REALTIME MONITORING OF PIPELINES FOR THIRD-PARTY CONTACT

FINAL REPORT
October 1, 2003–December 31, 2005

Principal Author
Gary L. Burkhardt

March 2006

DOE Cooperative Agreement DE-FC26-03NT41878
SwRI® Project 14.10211

Prepared by
Sensor Systems and NDE Technology Department
Applied Physics Division
Southwest Research Institute®

Prepared for
U.S. Department of Energy
National Energy Technology Lab
3610 Collins Ferry Road
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ABSTRACT

Third-party contact with pipelines (typically caused by contact with a digging or drilling device) can result in mechanical damage to the pipe, in addition to coating damage that can initiate corrosion. Because this type of damage often goes unreported and can lead to eventual catastrophic failure of the pipe, a reliable, cost-effective method is needed for monitoring the pipeline and reporting third-party contact events.

The impressed alternating cycle current (IACC) pipeline monitoring method developed by Southwest Research Institute (SwRI) consists of impressing electrical signals on the pipe by generating a time-varying voltage between the pipe and the soil. The signal voltage between the pipe and ground is monitored continuously at receiving stations located some distance away. Third-party contact to the pipe that breaks through the coating (thus resulting in a signal path to ground) changes the signal received at the receiving stations.

The IACC method was shown to be a viable method that can be used to continuously monitor pipelines for third-party contact. Electrical connections to the pipeline can be made through existing cathodic protection (CP) test points without the need to dig up the pipe. The instrumentation is relatively simple, consisting of (1) a transmitting station with a frequency-stable oscillator and amplifier and (2) a receiving station with a filter, lock-in amplifier, frequency-stable oscillator, and remote reporting device (e.g. cell phone system). Maximum distances between the transmitting and receiving stations are approximately 1.61 km (1 mile), although the length of pipeline monitored can be twice this using a single transmitter and one receiver on each side (since the signal travels in both directions). Certain conditions—such as poor pipeline coatings or strong induced 60-Hz signals on the pipeline—can degrade IACC performance, so localized testing should be performed to determine the suitability for an IACC installation at a given location. The method can be used with pipelines having active CP systems in place without causing interference with operation of the CP system.

The most appropriate use of IACC is monitoring of localized high-consequence areas where there is a significant risk of third-party contact (e.g. construction activity). The method also lends itself to temporary, low-cost installation where there is a short-term need for monitoring.

EXECUTIVE SUMMARY

Third-party contact with pipelines (typically caused by contact with a digging or drilling device) can result in mechanical damage to the pipe, in addition to coating damage that can initiate corrosion. Because this type of damage often goes unreported and can lead to eventual catastrophic failure of the pipe, a reliable, cost-effective method is needed for monitoring and reporting third-party contact events.

The IACC pipeline monitoring method developed by SwRI impresses electrical signals on the pipe by generating a time-varying voltage between the pipe and the soil at periodic locations where pipeline access is available. The signal voltage between the pipe and ground is monitored continuously at receiving stations located some distance away. Third-party contact to the pipe that breaks through the coating changes the signal received at the receiving stations.

In this project, the IACC monitoring method was further developed, tested, and demonstrated. The initial approach was to use a chirp excitation waveform that sweeps over a range of frequencies; this was chosen to facilitate rejection of interfering noise. A matched filter, implemented in software, is then used to compare received signals to the transmitted signal and determine changes resulting from third-party contact. Although this approach was viable, a second simpler approach was also developed that was as effective as the chirp method and ultimately replaced the chirp method. This approach was based on the use of a lock-in amplifier operating at a single excitation frequency. Lock-in amplifiers have very high dynamic range and are typically used to detect signals that are buried in noise. A lock-in amplifier typically requires a reference signal between the transmitter and receiver (that would normally require a wired connection); however, this need was eliminated by using highly stable oscillators for both the transmitter and receiver. The lock-in amplifier approach was effective, and the instrumentation and signal-processing requirements were straightforward.

Tests were performed on several operating pipelines by making electrical contact through existing CP test points. The tests showed that the maximum effective distance between the transmitting and receiving stations is approximately 1.61 km (1 mile), although the length of pipeline monitored can be doubled using a single transmitter and one receiver on each side. Certain conditions—such as poor pipeline coatings or strong induced 60-Hz signals on the pipeline—can degrade IACC performance, and localized testing should be performed to determine the suitability for an IACC installation at a given location. IACC can be implemented with active CP protection systems in place without interference with the CP system. In addition, published guidelines regarding AC corrosion show that the IACC signals should not result in corrosion of any pipe with adequate CP protection.

The most appropriate use of IACC is for monitoring localized high-consequence areas where there is a significant risk of third-party contact (e.g. construction activity). Because connections can be made using existing CP test points, the method can be implemented without the need to excavate the pipe. The method also lends itself to temporary, low-cost installation where there is a short-term need for monitoring. Design guidelines were developed and show how an IACC monitoring system can be implemented.

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INTRODUCTION AND BACKGROUND

Third-party contact with pipelines (typically caused by contact with a digging or drilling device) can result in damage to the pipe. Because this type of damage often goes unreported and can lead to eventual catastrophic failure of the pipe, a reliable, cost-effective method is needed for monitoring and reporting third-party contact events.

The impressed alternating cycle current (IACC) pipeline monitoring method developed by SwRI impresses electrical signals on the pipe by generating a time-varying voltage between the pipe and the soil at locations where pipeline access is available—typically, cathodic protection (CP) test points (Figure 1). The signal, which travels down the pipe in both directions from the transmitter (Figure 1, left), consists of a time-dependent waveform designed to maximize IACC system performance in the presence of various sources of external noise. Receiving stations (Figure 1, right), located at some distance from the transmitting station, continuously monitor the received signal by measuring the pipe-to-soil voltage waveform. Third-party contact to the pipe that breaks through the coating changes the signal received at the IACC receiving stations that are located in the segment of pipe being contacted. Figure 2 illustrates detection of a backhoe strike using an IACC system.

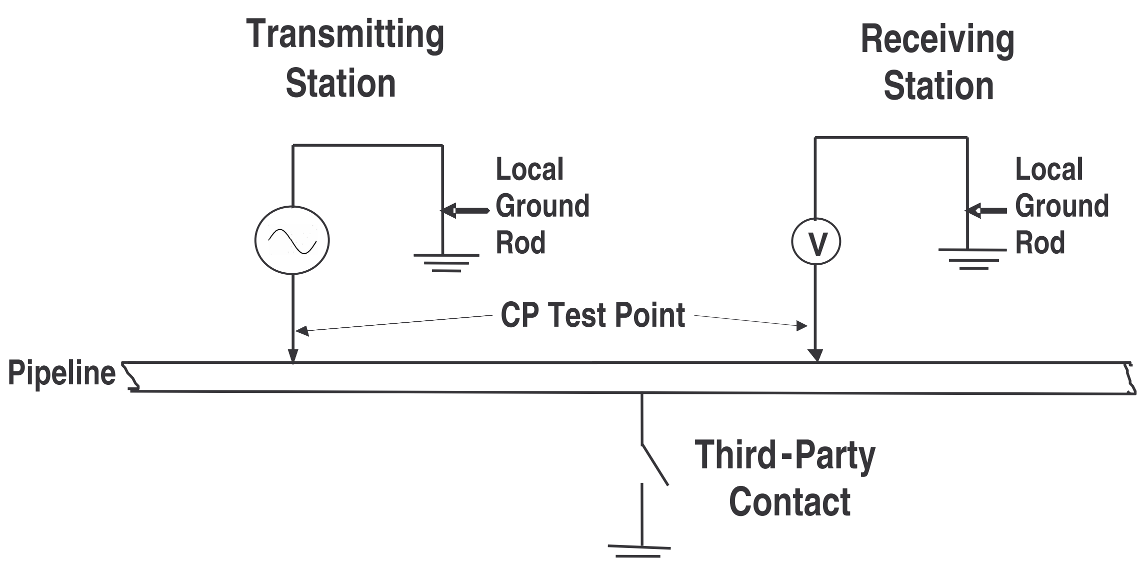


Figure 1. Schematic of IACC transmitting station (left), showing time-varying voltage applied to the pipe, and receiving station (right), showing measurement of pipe-to-soil voltage waveform. Third-party contact electrically connects the pipe to the soil.

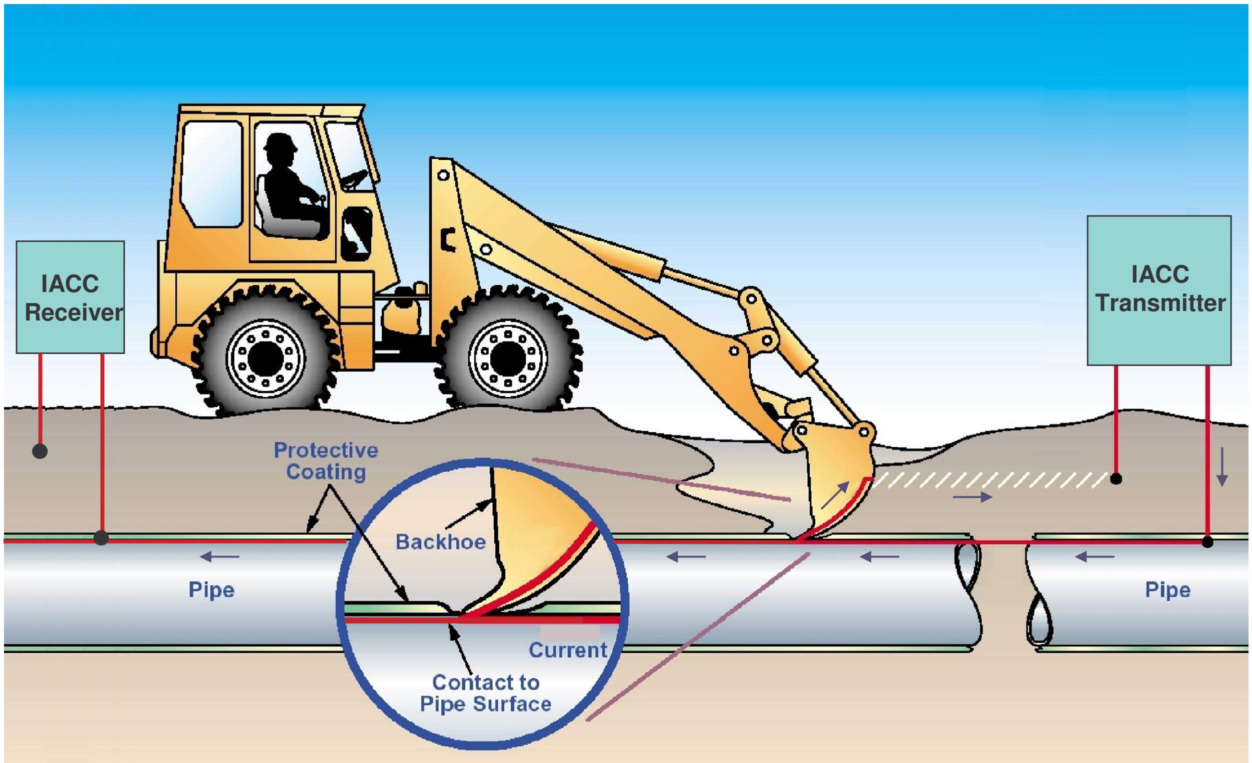


Figure 2. Illustration of IACC detection of backhoe strike

This method will allow existing pipelines to be retrofitted for monitoring without excavation because the technique uses existing CP test points for connection to the pipeline. In addition, the method is readily applied to new pipelines. The objectives of the project described here were to further develop, test, and demonstrate the IACC monitoring method for detecting third-party contact with pipelines in real time. Guidelines were also developed for use by a vendor to begin development of a commercial version of an IACC system.

RESULTS AND DISCUSSION

The sections below correspond to those used in the Research Management Plan.

1.1 Research Management Plan

A research management plan document was prepared as required by the Research Agreement. This document served as the main planning and tracking document for the project. The document included a concise summary of the technical objectives and technical approach for each task and included schedules, planned expenditures, and milestones.

1.2 Technology Status Assessment

In addition to IACC, several other methods exist, or are being developed, for monitoring and reporting third-party contact or activity near a pipeline. These methods include acoustic monitoring devices, continuous fiber-optic sensors buried alongside the pipe, satellite surveillance, cathodic protection monitoring, and methods that rely on telephone calls prior to digging. A technology assessment document was prepared to describe the state of the art of pipeline monitoring, including positive and negative characteristics of existing technologies, and to present a comparison to the IACC technology. This document is included in Appendix A.

The technology assessment was based on literature, Internet, and patent searches, as well as knowledge and contacts of Southwest Research Institute (SwRI) personnel. A comparison of the characteristics of the above pipeline monitoring methods is given in Table 1. All of these methods have inherent limitations that reduce their usefulness under certain conditions. The IACC method that is being investigated in this project offers distinct advantages that would allow it to be an attractive alternate or complementary approach.

Table 1. Comparison of Pipeline Monitoring Methods

THIRD-PARTY MONITORING SYSTEM	Requires breach of coating for installation?	Equally effective for impacts and boring contact?	Range between sensors	Effective in urban congestion?	Provides full-time coverage?	Requires excavation for installation?	Development status
Acoustic Sensing	Yes	No	10 miles	Reduced	Yes	Yes	Field testing
Fiber Optic	No	No	10's of miles	Reduced	Yes	Yes	Field testing
Satellite Monitoring	No	Yes	N/A	No	No	No	Under development
CP Monitoring	No	Yes	Unknown	Yes	Yes	No	Field testing
One-Call System	No	Yes	N/A	Yes	N/A	No	Commercial
IACC	No	Yes	Several miles	Yes	Yes	No	Under development

1.3 IACC Parameter Refinement

1.3.1 Modeling

This effort involved developing an equivalent circuit computer model to represent the electrical circuit formed by the pipe and its interaction with the earth (e.g. resistive and capacitative coupling). The purpose of the model was to allow simulations to be performed to study the effects of signal characteristics (e.g. excitation frequency) on the IACC signals. These simulations would allow signal characteristics to be selected to maximize range and sensitivity to third-party contact.

Justification of Lumped Parameter Model—Since pipeline lengths, and the planned distance between monitoring stations, are very large compared to systems typically modeled using discrete components, we decided to address the question as to whether or not it is appropriate to try to simulate the pipeline system using a lumped parameter model rather than a distributed model, such as has been developed for transmission lines. One way to address this question is to consider the distances of concern compared to a wavelength. As a lower bound on the wavelength, consider the extremely conservative assumption that the waves travel at the speed of light and that the highest frequency of interest is 30 kHz. In that case, the wavelength is approximately

$$\lambda = \frac{3\times10^{8}\, m/s}{30\times10^{3}/s} = 10000\, m\,.$$

In other words, the shortest wavelength of interest is more than 6 miles, much greater than characteristic lengths of the system. In conclusion, the distributed parameter model is not necessary.

Justification of Soil Model—Soil can generally be characterized electromagnetically by its resistivity (or conductivity) and permittivity. Relative permittivities for soils range up to approximately 30 for highly moist ground [1]. Typical conductivities are of the order of 0.0001 to 0.001 Mhos/m. In order to accurately model time-dependent electromagnetic fields in the soil, both properties should, in general, be used. However, the relative amplitude of the displacement current density (i.e. the current due to the dielectric properties) compared to the conduction current density (i.e. the current due to resistive losses) can be estimated as

$$\omega\varepsilon/\sigma \text{ [2]}$$

where

ω is the frequency in radians/sec,

ε is the permittivity in F/m, and

σ is the conductivity in Mhos/m

For example, if the frequency is 30 kHz and the permittivity is 30 ε_0, then

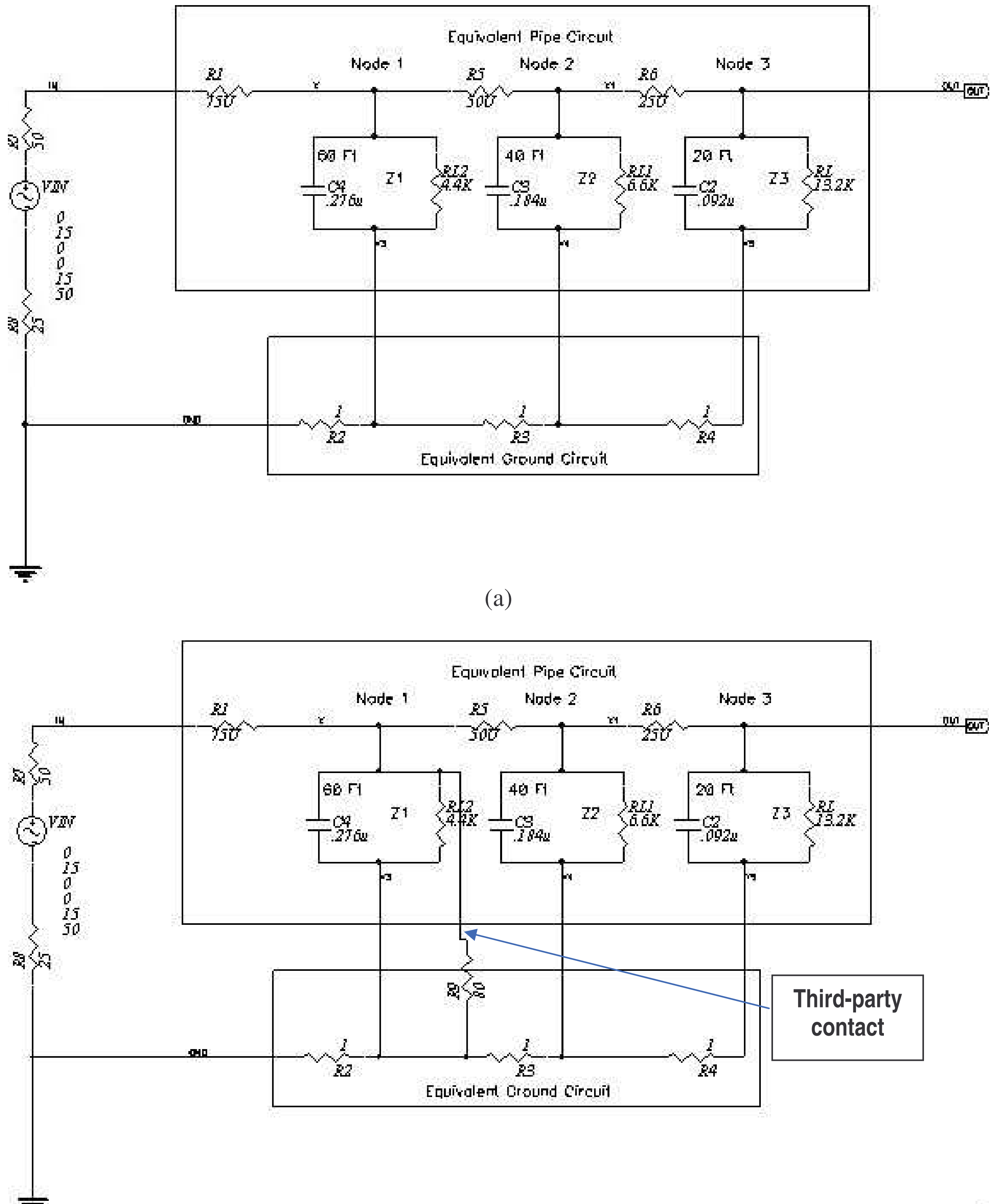
$$\omega\varepsilon/\sigma = 2\,\omega\varepsilon/\sigma \approx 2\pi\times30\times10^{3}\times30\times8.854\times10^{-12}/.0001$$

or approximately 0.5, which marginally favors the resistive model. For the lower frequencies planned and more typical higher soil conductivities, this ratio quickly becomes much less than 1, which means that electromagnetic fields in the soil will have a diffusive rather than wavelike behavior. In other words, at the prime frequencies of interest (<10 kHz), the soil behavior is more resistive than capacitive. Hence, we have chosen to model the soil as a series of resistors, with the relative value of the resistors indicative of the length of the return path.

Extension of Measured and Calculated Parameters to Operating Pipelines—From the above reasoning, it is clear that the lumped parameter model is likely to be a reasonable model for long operating pipelines. Then the question is how to extend parameters calculated and measured on the SwRI test bed to actual pipelines. First, measurements on the test bed were divided for model purposes into sections based on the available risers in the test bed. Next, the model is made of sections, with one section for each section in the test bed pipe. This leads to key values—in particular, capacitance per meter length of pipe, resistance per meter of pipe, and resistance per meter of soil (of average return path from each section). To extend the model to longer pipes of the same diameter and coating and soil conditions, it is now only necessary to add sections to the model. If soil conditions change, it is only necessary to scale the resistance of the soil return resistance by the ratio of the new soil resistivity to that used in developing the model (since, from the section above, we can safely ignore the soil permittivity). In this simple model, the amount of moisture in the soil should not be a large effect, since moisture primarily affects the permittivity rather than the resistivity. To scale the model to account for different pipe sizes, it is only necessary to scale the capacitance (of the coating) per linear meter by the pipe diameter, since area per unit length of the capacitor formed by the pipe-coating-soil layer is proportional to the circumference of the pipe. Finally, different coatings may have different permittivities; the capacitance value of the model should be scaled in proportion to the permittivity of the pipe coating.

PCAD Model Configuration—An equivalent circuit lumped parameter model was set up in PCAD (a circuit analysis software package) that will allow evaluation of the pipe response at different excitation frequencies. The model configuration is shown in Figure 3 and is based on the configuration and measured parameters of the pipe at the SwRI test site, as measured in Section 1.3.3. Each section of the model represents the section of pipe between two risers in the test pipe. Note that the distances between the risers are different and the parameters for each section are scaled to the appropriate distance. The model represents an IACC monitoring system with the excitation at the left (V_{in}) and sensing at the right (OUT). Figure 3(b) shows a third-party contact event represented by a path to ground through the added resistor R9.

The output voltage was calculated at different frequencies ranging from 50 Hz to 5 kHz for the 120-foot-long test pipe. The absolute signal level (without contact) at 5 kHz decreased by about 16 percent compared to 50 Hz. Because the pipe is so short, the frequency effect was expected to be minimal, as predicted by the model. Simulated third-party contact resulted in a decrease in signal level of about 46 percent at 50 Hz to 28 percent at 5 kHz, thus indicating that contact could readily be detected. The pipe parameters were then adjusted to simulate a 6,000-foot pipe. Under these conditions, the absolute signal level (without contact) at 5 kHz decreased by about 93 percent compared to 50 Hz. At 50 Hz, the change due to contact was still relatively large (27 percent); however, at 500 Hz up to 5 kHz, there was essentially no change due to contact. These results indicate that for longer pipe distances, the excitation frequency needs to be as low as possible.



(a)

(b)

Figure 3. PCAD model of SwRI test pipe: (a) normal pipe condition; (b) with simulated third-party contact

1.3.2 Instrumentation and Signal Processing

Chirp Waveform Approach—The initial approach for implementing IACC was to transmit repetitive chirp waveforms, each consisting of a frequency sweep of the signal over a fixed frequency range. The reason for using a chirp is that the signal is spread over a broad frequency range so that interfering noise that occurs at specific frequencies does not have a large contribution to the overall signal, and therefore the overall signal-to-noise ratio is improved.

Instrumentation for the chirp waveform approach is shown in the block diagram in Figure 4. At the transmitting station, an arbitrary waveform generator (programmed with the desired chirp waveform) drives a power amplifier, which applies the waveform to the pipe. At the receiving station, the signal is amplified using a preamplifier and then passes through a bandpass and/or comb (multiple notch) filter. The signal is then digitized using an analog-to-digital converter in a laptop computer. In early testing, only the bandpass filter was used; the comb filter (which provides notch filters at even and odd harmonics of 60 Hz) was added later.

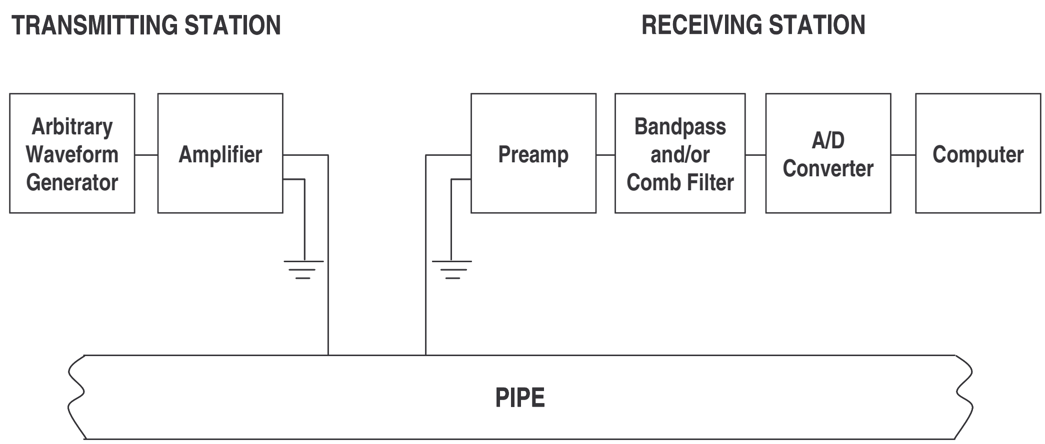


Figure 4. Chirp waveform instrumentation

The goal of signal processing was to identify changes in the chirp signal caused by third-party contact and to improve signal-to-noise ratios so that sensing of third-party contact could be extended over longer distances. The signal processing approach for the chirp initially consisted of bandpass and notch filtering, as well as matched filtering. The notch filtering was performed in software after the IACC signals were digitized. Bandpass filtering is used to limit the frequencies of the digitized chirp waveform to only those in the chirp bandwidth. Because of 60-Hz signals that are induced in the pipe from power lines, as well as signals resulting from CP systems using rectified 60-Hz power, the waveforms measured from the pipe contain considerable energy at 60 Hz and at even and odd harmonics of 60 Hz. Because these signals are quite strong (more than an order of magnitude compared to the received IACC signal), notch filters at 60 Hz and harmonics are needed to reduce interference at these frequencies. The matched filtering approach is performed in software and consists of comparing a waveform having the characteristics of the transmit waveform to that of the received waveform. This is accomplished by a process similar to performing a cross correlation between the two signals. Since there is no time synchronization between the transmitted and received waveforms, it is necessary to continuously increment the transmitted waveform in time compared to the received waveform and repeat the correlation process. A "match" between the waveforms produces a high correlation coefficient at that point in time. The result is a high correlation coefficient that occurs at the repetition rate of the chirp. Third-party contact reduces the amplitude of the chirp and thus produces a lower correlation coefficient.

Software filter routines for notch and matched filtering were written in Matlab. Implementation of the notch filter in software was effective. One difficulty with this approach, however, is that the 60-Hz signals can be much larger (e.g. orders of magnitude) than the IACC signals. Since the signals are digitized prior to filtering, the dynamic range of the digitizer has to accommodate the larger 60-Hz signals and, therefore, only a limited dynamic range is available for the IACC signals. Therefore, resolution is lost.

An alternate approach is to implement a comb filter prior to digitization of the IACC chirp signal so that the interfering signals do not occupy a large portion of the dynamic range of the digitizer. This filter consists of a series of notch filters at 60 Hz and its higher harmonics. This would allow greater resolution and an improvement in the signal-to-noise ratio.

A comb filter was fabricated and was very effective for removing the 60 Hz and harmonics signals when operated with steady-state excitation. Use of a chirp excitation waveform with this filter, however, resulted in unsatisfactory results because there is a slight instability in the signal as the chirp frequency sweeps past each of the notch filter frequencies; this makes it difficult to resolve the small changes in IACC signal caused by third-party contact when using the chirp waveform.

Lock-In Amplifier Approach—An alternate sensing approach based on the use of a lock-in amplifier operating at a single frequency was also investigated and subsequently replaced the chirp approach. Lock-in amplifiers are commonly used to provide detection of signals buried in noise. Normal operation of a lock-in amplifier requires a reference signal that is at the same frequency and in phase with the signal to be detected. This allows the instrument to phase lock on the signal of interest and to reject signals at other frequencies. For IACC, the use of a reference signal in the conventional sense would require a physical or wireless connection between the transmitting and receiving stations. An alternate approach was developed that is attractive for IACC. With this approach, separate oscillators with very high-frequency stability (through the use of direct digital synthesis) are used at both the transmitting and receiving stations. Because these devices are highly stable, there is essentially no short-term frequency drift, and thus the lock-in amplifier (at the receiving station) can be referenced to the transmitted signal without the requirement for a connection between the two. Any frequency drift that does occur is over a relatively long period of time; this can be filtered from the signal because only short events are of interest for third-party contact.

A block diagram of the instrumentation for the lock-in amplifier approach is shown in Figure 5. At the transmitting station, a high-stability function generator drives an amplifier, which drives the pipe with the excitation waveform. At the receiving station, the signal is passed through a preamplifier and bandpass filter and then to a lock-in amplifier. The reference signal for the lock-in is generated by an oscillator with high-frequency stability (for the instrumentation used here, the oscillator is internal to the lock-in amplifier instrument). The lock-in produces DC signals in proportion to the magnitude and phase of the measured signal (as referenced to the excitation signal). These signals then change when third-party contact is initiated. The DC signals are digitized and stored using an analog-to-digital converter and a notebook computer.

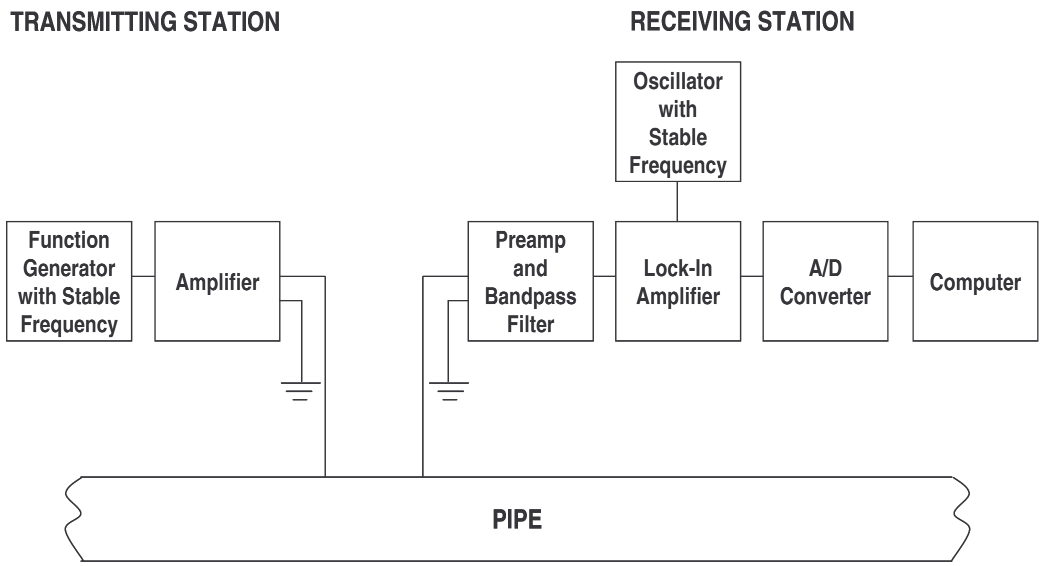


Figure 5. Lock-in amplifier instrumentation

1.3.3 Experimental Evaluations

The purpose of the experimental evaluations was to measure input parameters for the model and test signal parameters and signal-processing approaches. Experiments were conducted at the existing SwRI test site. This site contains a 150-mm (6-inch)-diameter, 37-m (120-foot)-long asphaltic coated pipe buried approximately 1 m (3 feet) deep (using standard industry practices) with four tape-insulated risers that extend above the soil surface. These risers are used to make electrical contact with the pipe in the same manner as cathodic protection (CP) test points would be used on actual pipelines. The risers can be used to inject signals and to generate ground shorts or partial shorts to simulate third-party contact.

Input Parameters for Model—In order to generate input parameters for the pipeline model, measurements were made of electrical parameters of the soil, pipe, and pipe coating. Impedance measurements of the insulated pipe were made using the setup shown in the diagram in Figure 6. Measurements were made over a frequency range of 10 to 5,000 Hz, and the results were fit to the response of the equivalent circuit shown in Figure 7.

The series resistance of the pipe/ground path (Figure 6) was determined by measuring the resistance between the pipe and a ground rod at riser A, using a 100-ohm resistor for Rs. The results of the measurements are as follows:

Capacitance, C = 0.55 microfarad

Resistance to ground through coating, Rg = 2200 ohms

To determine Rp (Figure 7), a DC power supply was used to supply a current of 10 amperes by connecting between risers A and D using an aboveground wire return. The voltage drop between risers B and C was then measured to determine resistance. The result indicated the pipe resistance for 40 feet of pipe (distance between risers B and C) was 500 micro-ohms. Therefore, Rp would be 1.5 milliohms (for the entire 120-foot pipe).

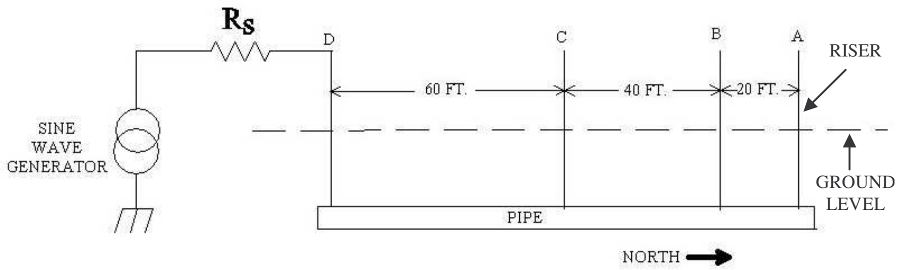


Figure 6. Connection for impedance measurements

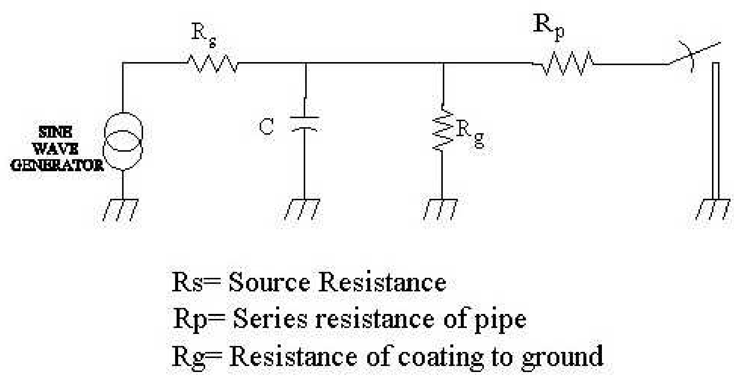


Figure 7. Simple equivalent circuit showing circuit constants from impedance measurements

The resistance of the soil was determined by grounding the pipeline to a ground rod near riser A and measuring the resistance of the path from riser D through the pipe and back through the ground. The measured value was 25 ohms.

Dielectric Constant of Pipe Coating—It was uncertain whether the value of C determined above was only a function of the dielectric constant of the pipe coating or whether the dielectric constant of the soil was also a factor. This would be important for predicting the response of pipelines under other soil and coating conditions.

The properties of the asphaltic coating from the test pipe were unknown; however, sections of asphaltic coatings were removed from two other pipes for testing. These coating thicknesses ranged from approximately 3 to 5 mm (0.12 to 0.2 inch), with many locations having the smaller thickness. (Note that where the wrapped coating overlaps, the thickness is greater.) The dielectric constant of this material was measured using a fixture consisting of two parallel conductive plates, each 39 mm (1.5 inches) square. The plates were connected directly to a capacitance meter, as shown in Figure 8.

The coating material was inserted between the plates, and the capacitance was measured. The ratio of the capacitance with the coating to the empty plates gave a dielectric constant of 2.2. This compares with a published value for asphalt of 2.6.

Figure 8. Setup for measuring dielectric constant of pipe coating

The capacitance of the test pipe was then calculated (based on the pipe dimensions) as a function of coating thickness for dielectric constants ranging from 1 to 10, as shown in Figure 9. The actual measured value of the capacitance is shown by the horizontal dashed line. Assuming a dielectric constant of 2.2, the coating thickness would be estimated at about 0.8 mm (0.03 inch). It is believed that the actual thickness would be approximately 3 mm (0.12 inch) based on the coatings removed from the other pipes. To obtain this thickness, the dielectric constant would have to be about 9, greater than the measured dielectric value. It is not clear whether the pipe coating is thinner than expected or whether soil properties contribute to the capacitive effect.

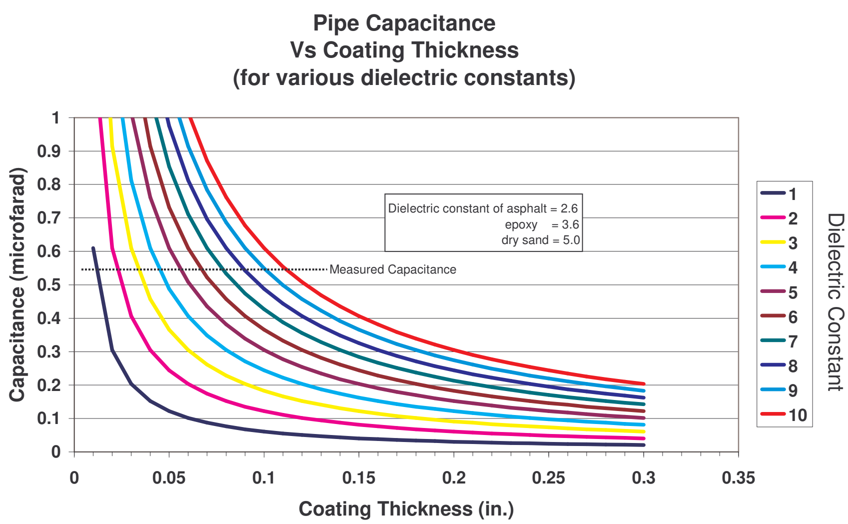


Figure 9. Calculated capacitance of test pipe for different coating thicknesses and dielectric constants of coating

Monitoring Simulation Tests—An experiment was performed to simulate an IACC monitoring situation on the test pipe. Figure 10 shows the pipeline layout. A signal source with amplifier was connected between riser D and ground rod 5. A sensitive digital voltmeter was used to measure the potential between riser A and ground rod 1. Measurements were made without and with shorting between riser C and ground rod 3. This shorting simulates a grounding of the pipe, such as with a backhoe strike.

Ratios of output voltage to input voltage were compared at different excitation frequencies to see how sensitive the ratios were to the shorting event; these are shown in Table 2. It was found that there was a clear reduction in signal $(R2/R1)$ when the pipe was shorted, suggesting that it will be feasible to detect coating breaches using the IACC method.

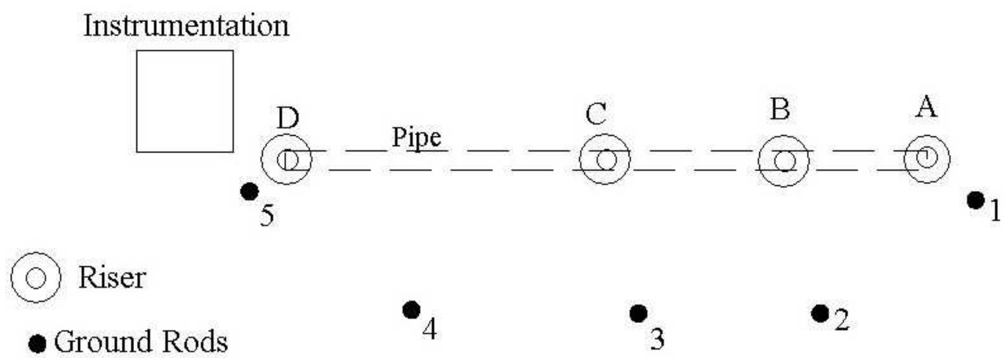


Figure 10. Pipeline plan view showing location risers and ground rods

Table 2. Results of Simulated Third-Party Contact Measurements on SwRI Test Pipe

Switch	Input (v.)	Output (v.)	R1	R2	R2/R1	Freq. (Hz)
Open	10.0288	9.7765	0.216008	0.061322	0.283886	10
Shorted	2.1663	0.59951				10
Open	10.018	9.7613	0.207876	0.055014	0.264649	100
Shorted	2.0825	0.53701				100
Open	7.5517	7.5876	0.092202	0.084539	0.916894	1000
Shorted	0.69628	0.64145				1000
Open	0.98322	1.39434	0.890584	0.411829	0.462426	10000
Shorted	0.87564	0.57423				10000

R1 = Input ratio of shorted to open
R2 = Output ratio of shorted to open

In addition to the test site pipe parameters reported previously, measurements made at the SwRI test bed attempted to determine a relationship between earth resistance and distance. Several ground rods were installed with separations varying from 5 to 40 m. Resistance measurements were made using a 12-VDC source and dropping resistors to avoid ground rod contact resistance problems. The resistance did not relate to the distance between rods, as shown in the graph in Figure 11. This finding was consistent with indications in the literature [3,4] that the resistance between two ground rods is most dependent on the local interaction between the ground rods and the soil and not the distance between them. Thus, for IACC measurements on pipelines, it is expected that the dominant resistance factor for detecting third-party contact is the local resistance between the contacting device (e.g. backhoe) and the soil, and not the return path through the soil to the transmitter and receiver sites.

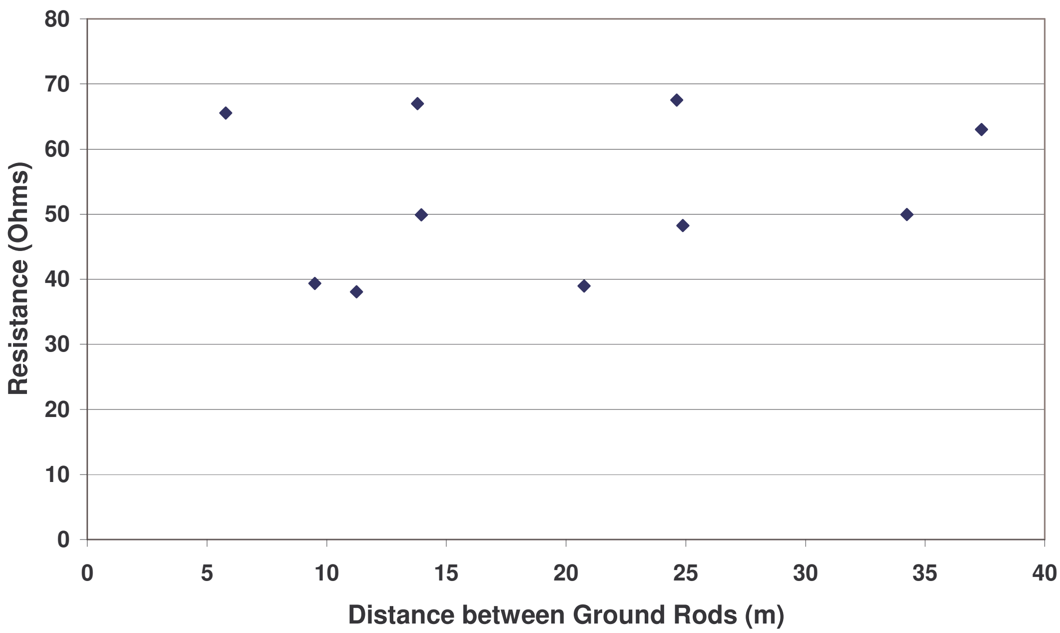


Figure 11. Earth resistance measurements

1.3.4 Backhoe Test

The IACC method requires that a conductive path be set up between the pipe wall and earth ground when third-party contact is made by a backhoe or boring drill. We were unable to find any published data regarding the resistance between a backhoe bucket and the earth when the backhoe is in a digging process. As a result, we conducted experiments using a commercial backhoe. The experiment consisted of a number of measurements of resistance between a backhoe bucket and ground rods, with multiple rods used to isolate the ground-rod contact resistance.

Since experience had already shown that soil moisture was a strongly controlling factor in ground rod resistance, we prepared three dig areas with different moisture content by selectively watering the ground for controlled amounts of time. The areas were designated “dry,” “moist,” and “wet.”

A wire was attached to the backhoe bucket using locking pliers, as shown in Figure 12. An instrumentation station was set up with signal source, lock-in amplifiers, and data acquisition system. Figure 13 shows the instrumentation complement. Using a dropping resistor and lock-in amplifiers to measure voltage across the resistor and across the bucket to ground, several digs were made in each different moisture condition. Figure 14 and Figure 15 show digging into two moisture levels of dirt.

Figure 12. Attachment of cable to backhoe bucket

Figure 13. Instrumentation for backhoe measurements

Figure 14. Backhoe digging in dry soil.

Figure 15. Backhoe digging in moist soil

Table 3 gives the results of average ground rod resistance in the different moisture soils and individual measurements of backhoe bucket resistance. Note that the bucket and rod resistances are comparable for a given soil type, supporting our decision to use ground rods in our evaluation tests.

Table 3. Ground-Rod Resistance Measurements

Soil Condition	Rod Resistance (ohms)	Backhoe Resistance (ohms)
Dry	206	250
Moist	47	21
Wet	13	20

Waveforms of bucket contact with the ground show the expected sudden conduction with small variations as the bucket progresses through the soil. Note in Figure 16 that the bucket resistance to soil quickly reaches a stable value that holds over the 4 to 5-second ground contact time. There is some variation as the bucket digs, as shown in the expanded graph.

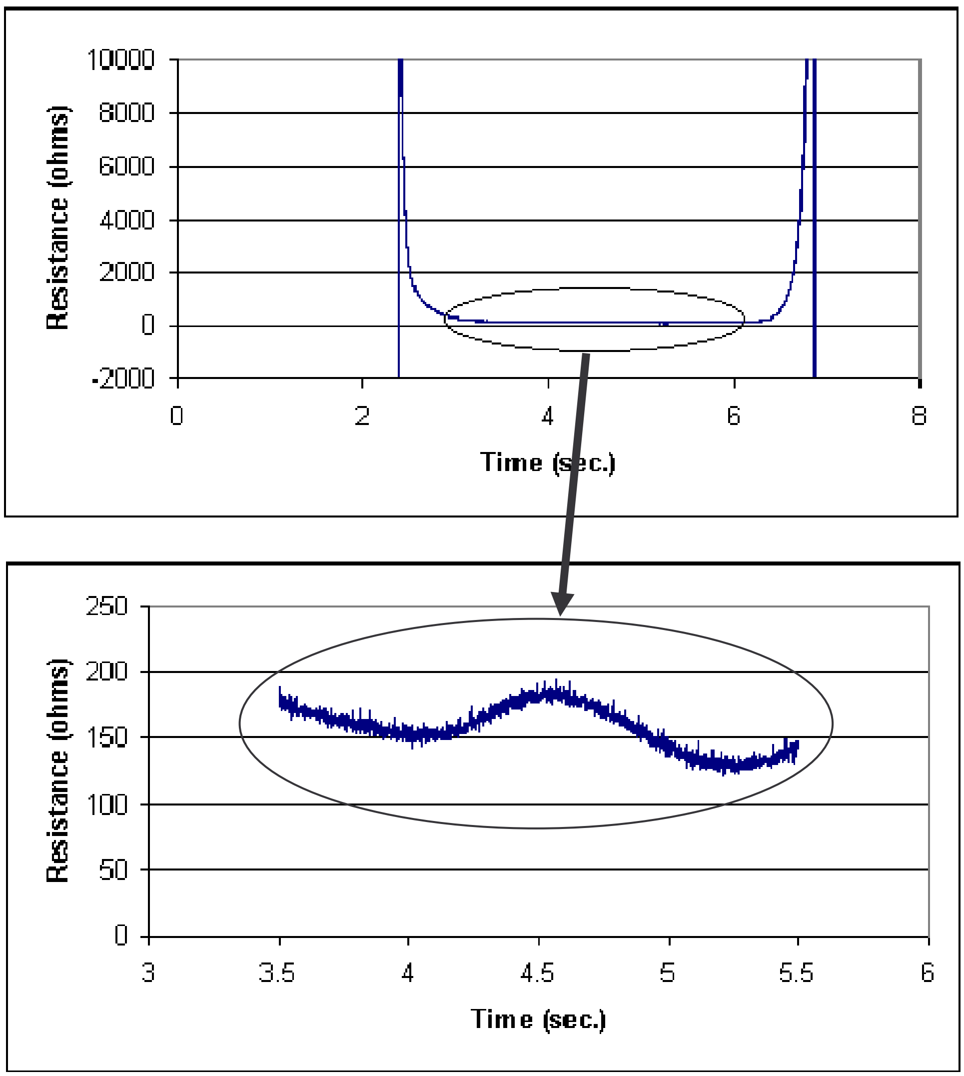


Figure 16. Bucket-to-soil resistance as bucket digs

1.4 Investigation of CP Interactions

The purpose of this task was to determine any effects of cathodic protection (CP) systems on the functioning of the IACC method and to determine any effects of the IACC signals on the CP system or other pipeline operation parameters.

1.4.1 Effects of CP Systems on IACC

The first step in evaluating the effect of CP systems on the IACC method was to install a CP system on the SwRI test pipe. A licensed CP engineer was hired for installation of an active CP system. Measurements were made on the pipeline to determine what capacity of cathodic protection would be required to protect the pipeline. A DC current was injected into the pipeline, and the current required to put the pipe at –0.85 volts DC was measured. That current was found to be less than 1 mA. It was concluded that the pipe coating was intact and that no significant leakage paths to ground existed. The contractor also made measurements of the soil resistivity at the test site. The average measured value was approximately 8 kΩ-cm.

An oversized 10-ampere rectifier CP system to be powered from 110 VAC was installed for the active CP system. A 100-kΩ rheostat was placed in series with the output so that the current could be adjusted. This allowed the effect of breaches in the coating to be simulated by grounding test points and increasing the CP current to a higher level than the required 1 mA. Figures 17 and 18 show the active CP system installation.

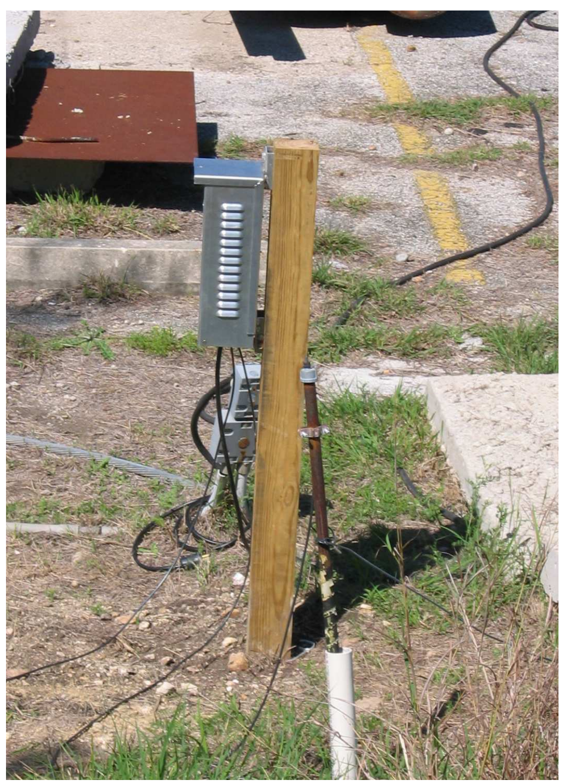


Figure 17. CP installation at the north end of test pipeline

Figure 18. Details of CP rectifier installation

Evaluation of the IACC approach on the SwRI test pipe showed that the active system introduced harmonics of 60 Hz on the test signal. The harmonics are generated from rectification of AC power to produce the DC voltage applied to the pipe. These harmonics can be removed from the IACC signals by notch filtering at 60 Hz and its harmonics within the IACC signal frequency range when a chirp signal is used. When using the lock-in amplifier approach, a bandpass filter centered around the excitation frequency is sufficient to remove the CP signals as long as the excitation frequency is not near 60 Hz or its harmonics. As described in Section 1.6.3, data were obtained while applying IACC signals to operating pipelines, both with and without the active CP system connected.

1.4.2 Effects of IACC on Pipeline CP Operation and Other Parameters

The proposed IACC method applies an alternating current signal onto the pipeline. The signal has a maximum amplitude of 15 volts RMS at a frequency between 10 and 100 Hz. Ground reference is a local ground rod at the transmitting site. There are three potential concerns about using this type of excitation:

1. Does the excitation present any shock hazard to pipeline workers or the general public?

2. Can the excitation initiate or accelerate corrosion of the pipeline?

3. Will the excitation interfere with existing DC cathodic protection systems?

In order to answer these concerns, the project staff did an information search that included questioning pipeline maintenance personnel and searching relevant literature [5,6,7,8, 9]. Findings are referenced to the three concerns above. Numerical data quoted are from Ref. [5].

1. Shock Hazard—Most operating pipelines follow published USA and Canadian standards that dictate a maximum safe voltage of 15 volts RMS on operating pipelines. The IACC excitation is always kept within that limit, even at the signal generator—the strongest signal point on the pipeline. Furthermore, the signal source used cannot deliver enough power to harm a person who comes in contact with it. Therefore, we conclude that the IACC system poses no shock hazard to pipeline workers or the general public.

2. Initiation or Acceleration of Corrosion of the Pipeline—Corrosion found on pipelines in the USA and Germany prompted research into the likelihood of AC currents either initiating or exacerbating pipeline corrosion. The investigation was triggered by finding significant corrosion on a pipeline that ran parallel to a railway using 16-2/3-Hz AC power. In addition, the soil resistivity was very low due to soil contamination from deicing salt. Subsequent investigation concluded with guidelines for avoiding any AC current effects. These guidelines include:

- ✓ *Keep AC frequencies higher than 10 Hz*. Note Figure 19 that shows one set of experimental data relating coefficient of corrosion to impressed frequency. The coefficient relates the corrosion from the AC current to the corrosion that would come from DC, i.e. the value at DC would be 100 percent. The curve suggests that the IACC system at 10 Hz would produce no more than 5 percent of the amount of corrosion from DC. And this would be only in the case of adequate current density.

- ✓ *Keep AC current densities low*. Note in Figure 20 that corrosion rates due to AC currents can be related to the current density. A reasonable guideline from the data would be to limit the current density to no more than 6.45 μA/sq. m. (10 mA/sq. in). Our excitation system will put out 15 VRMS into an impedance of several ohms. Assume a circuit resistance of 15 ohms including the ground rod resistance. That yields a current of 1 A. If that current supplies, for example, 1.6 km (1 mile) of pipe of 0.305-m (12-inch) diameter, it equates to roughly 258 pA/sq. m. (400 nA/sq. in.) over the total pipe surface. This is only a negligible fraction of the limit on the curve. A complication arises when the coating is not uniform, allowing current to become concentrated in a smaller area. In that case, the current density could be higher, but one must assume that the CP protection is also concentrated in that same way. This suggests that a comparison between CP current and IACC current might be of value. While some well-coated lines require only milliamps per mile from an impressed current CP system, others with poorer coatings may require tens of amperes per mile. This far exceeds the maximum current the IACC system can deliver; thus, it is unlikely that there would be any noticeable effect on corrosion from the IACC.

3. Interference with Normal CP Operation—The guidelines for avoiding interference with CP are the same as for avoiding corrosion. We do not anticipate any effect on existing CP. Our test results also show that we do not suffer any significant reduction in our effectiveness due to the presence of impressed current CP systems. IACC functions with the CP system on or off. The noise level from the full-wave-rectified 60-Hz CP can be reduced by filtering out 60-Hz harmonics and by the natural rejection of the lock-in amplifier used to detect the IACC signal.

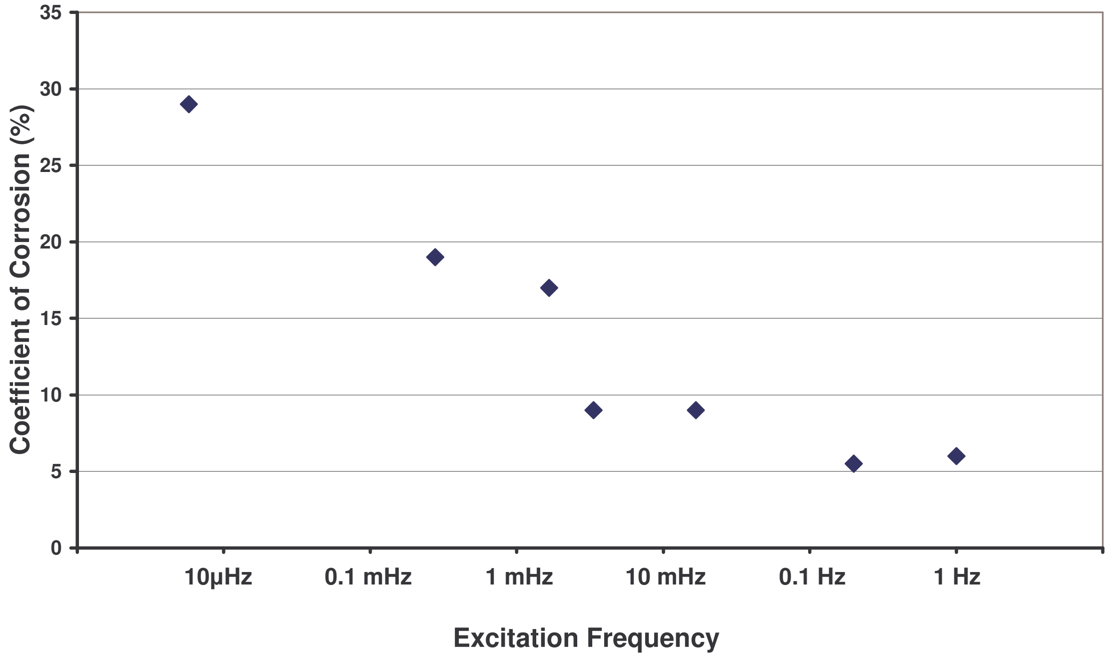


Figure 19. Effect of excitation frequency of impressed current on corrosion of buried pipelines

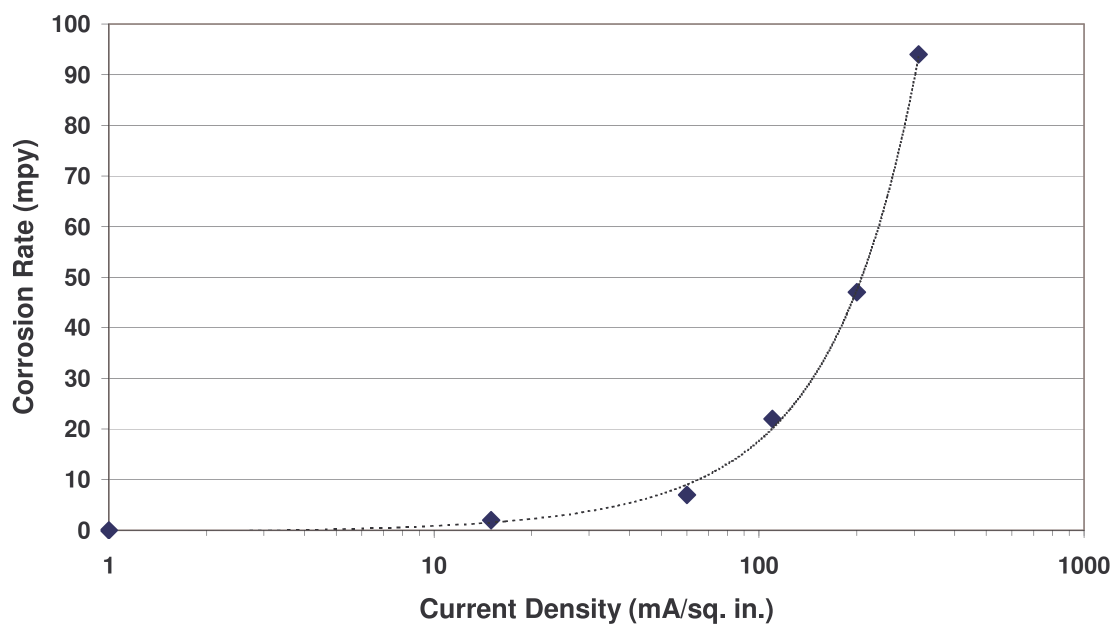


Figure 20. Effect of AC current density on corrosion rate

1.5 Contact Simulator

A pipeline contact simulator device was designed and fabricated. The purpose of this device is to generate controlled momentary shorts between the pipe and the soil to simulate intermittent contact that would be caused by digging machinery. This device consists of a low-voltage relay that can be used to ground the pipe at CP monitoring stations. The relay and associated circuitry are controlled by an arbitrary waveform generator that can be programmed to allow simulation of various contact scenarios such as strikes from a backhoe or boring tool. The relay contacts will be electrically connected to the pipe and a ground, and closing the relay in the desired sequence will simulate the strike.

A schematic diagram of the contact simulator is shown in Figure 21. The simulator is controlled by an HP33120A arbitrary waveform generator. The waveform generator was programmed to provide momentary contact of either 2 seconds or 5 seconds to simulate third-party contact. These values were derived from contact tests with a backhoe, as described in Section 1.3.4. So that tests could be made on a repetitive basis with unattended operation of the contactor, the contact was repeated after a "no contact" duration of 10 seconds.

For field tests, the contact simulator and arbitrary waveform generator were configured with a battery and inverter power supply, and all components were placed in a case for portable operation. This arrangement is shown in Figure 22.

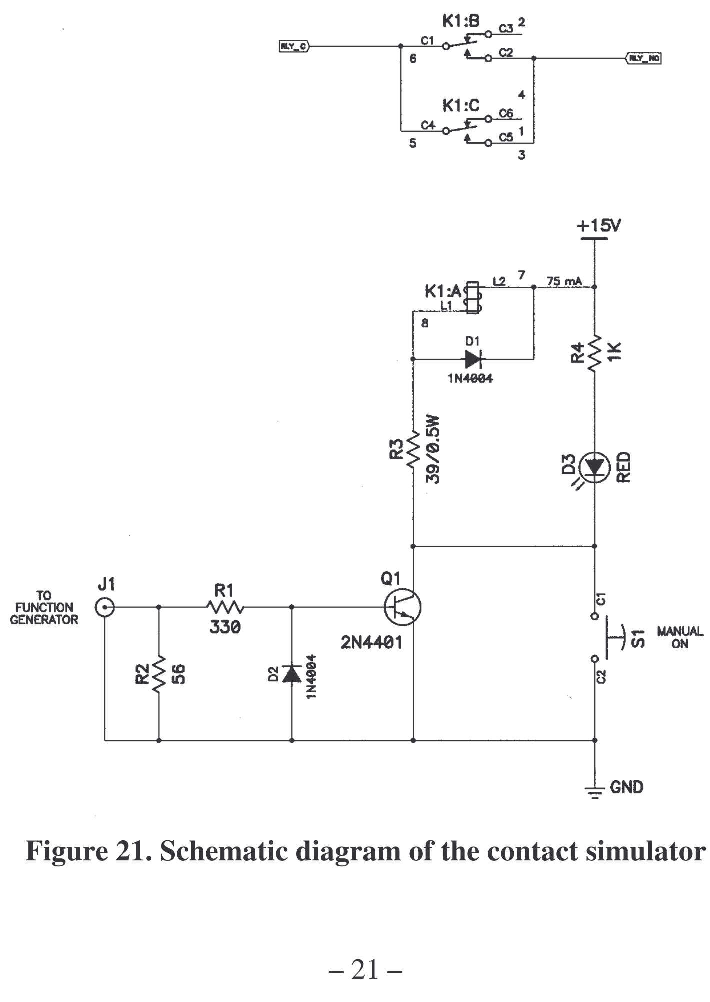


Figure 21. Schematic diagram of the contact simulator

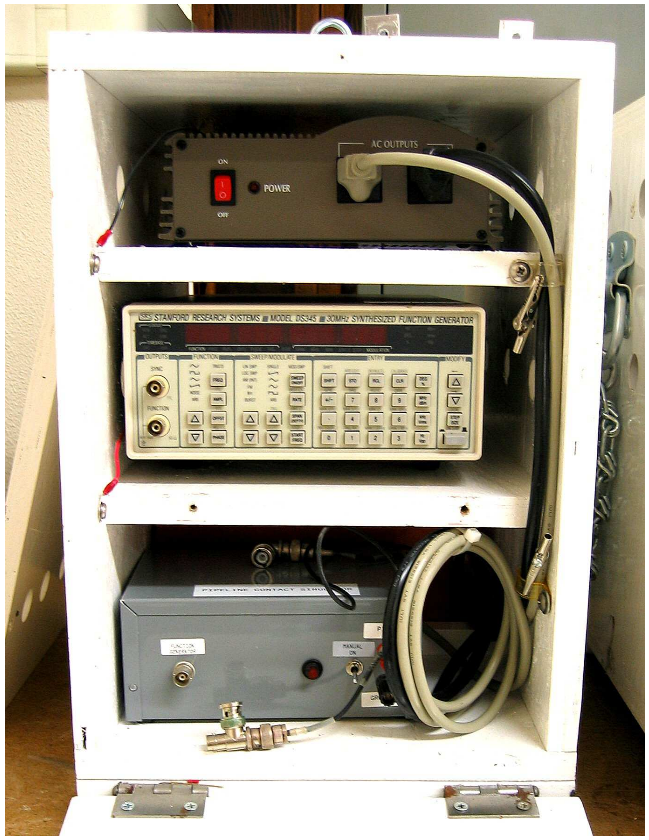


Figure 22. Contact simulator configured for portable operation for field tests

1.6 Pipeline Tests

Tests were conducted on operating pipelines to determine IACC capabilities under actual field conditions and to determine electrical characteristics of actual pipelines. Arrangements were made with CPS Energy for tests on pipelines in the San Antonio, Texas, area and with Duke Energy Gas Transmission Corp. for tests on pipelines near McAllen and Corpus Christi, Texas.

Characteristics of the pipelines tested are shown in Table 4. Pipe diameters ranged from 15.2 cm (6 inches) to 76.2 cm (30 inches). For the CPS pipelines, the sections examined had electrically insulated joints at each end, with distances between the joints ranging from 0.25 km (0.15 mile) to 5.9 km (3.5 miles). For the Duke pipelines, there were no insulating joints, and the pipeline lengths ranged from 16 km (10 miles) for Pipeline D to hundreds of km for Pipelines E and F. Coating conditions ranged from good to poor (determined from pipeline age and CP current), and all pipelines had CP systems in place. Measurements performed on the pipelines were IACC and/or impedance characteristics. In most cases, contact was made to the pipe through existing CP test points. Figure 23 shows the layout for Pipeline A with the CP test points labeled with red numbers.

Table 4. Pipeline Summary

Pipe-line	Owner	Location	Diameter [cm (in.)]	Coating Type	Coating Condition	CP System	Distance between Electrically Isolated Joints [km (mi)]	Measurements Made
A	CPS	San Antonio, TX–Leon Creek	40.6 (16)	FBE*	Good	Rectifier	2.6 (1.6)	IACC Impedance
B	CPS	San Antonio, TX-Calaveras	61 (24)	FBE*	Good	Rectifier	5.9 (3.5)	Limited IACC Impedance
C	CPS	San Antonio, TX-Calaveras	20.3 (8)	FBE*	Good	Anode***	0.24 (0.15)	Impedance
D	Duke	McAllen, TX	15.2 (6)	Asphaltic	Moderate	Rectifier	No isolated joints	IACC
E**	Duke	McAllen, TX	76.2 (30)	Asphaltic	Moderate	Rectifier	No isolated joints	IACC Impedance
F**	Duke	Corpus Christi, TX	76.2 (30)	Asphaltic	Poor	Rectifier	No isolated joints	IACC Impedance

*Fusion bonded epoxy
**Pipelines E&F are the same pipeline, but the measurement locations are different [approximately 225 km (140 miles) apart]
***Disconnected for tests

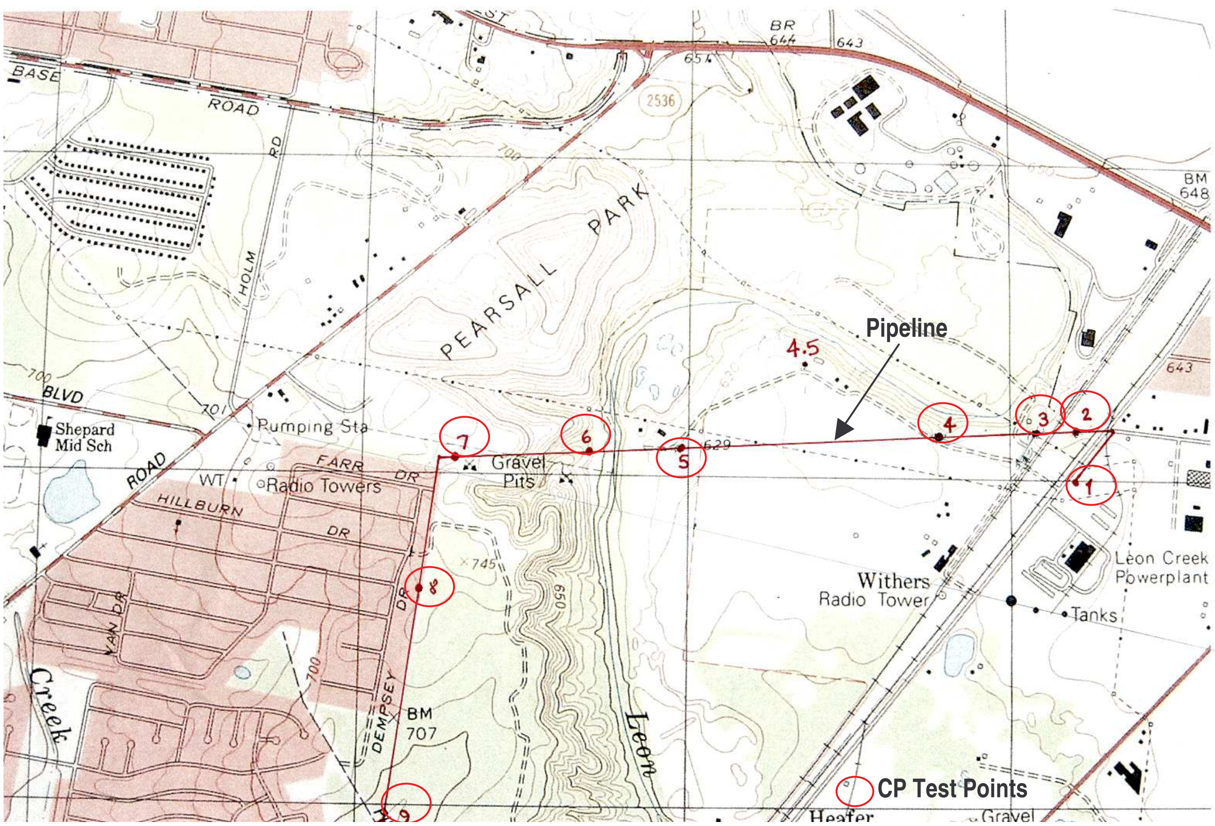


Figure 23. Layout for Pipeline A with CP test points labeled with red numbers

1.6.1 Impedance Measurements

Electrical impedance measurements were made between the pipe and soil. The purpose of these measurements was to understand the pipeline parameters so that the IACC performance could be better understood and so that test frequencies and parameters could be optimized. These measurements were made between a CP test point on the pipe and one or more ground rods driven into the soil several feet away. Tests were performed on most of the pipelines shown in Table 4 and, in some cases, under different soil moisture conditions at the same location. Initial measurements were done using only a single ground rod and therefore reflect the combination of both the pipe and ground rod impedances. Later measurements were done with one rod and then repeated with two rods; this allowed both the pipe-to-soil and rod-to-soil measurements to be determined by solving simultaneous equations.

Some measurements were taken using an impedance analyzer, but most were taken using a waveform generator connected to the pipe in a similar way to the IACC tests. This generator was set to a series of specific frequencies over the desired range and was connected to the CP test point through a resistor. A lock-in amplifier, phase referenced to the waveform generator, was then used to measure the magnitude and phase of (1) the voltage waveform applied to the pipe and (2) the voltage across the series resistor. From these measurements, the complex impedance (voltage divided by current) was calculated as a function of frequency.

Based on measurements on the SwRI test pipe (Section 1.3.3), it was expected that the impedance between the pipe and soil would be relatively high when the coating is sound because of the high resistivity of the pipe coating. It was also expected that the pipe would act as a capacitor, with the pipe surface being one conductor, the soil being the other conductor, and the pipe coating acting as a dielectric.

In contrast to these expectations, it was found that impedance between the pipeline and soil was actually very small on all operating pipelines tested, as shown in Table 5, which summarizes the impedance measurements on operating pipelines. For all of the pipelines except C (which was only 20.3 cm (8 in.) diameter and 0.24 km (0.15 mile) long), the total impedance between the ground rod and the pipe ranged from 7 to 28.5 ohms, and the impedance between the pipe and soil (not including the ground rod resistance) ranged from 0.3 to 3.6 ohms. Similar measurements were obtained both with and without the active CP system connected to the pipe.

According to Peabody's *Control of Pipeline Corrosion* (Second Edition) [10], the expected DC resistance (approximately the same as low-frequency impedance) between a pipeline with coating in good condition and ground should range from 0.2 to 10 ohms for a 91.4-cm (36-in.)-diameter pipeline that is 16.1 km (10 miles) long. The variation is caused by differences in coating quality and the presence of minor coating holidays. If we take this resistance range and scale it to Pipeline A based on the surface area of the pipe, then the expected range for a coating in good condition is 2.8 to 140 ohms. The measured impedance values of Pipeline A are approximately in this range, thus indicating that the coating characteristics are typical of good coatings. Even though the pipeline coating has high electrical resistivity (which would make the low-frequency impedance to soil high), the fact that the coating has a large surface area on a relatively long pipeline results in a low overall impedance because the resistance is inversely proportional to the surface area (for a given resistivity). Note that a 91.4-cm (36-inch)-diameter pipeline 16.1 km (10 miles) long has a surface area of almost 46,500 sq m (500,000 sq. ft.).

Table 5. Pipeline Impedance Measurements

Pipeline	Date	Condition	Frequency (Hz)	Impedance Pipe & Rod (ohms)	Impedance Rod–Gnd (ohms)	Impedance Pipe–Gnd (ohms)
A	1/11/05	Black Clay-Based–Moist	50	23.9		
			100	23.9		
			200	24.4		
			500	25.4		
			1000	23.7		
			2000	23.6		
			5000	24.4		
A	3/8/05	Black Clay-Based–Moderately Moist	100	21.3	20.0	1.3
			200	17.2	13.9	3.3
			500	19.7	16.5	3.2
			750	17.2	13.6	3.6
			1000	18.4	17.0	1.5
			2500	17.5	15.4	2.1
			5000	18.6	15.8	2.7
B	3/21/05	Sandy Loam–Wet	50	28.5		
			100	28.3		
			500	28.1		
			1000	27.9		
			2500	28.0		
			5000	28.4		
C	5/12/05	Sandy Loam–Dry	50	35.4	21.1	14.2
			500	34.5	20.7	13.8
			5000	31.0	20.7	10.3
E	10/26/05	Sandy Loam–Dry	10	7.7	6.9	0.8
			50	7.5	6.7	0.8
			500	7.6	6.6	1.0
F	11/28/05	Black Clay-Based–Wet	10	7.3	6.9	0.4
			20	7.1	6.8	0.4
			50	7.1	6.7	0.4
			100	7.1	6.8	0.3
			200	7.1	6.7	0.3
			500	7.0	6.7	0.4
			1000	7.1	6.7	0.4

As discussed in Section 1.3.4, a third-party contact event can be represented by an electrical connection between the pipeline and a ground rod. The change in impedance caused by a contact event is approximately equivalent to placing the ground rod-to-soil impedance in parallel with the pipe-to-soil impedance, computing the total impedance of this combination, and computing the change in impedance compared to the original impedance of the pipe. As shown in Table 5, the impedance between the ground rod and the soil ranges from about 7 to 20 ohms. This is in contrast to the much lower pipe-to-soil impedances of 0.3 to 3.6 ohms. At 100 Hz, this computed impedance change due to third-party contact is approximately 6 percent for Pipeline A, 11 percent for Pipeline E, and 5 percent for Pipeline F. It is expected that the change in sensed voltage at the IACC receiving station would be approximated by this impedance change, and thus it should be expected that the received signal changes with third-party contact would be on the order of several percent.

For the operating pipelines, it was expected that the capacitance would be greater than observed on the SwRI test pipe because the operating pipes are greater in diameter and length, which results in much greater surface area and, therefore, a larger capacitor plate size. Also, in the case of fusion-bonded epoxy coatings, the coating is thinner, which results in smaller separation between the capacitor plates (pipe and soil). For example, the calculated capacitance of Pipeline A was 250 uF (compared to 0.55 uF for the SwRI test pipe). For Pipeline A (or any other pipeline), there was no consistent frequency dependence of the impedance measurements (capacitative effects would cause a decrease in impedance with increasing frequency, as the capacitive reactance is inversely proportional to the frequency). This lack of observed frequency dependence meant that capacitive effects were minimal, and it was not possible to calculate a capacitance value. An impedance analyzer instrument was used to measure the capacitance directly; however, the measured value was only 0.3 uF—much less than expected. The lack of frequency dependence was observed on all other pipelines except for Pipeline C, which is very short and small in diameter. It is believed that the low observed capacitance effects are because the pipe-to-soil resistance is so small that it effectively "shorts" the capacitance and dominates the overall impedance.

1.6.2 Detection of Impressed Waveforms

Chirp Excitation—IACC tests were performed on Pipeline A by applying a chirp waveform having a frequency range of 50 Hz to 2.5 kHz to the pipeline at CP3 (see map in Figure 23). An arbitrary waveform generator was used to generate the chirp waveform. Signals were applied both with the active CP system connected and with it disconnected to determine effects of the CP system operation on the IACC measurements.

The IACC signal was monitored using a preamplifier and bandpass filter connected between a CP test point and a ground rod, with the output of the filter connected to an analog-to-digital converter in a notebook computer. Note that a data acquisition program was written in LabView specifically for this measurement.

With the impressed waveform applied at CP3, the pipeline was monitored at CP5 [distance of 1.1 km (0.7 mile) from CP3] and at CP8 [distance of 2.3 km (1.43 miles) from CP3]. Third-party contact was simulated by connecting the CP test point at CP4 [distance of 0.3 km (0.19 mile) from CP3] to a ground rod at that location

Analysis of the data taken with impressed chirp waveforms showed that the waveforms could be successfully detected when the voltage applied to the pipe was 10 Vpp. Figure 24 shows a spectrogram of the received signal at CP5 with the CP system on. In the figure, the horizontal axis represents time, the vertical axis represents frequency, and the color represents signal amplitude (green is lower amplitude and red is higher amplitude). The chirp signal is seen as the diagonal lines that begin at 50 Hz and change frequency linearly with time up to 2.5 kHz. The red and orange horizontal lines are noise signals that do not change in frequency with time. These signals are primarily at multiples of 60 Hz and are caused by induction from AC power lines and by the CP system. Note that although these noise signals are strong, the chirp signal can be distinguished from them because of its time-dependent frequency change.

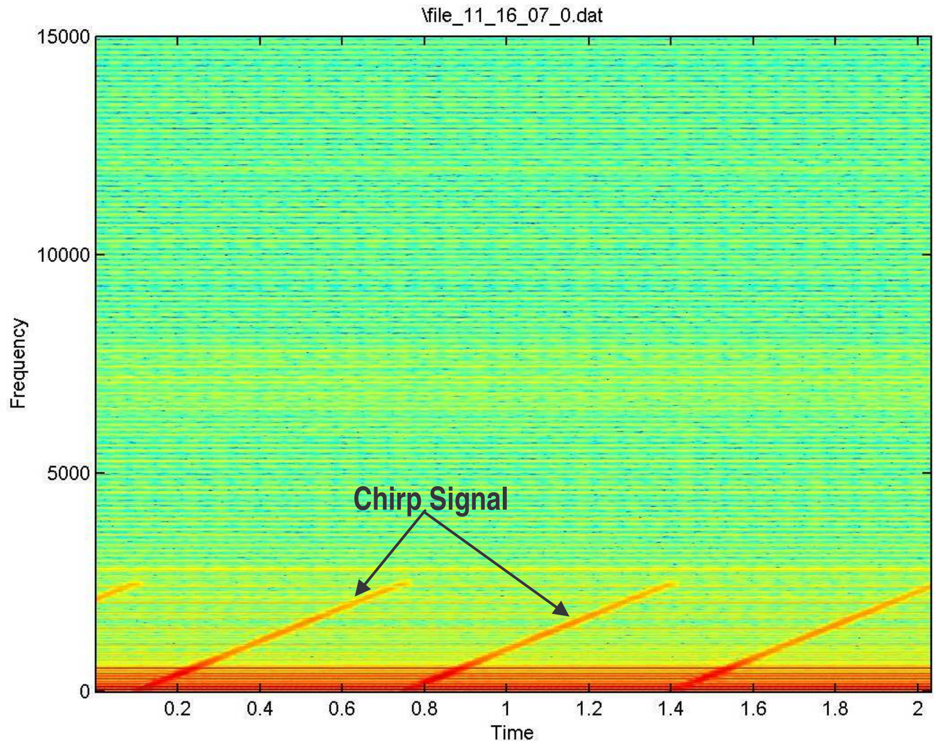


Figure 24. Spectrogram of the received signal at CP5 with the CP system on

Software-based notch filtering (at harmonics of 60 Hz) and matched filtering were applied to the waveforms. Additional bandpass filtering was also applied so that the response could be evaluated in different frequency ranges. Figure 25 (top) shows results obtained in the frequency range from 200 to 500 Hz. The largest changes resulting from simulated contact were obtained in this frequency range. The vertical axis represents the output of the matched filter and is in arbitrary units. The horizontal axis is simply a condition number used to classify the data and has no meaning other than to show the data in separate locations for different conditions. The plot on the left shows data with the CP system turned on, and the plot on the right shows data with the CP system off. With the CP system on, the grouping of points at condition 18 represents five repeats of the signal measurement at CP5 with no third-party contact, and the grouping of points at condition 19 represents five repeats of the measurements at CP5 with simulated third-party contact at CP4. These conditions clearly are distinguishable from each other, although the percentage change in the matched filter output is relatively small at 2.3 percent. With the CP system on (plot on right), the overall signal levels are somewhat greater; however, the change from the contact event is about the same at 2.2 percent.

The plots at the bottom of Figure 25 are from data in the frequency range of 500 Hz to 1 kHz. In this range, the variation in signal from noise is less (tighter grouping of the individual data points); however, the changes from contact are somewhat smaller (2 percent with CP on and 1.7 percent with CP off). These results show that the simulated third-party contact can clearly be detected over a distance of 1.1 km (0.7 mile).

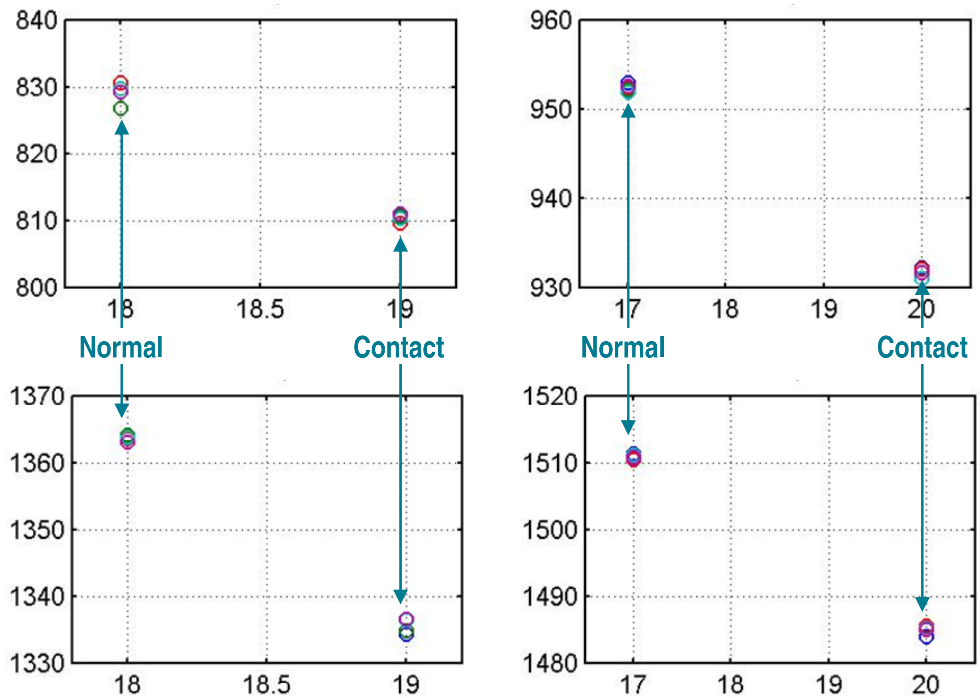


Figure 25. IACC matched filtering results from operating pipe at the Leon Creek site; top: 200 Hz–500 Hz; bottom: 500 Hz–1 kHz; left: CP on; right: CP off

Tests were also performed with the signal measured at CP8, which provides a larger separation between transmitter and receiver [2.3 km (1.43 miles)]. At this location, the signal was readily detectable after application of the bandpass and notch filters; however, the change with simulated third-party contact was not detectable above the noise level after matched filtering was also applied. Figure 26 shows the results of applying the matched filter to the data at CP8. Condition 7 shows multiple repeats of the test with no contact. Condition 8 shows the result of multiple repeats with simulated contact at CP4, and condition 9 shows simulated contact at CP5. There is no change in signal level from contact that can be distinguished above the variation from the repeats in the test. This is attributed to greater signal attenuation over the longer distance in this test.

Based on the signal levels from Pipeline A (without contact), projections were made to project the distance over which the impressed signals could be propagated. Figure 27 shows the SNR as a function of distance from CP3 to CP8. A best fit was made to these data as shown in the figure. Using this fit, it was projected that the signal level would drop to the noise level over a distance of 7.24 km (4.5 miles).

The same setup used for the field tests was also repeated on the SwRI test pipe, which has a length of 120 feet. A simulated third-party contact event at an intermediate test point on this pipe resulted in a very substantial change in matched filter output of 35 percent. This compares with approximately 2 percent for Pipeline A. The reason for the large change with the short SwRI test pipe is that the pipeline-to-ground resistance is much higher than for the much longer Pipeline A. Thus, a contact event results in a greater impedance change.

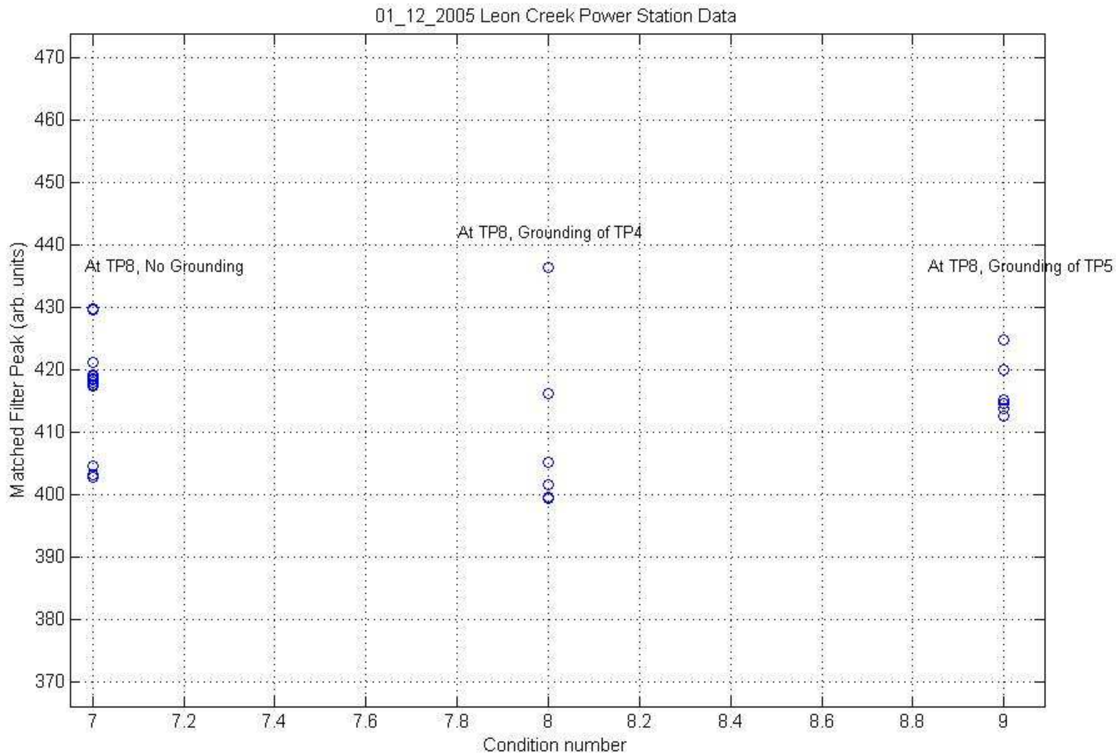


Figure 26. Results of applying the matched filter to the data at CP8

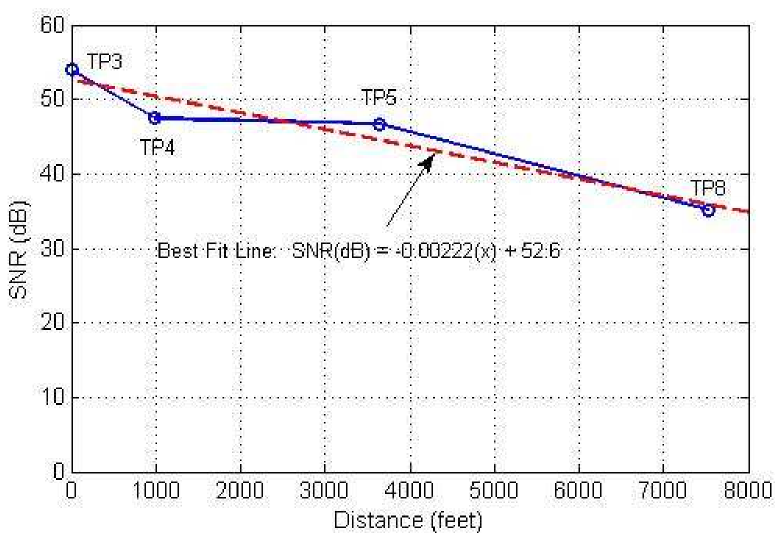


Figure 27. Signal-to-noise ratio as a function of distance from CP3 to CP8

It is clear from these measurements that the IACC signal can be propagated over a distance of at least several km. The difficulty, however, is that changes in signal level from a third-party contact event are small, and resulting signal-to-noise ratios become small. As discussed in Section 1.3.2, a comb filter was developed to remove the 60-Hz and harmonics signals prior to digitization so that the dynamic range could be extended and possibly result in an improvement in signal to noise. Because this resulted in instabilities near each harmonic frequency, it was not used. Tests on longer pipelines (Section 1.6.3) also showed that it was necessary to use frequencies as low as 10 Hz to increase propagation distance and that this distance was reduced even at frequencies of 40 Hz. There was little advantage to having a chirp with bandwidth covering only 10 to 40 Hz. Because of the difficulties with the comb filter instability, the need to operate in a narrow frequency range, and the development of an effective lock-in amplifier approach, no additional testing was performed using the chirp excitation approach.

1.6.3 Lock-In Amplifier Measurements

IACC tests were performed on Pipelines A, D, E, and F (Table 2) using the lock-in amplifier approach.

Pipeline A—The first lock-in amplifier test was conducted on Pipeline A, as shown in Figure 23. The transmitter station was located at the CP test point designated CP3 in the figure, and the receiver was located at CP8, a distance of 2.3 km (1.43 miles) away. Simulated third-party contacts were made at CP4 and CP5 at distances of 0.3 km (0.19 mile) and 1.1 km (0.7 mile) from the transmitter. At the time of the test, the soil was dry. Testing was accomplished at excitation frequencies of 270 and 570 Hz. Although it was desirable to test at lower frequencies, the lock-in amplifier approach used at that time could not be operated below 270 Hz. Also, the lock-in output signal was not digitized for these tests; the signal voltages were read from the lock-in and recorded by hand.

The IACC signal was successfully detected at the receiving station with the third-party contact applied at both locations. Figure 28 shows a plot of the readings for four trials with the contact made at CP4; the signal changes about 2.3 percent when contact is made. Although this pipeline had significant induced 60-Hz signals, these were effectively removed by a bandpass filter with a center frequency set to the excitation frequency.

Pipeline D—Pipeline D was the first operating pipeline examined that had a length greater than the anticipated operating distance of IACC with no electrically isolated joints. This pipeline was 17 km (10.6 miles) in length, but joined Pipeline E at one end, so it was effectively much longer as far as IACC was concerned. The pipeline diameter was 15.2 cm (6 inches), and the pipe had an asphaltic coating in moderate condition. The soil condition at the time of the tests was dry.

Initial tests were performed with the lock-in amplifier to measure the IACC propagation distance at different frequencies without third-party contact. The results are shown in Figure 29. At 10 Hz, it was possible to detect the IACC signal up to 7.4 km (4.6 miles), although the signal-to-noise ratio at this distance was approximately 2:1. Measurements at 5 Hz at limited distances showed a stronger received signal, while measurements at 40 Hz at a single distance showed a smaller received signal. These results showed that it was best to operate at the lowest frequency possible for the best propagation distance. The frequency chosen for the remaining tests was 10 Hz because, at a lower frequency, not enough waveform cycles would occur over a short-duration contact event to allow the lock-in amplifier to provide stable detection of the signal change.

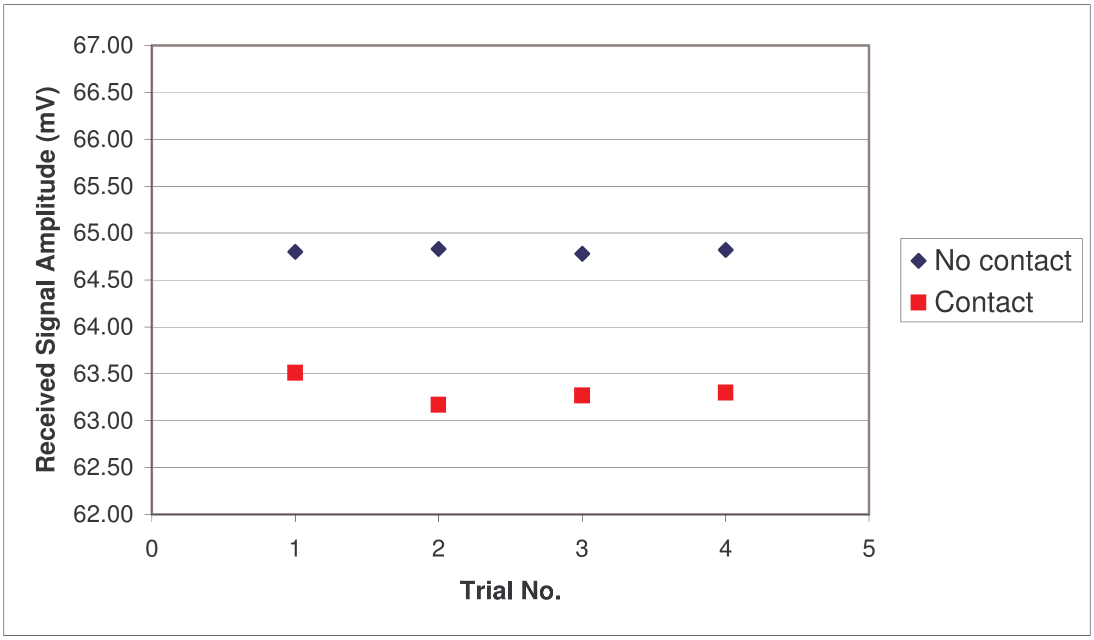


Figure 28. Received signal amplitude for Pipeline A with transmitter and receiver positioned 2.3 km (1.43 miles) apart

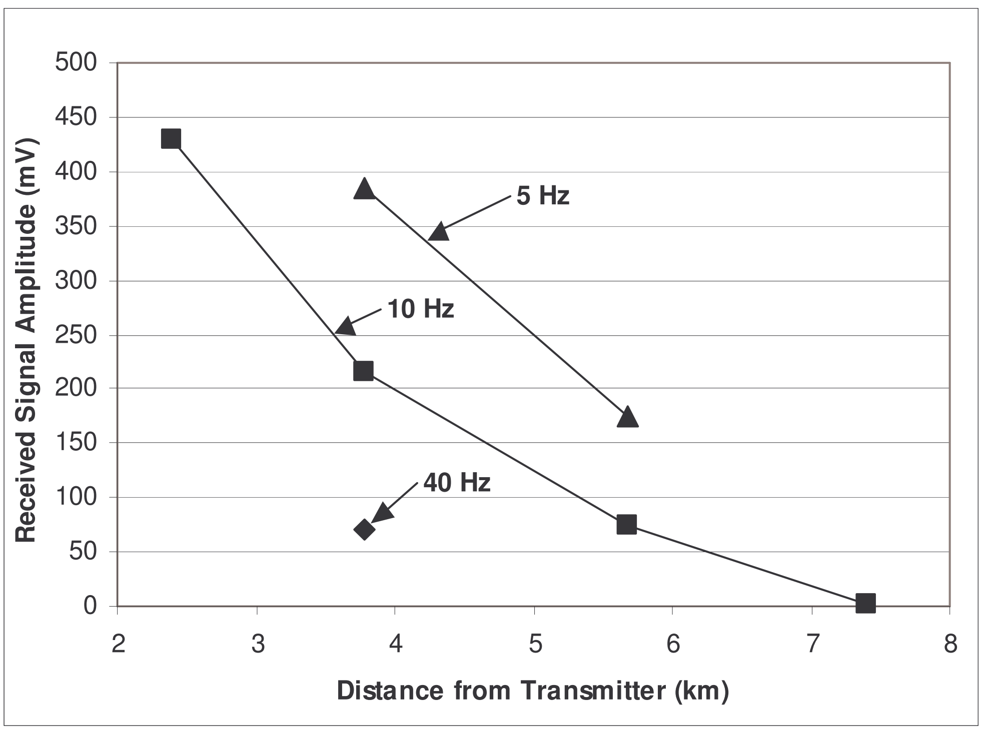


Figure 29. Relationship between IACC received signal amplitude and distance for different frequencies

Tests were then performed for detection of third-party contact at an excitation frequency of 10 Hz. The IACC transmitter and receiver were set up at CP test points located 2.4 km (1.49 miles) apart, with the contactor positioned between them at a distance of 1.61 km (1 mile) from the transmitter. These were the closest CP test points available. At these distances, third-party contact could not be detected above background noise. A portion of this pipeline line was close to power lines, and at the receiving station, a strong 60-Hz signal was present. Even though the bandpass filter was used, the 60-Hz signal may have contributed to the background noise. The background signals were not associated with the active CP system because the same results were obtained with and without the CP system connected to the pipeline.

Pipeline E—Pipeline E had a diameter of 76.2 cm (30 inches) and was hundreds of km in length. The coating on this pipeline was in moderate condition and required CP currents of 9.2 amperes applied every 1.61 km (1 mile). IACC tests were performed for detection of third-party contact using an excitation frequency of 10 Hz. At the time of the tests, the soil was dry.

The receiving and transmitting stations were set up at CP test points located 1.61 km (1 mile) apart with the contactor located 1.16 km (0.72 mile) from the transmitter [Figure 30(a) and (b)]. Third-party contact was successfully detected using these distances. Figure 31 shows the received signal at the lock-in amplifier output. The change in signal level from contact is about 2.4 percent. The test was repeated with the transmitter moved to a distance of 3.2 km (2 miles) from the receiver (the next closest CP test point location) with the contactor remaining at the same location). Third party contact could not be reliably detected above noise at that distance.

Pipeline F—Pipeline F was the same pipeline as E, but the test location was 2.25 km (140 miles) away from the test location designated as E. At the location of the Pipeline F tests, the coating was in poor condition and required CP currents of 27 amperes applied every 1.6 km (1 mile). At the time of the tests, the soil was very wet due to recent heavy rainfall. A frequency of 10 Hz was used for these tests.

The transmitting and receiving stations were located at CP test points positioned 2.35 km (1.46 miles) apart, with the contactor located 0.47 km (0.29 mile) from the transmitter. It was not possible to distinguish third-party contact during this test. This was attributed to the extremely low pipe-to-soil impedance (0.4 ohm) resulting from the coating condition. This low impedance caused additional attenuation of the IACC signal and resulted in signal changes from contact being below the noise level.

1.6.4 Discussion

The IACC test results from operating pipelines show that the IACC signal can be detected over a distance of over 7 km (4.4 miles) between the transmitting and receiving stations. The change in IACC signal that occurs when third-party contact is made, however, is small (on the order of a few percent) and was detectable over distances of 1.6 to 2.3 km (1 to 1.43 miles) on two of the four pipelines tested with active CP protection systems operating. Third-party contact was not detected on the other two pipelines with 1.61 km (1 mile) between stations. The difficulties with these pipelines resulted because one pipeline had strong induced 60-Hz signals present (apparently from nearby power lines), which caused excessive noise on the IACC signal (even after filtering), and the other pipeline had a poor coating which significantly attenuated the IACC signal so that background electrical noise masked the signal change.

(a)

(b)

Figure 30. Transmitter (a) and receiver (b) station setups for tests on Pipeline E

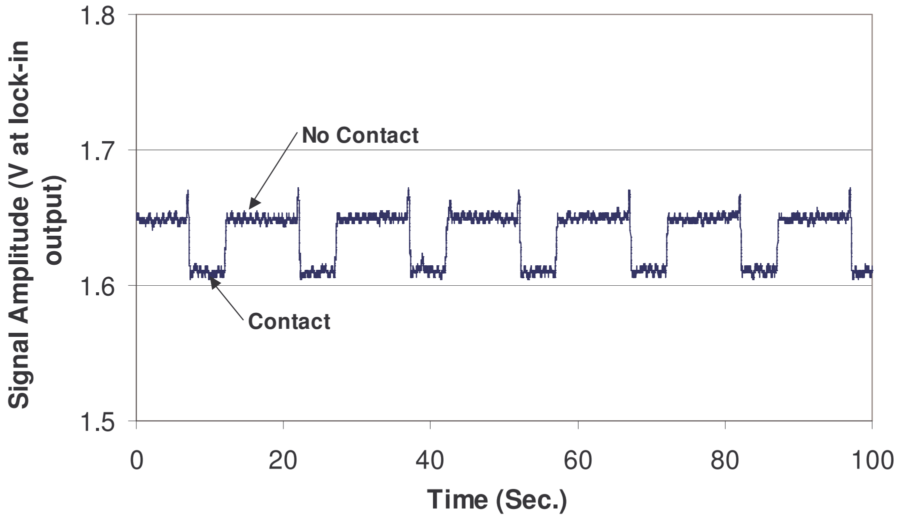


Figure 31. IACC signals from simulated third-party contact on pipeline E

It is believed that the IACC method is viable as a monitoring method for third-party contact when operated within certain parameters. The maximum distance between transmitting and receiving stations should be limited to approximately 1.61 km (1 mile), although the distance could be extended to 3.22 km (2 miles) using one transmitter with one receiver on each side (since the transmitted signal travels in both directions). The distance could be further extended using multiple stations. Before considering the IACC method for a given pipeline, the pipeline should be tested to determine if there are interfering factors that would cause interference with its use. These factors include poor coating quality and strong induced 60-Hz signals. Coating quality can be determined by the current required for operation of existing CP systems or by impedance or resistance measurements. The presence of 60-Hz signals can be readily determined by direct measurement from a CP test point to a ground rod. It is also possible that better filtering approaches can be employed to reduce the 60-Hz interference problem.

The most appropriate use of IACC appears to be as a monitoring method for localized high-consequence areas where construction or other activity is underway and there is considerable risk of third-party contact with a pipeline. Because a monitoring system could be installed using existing CP test points without the need to dig up the pipeline, it could be easily installed at low cost even as a temporary monitoring system and then removed when construction activity ceases. Design guidelines for IACC stations are described in Section 1.8.

1.7 Guidelines for Commercializing the IACC Monitoring System

Even though signal reception has been demonstrated for distances of several miles, field test results indicate that the IACC method is most effective when deployed over distances of 1 mile or less. Therefore, the implementation most likely to be a commercial success will be one that operates within that distance limit.

Often, pipeline monitoring is needed for relatively short distances. A common cause of third-party contact is development encroachment onto pipeline rights of way. Pipelines that were installed in Class 1 locations often must be reclassified due to new housing or business development in the previously unpopulated area. Developers of subdivisions, schools, shopping facilities, and the like pay little attention to pipeline locations when they are platting their developments, with the result that residents and business owners often find themselves living or working within a few feet of a high-pressure gas pipeline.

It is during the infrastructure construction phase of such facilities that many third-party pipeline contacts take place. Drainage, water lines, electrical service, and similar facilities require ditching and burial. Soil sampling and foundation installation may require vertical drilling to depths that can intercept the pipeline. The pipeline operator would be well-served to have a monitoring system available to detect such third-party contact for the duration of the facility construction. IACC could offer a solution to that need.

The section of pipeline vulnerable to this intrusion is usually significantly less than 1 mile for a given construction project. It should be feasible to install automated monitoring stations at CP test leads adjacent to the sensitive area. Either a transmitter at one end and a receiver at the other end or, alternatively, transmitters and receivers at each end using separate frequencies for redundancy and enhanced reliability could be feasible. Electronics could be powered by batteries recharged from a solar panel. Communication could be via cell-phone technology to a monitoring station at the most convenient pipeline office. If a backhoe or a drill made third-party contact, notification would be nearly instantaneous to the pipeline operator. Immediate attention could be given to the damage and repairs ordered if necessary. This would be a much more reliable approach than depending on the construction crew to use the One-Call system or to notify the pipeline company after the contact was made. Figure 32 illustrates this approach schematically.

The application described here covers monitoring of an isolated discrete location with local IACC electronics. The concept could be extended to coverage of a longer section of pipeline by a system called "daisy chaining," referring to a series connection with communication between elements of the chain.

Alternate test stations could be transmitters, with those in-between acting as receivers. Different frequencies could be used to avoid ambiguity in locating third-party contact. Each module would also have the capability of sending and receiving low bandwidth data along the chain, so that third-party contact could be reported along with the location of the detected contact. Communication could use frequency shift keying at frequencies compatible with pipeline conduction.

Figure 33 shows a block diagram for a proposed daisy-chained monitoring system. Sensing/communication modules are placed approximately 1.6 km (1 mile) apart, connected to the pipeline through standard CP test leads. Ground reference is by a local ground rod. When third-party contact is detected, the event and the location on the pipeline are coded for transmission by the communication module. Since transmission along the pipeline is for only a limited distance, each module must pass along the information until it reaches the monitoring station for the whole pipeline segment. Frequency shift keying at a convenient carrier frequency can be used for reliable transmission of digital information. Alternatively, one could assign specific precise frequencies to each station, and then the communication modules could act as repeaters to boost the signal and pass it along until it was detected and identified at the main monitoring station.

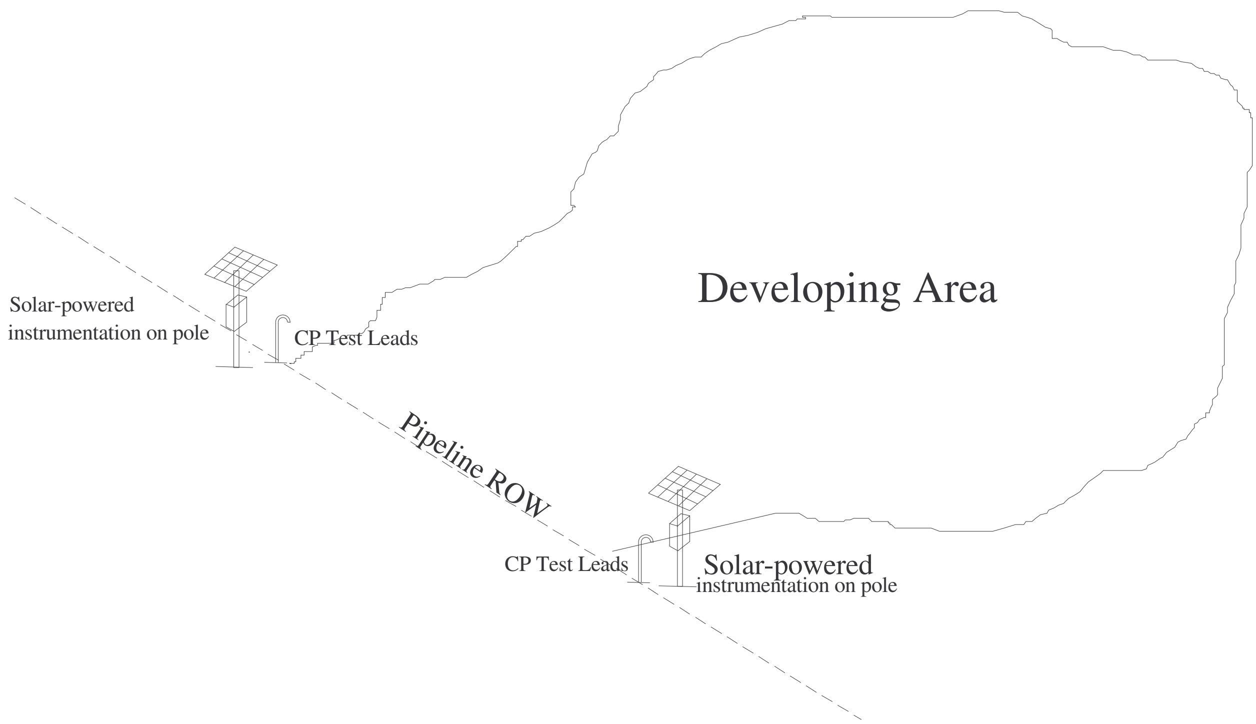


Figure 32. Use of local automated stations to monitor development in progress

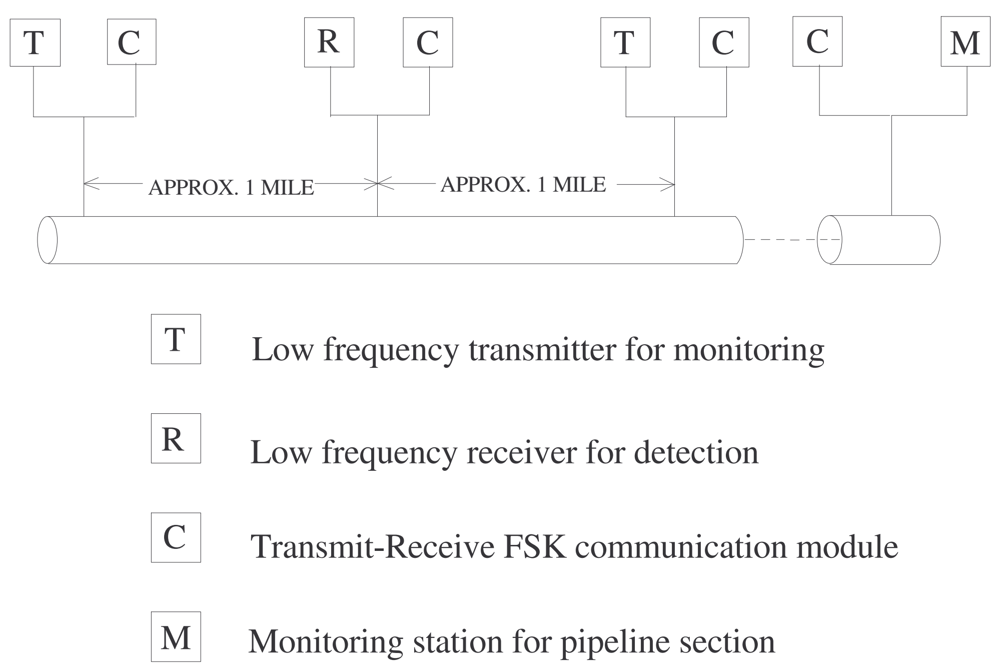


Figure 33. Conceptual design of daisy-chained monitoring system

Commercialization of IACC monitoring technology could follow either of the following two approaches:

1. An electronics design/fabrication organization could produce monitoring equipment, sell it to the pipeline operator, and train the pipeline maintenance personnel to install and operate it.

2. A pipeline service company could provide monitoring services on call. They would own and deploy the equipment and maintain both the field modules and the central reporting station. The type of company to offer such a service would be a company like Corrpro, Inc. of Medina, Ohio, or T. D. Williamson Co. of Tulsa, Oklahoma.

1.7.1 System Characteristics

The commercial IACC system will have the following characteristics:

1. Applied AC voltage as high as practical, but not exceeding 15 volts RMS.

2. Applied AC frequency at least 10 Hz, but avoiding harmonics of the 60-Hz power line frequency.

3. Connection to the pipeline at existing cathodic protection test leads.

4. Ground reference for transmission and reception to be through local copper-plated ground rods driven at least 8 feet deep in a location that is not subject to contact with the buried pipe.

5. If possible, each installation should be tested after installation by grounding an adjacent CP test point by momentarily connecting it to a local ground rod to simulate third-party contact.

1.7.2 System Configuration

The system typically consists of the following components, as shown in Figure 34.

1. Sine-wave signal source

2. Meter for transmitter amplitude

3. Preamplifier

4. Bandpass filter

5. Lock-in amplifier

6. Drift compensation

7. Threshold detection

8. Alarm annunciator

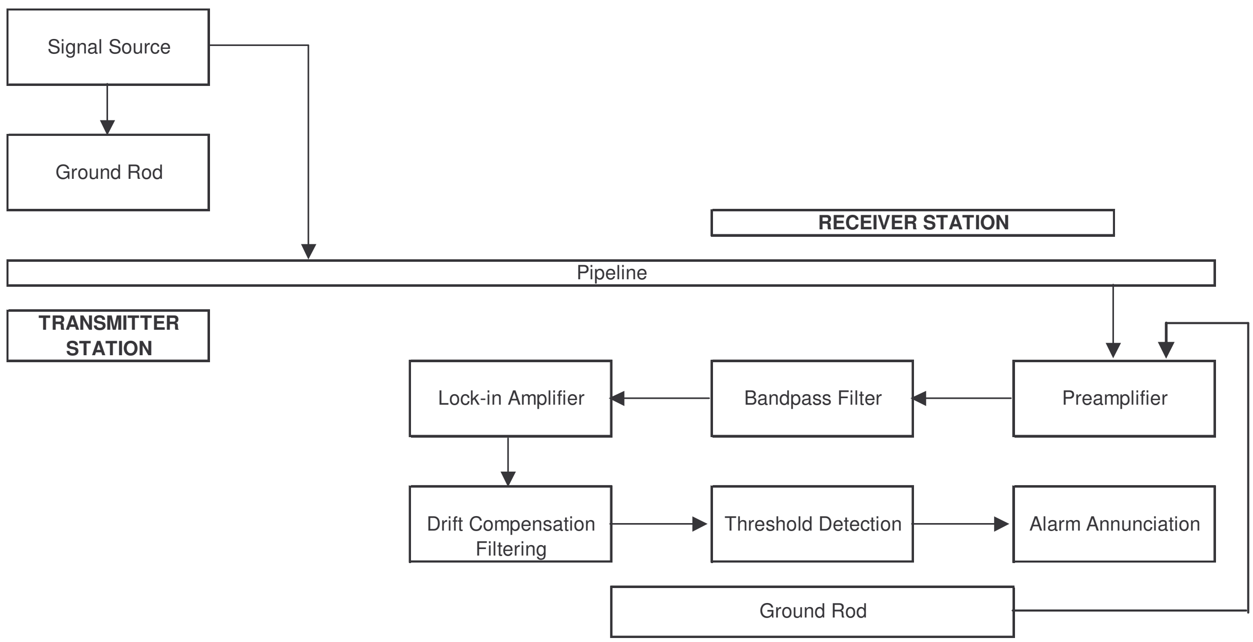


Figure 34. Block diagram of IACC system

1.7.3 Industry Feedback

Discussions with pipeline operational personnel revealed the following comments:

1. There are definite instances where a short-range [1.6 km (1 mile)] monitoring system would be valuable. This included not only new site development, but also ongoing excavation sites such as gravel pits and quarries.

2. In locations where there are no existing CP test leads to make connection, it would be feasible to expose the pipe and Cadweld a test lead to the pipe surface.

3. Security of the monitoring system hardware will be an issue. A recommended procedure will be to bury the hardware at the test site for the duration of the test. Power for the circuitry must be provided from aboveground unless one designed custom circuitry to convert the CP voltage to electronic supply levels.

CONCLUSIONS

The IACC method was shown to be a viable method that can be used to continuously monitor pipelines for third-party contact. Electrical connections to the pipeline can be made through existing cathodic protection (CP) test points without the need to dig up the pipe for installation. The instrumentation is relatively simple, consisting of (1) a transmitting station with a frequency-stable oscillator and amplifier and (2) a receiving station with a filter, lock-in amplifier, frequency-stable oscillator, and remote reporting device (e.g. cell phone system). Maximum distances between the transmitting and receiving stations are approximately 1.61 km (1 mile), although the monitoring distance can be doubled using a single transmitter and one receiver on each side (since the signal travels in both directions). The method can be used with pipelines having active CP systems in place. Certain conditions—such as poor pipeline coatings or strong induced 60-Hz signals on the pipeline—can degrade IACC performance, and localized testing should be performed to determine the suitability for an IACC installation at a given location.

The most appropriate use of IACC is for monitoring localized high-consequence areas where there is a significant risk of third-party contact (e.g. construction activity). The method also lends itself to temporary, low-cost installation where there is a short-term need for monitoring.

ACKNOWLEDGMENTS

SwRI greatly appreciates the support it received from Duke Energy Gas Transmission Corp., Southern California Gas Co., and CPS Energy.

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Appendix A

TECHNOLOGY STATUS ASSESSMENT

Technology Status Assessment

"REALTIME MONITORING OF PIPELINES FOR THIRD-PARTY CONTACT"

Cooperative Agreement DE-FC26-03NT41878

Southwest Research Institute® Project 14.10211

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December 2003

DISCLAIMER

INTRODUCTION

Third-party contact with pipelines (typically caused by contact with a digging or drilling device) can result in mechanical damage to the pipe. Because this type of damage often goes unreported and can lead to eventual catastrophic failure of the pipe,[1] a reliable, cost-effective method is needed for monitoring and reporting third-party contact events. Since over half of subsurface damage results from third-party infringement, the capability for detecting contact and locating encroachment would be greatly beneficial.

Several methods exist, or are being investigated, for monitoring and reporting third-party contact or activity near the pipeline. These include acoustic monitoring devices, continuous fiber-optic sensors buried alongside the pipe, satellite surveillance, cathodic protection monitoring, and methods that rely on telephone calls prior to digging. Because all of these methods have inherent limitations or are undesirable under certain conditions, the current project was initiated to investigate an alternate monitoring method. This method, impressed alternating cycle current (IACC), is capable of directly and continuously monitoring pipelines for third-party contact. Implementation of this method is relatively straightforward, and it can be retrofitted to existing pipelines without the need for excavating the pipeline.

The purpose of this technology assessment document is to describe the state of the art of pipeline monitoring, including positive and negative characteristics of existing technologies, and to present a comparison to the IACC technology being developed in the current project.

LITERATURE SEARCH

Literature searches were performed to obtain information about relevant pipeline monitoring methods. Searches made use of the resources of the STNEasy computerized search system. This included the following computerized databases:

- COMPENDEX (Engineering Index)
- ENERGY (DOE Energy database)
- FEDRIP (Federal Research in Progress)
- INSPEC (Database for Physics, Electronics, and Computing)
- NTIS (Government Reports and Announcements)
- PASCAL (Multidisciplinary scientific, technical, and medical database)
- ENTEC (German Energy Database).

Internet searches were performed using the search engine Google. Information was also obtained from the knowledge and contacts of Southwest Research Institute (SwRI®) personnel. A search for relevant patents was also performed using the United States Patent and Trademark Office web site (www.uspto.gov).

EXISTING MONITORING METHODS

Acoustic Monitoring Systems

The acoustic approach to pipeline intrusion monitoring is based on detection of impacts against the pipeline. Such impacts include backhoe strikes and the like. The history of this approach dates to the early 1990s. According to a Battelle chronology[2] of developments in this technology, British Gas first used the pipe wall as an acoustic signal carrier with a detector on the pipe wall. Tokyo Gas' approach was to use the gas column as the conductor with the sensor in the gas stream inside the pipe. Battelle followed those efforts with GRI-sponsored research that used sound conduction in the gas stream, but put the sensor on the outside wall of the pipe.

Battelle claimed a sensitivity range on the order of 5 miles for a backhoe strike. Parallel work by others, including ETOS Acoustics, Ltd. of Prague, Czechoslovakia, achieved similar results. The ETOS system, AMOS,[3] is claimed to detect hammer blows to the pipeline at a distance of 4 km.

Positive characteristics:

- A passive system that does not require any signal applied to the pipeline.
- Potential detection of other significant conditions such as leaks or product theft.
- Sensor deployment potentially no more frequent than approximately every 10 miles.

Negative characteristics:

- Susceptible to confusion from benign acoustic sources such as valve closures and routine maintenance operations.
- Reduced sensitivity to potentially damaging contact such as boring tools and drills, which do not have impact characteristics.
- Require sophisticated filtering techniques to reach acceptable signal/noise performance.

Two US patents were located with bearing on this technology:

- Pat. No. 5,333,501, Okada et al., "Abnormality Monitoring Apparatus for a Pipeline," August 2, 1994.
- Pat. No. 6,614,354, Haines et al., "In-Ground Pipeline Monitoring," September 2, 2003 (Covers the GRI/Battelle development).

Fiber-Optic Systems

The principle of operation of fiber-optic systems is that optical fibers are sensitive to stress applied to the fiber. Changes in the fiber's light transmission may be detected and located by using optical time domain reflectometry (OTDR). NYGAS (now Northeast Gas Association) has evaluated a system developed by Future Fiber Technologies, a system known as "Secure Pipe." The fiber detects vibrations and pressures generated in the area of the pipeline. The project is described at http://www.nygas.org/M-2002-011.htm.

The major work in fiber-optic detection of pipeline right-of-way intrusion has been carried out by the Gas Research Institute[4] (now Gas Technology Institute), most recently under funding provided by the Department of Energy. GTI work has concentrated on development of techniques to separate signals indicating potentially harmful encroachment from those indicating harmless encroachment.[5]

Positive characteristics:

- Continuous realtime monitoring.
- Range of tens of miles.
- Ability to detect and locate simultaneous encroachments at different locations along the pipeline.

Negative characteristics:

- Fiber must be installed in the right-of-way.
- Signals from benign pipe-loading events may mask the rare significant event.
- Sophisticated instrumentation and signal processing are required.

An on-line patent search at www.uspto.gov did not reveal any patents covering encroachment detection using optical fiber technology.

Satellite Monitoring

Commercial satellites can now monitor pipeline rights-of-way for ground motion and encroachment. For example, synthetic aperture radar (SAR) can be used to provide RADARSAT images that can be processed to reveal the presence of trucks or earthmoving equipment in proximity to the pipelines.[6],[7]

Remote sensing technologies have been used for some time to monitor natural resources. Twenty years ago, the industry had to rely on black/white aerial photography as the main tool for pipeline due to inadequate resolution of the satellite radar systems. Because newer systems can produce resolutions on the order of 1 m and provide hyperspectral data (>100 narrow spectral bands), remote sensing for pipeline encroachment detection is more feasible.

Much of the recent work in this area has taken place in Canada by the C-Core Company (www.c-core.ca).

Positive characteristics:

- Can cover the rights-of-way of an entire pipeline quickly and efficiently.
- Systems already in place that can provide pipeline coverage in parallel with other functions using existing satellites.

Negative characteristics:

- New software is needed to improve characterization of reflected targets.
- Urban congestion limits the application in highly developed areas.
- Monitoring cannot be done in real time.

Cathodic Protection Monitoring

A third-party contact detection system that monitors cathodic protection system potentials has been demonstrated by EUPEC RMS (www.eupecrms.com). This approach is based on changes in cathodic protection current paths when contact is made by a digging device. Changes in potential caused by contact with a backhoe have been demonstrated on a 250-foot test pipe.

Positive characteristics:

- Detects contact from backhoe strike as well as contact from drills and boring tools.
- Does not require digging to attach sensor; attachment is made to existing cathodic protection systems, thus allowing low-cost retrofitting of existing pipelines.

Negative characteristics:

- Detection range may be short.
- Sensitivity may be reduced by breaches in pipe coating.
- Relies on CP signals that may be variable.
- May be adversely influenced by 60-Hz (and harmonics) signals from other sources.

One-Call System

An alternate approach to monitoring is to prevent pipeline contact by observance of proper precautions and planning. The "one-call" systems in use in most states are an important element of such precaution/planning.

Since 1994, the primary component of damage prevention has been the one-call system. In order to promote the one-call system, the Office of Pipeline Safety (OPS) issued federal regulations that mandate participation in one-call systems for natural gas and liquid pipeline operators.[8] And in 1996, the OPS organized the Damage Prevention Quality Action Team to develop a national damage prevention campaign, now known as Dig Safely. The Dig Safely campaign was developed to address the problem of excavation damage to pipelines and other buried infrastructure. Since its formation, the Dig Safely campaign has grown tremendously, and is used throughout the country to promote damage prevention.

Dig Safely has a toll-free telephone number (888-258-0808) that can be used by anyone prior to excavation in any location in the country. The Dig-Safely web site (www.digsafely.com) also provides links to the state one-call systems that must be used prior to digging in any pipeline or other buried infrastructure right-of-way.

Statistics show that the incidence of third-party damage to pipelines has fallen significantly in states where one-call systems are in place.

Positive characteristics:

- Can prevent third-party damage or give immediate notification when it occurs.
- Gives the pipeline operator notice that activity is in his right-of-way.

Negative characteristics:

- Many excavation activities do not observe the one-call requirement.
- Some rights-of-way are not marked to prompt the one-call.

IACC

The IACC method consists of impressing electrical signals on the pipe by generating a time-varying voltage between the pipe and the soil at periodic locations where pipeline access is available (Figure 1). The signal, which travels down the pipe in both directions from the transmitter (Figure 1, left), consists of a time-dependent waveform designed to maximize IACC system performance in the presence of various sources of external noise. The signal voltage between the pipe and ground is monitored continuously at this transmission station. In addition, neighboring receiving stations with similar configurations (Figure 1, right), located some distance from the transmitting station, continuously monitor the received signal by measuring the pipe-to-soil voltage waveform. Third-party contact to the pipe that breaks through the coating changes (1) the impedance seen by the transmitting station and/or (2) the signal received at the IACC receiving stations that are located in the segment of pipe being contacted.

Figure 1. Schematic of IACC transmit station (left), showing time-varying voltage applied to the pipe, and receive station (right), showing measurement of pipe-to-soil voltage waveform

Initial work involving IACC[9] showed that the method is feasible. Projections from limited test results on an inservice pipeline showed that IACC was functional at a distance of 500 feet using excitation frequencies of 500 Hz and above.

The signal losses in the pipe are primarily capacitive, e.g. the pipe acts as one plate of a capacitor, the coating acts as a dielectric, and the soil acts as the other plate. Since capacitive losses are proportional to frequency, one approach to overcome problems with signal attenuation over long distances, and therefore extend the IACC range, is to reduce the operating frequencies below 500 Hz. Reducing the frequency by a factor of 5 to 10 should result in an increase in operating range of an equivalent factor. The use of lower frequencies, however, leads to potential interference from 60 Hz (and its harmonic frequencies) that are introduced from mechanisms such as cathodic protection systems. Advanced signal processing, such as digital filtering, can be used to process the IACC response and reduce interference effects, thus enhancing signal-to-noise ratio.

Positive characteristics:

- Active system that allows pipe excitation characteristics to be chosen to achieve optimum results.
- Does not rely on energy input from damage-creating mechanism that may be low-level and unpredictable.

- Detects contact from backhoe strike as well as from boring tools and drills.
- Does not require digging to attach sensor; attachment is made through existing cathodic test point, thus allowing low-cost retrofitting of existing pipelines.
- Can be temporarily applied for short-term monitoring of high-construction areas.

Negative characteristics:

- Detection range may be short.
- Sensitivity may be reduced by breaches in pipe coating.
- May have interference from cathodic protection systems.

COMPARISON OF METHODS

A comparison of the characteristics of the above pipeline monitoring methods is given in the following table.

Third-party monitoring systemd	Requires breach of coating for installation?	Equally effective for impacts and boring contact?	Range between sensors	Effective in urban congestion?	Provides full-time coverage?	Requires excavation for installation?	Development status
Acoustic sensing	Yes	No	10 mi.	Reduced	Yes	Yes	Field testing
Fiber Optic	No	Yes	10's of miles	Reduced	Yes	Yes	Field testing
Satellite monitoring	No	Yes	N/A	No	No	No	Under development
CP monitoring	No	Yes	Unknown	Yes	Yes	No	Field testing
One-Call System	No	Yes	N/A	Yes	N/A	No	Commercial
IACC	No	Yes	Several miles	Yes	Yes	No	Under development

CONCLUSIONS

Numerous methods are currently and potentially available for monitoring pipelines to detect third-party activity or contact. All of these methods have inherent limitations that reduce their usefulness under certain conditions. The IACC method to be investigated in this project offers distinct advantages that would allow it to be an attractive alternate or complementary approach.

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