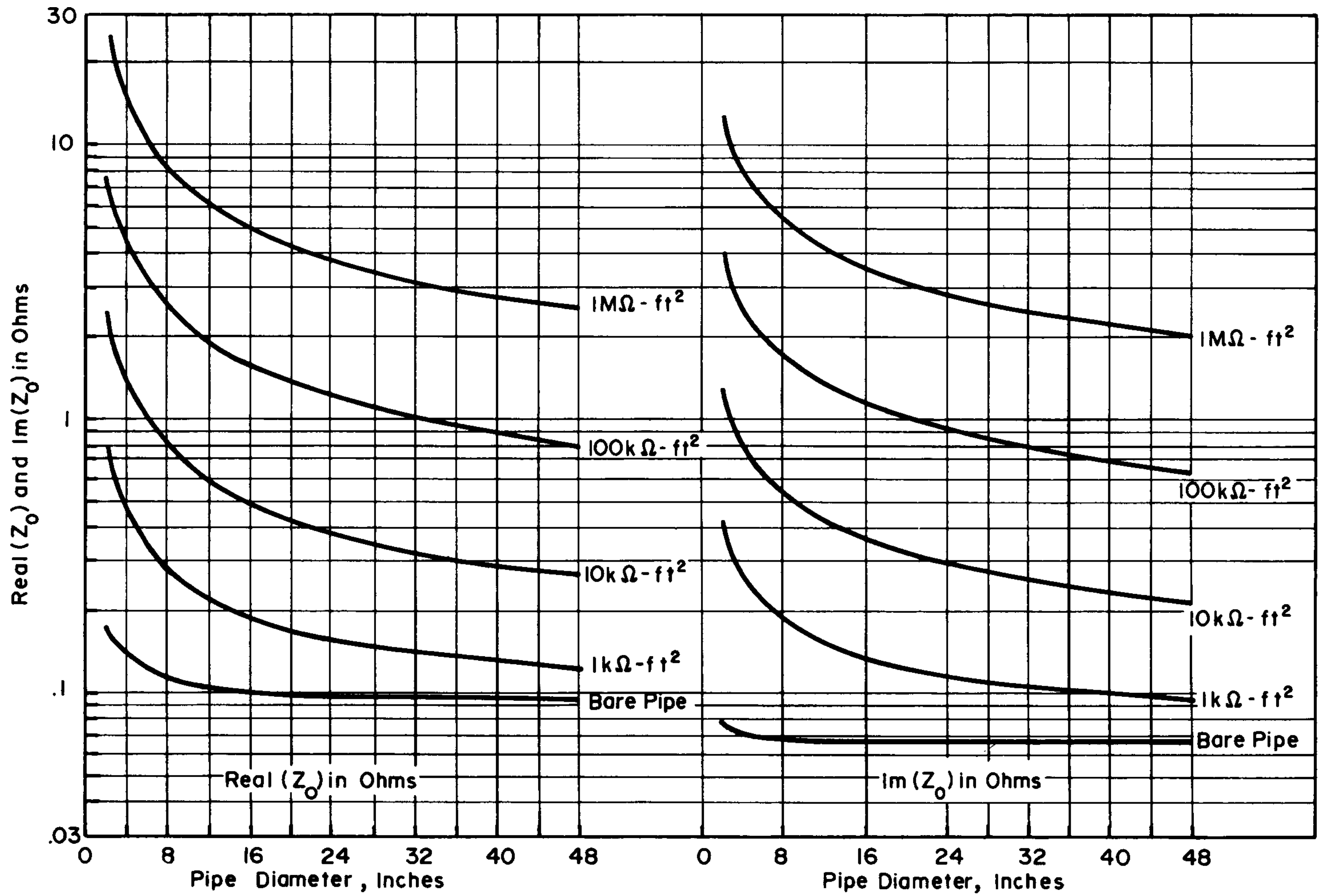


Fig. D-10 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR $\rho = 2\,k\Omega$-cm ($\sigma = 0.05$ mho/m) SOIL

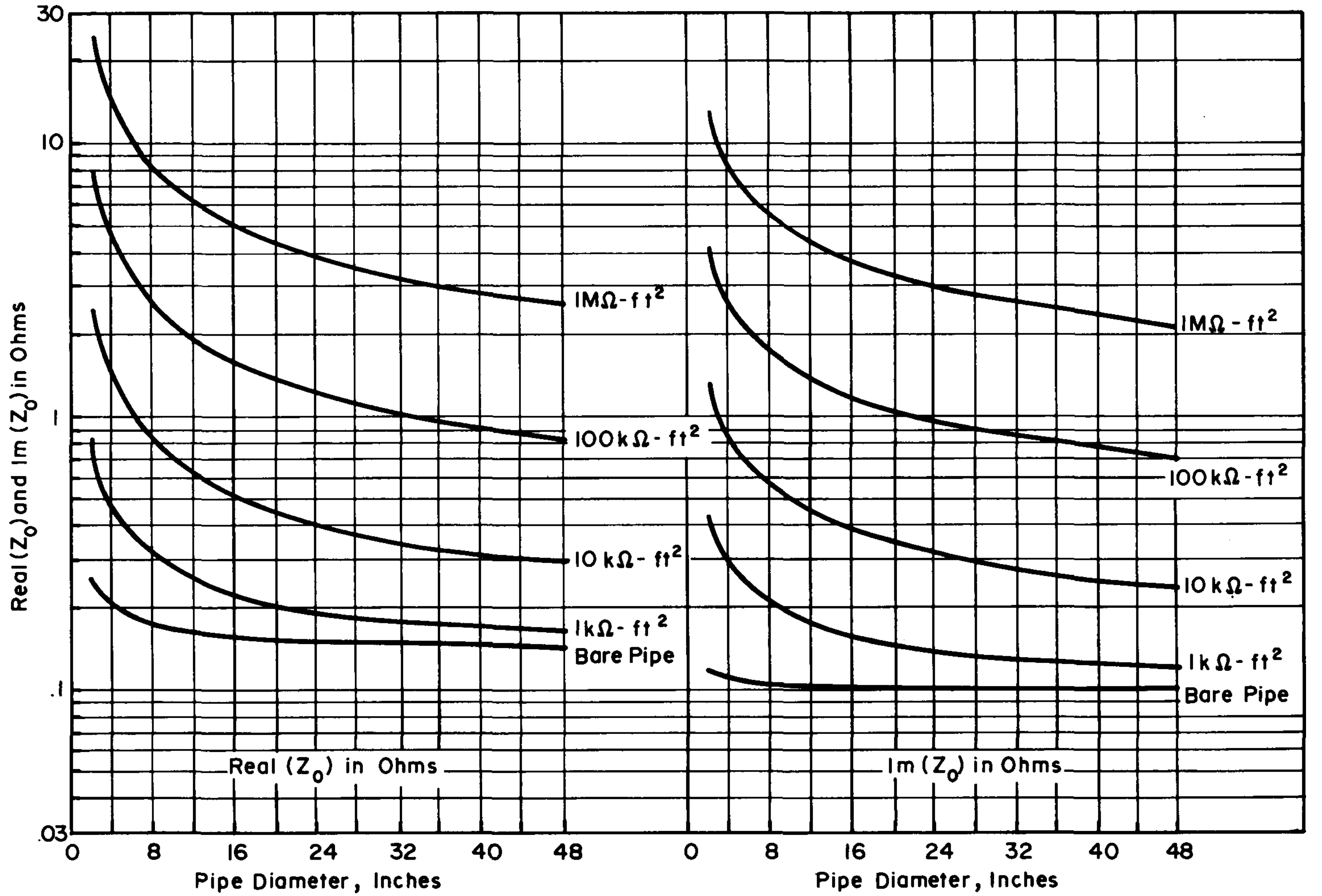


Fig. D-11 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR $\rho = 4k\,\Omega$-cm($\sigma = 0.025$ mho/m) SOIL

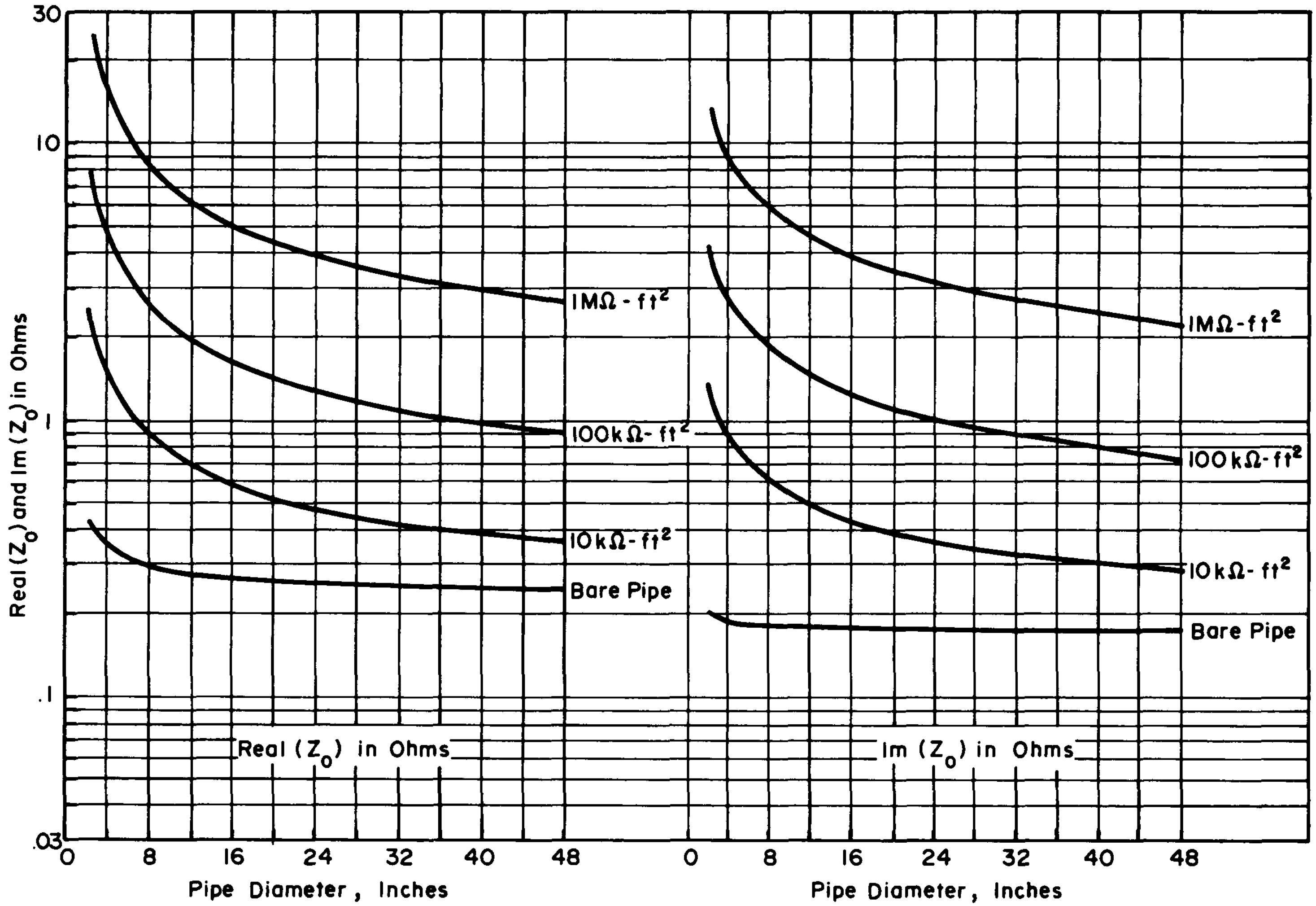


Fig. D-12 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR $\rho = 10\,k\Omega$-cm ($\sigma = 0.01$ mho/m) SOIL

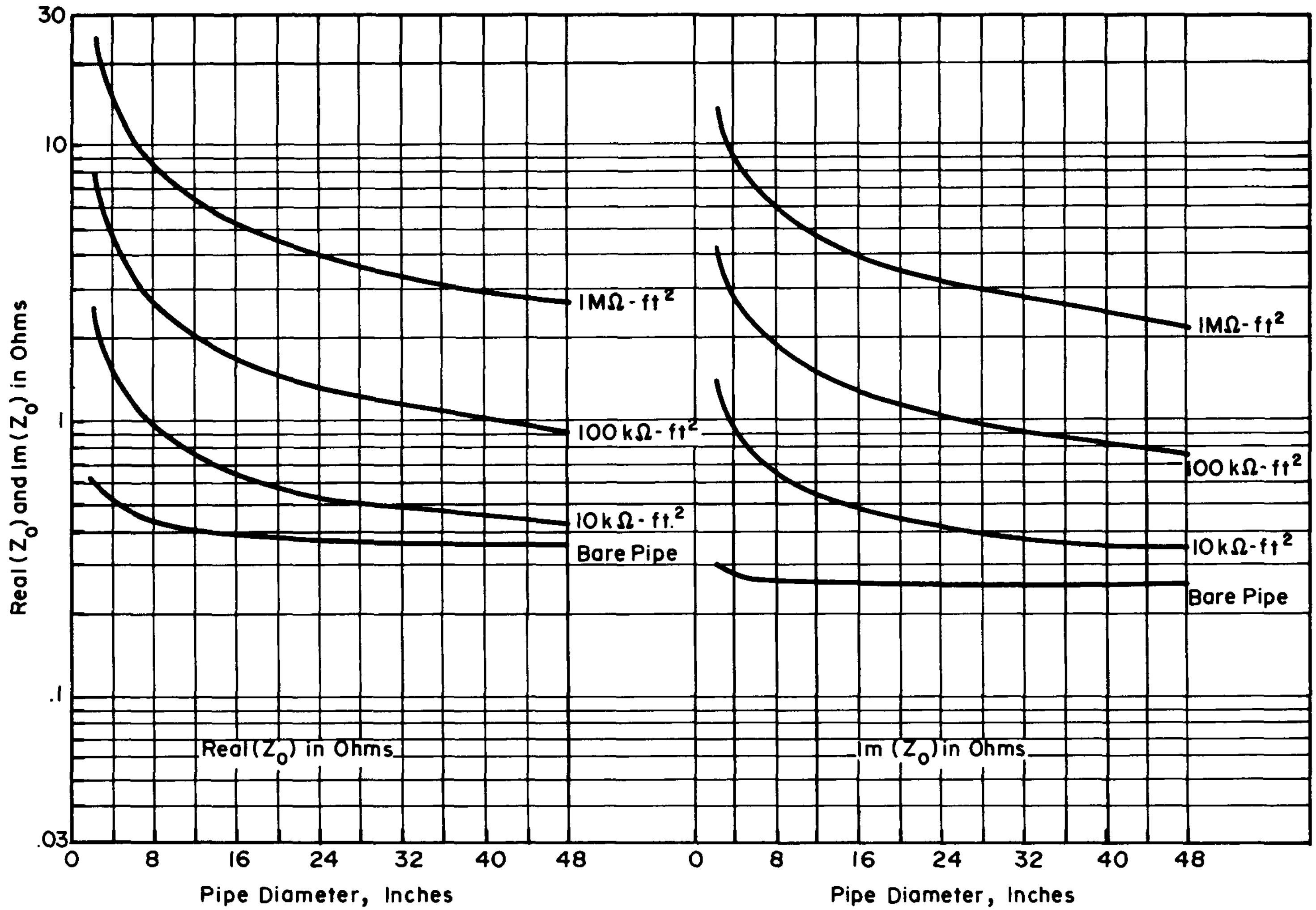


Fig. D-13 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR $\rho = 20\ k\Omega$-cm ($\sigma = 0.005$ mho/m) SOIL

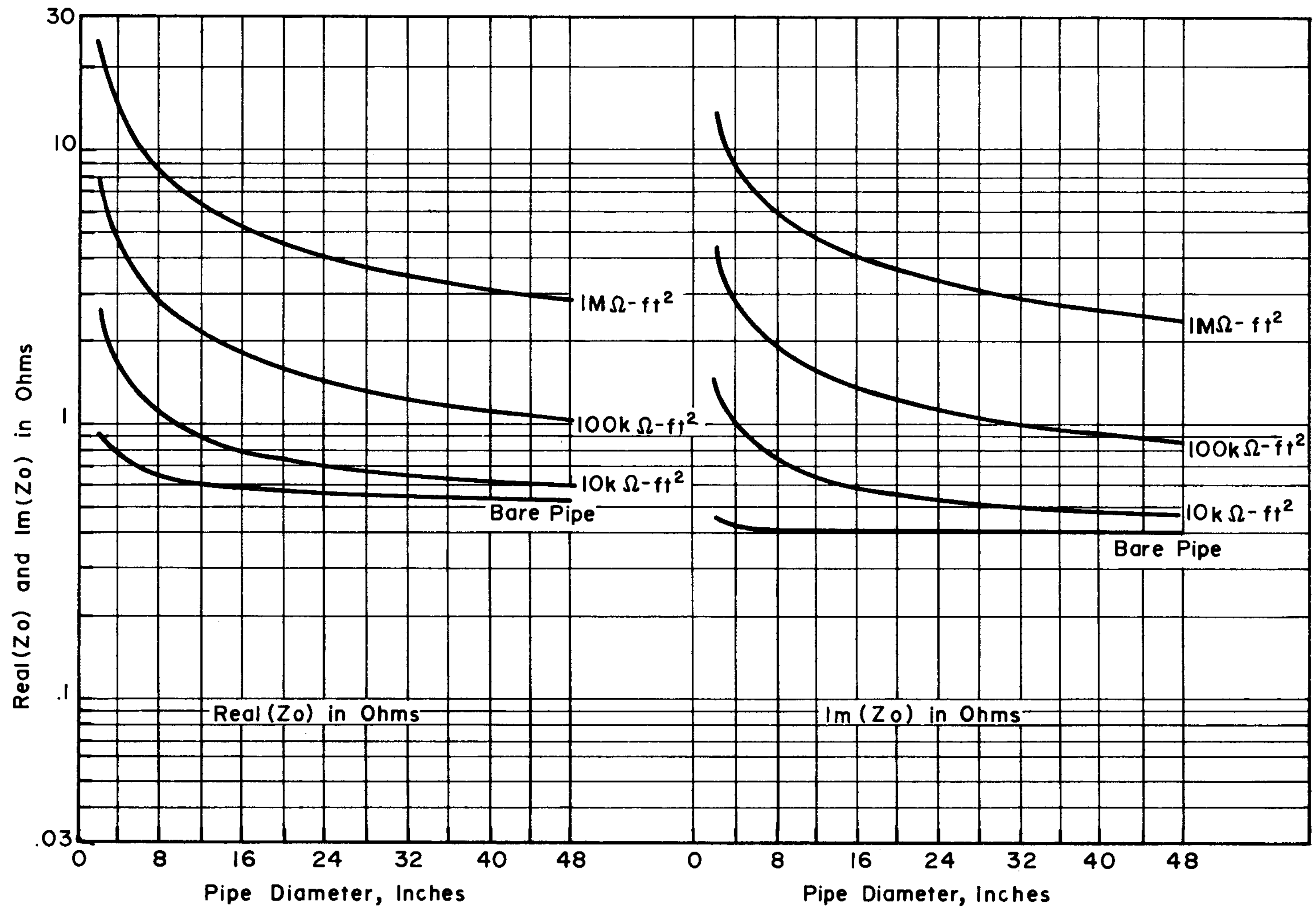


Fig. D-14 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR $\rho \doteq 40k\,\Omega$-cm ($\sigma \doteq 0.0025$ mho/m) SOIL

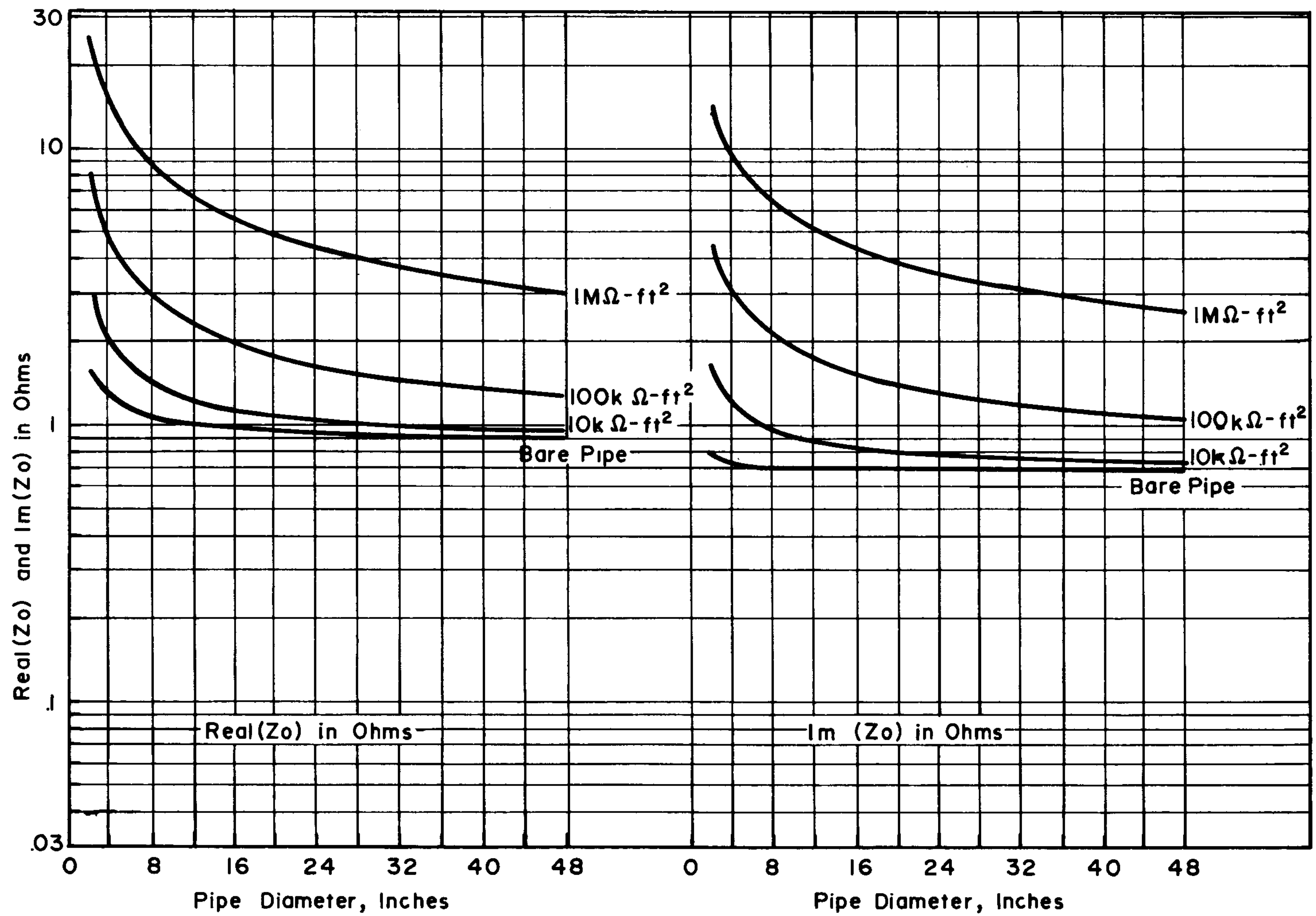


Fig. D-15 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR ρ=100kΩ-cm (σ=0.001mho/m) SOIL

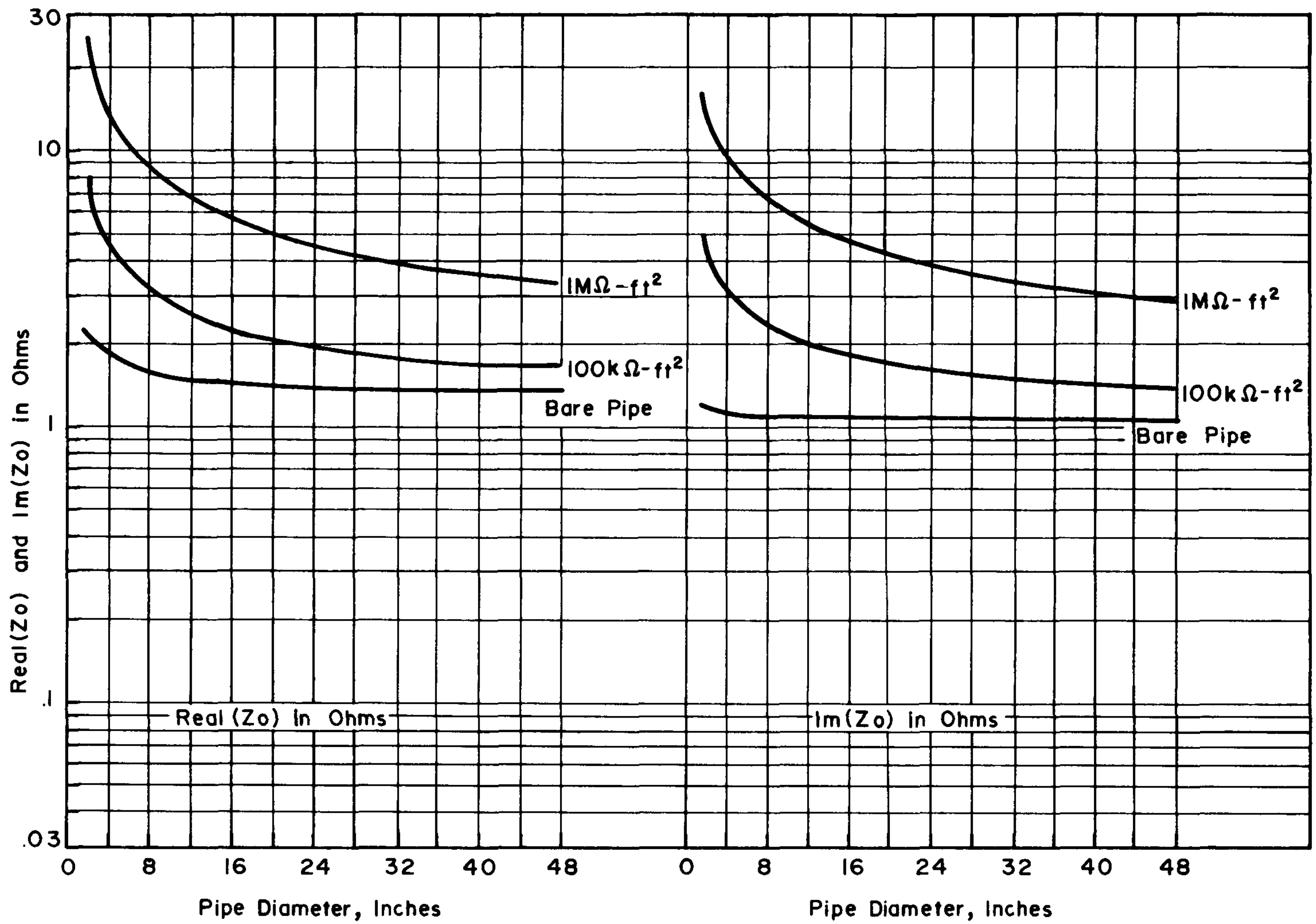


Fig. D-16 BURIED PIPELINE CHARACTERISTIC IMPEDANCE, Z_0, FOR $\rho = 200k\Omega$-cm ($\sigma = 0.0005$ mho/m) SOIL

Solution: Figure D-13 gives the graphs of the real and imaginary parts of the characteristic impedance for the 0.005 mhos/m soil conductivity. By interpolation, the curves for a coating resistance of 50 kΩ-ft^2 are located. Values read from the curves yield

$$Z_0 = 1.1 + j\,0.9 \text{ ohms.}$$

FIELD ESTIMATION OF Z_0

Knowledge of both the propagation constant γ, and the characteristic impedance Z_0, is necessary in order to determine the induced voltage profile on a pipeline. As seen from the preceding graphs, determination of both quantities require the pipe coating resistivity to be known, which in many situations can only be estimated.

This problem of establishing the pipeline electrical parameters may be solved in a practical manner for a pipeline wherein access to a reasonably good grounding system, such as a road casing, is possible. At the location where the ground system exists (this site must also be far enough away from any points of pipeline discontinuity so that the characteristic impedance level is established), the pipeline is shorted to ground and the drop in the pipeline induced voltage level is measured along with the impedance of the ground to remote earth. Insertion of these measured values into the pipeline Thevenin equivalent circuit (c.f., Section 1) will allow calculation of Z_0. Entering the preceding characteristic impedance curves with this value of Z_0, allows an estimate for the coating resistivity to be made. With this information, an estimate of the propagation constant can also then be made using the preceding γ curves.