REALTIME MONITORING OF PIPELINES FOR THIRD-PARTY CONTACT

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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 and reporting third-party contact events.

The impressed alternating cycle current (IACC) pipeline monitoring 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. 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 is being developed, tested, and demonstrated. Work performed to date includes (1) a technology assessment, (2) development of an IACC model to predict performance and assist with selection of signal operating parameters, (3) Investigation of potential interactions with cathodic protection systems, and (4) experimental measurements on buried pipe at a test site as well as on an operating pipeline. Initial results showed that IACC signals could be successfully propagated over a distance of 3.5 miles, and that simulated contact can be detected up to a distance of 0.7 mile. Unexpected results were that the electrical impedance from the operating pipelines to the soil was very low and, therefore, the changes in impedance and signal resulting from third-party contact were unexpectedly low. Future work will involve further refinement of the method to resolve the issues with small signal change and additional testing on operating pipelines.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION AND BACKGROUND

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, a reliable, cost-effective method is needed for monitoring and reporting third-party contact events.

The impressed alternating cycle current (IACC) pipeline monitoring method involves 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 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 (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

The objectives of the proposed work are to further develop, test, and demonstrate the IACC monitoring method for detecting third-party contact with pipelines in real time. This method will allow existing pipelines to be retrofitted for monitoring without excavation because the technique uses existing cathodic protection (CP) test points. In addition, the method could be readily applied to new pipelines. Upon completion of the work, guidelines will be developed for use by a vendor to begin development of a commercial version of an IACC system.

RESULTS AND DISCUSSION

The sections and corresponding numbers below correspond to those used on the Research Management Plan.

1.1 Research Management Plan

A research management plan document was prepared and submitted during the first reporting period.

1.2 Technology Status Assessment

A technology status assessment was prepared and submitted during the first reporting period.

1.3 IACC Parameter Refinement

1.3.1 Modeling

This effort involves 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 model allows simulations to be performed to study the effects of signal characteristics (e.g. frequencies and excitation levels) on the IACC signals. These simulations will allow signal characteristics to be selected to maximize range and reduce interference.

As previously reported, calculations were performed to determine signal performance for a 6,000-foot-long pipeline. These calculations were based upon projections from electrical impedance measurements made on the 120-foot SwRI test pipe. As will be discussed in Section 1.6, the impedance measurements from an operating pipeline do not agree with expected values. Therefore, no additional modeling calculations will be made until the pipeline values are reconciled.

1.3.2 Signal Processing

The goal of the signal processing is to provide improved signal-to-noise ratios SNRs) for the data so that sensing of third-party contact can be extended over longer distances. The signal processing approach consists of bandpass and notch filtering, as well as matched filtering operating on a chirp waveform. 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, 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 harmonics of 60 Hz. Because these signals are quite strong, notch filters at 60 Hz and harmonics are needed to reduce interference at these frequencies. The matched filtering approach consists of comparing a waveform having the characteristics of the transmit waveform to that of the received waveform, similar to performing a cross correlation. A “match” between the waveforms produces a high correlation coefficient. By using a chirp, the signal is spread over a wide range of frequencies, thus reducing the effect of interfering noise at specific frequencies. Software filter routines for bandpass, notch, and matched filtering have been written in Matlab and are being used in the data analysis, as described in Section 1.6.2.

An additional processing approach was also being evaluated. This involved system identification using an auto-regressive parameter estimation technique. With this technique, the processing calculates an equivalent circuit and its electrical parameters (e.g. resistance and capacitance) for the pipe based on analysis of the data and behavior as a function of frequency. Changes in parameters specific to third-party contact are then identified. These parameters are monitored to determine if contact has occurred. This could provide an approach that is more sensitive to contact and less sensitive to other noise sources. The auto-regressive parameter estimation technique was evaluated on the data from an operating pipeline; however, the results of this technique were determined to be very dependent on knowing the precise nature of the transmitted waveform, both with and without third-party contact. Since it is difficult to know the precise transmitted waveform at the receiver site when contact is made, this method will be difficult to implement. Therefore, this approach will not be pursued further.

1.4 Investigation of CP Interactions

The purpose of this task is 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. 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. As described in Section 1.6, data were obtained while applying IACC signals to an operating pipeline, both with and without the active CP system connected. The notch and matched filtering routines that have been developed effectively removed the CP system signals from the IACC waveform. It was demonstrated that the active CP system in place on the operating pipeline had no significant effect on operation of the IACC system.

Potential Effects of Impressed A-C Signal—The question has been raised whether the IACC signal, either chirp or single frequency, would have any deleterious effect on existing CP systems. Guidelines for CP application recommend that the pipeline be maintained at a negative potential (relative to the surrounding soil) of 0.85 volts, not to exceed –1.10 volts. Excessive negative potential can cause coating degradation and creation of hydrogen “bubbles” that can lead to coating disbond.

We propose to apply an alternating current waveform onto the pipe. For maximum SNR of our measuring system, we need to have the strongest signal allowable. To keep within the range of recommended CP voltages, we will be limited to approximately 0.5 volts peak-to-peak (Vpp) for our excitation waveform. We would prefer a signal of 10 Vpp. At issue is the severity of degradation, if any, of the CP system when a signal of this magnitude is present on the pipeline.

There are guidelines in corrosion manuals that allow one to relate metal loss from the pipeline to the amount of electrical charge transferred over time. There are tables showing weight of iron lost per ampere-year of accumulated charge. In a simple model, we can integrate our excitation waveform over the time period during which it is outside the bounds of CP protection and thus estimate the metal loss to be experienced.

There are two difficulties in this approach. First, the pipeline has a native potential to which it returns after CP is removed and from which it drops when CP is applied. These transitions are not instantaneous, exhibiting a time constant that is significantly longer than the period of our excitation voltage. Thus, there is the possibility that any degradation due to charge transfer may be mitigated by the relatively high frequency or our excitation waveform. We will continue to investigate this possibility.

Second, a net weight loss may be insignificant if spread uniformly over the full affected length of the pipeline, but very significant if concentrated in a few areas of coating failure. So an accurate appraisal of the effect of a continuous AC excitation would not be possible without knowing, *a priori*, the condition of the line.

1.5 Contact Simulator

The contact simulator was completed, as described in the first report.

1.6 Pipeline Tests

A series of field tests was performed on two operating pipelines owned by City Public Service (CPS) of San Antonio. The first test site involved a 16-inch pipeline that feeds the Leon Creek Power Plant off Quintana Road on San Antonio’s southwest side. The pipeline is relatively new (about 1 year) and has a fusion-bonded epoxy coating. Impressed current CP is in place. The total length of the line is approximately 1.6 miles. The general layout of the pipeline is shown in Figure 2. Approximate locations of CP test points are labeled 1 through 9. The

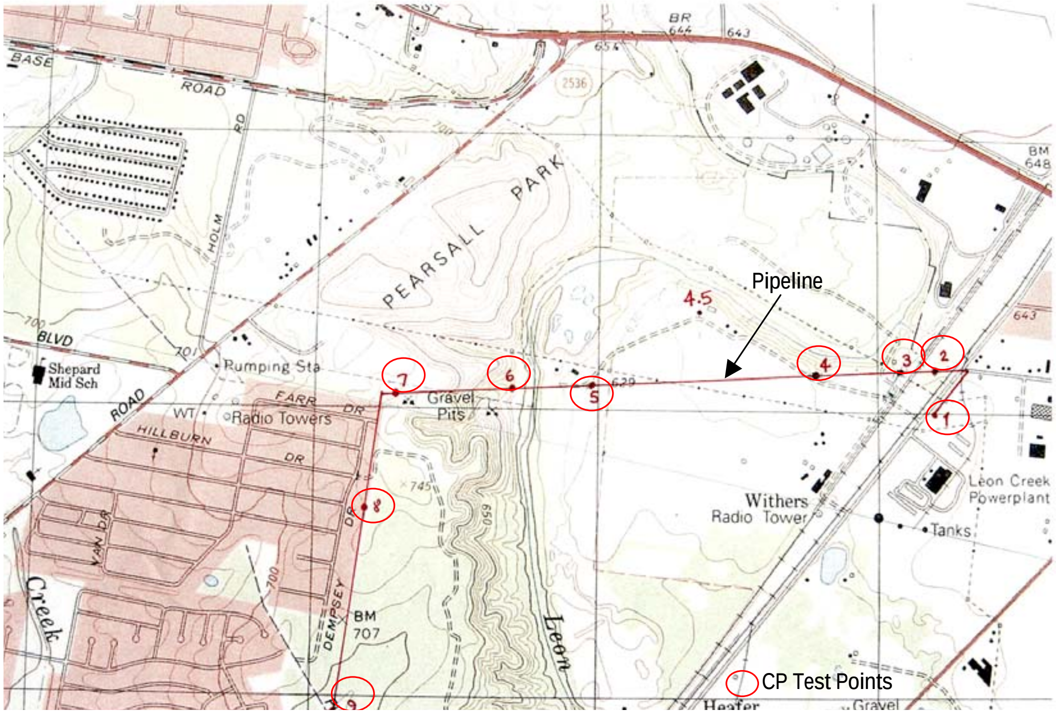

Figure 2. General layout of test pipeline at the Leon Creek site

second site involves a 24-inch pipeline that feeds a transfer station near the Calaveras Lake power plants on the southeast side of San Antonio. This pipe also has a fusion-bonded epoxy coating and is approximately 3.5 miles long; active CP is in place on this pipeline also. Both pipelines are intended to have electrical isolation from connecting pipelines on each end and are not intended to have passive anode CP systems.

Field tests were made on the Leon Creek pipeline during three different visits (9/28/04, 1/11/05, and 3/8/05). These tests involved electrical impedance measurements and IACC measurements with impressed waveforms and simulated third-party contact. One field test was performed at the Calaveras site (3/31/05). This test was directed primarily at impedance measurements, although limited IACC measurements were also made. Figures 3 and 4 show the test setups. Supporting measurements were also made on the SwRI test pipe. These tests and results are described below.

1.6.1 Measurement of Pipe Parameters

Electrical impedance measurements were made between the pipe and soil. The purpose of these measurements is to understand the pipeline parameters so that the IACC test frequencies and parameters can be optimized. These measurements were made between a CP test point on the pipe and a ground rod driven into the soil several feet away. In order to cover the same frequency range anticipated for IACC (50 Hz to 2.5 kHz) and to use similar pipe excitation conditions as in the IACC tests, the impedance measurements were made using the same 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.

As discussed in the previous reports, it is expected that the resistance between the pipe and soil is relatively high when the coating is sound. It is also expected that the pipe will 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. It was also expected [1,2] that the resistance between a ground rod and the soil is dominated by the local area around the rod and that the resistance between rods is not a strong function of distance.

Measurements on the 6-inch-diameter, 120-foot-long SwRI test pipe bore out the above expectations. The impedance between the pipe and soil ranged from 2.3 k ohms at 50 Hz to 111 ohms at 2.5 kHz, with the change in impedance with frequency caused by capacitative reactance. The capacitance was 0.5 uF (approximately the same as the value calculated using the pipe surface area and the dielectric constant of the coating).

For the operating pipelines, it was expected that the capacitance would be much higher because these pipes are greater in diameter and length, which results in much greater surface area and, therefore, a larger capacitor plate size. Also, the coating is thinner, which results in smaller separation between the capacitor plates (pipe and soil). For example, the calculated capacitance of the Leon Creek pipeline was 250 uF (compared to 0.55 uF for the SwRI test pipe).

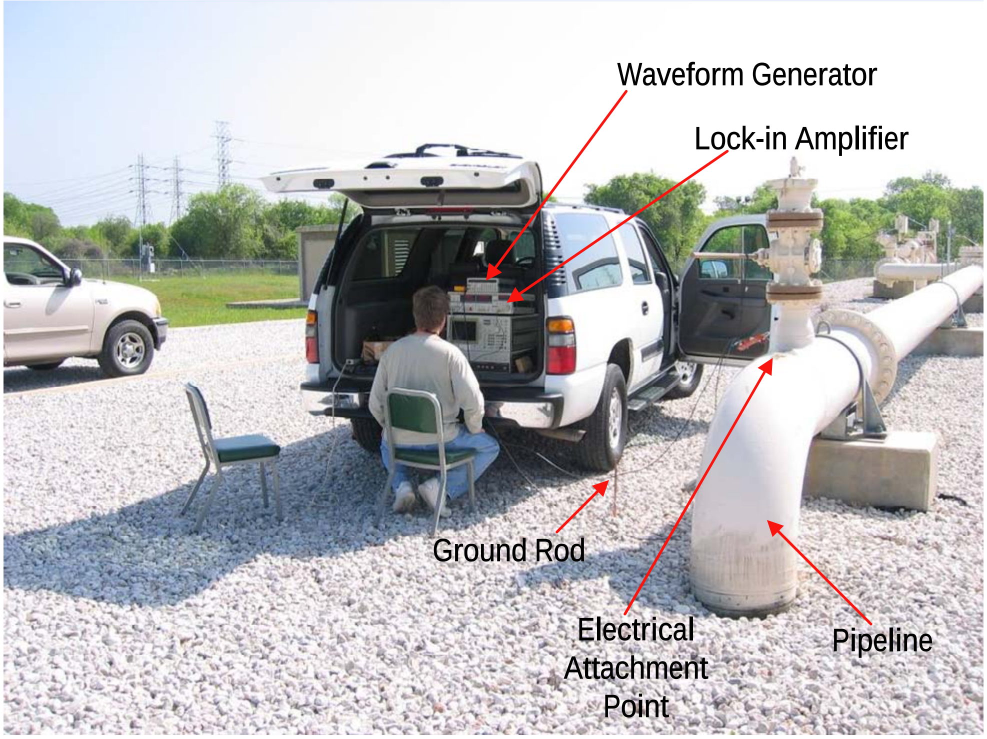

Figure 3. Setup at excitation location (Calaveras site)

Figure 4. Setup at receiving location (Leon Creek site)

At the Leon Creek pipeline, the measured impedance (at CP3) was approximately 18 ohms with negligible frequency dependence. The measured value of capacitance was 0.3 uF, considerably less than expected from the calculated value above. These measurements were surprising in that the capacitative effects were so minimal and that the impedance to soil was so low. Note that similar measurements were obtained both with and without the active CP system connected to the pipe. The impedance was also measured with at CP3 with CP4 shorted to a ground rod (simulated third-party contact). The change from shorting was less than 0.5 percent. Similar results were observed at the Calaveras test site with the impedance measured at 28 ohms and minimal change with shorting.

Analysis of these data is continuing; however, initial indications are that the pipelines have a low impedance path to ground. It is possible that this is due to defects in the coating; however, the pipelines are relatively new, and the coatings should be in good shape. It could also be due to the use of a passive anode CP system; however, these pipeline segments are supposed to be electrically isolated from adjacent legs that could have anodes. At the current time, the cause of these low impedance values and low capacitance values is not clear.

1.6.2 Detection of Impressed Waveforms

1.6.2.1 Measurements at Leon Creek Site

During field tests 1 and 2 at the Leon Creek pipeline site, IACC tests were performed 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 2). An arbitrary waveform generator was used to generate the chirp waveform. In one setup, the waveform generator output was connected directly between the CP test point and a ground rod, and an output voltage of 10 Vpp was applied. In a second setup, a power amplifier was used to apply a voltage of 78 Vpp. 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 (frequency range 30 Hz to 3 kHz, and gain = 1 or 5) 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 0.7 mile from CP3) and at CP8 (distance of 1.43 miles from CP3). Third-party contact was simulated by connecting the CP test point at CP4 (distance of 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. Although higher voltages could potentially improve the SNR, any voltage greater than 15 V is considered a shock hazard and is not desirable as an operating voltage. Therefore, the remainder of the tests and analysis were conducted with the 10-Vpp signal level.

Figure 5 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.

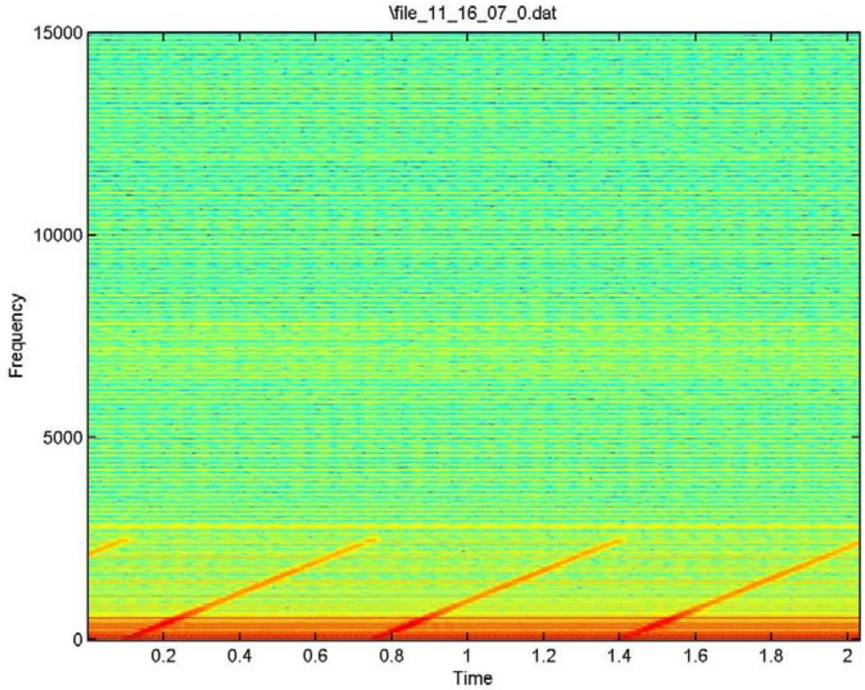

Figure 5. Spectrogram of the received signal at CP5 with the CP system on

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 6 (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.

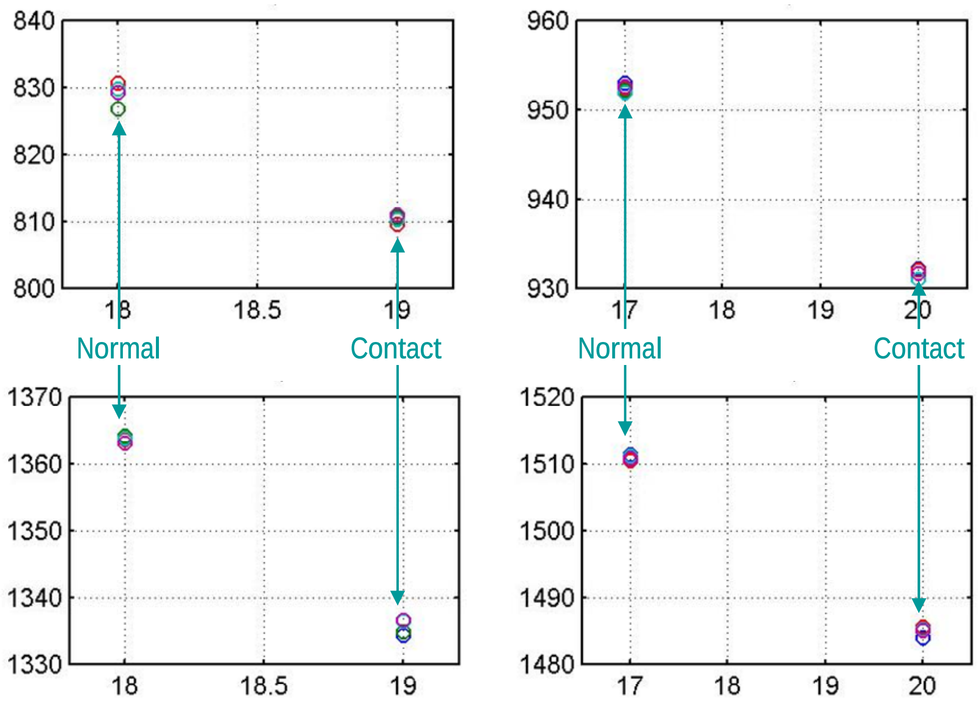

Figure 6. IACC matched filtering results from operating pipe at the Leon Creek site; top: 200 Hz–500 Hz; bottom: 500 Hz–1 kHz; left: CP on; right: CP off

The plots at the bottom of Figure 6 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 0.7 mile.

Tests were also performed with the signal measured at CP8 (1.43 miles from the transmitter at CP3). 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 7 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.

Based on the signal levels from the Leon Creek pipeline (without contact), projections were made to project the distance over which the impressed signals could be propagated. Figure 8 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 4.5 miles.

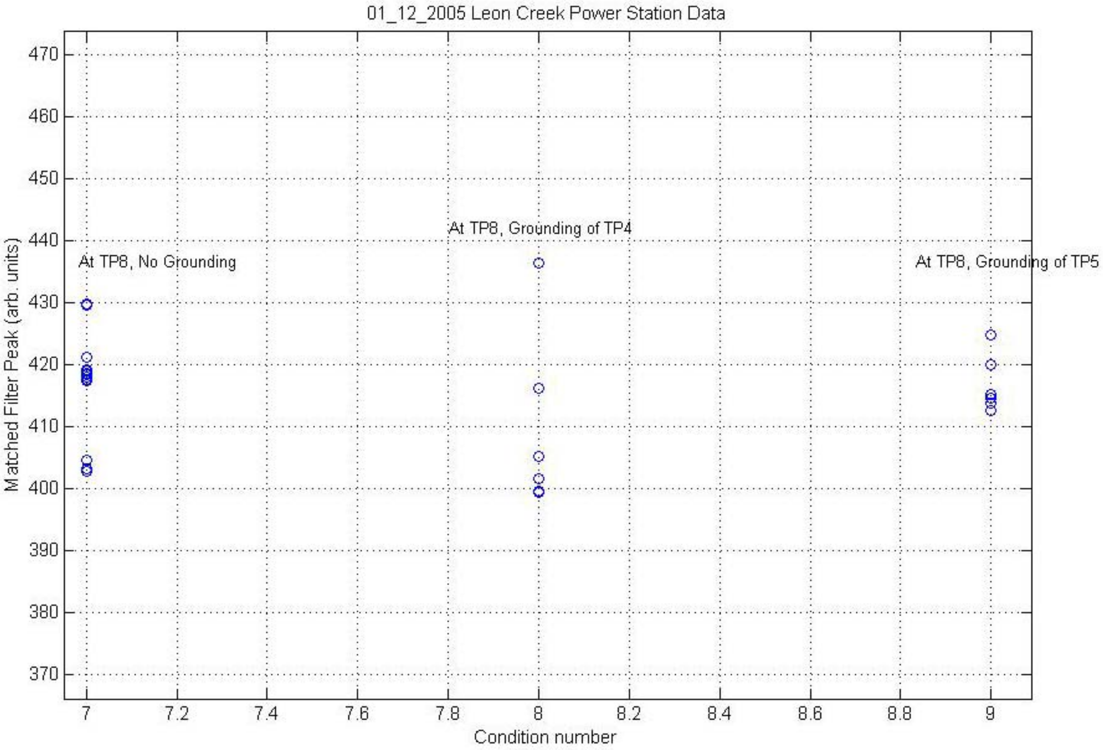

Figure 7. Results of applying the matched filter to the data at CP8

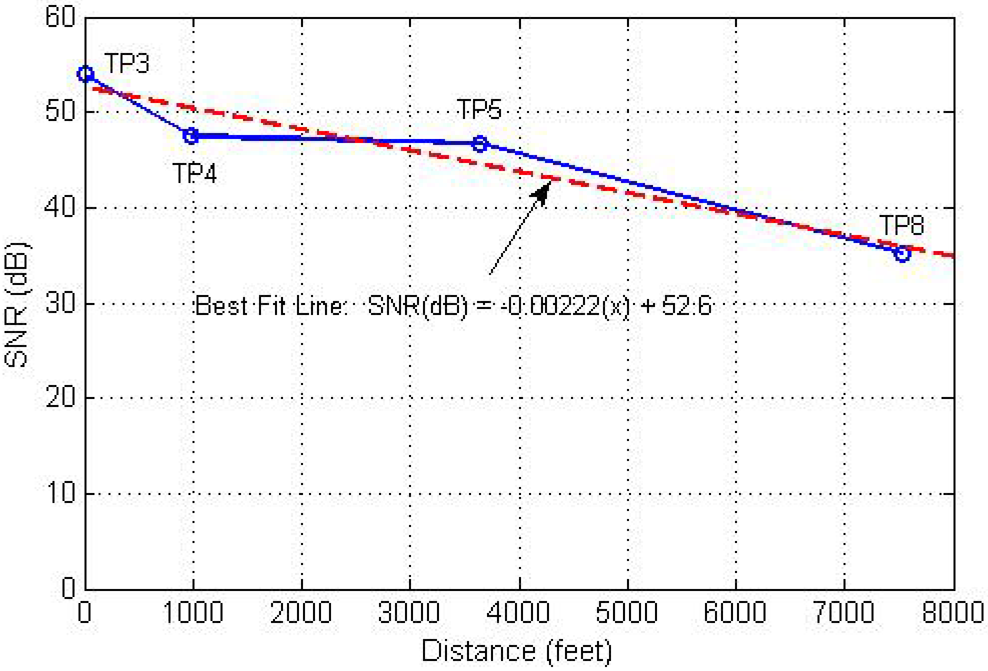

Figure 8. Signal-to-noise ratio as a function of distance from CP3 to CP8

1.6.2.2 Measurements at Calaveras Site

The measurements performed on an operating pipeline at the Calaveras site were primarily to measure impedance, and chirp waveforms were not applied. Simplified tests using single-frequency excitation were performed; however, the signals were only observed on an oscilloscope, and processing was not applied since the signals were not digitized. These measurements did show, however, that signals could be propagated over a distance of approximately 3.5 miles. A simulated third-party contact event at an intermediate test point could not be observed in the signal at the 3.5 mile point; however, the measurement accuracy was not sufficient to observe small changes.

1.6.2.3 Measurements at SwRI Site

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 the Leon Creek pipeline.

1.6.2.4 Overall Assessment

It is clear from the measurements made so far that the IACC signal can be propagated over a distance of at least several miles. The difficulty that has been observed, however, is that changes in signal level from a third-party contact event are small. For the Leon Creek pipeline, the change was about 2 percent at a distance of 0.7 mile. Although the repeatability of the tests was very good, it is desirable to observe a larger change in response. At a distance of 1.43 miles, third-party contact could not be observed. For the SwRI test pipe, the signal change was significantly larger (35 percent), although the pipe length was only 120 feet.

The difficulty with the small changes in the response of the operating pipelines appears to be because the impedance between the pipe and ground is very small. Therefore, when the pipe is shorted to ground at an intermediate location, there is only a small change in the overall impedance and, therefore, the effect on the IACC signal is minimal. The larger signal changes observed on the SwRI pipe are a result of the higher initial pipe-to-ground impedance measured from this pipe. It is not clear why the operating pipelines tested so far have such low impedance when they are supposed to be electrically isolated from adjacent pipeline segments and not connected to any passive anodes (which would provide a low-impedance ground path). It is also not clear why measured capacitance values are so low and do not agree with calculated values for the operating pipelines. It should be noted that for the SwRI test pipe, the capacitance values generally agree with calculations.

Future work will be directed toward understanding the impedance conditions of the operating pipelines, and additional measurements on these and additional pipelines will be performed to characterize the impedance characteristics. This understanding is essential to determining how the IACC method can be made more effective at detecting third-party contact events.

1.7 Evaluation

No work was planned or accomplished.

1.8 Technology Transfer

The Technology Assessment document was submitted during the first reporting period.

1.8.1 Meetings

A project update meeting was held with Richard Baker from DOE at SwRI in January 2005.

1.8.2 Deliverables

Documents were delivered per the project schedule. These included Semi-Annual Technical Progress Report No. 2, Informal Status Reports, Financial Status Reports, and Federal Cash Transaction Reports.

1.8.3 Milestones

Project milestones are shown in the following table. The Modeling and Simulations and Parameter Optimization milestones are considered completed, although some additional work will continue in order to support the Pipeline Testing task. The Contact Simulator milestone is also complete. The CP Interactions milestone is being extended in order to allow evaluation of frequency-dependent effects. Because of the unexpected results obtained from the operating pipelines, the remaining milestones are being extended so that these issues can be resolved. It is possible that a time extension will be required to allow resolution of these issues.

Milestone	Due Date	Revised Due Date
Modeling and Simulations Completed	Complete	
Parameter Optimization Completed	Complete	
CP Interactions Determined	8/2/04	6/15/05
Contact Simulator Completed	Complete	
Pipeline Testing Completed	6/1/05	8/1/05
System Demonstration	6/1/05	8/1/05
Data Evaluation Completed	8/1/05	9/1/05
Design Guidelines Completed	8/1/05	9/1/05

WORK ANTICIPATED IN NEXT REPORTING PERIOD

In the next reporting period, additional testing will be performed on operating pipelines, including locations at additional sites. A major goal will be to overcome the small changes in IACC signal with third-party contact. A further investigation of the frequency effects of AC signals on CP systems will be undertaken to determine if the use of certain frequencies for IACC will have less interference with CP. According to the current schedule, a demonstration will be performed and design guidelines for an IACC system will be completed. It is possible, however, that a time extension will be needed to address unexpected pipeline impedance conditions that result in small changes from third-party contact.

CONCLUSIONS

The IACC method is promising as a monitoring method for third-party contact. Initial tests on an operating pipeline showed that IACC signals were detectable up to a distance of about 3.5 miles. Simulated third-party contact has been detected over a distance of 0.7 mile, and the presence of active CP signals was shown to not have a significant effect on the IACC response. Changes in IACC signals from simulated third-party contact to operating pipelines were unexpectedly small. This is a result of unexpected low electrical impedance between the pipe and soil. Future tests will be undertaken to resolve these issues.

REFERENCES

[1] Marshall, J. L., *Lightning Protection* (New York: John Wiley & Sons, 1973), 37–79.

[2] Carpenter, R. B., Jr., and J. A. Lanzoni, “Designing for a Low Resistance Earth Interface (Grounding),” an LEC publication, revised July 1997.