OVERVIEW OF HVAC TRANSMISSION LINE INTERFERENCE ISSUES ON BURIED PIPELINES

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ABSTRACT

The paper is an overview of the various interference problems that may affect pipelines in common right of ways or near high voltage AC power (HVAC) transmission lines. Safety, AC assisted corrosion damage and mitigation options will be discussed as well as data from several case histories.

Keywords: AC pipe-to-soil (P/S) potential, induced AC assisted corrosion, AC current density, HVAC transmission line fault, mitigation

BACKGROUND

Pipelines sharing, paralleling or crossing HVAC transmission line rights-of-way (ROW) are often subjected to electrical interference. These effects can occur during pipeline construction, normal pipeline/HVAC operation or HVAC faults. Both the Canadian Standards Association (CSA) and the National Association of Corrosion Engineers International (NACE) have developed published standards dealing with these interference effects. The CSA standard CAN/CSA-C22.3 No. 6-M91 is titled "Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines". The NACE standard practice SP0177-2007 is titled "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems". Both these standards primarily discuss safety issues but also mention the effects of HVAC interference on pipeline corrosion control systems. The electrical power grid in North America consists of three general circuit classifications. Bulk or high voltage transmission lines from the generation source to primary substations typically run at 230 kV (kilovolts), 345 kV or 500 kV. Sub-transmission lines between major distribution centers operate at 69 kV, 115 kV, 138 kV or 161 kV. The distribution system at the customer level operates at 4.2kV, 7.5 kV, 12.5kV or 34.5 kV. The CSA standard sets recommendations for pipeline/transmission line coordination when the line is greater than 35 kV. However from a practical strand point HVAC lines 69 kV and under rarely have high enough phase load or available fault current to significantly affect the pipeline unless it is directly under the transmission line.

Electromagnetic induction is the primary effect of the HVAC transmission line on the buried pipeline during normal (steady state) operation. This form of interference is due to the magnetic field produced by AC current flowing in the conductors of the transmission line coupling with the pipeline and inducing a voltage on the pipeline. Conductive interference results from currents being conducted through the soils and into the pipeline. Conductive effects are primarily a concern when a fault occurs in an area where the pipeline is in close proximity to the transmission line and the fault currents in the soil are high. The electromagnetic effects are also significant during a fault condition because the phase current of at least one conductor is very high. Capacitive effects are primarily only a concern during construction when sections of the pipeline are above ground.

If these electrical effects are great enough during steady state normal operation or during a fault, a potential shock hazard exists for anyone that touches an exposed part of the pipeline such as a valve, CP test station or other above ground appurtenance of the pipeline. During steady state normal transmission line operation AC current density at a coating holiday (flaw) above a certain threshold may cause accelerated external corrosion damage to the pipeline. In addition damage to the pipeline or its coating can occur if the voltage between the pipeline and surrounding soil becomes excessive during a fault condition.

Both the CSA and NACE standards recommend maintaining the continuous (steady-state) induced AC voltage to below 15 Volts at any location where a person could touch the pipeline or pipeline appurtenance. This is a very conservative level based on limiting the available maximum current through the human body to 6 mA. Figure 1 shows the shock circuit assumptions used to set this 15 VAC level.

This 6 mA “let go” safety threshold is well below the level that for continuous exposure may result in injury or death. The IEEE 80 (Guide for Safety in AC Substation Grounding) includes detailed information on touch and step potential safety. In the 9-25 mA range the currents may be painful and can make it difficult to release an energized object grasped by hand. When body currents reach the range of 60-100 mA ventricular fibrillation or inhibition of respiration might occur that could cause injury or death. In Section 4 of this guide the effects of time on tolerable shock current are discussed. Based on energy absorbed by the body for 99.5% of 155# (70kg) adults the calculated survival threshold value of 3 seconds is 91 mA, 1 second is 116 mA and 0.1 second is 367 mA. Others suggest that the threshold should be based on the relationship between the length of time the shock current is present and the length of one heart beat. Biegelmeier proposed survival values of 500 mA at durations less than one heartbeat (1 sec+/-) and 50 mA at longer durations. IEEE 80 guide suggests using 1000 Ohm based on the assumption of the hand and foot/shoe contact is equal to zero. At the much higher voltages expected in a substation this assumption may be valid as the hand contact resistance could be very low if the skin is damaged by arcing. Based on Dalziel’s work on let-go currents with wet (in salt water) hands and feet, the minimum measured resistance in the circuit above was 1030 Ohm.

HAZARDS DURING CONSTRUCTION

Besides the obvious lethal hazard of equipment contact with an energized overhead HVAC conductor, high AC potentials can be generated on sections of pipe strung on skids in preparation for lowering into the ditch. When the pipe sections are on skids it is suspended in the electromagnetic field of the HVAC line with no contact to the ground. Even relatively short pipeline sections will have an AC potential due to the capacitive effect of the high dielectric strength of the coating in air. Figure 2 is a sketch of this capacitive coupling.

Figure 3 is a pipeline under construction in a common ROW with a single 345 kV HVAC line. The 20-inch (50.8 cm) diameter FBE coated pipe section on the skids is approximately 2,000 feet (600 meters) long and laying on wooden skids over a wetland (bog). In this example 178 VAC to ground was measured at this end of the section (Figure 4) and 177 VAC at the other end. In this example standard safety and mitigation procedures were not being followed.

A second example includes several shorter section of pipe in a HVAC ROW with three circuits. Figure 5 is a photograph of the ROW showing three sections of the 16-inch (40.6 cm) FBE coated pipe on skids. The longer section (left green coating) is approximately 1,500 feet (460 meters) long and the short section 80 feet (24 meters) long. Here the observed pipe-to-soil (P/S) potential was 243 VAC at the long section and 7.2 VAC at the short section.

Neither of these two pipeline sections had any mitigation at the time of the site visit. Both the CSA and NACE standard include very definitive safety procedure for induced AC safety during pipeline construction in HVAC shared ROW. These procedures include daily P/S potential measurements, record keeping and temporary grounding mitigation to maintain the induced potential below 15 VAC. The pipeline section to the far left (red FBE coating) did have mitigative grounding in place even though it was the furthest away. Figure 6 is a photograph of the mitigative grounding for this approximately 1,500-foot (460 meter) long section. Although the clamping method to the pipe is crude, the mitigation was effective. With the ground rod connected the induced AC P/S potential was 0.69 volts and with it removed it was 65.2 VAC. The drain current to the ground rod (measured with the added resistance of the meter and leads) was below 1 mA. This is well below the safety threshold, however this pipeline section was over 200 feet (60 meters) from the HVAC towers.

STEADY STATE HVAC TRANSMISSION LINE OPERATION

The level of induced AC from an HVAC power transmission line on an adjacent pipeline is a function of geometry, soil resistivity, coating resistance, and the transmission line operating parameters. The geometry characteristics include separation, depth of cover (DOC), pipe diameter, the angle between pipeline and transmission line, tower footing design and phase conductor spacing and distance above the ground at the towers. These remain constant over the life of the installation. The coating resistance, power system ground resistance and soil resistivity may change slightly with the seasonal variations and as the installation ages but remain reasonably constant. The AC voltage induced on the collocated pipeline is generated by the electromagnetic field in the soil. This field is much weaker than the field in the air above but it still exists and over long collocations can generate significant AC P/S potentials. Because the pipeline is grounded (has a finite resistance to ground even with a good coating) and has and longitudinal conductivity it becomes part of the transmission circuit. This is much like a transformer in a normal electrical circuit. In the steady-state (normal) HVAC line operation there is no significant AC ground current even near the tower footings or counterpoise. Figure 7 is a sketch showing this inductive coupling on a collocated buried pipeline.

Experience and predictive modeling of induced AC on collocated buried pipelines show that the highest AC P/S potentials are found at the beginning and end of a simple common ROW. However, typical configurations have changes in geometry, soil resistivity, coating resistance along the ROW that affects the induced AC potential profile. Grounding features such as terminal/pump station grounding isolation and CP system anode beds also affect the potential profile. These all lead to induced AC potential profiles that are often very complicated. With high dielectric coatings in good condition and high resistivity soils elevated AC potentials can be found miles downstream or upstream of the HVAC collocation. Figure 8 is a plot of observed induced AC potential versus pipeline milepost for a relatively simple and short configuration. Figure 9 is a plot for a more complicated example.

The normal HVAC line operating condition described as steady state is a bit misleading. As discussed above, the level of induced AC potential on a pipeline is a function of numerous variables including pipeline and HVAC transmission line geometry, spacing, soil resistivity, coating condition and conductor current load. Nearly all of these factors are dynamic except for the geometry (even this may vary slightly due to conductor sag from temperature changes). In most HVAC lines the phase current load is constantly changing. As a result the induced AC potential all along the pipeline is constantly changing. A common way pipeline operators monitor the level of induced AC on their collocated sections of pipe is to include AC P/S potential measurements during annual cathodic protection (CP) potential surveys. Typically the CP technician will complete a continuous section of the pipeline in one day and move to another section the next day. These sections may not be continuous from day to day depending on the base location of the technician. Because the HVAC line load is changing the AC potential readings may not represent the true induced potential profile. In addition the readings are typically taken during the day and the HVAC line load is normally very different at night. Figure 10 is a plot of the 345 kV HVAC line load of versus time with the time period and MP location of a sample recorded AC potential data set on an adjacent pipeline. In this example the day of the measurement was recorded but not the time of day. It was also assumed that the readings were taken during typical working hours of 8:00 AM to 5:00 PM. The HVAC line operator supplied the recorded hourly average load (Amperes/phase) over the time period of the pipeline survey. The red bars in the figure indicate the average load during the time it was assumed the technician took the readings. Not only is there a large variation in the load from day to day but also there is a large variation during the testing each day. Note during the first half of the testing the load averaged much higher at night than when the potentials were recorded. However during the last half of the testing the nighttime loads were about the same or a little less than during the testing.

It would be unrealistic to time stamp each AC P/S potential and correlate it to the HVAC line load at that moment. HVAC line operators are reluctant to release load data and CP technicians already have plenty to do. However the dynamic nature of induced AC potentials should be considered when evaluating field data. Figure 11 is a plot of the observed induced potentials and the potentials normalized to the 680-ampere load level. With all other factors remaining constant the induced potential will be a linear function of the HVAC line load. In this case the maximum average testing day load was 680 amperes (Sept. 23). The observed potentials from each test day were normalized to this level by the ratio of the average that day. Although both data sets show a similar profile, the normalized potentials are generally higher. All of the observed induced AC potentials are below the 15 VAC safety threshold while several of the normalized potentials are above 15 VAC. The point is that although the recorded AC potentials on your pipeline may indicate the locations of the highest induced AC interference there are times when it is likely they are higher than any of the observed readings.

There are some circumstances where AC can be a concern at induced voltages below the 15 VAC safety threshold in low resistivity soils. AC assisted external corrosion damage has been observed numerous times at induced AC potentials below 15 VAC. Numerous field and laboratory research and testing programs to assess the nature of induced AC external corrosion problems on buried pipelines have been completed. Nearly all of the work conducted has reached one important conclusion: in order to have a noticeable effect on the corrosion rate, AC current densities must be very high. These current densities most recently reported have been divided into the following:

- AC Current Density <20A/m2 – No AC induced Corrosion
- 20A/m2 < AC Current Density <100A/m2 - Corrosion is unpredictable and influenced by many environmental factors
- AC Current Density >100A/m2 - AC Corrosion likely occurs

Many cases indicate that AC corrosion is most likely to occur only on well coated structures (typically FBE) where the AC current is shown to discharge from very small holidays in the coating, thereby reaching the current densities listed above. The soil resistivity, holiday geometry and AC potential determine the current density. FBE is particularly susceptible because as a thin film coating the formation of pinhole holidays is much more likely than thick coating such as coal tar epoxy of tape. The holiday geometry and induced AC potential are dynamic and generally the AC current density varies with time. In the low resistivity soil found in this collocation AC current densities above the level for concern can be reached at induced potentials well below the 15-volt safety threshold.

Induced AC current densities can be estimated with interruptible coupons. The induced AC current discharge from a correctly sized coupon represents the current that would discharge from a coating holiday at that location. Measured and calculated current densities from a standards (1.4 sq. in.) have shown that in soils below 6,000 Ohm-cm induced AC current densities in the range where AC assisted corrosion may be a concern may be present at potentials below the 15 VAC safety threshold. The bulk resistivity to depths below the pipeline depth of cover (DOC) is one of the controlling factors in the level of HVAC interference. However the specific resistivity of the soil at the coating holiday is the primary factor in the corrosion activity (conventional galvanic and AC assisted). In rocky soil the bulk resistivity is usually much higher than the specific resistivity of the intermixed soil. Therefore the indicated AC current densities observed in the field vary considerably from those calculated based on the coupon or holiday size, particularly in heterogeneous soils.

AC assisted corrosion damage has a distinct morphology. The corrosion product typically remains next to the pipe surface forming a hard dome shape and forces the coating up off the pipeline. The underlying pit has a geometric shape often with a brown fringe. Figure 12 is a photograph of typical AC assisted corrosion damage showing the corrosion product. Figure 13 is a photograph after the coating and corrosion product were removed. In this case the measured induced P/S potential was 7.2 VAC and the soil resistivity 1,293 Ohm-cm at the dig site. The DC P/S potential was –1,590 mV to CSE (CP current applied) with a pH of 11 at the pipe surface indicating adequate protective DC polarization.

Experience with several AC assisted corrosion case histories has shown that the risk increases with higher induced AC voltage and lower soil resistivity. This suggests that the relative risk of AC assisted corrosion for a specific location could be indicated by dividing the induced AC Voltage by soil resistivity (**RR=VAC/Ohm-m)**. In a recent study analysis of several cases we found that where the RR (defined as relative risk) value was above 0.22, AC assisted corrosion damage might be found. When the RR value was above 1.0, damage was found in each case. Table 1 is a summary of calculated relative risk values (based on VAC/Ohm-m) and the ranges where AC assisted corrosion damage were found.

The relative risk values, based on the above analysis, were calculated for a 21 mile (34 km) pipeline/HVAC collocation. The recorded AC potentials and soil resistivity (at pipe depth) values associated with each potential location were used to determine the relative risk for each measurement. The soil resistivity along the pipeline varied from 2,875 Ohm-cm (near the beginning of the section) to 590 Ohm-cm along the last half of the section. All of the recorded AC P/S potentials were below 15 VAC due to the mitigation installations on the pipeline. None of the values approached the value where AC corrosion has been found (1.0) in the pilot study described above. However there are three (3) distinct areas where the calculated relative risk is in the range where AC assisted corrosion might occur (above 0.22). As a result the AC current density at these locations should be monitored with coupon test stations and additional mitigation installed if the indicated. Figure 14 is a plot of these calculated relative risks of AC corrosion for the AC potentials observed versus pipeline milepost.

Mitigation of steady state induced AC potentials on collocated pipelines is covered in both the CSA and NACE standards. Generally mitigation involves the installation of grounding at strategic locations along the pipeline. This mitigation is normally most effective when installed at the beginning or end of the common ROW. However in complicated pipeline/HVAC line geometries grounding installations are required at locations along the entire collocation. These installations can be parallel wire (bare copper of zinc ribbon), individual vertical rods or anodes, horizontal ground beds or wells. All these installations should be connected to the pipeline through DC decouplers to prevent galvanic couples and impressed current CP shielding (parallel zinc ribbon has been found to shield ICCP). Care should also be taken no to install too much grounding mitigation as the more grounding installed the higher the conductive AC fault current. Figure 15 is a plot of induced AC potential versus pipeline MP for a simple collocation with and with out mitigation at one end. In this case the mitigation at MP 0 included several vertical wells (total resistance of 0.31 Ohms) connected to the pipeline through a solid state DC decoupler.

HVAC FAULT CONDITION

A phase to ground fault on a HVAC transmission line causes large currents in the soil at the location of the fault and large return currents on the phase conductor and ground return. Seventy percent (70%) of AC Transmission line faults are phase to ground faults and are usually caused by lightning (most cases), phase insulator failure, mechanical failure of the phase conductor or support tower allowing the phase conductor to touch the ground and transformer failure. The high AC potentials generated on the adjacent pipeline during a fault are a result of the very high fault current in the faulted conductor (inductive coupling) and ground current near the faulted tower (conductive coupling). Figure 16 is a sketch of the inductive and conductive coupling elements during a HVAC line fault.

Obviously measurement of the AC potential profile during a HVAC line fault is difficult if not impossible. The analysis of the HVAC line fault conditions is completed with computer modeling software. Fault current levels must be supplied by the HVAC operator and vary significantly. Generally the available fault current at a given tower depends on the distance from the nearest substation, the substation bus voltage and generation source locations. Typical available fault currents are in the range of 5,000 amperes for a 115 kV line to over 20,000 amperes for a 500 kV line. The current feeds the faulted tower from each direction with the amount of current typically inversely proportional to the distance from the end of the HVAC circuit. Figure 17 is a typical predicted AC potential profile for a faulted 138 kV HVAC line and a simple short pipeline configuration. The highest AC potentials are adjacent of the faulted tower at MP 1.1 due to the high conductive soil coupling at that point. The entire pipeline will have elevated AC potentials due to successively less conductive coupling at each tower (energized by the shield/ground wire above the phase conductors and the high fault current in the faulted conductor. Nearly the entire pipeline is above 100 VAC in this fault condition while it is below 5 VAC in the steady state condition (this is the same pipeline shown in Figure 15).

Although these faults are normally of short duration (less than a second) pipeline damage can occur from high potential breakdown of the coating, resistive conductive arcing across the coating near the fault and high-induced currents along the ROW. Fault current conditions that produce excess voltages across the coating are of concern for dielectric coatings. The value for each coating type is derived from the generally accepted rule of 125 volts per mil of coating thickness before possible coating breakdown. These calculated over voltages can range from 10,000 volts for three layer tape (80 mils) to 1750 volts for FBE (14 mils). However recent experience indicates that newer FBE coatings have a much higher breakdown voltage in the order of 5,000 to 6,000 volts. The CSA standard recommends a minimum spacing between a HVAC tower leg and pipeline of 10 meters (33 feet). This is a reasonable separation is more than the calculated arc distance for most HVAC voltages and soil resistivities under 100,000 Ohm-cm. When the pipeline is closer to a tower footing than the predicted arc distance or the predicted AC voltage across the coating a buried shield wire (connected through a DC decoupler) should be installed between the pipeline and tower footing.

These conductive currents and high induced voltages represent a significant safety hazard if personnel are working on or testing the pipeline during a fault condition. Most HVAC lines have fault clearing times of 1 to 5 cycles (0.02 to 0.08 seconds) so that the safety threshold is higher than the 15 VAC continuous exposure level. The IEEE 80 substation grounding safety guide includes methods for calculating tolerable voltages for a given threshold of body current. It includes an analysis of a touch potential circuit through a hand and the feet similar to the CP test station circuit Shown in Figure 18. This calculation is conservative and yields a resistance below what would be expected because: one, it assumes each foot as a conducting metal disk with the contact resistance of the shoes and socks as zero (pipeline technicians typically wear rubber soled work boots) and two, the calculation is based on a foot separation of a one meter pace (the technician would be standing at the test station with feet closer together and a resultant higher resistance to ground). Within the range of normally encountered soil resistivities these calculations typically lead to safe short-term touch voltages over 15 VAC.

It is not practical to mitigate fault induced AC potentials to below 15 VAC or even safe short-term substation level touch voltages. The strategy for fault safety on pipelines is to minimize exposure to unsafe voltages with gradient control (grounding) mats and gravel pads at pipeline appurtenances such as valves where access may be required at any time. A steel, copper cable or zinc ribbon ground mat will raise the local ground potential around the appurtenance to near the potential of the pipeline to minimize the touch potential. The gravel pad will increase the foot contact resistance to limit the body circuit current. CP test stations should be of dead front design and metallic casing vents should be shielded to prevent accidental contact. Figure 19 from the CSA standard show the layout of a zinc ribbon gradient control mat. Figure 20 is a photograph of a mainline valve with a DC decoupler as recommended with a gradient control mat. Figure 21 shows a typical casing vent shield.

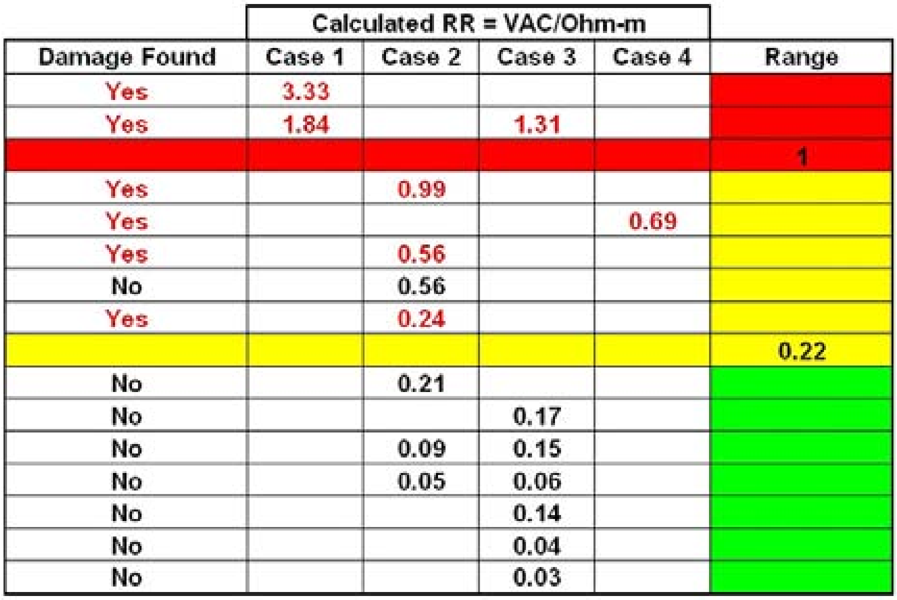
CONCLUSIONS

The interference problems that affect pipelines in common right of ways or near high voltage AC power (HVAC) transmission lines have been well defined in recent years. CSA and NACE have both published standards that deal with the safety, AC assisted corrosion damage and mitigation options. The author's experience indicates that the pipeline operator should pay particular attention to the following issues;

- During pipeline construction near HVAC transmission lines confirm that the contractor has a safety program the meets the requirements in the industry standards for limits of shock hazards. Monitor the contractor during construction.
- Include AC P/S potential measurements at each test station during annual CP P/S potentials surveys
- Perform an safety, coating damage and AC corrosion interference analysis of the steady state and fault conditions on pipeline sections where AC P/S potentials are found (suggest a cut off of 2 Volts unless the soil resistance is less than 1,000 Ohm-cm)
- Perform a fault analysis if pipeline is closer than the recommended CSA 10-meter (33 Feet) spacing, even if AC potentials are not observed during HVAC steady state operation.
- Install, monitor and maintain mitigation if the analysis indicates safety, AC corrosion or pipe coating/wall damage is possible.
- Train operating personnel (particularly CP technicians) in the hazards involved and protective techniques when working on pipelines subject to HVAC transmission line interference.

TABLE 1:

CALCULATED AND SUGGESTED RANGES OF CONCERN FOR RELATIVE AC CORROSION RISK



	Calculated RR = VAC/Ohm-m				
Damage Found	Case 1	Case 2	Case 3	Case 4	Range
Yes	3.33				🟥
Yes	1.84		1.31		🟥
					1
Yes		0.99			🟨
Yes				0.69	🟨
Yes		0.56			🟨
No		0.56			🟨
Yes		0.24			🟨
					0.22
No		0.21			🟩
No			0.17		🟩
No		0.09	0.15		🟩
No		0.05	0.06		🟩
No			0.14		🟩
No			0.04		🟩
No			0.03		🟩

FIGURES

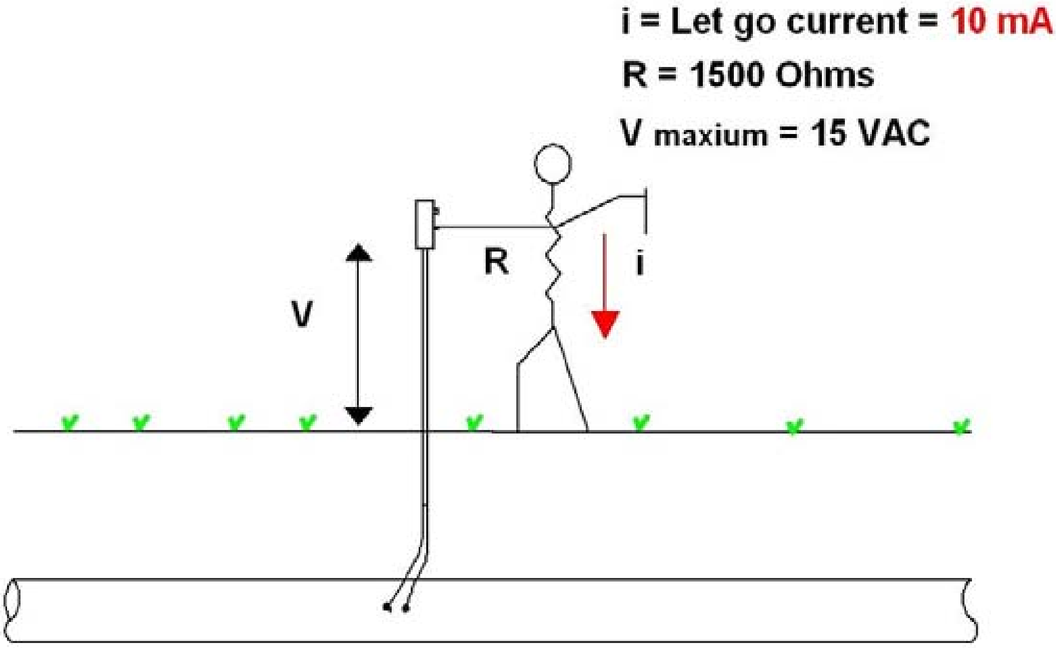


FIGURE 1: Circuit Assumptions for 15 VAC Safety Standard

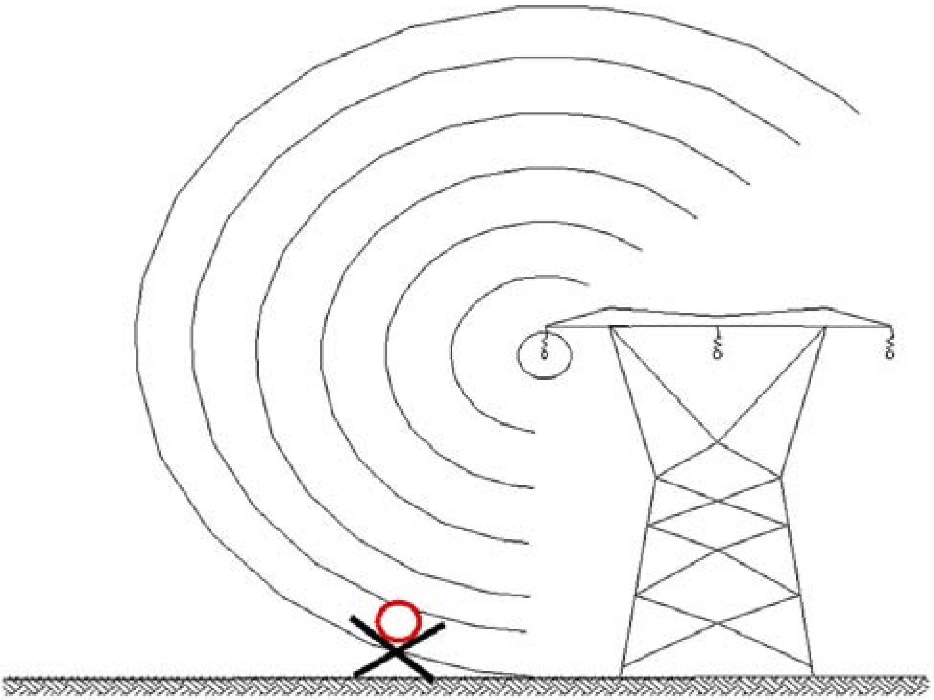


FIGURE 2: Capacitive Coupling of Pipeline Section on Skids

FIGURE 3: Example of HVAC Hazard during Pipeline Construction in HVAC ROW

FIGURE 4: Pipe-to-Soil AC Potential at End of Pipe in Figure 3

FIGURE 5: Various Length Pipe Sections on Skids in HVAC ROW

FIGURE 6: Capacitive Coupled AC Temporary Grounding Mitigation

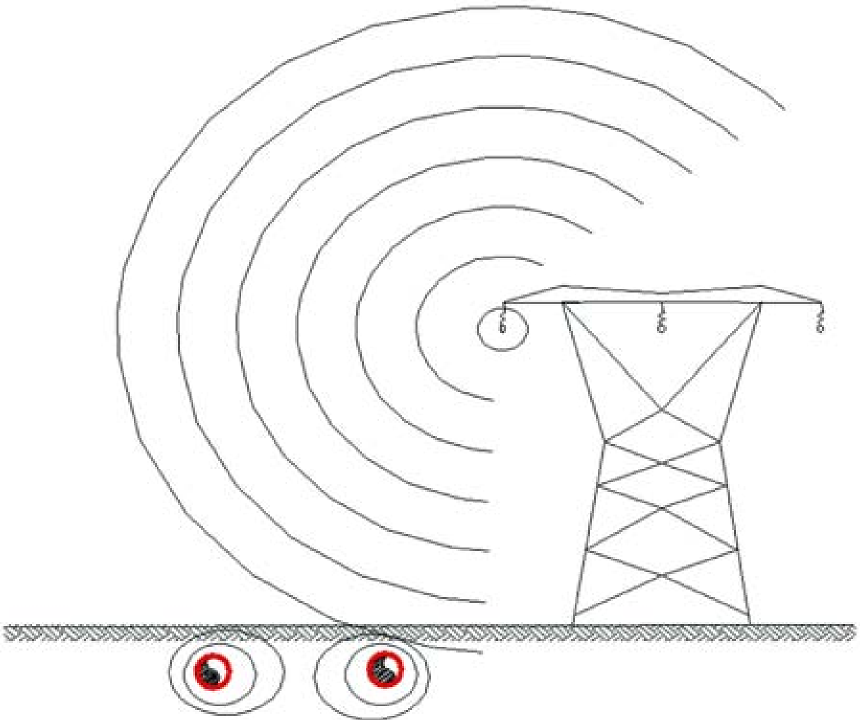


FIGURE 7: Inductive Coupling of Collocated Buried Pipelines

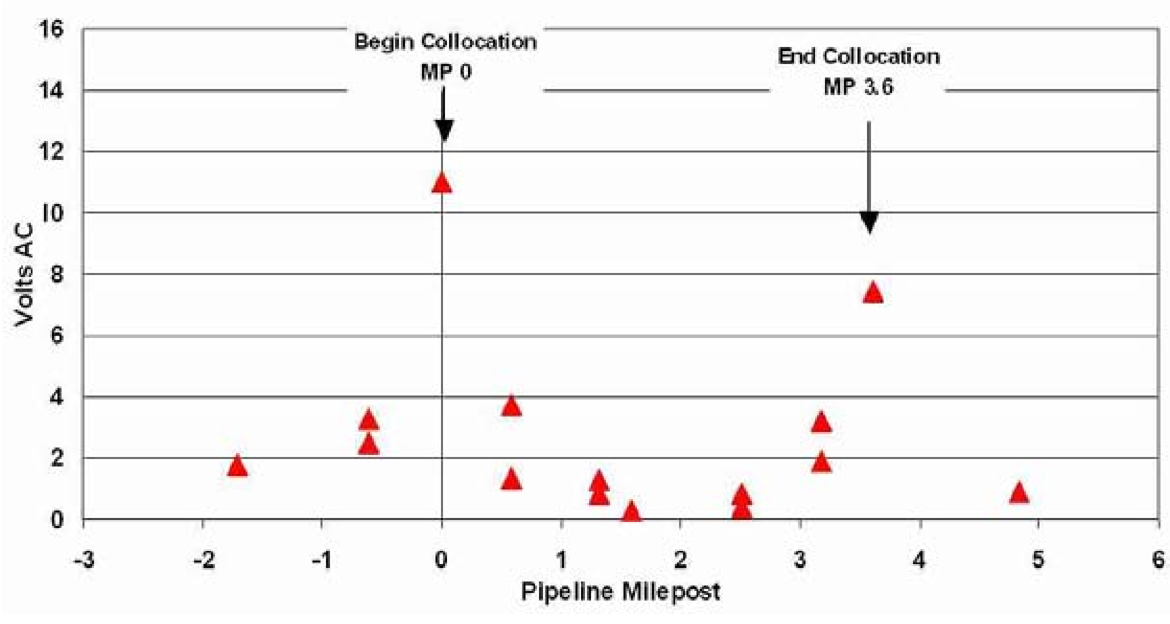


FIGURE 8: Observed Induced AC Potentials on a Short 3.6-mile Pipeline / HVAC Collocation

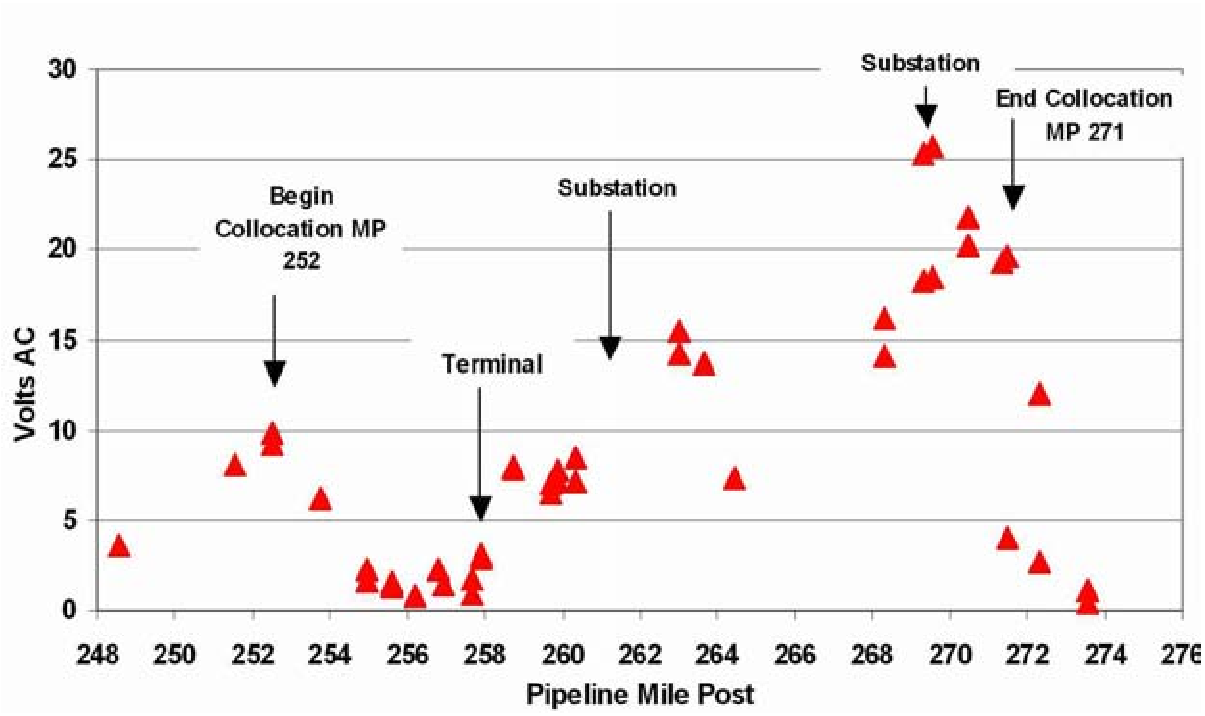


FIGURE 9: Observed Induced AC Potentials on a 19-mile Complicated Pipeline / HVAC Collocation

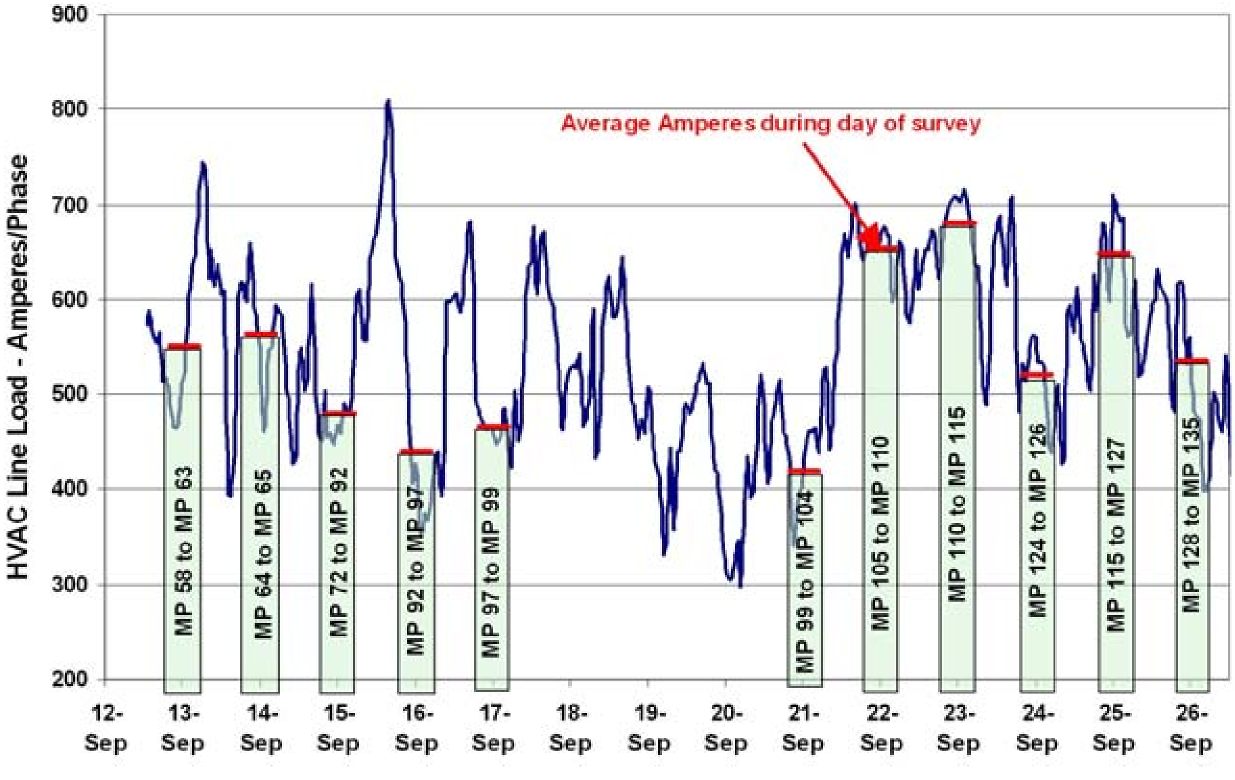


FIGURE 10: Example of HVAC Line Loads versus Time and Typical Potentials Survey Data Collection

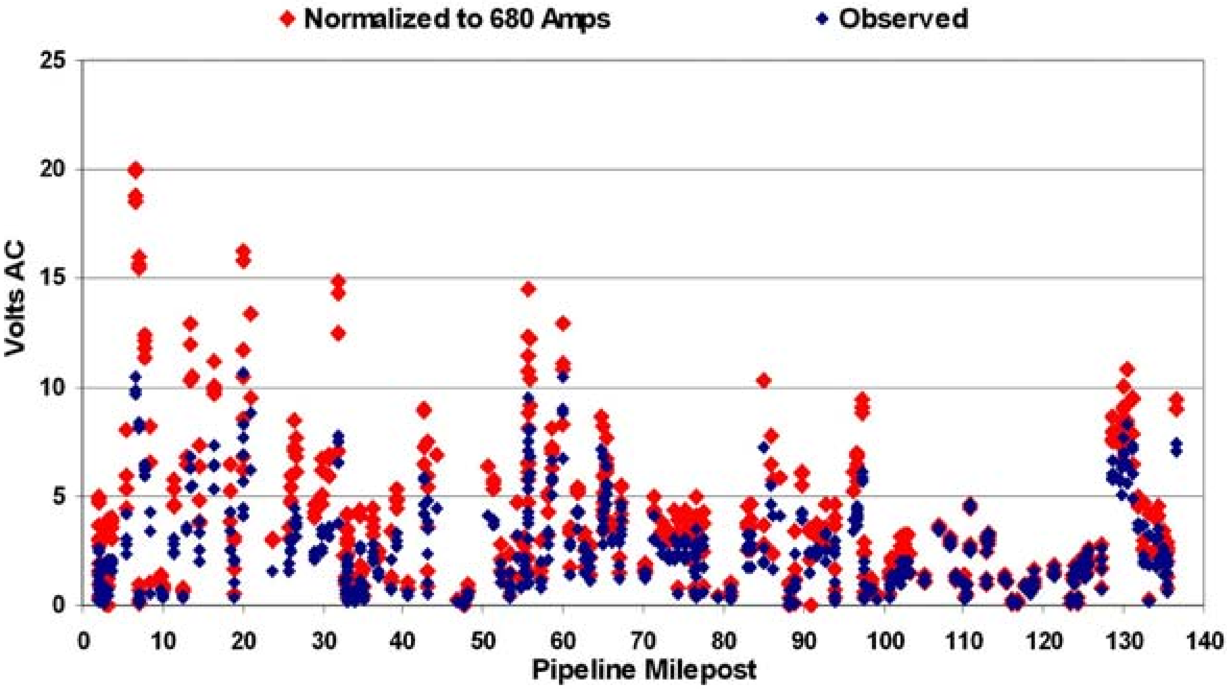


FIGURE 11: Observed and Normalized (to Maximum Day Average Load) Induced AC Potentials versus Pipeline Milepost

FIGURE 12: Typical AC Assisted Corrosion Product Formation

FIGURE 13: Figure 12 with Corrosion Product Removed

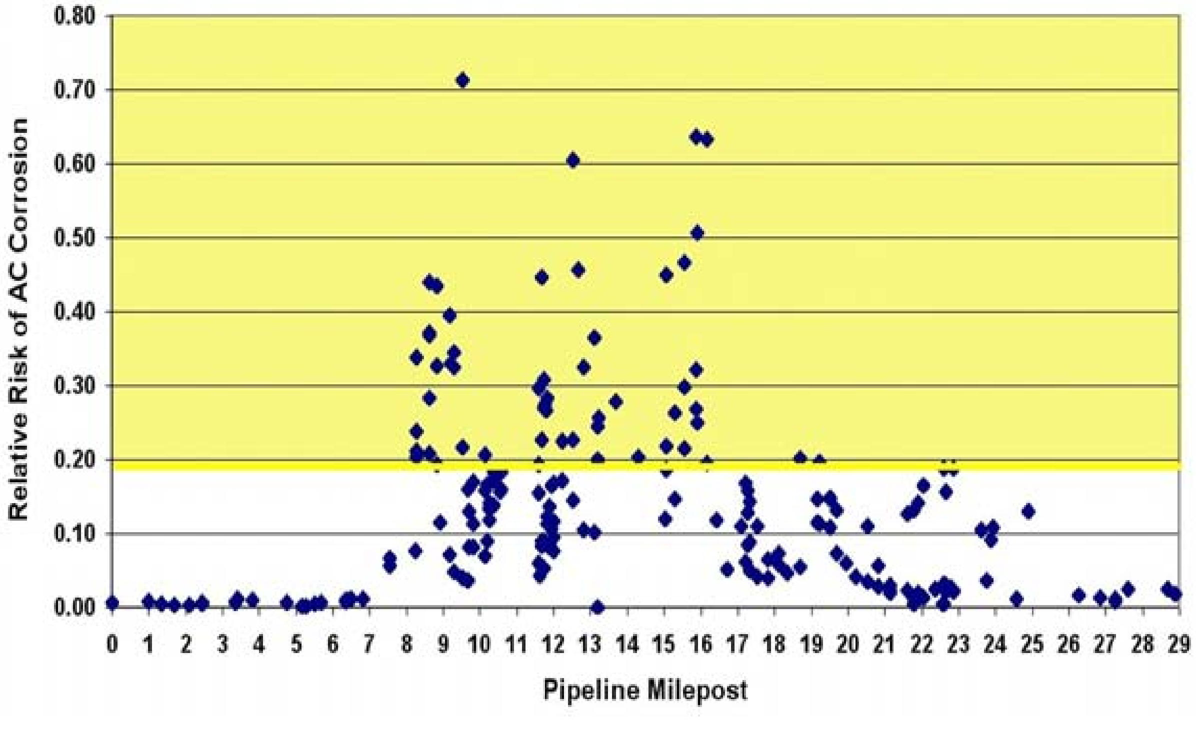


FIGURE 14: Example of Relative Risk of AC Corrosion versus Pipeline Milepost

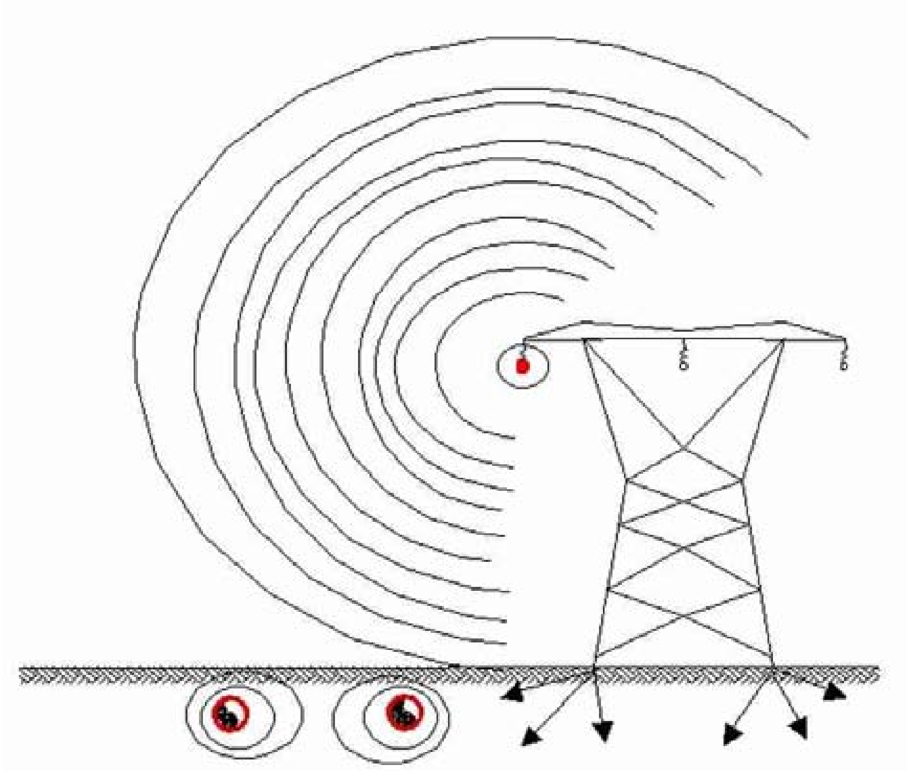


FIGURE 15: Example of Mitigation of Induced AC on Simple Pipeline Configuration

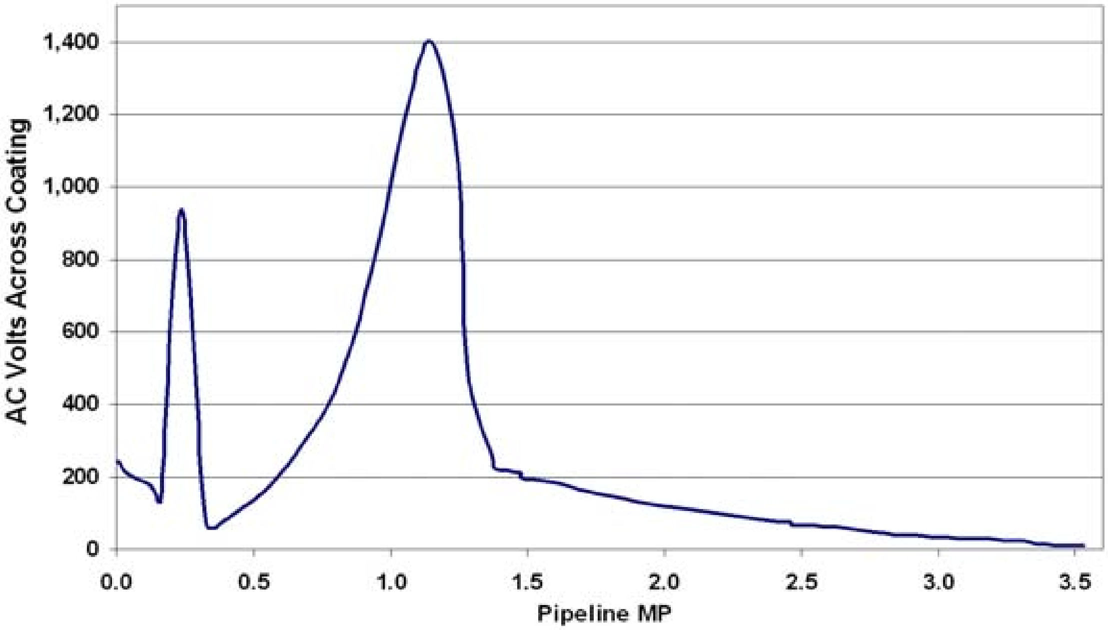


FIGURE 16: Typical Predicted AC Voltage Profile with Fault HVAC Tower

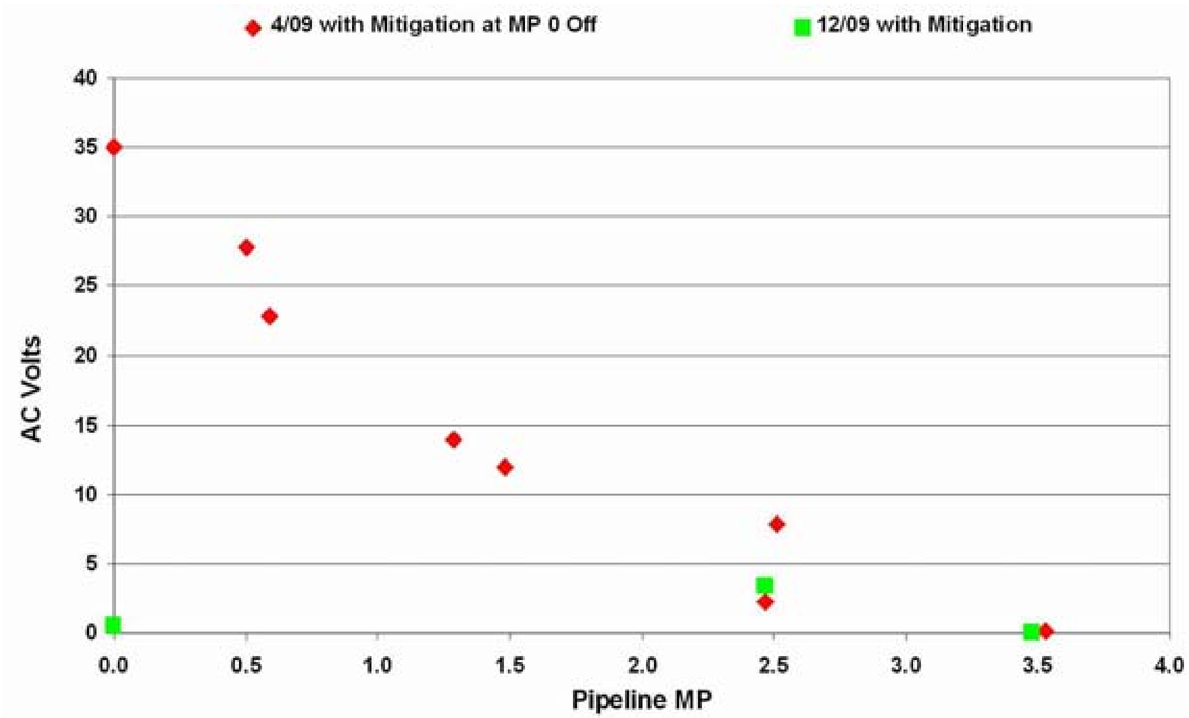
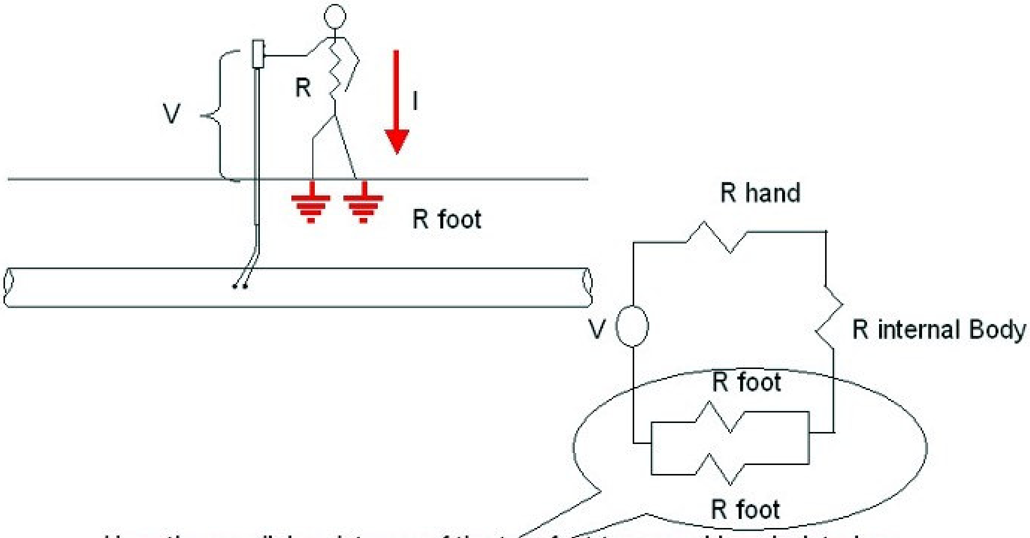


FIGURE 17: Inductive and Conductive Coupling during an HVAC Line Fault



Here the parallel resistance of the two feet to ground is calculated as
R (2 feet parallel) = 11/2 (ρ)
Where ρ = Soil Resistivity in Ohm-Meters

FIGURE 18: Accidental Touch Voltage Circuit at CP Test Station

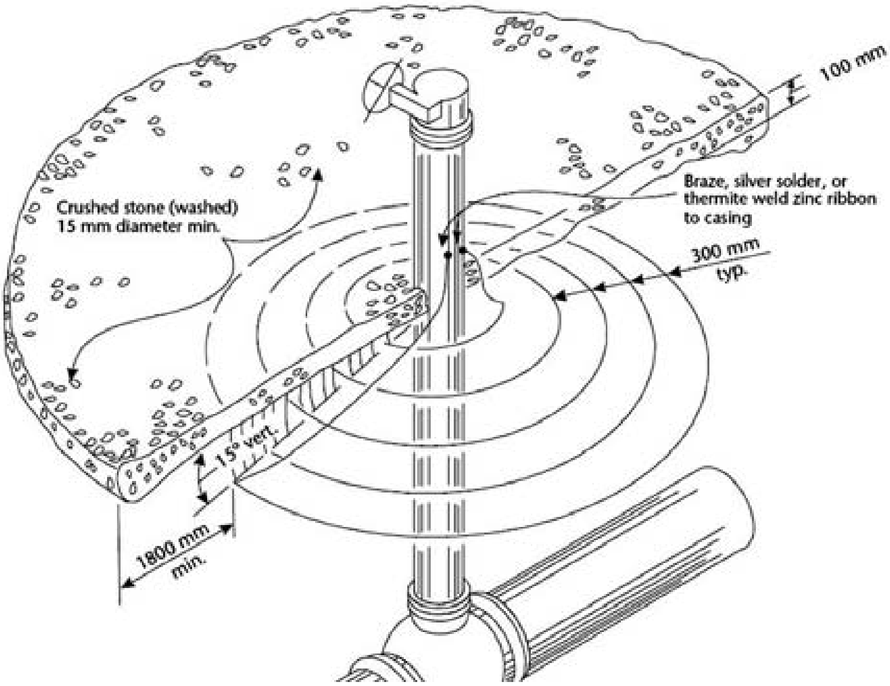


FIGURE 19: CSA Gradient Control Mat Detail

FIGURE 20: DC Decoupler at Mainline Valve Ground Mat

FIGURE 21: Casing Vent Shield