GIC Effects on Pipeline Corrosion & Corrosion Control Systems

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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 equations. He has shown that the magnitude of the telluric voltage (Vt) is not only a function of the direction and magnitude of the electric field but also directly dependent on the length and the pipe's 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 for pipelines located in Canadian latitudes.

For the corrosion control practitioner there are three main areas of concern as follows:

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

CORROSION

Research Results

A research study[1] on the "Earth Current Effects on Buried Pipelines" sponsored by the American Gas Association (AGA), 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 Oct. 1969, just past the 11 year peak of solar cycle 20, during which reasonably high levels of telluric activity would be expected. The conclusion drawn from this investigation, undertaken more than 30 years ago, may not be as relevant when applied to 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[2],[3] are common. Tellurically induced voltages would therefore be expected to be considerably greater on better coated pipelines, since the level of telluric voltage is directly proportional to coating resistance.

Secondly, all the pipelines under test were electrically short (only one greater than 65 km) which, according to the distributed source transmission line (DSTL) method would produce

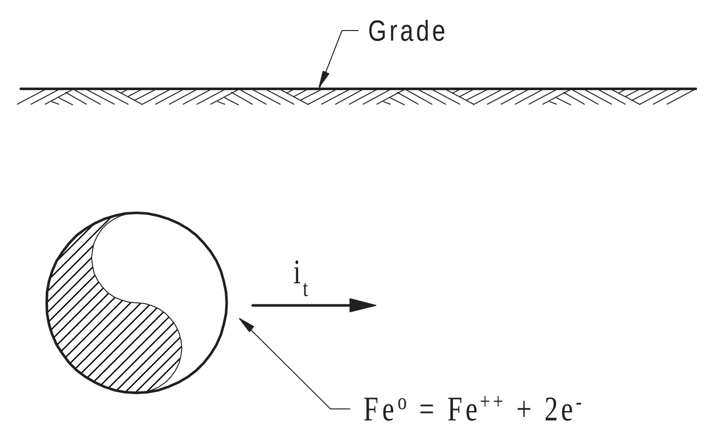

FIGURE 1a • Charge Transfer Reaction at Steel/Soil Interface During Telluric Current Positive Period in the Absence of Cathodic Protection

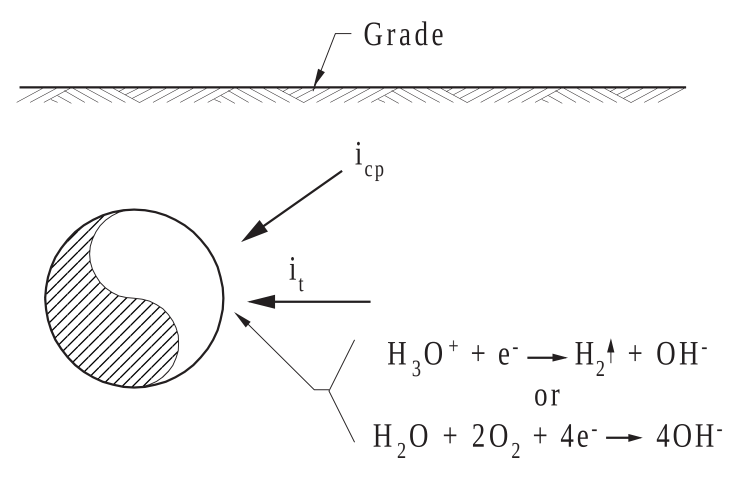

FIGURE 1b • Charge Transfer Reaction at Steel/Soil Interface During Telluric Current Negative Period with Cathodic Protection

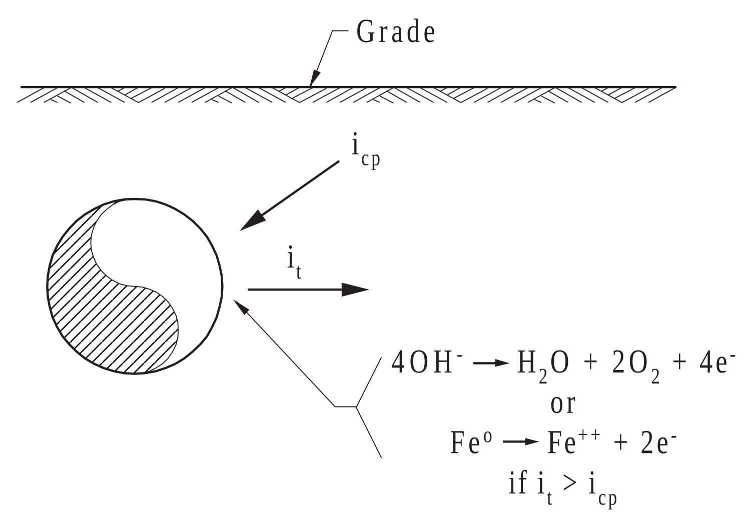

FIGURE 1c • Charge Transfer Reaction at Steel/Soil Interface During Telluric Current Positive Period with Cathodic Protection

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[4].

Fourthly, even though the study spanned a time period which was near the peak of solar cycle 20, the GIC annual ‘aa’ index was lower than in any of the following 30 years[5].

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 storm as previously defined is only 0.003%. It is apparent therefore that the results of the AGA study my not be appropriate for long pipelines, for better coated pipelines, for pipelines located in Canadian latitudes, and even for similar pipelines today since the telluric intensity, as represented by the ‘aa’ index, has generally increased.

Reported Instances of Telluric Corrosion

In 1986, Seager[1] conducted a study on a 522 km cathodically protected oil transmission pipeline, located between 55° to 70°N geomagnetic latitude, using small steel coupons installed along the pipe length and concluded “…telluric related corrosion can override any standard corrosion prevention system and cause pipe perforation in unacceptably short periods of time…”.

By measuring the coupon’s potential instantaneously after disconnecting the coupons from the pipeline (i.e. the ‘off’ potential), the ‘polarized’ potential was determined, free of IR drop due to potential gradients caused by either the cathodic protection and telluric current. This showed that there were periods of time when the polarized potential was more electropositive than the generally accepted -850 mVcse cathodic protection criterion[2] and more positive than -650 mVcse prompting Seager to assume that corrosion would occur for an estimated 15% and 4% of the time respectively. Based on this pattern, he calculated that the pipe could be perforated in less than four years at a 0.6 cm diameter coating flaw.

Martin[3] has also reported telluric corrosion on a 515 km gas pipeline in northeastern Australia, where the potential 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.

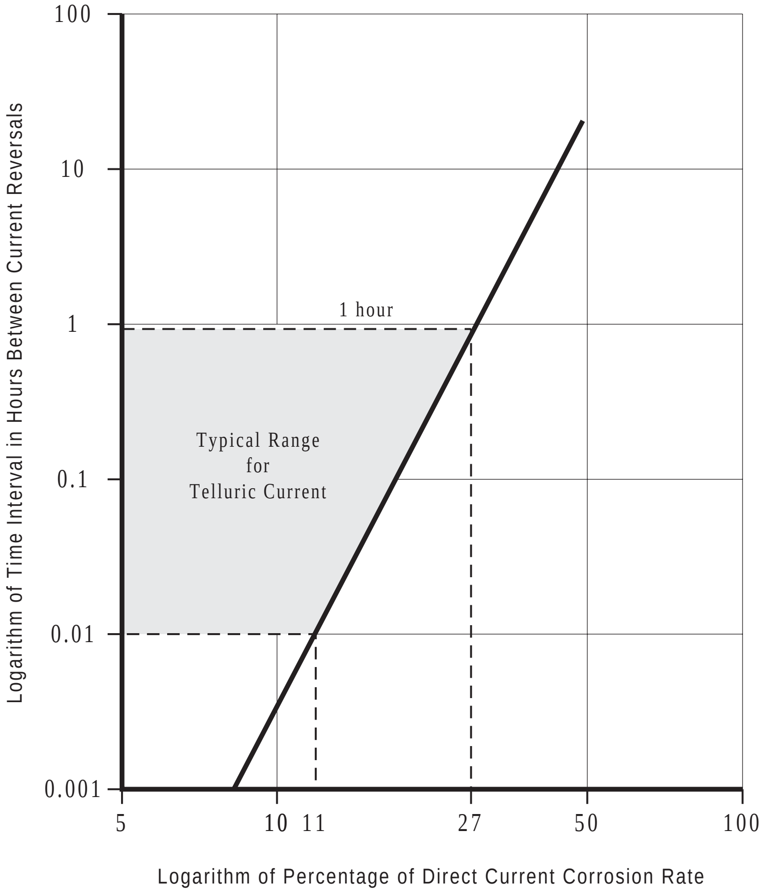

FIGURE 2 • Effect on Corrosion Rate of Reversing Direction of Current Compared to Steady State Direct Current and Length of Time between Reversals (redrawn from Peabody[11])

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:

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

For steel, approximately 10 kg 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;

$$\mathbf{H_3O^{+} + e^{-} \Rightarrow H_2 + OH^{-}} \quad 2]$$

(in de-aerated or acidic soils)

or

$$\mathbf{H_2O + 2O_2 + 4e^{-} \Rightarrow 4OH^{-}} \quad 3]$$

(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). Regardless of which reduction reaction transfers the charges, cathodic protection current results in the formation of high pH environment, typically in the range of 10-13, at coating flaws (holidays). Typically, the magnitude of the pH is proportional to the logarithm of the current density. When a positive current transfers from a cathodically protected pipe the initial oxidation reaction therefore is likely to be as follows rather than reaction [1].

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

This charge transfer reaction (depicted in Figure 1(c), doesn't cause corrosion and will continue as long as the concentration of OH^{-} ions remains high.

Therefore, 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 therefore 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[1]. This finding was summarized by Peabody[2] as shown in Figure 2 and indicates that there is a

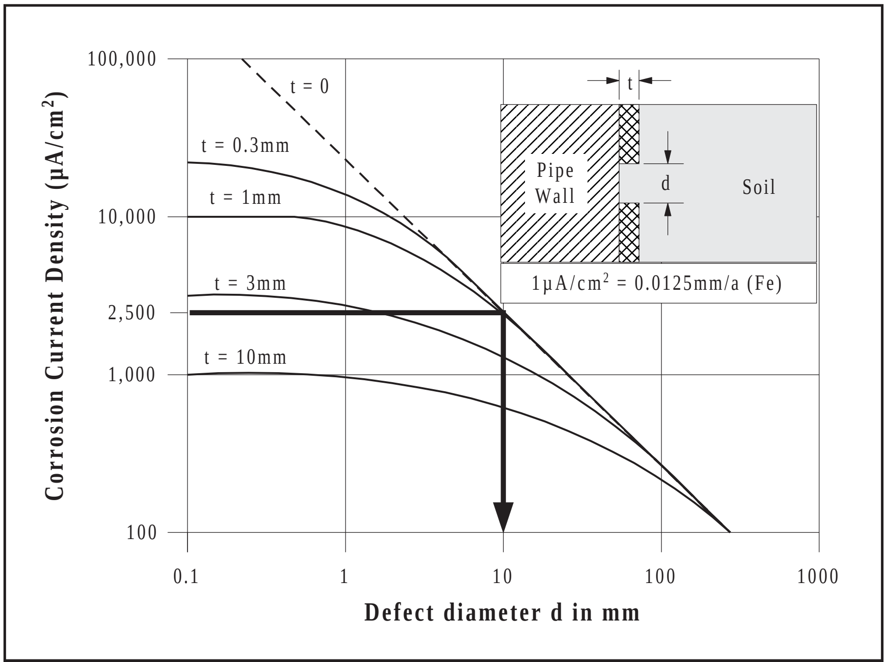

FIGURE 3 • Corrosion Current Density at a Coating Defect having an Applied Voltage of 1.0V in 1,000 ohm-cm Soil for Various Coating Thicknesses (redrawn from Von Baeckman & Schwenk[12])

relationship between the logarithm of the period and the logarithm of the percentage of corrosion to an equal amount of direct current.

As the vast 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.

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 - 1.0V can produce a large current density as shown in Figure 3[1]. 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 1.0V, would be approximately 2500 µA/cm producing a corrosion rate of approximately 31.3 mm/a for a direct current. However, the corrosion rate formula must be modified to account for the telluric period and intensity as follows.

$$CorrosionRate(Fe) = \frac{2.5x10^{-3}A}{cm^2V} \bullet \frac{12.5x10^{-3}mm/a}{10^{-6}A/cm^2} \bullet \Delta Vt \bullet F(p) \bullet F(t)$$

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 the 0.5V potential change 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 1hr 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 1cm diameter holiday can be calculated for various telluric intensity levels (Kp index) and telluric voltage effect (Vt) as shown in Figure 4.

It can be seen that even modest telluric voltage effects of 0.10V can have a significant corrosion impact if produced by a Kp3 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.

CATHODIC PROTECTION SYSTEM EFFECTS

General

It is typical[1] to design cathodic protection systems to produce a minimum of 0.3V change in potential at the pipe/soil interface and hence the corrosion impact of a 0.3V 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 0.3V either requires a proportionate increase in the output of the cathodic protection system on a regular basis or the cathodic protection system must be designed to increase its output in response to a telluric event.

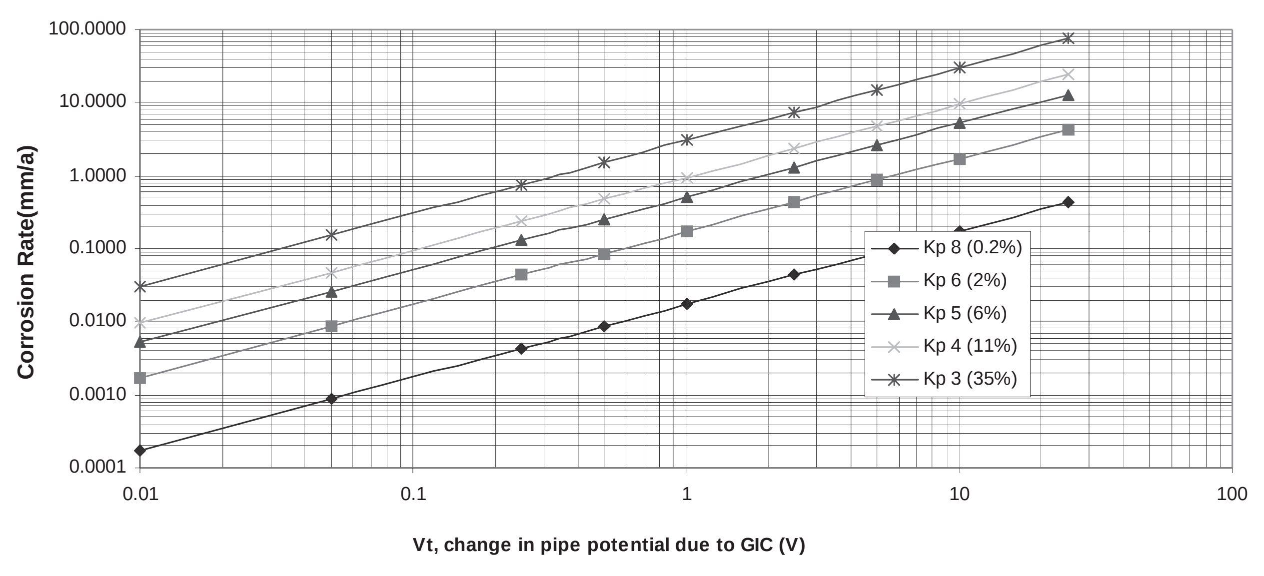

FIGURE 4 • Calculated Corrosion Rate vs. Telluric Potential Change at a 1 cm Holiday in 1000 ohm-cm Soil for Various Telluric Intensities (Kp Indexes) Having a Period of 1 Hour

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 but do offer an alternative path to earth for the telluric current because of their relative low resistance to earth compared to a coated pipeline. Hence some proportion of the telluric current will transfer to the earth via the anode as shown in Figure 5.

As long as the cathodic protection current (Icp) is equal to or greater than the residual telluric current (It"), then the telluric current effect is fully mitigated at the anode location. The 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[1] in the form of a zinc ribbon anode, placed at pipe invert elevation on each side of the pipe for the full extent of the underground portion of the system.

Impressed Current Systems

Impressed current cathodic protection 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 voltage shift. In addition very high negative potentials can cause coating failure through cathodic disbondment. DC power supplies operating in the potential control mode have been used to ameliorate telluric currents[9],[2]. The output of these units change 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. As the pipe potential is moved electropositively by a positive telluric current, the output of the controlled power supply will automatically increase in an attempt to maintain the set potential.

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

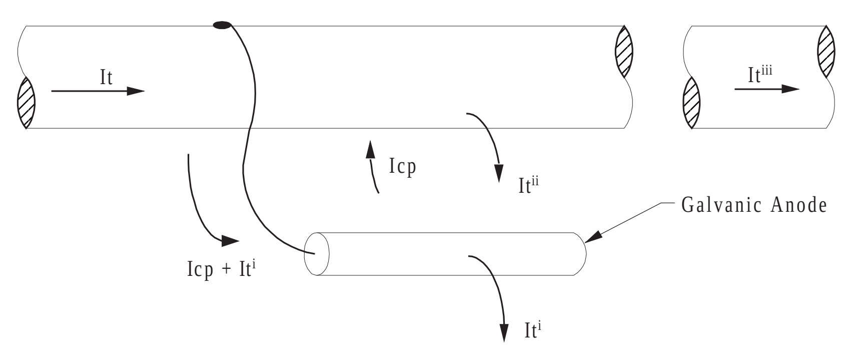

FIGURE 5 • Mitigation of Telluric Current Discharge Effects using Galvanic Anodes

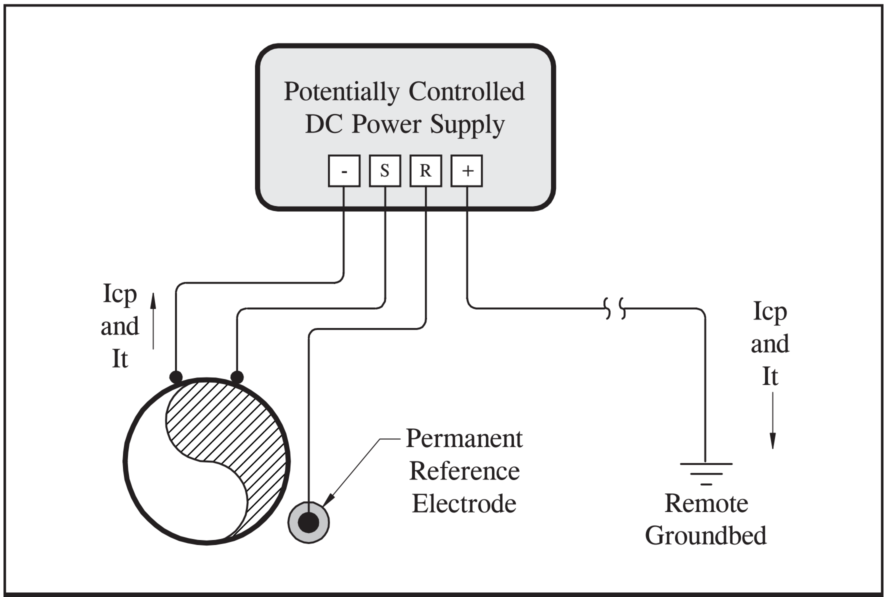

FIGURE 6 • Schematic of Potentially Controlled Cathodic Protection System

supply immediately increases its output to maintain the set potential value. The power supply 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 cathodic protection system functions as a telluric current forced drainage system. Its mitigating effect is illustrated in Figure 7 which compares a typical before and after mitigation record of the pipe-to-soil potential with time.

It should be noted that the magnitude in the negative direction is also reduced since the current output will decrease automatically during periods of telluric current pick-up. This will conserve the life of the groundbed as well as reducing the possibility of cathodic disbondment of the coating.

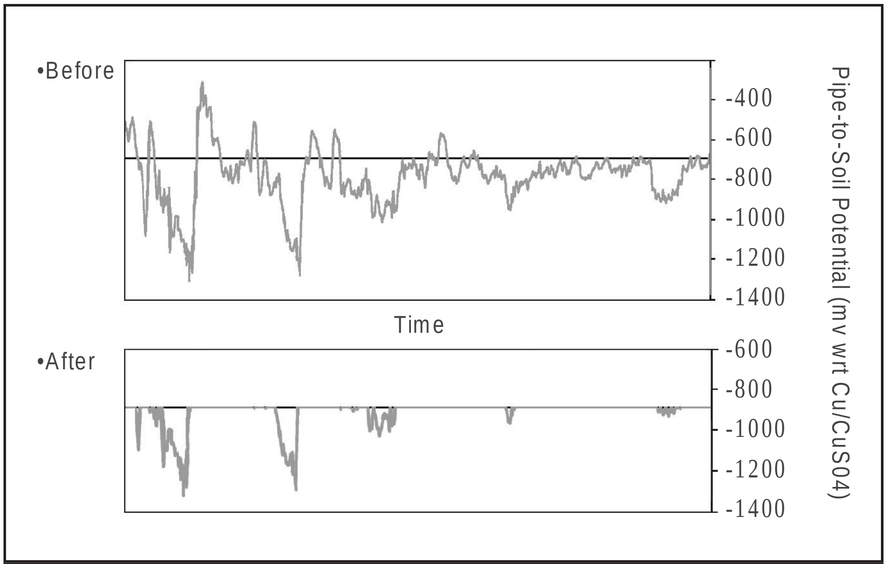

FIGURE 7 • Typical Telluric Affected Pipe-to-Soil Potential vs. Time at a Test Station Before and After Mitigating with a Potential Controlled Impressed Current System

CATHODIC PROTECTION PERFORMANCE MONITORING

It is usual to measure the pipe-to-soil potential on a routine basis to ensure that a minimum 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 (Vp/s) is measured using a high impedance voltmeter connected between a pipe test lead and a reference electrode placed in contact with the soil such that:

$$Vp/s = Ep + Ve$$

where
Ep = the pipe polarized potential across the pipe/soil interface
Ve = Icp Re = the voltage drop in the earth caused by the cathodic protection current in the earth between the reference and the pipe surface

A pipeline is considered effectively protected from corrosion[8] when the pipe polarized potential is equal to or more negative than -850mV 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 goes to zero and the voltmeter measures the ‘instant off’ potential for comparison to the 850 mVcse criterion.

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

Therefore: $Vp/s = Ep + Ve \pm Vt$

Since the geomagnetically induced current cannot be arbitrarily interrupted an alternative method has been employed by some companies[1],[2] that have installed a small steel coupon next to the pipe which 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 current effect is removed and the 'instant off' potential (Ep) of the coupon is measured for comparison to the -850mVcse criterion.

Although the use of a disconnectable coupon is a relatively simple solution at a test station, the determination 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 < 3m) along the length of the pipeline.

Proctor[1] proposed a measurement method to compensate for the telluric induced voltage which involved the correction of the measured potential (Vr) with respect to the roving reference by the change in potential (ΔVf) measured with respect to a fixed reference located at a nearby test station such that

$$Vp/s = Vr \pm \Delta Vf$$

where

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

This measurement technique is illustrated in Figure 10 in which two separate data loggers are used to record the

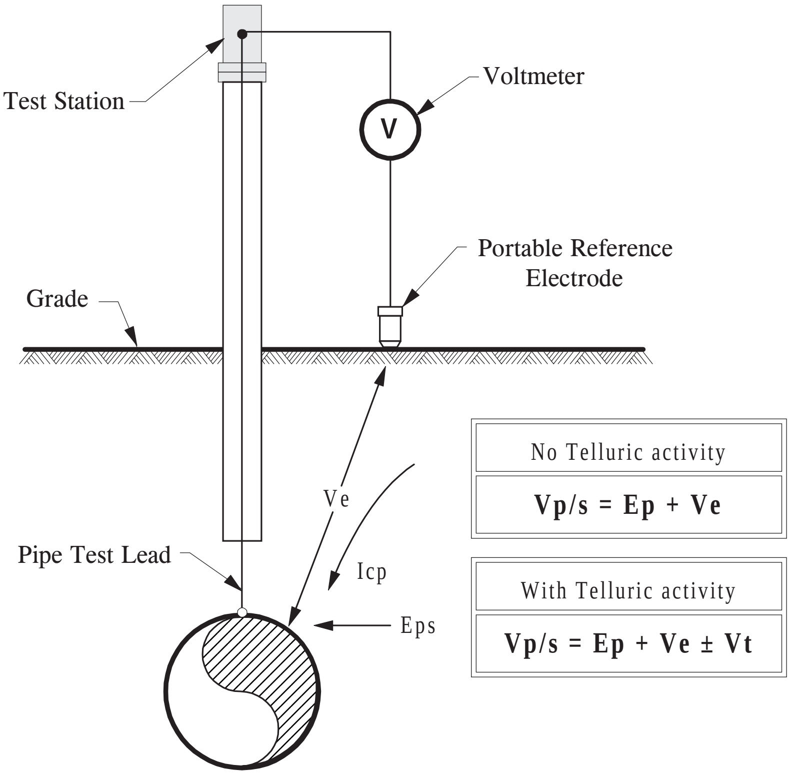

FIGURE 8 • Typical Pipe-to-Soil Potential Measurement

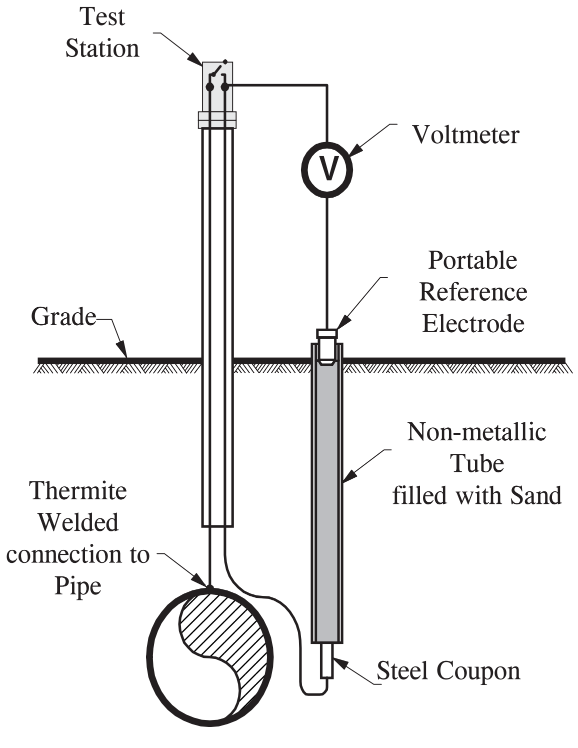

FIGURE 9 • Test Station Facilities Incorporating a Steel Coupon

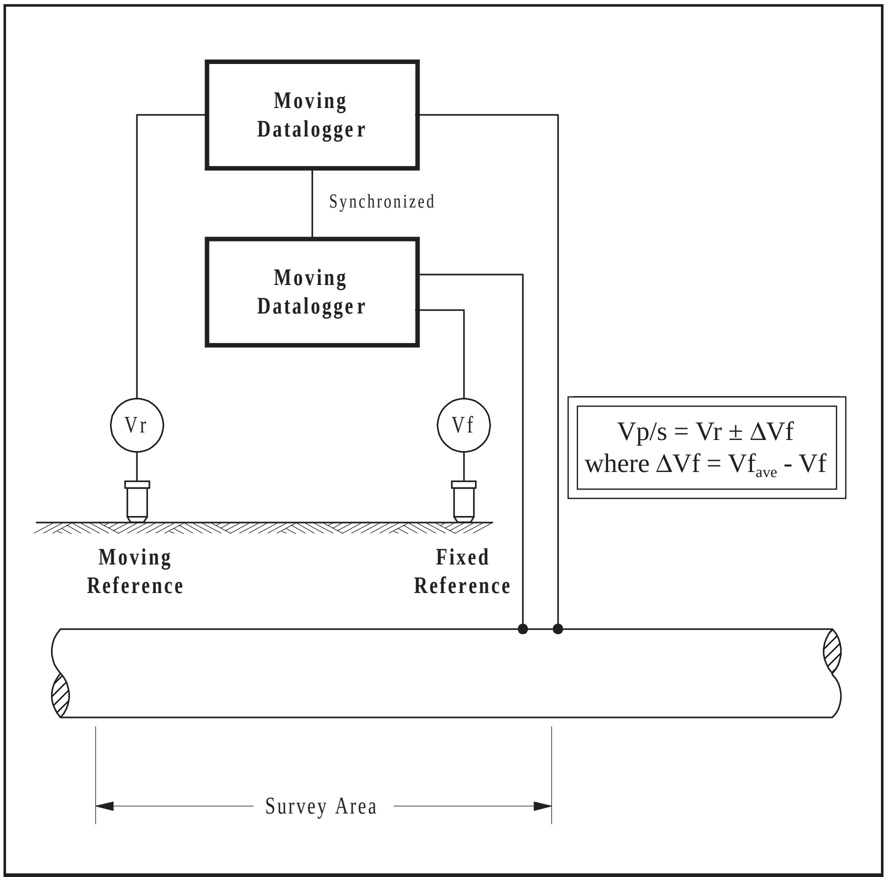

FIGURE 10 • Pipe-to-Soil Measurement Method to Compensate for Telluric Current Effects during a Close Interval CP Survey

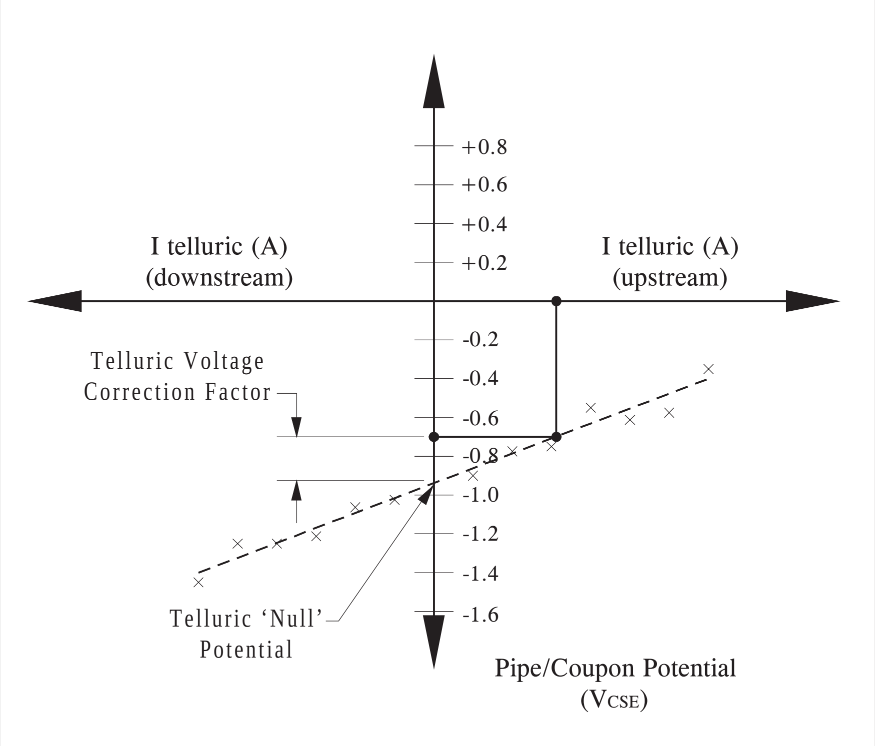

FIGURE 11 • Pipe Potential/Telluric Current Relationship at a Coupon Test Station

potentials with respect to the fixed and roving 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}) accurately represents a 'telluric free' condition and on the proximity of the fixed location to the roving electrode since long separation distances can introduce an error due to potential differences in the earth parallel to the pipe route.

Degerstadt et al[1] have used a 'telluric null' technique on the Trans Alaska Pipeline System (TAPS) which overcomes the limitation in the foregoing survey method that records the potential and current parameters at a test station to produce a fundamental characteristic for each test location as illustrated in Figure 11.

The telluric current was measured using proton magnetometers placed 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 position system (GPS) time stamping to record both pipe current magnitude and potential with respect to the roving reference and this potential is corrected relative to the voltage at the fixed electrode at the test station by the correction factor.

The pipe current can also be determined by measuring the voltage drop along the pipe as illustrated in Figure 12, although this arrangement requires extensive installation of pipe test leads.

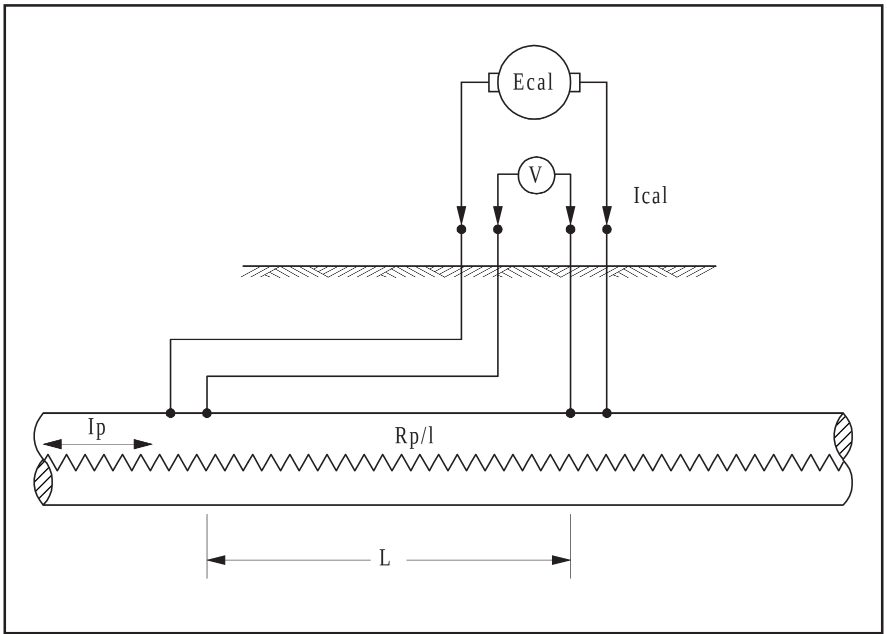

FIGURE 12 • Four Wire Test Lead Arrangement for Measuring Pipe Current

SUMMARY

In order to maintain effective corrosion control on relatively long pipelines that have factory applied coatings of high dielectric quality and that are located in latitudes close to the magnetic poles, the following measures should be taken:

- Maintain good electrical continuity throughout the system
- Integrate mitigation facilities integrated 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 temporarily disconnected to measure telluric free pipe-to-soil potentials
- Use of data loggers that are time synchronized and apply a correction factor to obtain accurate close interval pipe-to-soil data

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