AN INTERPRETATION OF INDUCED ELECTRIC CURRENTS IN LONG PIPELINES CAUSED BY NATURAL GEOMAGNETIC SOURCES OF THE UPPER ATMOSPHERE

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Abstract. Electric currents in long pipelines can contribute to corrosion effects that limit the pipe's lifetime. One cause of such electric currents is the geomagnetic field variations that have sources in the Earth's upper atmosphere. Knowledge of the general behavior of the sources allows a prediction of the occurrence times, favorable locations for the pipeline effects, and long-term projections of corrosion contributions. The source spectral characteristics, the Earth's conductivity profile, and a corrosion-frequency dependence limit the period range of the natural field changes that affect the pipe. The corrosion contribution by induced currents from geomagnetic sources should be evaluated for pipelines that are located at high and at equatorial latitudes. At midlatitude locations, the times of these natural current maxima should be avoided for the necessary accurate monitoring of the pipe-to-soil potential.

1. Introduction

With the introduction of long manmade electric conductors on the Earth's surface over 100 yr ago, there arose a concern about the surging electric currents of natural origin that sporadically appeared in such systems. It was soon realized that the spontaneous currents in telegraph wires were associated with aurorae and geomagnetic storms (Barlow, 1849; Clement, 1860; Prescott, 1860, 1866; Hansteen, 1860; Burbank, 1905; Chapman and Bartels, 1940; Harang, 1951; and Stormer, 1955). Similar current fluctuation problems were reported in submarine communication cables (Saunders, 1880, 1881; Axe, 1968; and Meloni *et al.*, 1983) and long power transmission lines (Davidson, 1940; Slother and Albertson, 1967; Albertson and Van Baelen, 1970; Albertson *et al.*, 1974; Akasofu and Merritt, 1979; Akasofu and Aspnes, 1982; Boerner *et al.*, 1983; and Pirjola, 1983). Although the existence of natural induction currents in pipelines had been reported at an early date (Varley, 1873, reported in Lanzerotti and Gregori, 1985), it has been only in recent years, concurrent with the construction of very long oil and gas transmission systems and with the concern for pipe corrosion protection, that research started on this effect (Gideon *et al.*, 1970; Campbell and Doeker, 1974; Hessler, 1974; Cambell, 1978; Peabody, 1979; Cambell and Zimmerman, 1980; Campbell, 1980; Barker and Skinner, 1980; Smart, 1982; Brasse and Junge, 1984).

A detailed corrosion analysis of a particular pipeline section can be rather complicated. Nevertheless, it is relatively easy to understand the important physical processes that are responsible for the electric currents in a long conduction pipe during geomagnetic field disturbances. These fields are a result of source currents flowing above the Earth's surface. With every changing magnetic field there is an associated electric field of identical frequency and related amplitude and phase. The

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electric fields enter the Earth's surface to a depth that is dependent upon the source frequency and the penetration region conductivity. Electric currents driven by these 'internal' processes have associated magnetic and electric fields that add to the observations at the Earth's surface. Small-scale conductivity irregularities at the surface modify these Earth currents (and its driving potential difference). A grounded conductor, such as a pipeline, represents a low resistivity path for the flow of Earth-induced currents. Corrosion occurs at a grounded pipe, in contact with suitable ions of the soil, whenever the current through this location is large enough, of the correct frequency, and in the proper direction. In the following sections, the above process will be outlined in greater detail.

Three subjects are to be covered in this review. First, I will discuss some of the most important source-field characteristics, focussing upon the variability with location, spectral composition, direction, time-of-day, season, and solar cycle predictions. Second, I will review the effects of these varying fields upon both the current flow and the corrosion in a long grounded pipeline. Third, some measurement methods for pipe current and pipe-to-soil potential will be given. Battery effects of pipe contact with the soil, lightning strike and induction phenomena, or manmade causes of pipeline currents, are not within the subject or this presentation. The focus of this paper is upon the understanding of the physical processes that cause natural electric currents to flow in long pipelines during times of geomagnetic field fluctuations; it is not the purpose of this paper to give detailed pipe current analysis or protection techniques for pipeline engineers.

2. Source Field Characteristics

Upper atmospheric currents are a major source of the natural field variations that are of interest for the pipeline effects presented in this paper. The majority of these currents flow in an ionized region (ionosphere) at about 100 km altitude. The currents differ in character depending upon the active or quiet behavior of the Sun. Active times have been correlated with a string of solar-terrestrial phenomena that begin with observable changes on the solar surface (related to sunspots) (White, 1977) and include modifications during the flow of fields and particles to the vicinity of the Earth, deformation of the shape of the Earth's main field in space, and the development of currents that flow both at a great distance about the Earth and into the auroral region. By way of the ionosphere, the strong auroral currents (sometimes called 'electrojets') are communicated to the entire globe. A secondary concentration of these currents occurs in the equatorial region because the horizontal direction of the Earth's main field creates an ionospheric band of high conductivity there.

Two 3-hr planetary indices are commonly used to indicate the geomagnetic field disturbance level. The *Kp* index has a quasilogarithmic scale of 0 to 9 that is convenient for general indications of the activity levels. These indices are usually converted to equivalent *Ap* indices which are linear with respect to field strength. As a 'rule of thumb' the *Ap* may be taken as an indicator of a 3-hr range of the

TABLE I

Ap geomagnetic activity index

(a) *Occurence*	*Ap* index
Most probable value	5
50% occurrence	< 8
Low value, once every 2 yr	0
Active value, once every 2 months	≥ 52
High value, once every 2 yr	≥ 150
(b) *Formula representations*	
Days per year with activity $\geq Ap$	
$N(\text{high}) = 4.14 \times 10^4\ Ap^{-2.25} \pm 6\%$ (for $Ap = 15$ to 150)	
Days per year with activity $\leq Ap$	
$N(\text{low}) = -52.3 + 267.4 \log Ap \pm 4\%$ (for $Ap = 2$ to 20)	

excursions in *H*, the magnetic northward component of the geomagnetic field in gammas (nanoteslas), at midlatitudes. On a long time sample over many years, the occurrence of various levels of *Ap* indices are statistically predictable. Table I illustrates how *Ap* behaves over a 40-yr sample. For example, the expected number of days that *Ap* would be at some quiet level below a specified value is obtained from the last equation in Table I. In the pipeline corrosion studies, attempts are made to identify the induction-related currents with *Ap* indices. Table I then allows prediction of the statistical occurrence of such currents over the estimated lifetime of the pipeline.

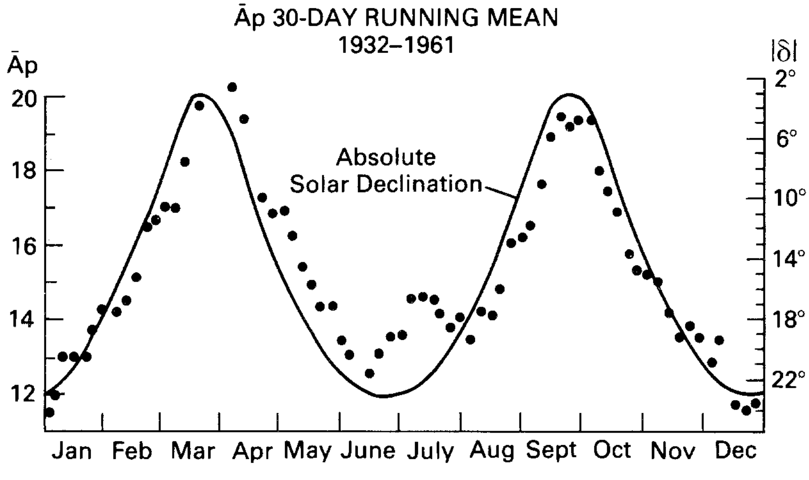

Fig. 1. 30-day running mean of geomagnetic activity index, *Ap*, for 1932 to 1961 (dots and scale to left) and δ the absolute value of solar declination (curved trace) showing semiannual characteristics of the geomagnetic index with maxima at the equinoxes and the slightly greater values in northern hemisphere summer because of the dominance of northern stations that contribute to the index (figure redrawn from Roosen, 1966).

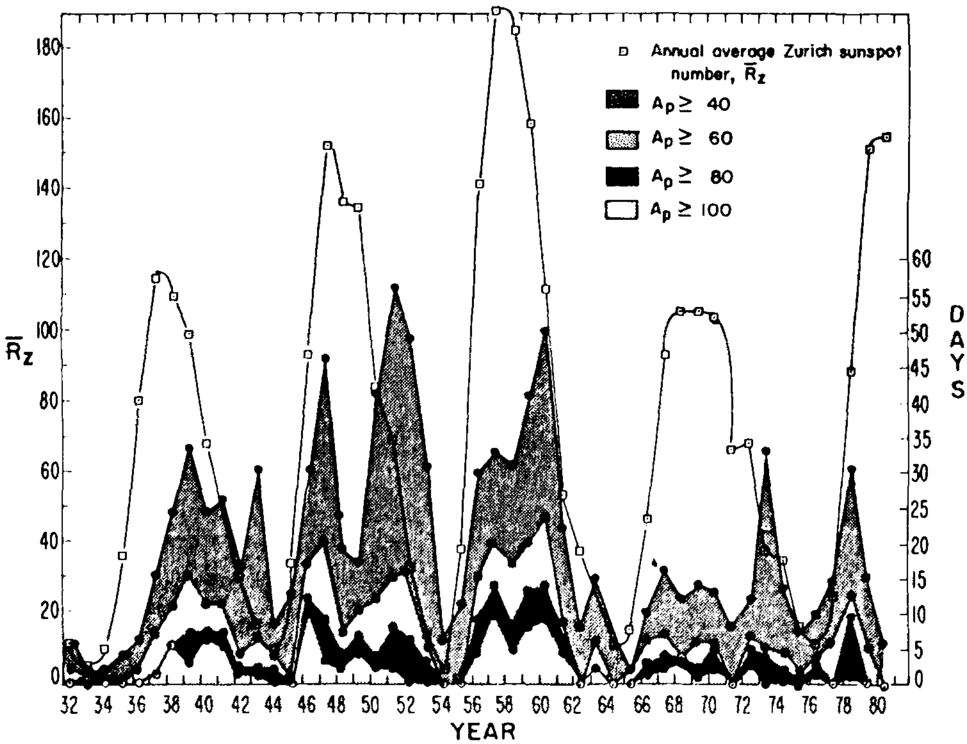

Fig. 2. The number of days per year (scale at right) in which the geomagnetic index *Ap* exceeded values of 40, 60, 80, or 100 in the period 1932 through 1980. Annual sunspot number indices, *Rz*, are also indicated on scale at left (figure from Allen, 1982).

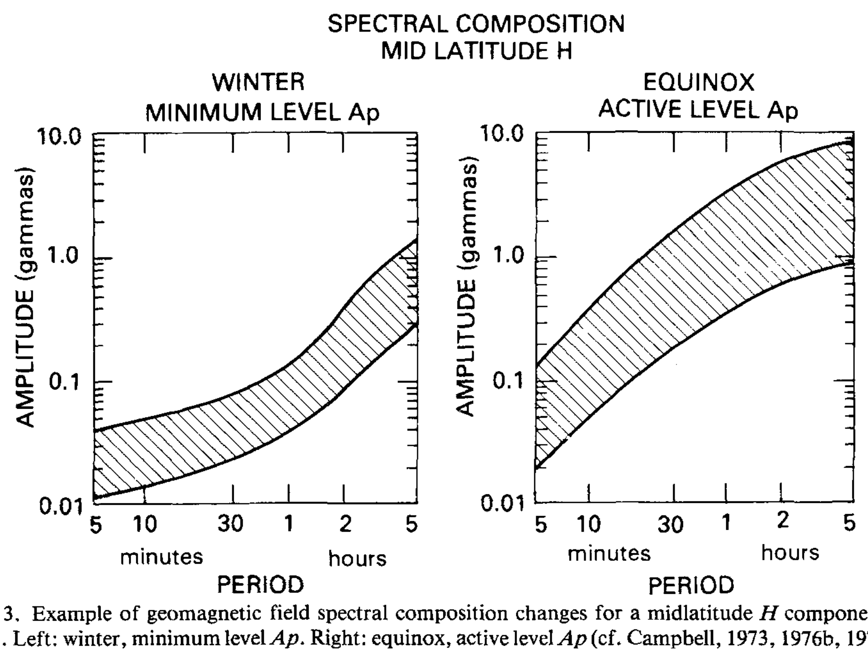

Fig. 3. Example of geomagnetic field spectral composition changes for a midlatitude *H* component of field. Left: winter, minimum level *Ap*. Right: equinox, active level *Ap* (cf. Campbell, 1973, 1976b, 1977b).

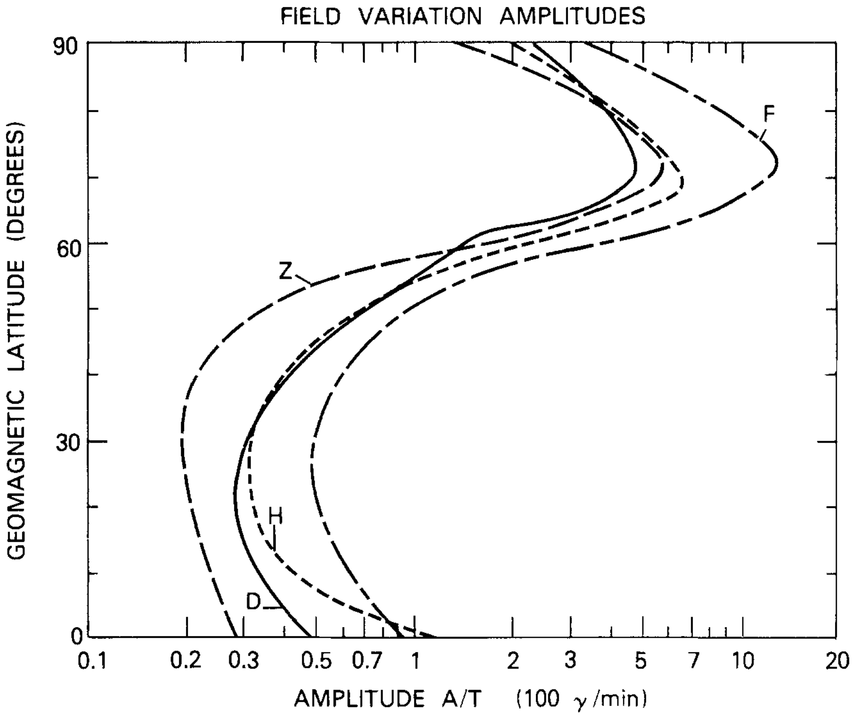

Fig. 4. A representation of the geomagnetic variation amplitudes for the period range of 5 min to 4 hr during a year of minimum activity. *H, D,* and *Z* orthogonal field components and total field amplitudes, *F*, are shown. The spectral amplitudes (divided by the period in minutes and multiplied by 100) are averaged to form the amplitude scale shown here (figure redrawn from Campbell, 1976a).

Geomagnetic activity has both a seasonal and solar-cycle behavior. Figure 1 (Roosen, 1966) shows the outstanding equinoctial maxima in *Ap* indices; this means that the Sun-Earth alignment during March and September favors the interaction of the solar wind with the Earth's magnetosphere so that larger disturbances occur about the globe. The annual geomagnetic activity rises and falls with 10 to 11-yr cycles in general agreement with the annual average sunspot number index. Figure 2 illustrates this behavior for the period of 1932 to 1980 (Allen, 1982). Once a relationship is established between the pipeline current and the *Ap* index, estimates of the current activity levels in a future time or over the expected life of the pipeline are possible from the predictions of *Ap* available at World Data Center A for Solar Terrestrial Physics and/or the Space Environment Forecasting Center, both operated by NOAA in Boulder, Colorado, U.S.A.

As the geomagnetic levels of activity change, both the relative spectral composition and the amplitudes of the disturbance field variations change. Figure 3 illustrates this point by comparing the spectral samples of a quiet day, having *Ap* values near zero, to that of an active day, having *Ap* values near 70, for the field variation periods of 5 min to 5 hr. A clear diurnal variation of the amplitudes has also been found. Because of the unique global distribution of the geomagnetic disturbance currents

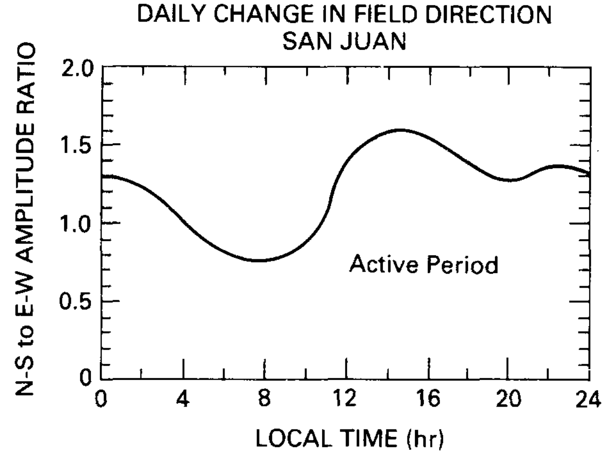

Fig. 5. The average daily change in field direction for variations of 10 to 60 min period at San Juan (during a time of high geomagnetic activity) displayed as the ratio of N–S component to E–W component amplitudes (figure redrawn from Campbell, 1977a).

about the Earth there is a unique distribution of field amplitudes with latitude. In Figure 4 note the minimum field sizes between about 15 to 40 deg geomagnetic latitude, the maximum at the high latitude auroral zone, and a seondary maximum near the equator. There is some seasonal shift in these locations as well as in the amplitudes.

One further characteristic needs to be described to complete the picture of the disturbance source currents. Note in Figure 4 the change of component relative amplitudes with respect to latitude means that the source current direction is latitude dependent. There is also a time-of-day change in these current directions at all locations as illustrated for San Juan in Figure 5. If the ground conductivity is assumed to be uniform horizontally over a region that is large with respect to the source size, a pipeline grounded in the direction of the source-current flow will carry the largest induced electric current.

Another cause of the special pipeline geomagnetic effects is the ionospheric dynamo current driven by winds and thermal-tidal motions. These currents, called *Sq* by geomagneticians, cause most of the 24-, 12-, 8-, and 6-hr daily variations of field at the Earth's surface (Figure 6). The amplitude of these currents increases with the *Ap* index, and therefore *Sq* responds to sunspot-cycle changes. Figure 7 illustrates the expected fields from an external ionospheric dynamo current system determined for an average quiet day of each month during a year of low solar activity. Note three things in particular: there is a shift between the northward (*H*) and eastward (*D*) components at specific latitudes and seasons of the year; there is an annual amplitude change at all latitudes and a semiannual change at low latitudes; amplitudes of *Sq* fields are particularly large near the equator. With increasing activity level the amplitudes of *Sq* increase two to three times in size and the phase shifts slightly. In

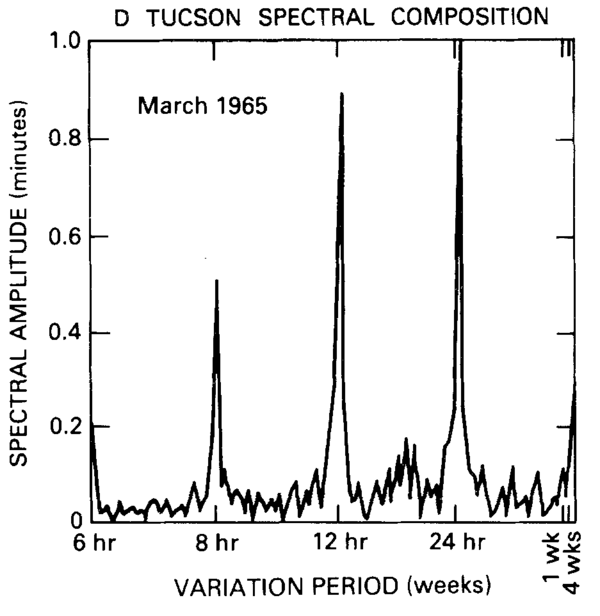

Fig. 6. Fourier analysis spectral amplitudes in the period range of 4 weeks to 6 hr for averaged Tucson D-component daily magnetograms in March 1965.

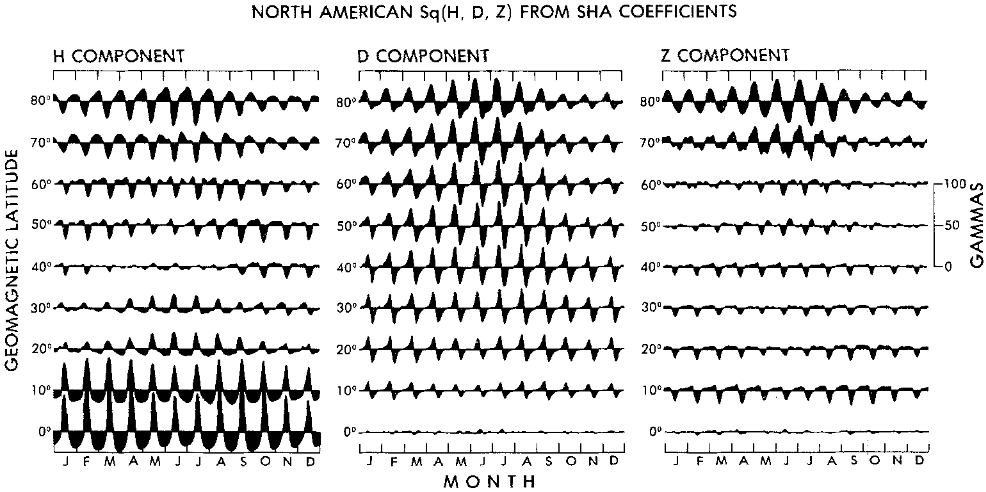

Fig. 7. Annual picture of the daily variations (in local time) of *Sq* from the equator to 80° latitude (bottom of top rows) displayed for *H*, *D*, and *Z* field components at left, center, and right sections respectively. The scale size between baselines is 50 gammas. Months of the year are indicated at the bottom of each section (Campbell, 1983).

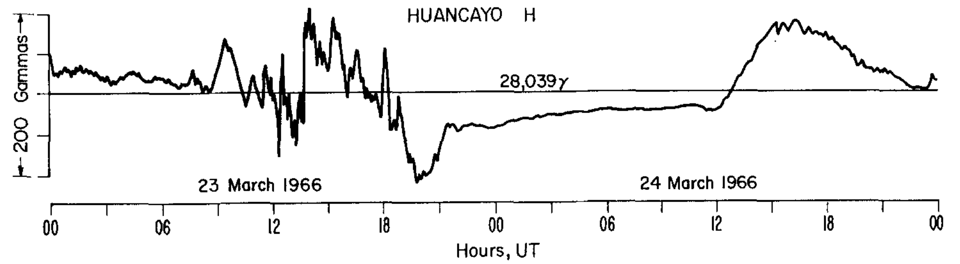

Fig. 8. Magnetogram of H component of field for the equatorial observatory at Huancayo, Peru, for a geomagnetically active day (23 March) and a relatively quiet day (24 March). Local time is 5 hr earlier than the UT time given at bottom of figure.

Figure 8 we see, in sequence, a solar-terrestrial disturbance variation (23 March) and a *Sq* variation (24 March) at an equatorial location. For the study of pipeline effects, the most important features of geomagnetic fields in the active or quiet times are the frequency composition, the amplitudes, and the direction relative to the grounded locations of the pipeline.

3. Induction in Earth and Pipe

The depth of penetration into the Earth by the upper atmospheric source fields depends upon the frequency and Earth's conductivity profile: the lower the frequency, the deeper the penetration and the higher the conductivity, the shallower the penetration. A 'skin depth' concept is used for visualizing a comparison of the penetration of fields within a conductor. For a homogenous region of conductivity σ [Siemens/meter or $(\Omega\text{m})^{-1}$] with the period of the field oscillation given as T (minutes) we call the 'skin depth' in kilometers

$$\delta = \sqrt{600\ T/\sigma}\ /2\pi, \tag{1}$$

the depth at which the amplitude of the field drops to about one-third (1/2.718) of the original size. If the conducting material is very thin with respect to δ, then we consider the electromagnetic wave to be unaffected ('not seen') by the conductor.

For the geomagnetic fields of interest here the pipe is too thin to be noticed. For example, consider a steel pipe with a conductivity of 4 to 6×10^6 Siemens m^{-1}. For field changes of 2 to 40 min periods the skin depth would be about 2 to 12 m; for field changes of 6 to 24 hr periods the skin depth would be about 30 to 74 m. Steel pipe wall thickness of even 2 cm hardly disturb these long waves. No interaction means that there is no induction process, or induction currents of importance, in the pipe directly. Yet we know that induction-like currents are measured in the pipeline so how do they get there?

Figure 9 from Campbell and Zimmerman (1980) and Figure 10 from Barker and Skinner (1980) illustrate the association of pipeline currents with the natural electric and magnetic fields. These currents occur in the pipeline because the currents induced within the Earth by the natural sources have found an easy-flowing path through the

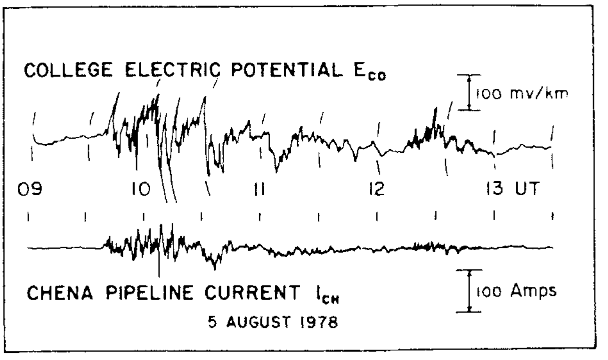

Fig. 9. Simultaneous appearance of the Earth's electric field potential, E_{co}, in milliwatts km^{-1} measured at College, Alaska, (top trace) and the Alaska oil pipeline current, I_{ch}, in amperes (bottom trace) measured at nearby Chena, Alaska, between 0900 and 1330 UT on 4 August, 1978. Local time is 10 hr earlier than the UT time given (figure from Campbell and Zimmerman, 1980).

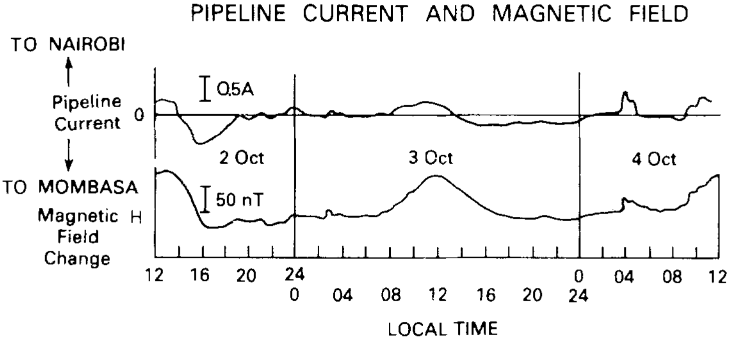

Fig. 10. Simultaneous appearance of the H component of magnetic field variations (in nanotesla) measured at Nairobi, Kenya, and the current (in amperes) in the 450 km pipeline between Mombassa and Nairobi. The period from noon 2 October to noon 4 October, 1978, local time, is shown (figure redrawn from Barker and Skinner, 1980).

pipe. Thus, our next step toward understanding the process is to look at the frequency, amplitude, and directional effects that the induction processes play in establishing the Earth's currents.

The equations for the relationship of the orthogonal magnetic and electric fields measured for each frequency component at the Earth's surface were originally developed by Caignard (1953) and Tickhonov (1953). If a plane wave source is assumed, the relationship between the magnetic and electric field magnitudes may be represented by the formula

$$\left|\frac{B_y}{E_x}\right| = \sqrt{12\sigma T} \tag{2}$$

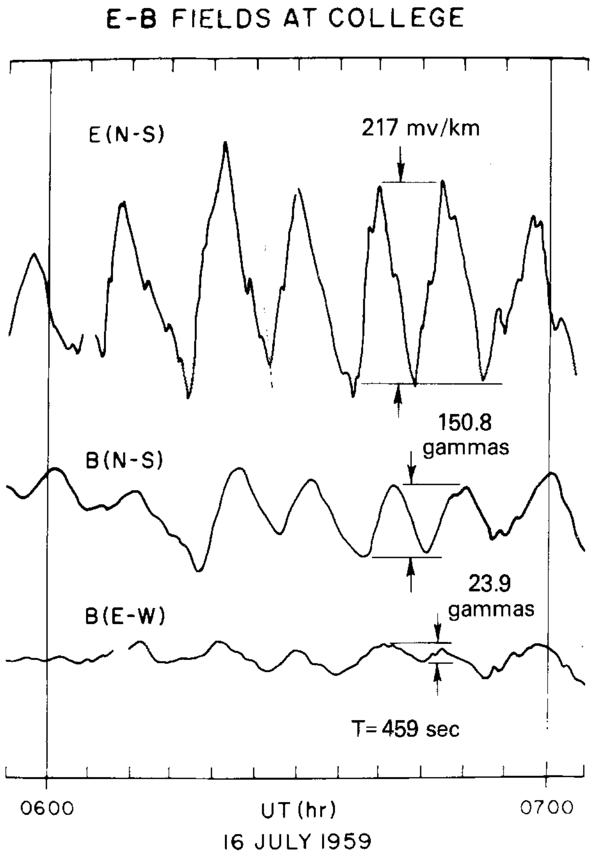

Fig. 11. Corresponding north-south (N-S) electric (E) fields (mV km^{-1}) and magnetic (B) fields (gamma) for north-south and east-west (E-W) fluctuations at College, Alaska.

where B_y and E_x are the horizontal, orthogonal, magnetic (B), and electric (E) field components in nT and mV km^{-1}, respectively; T is the oscillatory period in minutes and σ is the effective conductivity of the model Earth in S m^{-1}. Figure 11 is an example of the corresponding variations of electric and magnetic fields.

The importance of electromagnetic methods to the surveying of crustal materials has led to extensive theoretical developments in this subject (cf., Wait, 1982; Filloux, 1979). For the typical situations that are of interest at mid and low latitudes, one may consider the ionospheric currents as quite large and sheet-like with respect to the study size of a pipeline so that the source fields represent a plane wave at the Earth's surface. At the high latitude auroral region the sources are more like line currents, rather than sheet currents, and special source dimension factors need to be included in the analysis. The intense aurorally associated currents at high latitudes have an approximate size L (km) of 12 times the oscillatory period T (min). For a given subsurface conductivity structure the amplitude and phase of the ratio for orthogonal electric to magnetic fields may be determined (cf., Wait, 1962; Jackson

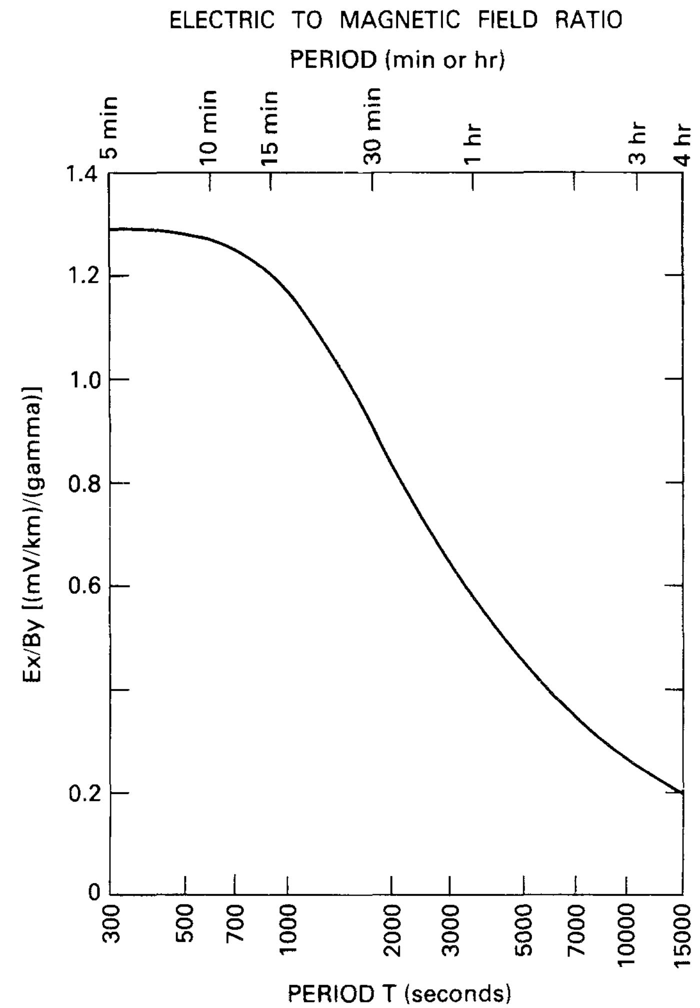

Fig. 12. Magnitude of the ratio of amplitudes of horizontal, orthogonal electric, E_x, and magnetic, B_y, fields for variations from 5 min to 4 hr period using a simplified earth conductivity model (figure redrawn from Campbell, 1978).

et al., 1962; Ward, 1967; Wait, 1982; and Rokityansky, 1982). If the conductivity substructure is assumed to be horizontally layered, the analysis is straightforward; otherwise, further computational complexities arise. The Earth conductivity profile models provide an amplitude and phase relationship between the orthogonal electric and magnetic fields with respect to frequency. In Figure 12, for a very simple layered Earth conductivity model, we see how the electric field amplitudes (with respect to the magnetic field amplitudes) decrease for the longer period variations. Most Earth models show the general increase in conductivity, $\sigma(\mathrm{S\ m^{-1}})$, with depth to about 700 km (excluding the immediate crust) not unlike

$$\sigma = 0.007 \exp(0.007d) \tag{3}$$

where d is the depth in km (Campbell and Anderssen, 1983).

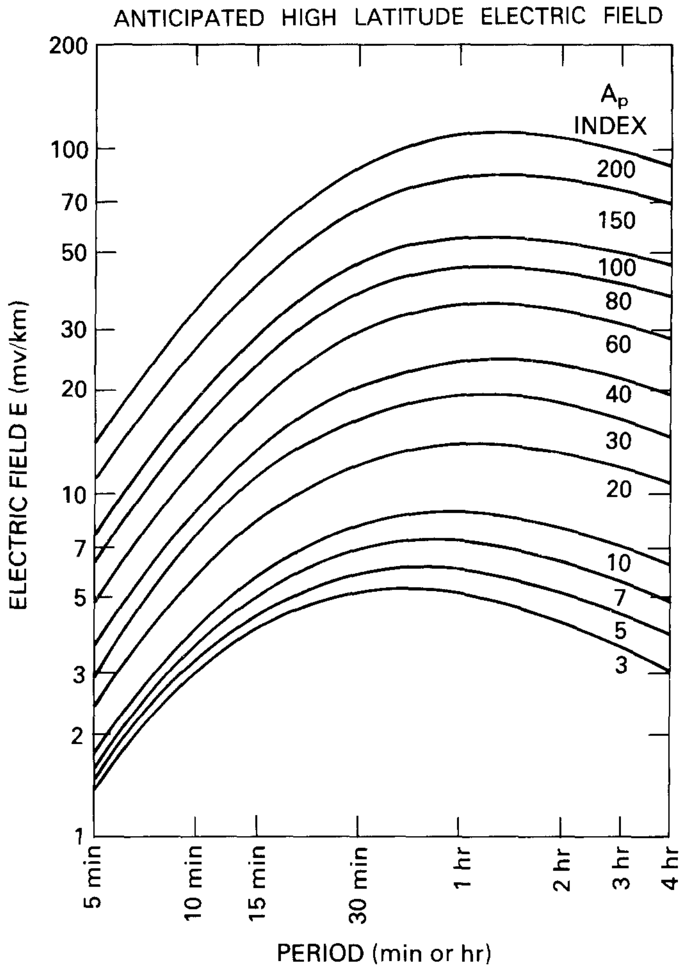

Fig. 13. East-west electric fields, E(mV km^{-1}), as a function of period, T, obtained from the relationship with magnetic field in Figure 12 for situations typical of the auroral zone in Alaska. Separate curves represent values at different geomagnetic activity index levels, Ap (figure from Campbell, 1978).

Spectral studies of geomagnetic field variations reveal that the form of the spectra may be represented (quite roughly) by the formula

$$B_x = CT^m,$$

where T is the period in min and C and m are constants for a given frequency range and activity (Ap) level. Thus, one may use the electric-to-magnetic field relationship (versions of Equation (2)) together with such formulae as Equation (4) (or with the spectral field representations such as those in Figures 3 and 6) to determine the equivalent regional electric fields. Figure 13 illustrates one such transformation for a special high latitude situation and different levels of activity and an interesting feature results. Although the amplitudes of the geomagnetic fields were increasing with increasing period, the corresponding electric fields show a clear maximum and decrease in amplitudes at the long wavelength region. This behavior is a direct result of the rapid increase of conductivity with depth in the Earth. Although we expect the different regions to have associated unique geomagnetic spectral features and conductivity characteristics, all regions should show a version of this natural electric field maxima similar to that of Figure 13.

One might ask, why go to all the trouble of determining the electric field connection to magnetic fields; why not limit the study to the Earth potential measurements. There are two good reaons. First, geomagnetic data are available throughout the world, over many solar cycles of time, and with these data we can make useful statistical predictions of activity levels. Second, the electric field measurements, made with spaced probes in contact with the ground, are considerably more sensitive to small surface changes in topography, geology, and variable moisture than are the magnetic counterparts. Studying one area of a 10-mile radius Wescott and Hessler (1962) found that the electric field relative magnitude could change by a factor of five and that the principal directions could range over 33 deg. For the field amplitudes and frequency range of present interest, the magnetic field sensors would average out any changes in the scale of the above study. The mean behavior of the electric field measurements in the Wescott and Hessler study properly matched the expected magnitude and direction derived from the magnetic determinations. The electric measurements are typically obtained as the potential difference between grounded probes, properly coupled to the conducting Earth and spaced about 1 to 300 m apart in the selected cardinal direction.

4. Pipe Current and Pipe-to-Ground Potential

The geomagnetically related current that flows in a pipeline is dependent upon where the pipe is grounded with respect to the Earth currents. Two arrangements are considered here. In Case 1 for distant grounding, there are long sections of pipeline, well insulated from the electrical contact with the Earth, and the grounded points are at established locations such as pumping stations or end points of the pipeline. In Case 2 for local multiple grounding, there are many electrical contact points along the pipeline, some of which are known such as sacrificial electrode locations. Others are at unknown points, such as those that are established at holes in the protective pipe sheath.

CASE 1: DISTANT GROUNDING

In this situation the current I(amperes) is just that flowing through the pipe resistance R (Ω m^{-1}) driven by the electric field E (V m^{-1}). This current can be calculated by the simple Ohm's law expression

$$I = E/R. \tag{5}$$

The current will be the same size at all places along the pipeline. In all cases that I am aware of, the resistance of the material transported in the pipeline is so much higher than the steel of the pipe that it may be neglected in the electric current computation. As an example of pipe resistance magnitudes, consider the Alaskan oil pipeline. It is about 1.28×10^3 km long, has a mean diameter of 1.22 m, an average wall thickness of 1.3 cm and a steel resistivity of $2.4 \times 10^{-7}\Omega$m. The pipe resistance is about $4.8 \times 10^{-6}\ \Omega\ m^{-1}$; the end-to-end resistance of the Alaska pipeline is only about 6 Ω.

The field value, E, used in Equation (5), is just the difference in potential between the grounding points divided by the separation distance. It represents the regional electric field in the direction of a line between those end points. When this direction is aligned with the ionospheric source current (and when there are no major conflicting horizontal Earth conductivity anomalies in the region) the pipeline current is maximized. Essentially, the Case 1 configuration represents an 'Earth current' system with ground probes spaced at such a great distance that the small local irregularities, reported by Wescott and Hessler (1962), are averaged out to give a better mean regional measurement. Brasse and Junge (1984) have suggested using such measurements for the regional determination of Earth conductivity profiles. Formulae similar in form to Equation (2), although much more complex, have been developed to determine the conductivity structure from the ratio of orthogonal magnetic to electric field components (c.f., Schmucker, 1970; Wait, 1982; and Rokityansky, 1982).

Potential measurements between the pipe and ground at any location should represent the difference between the regional mean potential (calculated from values at the grounded end points and the computed fractional distance along the resistive pipe) and the local potential at a point affected by the local topography, geology, and surface moisture. When there is a limited source frequency spectral composition and the regional magnetic field measurement is orthogonal to the line joining the grounded end points of this pipeline section, the records of the pipeline currents (or electric fields) and regional geomagnetic fields have a similar appearance (e.g., Figures 9 and 10).

CASE 2: LOCAL MULTIPLE GROUNDING

For this situation each pair of grounded points causes current flow in the pipeline between them. The potential differences driving these currents arise for two main reasons: there are different regional field magnitudes and directions sampled by each pair of grounded points along the pipeline; there are local topographic, geologic, and soil moisture features that have greatly modified the local fields at the pipe contact points. The difference in potential between the pipe and ground at any point will reflect what current can flow through the grounded portion of the pipe in that

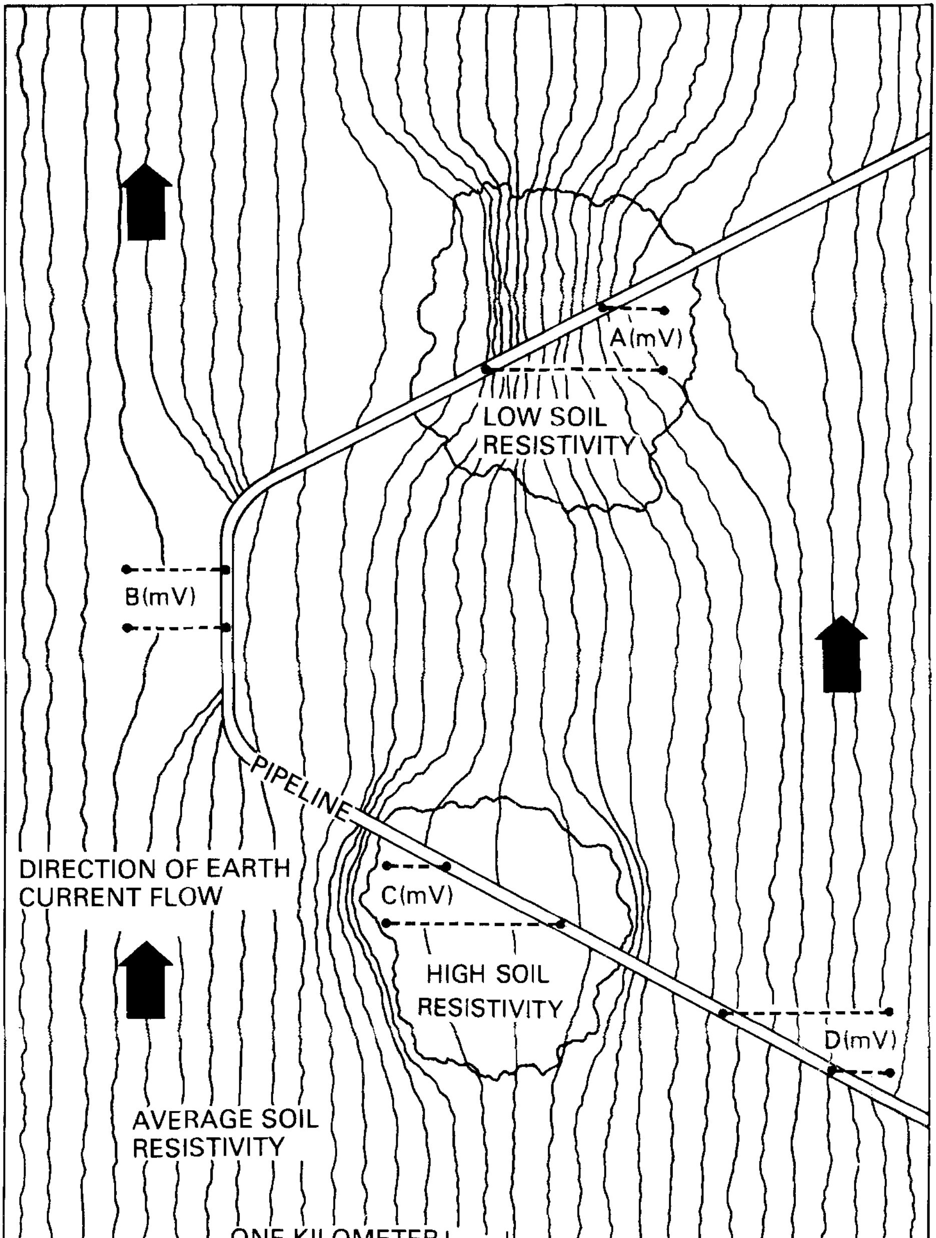

Fig. 14. Diagram to illustrate how differences in soil resistivity and pipeline axis direction create conditions that can modify the measured potential differences (and therefore the current flow) in a pipeline. The potential measurements in mV km^{-1} are indicated by A, B, C, and D. Each location could give a different value of potential (and current) for a single value of source field (indicated by large dark arrows) because of the different pipeline directions and different conductivity characteristics of the soil in the region grounded to the pipe (figure redrawn from Smart, 1982).

immediate location (cf. Figure 14). The pipe current will be a summation of all the driven currents and will not be uniform along the pipeline. This nonuniformity characteristic provides a way to determine whether the pipe is a Case 1 or Case 2 example. Local field determinations from the Case 2 pipeline would not be reliable for determinations of deep conductivity. Typically, a Case 2 pipeline provides the greatest opportunity for corrosion. A completely grounded pipe is the limiting case of a Case 2 situation.

5. Corrosion

The current flowing within a pipeline is no more a corrosion problem than the current that flows in the electric wiring of a house. It is when current flows between the pipe and ground that pipeline protection is to be considered. The regular reversal in direction of the upper atmospheric source and induced fields provide oscillations in the pipeline current such that only half of the time is the current through holes of the protective coating in a direction that can set up an electrolytic action in the presence of water. In this process water molecules are broken down into H^+ and OH^- ions and $Fe(OH)_2$ and $Fe(OH)_3$, common rust, is formed at the anode, consuming the pipe. The amount of metal removed in this way is directly proportional to the current at the anode (Peabody, 1967, 1979). Engineering tests on pipeline installation provide estimates of the average area of holes in the insulating covering to be expected from damage during the emplacement. The estimate of corrosion effect is made relative to a value of current density through these holes. Then from established corrosion studies such 'hole-current density' may be translated into inches-per-year of corrosion. Thus, for a given wall thickness, an effective pipe lifetime is estimated. Peabody (1967) states that "One ampere of direct current discharging into the usual soil electrolyte can remove approximately twenty pounds of steel in one year."

High frequency oscillations of the current are less effective than D.C. for the corrosion process. McCollum and Ahlborn (1916) prepared tables of this effect that may be represented roughly by the equation

$$C = (4.7 \pm 1.3)\ t^{0.186} \tag{6}$$

where C is the percent of direct-current corrosion at the same amplitude, and t is the oscillation period in seconds. For example, at 5-min, 1-hr, and 4-hr periods C becomes 14, 22, and 28% respectively. At the very high frequencies, such as 60 c/s, the rapid reversal of the polarity precludes the establishment of the electrolytic action necessary for corrosion to occur. Now let us recall that the magnetic field source spectrum showed an almost constantly increasing amplitude with increasing period. Next, we found that because of the induction in the Earth the resulting electric field spectra exhibited a midrange maximum. Although the pipe current would be directly proportional to the electric field, the corrosion-frequency relationship further modifies the effective spectral components forcing the maximum to lower

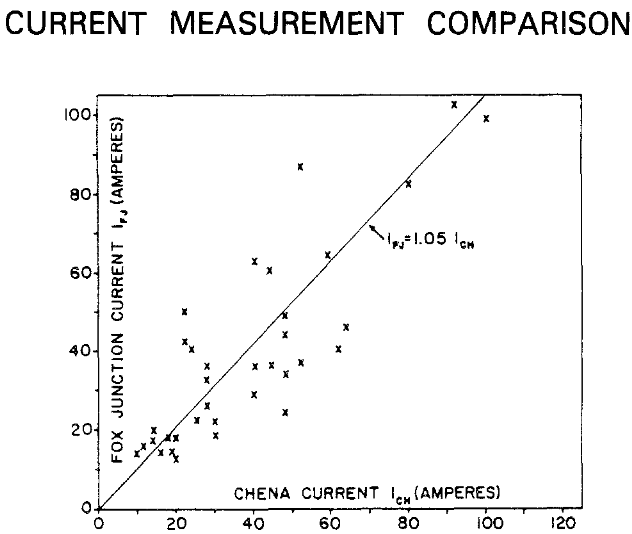

Fig. 15. Simultaneous observation of Alaska oil pipeline current by the shunt method at Chena, Alaska, and by the gradient field method at Fox Junction, Alaska, for the period 1100 UT, 3 August to 1400 UT, 5 August, 1978. The two sites are separated by 9.6 km (figure from Campbell and Zimmerman, 1980).

frequencies. During geomagnetic disturbances the corrosion effects are probably most important in the 1 to 60 min period range. The more quietly varying, much longer period, *Sq* currents have such extreme amplitudes near the equator that they can contribute to the corrosion for pipelines in that region. Typically, at mid latitudes the geomagnetic variations are more a nuisance during pipeline potential determinations than a contributor to corrosion.

6. Pipe Current Measurement Techniques

The determination of the electric current flowing in the pipeline is critical to the evaluation of the corrosion effects at the points where the pipe is grounded. Many measurement techniques have been used to determine this current but three of the most valuable are the pipe-to-ground potential method, the pipe-shunt method, and the pipe-field-gradient method. Traditionally, the pipeline industry has favored the first two. The third was introduced in Alaska several years ago (Campbell and Zimmerman, 1980).

The first method gives a measure of the difference between the potential at the grounding point and the potential necessary for supporting the many superposed currents at the contact point of the pipe. A simultaneous measurement of the resistance between the two points allows a determination of the current that could flow out the pipe with corrosive effects. For Case 1 the pipe-to-soil current flow is not occurring; for a Case 2 pipe the measured current is divided between one or more Earth contact points in the region. In the U.S.A. the Department of Transportation

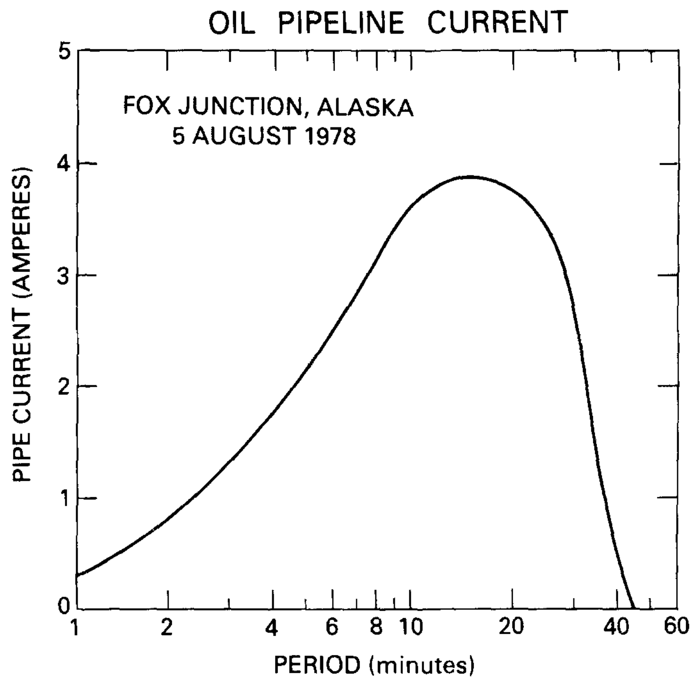

Fig. 16. Example of pipe current spectral composition during geomagnetically period at Fox Junction, Alaska, 0600–0730 UT, 5 August 1978, determined by a gradient field technique of observation (figure redrawn from Campbell, 1980).

sets pipe-to-ground potential level criteria for corrosion protection in the transport of hazardous materials such as oil and gas. During major geomagnetic disturbances these levels may be exceeded. Predictions of best times to avoid such high unrepresentative potential measurements are available (Campbell and Doeker, 1974).

In the shunt method the pipeline current is measured through a known low resistance ($\sim 10^{-6}\,\Omega$) path connected to the pipeline at two points separated by a few hundred meters. With a measurement of pipe resistance between the contact points, the electric current flow in the pipe may be determined exactly assuming that there are no pipe grounding points between the shunt contacts. Figure 9 pipeline current was measured in this fashion.

The field gradient method (Campbell and Zimmerman, 1980; and Campbell, 1980) uses the fact that the current in a linear conductor (pipe) produces a magnetic field encircling the conductor that decreases in direct proportion to the distance from the conductor. The gradient of this field (dB/dr in nT/m) is given by

$$I = r^2(dB/dr)/200 \tag{7}$$

where I is the current in amperes and r is the distance in meters from the pipe centerline to the measuring point. In practice two measurements of the Z-component of the field are made at two distances from the pipe giving Δr for dr. The difference of the field values, ΔB, is used for dB. Large scale nonpipeline sources of field change would cause essentially the same response at the two measurement locations; therefore, the ΔB values are free of such contributions. A computed location of the gradient equivalent to that between the two measurement points is taken as r. One advantage of this gradient method is that no contact with the pipeline is required so that both buried and above-ground pipes may be measured for their electric current flow. Figure 15 shows the similarity of values obtained for simultaneous measurements by the shunt and gradient methods in the Alaska pipeline at sites separated by 9.6 km. Figure 16 illustrates the spectral components of current in the Alaska pipeline determined by the gradient method during a geomagnetic disturbance.

7. Summary

Pipeline currents associated with geomagnetic field changes occur because sources of strong currents exist in the upper atmosphere. These currents vary in a way that is statistically predictable with respect to the time of day, geographic location, season of the year, and solar cycle; the currents show these variations in their amplitude, frequency and direction. These currents produce magnetic and electric fields at the Earth's surface. Because the Earth is a conducting material the source fields induce electric currents whose flow adds a field contribution at the Earth's surface. Longer period oscillations of the source fields penetrate deeper into the Earth whose conductivity increases at great depths. The spectral amplitudes of the observed surface fields are dependent upon both the source and induction characteristics. Earth surface topographic, geologic, and moisture anomalies modify the local size and direction of the fields. The conducting pipeline samples the Earth's electric field at grounded locations causing currents to flow between such points of potential difference. When the current flows out of the pipeline in contact with the ground through an imperfection in the pipe-insulation coating then corrosion may occur. The amount of corrosion depends on the current per unit hole area, the frequency of the current oscillations, and the chemical composition of the soil at the current exit contact point. Measurements of the pipeline currents are straightforward and may be predicted over extended time periods by establishing relationships to the local geomagnetic observatory records. Determinations of where the currents leave the pipeline and therefore where the concentration of corrosive effects are most likely to occur may be generalized from our knowledge of the physics of the phenomenon. However, exact evaluations of the corrosive effects are dependent upon local pipe and soil conditions that usually require detailed, and often difficult, field studies.

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References

Akasofu, S. I. and Merritt, R. P.: 1979, 'Electric Currents in Power Transmission Lines Induced by Auroral Activity', *Nature* **279**, 308.

Akasofu, S. I. and Aspnes, J. D.: 1982, 'Auroral Effects on Power Transmission Line Systems', *Nature* **295**, 136–137.

Albertson, V. D. and Van Baelen, J. A.: 1970, 'Electric and Magnetic Fields at the Earth's Surface Due to Auroral Current', *IEEE Trans. on Power Appar. Syst., PAS-89,* No. 4, Apr.

Albertson, V. D., Thorson, Jr., J. M., Clayton, R. E., and Tripath, S. C.: 1974, 'Solar-Induced Currents in Power Systems: Causes and Effects', *IEEE Trans. Power Appar. Syst., PAS-93,* 1031–1044.

Allen, J. H.: 1982, *Some Commonly Used Magnetic Indices: Their Derivation, Meaning and Use,* Proc. Workshop Satellite Drag, NOAA Space Environment Lab., Boulder, CO, March 18–19.

Axe, G. A.: 1968, 'The Effects of Earth's Magnetism on Submarine Cables', *Post Office Electr. Engr. J.* **61**, Part 1, 37–43.

Barker, R. H. and Skinner, N. J.: 1980, 'The Flow of Electric Currents of Telluric Origin in a Long Metal Pipeline and Their Effect in Relation to Corrosion Control', *Materials Performance* **19**, 25–28.

Barlow, W. H.: 1849, 'On the Spontaneous Electrical Currents Observed in Wires of the Electric Telegraph', *Phil. Trans. Roy. Soc.* **139**, 61–72.

Boerner, W. M., Cole, J. B., Goddard, W. R., Tarnewecky, M. Z., Shafai, L., and Hall, D. H.: 1983, 'Impacts of Solar and Auroral Storms on Power Line Systems', *Space Sci. Rev.* **35**, 195–205.

Brasse, H. and Junge, A.: 1984, 'The Influence of Geomagnetic Variations on Pipelines and an Application for Large Scale Magnetotelluric Depth Sounding', *J. Geophysics* (in press).

Burbank, J. E.: 1905, 'Earth Currents and a Proposed Method for Their Investigation', *Terr. Mag.* **10**, 23–49.

Cagniard, L.: 1953, 'Basic Theory of Magneto-Telluric Method of Geophysical Prospecting', *Geophysics* **18**, 605–635 (See also 'Comments and Discussions', in *Geophysics* **19**, 281–289, 1954.)

Campbell, W. H.: 1973, 'Spectral Composition of Geomagnetic Field Variations in the Period Range of 5 min to 2 hr as Observed at the Earth's Surface', *Radio Science* **8**, 929–932.

Campbell, W. H. and Doeker, R. B.: 1974, 'Pipe Induced Current Activity Indices', *Materials Performance* **13**, 9.

Campbell, W. H.: 1976a, 'An Analysis of Spectra of Geomagnetic Variations Having Periods from 5 min to 4 hr', *J. Geophys. Res.* **81**, 1369–1390.

Campbell, W. H.: 1976b, 'Spatial Distribution of the Geomagnetic Spectral Composition for Disturbed Days', *J. Geomagn. Geoelectr.* **28**, 481–496.

Campbell, W. H.: 1977a, 'Spectral Characteristics of Geomagnetic Field Variations at Low and Equatorial Latitudes', *J. Atmos. Terr. Phys.* **39**, 1217–1227.

Campbell, W. H.: 1977b, 'Spectral Characteristics of Field Variations During Geomagnetically Quiet Conditions', *J. Geomag. Geoelectr.* **29**, 29–50.

Campbell, W. H.: 1978, 'Induction of Auroral Zone Electric Currents within the Alaskan Pipeline', *Pure and Appl. Geophys.* **116**, 1143–1173.

Campbell, W. H.: 1980, 'Observation of Electric Currents in the Alaskan Oil Pipeline Resulting from Auroral Electrojet Current Sources', *Geophys. J. Roy. Astr. Soc.* **61**, 437–449.

Campbell, W. H. and Zimmerman, J. E.: 1980, 'Induced Electric Currents in the Alaskan Oil Pipeline Measured by Gradient Fluxgate and SQUID Magnetometers', *IEEE Trans. Geoscience and Remote Sensing* **GE-18**, 244–250.

Campbell, W. H.: 1983, 'A Description of the External and Internal Quiet Daily Variation Currents at North American Locations for a Quiet Sun Year', *Geophys. J. Roy. Astr. Soc.* **73**, 51–64.

Campbell, W. H. and Anderssen, R. A.: 1983, 'Conductivity of the Subcontinental Upper Mantle: An Analysis Using Quiet Day Records of North America', *J. Geomag. Geoelectr.* **35**, 367–382.

Chapman, S. and Bartels, J.: 1940, *Geomagnetism*, Clarendon Press, Oxford, 1049 pp.

Clement, K. T.: 1860, *Das grosse Nordlicht in der Nacht zum 29 August 1859 und die Telegraphenverwirrung in Nord-Amerika und Europa,* Hamburg, 121 pp.

Davidson, W. F.: 1940, ' The Magnetic Storm of March 24, 1940 –Effects in the Power System', *Edison Electr. Inst. Bull.* **365**.

Filloux, J. H.: 1979, 'Magnetotelluric and Related Electromagnetic Investigations in Geophysics', *Rev. Geophys. Space Phys.* **17**, 282–294.

Gideon, D. N., Hopper, A. T., and Thompson, R. E.: 1970, 'Earth Current Effects on Buried Pipelines: Analysis of Observations of Telluric Gradients and Their Effects', *American Gas Assn.*, Cat. No. L 30570, 77 pp.
Hansteen, C.: 1860, 'The Great Auroral Exhibition of Aug. 28th to Sept. 4th, 1859, 4th Article, I. Observations at Christiania', *Amer. J. Sci. Arts* **29**, 386–388.
Harang, L.: 1951, *The Aurorae*, Chapman and Hall, Ltd., London, 163 pp.
Hessler, V. P.: 1974, 'Causes, Recording Techniques, and Characteristics of Telluric Currents', *Corrosion* **56**, 1–18.
Jackson, C. M., Wait, J. R., and Walters, L. C.: 1962, 'Numerical Results for the Surface Impedance of a Stratified Conductor', *NBS Tech. Note*, No. 143, 43 pp.
Lanzerotti, L. J. and Gregori, G. P.: 1986, 'Telluric Currents: The Natural Environment and Interactions with Man-Made Systems', in R. Roble and E. P. Krider (eds.), *The Earth's Electrical Environment*, U.S. National Research Council Rept.
McCollum, and Ahlborn, G. H.: 1916, 'Influence of Frequency of Alternating or Infrequently Reversed Current on Electrolytic Corrosion', *NBS Tech. Paper*, No. 72, 31 pp.
McKinnon, J.: 1972, 'The August 1972 Solar Activity and Related Geophysical Effects', *NOAA Space Environ. Lab. Rept.*, Dec.
Meloni, A., Lanzerotti, L. J., and Gregori, G. P.: 1983, 'Induction of Currents in Long Submarine Cables by Natural Phenomena', *Rev. Geophys. Space Phys.* **21**, 795–803.
Peabody, A. W.: 1967, *Control of Pipeline Corrosion*, Nat. Assn. Corrosion Engr., Houston, 190 pp.
Peabody, A. W.: 1979, 'Consideration of Telluric Current Effects on Pipelines', in L. J. Lanzerotti, C. F. Kennel, and E. N. Parker (eds.), Chapter III. 2., of *Solar System Plasma Physics, III*, North-Holland Publ. Co., Amsterdam, pp. 349–352.
Pirjola, R.: 1983, 'Induction in Power Transmission Lines during Geomagnetic Disturbances', *Space Sci. Rev.* **35**, 185–193.
Prescott, G. B.: 1860, 'The Great Auroral Exhibition of August 28 to September 4, 1859, 2nd Article: 1. Observations Made at Boston, Mass., and its Vicinity', *Amer. J. Sci. Arts* **29**, 92–97.
Prescott, G. B.: 1866, *History, Theory and Practice of the Electric Telegraph*, IV ed., Ticknor and Fields Publ., Boston.
Rokityansky, I. I.: 1982, *Geoelectromagnetic Investigation of the Earth's Crust and Mantle*, Springer Verlag, New York, 381 pp.
Roosen, J.: 1966, 'The Seasonal Variation of Geomagnetic Disturbance Amplitudes', *Bull. Astron. Inst. Neth.* **18**, 295–305.
Saunders, H. C.: 1880, 'Earth-Currents', *Electrician* **167**, Aug. 21.
Saunders, H. C.: 1881, Discussion of paper by A. J. S. Adams, 'Earth Currents', *J. Soc. Tel. Eng. Electricians* **10**, 46–48.
Schmucker, V.: 1970, 'An Introduction to Induction Anomalies', *J. Geomag. Geoelectr.* **22**, 9–33.
Slother, J. C. and Albertson, V. C.: 1967, 'The Effects of Solar Magnetic Activity on Electric Power Systems', *J. Minnesota Acad. Sci.* **34**, 94–100.
Smart, A. L.: 1982, 'The Trans-Alaska Pipeline – Potential Measurements and Telluric Current', *IEEE Trans. Industry Appl.* **1A-18**, 557–567.
Stormer, C.: 1955, *The Polar Aurora*, Clarendon Press, Oxford, 403 pp.
Tikhonov, A. N.: 1959, 'The Propagating of Continuous Electromagnetic Waves in Luminary Anisotropic Medium', *Dokl. Akad. Nauk. SSSR* **4**, 556–578.
Varley, C. F.: 1873, 'Discussion of a few Papers on Earth Currents', *J. Sci. Tel. Engr.* **2**, 111–114.
Wait, J. R.: 1962, 'Theory of Magnetotelluric Fields', *J. Res. NBS* **66D**, 509–541.
Wait, J. R.: 1982, *Geo-Electromagnetism*, Academic Press, New York, 268 pp.
Ward, S. H.: 1967, 'Electromagnetic Theory for Geophysical Application', in *Mining Geophys.* **2**, 107–124, Soc. of Exploration Geophys., Tulsa.
Wescott, E. M. and Hessler, V. P.: 1962, 'The Effect of Topography and Geology on Telluric Currents', *J. Geophys. Res.* **67**, 4813–4823.
White, O. R.: 1977, *The Solar Output and Its Variations*, Colorado Associated Univ. Press, Boulder, 526 pp.