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ELF INTERFERENCE VOLTAGE THRESHOLDS
FOR PIPELINE SYSTEMS

Martin M. Abromavage

IIT Research Institute

Prepared for:

Naval Electronic Systems Command

October 1972

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Technical Memorandum #2
IITRI PROJECT E6212
Contract No. N00039-72-C-0106

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U.S. Naval Electronic Systems Command
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13. ABSTRACT <p>This report is a review and summary of the work completed to date to assess the interference potential of a Sanguine System to collocated pipeline systems. The work includes theoretical analysis of the problem, parametric studies of the influence of the important factors involved in ELF electro-magnetic coupling between long conductors, assessment of the potential of a Sanguine System to produce corrosion on buried pipes, and field studies of voltages induced on pipes by commercial power systems.</p> <p style="text-align: right;">I b</p>			

FOREWORD

Sanguine System studies were initiated in 1967 to determine the electromagnetic interference effects which might be expected from an operational Sanguine System. Much of the necessary research and development has been completed, so that it is now possible to recommend interference voltage thresholds for several public utilities.

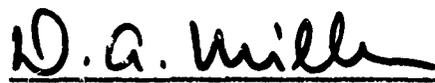
This report is a review and summary of the work completed to date to assess the interference potential of a Sanguine System to collocated pipeline systems. The work includes theoretical analysis of the problem, parametric studies of the influence of the important factors involved in ELF electromagnetic coupling between long conductors, assessment of the potential of a Sanguine System to produce corrosion on buried pipes, and field studies of voltages induced on pipes by commercial power systems.

The results of the work completed to date suggest an interference voltage threshold of 30 volts pipe-to-soil potential at the Sanguine operating frequency. This threshold, when generally applied, will ensure that excessive corrosion of pipe materials will not occur, malfunction of electrically-operated equipment will not be produced, and worker safety will be maintained.

APPROVED:

Respectfully submitted,
IIT RESEARCH INSTITUTE


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SECTION 1

OBJECTIVE AND SCOPE

1.1 INTRODUCTION

The Sanguine System is conceived as an Extremely Low Frequency (ELF) Command and Control Communication (C³) System.⁽¹⁾ Several definitive engineering studies have been completed since 1967, and the basic concept for an operational system design is now well-established.^(2,3) The completed system engineering studies have been accompanied by comprehensive environmental protection research and development across a broad spectrum of scientific, technical and public interest.⁽⁴⁾

The primary technical reason for performing environmental protection studies concurrent with conceptual system studies is that the ELF communications concept is based on the principle of the earth-return antenna. This type of antenna not only produces electromagnetic fields in air, but produces fields in the earth due to its ground currents. This being the case, it is expected that ELF electromagnetic interference could be produced (the extent of which is determined by basic system design concepts) on other collocated systems which make functional use of the earth. Examples of such systems are multi-grounded neutral power distribution systems and telephone systems employing grounded ringers.

While the likelihood for interference between a Sanguine System and other earth return type systems may be evident, it is less obvious that electromagnetic interference effects could be produced on systems that are functionally nonelectric, but are incidentally electrical conductors. For example, an ordinary wire fence is not intended to operate electrically, but it is nevertheless a conductive path between two points. A pipeline's function is to transfer some material mass from one point to another, but it also can provide a conductive path between two points under some circumstances. These nonelectric systems therefore must be considered in the Sanguine environmental

protection program. This report summarizes in some detail the research on pipeline interference performed between 1968 and 1971, and describes more completely the work done during 1972. The results obtained during the past four years also are interpreted in terms of interference mitigation requirements for pipelines in an ELF electromagnetic environment produced by existing electrical sources (principally 60-Hz sources) and a Sanguine System expected to operate at some frequency less than 100 Hz.

1.2 OBJECTIVE

The objective of the Sanguine pipeline interference research and engineering studies is five-fold:

- a. describe the mechanisms by which a Sanguine System could produce interference effects on collocated pipeline systems;
- b. identify the parameters of the Sanguine System and the parameters of representative pipeline systems which influence the interference produced by the former on the latter;
- c. define the nature of ELF interference effects on pipelines;
- d. identify practical interference mitigation techniques in the event that some pipeline mitigation might be required in a Sanguine-generated electromagnetic environment;
- e. accumulate and interpret sufficient data so that realistic ELF interference thresholds can be established for pipelines.

1.3 SCOPE

The mechanisms by which a Sanguine System could produce interference effects on collocated pipeline systems were described during studies conducted during 1968-1969.⁽⁵⁾ The contributing parameters of both the Sanguine System, as then defined, and representative pipeline systems were identified

during the study. A summary of this study is included in this report.

The nature of ELF interference effects on pipeline systems also was defined during the 1968-1969 studies.⁽⁶⁾ The potential effects included ac-induced pipe corrosion acceleration, influence on personnel safety, and ordinary electrical interference on control and monitoring devices. The likelihood of these effects occurring on pipelines exposed to a Sanguine-generated environment was investigated through laboratory research and literature surveys (corrosion effects) and routine engineering analyses (safety and equipment effects). The extent of this work, and the significant conclusions, are reviewed briefly in this report.

An initial survey of interference mitigation techniques likely to be useful for avoiding effects due to Sanguine-produced interference also was included in the initial pipeline studies.⁽⁷⁾ In 1970, advanced Sanguine System design studies indicated that additional attention should be given to Sanguine siting criteria and updated design features as "avoidance" mitigation possibilities. Pipeline studies were then renewed early in 1971 in which parametric analyses were stressed to depict interference mitigation possibilities through system design and emplacement studies.⁽⁸⁾ The results of the 1971 work are summarized in this report.

Field studies were planned and conducted during 1971 to accumulate information concerning ac-induced voltages on pipelines under realistic conditions. An existing pipeline located near the Sanguine Wisconsin Test Facility was selected for observation. Voltages measured on this pipeline (the Ashland-Rib Lake Northern Natural Gas Pipeline) were included in the 1971 report,⁽⁹⁾ as were data collected on two fuel gas pipelines in the State of Ohio. These studies were expanded in 1972. The field work concentrated on two pipelines located in or near the area of principal interest as an operational Sanguine site in Wisconsin. The approximate routes of these two pipelines are illustrated in Figure 1-1. The Northern Natural pipeline is included in the sketch as well. The

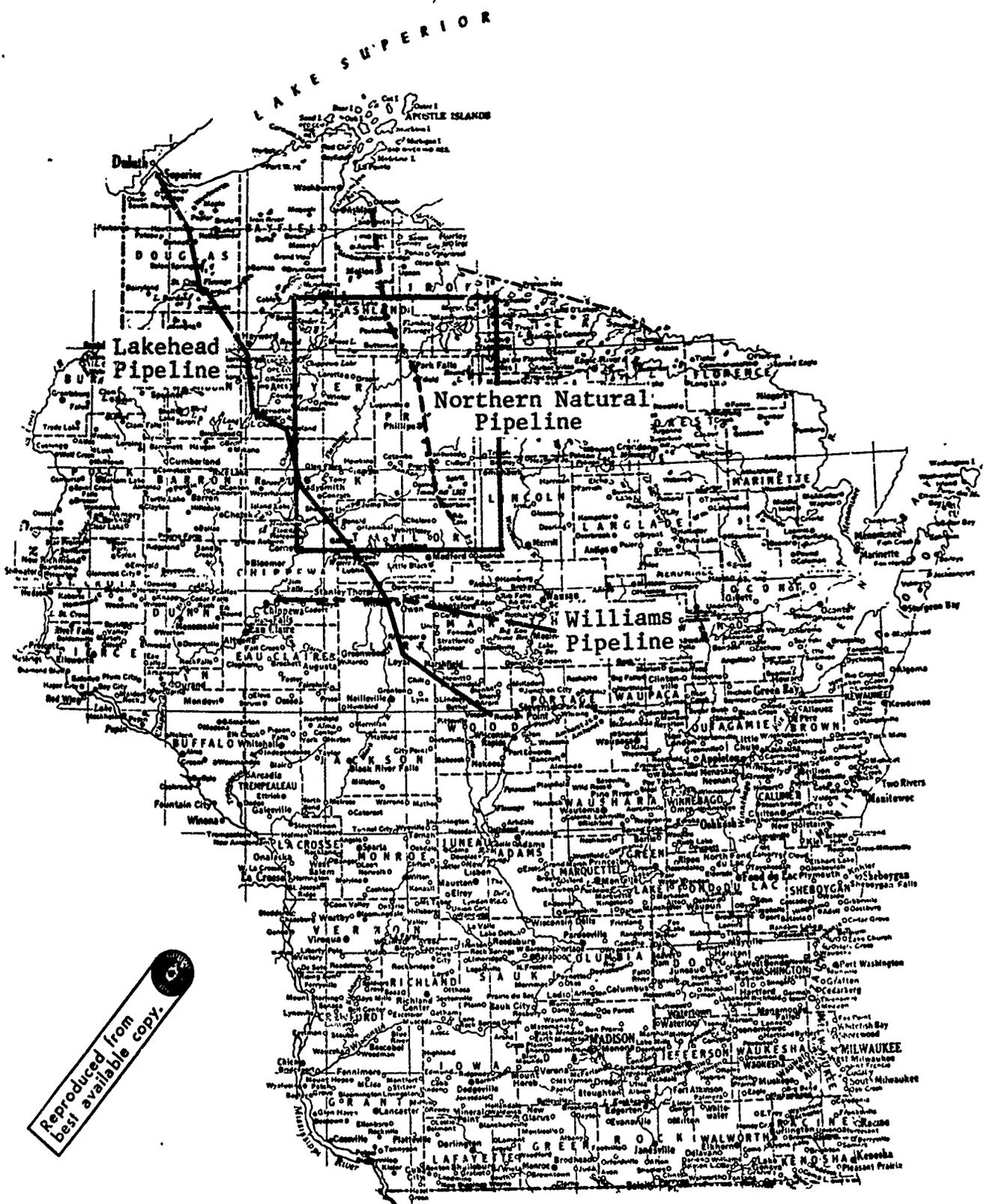


FIGURE 1-1 APPROXIMATE LOCATIONS OF PIPELINES IN WISCONSIN
IN SANGUINE DEPLOYMENT AREA OF INTEREST

Lakehead pipeline passes through the southwestern portion of the area of interest, as shown in the map insert. The Williams pipeline is located a few miles south of the area. There is another pipeline along the eastern edge of the area, but arrangements could not be made to include this pipeline in the 1972 survey.

The ac-induced voltages measured on the Wisconsin pipelines shown in Figure 1-1 are presented and discussed in this report. The results are interpreted in terms of interference mitigation requirements and recommended pipeline interference voltage thresholds for Project Sanguine.

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SECTION 2

REVIEW OF INTERFERENCE MECHANISMS

2.1 INFINITE LINE THEORY

The electric field due to an infinitely long straight wire at the surface of the earth⁽¹⁾ is

$$E = \frac{j\omega\mu_0}{2\pi\gamma y} \left[1 - \gamma y K_1(\gamma y) \right] \text{ volt/meter}$$

where

$$\omega = 2\pi f$$

f = frequency (Hz)

$$\mu_0 = 1.257 \times 10^{-6} \text{ henrys/meter (inductivity for free space)}$$

y = separation in meters between the wires

$$\gamma = (j\omega\mu_0\sigma)^{1/2}$$

σ = conductivity of the earth in mhos/meter

$K_1(z)$ = modified Bessel's function of the second kind and first order.

Figure 2-1 is a graph of the rms electric field or voltage gradient parallel to an infinitely long current-carrying wire versus separation for two values of earth conductivity. For separation distances greater than 5000 meters the rms fields differ by a factor of ten; i.e., they are inversely proportional to the earth conductivity assumed.

2.2 THE GRADIENT WITHIN THE GRID

Consider an antenna system consisting of a grid of grounded radiating elements as shown in Figure 2-2. The spacing between elements is 5.0 miles, and the terminal grounds are located 2.5 miles from the edge radiating elements. The grounds are modeled as point sources at the surface of semi-infinite uniform earth. It is assumed that 150 amperes of current at 45 Hz is used to drive each line of the antenna and that all currents are in phase.

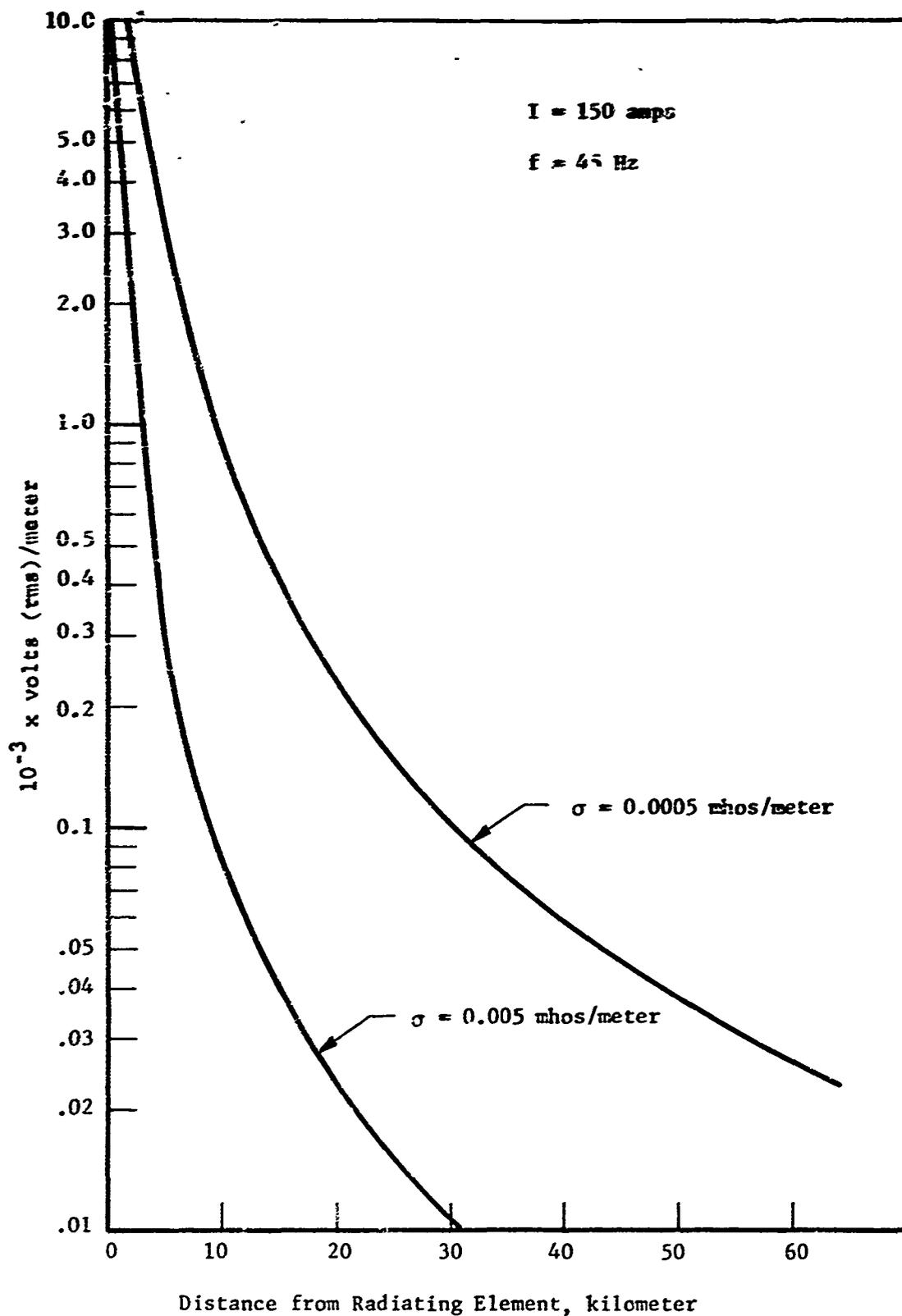


FIGURE 2-1 THE GRADIENT PARALLEL TO AN INFINITELY LONG CURRENT-CARRYING CONDUCTOR

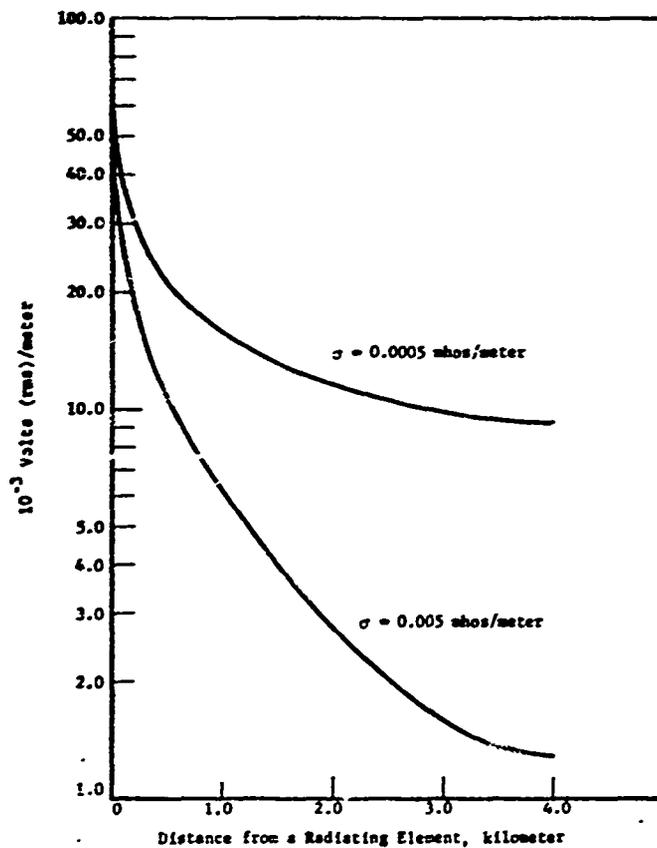
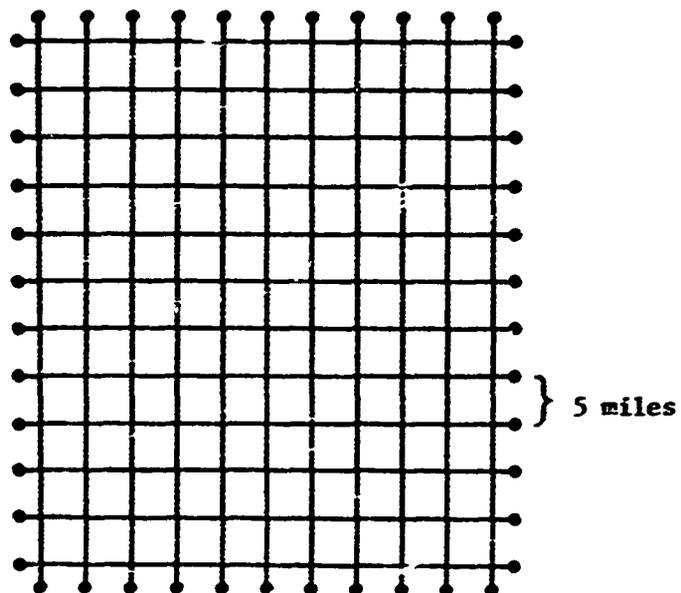


FIGURE 2-2 ASSUMED SANGUINE ANTENNA GRID AND COMPONENT OF THE GRADIENT WITHIN THE ANTENNA PARALLEL TO AN ELEMENT

Within any cell of the antenna array the electric field is easily calculated in terms of orthogonal components parallel to the sides of the square. It can be assumed that the field within a square is due only to the radiating elements bounding the area. Figure 2-2 shows the rms field parallel to one pair of sides as a function of separation from one of the sides. The curves are superpositions of the fields from opposite sides of the square. Due to symmetry the separation is only carried to 2.5 miles.

2.3 THE FIELD IN THE FRINGE AREA

The field pattern in the fringe area is calculated by superimposing the contributions from the radiating elements and the point grounds. Figure 2-3 shows the antenna and a point outside the antenna. It is assumed that the component E_y is due only to the radiating elements parallel to the vector E_y and that E_x is due entirely to the line of point grounds on that side of the antenna, because the y-components of the fields from the point grounds cancel to a great extent. The field ($E = \sqrt{E_x^2 + E_y^2}$) as a function of separation from the line of point grounds is included in the figure. The separation is measured along an extension of one of the antenna elements because the component E_x is greatest in magnitude there for small separations, and therefore gives a conservative value.

2.4 TYPICAL INDUCTIVE COUPLING CHARACTERISTICS

Inductive coupling occurs when pipelines are exposed to the electric fields produced by an ELF earth return circuit such as a grounded neutral power line or a Sanguine antenna element. For purposes of illustrating typical inductive coupling characteristics, consider a 50-mile long, 10-inch diameter pipeline exposed to a parallel Sanguine antenna operated at 150 amperes at 75 Hz. The pipeline and antenna are five miles apart.

The gradient produced by the antenna along the pipeline is illustrated in the top sketch in Figure 2-4. If the voltage between the pipe and earth were measured along the total length of the pipe, the pipe-to-soil potential (p-s-p) would appear typically like that shown in the second sketch. The current along the pipe is a maximum at the center, where the pipe-to-soil

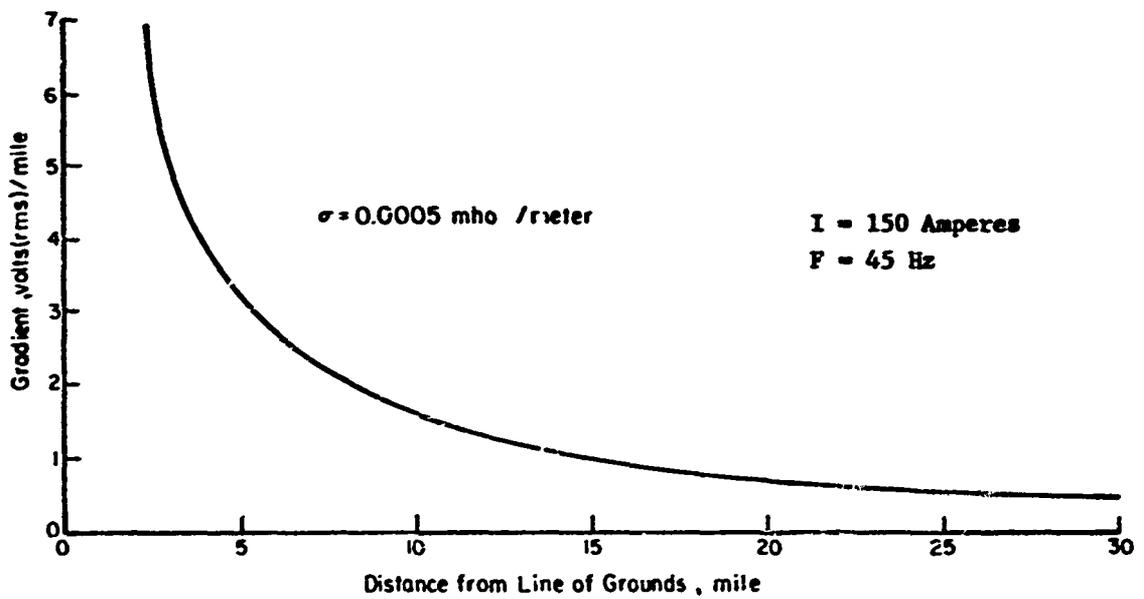
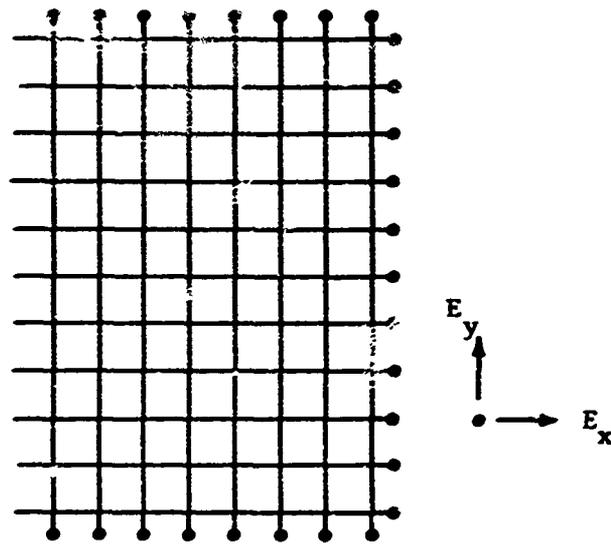


FIGURE 2-3 FIELD COMPONENTS AND RESULTING GRADIENT IN THE FRINGE AREA OF A SANGUINE ANTENNA

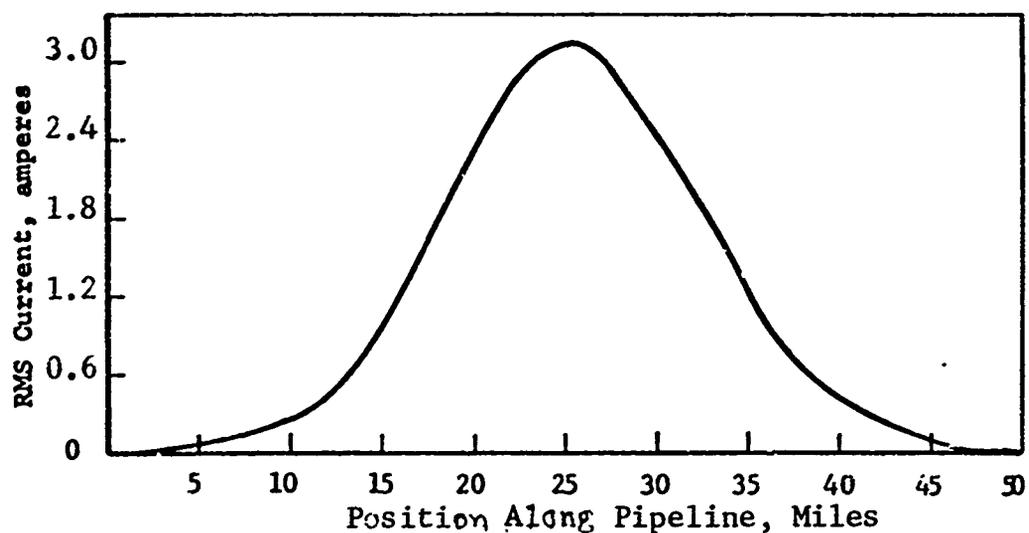
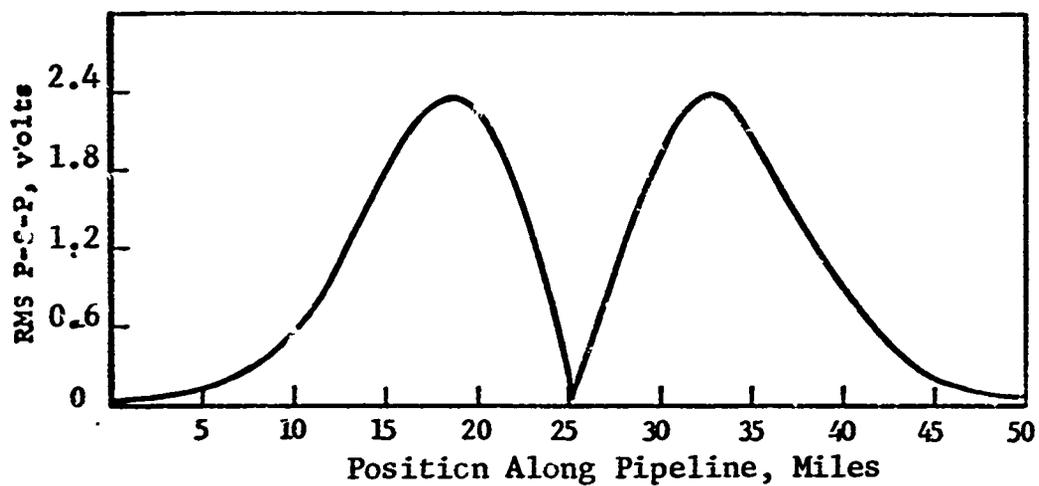
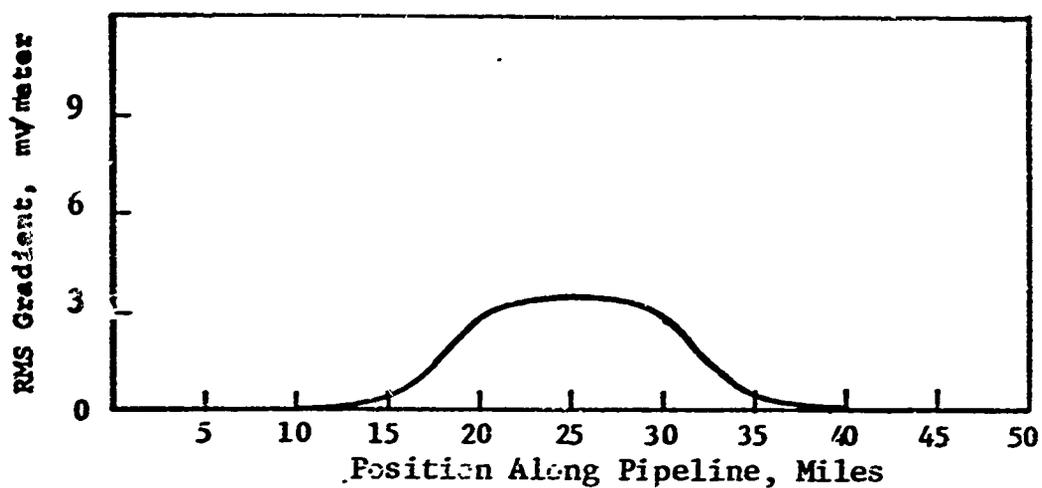


FIGURE 2-4 TYPICAL INDUCTIVE COUPLING CHARACTERISTICS FOR A 50-MILE LONG PIPELINE 5 MILES FROM AND PARALLEL TO A 150- AMPERE SANGUINE ANTENNA.

potential is a minimum.

2.5 TYPICAL CONDUCTIVE CHARACTERISTICS

The nature of the distributed gradient along the length of the illustrative 50-mile long, 10-inch diameter pipeline is shown in the top sketch of Figure 2-5. The source of the gradient is a point ground conducting 150 amperes at 75 Hz, located 2.4 miles from the pipeline at milepost 24. The voltage to ground, or the pipe-to-soil potential, produced along the pipe by the point source is shown in the second sketch, while the current along the pipe is depicted in the third sketch. Notice that the voltage to ground due to the point source is a maximum at the midpoint of the pipe, whereas this was a point of minimum voltage to ground due to the antenna. The current distribution on the pipe exhibits trends that are the inverse of the voltage characteristics..

2.6 SUPERIMPOSED EFFECTS

The interference produced by inductive coupling between an ELF source (a Sanguine antenna, for example) and a pipeline; and the energy on the pipeline from sources such as ground terminals combine on the pipe to present the total interference. The complexity of the superimposed effects depends upon the electrical characteristics of the interference sources and the relative orientation of the pipe with respect to these sources. For example, the current in a Sanguine antenna will be much larger than the current in a segment of the distributed ground terminal planned for the Sanguine System. For most relative pipeline orientations in the fringe area the inductive contribution from a North-South antenna will be accompanied by a conductive contribution from East-West terminal grounds. Little or no contribution from terminal grounds would be expected on a pipeline lying entirely within the system area.

2.7 COMPUTER PREDICTION PROGRAMS

Although the superimposed effects of interference on pipelines contributed by long wires (antennas or power lines) and point

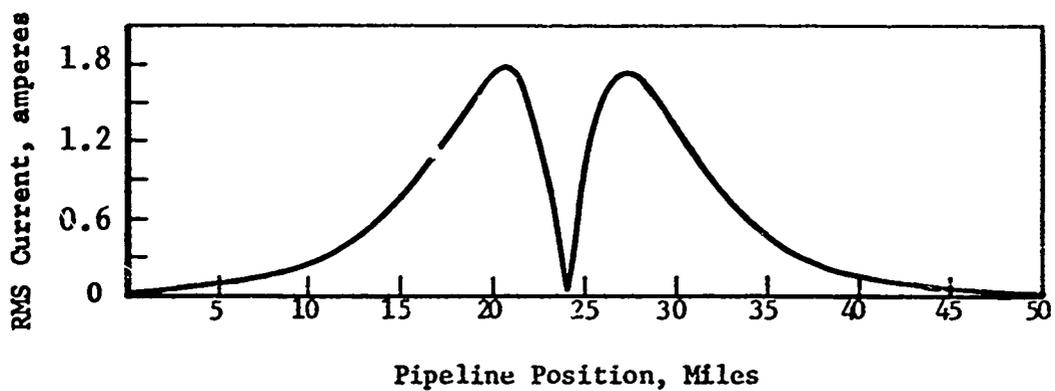
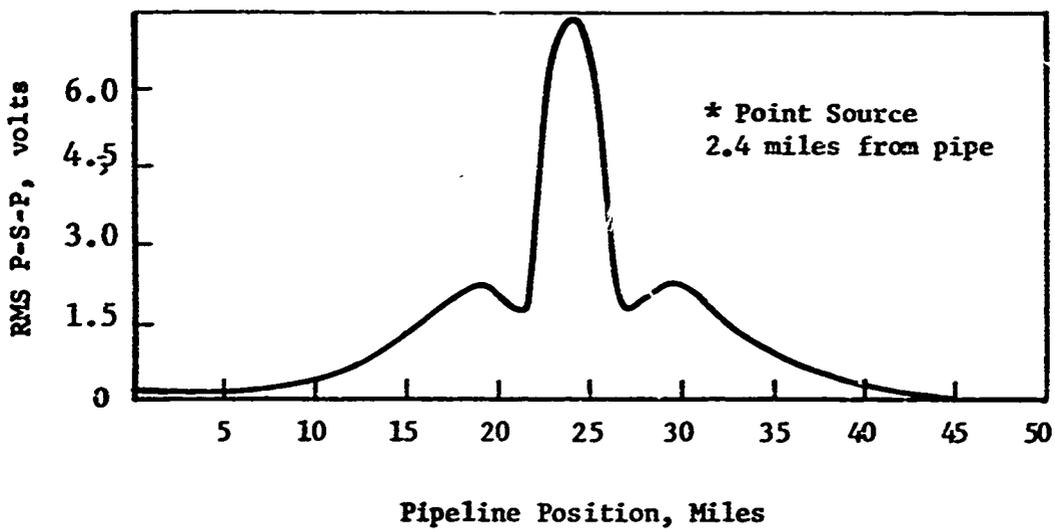
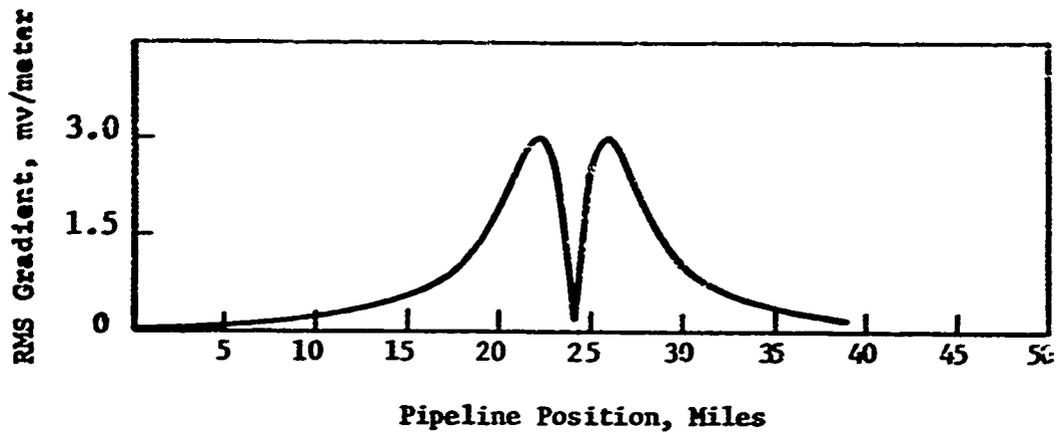


FIGURE 2-5 TYPICAL GRADIENT, VOLTAGE AND CURRENT CHARACTERISTICS PRODUCED ON A PIPELINE BY A 150-AMPERE POINT SOURCE AT 75 HZ

sources or their electrical equivalent (terminal grounds) may be complex in some given situation, they are not difficult to compute. The computations may be time-consuming, however, when the pipe is exposed to a grid of wires such as a Sanguine antenna system and several terminal grounds. Computer programs have been developed so that calculations can be made efficiently.

The electrical effects on a buried conductor are longitudinal current on the pipe which produces leakage current through the pipe coating, and a distributed pipe-to-soil potential due to the gradient along the pipe, as previously depicted. These effects are related through the transmission line differential equations. ⁽²⁾

The computer prediction of the effects from a Sanguine antenna is based on several practical assumptions: the earth is assumed to have a uniform resistivity; the pipeline is modeled as a lossy transmission line. The pipeline parameters taken into account are the diameter, coating resistance, depth of burial, longitudinal resistance, and the resistivity of the earth adjacent to the pipeline. These parameters together with the frequency of excitation of the antenna are used to estimate the shunt admittance and longitudinal impedance of the pipeline.

Two different approaches to the solution of the transmission line equations were developed and compared. In one approach the pipeline is treated as a lumped parameter system. The second approach involves the programming of the exact solution of the transmission line equations. Good agreement has been obtained between the programs.

The lumped parameter program predicts inductive and conductive effects for the antenna and distributed antenna grounds assuming a uniform, linear earth. The electromagnetic field is predicted at points on the surface of the earth. This field strength is assumed to be applied to the buried pipeline. The pipeline is assumed to consist of equivalent linear segments with

each segment represented by lumped impedance along the line and a lumped admittance to remote ground.

The exact solution program computes the voltage drop along a given section of the pipe. When divided by the distance over which the drop occurs, the required potential gradient is obtained. A closed form expression given by Lacey⁽³⁾ for the mutual impedance at large separations is used in the program to avoid distance limitations. The program is capable of handling layered earth models for conductive effects. The induced effects are based on a homogeneous earth.

The shunt admittance and longitudinal impedance can be changed in a piecewise fashion in both models. The various parameters (coating resistance, adjacent earth resistivity, longitudinal resistance) are permitted to assume different values along different sections of the pipe. The reason the adjacent soil resistivity is allowed to assume a different value is that the shunt admittance is sensitive to this parameter.

A third program has also been developed for the purpose of estimating interference effects on complicated networks of pipelines. The program uses the exact solution program as a subroutine and hence has all of its features. Outputs from the network program are only the effects at the nodes (intersections or terminations of pipelines). The distributed effects on any pipe in the network can then be calculated in a separate run by using either of the two basic programs.

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SECTION 3

EFFECTIVE INTERFERENCE PARAMETERS

3.1 EFFECTS OF RELATIVE ORIENTATION

The relative orientation between a pipeline and a Sanguine antenna, or antennas comprising a system, refers to the angle described by the pipe and the antenna, and the distance from a point on the pipe to a point on the antenna. Several relative angles must be considered in an analysis if a grid of antennas is assumed since both North-South and East-West antennas may contribute to the gradient along the pipeline if the pipe is not parallel to one side of the antenna system. Similarly, incremental separations may be necessary considerations in analysis. In practice, it is simplest to consider each contributing antenna in turn. Some basic interference behavior related to orientation factors is discussed in following paragraphs. The pipe-to-soil potential (p-s-p) distribution is used for illustrative purposes.

The inductive p-s-p distribution along a pipeline is shown as a function of relative angle in Figure 3-1. All other parameters of interest are constants for the three cases depicted in the sketch.

The upper diagram shows the p-s-p distribution (voltage to ground along the pipe) when the illustrative pipeline is parallel to an antenna. The locations of maximum voltage to ground shift along the pipe when the pipe is rotated 34 degrees with respect to the antenna, as shown in the center diagram. The distance to the pipe from the antenna varies, but the pipe does not cross the antenna. The amplitude of the maxima are much lower than when the pipe was parallel to the antenna.

If the pipe is rotated only 17 degrees but is displaced so that it crosses the antenna there is another shift in the locations

of the voltage peaks. This is shown in the lower sketch of Figure 3-1. There is also a substantial increase in the amplitudes of the peaks.

3.2 EFFECTS OF PIPELINE PARAMETERS

It should be expected that the diameter of a pipe will have some effect on the interference coupled from an ELF current source to a pipeline. An increase in the pipe diameter increases the area of the pipe exposed to the electric field. As the diameter is increased the wall thickness of the pipe is increased for strength. Consequently, the longitudinal impedance per unit length of pipe decreases. All other factors of interest being constant, these changes mean that longitudinal currents increase with pipe diameter, leakage current densities decrease, and pipe-to-soil potentials decrease in amplitude.

The effect of pipe diameter changes on pipe-to-soil potential is illustrated in Figure 3-2. A more complex situation is illustrated here to depict a situation that is conceivable in a Sanguine environment. The pipe is longer than the antennas, is parallel to the North-South antenna, and crosses the East-West antenna. The distributed ground terminal on the right is much closer than the ground on the left, while the upper and lower (north and south) ground systems are the same distance from the pipe and equidistant from its midpoint.

Changes in the quality of pipeline coatings also are predictable. High resistance coatings increase the pipe's shunt impedance thereby reducing leakage currents to ground while the voltage to ground, or the pipe-to-soil potential, is increased by improved pipe coatings. The high resistance coatings also reduce longitudinal currents generally. The effects of pipeline coatings on these interference factors are illustrated in Figure 3-3. All parameters of interest except coating quality were assumed to be constants in developing the illustration.

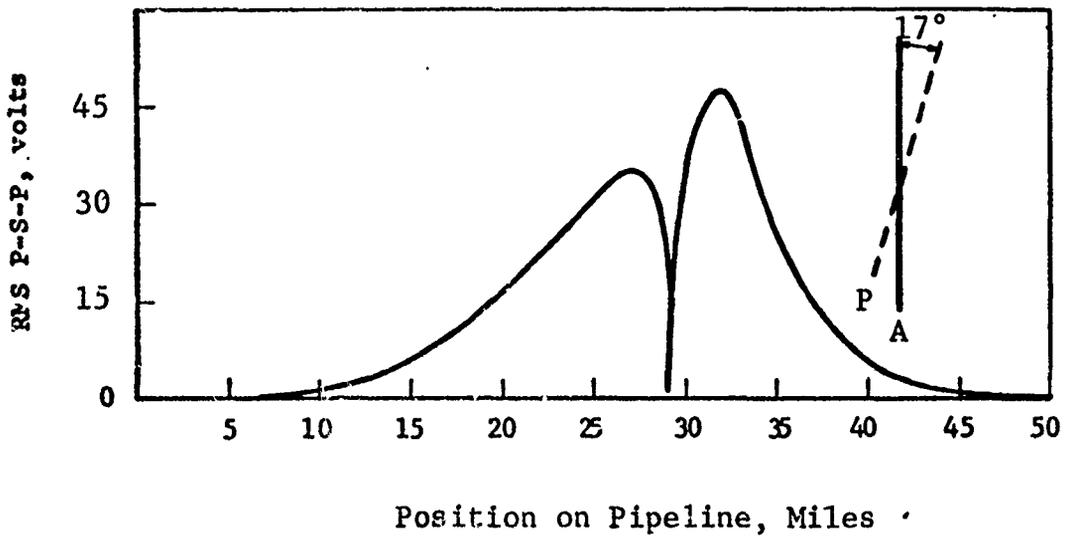
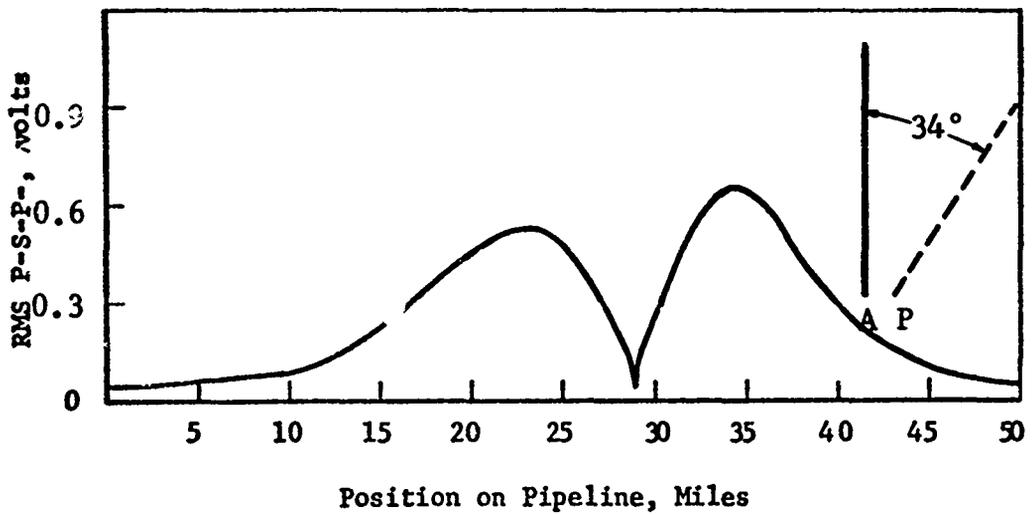
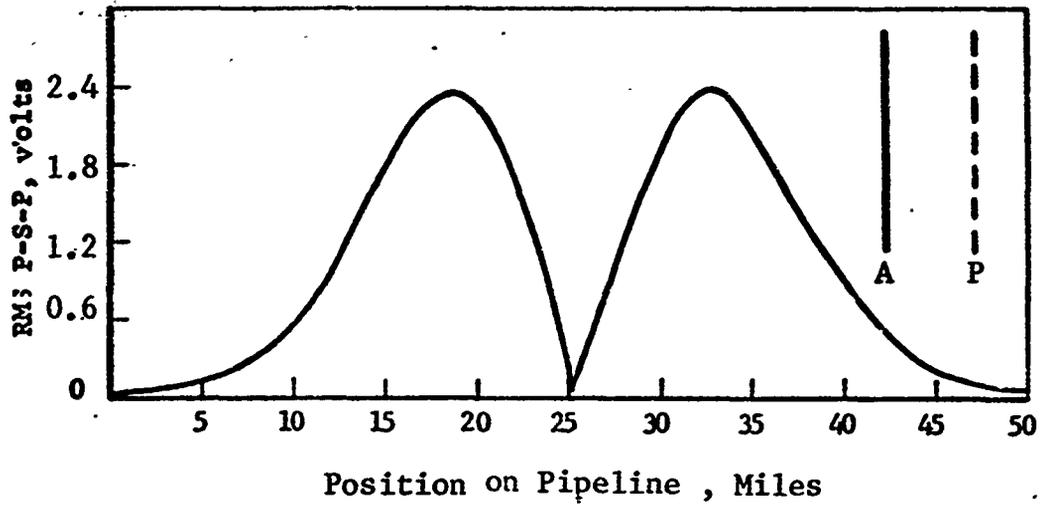


FIGURE 3-1 PIPE-TO-SOIL POTENTIAL AS A FUNCTION OF THE RELATIVE ORIENTATION BETWEEN THE PIPE AND ANTENNA

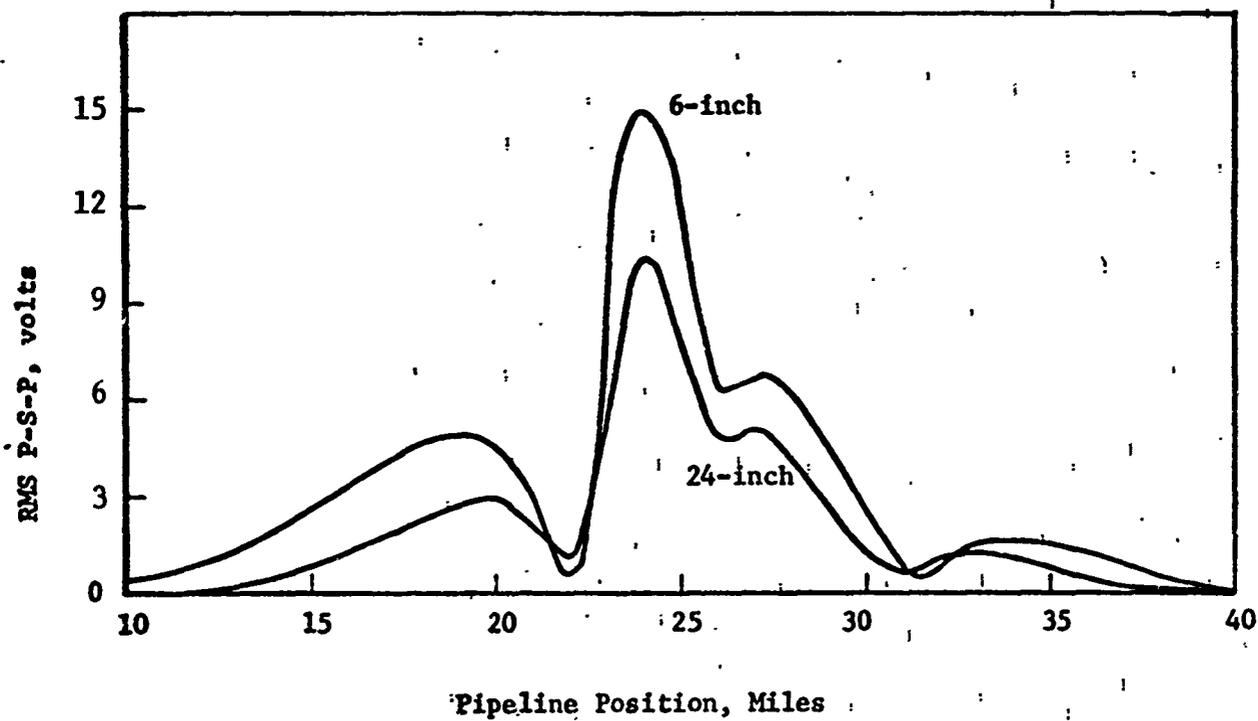
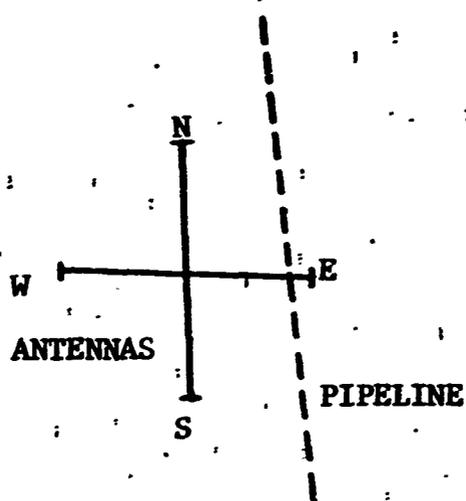


FIGURE 3-2 THE EFFECT OF PIPELINE DIAMETER ON TOTAL ELF INTERFERENCE COUPLED FROM A SET OF ORTHOGONAL EARTH RETURN ANTENNAS

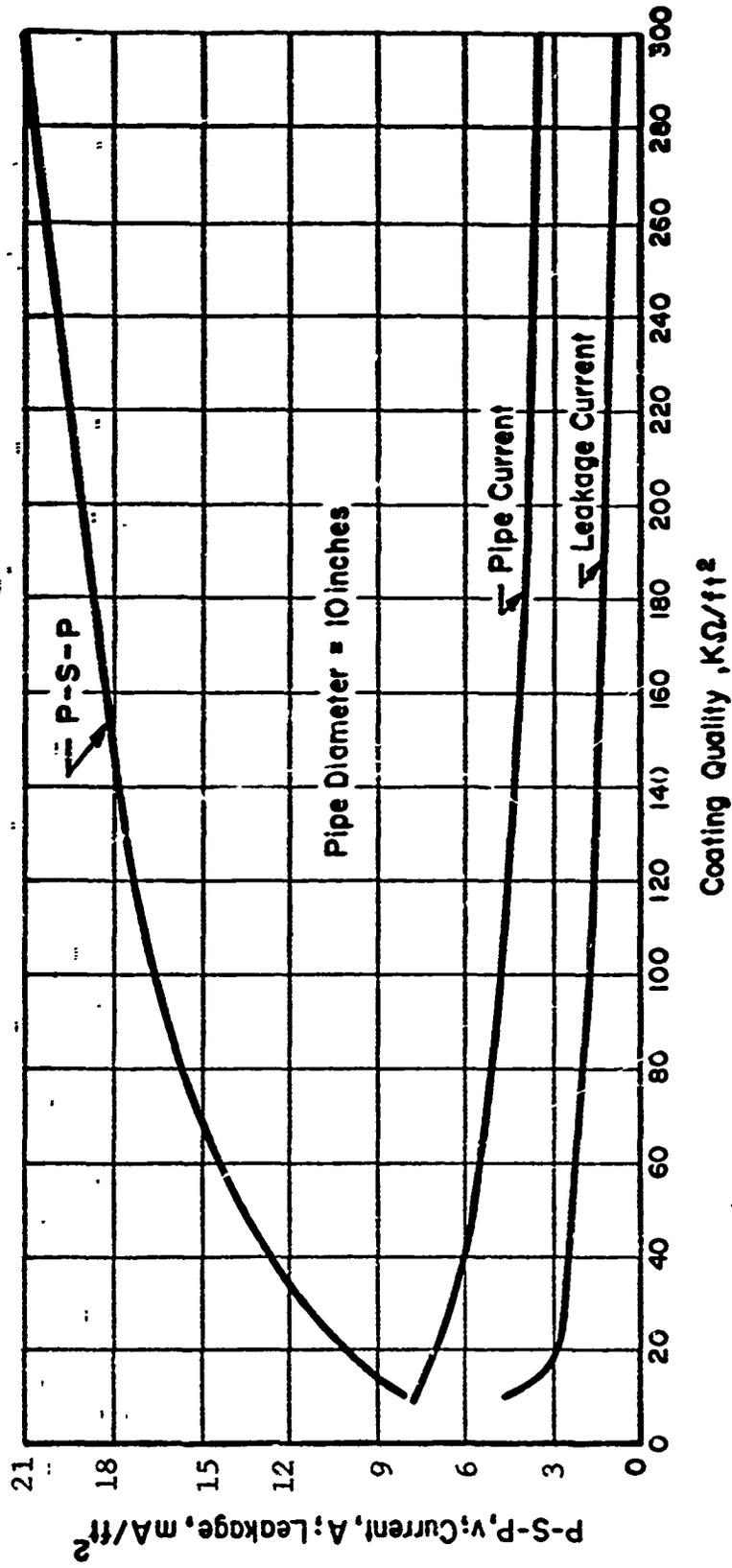


FIGURE 3-3 THE EFFECT OF PIPELINE COATING QUALITY ON ELF INTERFERENCE FACTORS

3.3 THE EFFECT OF SANGUINE SYSTEM FACTORS

Two Sanguine System operating factors are important in determining the interference that might be coupled to collocated pipelines: the antenna current and the system operating frequency.

The inductive coupling between a Sanguine antenna, or any other ELF earth-return current source, and a pipeline is directly proportional to the source current amplitude. The conductive effects on the pipeline produced by terminal grounds also are directly proportional to current.

The effect of the source operating frequency is somewhat more complex than the effect of operating current. This complexity is associated principally with the change in the longitudinal impedance of the pipe as frequency is changed, and the change in the electric field at the pipe location due to the source. The latter is a function of both frequency and separation between the source and the recipient.

As frequency is increased, the gradient along the pipeline increases to some degree. However, the longitudinal impedance of the pipe increases at a faster rate with frequency, so the net effect of increasing frequency is a reduction in the pipeline interference voltages and currents. This holds true unless the pipeline is quite close to the antenna (several hundred feet). Then some increase in pipeline interference voltages and currents might be expected. The changes in interference are not dramatic at the currents, frequencies and separation distances associated with Sanguine. For example, a change in interference amplitudes of ten percent or less occur for changes in frequency from 45 Hz to 75 Hz. Since these changes are not dramatic, frequency can be regarded for Sanguine System pipeline analysis as a minimal influence on interference.

SECTION 4

ELF PIPELINE INTERFERENCE EFFECTS

4.1 CLASSIFICATION OF EFFECTS

The pipeline interference studies conducted for Project Sanguine since 1968 have provided sufficient information to identify the types of effects which should be considered in an ELF electromagnetic environment produced by the proposed Sanguine communication system and other existing systems such as commercial power transmission and distribution circuits. The potential interference effects on pipelines to which attention should be directed are:

- a. the corrosion of pipe materials that might be produced by ac inductive interference from Sanguine antennas and/or ac conductive effects from Sanguine distributed ground terminals;
- b. effects that might be produced on pipeline control and monitoring electrically-operated equipment;
- c. Any impact that Sanguine-associated electromagnetic coupling might have on pipeline worker safety.

These three areas have received varying degrees of attention during the past four years. Some additional detailed study oriented toward associating these potential interference effects to actual Sanguine System designs and operating site selection will be performed during the project's Validation and Full-Scale Development phases. The conclusions and other impressions which have been developed from the work completed to date are summarized in this section.

4.2 THE POTENTIAL FOR AC CORROSION

There is an extensive body of technical literature available on natural and electrically-produced corrosion of metals buried in the earth. For example, the National Bureau of Standards lists more than 400 articles on this subject which were published

between 1906 and 1956.⁽¹⁾ As has happened in other technical fields of interest, the literature since that time has grown substantially. Clearly, it is beyond the scope of this report to attempt a comprehensive review of so large and specialized a body of knowledge. Nevertheless, the work reported in the past is important in understanding and estimating the pipeline corrosion potential of the proposed Sanguine System, and therefore has been studied in considerable depth.

The definitive work by Kulman⁽²⁾ was used principally to review the corrosion literature prior to 1960 and to identify work that seemed particularly pertinent to Sanguine. A search was made of the post-1960 literature to obtain recent data and views regarding pipe corrosion attributed to ac gradients and earth currents. The following statements summarize the salient points observed from studying the corrosion literature:

- a. metal buried in soils can be corroded by alternating currents;
- b. the rate of corrosion produced on most metals by alternating currents is higher than the natural corrosion rate of the metal in the same soil environment;
- c. the rate of corrosion produced by ac is affected by the current density produced on the metal, the frequency of the current, the composition of the metal, and the soil chemistry;
- d. all other factors being the same, corrosion produced by alternating current is a small fraction of that produced by the same magnitude of direct current. Generally the ac-produced corrosion is only about 1-2% of that caused by dc;
- e. the extrapolation of corrosion data obtained under controlled or simulated conditions in the laboratory to field problems must be made with care. Factors which mitigate against direct application laboratory-derived data to the field include:

1. somewhat different chemical reactions because constituents of soil in the field cannot be duplicated entirely in the laboratory, nor can the availability of oxygen, hydrogen, or carbonates;
2. the rate of corrosion is a function of exposure time. The short laboratory exposure periods (several months at best) produce much higher, early rates than should be expected in the field;
3. unsuspected direct current outputs produced by laboratory ac generators can dramatically affect corrosion rates and entirely mask the actual rate attributable to ac;
4. the efficiency of redeposition of metal by alternating currents (metal removed when the metal is anodic is redeposited to some extent when the metal is cathodic) often is lower in the laboratory than in the field. This is generally the case when simulated soils are used.

Some investigators suggest that the rate of laboratory corrosion should be reduced to 0.4 to 0.8 for direct current corrosion in the field, and to 0.1 to 0.01 for ac corrosion for bare pipe;

- f. the use of protective coatings on buried pipelines to prevent corrosion must be considered in estimating field corrosion rates. Little or no corrosion should be expected during the ordinary life of the coating except where the coating is punctured. The current density at a puncture (a "holiday") will be much higher than along protected surfaces, and therefore corrosion will be higher, at least for some initial

time, than one might expect from the average current density along the protected pipe.

For some metals, however, the rate of corrosion decreases as current density increases.

Items: (a) through (f) above should be recognized as useful for general guidance in evaluating a potential ac-induced corrosion problem such as that associated with Sanguine. That is, the statements are helpful in placing the potential for a Sanguine System to enhance pipeline corrosion in perspective, but they do not provide a sufficient basis for an in-depth evaluation of the problem. The laboratory and field work performed for Sanguine, the engineering studies completed to date, and some recent literature concerning power line induction under ordinary and fault conditions provide sufficient additional insight to at least qualitatively address the corrosion question.

A series of laboratory tests were performed to determine the corrosion rate of steel pipe material in simulated soils under several conditions of exposure to ac voltages. The voltages were not induced on the pipe samples, as would be the case if buried pipes were exposed to Sanguine-generated gradients. The voltages were applied to the metal samples directly with the electrodes, as is generally done in laboratory experiments for convenience. This difference is important in interpreting laboratory results. Several other limitations typical of experiments performed under controlled conditions also deserve attention. The simulated soils should not be considered to represent actual soil chemistry conditions which may exist in reality either in some large area or a smaller localized area. All tests were conducted for short periods of time, the longest being about two months for weight loss experiments. The purpose of the tests was to obtain data for comparison with results cited in the literature, and therefore the likely presence of direct current was considered to be no serious drawback. However, this factor must be recalled when attempts are made to estimate the likelihood of Sanguine-induced corrosion. Finally, the inherent limitations

of laboratory analysis techniques must be recognized. The literature emphasizes these limitations, and there is no reason to include them in detail in this report since the experiments were not intended to produce data directly applicable to field conditions.

The polarization behavior of several ordinary pipe metals in a simulated soil of known characteristics and pH was determined in an initial series of tests. The metals included new and used bare metal and coated new metal. A manufactured holiday was used with the coated material. The data from these tests provided the information required to select appropriate alternating voltages for ac exposure tests.

Using linear polarization techniques laboratory corrosion rates were calculated for new metal exposed to alternating voltages of amplitudes between 0.4 and 3.0 volts rms. As mentioned previously, any residual dc component from the laboratory generator was ignored. The computed rates were practically independent of the voltage level, and were highest for the lowest frequencies used in the tests as shown below:

<u>Frequency</u>	<u>Laboratory Corrosion Rate of Bare Pipe Steel</u>
No Voltage Applied	0.003 ipy*(New) -- 0.03 ipy* (used)
15 Hz	0.05 - 0.08
45	0.03 - 0.06
60	0.03 - 0.05
75	0.01 - 0.04

ipy* = inches per year.

The rate of corrosion of the metal when voltage was applied did not seem to depend very much on the condition of the metal, although an order of magnitude difference was computed with no voltage present. There also is about an order of magnitude increase in the rate when voltage was applied, based on the new metal. Unrealistic rates were computed for the case of the simulated holiday in the coated steel sample, so they are not included in this summary. Those tests were performed both with and without cathodic protection, but the results in all cases were regarded as unsatisfactory at best. In all cases the soil

resistivity was 400 ohm-cm (2.5×10^{-1} mho per meter conductivity) with pH controlled at 6.5.

Weight loss experiments were performed with the metal samples in the simulated laboratory soil exposed to the same range of 60-Hz signals (0.4-3.0 volts, rms). Soil conditions were the same as noted previously except that the resistivity was increased to 20,000 ohm-cm (or a conductivity of 5×10^{-3} mho per meter). Note that the linear polarization tests were performed in a medium generally regarded as very corrosive (400 ohm-cm) and slightly acid (pH of 6.5), while for weight loss observations the medium was changed to mildly corrosive (20,000 ohm-cm) with the same acidity.

After 1-1/2 to 2 months of exposure to the ac signals, the laboratory corrosion rates for bare new pipe steel were computed as follows:

<u>Test Condition</u>	<u>Laboratory Corrosion Rate of Bare New Metal</u>	
	<u>400 ohm-cm</u>	<u>20,000 ohm-cm</u>
No Voltage Applied	0.0005 ipy*	0.0002 ipy*
0.4-3.0 VAC, 60 Hz	-	0.02-0.03

*ipy = inches per year

There are several interesting observations that can be made from these data. The laboratory corrosion rate of the metal with no voltage applied was 0.003 ipy as computed from linear polarization tests, but was 0.0005 ipy, or an order of magnitude lower as computed from weight loss after 52 days in 400 ohm-cm soil. The original data also showed that the rate would be 0.0003 after 109 days in the same soil. These results point out the limitations that must be appreciated in interpreting laboratory-derived data. The results also show that there was about a 2.5:1 difference in the rate of corrosion between the very corrosive and slightly corrosive soils with no voltage applied. Finally, the weight loss data predict a corrosion rate that is lower, but not significantly so, than the linear polarization data. However, it is important to recognize that the weight loss data represent exposure times of two months or less.

Finally, the weight loss-derived corrosion rates seemed to corroborate the findings of others reported in the literature. If one assumes that direct voltages of the same average amplitude as the ac voltages were applied to the test samples, much higher corrosion rates would be computed. The ac rates in fact would be only 0.5 to 1.5% of the laboratory rates expected from dc exposure. This is consistent with the results reported by others.

Recent laboratory tests performed by other investigators should not be ignored in interpreting the results obtained for Project Sanguine. The highly-regarded work of Bruckner⁽³⁾ is particularly useful and interesting in this instance. Bruckner used many innovative approaches in his experiments, took great care in arranging and conducting his experiments and recognized and identified for the reader the necessary limitations in applying laboratory results to field conditions. For example, the reported experiments were performed with "gradient electrode cells" as well as with direct application of the voltage. That is, a gradient was produced along the length of the test specimen in some tests.

Bruckner observed that the corrosion rates attributable to alternating currents for steel buried in soils of pH between 5.0 and 9.0 were between 0.0005 and 0.019 ipy for current densities between 50 and 500 milliamperes per square inch when the initial current density was maintained throughout the test run. The higher rates corresponded to the higher current densities. The corrosion rates of his controls in these tests were 0.0006 to 0.008 ipy. The controls were immersed in the same media as the exposed samples so that they were exposed to the same temperature rises as the electrically-exposed samples (the test cells were not the induction type in this case). The investigator therefore concluded that the data from the exposed samples represented corrosion due to heating in the laboratory cells as well as to any purely electrical effect. Other experiments were conducted to isolate the corrosion contribution from local heating. The results

of isothermal tests showed that weight loss of the samples due to thermal activation was significant during laboratory tests for ac corrosion, accounting possibly for as much as 50% of the total evident loss.

Bruckner also observed that it was necessary to increase the impressed voltage on his metal samples to maintain desired current densities in the laboratory. The necessary voltage increases often resulted in applied voltages of several hundred volts during the late stages of testing. A series of constant voltage tests was performed in which constant voltage was maintained to obtain data which might represent field corrosion rates more realistically. It was observed that over a period of 5-7 weeks the initial current density was reduced by about 90% for all densities used between 50 and 500 milliamperes per square inch. The computed corrosion rates were only about 1/4 to 1/6 of those calculated for constant current tests.

It seems clear that the laboratory data from Project Sanguine experiments can be interpreted realistically with reasonable confidence by comparing the resulting data with the information from the literature. When this is done, the following statements seem to reasonably summarize the available information:

- a. laboratory ac corrosion rates for bare pipe steel (0.010 to 0.060 ipy between 45 and 75 Hz) are about the same as those reported by others;
- b. estimates of corrosion contributions from residual dc effects and thermal activation during laboratory tests suggest that field ac corrosion rates should not exceed about 0.015 ipy for bare steel pipe;
- c. the 0.015 ipy corrosion rate appears to be a conservative upper limit rate for buried pipelines in which coating perforations might be caused during installation or deterioration after some period of years.

This rate is considered to be conservative, because it represents a condition where a constant current density is required at the perforation of about 500 milliamperes per square inch. Such a high density is a very remote possibility from Sanguine-induced currents for even a short period of time;

- d. the likelihood that inductive coupling between a Sanguine antenna and a nearby coated pipeline or conductive effects from Sanguine terminal grounds could cause punctures in pipe coatings and thereby produce significant localized current densities also is remote.

Experience shows that coating breakdown requires voltages in the order of several tens of thousands of volts.⁽⁴⁻⁵⁾ Such induced voltage levels can be produced by large power transmission faults which result in several thousands of amperes of earth currents, but would not be produced under any likely circumstances by a Sanguine System;

- e. it seems reasonable to conclude that a Sanguine-generated contribution to the ELF electromagnetic environment should not result in any significant risk of advancing corrosion on collocated buried, coated pipelines.

4.3 THE POTENTIAL FOR EQUIPMENT EFFECTS

There is a variety of electrically-operated equipment used for control and monitoring functions on pipeline systems. Much of this equipment is immune to ELF interference voltages produced by power systems, and therefore would not be affected by a Sanguine System either. This is particularly true of communications equipment which might be installed permanently along pipeline routes.

Cathode protection systems probably are the most common electrically-operated devices used with pipelines. Two basic types of systems are used. One type of scheme uses a "sacrificial" anode to maintain the pipe-to-soil potential at a dc level which prevents corrosion from direct currents. The system works on the galvanic couple principal. A metal dissimilar from that used to manufacture the pipe is selected, and some amount of that metal is buried near the installed pipeline. The natural galvanic couple that is formed between the pipe and the selected "anode" then protects the pipe from excessive corrosion.

The second type of cathodic protection system is a rectifier system energized from conveniently-located power lines. This system generally is installed near road crossings. The 60-Hz voltage provided from the commercial power system is full-wave rectified to provide the desired dc bias on the pipeline with respect to earth. The location of the rectifier station and the number of installations along a line depends on local conditions contributing to the inductive coupling.

A general analysis of the sacrificial anode system of pipe protection would provide little information concerning the likelihood of Sanguine interference effects. Each system is designed and installed on an individual case basis to provide a pipe bias of -1.0 volt or less at the installation point. Any system of this type which might be encountered in a Sanguine operating area therefore should be studied separately for possible interference effects.

The externally-powered rectifier system has been studied as a class of device. Typically, the system includes an air-cooled selenium stack, a full-wave bridge, a filter and lightning protection on both the input and output terminals. A maximum of 12 amperes at 24 volts dc generally is available, but only a fraction of this output is usually used. The most likely susceptible device is the selenium stack which can be degraded if the inverse voltage rating is exceeded by more than about 10%. Since this rating usually is 30-40 volts, it is clear that interference effects on cathode protection devices could only occur for rather high pipe-to-soil

potentials. Sanguine-induced pipe-to-soil potentials of such high magnitudes are most unlikely under reasonably-expected situations.

Another class of electrical system often associated with pipelines is the fuel flow telemetry system. This system typically monitors the flow of the fuel in the pipe between some reference point and the consumer via relaying circuits on telephone lines. The balance of the telephone system is sufficient to prevent the high transverse interference voltages required to malfunction the telemetry dc relay (about 25 volts minimum).

4.4 POTENTIAL SAFETY EFFECTS

Electrical safety near pipelines is associated principally with the welfare of construction and repair workmen. Pipelines are almost always coated and buried, or otherwise protected if they are routed above ground level so that they are not accessible to the general public. The pipeline industry has established required practices to ensure worker safety from electrical hazards because of the prevalent routing of pipelines adjacent or within existing power systems rights-of-way.⁽⁶⁻⁸⁾ These practices recognize the various modes by which voltages and currents may be produced on pipelines from transmission line towers, grounds or inductive coupling under both ordinary and fault conditions. These ordinary practices are sufficient to avoid problems in a Sanguine-generated environment, as is discussed in a later section of this report concerned with pipeline interference thresholds.

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3. W. H. Bruckner; The Effects of 60-Cycle Alternating Currents on the Corrosion of Steels and Other Metals Buried in Soils; University of Illinois Engineering Experiment Station Bulletin 470; 1965.
4. B. Favez and J.C. Gougeuil; Contribution to Studies on Problems Resulting from the Proximity of Overhead Lines with Underground Metal Pipelines; Conférence Internationale des Grands Réseaux Electriques a Haute Tension; Paris, June 1966.
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6. F.W. Hewes; Potential Problems on Coated Pipelines Due to Proximity to High Voltage Power Lines; North Central Region Conference of the National Association of Corrosion Engineers; Chicago; September, 1968.
7. A. W. Peabody and A. L. Verhiel; The Effects of High Voltage Alternating Current (HVAC) Transmission Lines on Buried Pipelines; IEEE/IGA Petroleum and Chemical Industry Conferences; Tulsa, Oklahoma; September 1970.
8. E.C. Paver; Effects of Induced Current on a Pipeline; Materials Protection and Performance, Vol. 10, No. 8, pp. 29-31; March 1971.

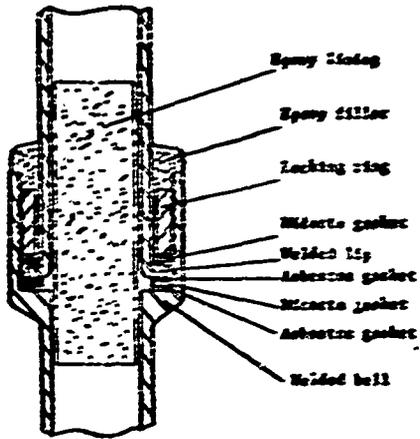
These sections may be as long as several miles.

Insulated joints are used in distribution system piping to separate the systems into areas for cathodic protection purposes. The amount of underground congestion will determine the size of the areas. Insulated areas may be limited to a few square blocks in "downtown" sections, but in outlying sections they may be much larger.

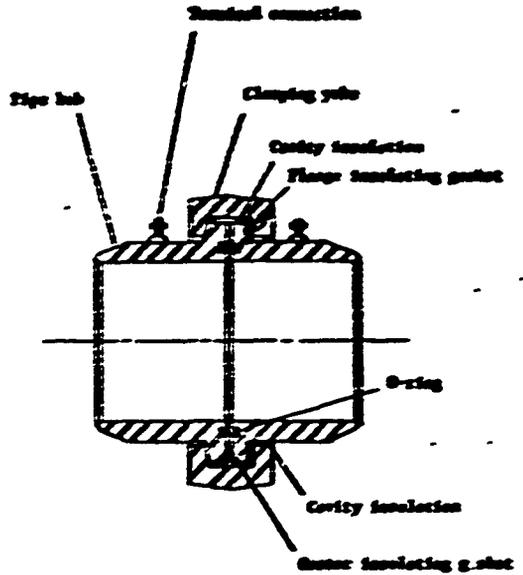
On transmission lines either insulated standard flange assemblies or pre-assembled devices of equivalent strength are used. Distribution mains and large service lines may use insulated flanges, pre-assembled devices, or insulated mechanical joints. Residential size service lines may be insulated at the meter with devices such as insulating bushings, unions, meter bars, or meters with insulating swivels. Service insulation at the main, if necessary, may utilize insulating main tapping fittings, bushings, or mechanical couplings. Some examples of the various devices are shown in Figure 5-1.

There are some disadvantages to using insulating devices in some cases. Since the device is an additional component in the system, it represents a potential problem source such as a leak or failure point. The installation of the device during the construction of a line is relatively simple and is not costly. However, the cost and interruption of service to consumers may be prohibitive for installing an insulation device in an existing in-service line. For example, the total cost of installation on a 6-inch diameter distribution line is about \$1600 before the line is in service; the cost on a line in which service is maintained by a temporary by-pass is more than \$5000. Respective costs on a 36-inch diameter transmission pipeline are \$7000 and \$50,000.

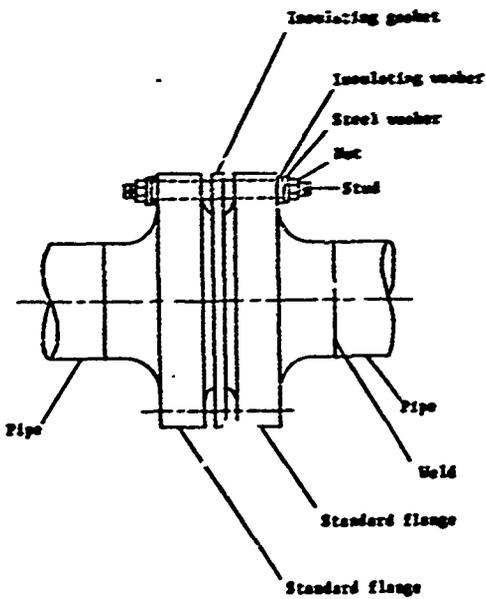
The purpose of the insulating joint in mitigating interference effects on pipelines from power systems or a Sanguine antenna is to reduce the electrical length of the pipeline exposed to the interference source. A given situation must be analyzed carefully,



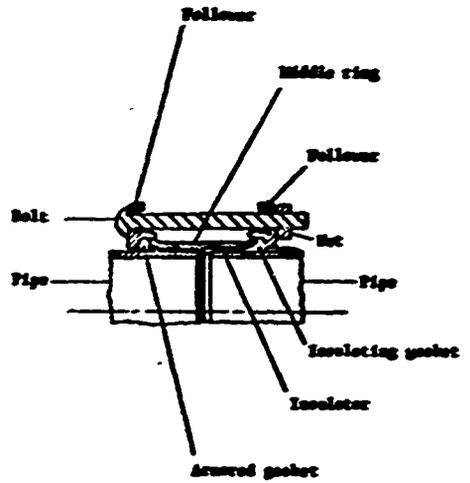
INSULATED JOINT



INSULATED JOINT



INSULATED FLANGE ASSEMBLY



INSULATING COUPLING

FIGURE 5-1 SOME EXAMPLES OF INSULATING DEVICES FOR PIPELINES

however, because reducing the length of exposure can increase rather than reduce the overall effective coupling to the pipe. An example is useful in illustrating the undesirable change that can occur.

Consider an 80-mile long pipeline exposed to a parallel ELF current source that produces a uniform electric field intensity of 10 volts per mile along the pipeline route. The expected induced voltage (the pipe-to-soil potential) along the pipe, as computed from the transmission line equation, is plotted in Figure 5-2. The maximum induced voltage is about 24 volts to ground, appears near the ends of the pipeline, and there is at least 8 volts to ground along the last 3.2 miles from either end (8% of the total length) of the pipe. If an insulating joint was inserted at the midpoint of the pipe to reduce the induced voltage, the characteristic on each of the two pipe sections would be that shown for the 40-mile curve. The maximum voltage remains at about 24 volts to ground, but now appears at four points on the pipe (the four end points) instead of two. Furthermore, there is now 8 volts or more on 16% of the line (12.8 miles) rather than on 8% of the line. As shown in Figure 5-2, adding more insulating joints may produce more intense coupling rather than contribute to a solution.

The example illustrated here shows that it is important to consider the distribution of pipe-to-soil potentials as well as maximum amplitudes. As discussed in the next section of this report, it may be preferable when selecting an interference threshold for induced voltages on pipelines to use the voltage distribution rather than the maximum amplitude as the governing criterion.

5.3 PIPELINE EXTENSIONS

The overall increase in pipe-to-soil potentials along a pipeline as the electrical length was reduced with insulating joints (Figure 5-2) suggests that the voltage can be reduced in some places by extending the length of the pipeline. While there are obvious limitations to this technique in practice, it is worth some attention. The advantage is that maximum voltages to ground can be transferred from a functional section of a pipeline

PIPE-TO-SOIL POTENTIAL, RMS VOLTS

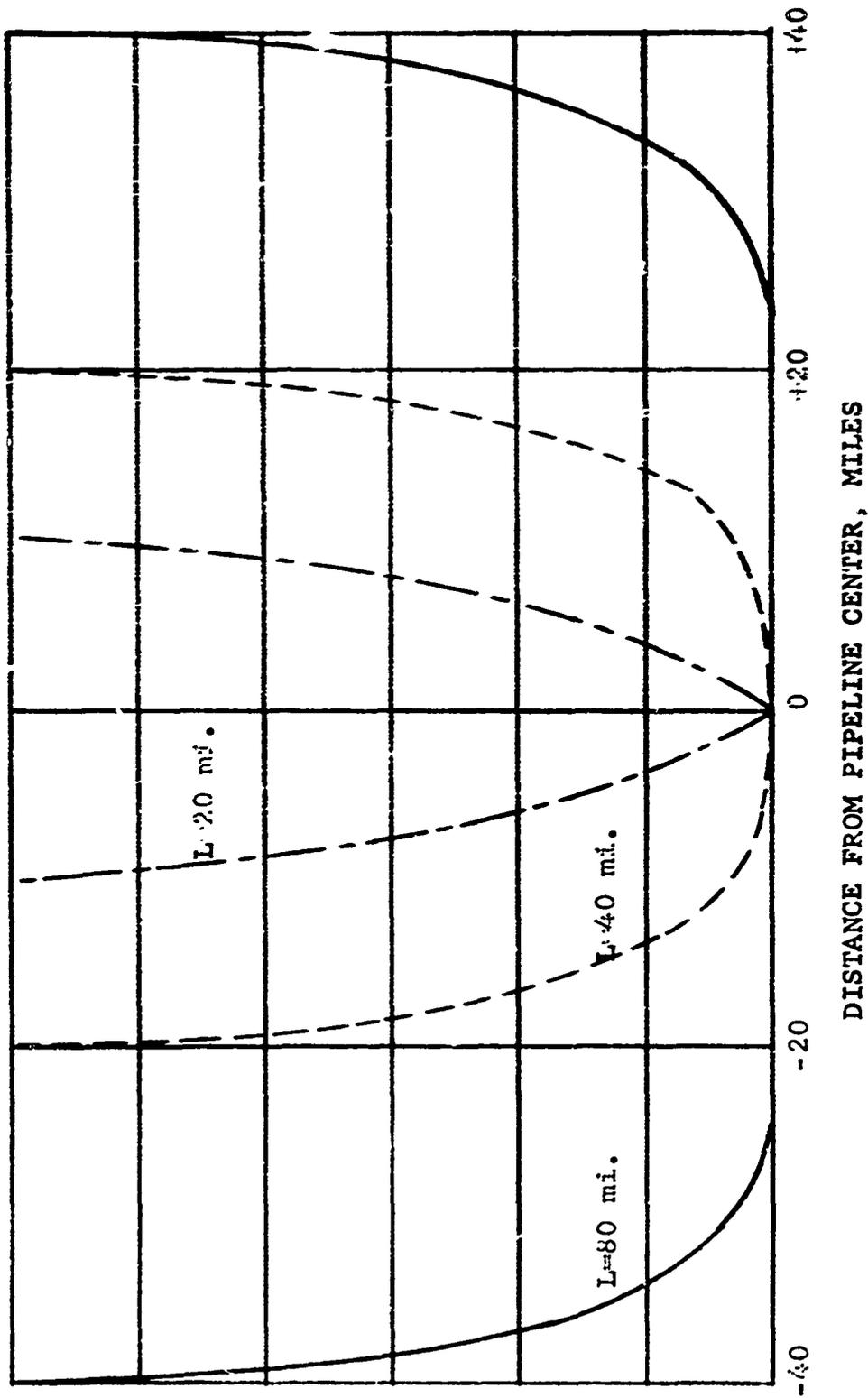


FIGURE 5-2 INDUCED VOLTAGE ON A PARALLEL BURIED PIPE AS A FUNCTION OF LENGTH IN A UNIFORM ELECTRIC FIELD OF 10 VOLTS PER MILE

to a nonfunctioning portion. It is conceivable that the technique could be preferred in some cases where mitigation might be required on a large, in-service line. Favez and Gougeuil have considered this technique in considerable analytical detail,⁽¹⁾ and Pohl⁽²⁾ also has tabulated his analytical results to illustrate the effectiveness of the pipe extension theory in reducing the effects of pipe-to-soil potentials by changing the distribution of the voltage along the line.

5.4 PARALLEL GUARD WIRES

Favez and Gougeuil observed during their analysis of coupling between high voltage transmission lines and buried pipelines that the presence of a grounded neutral wire was effective in reducing the coupling between the two systems. This being the case, an experiment was performed to illustrate the reduction in coupling that might occur if a bare wire was buried near to and parallel with a pipeline. The guard wire was expected to provide shielding for the pipe, the attenuation being a function of the mutual inductance between the wire and the pipe and the resistance to ground of the wire. Attenuation would increase with higher mutual inductance and lower ground resistance.

The experiments showed that the guard wire provided about 6 dB reduction in coupling between a high voltage transmission line and the pipeline. An additional reduction was achieved when the guard wire was connected to the pipeline. The connection was made through spark gap devices to prevent upsetting the cathodic protection system installed on the pipe. The reduction attributable to connecting the wire to the pipe was about an additional 10%.

5.5 SOIL CHEMISTRY CHANGES

Bruckner⁽³⁾ among others who have conducted corrosion experiments under simulated soil conditions in the laboratory, has shown that the constituents of the soil are important in determining the corrosion rate of pipe steel. The chemical, bacteriological and oxidative constituents contribute to corrosion to some degree. The chemical nature of the soil near a pipeline can be changed to

reduce ac corrosion. The absence of bicarbonate ion provides a significant reduction in the corrosion rate of steel. Any change in the soil chemistry should be localized to the vicinity of the pipe to prevent other undesirable environmental side effects.

5.6 INTERFERENCE AS A PROTECTION SOURCE

Cathodic protection of pipelines to prevent corrosion due to direct currents in the earth is a standard practice in the pipeline industry. The literature suggests that the principle of cathodic protection was recognized as early as 1891,⁽⁴⁾ and practical approaches for pipeline protection were well-developed between 1905 and 1920.⁽⁵⁻⁷⁾ Recently it has been suggested by a number of practitioners that ac-induced voltages can be used to provide corrosion protection, and several experiments have been reported in the literature to demonstrate the practicality of the suggestion.

Bruckner performed his tests in the laboratory with a sacrificial anode of magnesium. The rectified ac from the anode provided cathodic protection as long as the ac current density did not exceed a value which caused polarity reversal between the magnesium electrode and the pipe steel. A reversal in polarity would result in upsetting the original dc circuit formed by the galvanic couple and accelerate rather than inhibit corrosion. The current density depended upon a variety of test conditions. The experiment was successful in showing that ac interference could be used, within certain limits, to develop the dc bias required to protect a pipeline from electrically-accelerated corrosion.

Paver⁽⁸⁾ reports that voltages to ground between 2 and 26 volts were measured along a 36-inch pipeline in Illinois. A magnesium anode ground bed was constructed near the pipeline and connection was made to the pipe through a diode bank. The system was effective in protecting 12 miles of pipe for about 4 years.

Newly constructed power transmission lines and substations then changed the character of the area, and the protection system had to be changed to a rectifier system.

The laboratory and field experiments reported in the literature suggest that existing cathodic protection can be used to advantage in controlling ac-induced corrosion as long as the ac current density does not exceed about 25 milliamperes per square inch. For most pipelines this density is not exceeded for induced pipe-to-soil potentials in the order of 50 to 60 volts.

Another instance of converting alternating interference voltage to direct current cathodic protection by rectification has been reported by Bellassai.⁹ An ac pipe-to-soil potential of 8.5 volts was observed on a pipeline located in a salt marsh in New Jersey. Field experiments and computations were made that indicated the available interference voltage could be used to provide about 3 volts of cathodic protection voltage. A rectifier stack (5 amps, 15 volts dc rating) was connected between the pipe and a ground bed consisting of interconnected graphite ground rods. Ten rods, each 3 inches in diameter and 60 inches long, were spaced at 24-foot intervals and connected together with 1/0 copper cable to construct the ground bed. The measured rectified voltage was 2.8 volts. The rectifier station was reported to be operating according to specification after 18 months.

5.7 MITIGATION NEAR GROUND TERMINALS

Voltage differences between a pipeline and earth caused by increases in earth potential from ground terminals can be minimized most easily by separating the pipeline from the ground terminal as much as possible. Attaining maximum (and sufficient) separation clearly has its limitations in practice, and the utilities have studied alternative methods for reducing this type of interference to pipelines.

Favez and Gougeul provide a detailed mathematical model

for determining the minimum separation between a pipeline and various types of power system grounding arrangements. As an extension of this work, these investigators considered several alternatives when minimum separation cannot be attained. One alternative is to modify the potential distribution in the vicinity of the ground terminal. This can be done by constructing asymmetrical grounding arrangements to reduce the potential near the pipeline. Another method is to bury a sufficiently long bare low impedance conductor near the terminal ground to localize the otherwise distant equipotential lines. Model experiments indicated that practical reductions in earth potential rise of about one-third should be obtainable.

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SECTION 6

MEASURED INDUCED VOLTAGES

6.1 REPORTS FROM THE LITERATURE

Several recent reports provide some insight regarding the magnitudes of ac voltages induced on pipelines from commercial power systems. This information is helpful in understanding the likely impact of a Sanguine System on nearby pipelines and in developing an interference threshold criterion for Sanguine-induced voltages.

Measurements in Germany⁽¹⁾ during 1963-64 indicated that voltages to ground as high as 40 volts at 50 Hz existed on pipelines which were parallel for several kilometers to transmission lines of 220 and 380 KV. The voltages were highest near the ends of the pipeline, and were the magnitudes observed under normal operating conditions of the power lines. In another investigation measured voltages on older pipelines under ordinary power line conditions were extrapolated to show that up to 125 volts might be expected under conditions of full power line capacity (unfaulted).

Measurements were made in France⁽²⁾ on a 700-mm diameter gas pipeline which was close to and essentially parallel to a 150 KV line for a distance of about 8 kilometers. The power line was not equipped with a returned neutral, but one of the phase conductors was used in this manner during the reported investigations. The results showed that the distributed pipe-to-soil potentials were between 60 and 250 volts (per 1000 amperes of short-circuit current) without the returned neutral and were 40 to 190 volts (per 1000 amperes) when the synthesized neutral wire was used. The pipe was electrically continuous beyond the exposure to the power line and on the average the distance between the pipe and the line was about 150 meters. The power line frequency was 50 Hz. Voltages in excess of 400 volts were observed when the pipeline was terminated at one end within the span of

the power line exposure. These results compared very well with theory, which predicts more coupling when the interference source is not equipped with a return wire and when the pipeline is not continuous beyond the span of parallel exposure.

A measurement of 60 volts to ground was recorded in California⁽³⁾ where a power line and a pipeline crossed after a parallel exposure of 40 to 50 miles. The power line was rated at 250 KV. Levels of 20 to 30 volts were reported on pipelines which were parallel to other 210 and 250 KV lines.

As discussed in Section 5 of this report, the Northern Illinois Gas Company has measured 60 Hz voltages to ground of 2 to 26 volts along a 36-inch diameter pipeline.

5.2 MEASURED VOLTAGES ON WISCONSIN PIPELINES

Figure 1-1 showed an area in Wisconsin that is one of several candidate areas for an operational Sanguine System. The area exhibits many characteristics that make it the preferable candidate Sanguine site on purely technical grounds. Several pipelines in or near this area were selected for field study, the purpose being to describe the existing 60-Hz induced voltages on those lines, to compare the measured data on a qualitative basis with expected 60-Hz levels, and to obtain information from which Sanguine interference thresholds could be derived.

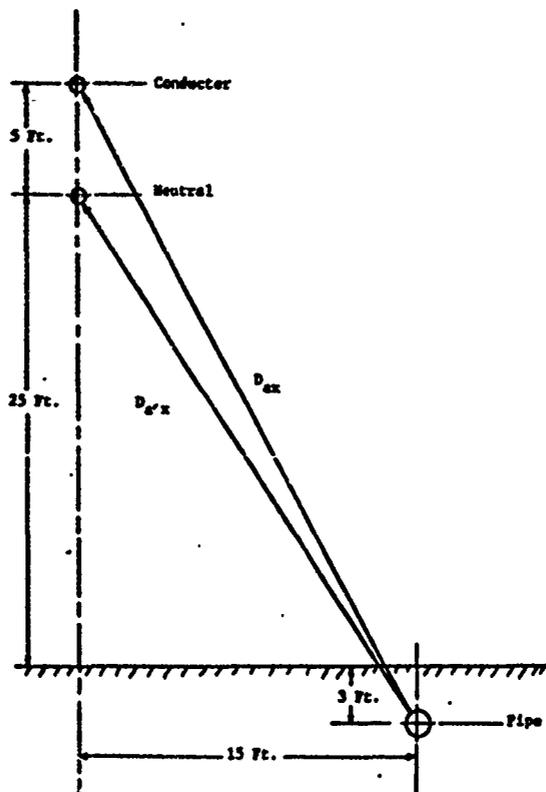
It is instructive to consider the nature of the Wisconsin area as regards pipeline induced voltages prior to presenting and discussing measured data. The literature referred to in several previous sections of this report indicates that substantial voltages might be expected on pipelines that are parallel and close to high capacity power transmission lines. A study of the Wisconsin area shows that the three pipelines available for study generally are not exposed in this way. There is some exposure to transmission lines of lower rating (less than 150 KV in most cases), and parallel situations do not exist for more than several miles in any one place. Therefore, voltages induced on the pipelines were not expected to be very high compared with some measures reported in the literature.

The Wisconsin pipelines are exposed to many power distribution lines, most of which are the single phase, multigrounded neutral type. The grounded neutral current in this type of system is often significant, and therefore it should be expected that these circuits would contribute measurable induced voltages if they were close to pipelines. This would be particularly true if power system pole grounds were located near to the pipe. Some numerical examples are helpful in illustrating these expectations. For convenience, the examples provided by Peabody and Verheil⁽⁴⁾ are used for this purpose.

The illustration and accompanying equations in Figure 6-1 can be used to compute the induced voltage on a pipeline from a single phase power line. If the load current is 30 amperes the line with the ungrounded neutral will induce only 0.5 volt per mile on the pipeline. The induced voltage from the same current in the line when the neutral wire is grounded is 20 volts per mile. The soil resistivity is assumed to be 10^3 ohm-meters in these computations.

Figure 6-2 provides the illustration and equations for computing the induced voltage on the pipeline from a three-phase power line. A reasonable assumption for the zero-sequence current for the line without the neutral is 10 amperes. The induced voltage on the pipeline is 18 volts per mile for a soil resistivity of 10^3 ohm-meters or almost the same as that produced by the grounded neutral single phase line conducting 30 amperes. If the three phase line is operated with a neutral so that there is some earth return, the phase wire current is important. If the current is 250 amperes the induced voltage would be 13 volts per mile of exposure.

The equations used in the numerical examples are conservative approximations for idealized conditions. Actual voltages would undoubtedly be substantially smaller than computed magnitudes. The examples are sufficient, however, to illustrate that measurable voltages should be expected in the field, and that actual amplitudes



Single Phase Line with Metallic Neutral

$$V_x = j.2794 \left(\frac{f}{60}\right) I_a \log_{10} \frac{D_{a'x}}{D_{ax}} \text{ volts}$$

V_x = Induced Voltage per mile

f = System frequency (assumed to be 60 Hz)

I_a = Phase Current in amperes rms

D_{ax} = Distance from conductor to pipe line

$D_{a'x}$ = Distance from neutral to pipe line

Single Phase Line with Earth Return

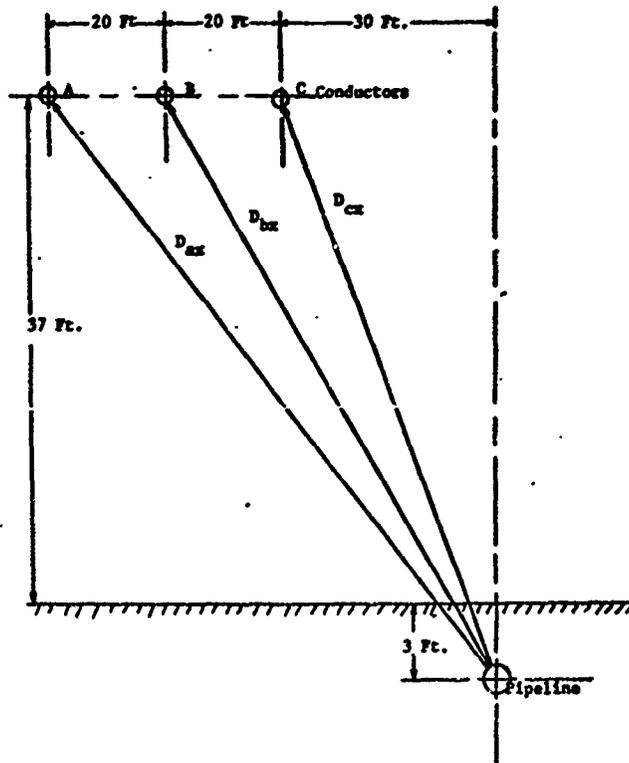
$$V_x = I_a \left(\frac{f}{60}\right) \left[.0954 + j.2794 \log_{10} \frac{D_{ex}}{D_{ax}} \right] \text{ volts}$$

in which D_{ex} is the distance of the return current in the earth to the pipe line. D_e is the equivalent depth of the earth return current below the outgoing conductor and can be determined from:

$$D_e = 216 \sqrt{\frac{\rho}{f}} \text{ feet}$$

in which ρ is the soil resistivity in ohm-cm.

FIGURE 6-1 ILLUSTRATION FOR COMPUTING INDUCED VOLTAGE ON A PIPELINE FROM A SINGLE PHASE POWER LINE



Three Phase Line without Neutral

$$V_x = I_o \left[.286 \left(\frac{f}{60}\right) + j.8382 \left(\frac{f}{60}\right) \log_{10} \frac{D_{ex}}{\sqrt[3]{D_{ax} D_{bx} D_{cx}}} \right] \text{ volts}$$

in which I_o is the zero sequence current.

Three Phase Line with Partial Earth Return

$$V_x = .286 \left(\frac{f}{60}\right) I_o + j.2794 \left(\frac{f}{60}\right) \left[I_a \log_{10} \frac{D_{ex}}{D_{ax}} + I_b \log_{10} \frac{D_{ex}}{D_{bx}} + I_c \log_{10} \frac{D_{ex}}{D_{cx}} \right] \text{ volts}$$

in which D_{ex} is the same parameter as in Figure 6-1.

FIGURE 6-2 ILLUSTRATION FOR COMPUTING INDUCED VOLTAGE ON A PIPELINE FROM A THREE PHASE POWER LINE

will depend on the type of power system that is near the pipeline as well as the distance between the systems.

It is impractical to attempt to predict the expected induced voltages on pipelines exposed to many power lines with various orientations to the pipes. However, one can reasonably expect to observe certain trends to be evident in measured data obtained in some area of interest. For the candidate Sanguine site in Wisconsin for example, the following was expected:

- a. the highest induced voltages were expected on the pipeline along the southern fringe of the area and the southern portion of the line through the eastern part of the area;
- b. the lowest voltages were expected to appear on the northern portion of the pipelines in the eastern part of the area and the western fringe of the area;
- c. maximum voltage amplitudes were expected near pipeline terminations and other places where power system grounds were located;
- d. induced voltages were expected to be between about 0.01 volt and 10 volts maximum at 60 Hz.

The expected areas of highest induced voltages were based first on the locations of highest social activity, since these areas generally represent centers for significant power system loads. Population centers in the Wisconsin area of interest generally are located along State Highway 13 from Park Falls south, along U.S. Highway 8, and along State Highway 29 between Eau Claire and Wausau. The Williams Brothers pipeline between Eau Claire and Wausau has a diameter of 8 inches, while the Northern Natural Pipeline diameter is 10 inches north of Park Falls and 4 inches to the south. The Lakehead pipeline diameter is 34 inches. Therefore one might expect the trends indicated in (a) above for these conditions.

The northern portion of the Wisconsin area is sparsely populated, and much of the area is classified as National Forest. The population

density on the western side (near the 34-inch line) is less than that along Highway 13 in the east. These conditions suggest the trends noted in (b) above even though the Lakehead pipeline diameter is much larger than that of the Northern Natural Line.

Pipeline terminations such as insulated joints generally are found near population centers where electrical loads are greatest. This is the basis for expecting higher voltages near these places than along the line between population centers. An exception to this trend might be expected at the northern end of the Northern Natural line. The line terminates in an isolated area of the Bad River Indian Reservation where few electrical loads are located.

The expected voltage amplitudes were estimated from the reported measured voltages by others along pipelines severely exposed to high voltage transmission lines, and computed values such as those discussed on previous pages.

Voltages induced on the Northern Natural Rib Lake pipeline by nearby power systems were measured during the summer of 1971. The voltages were measured at the operating frequency of 60 Hz, and the second (120 Hz) and third (180 Hz) harmonics of the power system frequency. Similar measurements were made on the Lakehead line and the Williams Brothers line (refer to Figure 1-1) during the 1972 summer season. The measurements were made at road crossings and other convenient places where the pipelines were equipped with vent pipes and voltage terminal blocks for monitoring dc pipe-to-soil potentials. Voltage was measured between the terminal block and a 0.5-inch copper-clad (4-foot long) grounding rod with a high impedance electronic voltmeter. The voltmeter was calibrated and tuned to the frequency of interest in each case. The voltage across the two pipeline terminals also was measured with the voltmeter at each location. A typical test arrangement is illustrated in Figure 6-3.

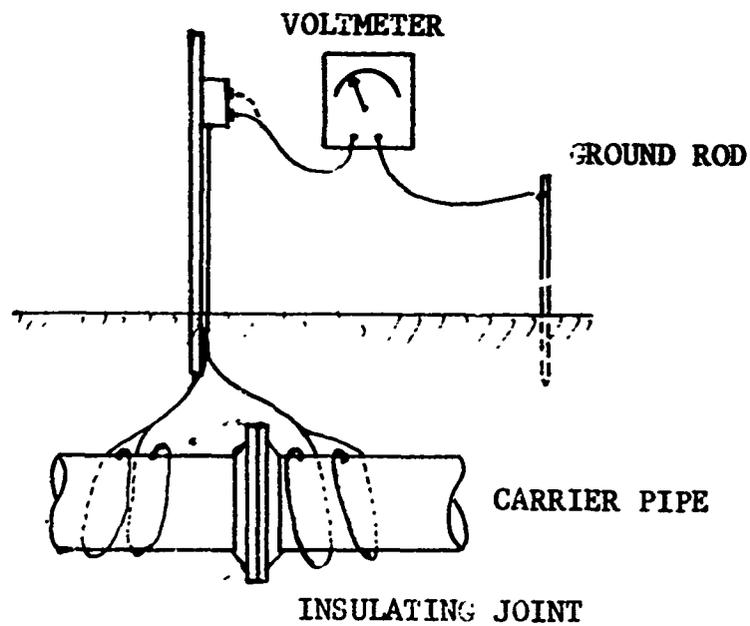
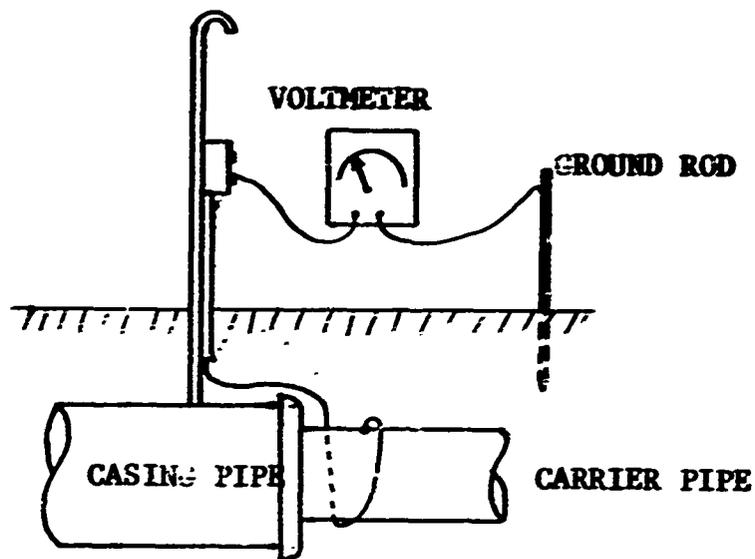


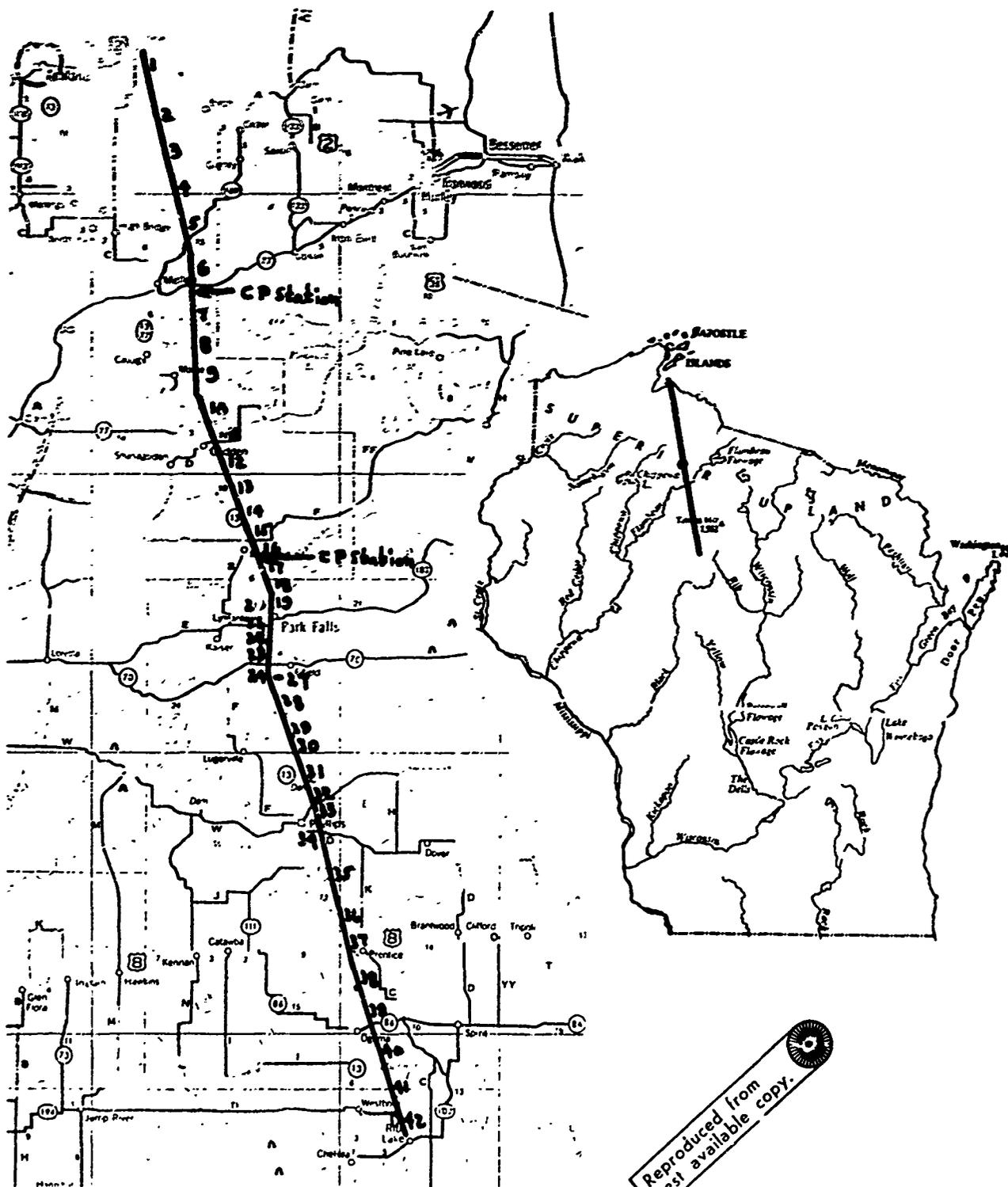
FIGURE 6-3 TYPICAL MEASUREMENT ARRANGEMENTS AT PIPELINE TEST POINTS

The approximate route of the Northern Natural pipeline between Odanah and Rib Lake is shown in Figure 6-4. The measurement locations are indicated on the map. The pipe-to-soil potentials measured at 60 Hz at these locations are listed in Table 6-1, and an envelope of the observations is plotted in Figure 6-5.

A study of the data listed in the table and illustrated in the graph shows that the results observed along the pipeline are consistent with expectations. With only two exceptions, the voltages observed north of Park Falls (locations 1-22) were less than one volt. The exceptions were near a cathode protection station near the Village of Butternut. There is a small electric substation in the vicinity. Most of the power distribution lines along this portion of the pipeline are either 7.2 KV or 12.4 KV, and the few transmission lines appeared to be 33 KV. In any event, there are few parallel exposures of significant length in the vicinity.

Commencing near Park Falls and continuing to about Prentice the pipeline is relatively close to and often parallel to a 33 KV power transmission line. The lines cross several times, and in some places the rights of way are adjacent. There are several power substations near the pipeline, and electrical loads on the power lines are probably quite variable and substantial. There is significant industrial activity along Highway 13 in this area. The data from the pipeline would seem to reflect these circumstances. The highest pipe-to-soil potentials were observed along this portion of the line. The measured voltages varied between 1.2 and 6.3 volts, rms (locations 23-36). The pipeline and the transmission line cross on a diagonal, incidentally, between locations 27 and 28, where the highest voltages were measured.

The voltages between the pipe and earth were lower between Prentice and the terminating town border station near Rib Lake, but were not as low as those measured along the northern end of the line. The amplitudes suggest the type of activity evident in this region.



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FIGURE 6-4 LOCATION OF MEASUREMENT POINTS ALONG THE NORTHERN NATURAL GAS PIPELINE

Table 6-1 MEASURED 60-HZ PIPE-TO-SOIL POTENTIALS ALONG THE NORTHERN NATURAL PIPELINE BETWEEN ODANAH AND RIB LAKE (REF: FIGURE 6-4)

<u>Test Point</u>	<u>P-S-P (rms)</u>	<u>Test Point</u>	<u>P-S-P (rms)</u>
1	No Data	22	0.300 Volt
2	0.230 Volt	23	2.80
3	No Data	24	1.25
4	No Data	25	3.50
5	0.053 Volt	26	4.50
6	0.070	27	6.30
7	0.360	28	6.00
8	0.145	29	4.60
9	0.054	30	4.50
10	0.220	31	2.15
11	0.001	32	5.90
12	0.240	33	6.20
13	0.590	34	4.20
14	0.160	35	3.00
15	0.125	36	2.80
16	0.400	37	0.890
17	1.90	38	0.820
18	0.950	39	0.730
19	1.40	40	1.40
20	0.650	41	2.00
21	0.640	42	1.10

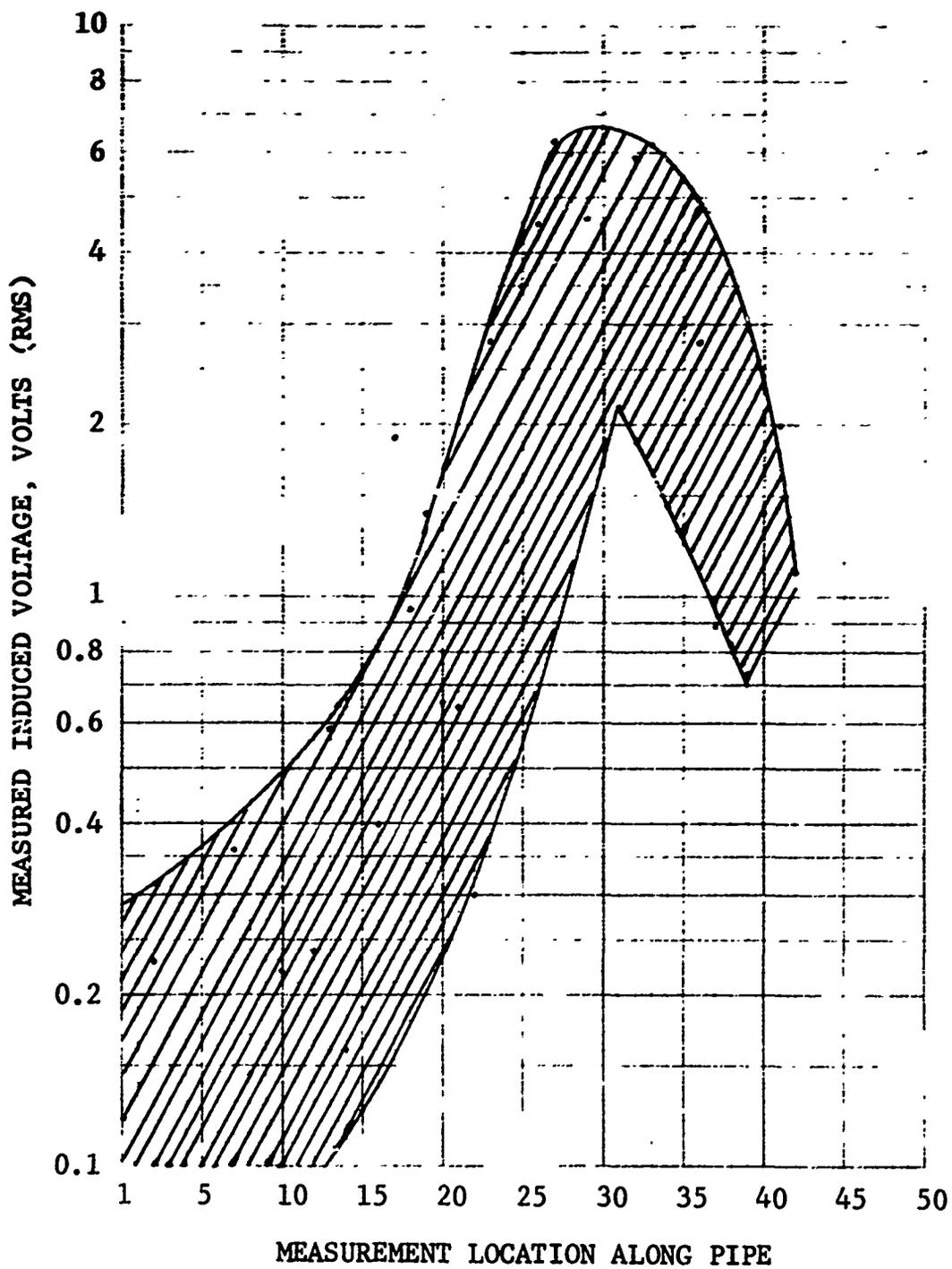


FIGURE 6-5 ENVELOPE OF MEASURED INDUCED VOLTAGES
ALONG THE NORTHERN NATURAL PIPELINE

The voltages measured along the northern portion of the Lakehead 34-inch line between Superior and Vesper were expected to approximate those measured on the northern segment of the Rib Lake Branch of the Northern Natural Line. The voltages to the South of about Hayward were expected to be about the same, and possibly somewhat lower than those along the southern segment of the Rib Lake Branch. The reasons for expecting these kinds of voltages were stated previously. Thus, not as many locations were selected for measurement along the Lakehead line since it was felt that the induced 60-Hz voltages could be characterized quite well from a few measurements and the experience on the Northern Natural Line.

The data collection points used during 1972 on the Lakehead Line are shown in Figure 6-6, and the measurements at 60-Hz are listed in Table 6-2. The data are not graphically illustrated because there is not sufficient information for a meaningful envelope.

The measured 60-Hz voltages listed in Table 6-2 show that the voltages on the Lakehead Line were between 0.1 and 1.0 volt as expected. These levels are comparable to voltages measured on the northern portion of the Northern Natural pipeline, also as expected. The measurement at Location 6 was considerably higher, and no likely reason was evident. The very low level at Location 8 was not surprising, since no power line was evident in the vicinity. The higher level at Location 9 was not surprising, since a single phase power line from the nearby village terminated near the pipe, and the voltage on the pipe should be higher for this reason along. A pole ground near the pipe at location 11 is likewise viewed as the principal contribution to the level measured at that point.

The approximate location of the Williams Brothers pipeline between Bateman and Rothchild (near Eau Claire and Wausau, respectively) is shown in Figure 6-7. The measured 60-Hz data obtained in 1972 are listed in Table 6-3.

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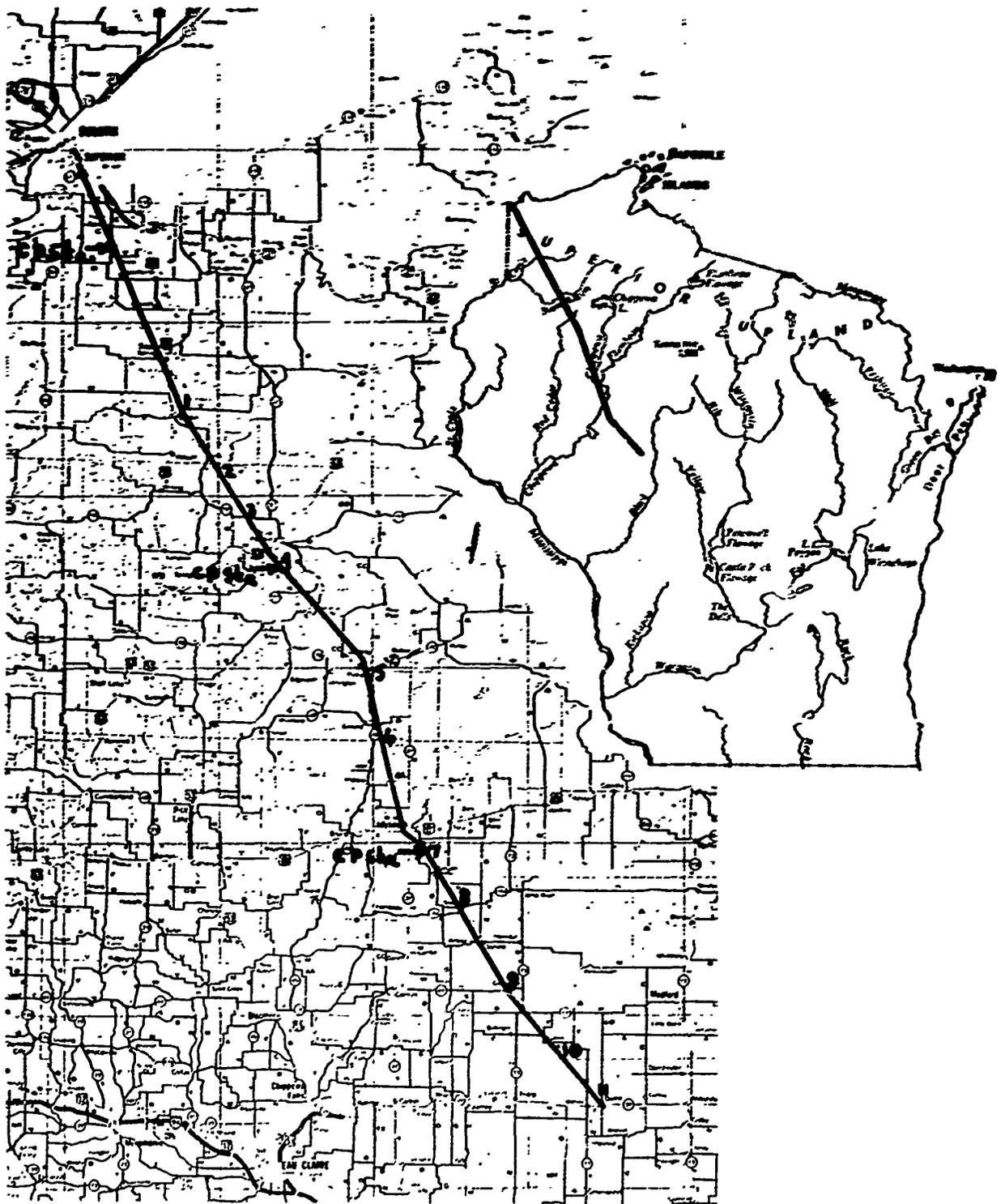


FIGURE 6-6 LOCATION OF MEASUREMENT POINTS ALONG THE LAKEHEAD PIPELINE

**Table 6-2 Measured 60-Hz Pipe-To-Soil Potentials Along
The Lakehead Pipeline Between Gordon and Owen**

<u>Test Point</u>	<u>P-S-P (rms)</u>
1	0.490 volt
2	0.083
3	0.245
4	0.100
5	0.280
6	1.30
7	0.280
8	0.007
9	2.60
10	0.500
11	1.30

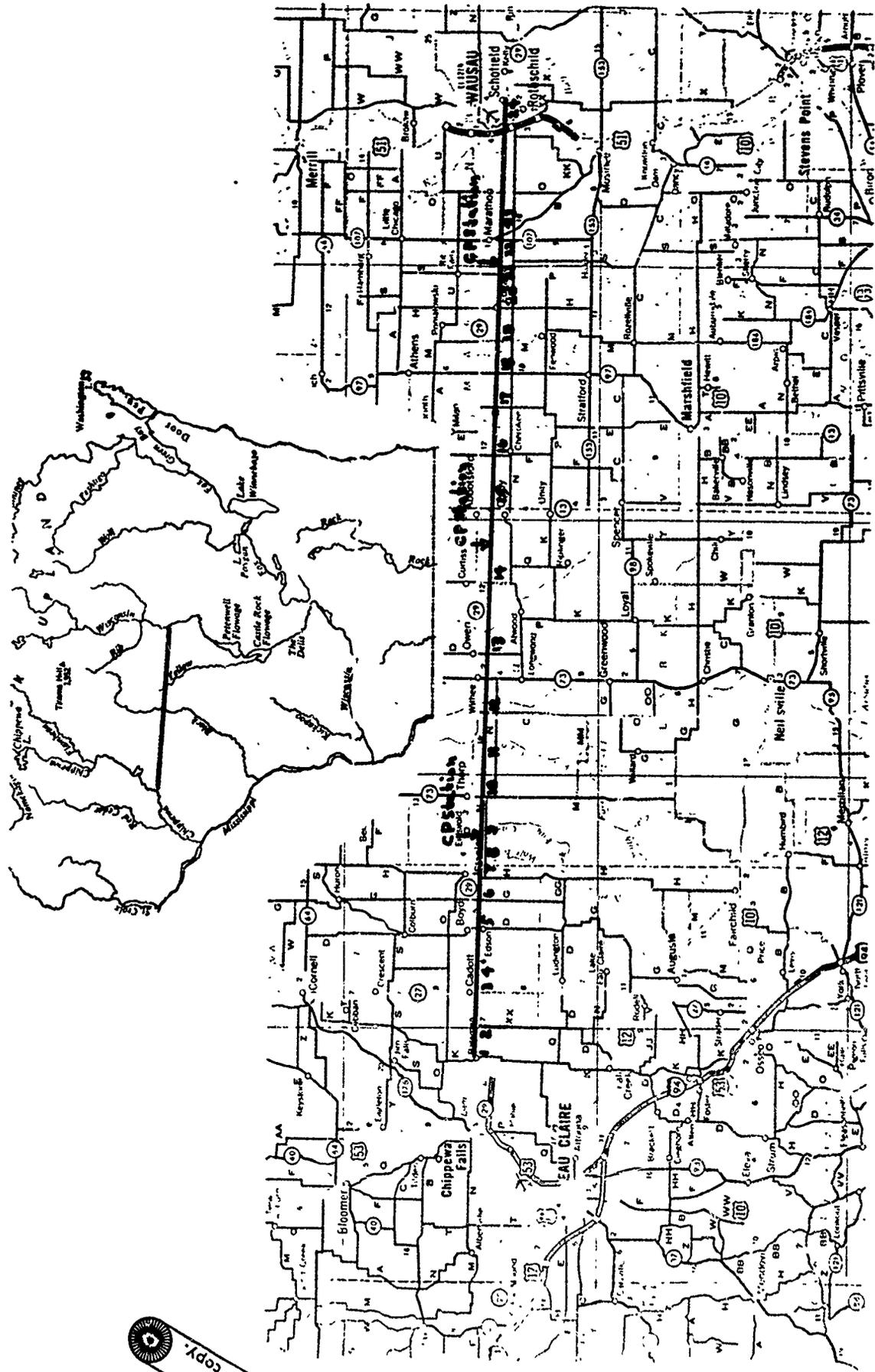


FIGURE 6-7 LOCATION OF MEASUREMENT POINTS ALONG THE WILLIAMS BROTHERS PIPELINE

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Table 6-3 Measured 60-Hz Pipe-To-Soil Potentials Along The
Williams Brothers Pipeline Between Bateman And
Rothschild

<u>Test Point</u>	<u>P-S-P (rms)</u>	<u>Test Point</u>	<u>P-S-P (rms)</u>
1	3.10 volts	13	1.30 Volts
2	11.00	14	3.30
3	1.20	15	1.10
4	2.30	16	2.20
5	3.20	17	3.50
6	2.30	18	6.00
7	1.65	19	7.40
8	1.10	20	3.50
9	2.35	21	3.10
10	5.90	22	0.19
11	1.10	23	4.20
12	4.00	24	0.56

The measured voltages clearly illustrate effects which should be expected when a pipeline is exposed to many identifiable (but not totally definable) power lines. The voltages to ground generally were in the 1-10 volt range, as expected. The pipeline is close to a parallel 69 KV power transmission line along much of the observed route. The power line crosses the pipeline on a diagonal between Locations 7 and 8, being south of the pipeline to the west and north of the line to the east. The angle between the lines on crossing is small. The pipeline is crossed by power distribution circuits at right angles at almost every road crossing in the north-south direction. Most of these circuits are 7.2 KV lines with multigrounded neutral wires. In summary, the amplitudes of the measured voltages are in the range of expectation, and illustrate effects of exposure to many widely-dispersed power lines and close proximity to a power transmission line.

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1. J. Pohl; Influence of High-Voltage Overhead Lines on Covered Pipelines; Conférence Internationale des Grands Réseaux Électriques à Haute Tension; Paris; June 1966.
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SECTION 7

RECOMMENDED INTERFERENCE THRESHOLDS

7.1 THRESHOLDS FOR PIPELINE EQUIPMENT

While there is a variety of communications and other types of monitoring equipment that might be used along pipelines, the most common device to be expected is the cathode protector. A single interference threshold is unnecessary for other equipment, since the sensitivity of such devices to electromagnetic interference depends upon operating and design characteristics. It is not difficult to analyze these characteristics to determine whether interference effects are likely; therefore, it is recommended that no interference threshold be adopted as applicable to pipeline-associated monitoring devices. Instead, it is believed preferable to perform an engineering analysis for each case of equipment exposure which might be encountered in a Sanguine operating area. Other studies performed to evaluate the total environmental impact of a Sanguine System show that ELF interference is an unlikely problem except for power and telephone lines, and occasional situations are best handled on a case-by-case basis. In any event, any necessary interference mitigation would not represent a significant economic or system impact for either the government or pipeline operators.

Cathode protection devices operate on the rectification principle. The types of rectifiers used along pipelines generally are rated at about 24 volts dc output. The inverse voltage rating is usually about 30 to 40 volts, and rectifiers can withstand over voltages of at least 10 percent without damage. The inverse rating is much higher than the 200-400 millivolt Sanguine interference threshold for power service lines, and therefore interference from a Sanguine System to powerline-fed cathode protection devices should not be expected.

A 30-volt interference threshold at the terminals of the rectifier unit is recommended for cathode protection systems which use a sacrificial anode. This level will not exceed the inverse voltage rating of most rectifiers, and therefore will not damage the unit. The threshold should be lowered in any case where the rating of the installation is less than 30 volts. It is not expected that 30 volts would appear at rectifier terminals from a Sanguine System.

7.2 THRESHOLDS FOR CORROSION PROTECTION

As discussed in Section 4 of this report, a study of the literature and laboratory investigations indicate that significant corrosion attributable to ac-induced voltages from a Sanguine System or ordinary 60-Hz power lines is not expected on coated pipelines. Extrapolating laboratory-derived data to the field suggests that an upper limit of 30 volts of Sanguine-induced voltage on a buried, coated pipeline should not cause corrosion problems in most soils. It is therefore recommended that a 30-volt limit be suggested to pipeline operators as the level at which additional analysis and testing (if necessary) be performed to ascertain whether interference mitigation techniques should be considered.

7.3 THRESHOLDS FOR SAFETY

The third interference concern for pipeline systems is worker safety. Expected leakage currents for given pipeline coatings were presented previously in Figure 3-3. Coating of resistance between 20,000 and 300,000 ohms per square foot represent the range of values typically used in practice. A resistance of 10,000 ohms per square foot is regarded as a good estimate for an uncoated pipe several years after installation. Present practice is to avoid burying bare pipe. Study of Figure 3-3 shows that a pipe-to-soil potential of 10 volts on a 10-inch diameter pipe with 20,000 ohms per square foot coating produces a leakage current of 3 milliamperes per square foot. Higher quality coatings produce less current with even higher pipe-to-soil potentials.

Other studies conducted for Project Sanguine environmental impact assessment refer to the scientific literature which cites a current of 9 milliamperes as the let-go level for 99.5 percent of the adult male population. Using this figure, a conservative induced voltage-to-ground threshold for pipelines is 30 volts on a 10-inch pipe. This threshold would produce less than 9 milliamperes on larger diameter pipes (see Figure 3-3), but somewhat more current for smaller pipes with poor coating. The latter situation would probably be rarely encountered and the threshold could be reduced if necessary.

Another method for determining a conservative safe voltage threshold can be used. The maximum induced voltage from a Sanguine System can be computed from the equation ¹

$$E_{\max} = I_s (R_B + R_C + R_W) \text{ volts}$$

where in this case

I_s = the safe current level, given as 5 milliamperes in Reference 1

R_B = the body resistance, given as a minimum value of 800 ohms in Section C11.5 of Reference 1

R_C = the earth/body contact resistance, estimated as 9,100 ohms

R_W = resistance of the pipe being contacted, and assumed to be zero.

Then for worker safety:

$$E_{\max} = 5 \times 10^{-3} (9.9 \times 10^3)$$

$$E_{\max} = 50 \text{ volts}$$

Since a lower voltage value results when the characteristics of the pipe are considered, it is recommended that an induced voltage-to-ground threshold for worker safety of 30 volts be adopted generally, with voltages not in excess of 50 volts permitted under extraordinary (localized) circumstances.

7.4 PIPELINE CONSTRUCTION SAFETY

Voltages induced on pipelines by a Sanguine System would be no different from those produced by commercial power systems. Voltages produced on pipes near Sanguine ground terminals also would be no different than those produced near power system grounds. Therefore the same construction safety practices adopted by the pipeline industry should be applied in the Sanguine operating area when pipelines are being replaced or initially installed. While these practices may vary between companies, the general precautions provided by Paver² appear to be useful in a Sanguine-generated electromagnetic environment.

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2. E.C. Paver; Effects of Induced Current on a Pipeline; Materials Protection and Performance, Vol. 10, No. 6, March 1971.

SECTION 8

CONCLUSIONS

8.1 INTERFERENCE MECHANISMS

Existing theories which describe electromagnetic coupling between a long current-conducting source (a Sanguine antenna) and a colocated long conductor (a pipeline, for example) are applicable to Project Sanguine. The equations developed from these theories can be used to estimate pipeline voltages and currents under all practical circumstances. For example, the lengths of the lines can vary, the distance and relative orientations between the lines can change, and the lines can be buried or be overhead. Theoretically-derived estimates can be validated by field experiments on existing pipelines without modifying or disturbing the pipelines.

Computer programs have been developed for calculating electromagnetic fields within the grid formed by an array of Sanguine antennas, and the fields in the fringe area of the grid. The programs apply these gradients to a pipeline of interest to derive the inductive (Sanguine antenna) and conductive (Sanguine ground terminal) voltages and currents on the pipe, and superimposes these effects to produce the total contribution on the pipe.

8.2 INTERFERENCE PARAMETERS

The parameters involved in electromagnetic coupling between a Sanguine System and a pipeline have been defined. The Sanguine System parameters include:

- a. antenna current
- b. antenna frequency
- c. antenna location (distance, orientation with respect to the pipeline).

The important pipeline parameters are:

- a. pipe diameter (longitudinal impedance)
- b. pipeline coating
- c. pipeline length.

The effect of each of these parameters on electromagnetic coupling can be studied with the computer programs developed for Project Sanguine.

8.3 INTERFERENCE EFFECTS

The effects which generally might be expected from electric currents and voltages induced on pipelines and associated system equipment include accelerated corrosion of the pipeline material, malfunction of electrically-operated equipment, and impact on worker safety. The degree to which any of these effects might occur are closely related to the frequency of the interference signal.

Since a Sanguine System would operate in the Extremely Low Frequency (ELF) band, the effects noted in the previous paragraph are not expected to be significant, or are expected to approximate the effects produced by commercial power systems. It is estimated that the corrosion of bare pipes in most soils attributable to as much as 30 volts induction by a Sanguine System would not exceed 0.015 inch per year. Since most buried metal pipes are coated, this rate of corrosion would be possible only where the pipe coating was punctured or otherwise deteriorated so that the metal is in intimate contact with soil. The corrosion rate would be reduced over a period of time even in this case.

Malfunction of electrically-operated equipment used on pipelines is not expected from Sanguine-generated interference voltages. Much of the equipment is inherently immune to voltages at extremely low frequencies, or would be protected from Sanguine-induced voltages by the low interference thresholds established for commercial power service lines (nominally 200 millivolts). Cathodic protection schemes based on the use of sacrificial anodes should not be disturbed by Sanguine voltages in the 30-40 volt range. Voltages of this magnitude are not expected.

The safety of pipeline workers would not be impaired in a Sanguine-generated electromagnetic environment. The coupling between Sanguine System elements and piping systems is no different than that which occurs between commercial power lines and pipelines.

Ordinary safe working practices adopted by the pipeline industry are sufficient in a Sanguine environment.

8.4 MITIGATION TECHNIQUES

It is unlikely that significant interference effects would be produced on pipelines by a Sanguine System. There are three factors associated with Sanguine that are helpful in minimizing these effects. The Sanguine operating frequency is relatively high so that corrosion is not enhanced. The antenna current (150 amps, nominal) has been selected so that inductive coupling is not severe. Antenna placement can be selected to obtain near-optimum spacing between antennas and pipelines, thereby further reducing coupling.

Mitigation techniques have been identified so that any isolated situation requiring reduction of pipeline interference voltages can be accommodated. Insulating devices can be used to reduce the electrical length of a pipeline and thus change the voltage distribution along the pipe in instances where excessive voltages might appear. An alternative is to use a nonfunctional extension of the pipeline to achieve essentially the same result.

Parallel, buried guard wires can be used to reduce coupling between Sanguine System elements and pipelines. This technique could be useful in maintaining pipe-to-soil potentials below those magnitudes that might cause excessive pipe corrosion in some soils. Soil chemistry changes might also be useful in localized cases to prevent corrosion.

Voltages produced by a Sanguine System could be useful in providing cathodic protection for pipelines. Protective schemes have been developed to use powerline-induced signals in this way, and may provide a favorable means of pipe corrosion protection in a Sanguine operating area as well.

8.5 MEASURED INDUCED VOLTAGES

Voltages induced on pipelines from commercial power systems have been reported in the literature, and have been measured on pipelines in the candidate Sanguine operating area in Wisconsin. These data have been helpful in understanding the amount of electromagnetic coupling one might expect in the field from certain conditions (type of exposure, presence of grounding systems, etc.). The data obtained in Wisconsin depict the voltages presently existing on pipelines, and therefore will be helpful in the future in assessing the impact a Sanguine System would have on existing pipelines. Finally, the field exercises showed that induced voltages can be measured on emplaced pipelines without disturbing the line in any way.

8.6 RECOMMENDED INTERFERENCE THRESHOLD

Based on the studies of the effects of induced voltages and currents on pipeline systems, it is recommended that an interference voltage threshold of 30 volts be considered for pipeline systems collocated with a Sanguine System. This threshold should be applied generally, but it should be recognized that isolated cases may be encountered where some change in the threshold may be useful. Two examples illustrate this point. A situation could exist where a pipe is equipped with a cathode protection unit that is affected by 30 volts but not by 20 volts. Some local form of mitigation might be preferable to a significant change in pipeline construction or a relocation of the Sanguine antenna element. "Local" mitigation in this sense could be a change in the rectifier unit of the cathodic protector, or conversion to a method which uses the interference voltage to produce corrosion protection. Another example might be an instance where a 50-volt signal is induced on a large diameter pipe located in soil which is essentially noncorrosive. Although the signal is higher than the preferred 30-volt maximum, accelerated corrosion would be a remote likelihood, and it might be better to avoid mitigation in this case.

The recommended 30-volt interference voltage threshold is based on avoiding significant pipe material corrosion, preventing malfunction of electrically-operated devices used on pipeline systems, and maintaining safe conditions for pipeline workers during initial construction or subsequent system repair.