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 a technology assessment, development of an IACC model to predict performance and assist with selection of signal operating parameters, and experimental measurements on a buried pipe at a test site. Initial results show that simulated contact can be detected. Future work will involve further refinement of the method and testing on operating pipelines.

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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 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. That document will serve as the main planning and tracking document for the project. The document includes a concise summary of the technical objectives and technical approach for each task and includes schedules, planned expenditures, and milestones.

1.2 Technology Status Assessment

In addition to IACC, several methods exist, or are being investigated, 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 being developed in the current project.

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 the following table. 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.

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	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

1.3 IACC Parameter Refinement

1.3.1 Modeling

This effort will involve 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 will allow 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.

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

$$\lambda = \frac{3 \times 10^8 m/s}{30 \times 10^3 / s} = 10000\, m\, .$$

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

$$\omega\varepsilon / \sigma \;\; [2]$$

where

ω is the frequency in radians,

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

$$\omega\varepsilon / \sigma = 2\,\omega\varepsilon / \sigma \approx 2\pi \times 30 \times 10^3 \times 30 \times 8.854 \times 10^{-12} / .0001$$

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 measured 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. This initial configuration is shown in Figure 2, and is based on the configuration and measured parameters of the pipe at the test site (Section 1.3.3). Each section of the model represents the section of pipe between two risers. 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 (V_{out}). The switch represents a path to ground caused by third-party contact at that location. The model can be extended and the parameters varied to represent pipelines of different lengths and diameters, and in different soil conditions.

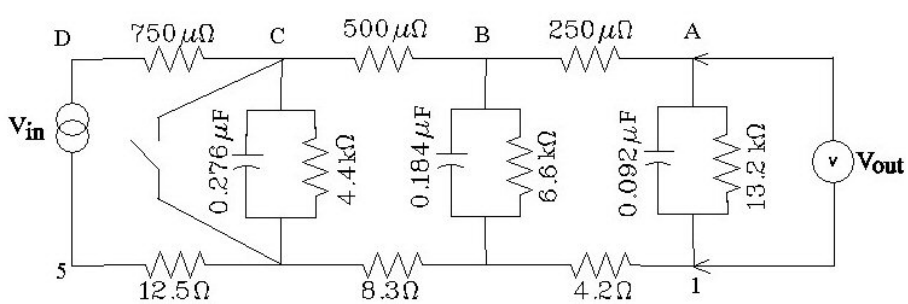


Figure 2. PCAD model of pipeline. A–D correspond to pipe risers on the test site pipe, as shown in Figure 3

The output voltage at the monitoring location will be calculated at different frequencies for a constant input voltage and with and without third-party contact (switch open and closed, respectively). These results will be compared to experimental results such as those shown in Section 1.3.3 for verification of the model.

1.3.2 Signal Processing

A matched filter has been designed for use with chirp excitation waveforms that are anticipated to be used as IACC excitation waveforms.

1.3.3 Experimental Evaluations

The purpose of the experimental evaluations is to measure input parameters for the model, verify the model, and test signal parameters and signal-processing approaches. Experiments were conducted at the existing test site (shown in Figure 8). 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. 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 that represent the soil, pipe, and pipe coating. Impedance measurements of the insulated pipe were made using the setup shown in the diagram in Figure 3. 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 4.

The series resistance of the pipe/ground path (Figure 3) 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 4), 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).

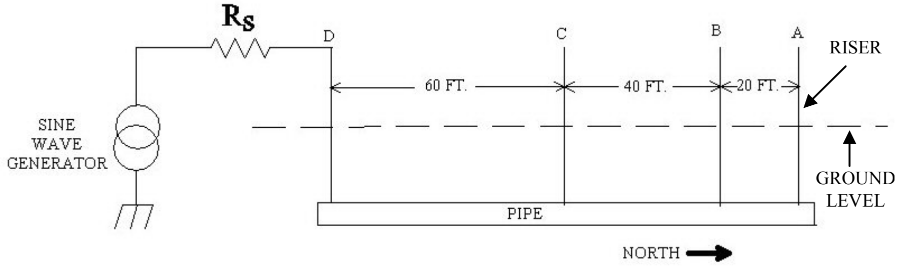
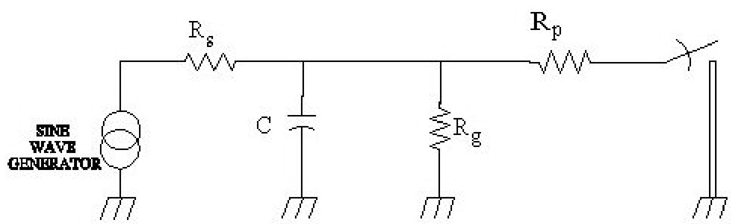


Figure 3. Connection for impedance measurements



Rs= Source Resistance
Rp= Series resistance of pipe
Rg= Resistance of coating to ground

Figure 4. 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 5.

Figure 5. Setup for measuring dielectric constant of pipe coating

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.

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 6. 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. Thus, the dielectric constant of the soil must also have an effect on the overall capacitance. It is currently not clear how to account for this factor. More investigation will occur during the next reporting period.

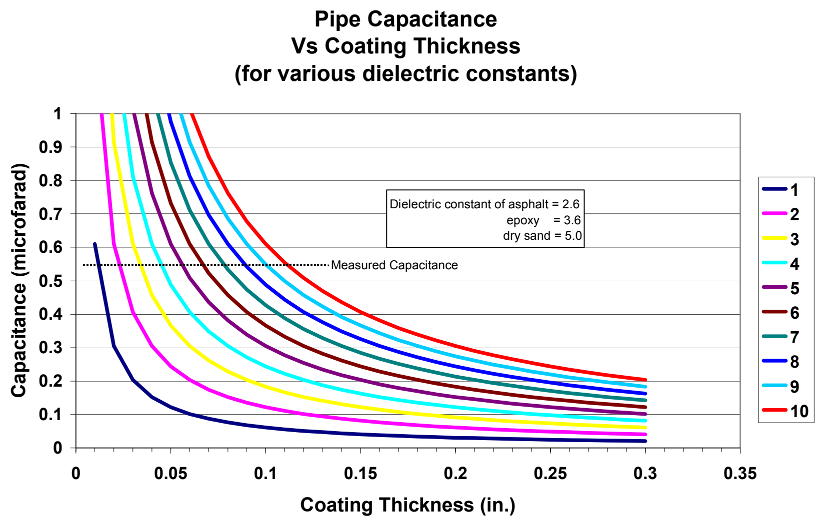


Figure 6. Calculated capacitance of test pipe for different coating thicknesses and dielectric constants of coating

Monitoring Simulation Tests—An experiment was performed to simulate an IACC monitoring situation on the test pipe. Figure 7 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 the following table. It was found that there was a clear reduction in signal $\left(\frac{R2}{R1}\right)$ when the pipe was shorted, suggesting that it will be feasible to detect coating breaches using the IACC method.

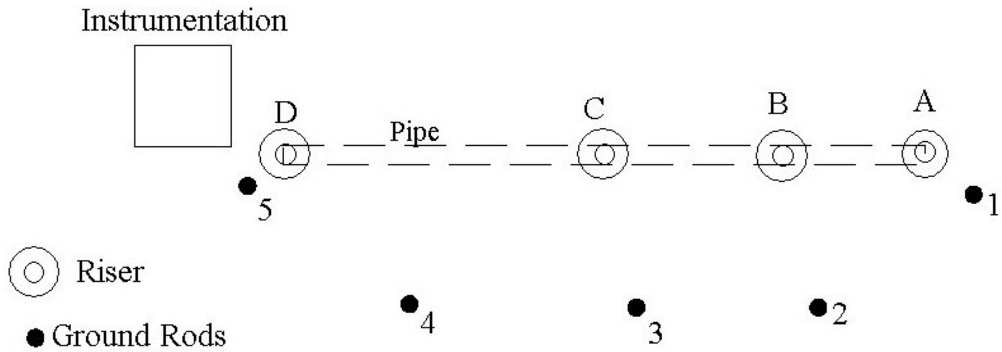


Figure 7. Pipeline plan view showing location risers and ground rods

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

1.4 Investigation of CP Interactions

The purpose of this task is to determine any effects of cathodic protection systems on the functioning of the IACC method and to determine any effects of the IACC signals on the CP system. Both active and passive systems were included, with the means for selecting either, both, or none.

A contractor was hired for installation of CP systems on the test pipeline. 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 is intact and that no significant leakage paths to ground exist.

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 will allow 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. Figure 8 shows an overall view of the test site, and Figures 9 and 10 show the active CP system installation.

Figure 8. Test pipeline "right of way" viewed from south to north. Ground rods are set 15 feet to the right of the pipeline in this view.

Figure 9. CP installation at the north end of test pipeline

Figure 10. Details of CP rectifier installation

The passive CP system consisted of a 40-lb. magnesium anode that was buried about 10 feet from the north end of the pipeline. Figure 11 shows the anode in place before covering. A wire attached to the anode was brought out to be connected to the pipeline.

Three ground rods about 15 feet to the east of the pipeline and at three locations along the pipeline length were also installed. These rods can be used for grounding of the active CP system, as well as for grounding points for IACC tests.

The contractor also made measurements of the soil resistivity at the test site. The average measured value was approximately 8 kΩ-cm.

Figure 11. Magnesium anode in place before covering

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 12. The simulator is controlled by an HP33120A arbitrary waveform generator. An initial contact sequence has been programmed; this waveform will be further refined in the next reporting period.

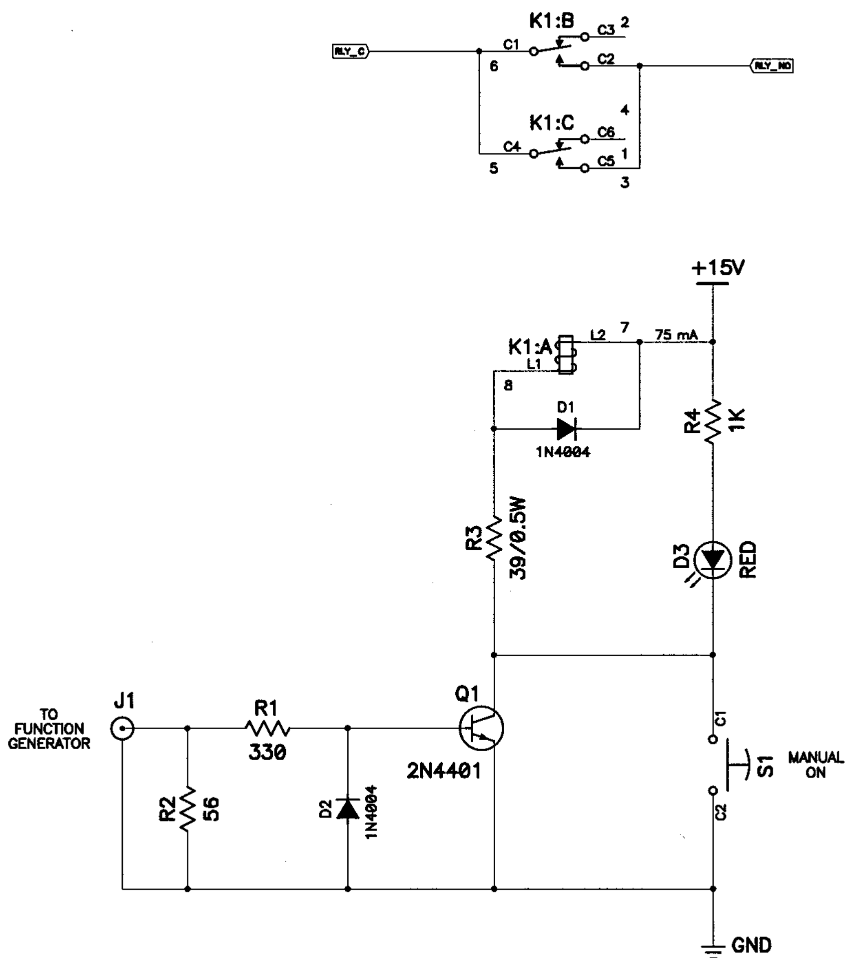


Figure 12. Schematic diagram of the contact simulator

1.6 Pipeline Tests

A meeting was held with representatives of San Antonio City Public Service (CPS) in order to plan tests on their pipelines. CPS agreed with multiple measurements at multiple sites over a period of approximately 1 year. CPS will provide information on pipeline locations and availability. In order to help plan site selection, maps of Bexar County were obtained that show locations of soil types and soil conductivity. A large range of soil conductivities is available over the Bexar County area. Discussions are currently under way with Duke Energy about the possibility of performing measurements on their pipelines in Texas. This could provide additional soil conditions for evaluation of the third-party contact detection system.

1.7 Evaluation

No work was planned or accomplished

1.8 Technology Transfer

The Technology Assessment document was submitted.

1.8.1 Meetings

Richard Baker and Rodney Anderson from DOE are planning a kickoff and project update meeting at SwRI in mid-May 2004.

1.8.2 Deliverables

Documents were delivered as per the project schedule. These included the Research Management Plan, Technology Assessment, Hazardous Substance Plan, Informal Status Reports, Financial Status Reports, and Federal Cash Transaction Reports.

1.8.3 Milestones

Project milestones are shown in the following table. The completion of Modeling and Simulations and Parameter Optimization have been extended as shown in the table. The Contact Simulator will be completed ahead of schedule. None of the other milestone dates are projected to change.

Milestone	Due Date	Revised Due Date
Modeling and Simulations Completed	2/1/04	6/1/04
Parameter Optimization Completed	6/1/04	8/1/04
CP Interactions Determined	8/2/04	
Contact Simulator Completed	7/2/04	5/15/04
Pipeline Testing Completed	6/1/05	
System Demonstration	6/1/05	
Data Evaluation Completed	8/1/05	
Design Guidelines Completed	8/1/05	

WORK ANTICIPATED IN NEXT REPORTING PERIOD

In the next reporting period, the modeling will be extended to pipelines of other sizes (in particular, longer lengths) and additional soil conditions. Optimum operating frequencies will be determined using the model, and evaluations will be conducted using the test pipe. Signal processing methods will be finalized and tested on signals from the test pipe. Measurements will be taken with the active and passive CP systems to determine interactions. Programming of waveforms for the contact simulator will be completed. Tests on operating pipelines will be initiated.

CONCLUSIONS

Although still early in the development stage, the IACC method is promising as a monitoring method for third-party contact. Simulations on a buried pipe at a test site have shown that simulated contact is readily detectable. Continued development of the method through selection of operating parameters and signal processing will be key to successful operation on pipelines with significantly longer length.

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