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TELLURIC CURRENT CONSIDERATIONS IN THE CP DESIGN FOR THE MARITIMES AND NORTHEAST PIPELINE

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ABSTRACT

The Maritimes and Northeast Pipeline on the east coast of North America is constructed through an area where large geomagnetic disturbances can be expected. Because of this it was decided to include consideration of telluric current effects in the design of the cathodic protection (CP) system for the new pipeline.

An evaluation was made of the electric fields expected to be produced by geomagnetic disturbances. A computer model was set up to examine the pipeline response to these electric fields. This allowed calculations of the pipe-to-soil potentials produced with different coating resistances and placement of insulating flanges and groundbeds, which therefore allow various cathodic protection schemes to be evaluated before construction. The modeling showed that putting insulating flanges into the pipe created extra sites where large pipe-to-soil potentials would be produced. Accordingly it was decided to make the pipe electrically continuous and drain the telluric currents off at the ends of the pipeline using potential-controlled rectifiers. This paper describes the CP system installed to mitigate the telluric current effects and presents observations of telluric currents both before and after commissioning of the CP system.

Keywords: cathodic protection, telluric currents, geomagnetic disturbances, potential control

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INTRODUCTION

The Sable Offshore Energy Project includes both the offshore production and onshore transportation of natural gas. Sable Offshore Energy Incorporated (SOEI) is responsible for the offshore facilities while Maritimes and Northeast Pipeline (M&NP) is responsible for the onshore pipeline. Total project value is $3 billion.

The M&NP pipeline is 1051 km long and extends through Nova Scotia, New Brunswick and New England (Figure 1). The Canadian section of the pipeline consists of a 30" (762mm) diameter mainline and three laterals. The mainline starts at the Goldboro meter station on the eastern coast of Nova Scotia and travels 568 km to River St. Croix in New Brunswick at the Maine, U.S.A. border. It has twenty-one mainline valves at approximately 27 km spacing. There is no compression on the Canadian portion of the line. The three laterals include the 8" (219mm) diameter Point Tupper pipeline, the 12" (324mm) diameter Halifax lateral (both in Nova Scotia), and the 16" (406mm) Saint John lateral (in New Brunswick). The Point Tupper lateral connects into the mainline 5 km west of Goldboro and is paralleled by another 8" (219mm) pipeline, for natural gas liquids. Both the Mainline and the Point Tupper lateral pipelines were constructed in 1999, while the Saint John and Halifax laterals were constructed in 2000.

Telluric currents have been observed on many pipelines around the world[1-8] and there was concern about what effect they might have on the new pipeline. Most telluric currents are caused by electric fields associated with variations in the earth's magnetic field and are larger at higher latitudes where the magnetic field variations originate. In addition geo-electric fields are larger near the coast and can also be produced by the dynamo action resulting from movement of the conducting seawater through the earth's magnetic field.

As there are no existing pipelines having a similar route and extent as the M&NP pipeline, there is no direct historical record of the telluric activity that could be expected in the Atlantic seaboard region. There was however indirect evidence that telluric current activity on the M&NP pipeline could be severe enough to require the design of a telluric mitigation system. The pipeline has a long length (over 1000 km), is well coated and surrounded by high resistivity soil (both of which increase the telluric voltage), and is located between 52° and 56° geomagnetic longitude (i.e. closer to the north geomagnetic pole than the geographic north pole). Moreover, telluric current activity has been reported on the other pipelines and on electrical power grids in eastern Canada and the northeastern U.S. states. Because of this indirect evidence, a study was made to evaluate the telluric current activity of the M&NP pipeline by modeling the pipeline network and calculating the resultant telluric current and voltage magnitudes.

This paper briefly describes the phenomena involved, the results of the calculations, and how this information influenced the design of the cathodic protection system. Actual operating data are presented for comparison.

GEOMAGNETIC INDUCTION IN THE PIPELINE

Pipeline Modeling

Electromagnetic induction in pipelines can be modeled using distributed-source transmission line (DSTL) theory first described by Schelkunoff.[9] DSTL theory has been used extensively for modeling AC induction in pipelines,[10] and was applied to geomagnetic induction in pipelines by

Boteler and Cookson.[11] Boteler[12] has also extended the DSTL theory to provide a way of modeling geomagnetic induction in multi-section pipelines.

In the DSTL approach the pipeline is represented by a transmission line with a series impedance given by the resistance of the pipeline steel and a parallel admittance given by the conductance through the pipeline coating. The induced electric field is represented by voltage sources distributed along the transmission line. The series resistance and parallel conductance can be used to determine the characteristic impedance and the propagation constant – key parameters that describe the electrical response of the pipeline. Another useful parameter is the inverse of the propagation constant which is a measure of the distance along the pipe for the potential to adjust to a change in pipeline characteristics.

The M&NP Mainline uses a 30" (762mm) diameter epoxy-coated pipe. Model calculations were made for three values of coating resistance to provide an indication of how pipeline response to telluric currents may change as the pipeline coating ages. The electrical characteristics on the pipeline for the different coating resistances are shown in Table 1.

The electric field produced during geomagnetic disturbances tends to be larger in the east-west direction because of the alignment of the disturbance currents in the ionosphere. Accordingly, calculations were made for an east-west electric field of 0.1 V/km which is representative of the electric fields that can be expected to occur fairly regularly. (Larger electric fields will also occur, but less frequently.) The pipeline was modeled as four straight sections with bends at 300 km, 400 km, and 800 km from Goldboro. The model calculations were used to examine the effect of various parameters on the pipeline voltages and currents. These included the effect of different values of coating conductance, the use of insulating flanges in the pipeline, the effect of different values of termination resistance, and the effect of a groundbed at km 300.

Effect of Insulating Flanges. For the first set of calculations it is assumed that there are insulating flanges at the bends so that the pipeline can be modeled as four isolated sections with lengths: 300 km, 100 km, 400 km, and 200 km. Figure 2 shows the pipeline potential along the four sections produced by an eastward electric field of 0.1 V/km. For the second set of calculations the computer model was set up to determine the electrical response of the interconnected system, taking account of the variation in electric field from one section to another (Figure 3). Comparing these two figures it can be seen that splitting the pipeline into shorter lengths reduces the maximum potential that is produced but creates more sites where the telluric potential variations occur. Hence, it is preferable to minimize the number of in-line insulation joints in the pipeline.

Effect of Coating Conductance. The effect of the coating conductance on the adjustment distance and the pipeline potential can be seen in Figure 2. For the higher coating conductance of 10 μS-m^2 the pipeline is 'electrically long'. In this case, over the middle section of the pipeline the current is driven solely by the induced electric field and there is no potential difference between the pipe and the soil. It is only at the ends of the pipeline sections that the current causes a build up of electrical charge resulting in a potential difference between the pipe and the soil. For a pipe with a smaller coating conductance this end effect spreads out further along the pipe (as seen by the increased adjustment distance in Table #1). For a very low coating conductance the end effects spread out so far that they overlap in the middle of the pipeline and a nearly linear variation in voltage is seen from one end of the pipe to the other.

Effect of End Ground Connections. The above model calculations were made with a resistance to ground at the ends of the pipeline of 1000 ohm, i.e. the pipe was effectively isolated from ground. To examine the effect of a low resistance connection to ground at the ends of the pipeline the model calculations were repeated for end resistances of 0.0, 0.1, and 1.0 ohm. As well as calculating the pipe-to-soil potential, model calculations were made for the telluric current flowing along the pipeline.

The model calculations were repeated for a 560 km long electrically-continuous pipeline running from Goldboro to the Maine/New Brunswick border. In this configuration it is assumed that there is an insulating flange isolating this pipeline from the pipeline on the U.S. side of the border. Calculations were made for different values of the termination resistance to ground at the Goldboro and Maine/New Brunswick border ends of the pipeline. Reducing the termination resistance to 0.1 ohm reduces the end potential to 1 V. For an east-west electric field, telluric currents can flow easily into the pipe at one end and out at the other and have a value of 12 A over the whole length of the pipe (Figure 4). For a north-south electric field, telluric currents flow in and out of the pipe at both ends and also at the northernmost sections of the pipe. This produces voltage peaks as shown in Figure 5.

Calculations were also made to examine the effect of a groundbed at km 300, the first bend on the New Brunswick side of the isthmus between the Bay of Fundy and Northumberland Strait. For an eastward electric field this groundbed was found to have very little effect because the potential profile for the pipeline goes approximately through zero at that point anyway.

Coast and Tidal Effects. An examination[13] was made of the effect of the coast on geomagnetic induction and of voltages produced by the tidal dynamo. The "coast effect" arises because, during geomagnetic disturbances, larger induced currents occur in the more conductive seawater than in the land, leading to an accumulation of charge at the coast. This charge accumulation produces potential gradients in both the land and the sea. Electric fields are also generated by the dynamo action produced by the movement of conducting seawater through the earth's magnetic field. These electric fields are especially large in the Bay of Fundy because of the water movement associated with the tidal rise and fall (the highest in the world). Water movement up the bay produces an electric field across the bay, causing charge accumulation and potential gradients on either coast. Model calculations showed that the potential gradients produced by both the coast effect and the tidal dynamo are perpendicular to the coast of the Bay of Fundy. As the pipeline runs approximately parallel to this coast the coast effect and tidal potentials were expected to have little effect on the pipe-to-soil potentials.

Need for Mitigation. With both ends of the pipeline electrically isolated, as would be the normal procedure to obtain cathodic protection efficiency, the telluric voltage at the ends were predicted to be about ±17 V, as shown in Figure 3 for an east-west electric field of 0.1 V/km and a coating conductance of 1 $\mu S\text{-}m^{-2}$. While this is a likely voltage maximum, the end point induced voltages are still generally in excess of ±8 V when the pipe is divided into its four directionally distinct but electrically continuous segments, as shown in Figure 2. Clearly, this would impose a significant corrosion risk when the pipe potential was electropositive, if the positive shift was sustained for a period of time, and if telluric current transferred from the pipeline to earth through the following corrosion reaction:

$$Fe^0 \rightarrow Fe^{++} + 2e^-$$

The duration and intensity of the discharge is therefore of particular importance. The size of the geomagnetic disturbances that produce telluric currents is measured (in 3-hour intervals) using the Kp index which has a scale from 0 (quiet) to 9 (severe storm). Figure 6 shows that small disturbances occur frequently and that the number of disturbances decreases as the size increases. Figure 7 shows the electric field values that can be expected in the Maritimes region for different levels of magnetic activity.[14] The electric field intensity of 0.1 V/km, used in the prediction calculations, relates to a magnetic disturbance index of Kp 6. The probability of such an event is about 2%, as illustrated in Figure 6, which is considered statistically significant, since such a disturbance could be expected for one 3-hour period per week on average. It should be noted that very severe magnetic storms, having an index of Kp 8-9, would produce an electric field of about 1 V/km once per year on average, which was not considered a statistically significant corrosion risk.

CATHODIC PROTECTION DESIGN CONSIDERATIONS

Potential Controlled Rectifiers

The telluric model showed that a ground resistance of almost zero ohms was required to reduce the telluric influence to negligible levels. Because soil resistivities along the pipeline are generally high (greater than 20,000 ohm-cm), it was decided to use impressed current type cathodic protection rather than passive anodes. Potential control DC power supplies were selected since they provide a zero resistance path to earth when operating in response to a positive shift in pipe potential. Also, they will automatically reduce their current output during telluric current pick-up periods which will reduce any contribution to cathodic disbondment of the fusion bond epoxy (FBE) coating. To help reduce IR drop error, a coupon set was installed immediately adjacent to the reference electrode to simulate a coating holiday of 25 cm^2 or 500 cm^2. A total of 14 potential controlled/forced drainage systems (Figure 8) were installed on the Mainline and 3 systems on each of the Point Tupper, Halifax and Saint John Lateral pipelines. The selected power supplies have the added feature of operation in constant voltage or constant current mode to give flexibility in CP system set-up, operation and testing.

Telluric Mitigation

Since the U.S. and Canadian sections of pipeline are electrically continuous (i.e. zero resistance at km 568), the primary locations for draining telluric currents are at the three peak voltage points of km 0.0 (Goldboro), km 317 (Moncton, N.B) and km 378 (Chipman, N.B.). The current capacity for these three rectifiers has to accommodate the telluric current, estimated at 12A from Figure 4, plus their normal amount of cathodic protection current.

The soil resistivity in vicinity of the Goldboro Gas Plant is so high (>150,000 ohm-cm) that the CP system there could not be sized to drain the required current. As an alternative, an additional capacity of 12A and a low resistance groundbed (0.5 ohm) were provided for the potential controlled system at the Canso Strait. This CP system provides cathodic protection to the two Point Tupper lateral pipelines that connect to the M&NP Mainline approximately 5 km west of Goldboro. Further, to supplement the forced drainage systems, a telluric bond switch was designed as detailed in Figure 10 for insertion between the M&NP pipeline at the Goldboro transfer station and the SOEI offshore pipeline. The interconnection was made via a 1 km long 4/0 cable and the combined resistance of the bond cable and the resistance of the 26" (660mm) diameter offshore line to the sea was estimated at 0.25 ohm. The telluric switch includes a resistance bond so that the bond current can be controlled if necessary and incorporates back-to-back power diodes to protect the resistor by passing the large telluric currents estimated at 120A that are expected once per year. The power diodes pass current in both directions when the voltage difference across the bond switch exceeds ±0.8V. A schematic diagram of the telluric mitigation system is shown in Figure 9.

Cathodic Protection Criterion

The protective level set on this project is –850 mV vs. $Cu\text{-}CuSO_4$, at the pipe/soil interface. In practice a P/S monitoring read of –1.0 volts measured at finished grade has traditionally been used, with appropriate offset for IR drop caused by current flow through the soil.

This pipeline, however, traverses a wide range of soil conditions, from tidal rivers to high resistivity sand and gravel hills, much of it with bedrock at or near the surface. Soil resistivity readings ranged from 520 ohm-cm to 1.1 M ohm-cm with very high values (mean>50,000 ohm-cm) over 40% of the pipe route. It was therefore anticipated that some sections of coated pipe may not readily polarize to the –850 mV criterion, particularly where well aerated sand or gravel with low moisture content prevails, regardless if impressed current cathodic protection or galvanic anodes were used. Consequently, the need to use other criteria (e.g. 100 mV polarization decay) was not ruled out. Further, the requirement for special protection criteria for sections in acid rock formations was not considered necessary since the FBE pipe coating proved stable in low pH (pH<3.0) test solutions.

Coupon Test Station

Even though the telluric mitigation system can substantially reduce the magnitude of the positive potential shifts, the ability to accurately measure the level of protection is still compromised by the residual potential shifts in the cathodic direction. Furthermore, attempts to interrupt the rectifier output to obtain an 'instant off' (polarized) potential by conventional means, will simultaneously disconnect the telluric mitigation. To provide a reasonably efficient means of measuring the polarized potential, test station facilities were designed[15] to incorporate a coupon that could be disconnected from the coated pipe and its potential measured free of IR drop caused by telluric or cathodic protection current effects on the pipeline. The coupon was designed to be placed beside the pipe in the pipe backfill material so that it simulates the pipe surface as a coating holiday of similar area and, hence, will polarize/depolarize in the same manner as the pipeline. Current density on the coupon is determined by measuring current pick-up (or discharge) through the pipeline connection using a zero-resistance ammeter. This arrangement also includes a soil tube, inside of which is placed a portable reference electrode, as illustrated in Figure 11. Coupon test stations were installed on the pipeline at 5 km intervals.

Pipe Current Test Stations

The coupon test stations are augmented by 4-wire IR drop spans (Figure 12) to facilitate the measurement and recording of telluric current in the pipe. When the coupon potential is recorded simultaneously with the telluric current, then the relationship between these two parameters can be plotted as illustrated in Figure 13. This information can be used to produce an accurate polarized pipe potential by not only correcting for IR drop but by also providing a means of determining the polarized potential at a telluric 'null' condition. (Note: Data for this method, 'telluric compensation', has not been presented in this paper.)

OBSERVATIONS AND DISCUSSIONS

Telluric activity is produced by variation of the earth's magnetic field. Two main processes cause these magnetic field variations. The first is due to solar heating that causes convection in the upper atmosphere and drives electric currents in the ionosphere on the sunward side of the earth. This electric current creates a magnetic field fixed in space and a pipeline carried through this magnetic field by the earth's rotation experiences a regular change in the magnetic field each day. Magnetic field variations are also produced by bursts of particles sent out by eruptions on the sun. These particles are guided by the earth's magnetic field into the high-latitude ionosphere where they cause the aurora and electric currents that produce magnetic variations on the ground. The standard unit for magnetic fields is Tesla but for geomagnetic variations it is more convenient to use nanoTesla (nT) = 10-9 Tesla. Magnetic disturbances are also measured using the Kp magnetic activity index which has a scale from 0 (quiet) to 9 (major storm) and is derived from the 3-hour range of magnetic variations recorded at observatories around the world.

Figures 14 and 15 illustrate telluric activity occurring on the pipeline prior to commissioning the telluric mitigation system. Both sets of data were collected at coupon test stations using Cu-$CuSO_4$ reference positioned adjacent to the coupon at pipe elevation, and with the coupons connected to the pipe. The pipe current and potentials at km 565 (Figure 14) are affected by a constant voltage rectifier operating with 3A output on the U.S.A. portion of the pipeline, approximately 5 km downstream (thus potential readings are more electronegative than at km 387).

These data clearly show the relationship between magnetic field variations and telluric activity on the pipeline. The distinctive diurnal effect seen at km 565 is caused by the regular daily magnetic variations described above. For most of the period shown, the irregular geomagnetic variations are small ($Kp \leq 2$); however, bursts of magnetic activity on December 24 ($Kp = 4$) can be seen to produce corresponding bursts of telluric activity on the pipeline.

The pipe potential at km 387 (Figure 15) is typical for the pipeline prior to energizing the CP rectifier systems. Potentials fluctuate around an average value of –700 mV_{CSE} (coupon connected to pipeline), which is consistent with the coupon 'disconnected' potentials recorded along the pipeline (Table 2). Note that pipe potentials varied ±100 mV for $Kp \leq 3$ (December 9th to 11th) and by ±600 mV for $Kp = 6$ (December 13th).

Figure 16 illustrates pipe potential variations at km 387 with the cathodic protection system operating. Potentials fluctuate around an average value of –1300 mV_{CSE} (coupon connected to pipeline) and shift in the electro-negative direction by as much as 1500 mV during a magnetic storm ($Kp = 5$) on April 24th. The potential shift in the electro-positive direction, however, is only 200 mV because of rectifier potential control operation which was set at –100 mV_{zinc}. Figure 17 shows typical rectifier operation over a 6 day period during geomagnetic activity of $Kp \leq 4$.

Data were also captured for a very severe magnetic storm $Kp = 9$ on April 6th. Figure 18 shows the impact on pipe potentials and current flow at the Telluric Bond Switch during the storm period. Normal current flow through the bond is about 3 amperes from offshore-to-onshore, which is primarily current picked up by the sub-sea pipeline and returning to the CP systems on the Point Tupper Lateral. During the magnetic storm, however, telluric currents frequently change magnitude and direction and in this case ranged from 63 A flowing in the onshore direction to 41A flowing offshore.

Data listed in Table 2 compares the initial coupon 'instant-off' potentials prior to commissioning the CP rectifiers, to the coupon 'instant-off' potentials obtained after 6 weeks of potential controlled cathodic protection. The data was selected from test post locations having about 50 km spacing along the M&NP Mainline to show that coupon 'polarized' potentials generally adhere to both the $-850\ mV_{CSE}$ criterion and the 100 mV polarization decay criteria criterion. Of 120 coupon sets along the Mainline, only one did not meet these criteria.

CONCLUSIONS

- Significant telluric currents produced by geomagnetic field variations have been observed in the Maritimes and Northeast Pipeline as predicted during the design phase.

- Modeling of the pipeline response to telluric currents indicated that a significant amount of telluric activity could be expected on the pipeline with electric fields as large as 1 V/km occurring, on average, once per year and 0.1 V/km once per week. These telluric effects were predicted to be most noticeable at the ends of the pipeline where excursions as high as ±200 V and ±20 V respectively could be expected without mitigation.

- As a result of telluric modeling, a number of measures were incorporated into the cathodic protection design to compensate for the most frequent telluric current fluctuations, including:

    1. potential-controlled rectifiers to drain off telluric currents at major bends and the ends of the pipeline;

    2. a bond switch connected between the sub-sea and land pipes to allow high telluric currents to pass without creating large pipeline potentials;

    3. interruptible test coupons to obtain instant-off polarized potential readings without interrupting the rectifiers; and,

    4. 4-wire IR drop spans to facilitate measurement of telluric currents in the pipeline.

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Table 1
Electrical Characteristics of the Maritimes and Northeast Pipeline

	Low Coating Resistance	Medium Coating Resistance	High Coating Resistance
Coating Conductance	100 μS-m^{-2}	10 μS-m^{-2}	1 μS-m^{-2}
Coating Resistance	10^4 ohm-m^2	10^5 ohm-m^2	10^6 ohm-m^2
Series Resistance	7.6 10^{-3} ohm-km^{-1}	7.6 10^{-3} ohm-km^{-1}	7.6 10^{-3} ohm-km^{-1}
Parallel Admittance	0.24 S-km^{-1}	0.024 S-km^{-1}	0.0024 S-km^{-1}
Characteristic Impedance	0.178 ohm	0.564 ohm	1.78 ohm
Propagation Constant	42.710^{-3} km^{-1}	13.5 10^{-3} km^{-1}	4.27 10^{-3} km^{-1}
Adjustment Distance	23.4 km	74 km	234 km

Table 2
Comparison of Pipe Coupon 'Initial' Potentials vs. Pipe Coupon 'Polarized' Potentials (mV$_{CSE}$)*

Location	Initial Potentials Without Cathodic Protection (Coupon Disconnected)	Polarized Potentials With Cathodic Protection (Coupon Disconnected)
km 5	-709	-886
km 58	-664	-1127
km 101	-777	-1283
km 154	-638	-1088
km 207	-776	-1120
km 250	-684	-1065
km 301	-584	-1147
km 355	-784	-1027
km 405	-820	-1073
km 452	-774	-1058
km 502	-758	-1014
km 539	-752	-1016
km 566	-990	-987

*Data in this table were selected from locations at approximately 50 km spacing to show typical potentials of 25 cm^2 coupons along the M&NP Mainline.

Compressor Station

Compressor Station

Proposed Interconnect with Sable Offshore Energy Project at Goldboro, Nova Scotia

Proposed Interconnect with Tennessee Gas at Dracut, MA

October 1997

* Map not to scale

Figure 1: Route of Maritimes and Northeast Pipeline

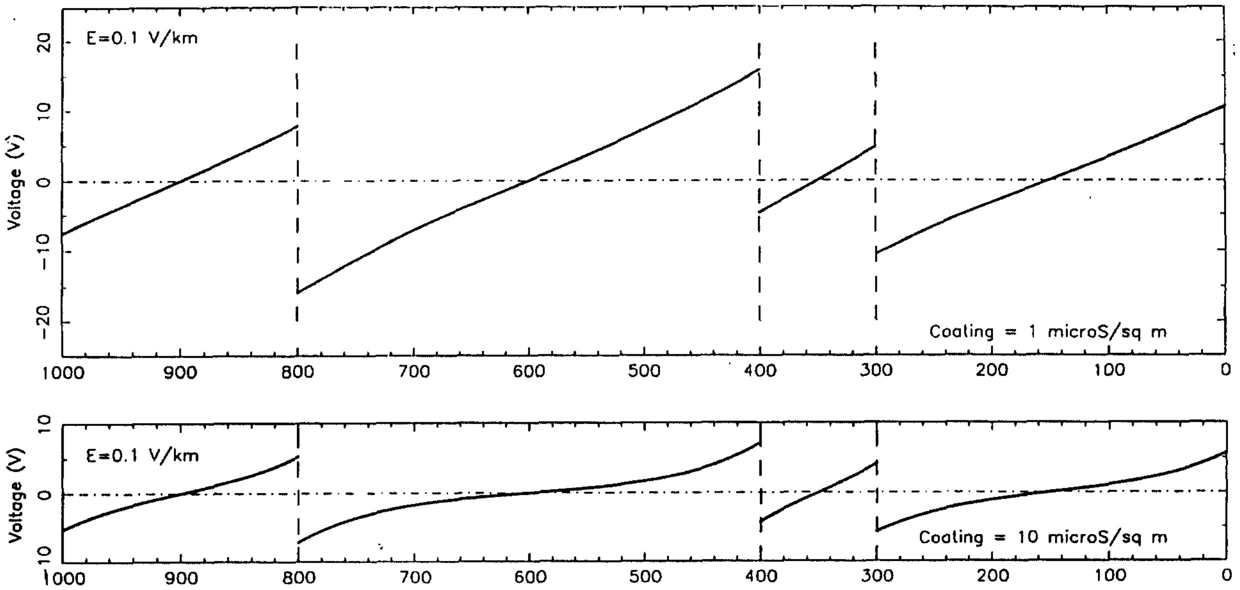


Figure 2: Pipeline Potential Produced when Pipe Sections are Separated by Insulating Joints with Termination Resistances set at 1000 ohm.

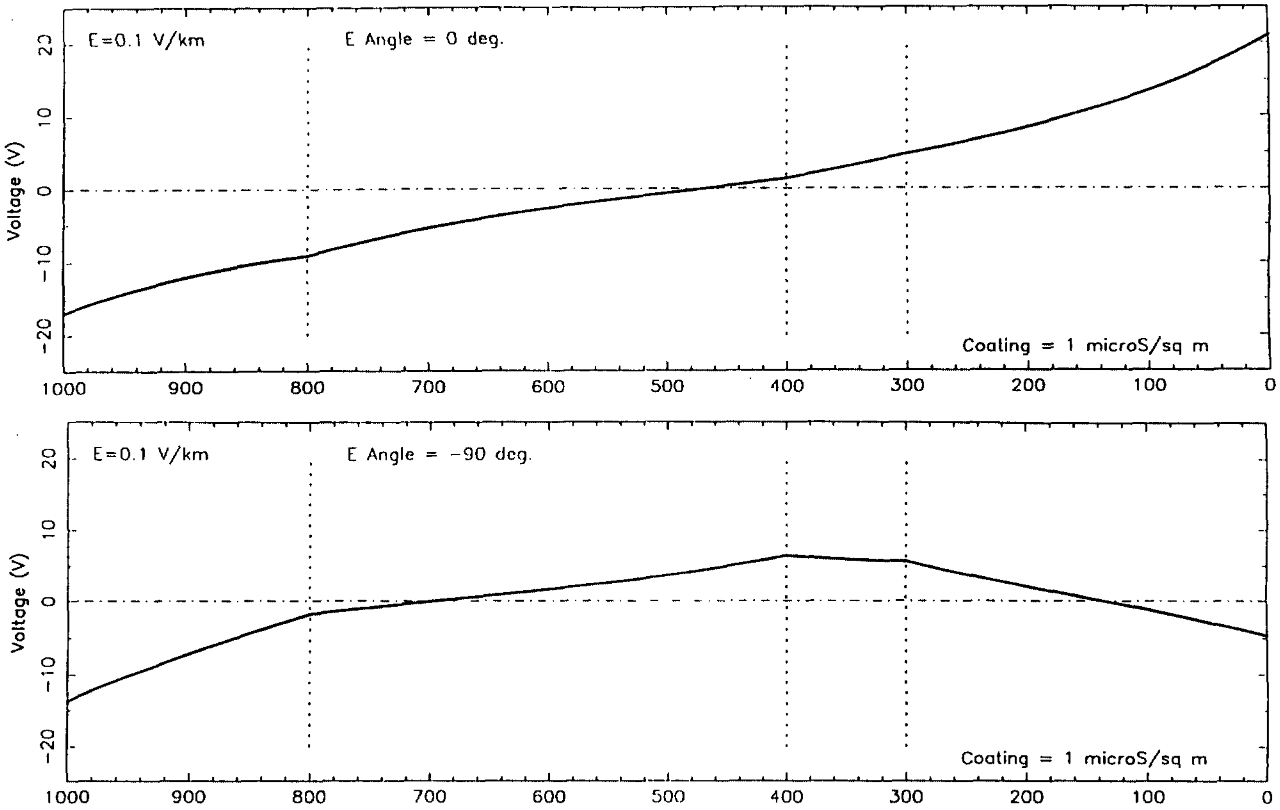


Figure 3: Pipeline Potential Produced on Electrically Continuous Pipe with Termination Resistances set to 1000 ohm

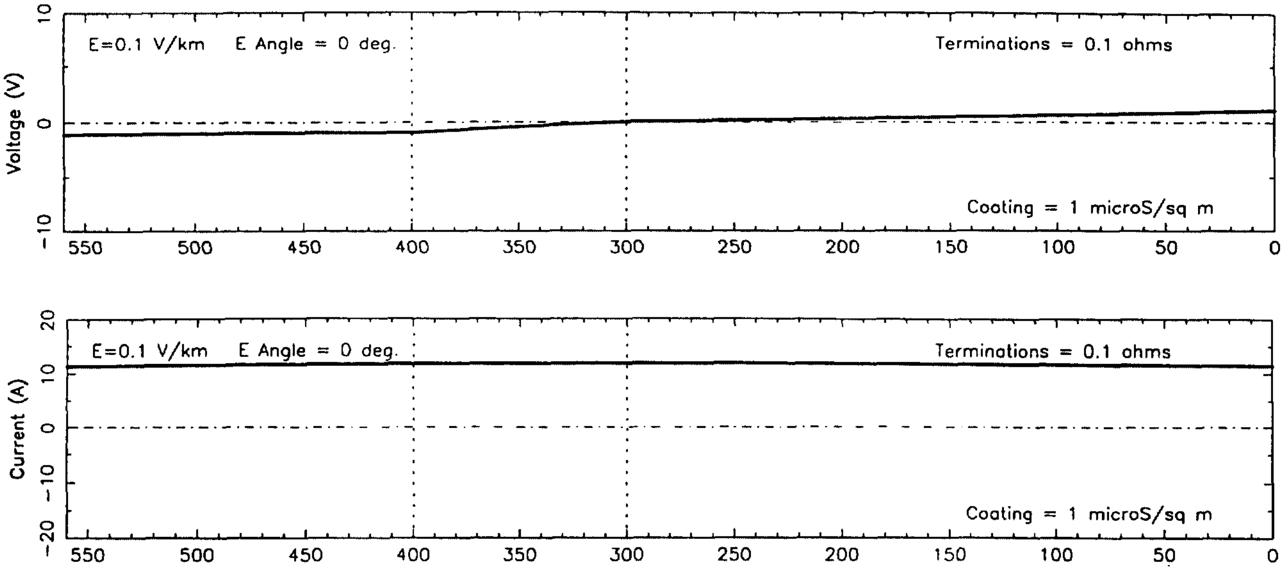


Figure 4: Pipeline Potential and Current Produced by an Eastward Electric Field of 0.1V/km in Pipeline with Termination Resistances of 0.1 ohm

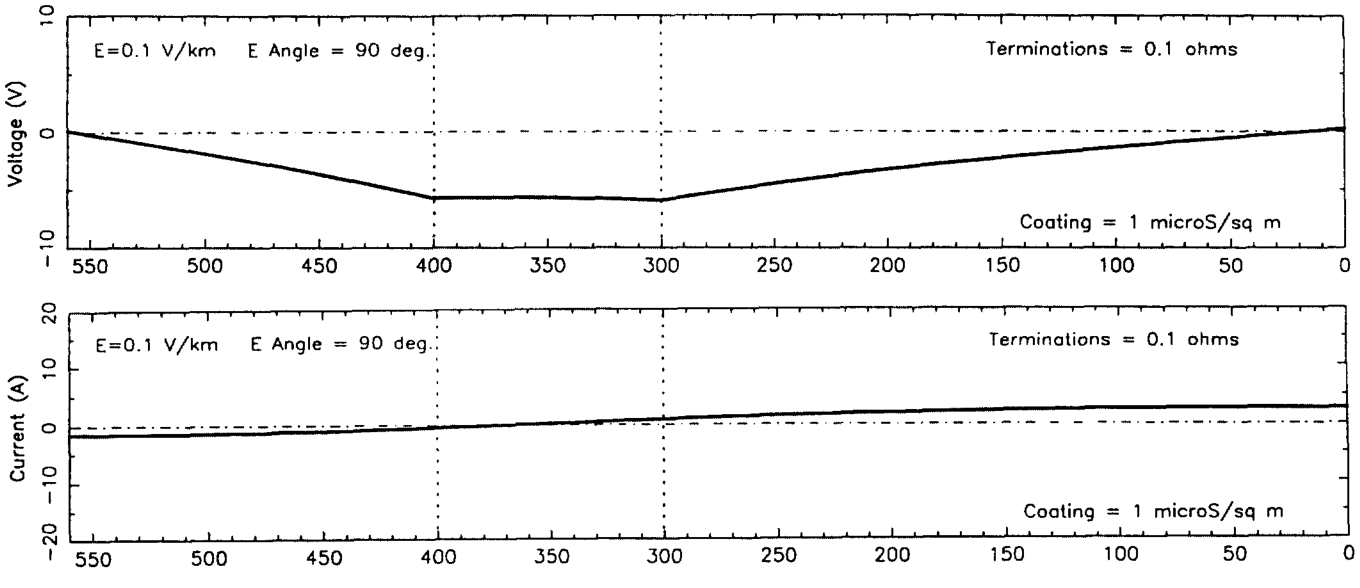


Figure 5: Pipeline Potential and Current Produced by a Southward Electric Field of 0.1V/km in Pipeline with Termination Resistances of 0.1 ohm

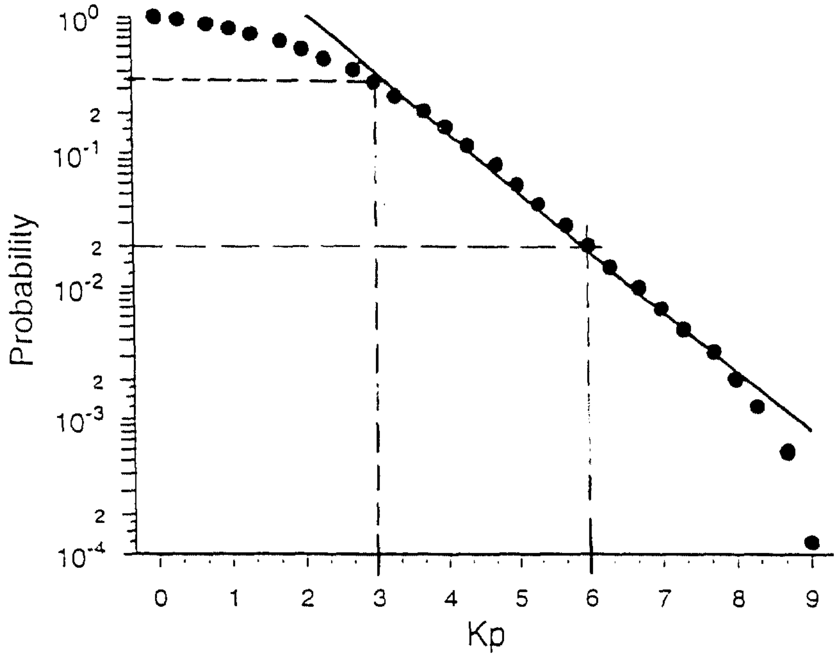


Figure 6: Average Occurrence of 3-Hour Intervals with the Magnetic Activity Index Kp Equal To or Greater Than a Specified Value. Kp=9 Corresponds to a Severe Magnetic Storm

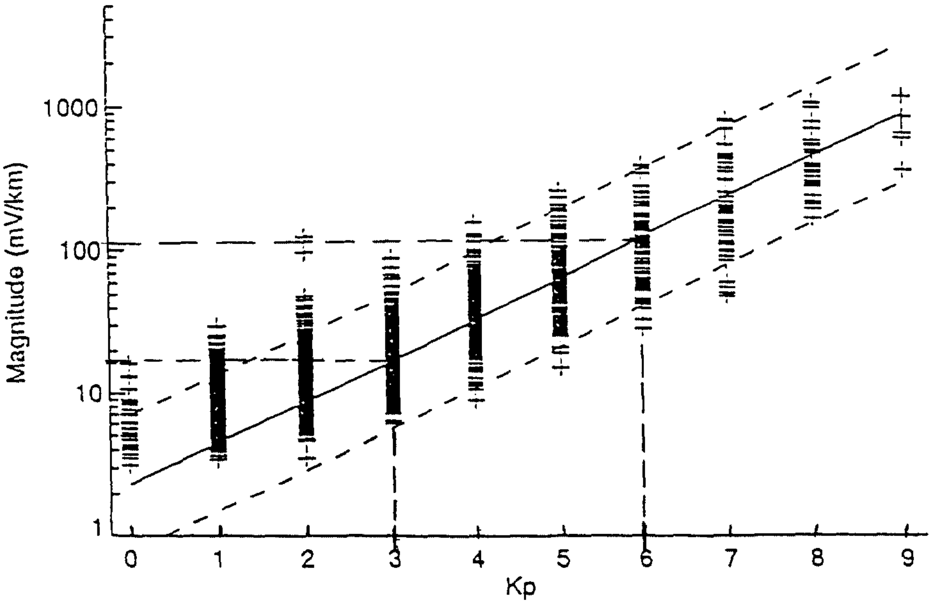


Figure 7: Peak Electric Field Magnitudes as a Function of Kp

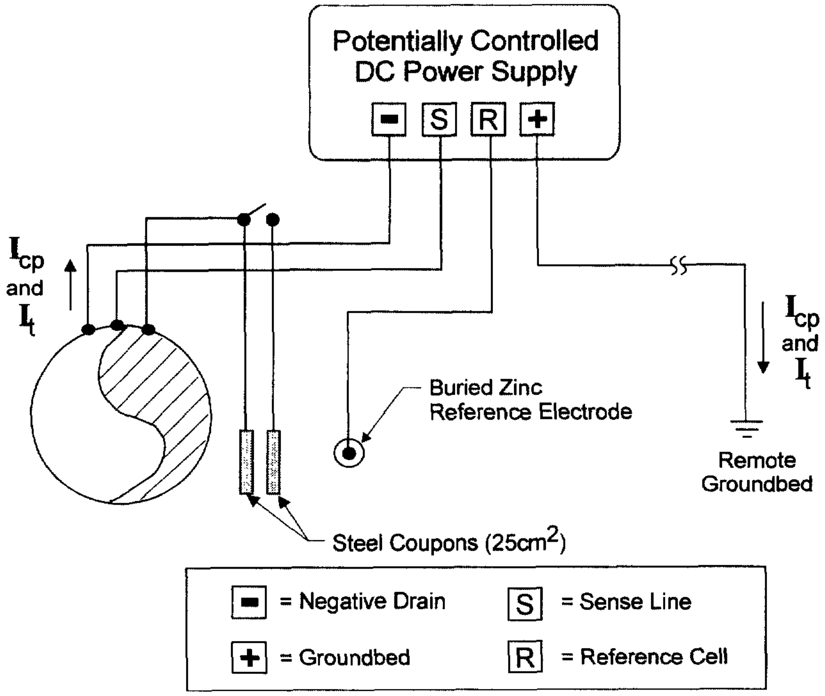


Figure 8: Schematic of Potential Controlled Cathodic Protection System

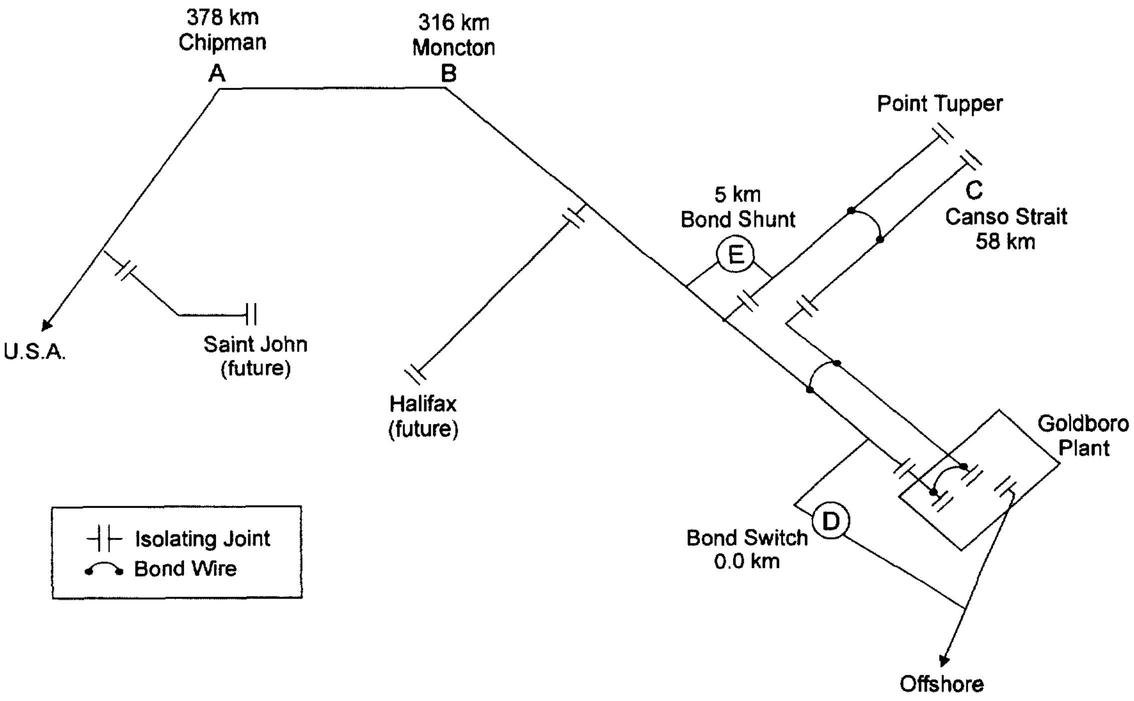


Figure 9: Schematic of Telluric Mitigation System

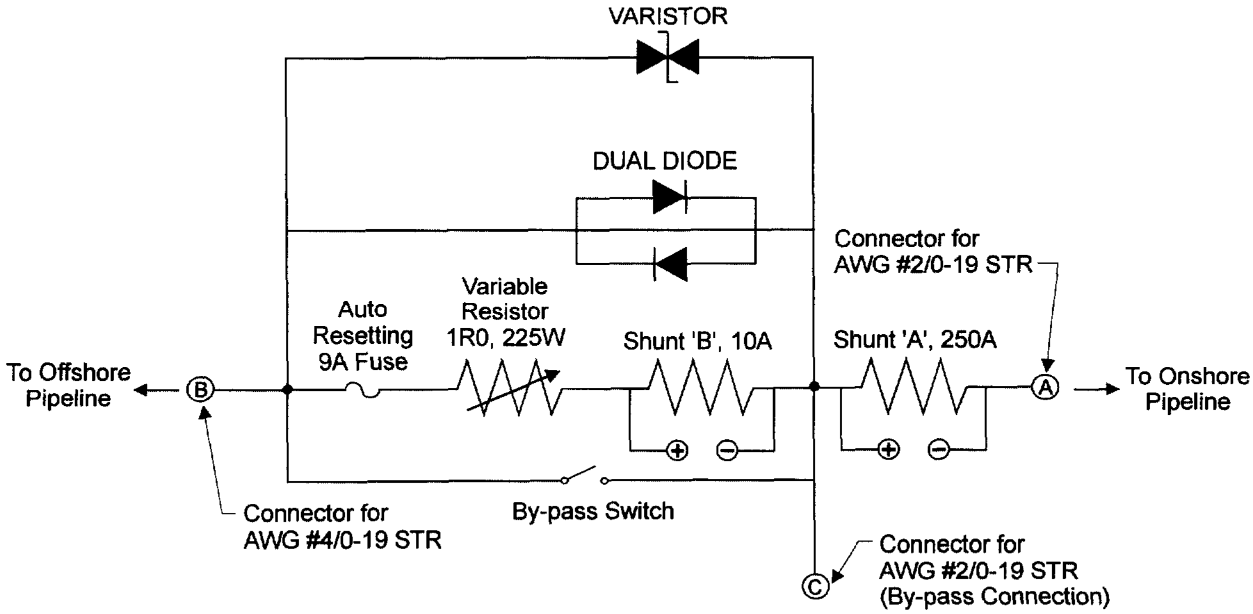


Figure 10: Schematic of Telluric Bond Switch

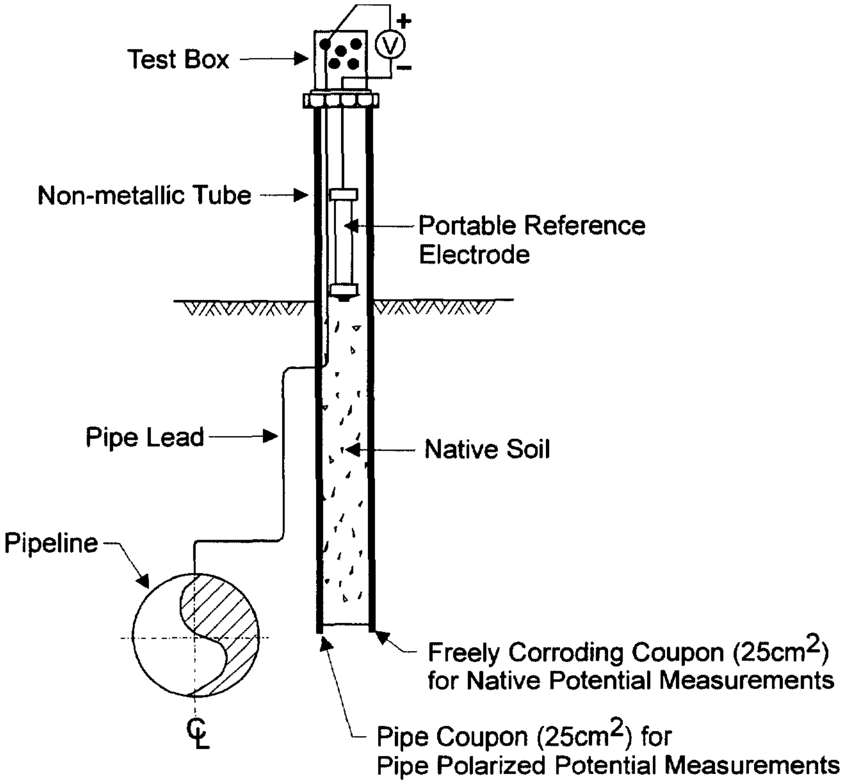
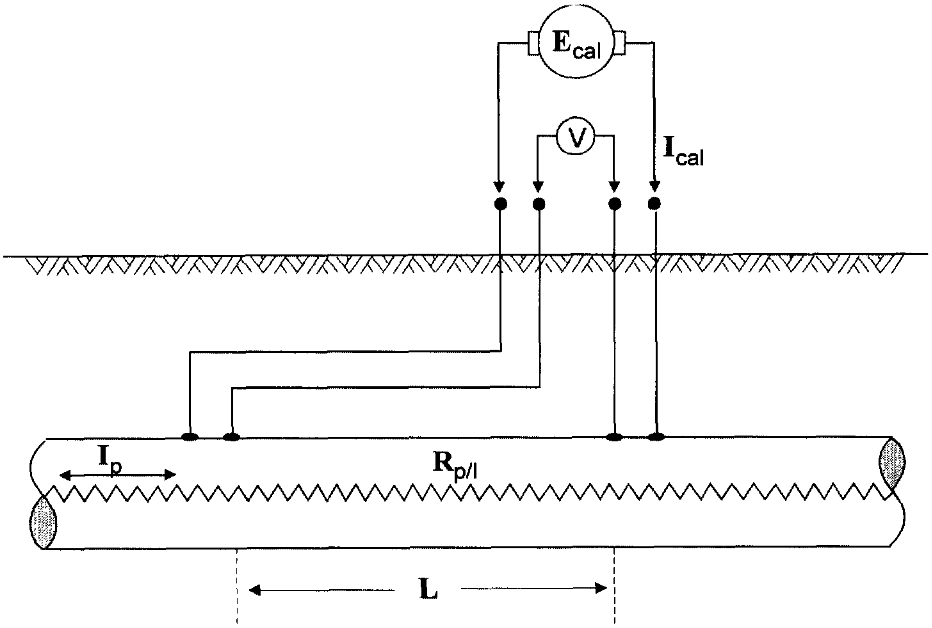


Figure 11: Test Station with Steel Coupons



L = 30 m for NPS 1 to NPS 16 Pipelines
L = 60 m Larger than NPS 16 Pipelines

Figure 12: Test Station for Measuring Pipe Current

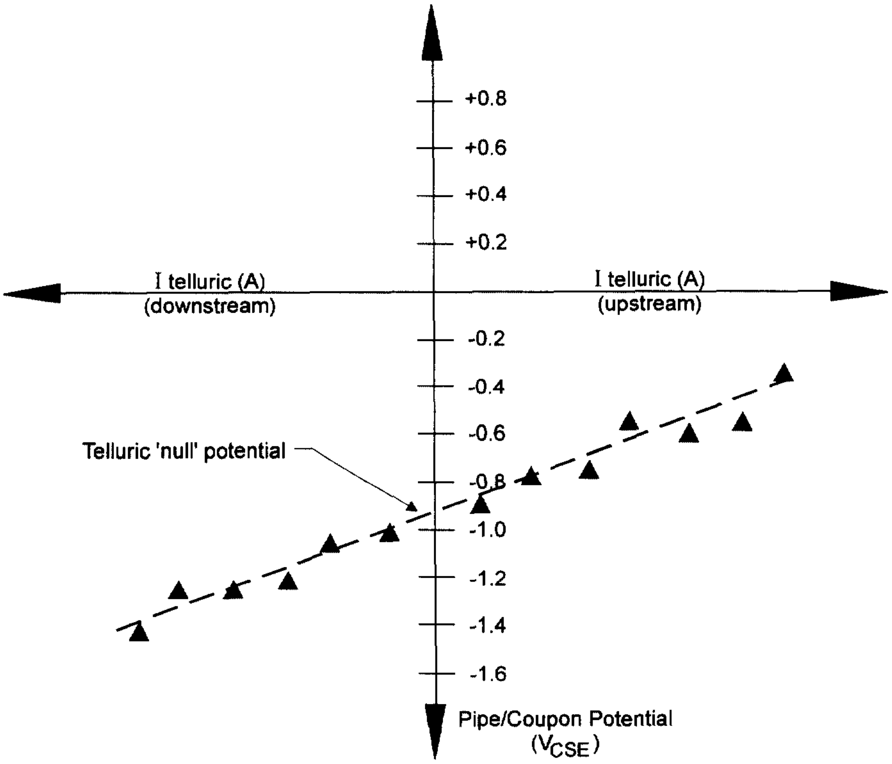


Figure 13: Pipe Potential/Telluric Current Relationship at a Coupon Test Station

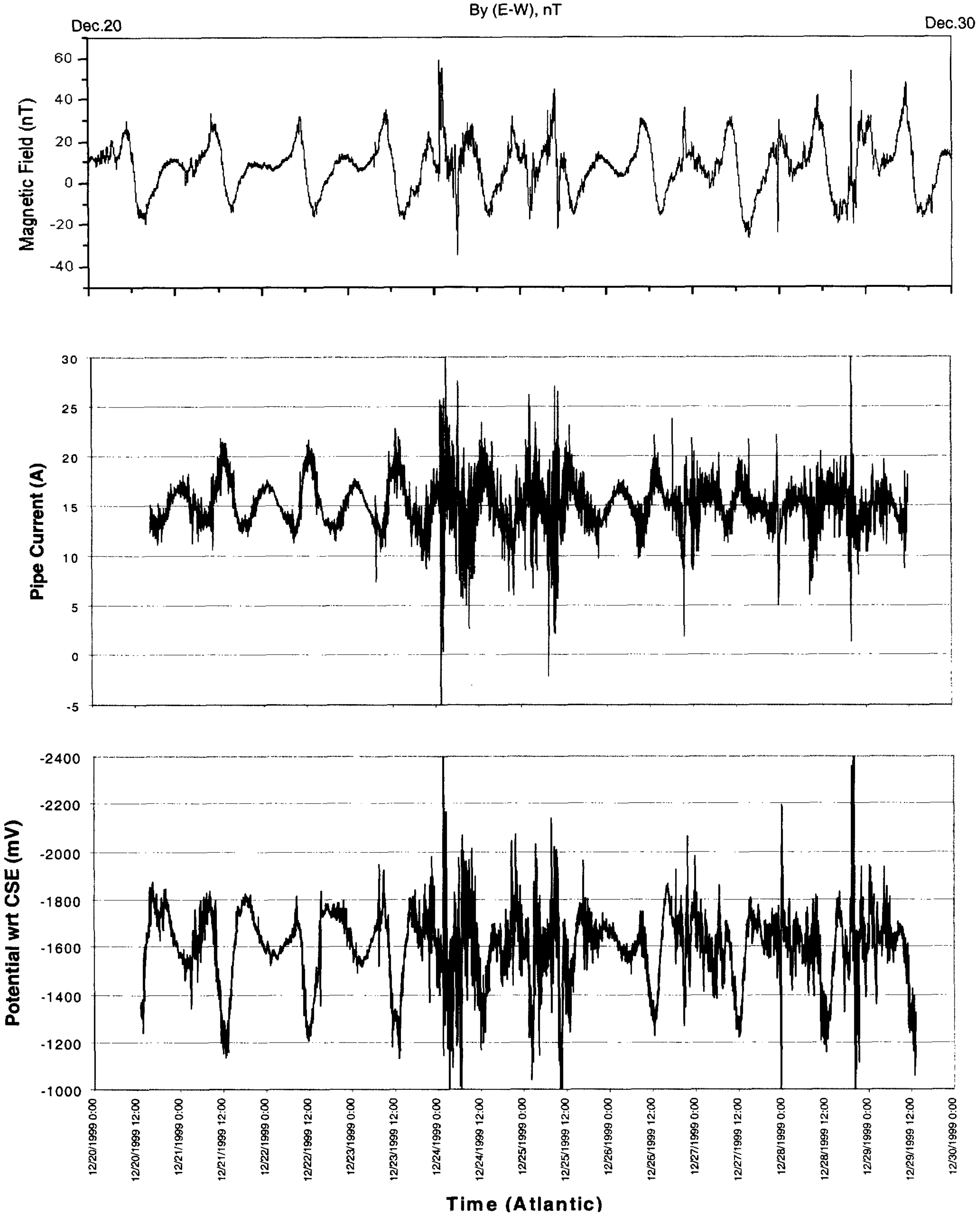


Figure 14: Pipeline/Coupon Potential and Current Fluctuation Versus Geomagnetic Activity at km 565

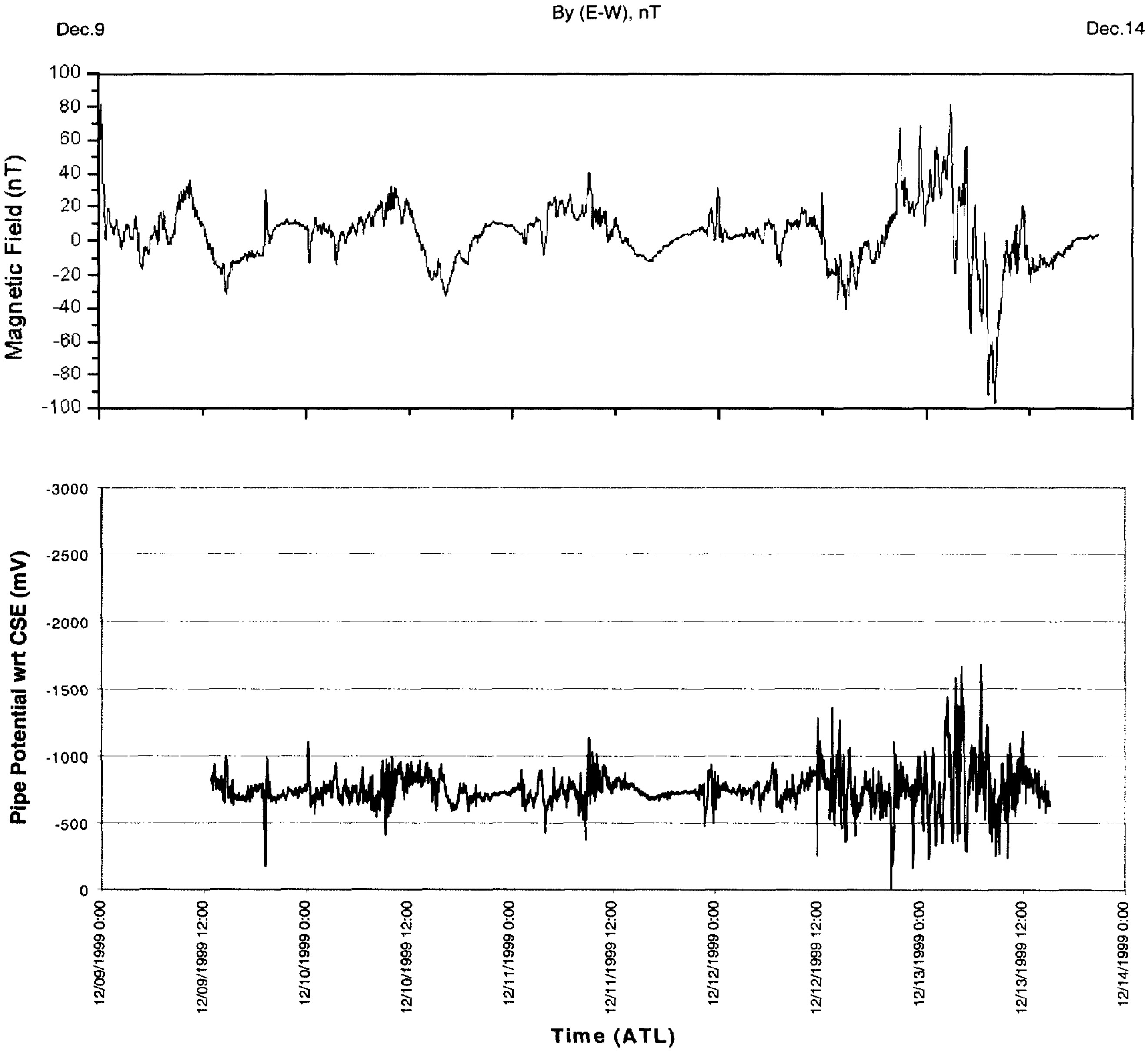


Figure 15: Pipeline/Coupon Potential Variation Versus Geomagnetic Activity at km 387 Prior to Telluric Mitigation and Cathodic Protection

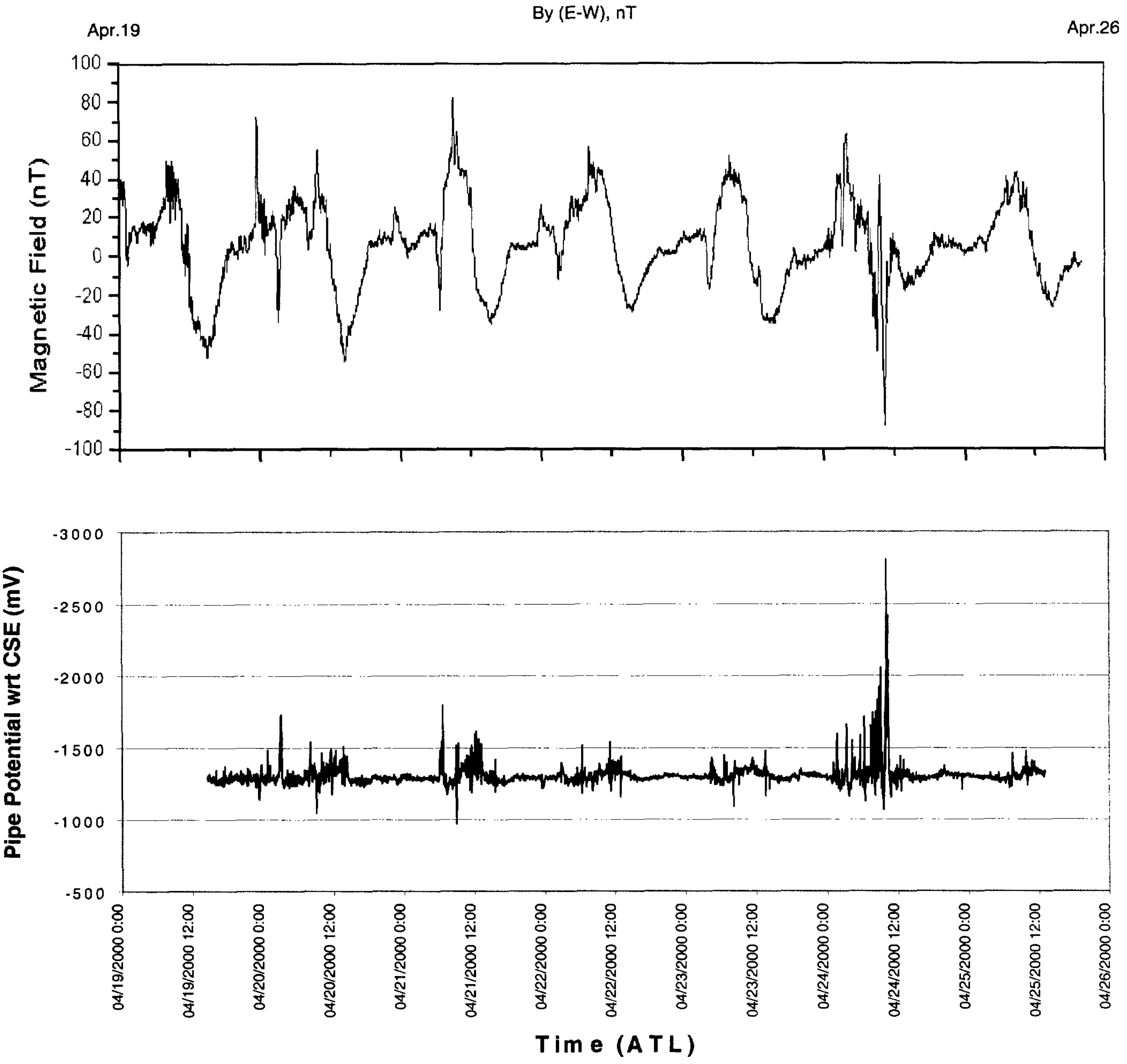


Figure 16: Pipeline/Coupon Potential Variation Versus Geomagnetic Activity at km 387 With Telluric Mitigation and Cathodic Protection

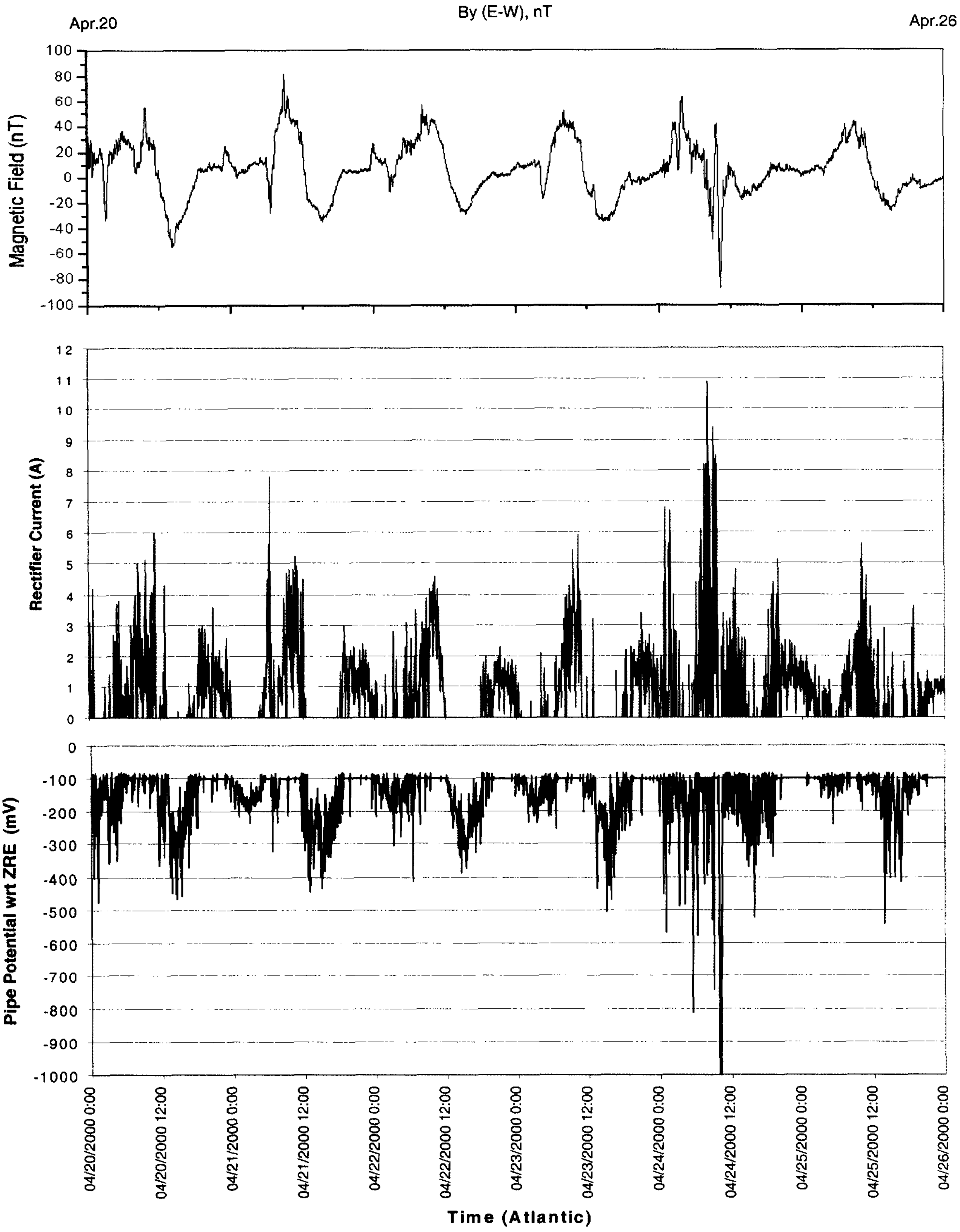


Figure 17: Pipe Potential (w.r.t. Zinc Reference) and Rectifier Current Output Versus Time For CP System Operating in Potential Control at km 317

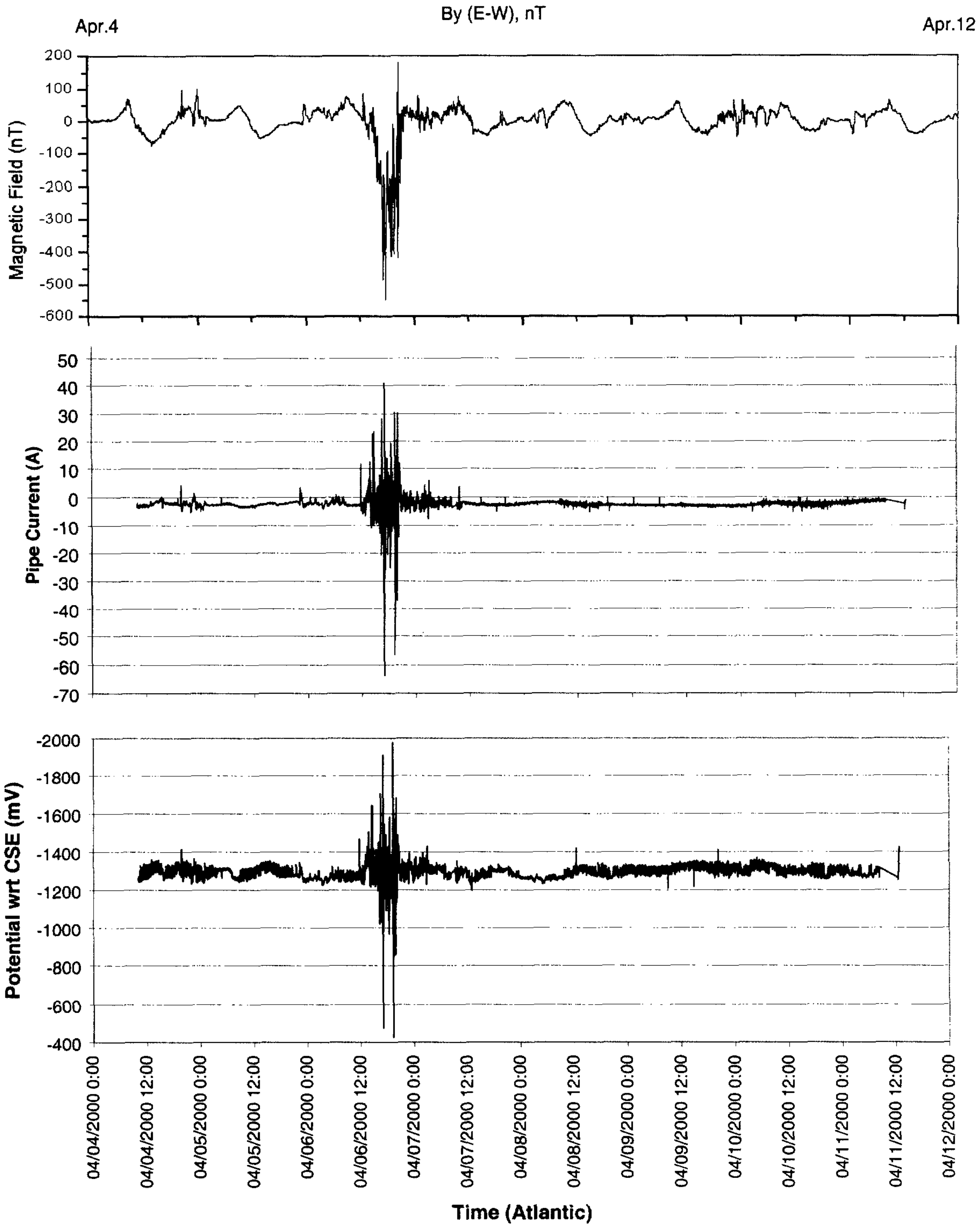


Figure 18: Typical Pipe Potential and Current Fluctuation Versus Geomagnetic Activity at Telluric Bond Switch (km 0.0) for a Severe Magnetic Storm