Telluric Current Effects on Corrosion & Corrosion Control Systems on Pipelines in Cold Climates

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The impact of telluric current activity on the corrosion control systems on pipelines in northern regions and cold climates is examined. Three specific areas of concern are identified. These factors are corrosion of the pipe during positive cycles of the telluric disturbances, accurate measurement of cathodic protection performance parameters, and coating damage during negative cycles of the telluric activity. Corrosion rates are calculated versus the magnitude of the pipe potential change caused by discharging telluric current for different values of the Kp geomagnetic index. Methods of compensating and mitigating telluric current effects are discussed in the context of the cathodic protection design and monitoring procedures. The benefits of using potential controlled rectifiers and integrated reference/coupons in mitigating telluric current effects are illustrated.

Potential and current fluctuations on oil and gas pipelines attributed to telluric currents have been observed for many years by corrosion control personnel when conducting routine cathodic protection performance surveys. The impact of these geomagnetically induced currents has generally been considered more of a nuisance when measuring cathodic protection parameters than a serious corrosion concern. Boteler[1] has shown that the telluric voltage induced on a pipeline can be calculated using distributed source transmission line (DSTL) equations and that the magnitude of the telluric voltage (V_t) is not only a function of the direction and magnitude of the electric field, but is also directly dependent on the pipe's length and resistance to earth. These calculations when applied to modern well coated pipelines, suggests that telluric current effects may not be as innocuous as originally thought, especially for long pipelines located in northern latitudes.

For the corrosion control practitioner there are three main areas of concern regarding the effects of geomagnetically induced current as follows:

- corrosion during the positive half cycles of the telluric wave form, and
- accuracy of pipeline current and potential measurements when determining the level of cathodic protection for comparison with industry criteria, and
- coating damage caused by excessively negative potentials during the negative half cycles of the telluric waveform.

CORROSION

Research Results

A research study[2] on the "Earth Current Effects on Buried Pipelines" sponsored by the American Gas Association (AGA), which was conducted in 3 phases between 1966 and 1970, concluded that *"the effects are insignificant, both for coated, protected lines and for bare lines"*. This conclusion was based on the analysis of field data recorded on four pipelines between the summer of 1968 and October 1969, close to a peak of sunspot activity when a reasonably high level of geomagnetic activity was expected. The conclusion drawn from this investigation, undertaken more than 30 years ago, may not be as relevant for some modern pipeline networks, especially in latitudes closer to the magnetic poles.

Firstly, the coated pipelines chosen in the AGA study had relatively low leakage resistance, in the order of 10K-ohm-m^2, compared to modern pipeline coatings for which values of greater than 100K-ohm-m^2 [3,4] are common. Geomagnetically induced voltages would, therefore, be considerably greater on better coated pipelines, since the level of induced voltage is directly proportional to coating resistance. On northern pipelines the geomagnetic activity would be greater during the winter months simply because of the increase in pipe/earth resistance due to the over 10 fold increase in soil resistivity when the soil around the pipe freezes.

Secondly, all the pipelines under test were electrically short (only one greater than 65 km) which, according to the DSTL equations would produce much lower amplitude fluctuations than on longer pipelines.

Thirdly, the pipelines were also located in the U.S. at mid-latitudes (all were at latitudes lower than 46°N), where the probability of a large storm is up to 100 times less than in Canada and Alaska.[5]

Fourthly, even though the study spanned a time period which was near the peak of solar cycle 20, the GIC annual 'aa' index, representing geomagnetic intensity, was lower than in any of the following 30 years.[6]

Finally, the longest pipeline in the study (190 km) and the one that exhibited the largest telluric pipe-to-soil amplitudes was located about 35°N where the probability of a large geomagnetic storm, as previously defined is only 0.003%. It is apparent therefore that the results of the AGA study may not be applicable to long pipelines, to very well coated pipelines, to pipelines located in Northern latitudes, and even to similar pipelines today since the telluric intensity, as represented by the 'aa' index (i.e. >60 nT), has generally increased with time.[7]

Reported Instances of Corrosion Caused by Telluric Currents

Pipe-to-soil potential measurements on a cathodically protected pipeline in Northern Norway were recorded over a 2-3 month period in 1971 and analyzed by Henriksen et al.[8] with respect to their probable corrosion impact. By correlating the duration and magnitude of potential excursions more positive than the -850mV_{cse} criterion with corrosion rate versus potential data obtained in laboratory tests, it was concluded "*that telluric current corrosion in auroral zones has about the same magnitude as the normal corrosion is (sic) soil where telluric corrosion is lacking*". This conclusion however assumed that the telluric discharge involved purely metal dissolution rather than oxidation of any other species, which probably overstates the corrosion activity.

In 1986, Seager [9] conducted a study on a 522 km cathodically protected oil transmission pipeline, located between 55° and 70° N geomagnetic latitude, using small steel coupons installed along the pipe length, and concluded "*…telluric related corrosion*

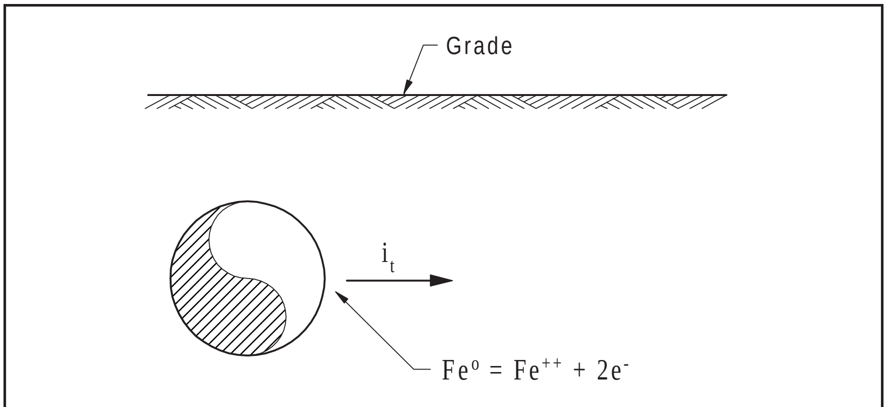

FIGURE 1a • Telluric Current Discharge from Pipe Surface during Positive Cycle

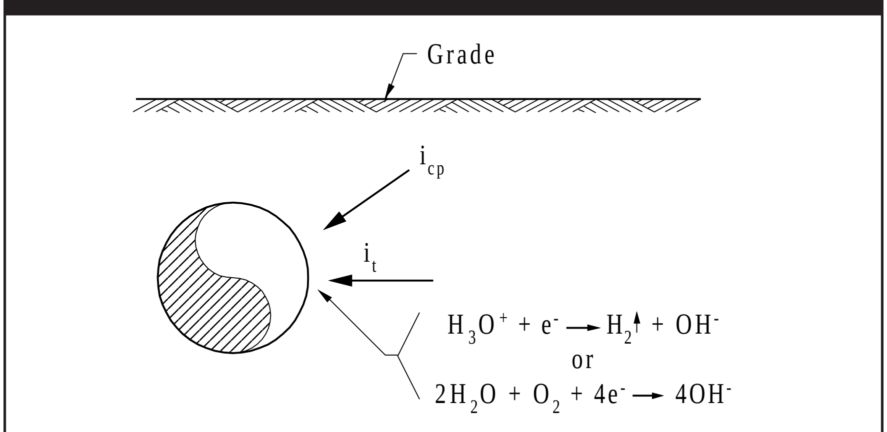

FIGURE 1b • Telluric Current Pick-up During Negative Cycle & Cathodic Protection Current

can override any standard corrosion prevention system and cause pipe perforation in unacceptably short periods of time…”.

By measuring each coupon’s potential instantaneously after disconnecting them from the pipeline (i.e. an ‘instant off’ potential), the ‘polarized’ potential was determined, free of IR drop due to potential gradients caused by both the cathodic protection or the telluric current. This showed that there were periods of time when the polarized potential was more electropositive than the generally accepted -850 mV_{cse} cathodic protection criterion[10] and other periods of time where it was more positive than -650 mV_{cse}, prompting Seager to conclude that corrosion would occur for an estimated 15% and 4% of the time respectively. Based on this pattern of activity, he calculated that the pipe could be perforated in less than four years at a 0.6 cm diameter coating flaw.

Martin[11] has also reported telluric corrosion on a 515 km gas pipeline in northeastern Australia, where the cathodic protection monitoring criterion was being met but the buried resistance probes indicated corrosion rates in excess of .010 mm/a. In one location the corrosion rate was .038 mm/a, a rate that would cause a 10% pipe wall penetration in about 14 years.

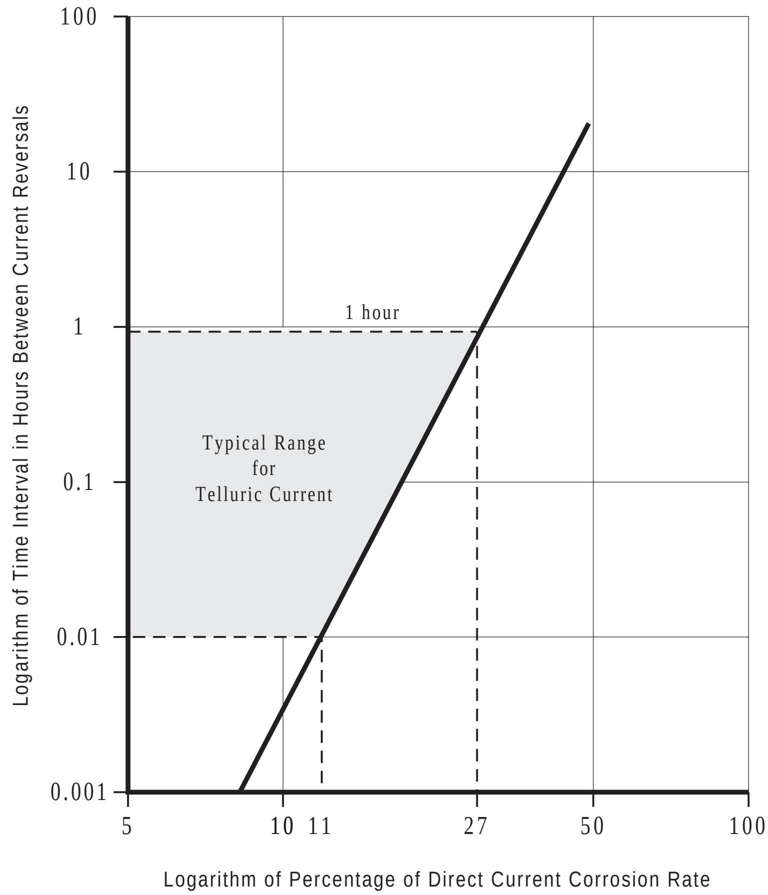

FIGURE 2 • Effect on Corrosion Rate of Reversing Direction of Current Compared to Steady State Direct Current and Length of Time between Reversals (redrawn from Peabody, 1979)

Corrosion Theory

During the time when telluric current transfers from the pipe to earth (positive portion of the telluric cycle) the charges must transfer through an oxidation reaction. For a pipe without cathodic protection, the primary oxidation reaction is corrosion of the steel as illustrated in Figure 1(a) and as expressed by the following reaction:

$\mathbf{Fe^\circ \Rightarrow Fe^{++} + 2e^-}$ (corrosion) [1]

For steel, approximately 10kg will be lost in 1 year for every ampere of continuous direct current that discharges.

When a pipeline is cathodically protected, a cathodic current transfers from the earth to the pipe via one or both of the following reduction reactions depending on the soil conditions;

$\mathbf{H_3O^+ + e^- \Rightarrow H_2 + OH^-}$ [2]
(in de-aerated or acidic soils)

or

$\mathbf{2H_2O + O_2 + 4e^- \Rightarrow 4OH}$ [3]
(in alkaline or neutral aerated soils)

This is also true for a telluric current for the negative half cycle as shown in Figure 1(b).

Cathodic protection current therefore results in the formation of a high pH environment, typically in the range of 10-13, at coating flaws (holidays) regardless of which reduction reaction transfers the charges. The magnitude of the pH has been shown to be proportional to the logarithm of the current density.[12]

When a positive current transfers from a cathodically protected pipe, the initial oxidation reaction is likely to result in the formation of a passive film where the corrosion rate is low. If the telluric current discharge is intense, sustained, and the residual pH remains high, then the oxidation reaction could be equation [4].

$\mathbf{4OH^- \Rightarrow 2H_2O + O_2 + 4e^-}$ [4]

This charge transfer reaction, does not cause corrosion.

Accordingly, the total corrosion that occurs at a coating defect as a result of current discharge is not strictly proportional to the charge transferred as would be predicted by Faraday's Law for a steady state direct current. Cyclic variations in telluric current of equal amplitude and period will corrode steel less than a steady state direct current of the same magnitude applied for the same time period, as discovered in a National Bureau of Standards investigation.[13] This finding was summarized by Peabody[14] as shown in Figure 2 and indicates that there is a relationship between the logarithm of the period and the logarithm of the percentage of corrosion compared to an equal amount of direct current.

As the majority of telluric periods are between 0.01 and 1 hour, then the amount of corrosion activity would be about 11-27% of an equivalent direct current. It should be noted that diurnal telluric activity, although typically less intense than the shorter periods, would produce a corrosion rate of approximately 50% of an equivalent direct current because it would have a 12 hour period.

The amount of corrosion that occurs during the positive period will also depend on the intensity of the telluric disturbances. On very well coated modern pipelines, current transfer between the pipe and soil occurs at small coating defects. Relatively small potential fluctuations in the order of 0.5 - 1.0 V can produce a large current density as shown in Figure 3.[15] Here, for a 1 cm diameter circular holiday in a 0.3 mm thick coating (a typical thickness for fusion bonded epoxy coatings) the current density, for a soil resistivity of 1000 ohm-cm and a telluric voltage change of 1.0 V, would be approximately 2500 $\mu A/cm^2$ producing a corrosion rate of approximately 31.3 mm/a. To account for the telluric current period and intensity, the corrosion rate formula must be modified as follows:

$$\text{CorrosionRate(Fe)} = \frac{2.5\times10^{-3}\,\text{A}}{\text{cm}^2\text{V}} \bullet \frac{12.5\times10^{-3}\,\text{mm / a}}{10^{-6}\,\text{A / cm}} \bullet \Delta V_t \bullet F(p) \bullet F(t) = \text{mm / a}$$

ΔVt = change in potential of the pipe caused by telluric activity
$F(p)$ = fraction of steady state corrosion due to alternating period of the telluric current
$F(t)$ = fraction of time that telluric current is present

The corresponding corrosion rate based on a 0.5 V potential change (V_t = 0.5V) caused by a telluric current occurring for 6% of the time (Kp $\cong$ 5), in the absence of any cathodic protection current, is calculated to be between 0.06 and 0.152 mm/a for telluric periods of 0.01 and 1 hour respectively. These resultant corrosion rates both exceed 0.025 mm/a which is generally considered the maximum acceptable corrosion rate for oil or gas transmission pipelines when cathodically protected.

The range of corrosion rates in 1000 ohm-cm soil at a 1 cm diameter holiday can be calculated for various geomagnetic intensity levels (Kp indexes) and telluric voltage effects (V_t) as shown in Figure 4. The Kp geomagnetic activity index was used by Boteler[16] to calculate peak electric fields in the Ottawa area based on 3 hour intervals and then was related to the probability of occurrence. It can be seen that even modest telluric voltage effects of 0.10V can have a significant corrosion impact if produced by a Kp

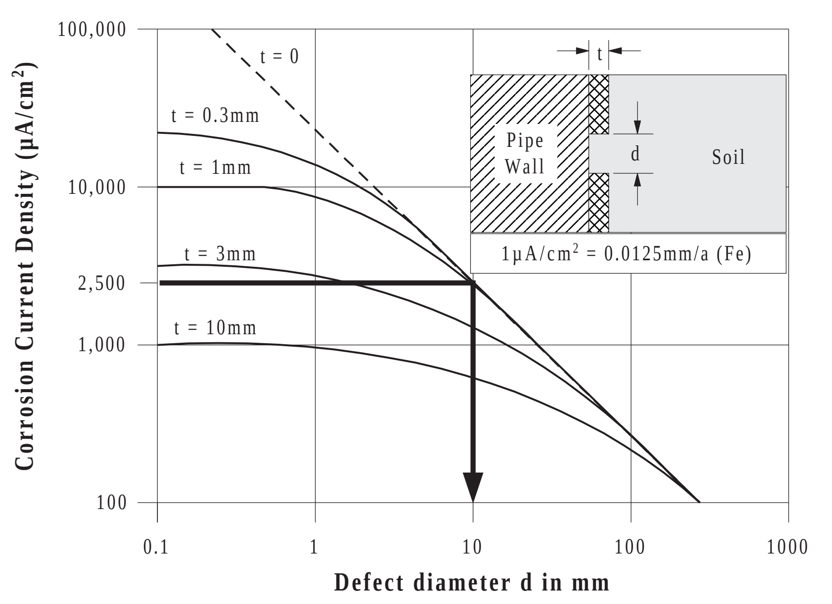

FIGURE 3 • Corrosion Current Density at a Coating Defect having an Applied Voltage of 1.0V in 1,000 ohm-cm Soil for Various Coating Thicknesses (redrawn from Von Baeckman & Schwenk, 1975)

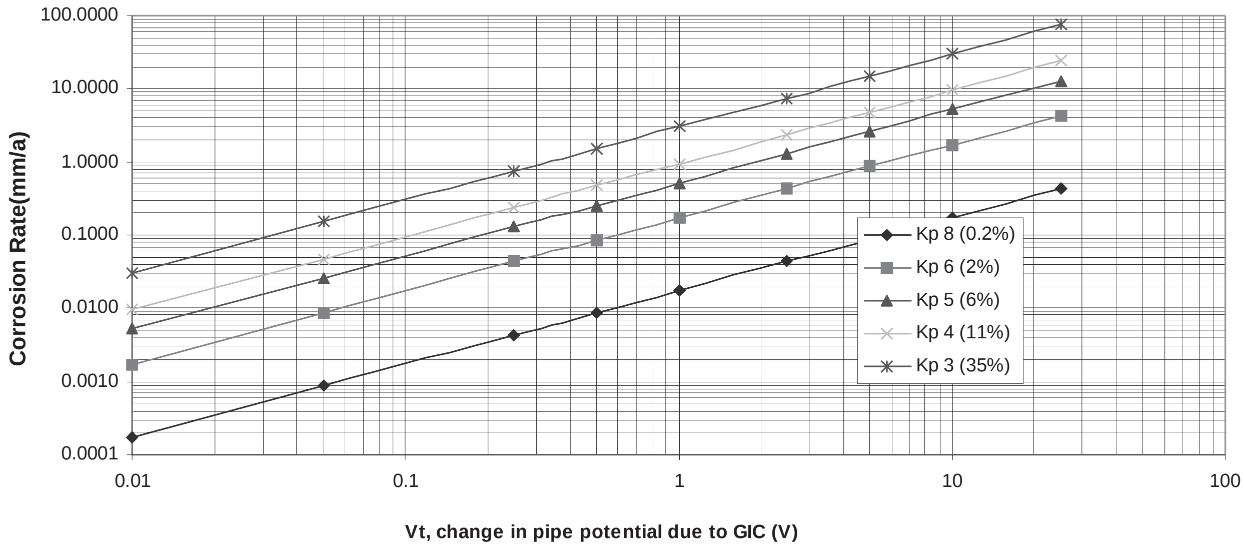

FIGURE 4 • Calculated Corrosion Rate vs. Pipe Potential Change (V_t) having a Period of 1 Hour at a 1 cm Holiday in 1000 ohm-cm Soil for Various Geomagnetic Intensities (Kp Index) and Percent Probabilities

3 magnetic disturbance in the absence of cathodic protection. Cathodic protection will of course reduce the telluric corrosion depending on the level of protection on the pipeline at the time of the telluric activity. Cathodic protection systems should be designed to mitigate the higher probability telluric activity rather than the low probability activity (i.e. Kp 8) since the latter, although more intense, are only present for a short period of time.

EFFECTS ON CATHODIC PROTECTION SYSTEMS

General

It is typical [17] to design cathodic protection systems to produce a minimum of -0.3 V change in potential at the pipe/soil interface and hence the corrosion impact of a +0.3 V potential change created by a telluric current would be largely mitigated by a properly operating cathodic protection system. To ameliorate telluric voltage shifts of greater than +0.3 V, either requires a proportionate steady state increase in the output of the cathodic protection system, or the cathodic protection system must operate to increase its output in response to a telluric discharge.

Sacrificial Systems

Sacrificial cathodic protection systems have a limited capacity to compensate for a telluric potential shift since they have a relatively small fixed output voltage. They do however, offer an alternative path to earth for the telluric current (I_t) because of their relative low resistance to earth compared to a coated pipeline. Hence some proportion of the telluric current (I_t) will transfer to the earth via the anode as shown in Figure 5.

As long as the cathodic protection current (I_{cp}) is equal to or greater than the residual telluric current (I_t''), then the telluric current effect is fully mitigated at the anode location. The

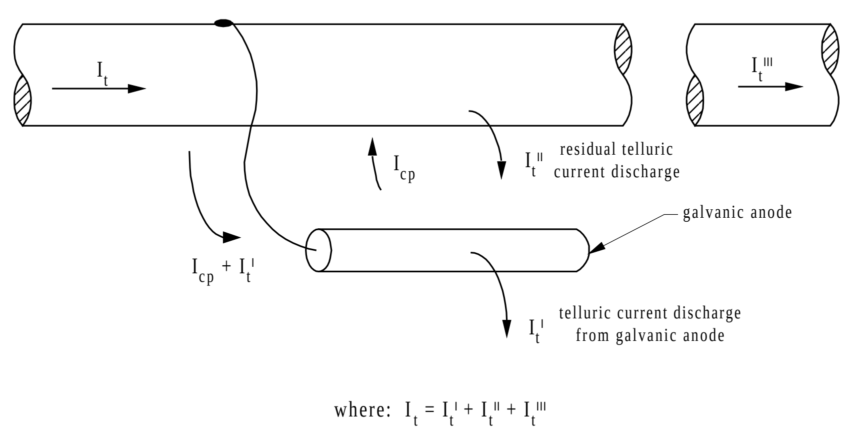

FIGURE 5 • Mitigation of Telluric Current Discharge Effects using Galvanic Anodes

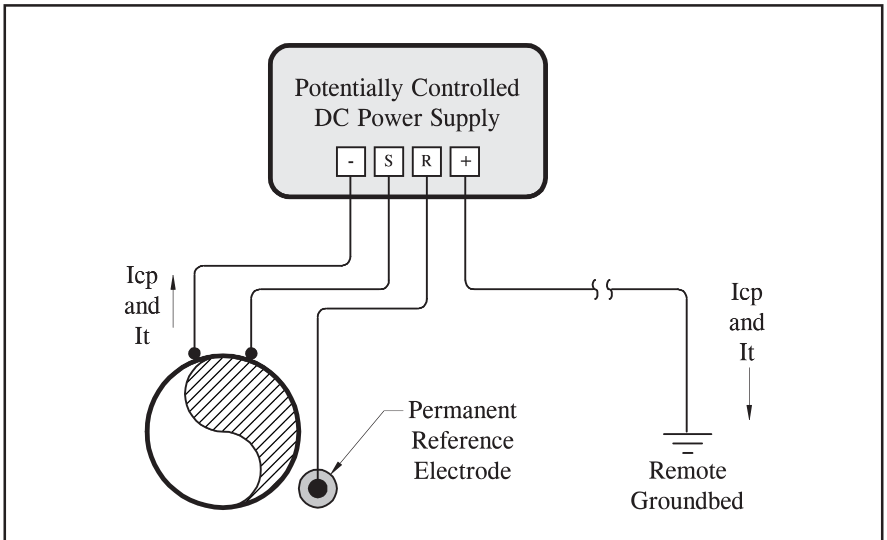

FIGURE 6 • Schematic of Potentially Controlled Cathodic Protection System Used to Mitigate Telluric Current Effects

resistance to earth of a well coated pipeline can be reduced by at least an order of magnitude simply by the attachment of galvanic anodes distributed along its length. This cathodic protection method, which makes the pipeline electrically lossy, was used on the Trans-Alaska pipeline[18] in the form of a zinc ribbon anode which was placed at pipe invert elevation on each side of the pipe for the full extent of the underground portion of the system. Grouping of zinc and magnesium sacrificial anodes at selected intervals has also been shown to be effective by Henriksen et al.[19] when used on a pipeline in northern Norway where the telluric potential fluctuations were reduced from ±5 V to ±0.1 V.

Impressed Current Systems

Impressed current cathodic protection (ICCP) systems can be designed with relatively unlimited voltage capacity, although it is inefficient to operate the system at higher voltages continuously just to provide a buffer for the anticipated telluric positive voltage shift. In addition the very high negative potentials produced by oper-

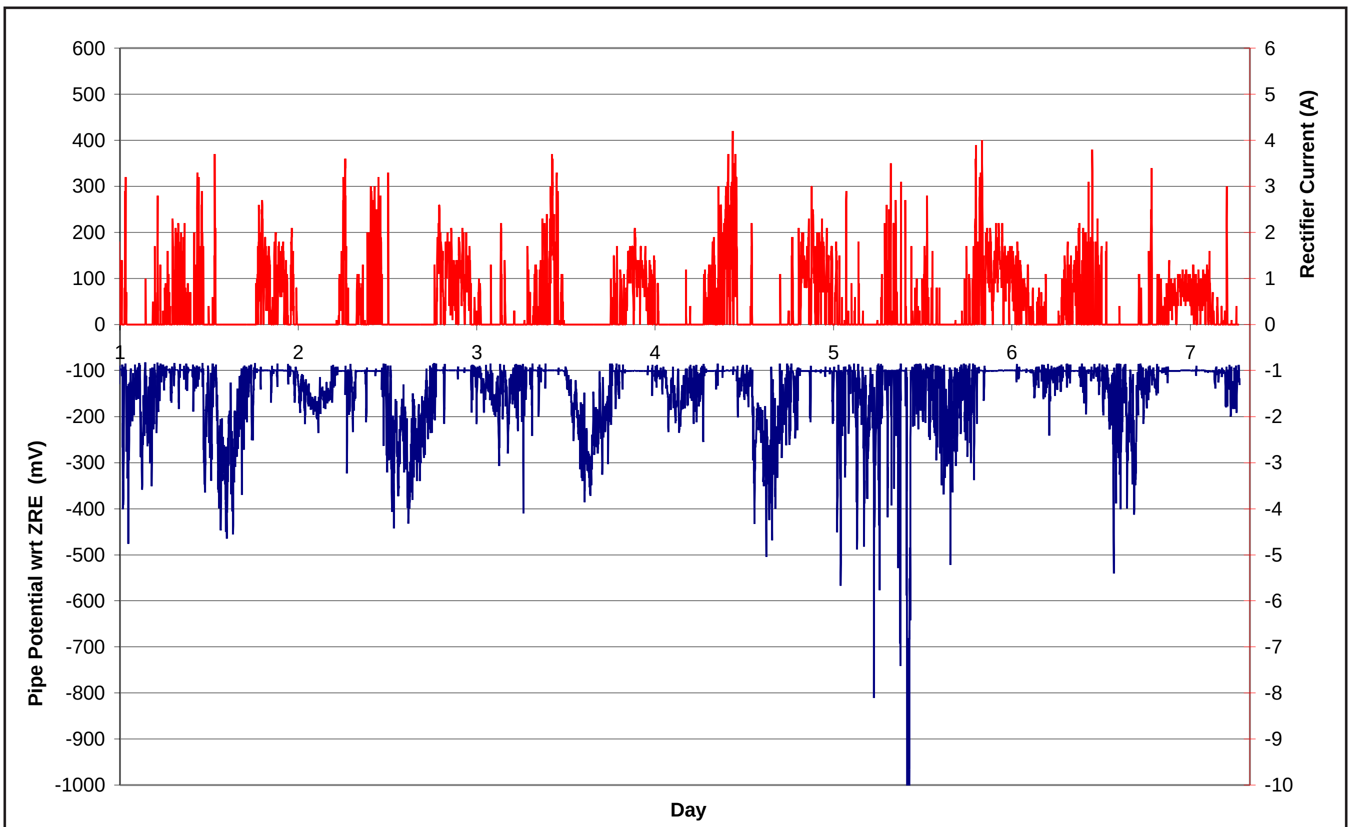

FIGURE 7 • Pipe Potential and Rectifier Current Output vs. Time for an Impressed Current System Operating in Potential Control

ating ICCP systems at high current outputs can cause cathodic disbondment of the coating. DC power supplies operating in the potential control mode have however, been used to ameliorate telluric currents.[20,21,22] The voltage and current output of these units change automatically in response to the pipe potential, as measured to a local reference electrode, which is compared with a minimum set potential as illustrated schematically in Figure 6.

Here, the pipe potential is measured continuously with respect to the buried reference electrode and compared to a pre-set potential in the controller of the DC power supply. When a telluric current attempts to discharge from the pipe the reference senses the positive potential shift and the power supply immediately increases its output to maintain the set potential value. The impressed current system therefore presents a negative resistance path for the telluric current to earth and there is no residual discharge of telluric current from the pipe as long as the voltage or current limit of the power supply has not been reached. The power supply voltage and current capacity must be sized to provide the needed cathodic protection current plus the amount of telluric current to be drained. This type of cathodic protection system functions as a telluric current ‘forced drainage’ system and its mitigating effect is illustrated in Figure 7 which compares typical rectifier output with time to the pipe potential. Note that the rectifier operates only when the pipe potential attempts to go more electropositive than -100 $mV/_{ZRE}$ (-1200 $mV/_{CSE}$). The potential controlled rectifier drains the telluric current during periods of telluric current discharge, limits how negative the potential across the coating is during periods of telluric current pick-up, optimizes the operation of the impressed current system and maximizes the life of the groundbed.

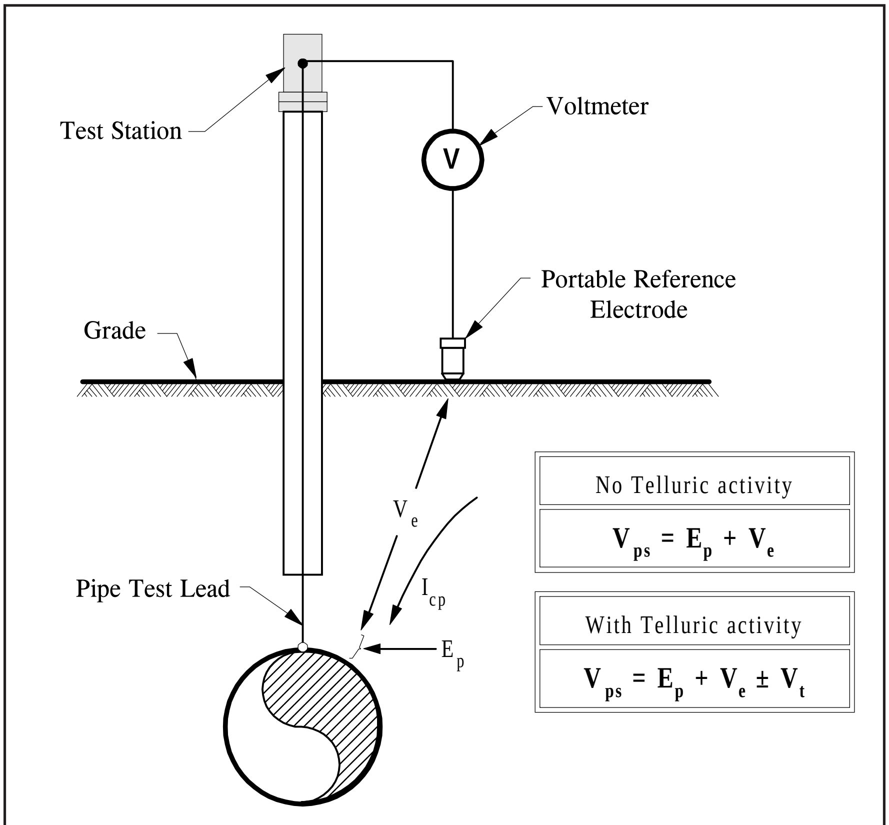

FIGURE 8 • Typical Pipe-to-Soil Potential Measurement at Test Station

CATHODIC PROTECTION PERFORMANCE MONITORING

It is usual and required by code[23,24] to measure the pipe-to-soil potential on a routine basis to ensure that a minimum cathodic protection potential is being maintained. This involves taking a potential measurement at test station locations as illustrated in Figure 8.

Here the pipe-to-soil potential (V_{ps}) is measured using a high resistance voltmeter connected between a pipe test lead and a reference electrode placed in contact with the soil such that

$$V_{ps} = E_p + V_e$$

where:

E_p = the pipe polarized potential across the pipe/soil interface (V)

V_e = $I_{cp} \bullet R_e$ = the voltage drop in the earth caused by the cathodic protection current in the earth between the point in the earth where the reference is placed and the pipe surface (V)

V_{ps} = voltage appearing on the voltmeter

A pipeline is considered effectively protected from corrosion[25] when the pipe polarized potential (E_p) is equal to or more negative than -850 mV with respect to a copper-copper sulphate reference electrode (cse).

To obtain the polarized potential, the cathodic protection current is cyclically interrupted so that the earth voltage drop (V_E) goes to zero and the voltmeter measures the ‘instant off’ potential for comparison to the –850 mV_{cse} criterion.

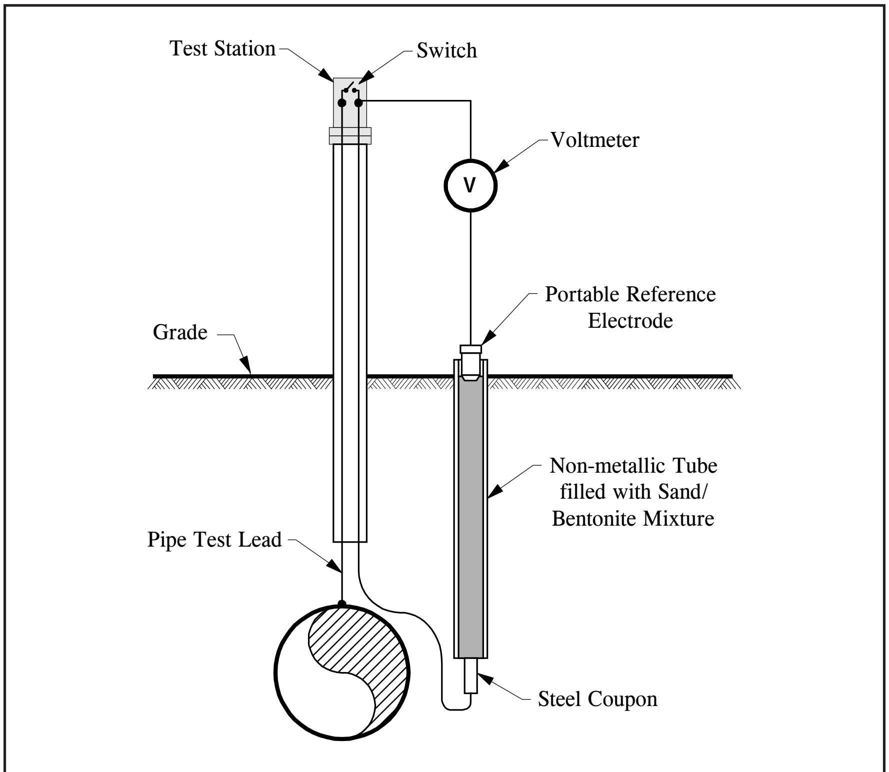

FIGURE 9 • Typical Pipe-to-Soil Potential Measurement at Test Station having a Steel Coupon and Soil Tube

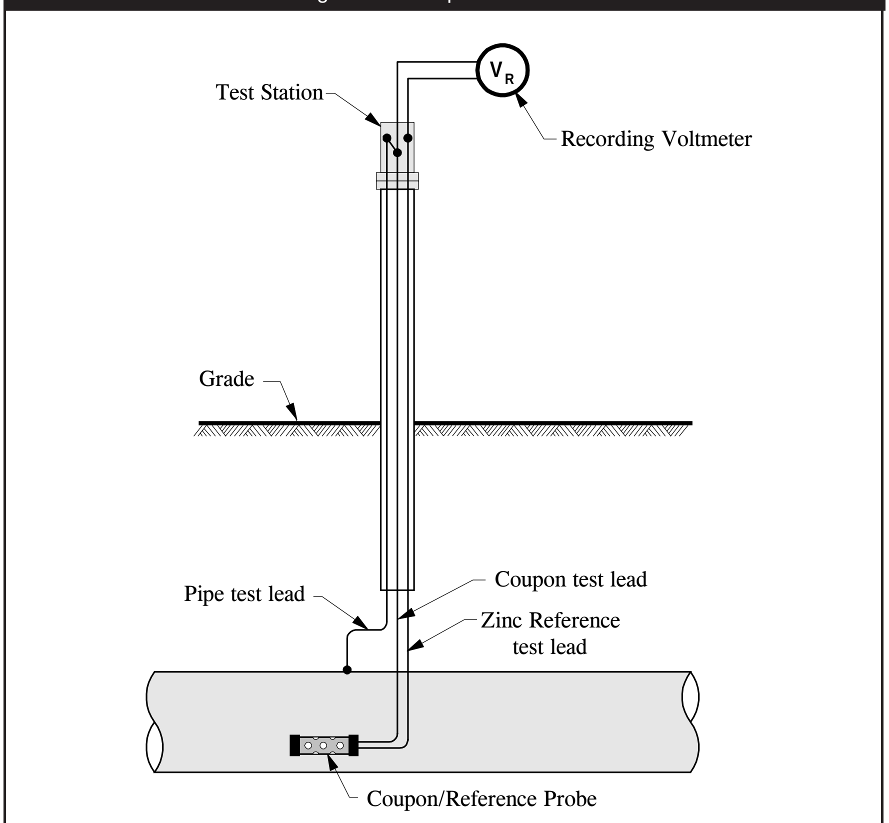

FIGURE 10 • Typical Pipe-to-Soil Potential Recording at a Test Station using a Coupon/Reference Probe

When telluric current is present the voltmeter reads an additional telluric potential difference (V_t) between the pipe and reference whose polarity alternates with time and whose magnitude fluctuates with time and location on the pipeline.

That is: $V_{ps} = E_p + V_e \pm V_t$

Since the geomagnetically induced current cannot be arbitrarily interrupted, an alternative method has been employed by some companies[26,27] where a small steel coupon is installed next to the pipe, and is interconnected with the pipe inside the test station. The coupon simulates the pipe/soil surface at a defect in the coating. When the coupon is temporarily disconnected and the reference electrode is placed in the soil tube, as illustrated in Figure 9, both the telluric and cathodic protection voltage drops in the earth are removed and the ‘instant off’ potential (E_p) of the coupon is measured for comparison to the -850 mV_{cse} criterion.

This test arrangement however is not suitable for recording the polarized potential with time, since the coupon has to be disconnected for each measurement. The use of a reference/coupon combination, as illustrated in Figure 10, has proved to be an excellent method of recording a polarized potential with time. The coupon in this device does not require disconnection, since a zinc reference is located inside the pipe coupon, where there is no cathodic protection nor telluric voltage gradient. Figure 11 is a comparison of the pipe/coupon potential recorded to a CSE reference placed on grade and to the zinc reference located inside the coupon. The difference between the potential values is the soil voltage gradient caused by both the telluric and cathodic protection currents. Note that, despite the significant potential fluctuations in the potential

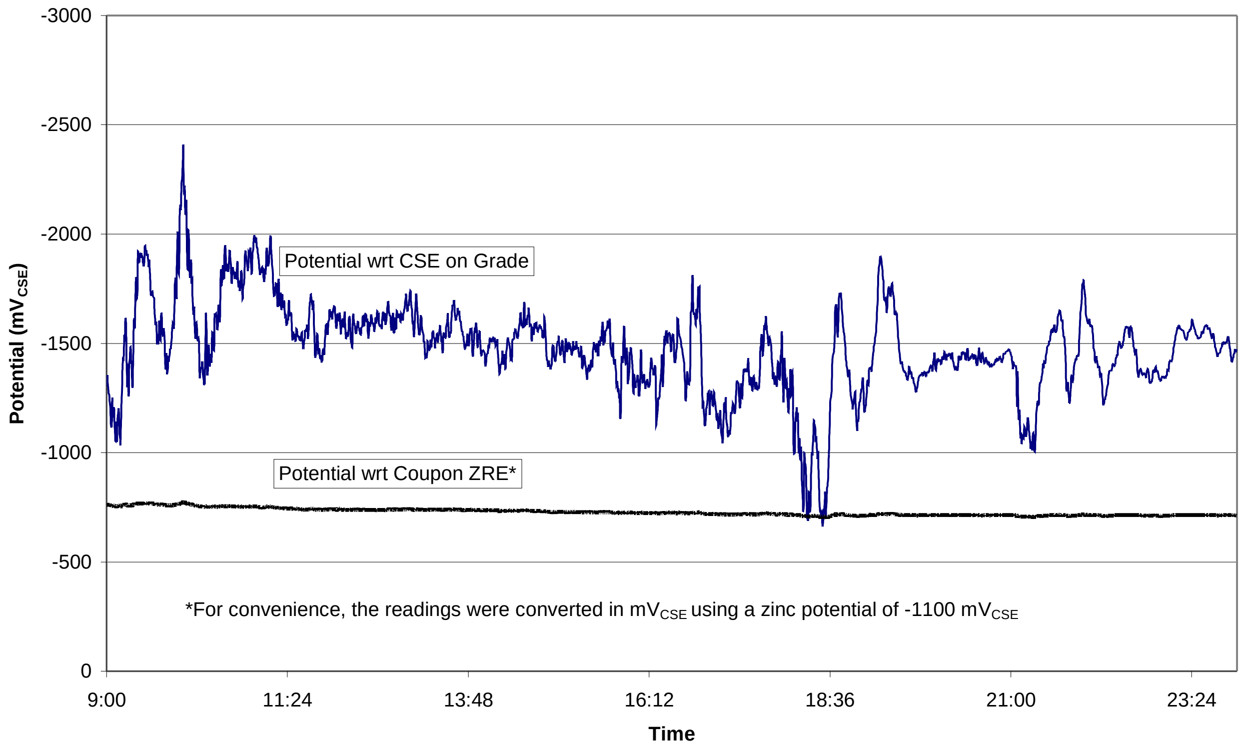

FIGURE 11 • Comparison between Pipe/Coupon Potential with Time between A Copper-Copper Sulphate Reference on Grade and a Zinc Reference Electrode Located inside the Coupon

measurement using a surface copper-copper sulphate electrode, the actual potential at the coupon/soil interface is relatively stable with time.

Although the use of a coupon is a relatively simple solution at a test station, the measurement of telluric free potentials is more complex for close interval potential surveys (CIS) where the reference is moved and placed over the pipe at intervals (typically < 3 m) along the route of the pipeline.

Proctor[28] proposed a measurement method to compensate for the telluric induced voltage which involved the correction of the measured potential (Vm) with respect to the moving reference by the change in potential (ΔVf) measured with respect to a fixed reference located at a nearby test station such that:

$$Vps = Vr \pm \Delta Vf$$

where

$$\Delta Vf = Vf_{ave} - Vf$$

This measurement technique is illustrated in Figure 12 in which two separate data loggers are used to record the potentials with respect to the fixed and moving electrodes. This technique can be used with synchronous interruption of the rectifiers such that a telluric compensated 'instant off' potential can be calculated in software from the recorded data. The accuracy of this technique depends on whether or not the average potential (Vf_{ave}) represents a 'telluric free' condition and on the proximity of the fixed location to the moving electrode since long separation distances can introduce errors due to potential differences in the earth parallel to the pipe route and to telluric current voltage drop in the pipe.

Degerstedt et al.[29] (1995) have used a 'telluric null' technique on the Trans Alaska Pipeline System, which overcomes the limitations in the foregoing survey method. They recorded the potential and current parameters at a test station with time to produce a fundamental characteristic for each test location as illustrated in Figure 13.

The telluric current was measured using magnetometers placed on grade on each side of the pipeline. It can be seen that there is a linear relationship between the telluric current and the pipe potential and through regression analysis the 'telluric null' potential is identified as the intercept with the pipe potential axis.

With a historical characteristic established at each test station, the CIS is conducted using global positioning system time stamping to record both

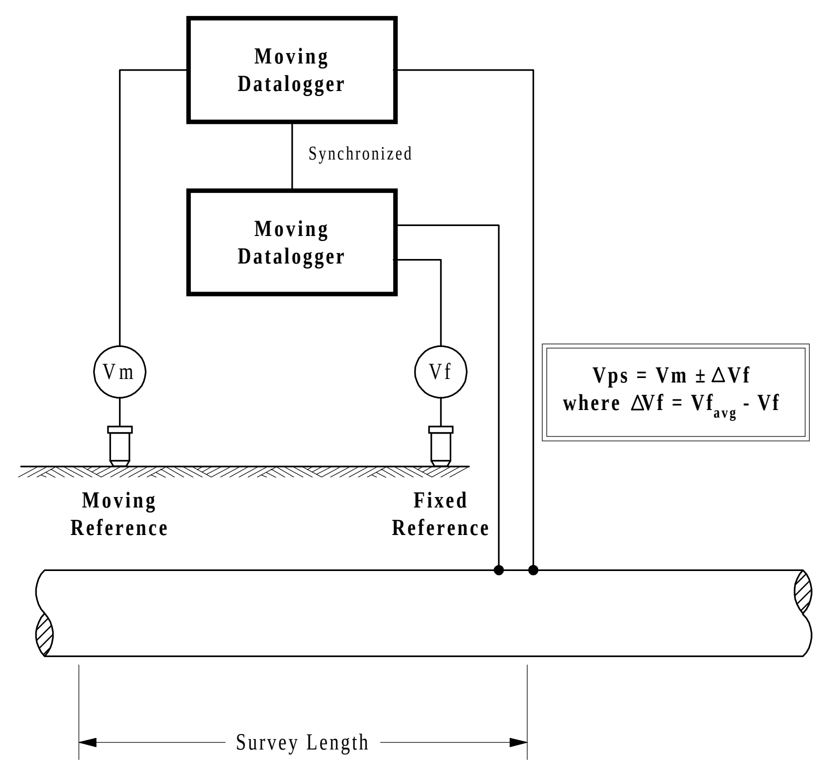

FIGURE 12 • Pipe-to-Soil Potential Measurement Method to Compensate for Telluric Current Effects During a Close Interval CP Survey

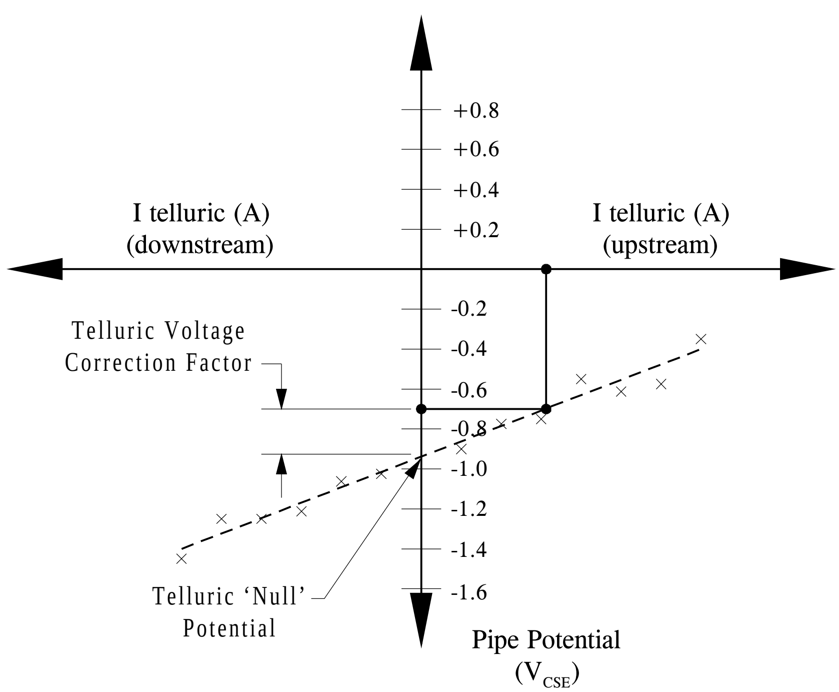

FIGURE 13 • Pipe Potential/Telluric Current Relationship at a Coupon Test Station

pipe current magnitude and potential with respect to a moving reference and this potential is corrected relative to the voltage at the fixed electrodes at the adjacent test stations by an appropriate correction factor.

In lieu of magnetometers, the pipe current can also be determined by measuring the voltage drop along the pipe as illustrated in Figure 14, although this arrangement would require installation of pipe test leads at each test station location. Where telluric current activity is anticipated, the four wire test arrangement should be installed at each test station location so that the telluric null method can be utilized. In addition, each test station should also incorporate a coupon/reference probe to facilitate the recording of pipe-to-soil polarized potentials with time.

SUMMARY

In order to maintain effective corrosion control on relatively long coated pipelines that have high leakage resistance and that are located in latitudes close to the magnetic poles and therefore subjected to telluric currents, the following measures should be taken:

- Maintain good electrical continuity throughout the system
- Integrate mitigation facilities with the cathodic protection system to reduce the magnitude of the telluric voltage fluctuations in both the positive and negative directions
- Install test station facilities incorporating coupons that can be used to measure 'telluric free' pipe-to-soil potentials
- Install four wire test station facilities so that the pipe current can be recorded with time.
- Use data loggers that are time synchronized and apply a correction factor to obtain accurate close interval pipe-to-soil data.

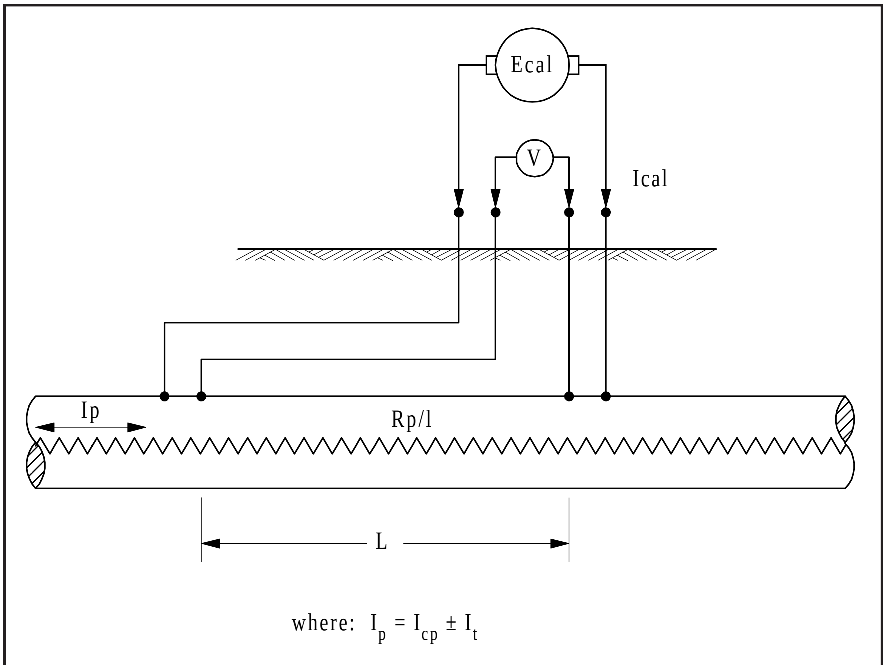

FIGURE 14 • Four Wire Test Lead Arrangement for Measuring Pipe Current

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