DETECTION OF UNAUTHORIZED CONSTRUCTION EQUIPMENT IN PIPELINE RIGHT-OF-WAYS

QUARTERLY TECHNICAL REPORT

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ABSTRACT

Natural gas transmission companies mark the right-of-way areas where pipelines are buried with warning signs to prevent accidental third-party damage. Nevertheless, pipelines are sometimes damaged by third-party construction equipment. A single incident can be devastating, causing death and millions of dollars of property loss. This damage could be prevented if potentially hazardous construction equipment could be detected and identified before the pipeline was damaged.

The Gas Technology Institute (GTI) is developing a system to solve this problem by using an optical fiber as a distributed sensor and interrogating the fiber with an optical time domain reflectometer. Key issues are the ability to detect encroachment and the ability to discriminate among potentially hazardous and benign encroachment.

The work performed in the first quarter of the project includes development of the Research Management Plan, writing a paper assessing of the state-of-the-art in encroachment and third party damage detection, and development of factors for selecting the optical fiber sensors.

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EXECUTIVE SUMMARY

Natural gas transmission companies mark the right-of-way areas where pipelines are buried with warning signs to prevent accidental third-party damage. Nevertheless, pipelines are sometimes damaged by unauthorized construction equipment. A single incident can be devastating, causing death and millions of dollars of property loss. Detection of construction equipment entering a pipeline right-of-way before it can damage the pipeline would greatly reduce 3rd-party damage.

Using an optical time domain reflectometer (OTDR) to monitor the light reflection properties of an optical fiber buried near the pipeline can provide continuous monitoring of several miles of pipeline from a single location. A long optical fiber, similar to those used in telephone systems, is buried above the pipeline. Periodically, light pulses are sent down the optical fiber. Normally, little light is reflected back to the source. When construction equipment is present, the ground above the fiber is compressed and vibrated. This changes the optical properties of the fiber and some of the light is reflected back to the source where it is detected.

The location of the equipment is determined by measuring the time for the reflected light pulse to return. (It is not necessary for equipment to break the fiber to be detected.) After the equipment leaves, the optical fiber returns to normal. Because potentially harmful encroachment is rare, methods of distinguishing harmful equipment from benign interferences, such as pedestrians and mowing equipment, are critical.

The project will work to 1.) develop the necessary hardware and demonstrate the ability to detect construction equipment near underground pipelines and 2.) develop methods for distinguishing between potentially hazardous and benign intrusions into the right-of-way. At the end of Phase 1, the Gas Technology Institute (GTI) will demonstrate the ability to detect construction equipment on a pipeline right-of-way and to discriminate among signal sources.

The project began in October 2001. The first order of business was to develop a detailed Research Management Plan for Phase 1 including technical, budgetary, and scheduling aspects. The draft was prepared. The final was submitted after making the changes requested by the COR. A Technology Status Assessment describing the state-of-the art in 3rd-party damage detection and right-of-way-encroachment for use on the NETL website was written and approved.

In December, our subcontractor, Nicor Technologies (NT), announced their decision to leave the research business. NT was to be the liaison with its sister company Nicor Gas to

provide the site for the installation of the optical fibers. NT would also provide for the construction equipment and operators for generating encroachment signals. As a result, a site must be selected in the Chicago area by the end of April 2002 for installing the test fibers. It may be possible to work directly with Nicor Gas under a different agreement. GTI considers this to be a minor set back and anticipates little difficulty in obtaining a site along a transmission line.

The ability to detect encroachment is one of the main Phase 1 goals. The ability to detect encroachment depends on the choice of the optical fiber distributed sensor. The literature was reviewed to identify mechanisms that create backscatter in general and stress related backscatter in particular. This information is being used to select candidate optical fibers for initial screening.

The digital oscilloscope, the first part of the custom Optical Time Domain Reflectometer was received. This had been expected to be a long lead-time item.

INTRODUCTION

The overall objective of this project is to develop and demonstrate an optical fiber intrusion detection device that will prevent outside force damage by detecting and alarming when construction equipment is near a pipeline. Such a technology would result in safer and more reliable pipeline systems and solve a long-standing problem of the natural gas industry. Alerting a pipeline company that construction equipment is moving close to its pipe permits immediate action to stop unapproved excavation and potential damage to the pipeline. The proposed system will provide real-time policing of pipelines 24 hours a day, seven days a week. Prevention of third-party damage will reduce public and utility injuries, service interruptions, and repair costs, resulting in a safer, more reliable transmission infrastructure.

Gas transmission pipelines are buried in utility right-of-ways marked with warning signs. These right-of-ways are well maintained. Nevertheless, pipelines are sometimes damaged by construction equipment not owned by the pipeline company. Referred to as third-party damage, it is the major cause of damage to natural gas transmission pipelines (ref. 1). A single incident can be devastating, causing death and millions of dollars in property loss. One highly publicized incident occurred in Edison, NJ, in 1994. Flames shot 125 to 150 meters (400 to 500 feet) into the air near an apartment complex. Nearly 100 people were treated in hospitals as a result of the accident. Damage from the incident exceeded \$25 million (ref. 2).

A cost-effective, continuous monitoring system is required to prevent third-party damage. “One-call” systems and greater legal penalties have reduced, but not eliminated, the number of incidents. A backhoe, trencher, or auger (for digging post holes) can move into the right-of-way, begin excavation, and damage the pipeline in less than 30 minutes. A boring machine can travel beneath the surface of the ground for greater than 30 meters. This type of equipment can damage the pipeline without ever having the aboveground portion of the equipment in the right-of-way.

The approach is to combine existing technologies in a novel way to achieve the required sensitivity to construction equipment and solve the critical problem of minimizing false positives. The use of an optical fiber strand as a distributed sensor has been investigated for many years. Optical time domain reflectometry (OTDR) is a standard telecommunication industry tool for testing fiber optic cables that are hundreds of kilometers long. GTI demonstrated that a fiber optic system with a commercial OTDR can detect construction equipment (ref. 3). The ability to bury a fiber optic cable with a vibratory plow has also been demonstrated (ref. 4). A large number of microprocessor-based signal processing and

recognition techniques exist. Thus, the basic technologies do not need to be developed, but rather modified and extended into a practical system.

Specifically, the technique will use an optical fiber with the techniques of OTDR and signal recognition as a method to provide an alarm when unauthorized construction equipment violates a pipeline right-of-way. The optical fiber would be buried above the pipeline. Light pulses would be periodically sent down the optical fiber. Normally, no construction equipment is near the fiber and little light is reflected back to the source. Construction equipment creates vibrations in the ground. It also causes compression of the soil. When close to the optical fiber, the vibrations and soil compressions stress and/or bend the fiber, changing its light transmission and reflection properties. When this happens, some of the light is reflected back to the source where it is detected. Because the velocity of light in the fiber is known, the location of the piece of equipment is determined by measuring the time for the reflected light pulse to return. It is not necessary for equipment to break the fiber to be detected. The optical fiber returns to normal after the equipment leaves.

To be economical, it will be necessary to monitor many kilometers of pipeline from a single location. Such long distances require a method to measure the location of each encroachment and be able to detect and monitor simultaneously occurring encroachments.

While third-party damage can be devastating, it occurs infrequently—much less than one hit per kilometer of pipeline a year. Every year, many intrusions occur in the right-of-way. Any third-party/interference detection system must be able to distinguish a benign activity from a potentially hazardous one, or the false positive count will be too high and the system will not be accepted.

The largest technical barrier is in developing methods to distinguish and characterize the different signals. Most of these are benign with no possibility of injuring the pipeline. (e.g., mowing the right-of-way, people walking, motorcycle and ATV traffic). In addition, benign background noises (thunder, airplanes) must be distinguished from other sounds. Soil conditions (moisture content and freezing) will vary throughout the year. These variations may affect the signals detected by the optical fiber. Compared to mowing equipment, pedestrians, etc., construction equipment will be large and have characteristic signals. Seasonal and temperature changes will occur slowly and can be eliminated by creating a time-averaged baseline where the time average is long compared to movement of equipment.

EXPERIMENTAL

Construction of the OTDR

In order to collect the required data to detect and then discriminate between encroachments, a custom Optical Time Domain Reflectometer (OTDR) is needed. It must be capable of collecting and storing a waveform digitized as a function of time from each “segment of optical fiber.” The resulting time histories from individual “segments” will be used to detect encroachment, characterize signals created by construction equipment and benign background noise, and discriminate signal sources. The segments are created by sending a narrow light pulse (~10 nanoseconds) into the optical fiber and digitizing the returning signal at 100 MHz. A typical index of refraction for glass optical fiber is 1.5. Thus, the velocity of light in the fiber is 2×10^8 meter/sec. A 100 MHz digitizer collects a data point every 10 nanoseconds. Light travels 2.0 meters in that time. For data analysis purposes, the fiber is divided into two-meter segments, which is the size of a backhoe.

To keep the data analysis speed and memory requirements manageable for the proof-of-concept, a fiber length of 1.0 kilometer will be used. Five hundred data points (segments) are required to monitor each kilometer of fiber and will take five microseconds (corresponding to the roundtrip travel time of one light pulse) to collect. Separating pulses by 10 microseconds or more will keep reflection signals from overlapping. A backhoe moving at 32 kilometers/hr covers 8.9 meters/second. Thus, the high-speed data collection system will be able to collect detailed information on the motion of the backhoe. These arguments can be extended to show that several kilometers could be monitored from one location in a commercial encroachment detection system.

The data collection process can be stated another way. Each light pulse will create a waveform on the digital oscilloscope. The amplitude of this waveform at each point gives information on the activity above that segment of the optical fiber. Collecting a series of waveforms and rearranging the data into amplitude as a function of time for each digitized time increment will give the time history above each segment.

GTI's technical approach is to purchase and assemble as many commercially available components as possible to construct an OTDR. Most, if not all, of the components—laser diode with pulsing circuitry, sensitive detector, high-speed digitizer and large memory—and a computer system capable of collecting and analyzing the data—are commercially available.

Components from National Instruments (NI) were selected because of the ease and flexibility of assembly and programming. A digital oscilloscope has been assembled using:

- NI 5112, 100 MHz, 100 MS/s 8-bit digitizer, dual channel, with 32 MB flash memory per channel
- PXI-1025 Mega PAC rugged portable chassis for PXI cards
- PXI-8170/850 high-performance embedded controller (850 MHz Pentium III) with 256 MB extended memory

A high-speed timing bus on the computer backplane facilitates precise launching and timing of light pulses. GTI's electronic laboratory has all of the tools and equipment needed to assemble the OTDR. GTI has National Instruments' LabVIEW 6.1 Professional Software Package and Signal Processing Toolset, Hi-Q mathematics package, Signal Processing Toolset. The latter provides abilities for joint time-frequency analysis and wavelet analysis, which may prove useful in discriminating signals. GTI also has the latest MATLAB with its signal processing toolbox.

A stable, repeatable light source such as a laser diode or LED, is required. Stability is required to eliminate any fluctuations and prevent normalizing to each light pulse. Variations in light intensity would be interpreted as signals. A stable, high-speed detector with a dynamic range large enough to detect light scattered from the stressed portions of the fiber is also needed. The light source and detector will be selected after the choice of optical fiber(s) is made. A LED-Laser/driver and low-noise light detector may also be purchased. It is anticipated that construction of the light source and light detector will be straightforward. However, it may be necessary to design and construct signal conditioning electronics to achieve a thermal noise floor sufficiently low to detect the returning light signal.

Delivery time on the digital oscilloscope was part of the critical path on the OTDR. Programming the OTDR is now the critical path. The OTDR due date is in June. At this time, no problems are expected.

Optical Fiber Selection

An important component of the detection system is the choice of the fiber used in the cable and its environmental shielding. The goal is to have an optical fiber that is sensitive to stress and vibrations at an affordable price. Environmentally, the cable must be impervious to water (to avoid degrading fiber properties), non-electrically conducting (to avoid damage from lightning strikes), and resistive to abrasion (being chewed by rodents, etc.). At the same time the environmental sheath must not make the system insensitive to the vibrations and stresses being measured.

GTI will evaluate optical fiber sensitivity and durability. GTI will then purchase the most promising distributed optical fiber sensors and bury short sections (100 - 200 feet) of optical fiber cables at GTI headquarters. These cables will be tested for sensitivity and durability to moisture and seasonal variations in soil conditions. From these tests, GTI will identify the one or two most promising fibers for installation above an operating gas transmission pipeline.

Cable lengths above the transmission pipeline site will be 1 kilometer. This length will permit testing of spatial and time resolution, sensitivity to various encroachments and the ability to detect and discriminate among simultaneous events, while limiting the initial signal processing and memory storage requirements of the OTDR. One site selection criteria is the ability to leave the fiber in place for several years with access to GTI. Cables at both sites will remain in place for the duration of the project and their durability to moisture and seasonal variations in soil conditions measured.

The first step in fiber selection was to review the mechanisms that reflect light back to the OTDR, especially those sensitive to stress and vibration. This discussion is given in the section on Results and Discussion. The next steps are to review optical fibers used in other distributed stress sensor applications and compare specifications to commercially available products.

RESULTS AND DISCUSSION

Brief Overview of Optical Fibers

Optical fibers are made from two transparent materials; usually glass, with differing indices of refraction. Index of refraction is the ratio of the speed of light in a vacuum to the speed of light in the material. An optical fiber is formed when a thin core of index n_1 is surrounded by an outer core (cladding) of index n_2 . If the cladding has a smaller index of refraction, and the light is incident on the interface between the two materials at an angle less than the critical angle, total internal reflection occurs. This creates an optical waveguide. Very little energy is lost from the light beam and the beam can propagate for long distances. A jacket can be added around the cladding to provide waterproofing or added strength.

Figure 1. TYPES OF OPTICAL FIBERS

There are two general fiber configurations: single mode and multi-mode. As shown in Figure 1, in a single mode fiber the core is smaller in diameter, while the multi-mode fiber is larger in diameter. In either case, the outside diameters of single- and multi-mode fibers are typically 125 micrometers (or about the size of the human hair). Light may enter a multi-mode fiber at several angles. Some of this light will travel in the waveguide with a minimum of reflections from the core/cladding interface. Light entering at a greater angle will also propagate in the waveguide by making more reflections (higher modes). Because of the extra reflections, the higher modes must travel a greater distance and take longer to transverse the optical fiber. In order to propagate in a single mode fiber, the light wave must enter the fiber nearly parallel to the axis of the fiber. Multi-mode fiber will carry more light than single-mode. On the other hand, if a pulse of light is injected into a multi-mode fiber and the fiber is bent, mode conversion will occur, broadening the pulse. Mode conversion occurs when some of the light is changed from a mode with few reflections to a mode with more reflections.

Figure 2. A HIGHER MODE LIGHT WAVE TRAVELS A LONGER DISTANCE

A continuous light wave can be sent into a fiber and the total light intensity measured as a function of time. If mode conversion occurs because of stresses to the fiber and microbending, variations will be produced in the output that are proportional to the vibrations of the fiber. This is used as a stress measurement technique. Unfortunately for our application, changes everywhere along the fiber are measured simultaneously. Location of the disturbance is not known. In the encroachment monitoring application with fiber lengths of a few miles, multiple events (disturbances to the fiber) will occur simultaneously. The use of OTDR has the potential to independently monitor the simultaneous vibrations.

Scattering Mechanisms

Light is attenuated as it travels down a fiber by several mechanisms. Any process that causes the angle of incidence to exceed the critical angle will cause some of the light to enter the cladding. These processes include bending of the optical fiber and scattering mechanisms. A scattering mechanism absorbs the incoming light and reemits it at all angles. Light reemitted at right angles to the incoming beam will be lost into the cladding. Some of the light is reemitted backwards and returns to the light source. This phenomenon of backscattering is used to detect stress and vibration to the fiber.

Much of the scattering in an optical fiber is caused by variations in the density of the fiber. Variations in density change the velocity of light and thus the index of refraction. Density variations are built into the fiber during its manufacture. These are caused primarily by thermal fluctuations in density and variations in the concentration of dopant materials just before the glass transitions into a solid. Normally, the fiber manufacturer tries to minimize these because they increase the attenuation in the fiber and thereby limit the distance a signal can be sent. Stress, vibrations, temperature change, and acoustic waves induce other density variations. The scattering induced by the density fluctuations can be elastic (no change in the wavelength

between the incoming and outgoing light wave) or inelastic (a shift in the wavelength between the incoming and outgoing light wave).

Rayleigh scattering usually refers to the scattering of light by air molecules. However the term is also applies to scattering from particles up to about a tenth of the wavelength of the light. (Green light has a wavelength of ~ 550 nanometers. Rayleigh scattering off the molecules in air creates the blue sky.) Lord Rayleigh modeled the air molecule as an electric dipole driven by the electric field of the light wave. Rayleigh scattering is elastic because energy of the scattered wave is the same as the incident wave. Lord Rayleigh (ref 5) calculated the scattered intensity from dipole scatters much smaller than the wavelength of light to be:

$$I = I_0 8p^4 N p^2 (1 + \cos^2\theta)/(R^2\lambda^4) \quad \text{eq. 1.}$$

where N = number of scatterers, p = polarizability, R = distance from the scatterer, λ = wavelength of the light, θ = angle of the scattered light with respect to the incoming light. Note that light is scattered in all directions, including directly back on the incoming light.

This equation 1 is for air molecules. Changing the geometry to backscattering in an optical fiber, the attenuation, a, caused by Rayleigh scattering is given by (ref 6)

$$a = 8p^3 (n^2-1) k T\beta/(3\lambda^4) \quad \text{eq. 2.}$$

where β = isothermal compressibility of the glass, T = temperature. For fused silica transitioning at 1500°C, this represents a loss of 1.7 dB/km at 820 nm.

Although equation 2 gives the total attenuation, part of the backscattered light propagates back through the waveguide. The important features to note are the temperature dependence of the backscattering and the very strong wavelength dependence, λ^4 . Decreasing the wavelength by a factor of two, increases the Rayleigh scattering by a factor of 16. Therefore we can adjust the amount of backscattering by the choice of the light source.

For many fiber optic sensor applications, Rayleigh scattering dominates. However, it is also possible to detect light from Raman and Brillouin scattering.

Brillouin scattering is the scattering of light from sound waves in the fiber. From the classical point of view, the acoustic waves locally change the density—i.e. the refraction and compression of the material. From the quantum point of view, the light photons interact with the acoustic or vibrational quanta (phonons). Brillouin scattering is inelastic with energy being gained or lost by the interaction with the moving sound wave. The shift in frequency is small and Brillouin light is difficult to separate from Rayleigh scattering. However, it can be separated

from the original wavelength with special instrumentation including an intense pulsed laser. Brillouin is much weaker than Rayleigh scattering.

Raman scattering, like Rayleigh scattering, depends on the polarizability of the molecules. For polarizable molecules, the incoming light wave (photons) can excite vibrational modes of the molecules, yielding scattered photons that are diminished in energy by the amount of the vibrational transition energies. Because there can be many vibrational modes in a molecule, a spectrum of Raman scattering yields a series of lines at lower frequencies (longer wavelengths) than the incoming light. Such lines are called “Stokes lines.” If there is significant excitation of the vibrational excited states, then it is also possible to detect scattering at higher frequencies. These spectral lines are called “anti-Stokes lines.” Anti-Stokes lines are normally weaker than Stokes lines. However, anti-Stokes lines are a sensitive indicator of temperature. Raman scattering is much weaker than Rayleigh scattering. Raman backscattering can be separated from Rayleigh and Brillouin scattering to improve the signal to noise ratio.

Because of the extra complexities and cost required to detect either Raman or Brillouin scattering, GTI will use microbending and/or Rayleigh scattering to detect encroachment.

There are several other phenomenon and measurement techniques that have the potential of measuring stress and vibrations. As in the case of Raman and Brillouin the added complexity is not justified for our application. Thus they have not been described.

Microbending

Microbending is another method of changing the transmission properties of an optical fiber. In microbending, the curvature of the optical fiber is increased over short distances. This causes some of the light to exceed the critical angle (sometimes as the result of multiple reflections). This results in an increased loss of light in the optical fiber that can be detected by a reduction in the light backscattered from further along the fiber. Wrapping a fiber with a wire or using a fiber with periodic variations in the core diameter can increase the amount of microbending.

Choice of Optical Fibers

As mentioned earlier, simulated encroachment type activities have been detected with commercially available OTDR. These instruments rely on a substantial amount of signal averaging (several minutes) to obtain good signal to noise ratio. Such times are too slow to provide data that will discriminate among encroachments. A greater sensitivity is required to permit faster data collection.

As the quality of optical fibers for communication improves, the scattering features useful for distributed sensor decrease. As new fibers enter the market, the older fibers are displaced.

Based on the above discussion we can begin to select which optical fibers to test. One choice based on low cost and general availability is to use the direct burial optical fibers used by the telecommunication industry. Direct burial has the advantage of having the environmental issues solved. Both a single mode and a multi-mode direct burial fiber will be selected and priced. The bare versions of the same bare optical fibers will also be priced.

An optical fiber “system,” with the trade name of Hergalite, features a fiber helically wrapped with a wire. A helical wire makes the system sensitive to microbending. However, the manufacturer cautions against its use in areas where easy access to the cable is difficult, such as buried near pipe. In many applications, pressure on the cable causes bending in the wire making detection of the source easy. Unfortunately, the set is permanent—that is the wire doesn’t return to its original position when the load is gone. It must be manually reset or replaced. It is possible that the amount of loading of buried Hergalite is too small to cause a permanent set. A small sample will be ordered for evaluation.

Research Management Plan.

The draft “Research Management Plan” was written. The DOE Contracting Officer’s Technical Representative (COR) made suggestions to improve the plan. GTI made the improvements and submitted the final plan. This plan was accepted.

Two items remain from Task 1:

1. Presentation of this material at a kick-off meeting at the NETL Strategic Center for Natural Gas. The time for this meeting has yet to be arranged.
2. Hazardous Substance Plan. No hazardous substances will be used or produced at GTI and the pipeline field site. Because the Hazardous Substance Plan is site specific, GTI will submit the plans after the site has been selected.

Technology Status Assessment.

GTI prepared and submitted a draft report describing the current state-of-the-art of the encroachment detection and impact detection. The DOE COR made suggestions to improve the report. GTI made the improvements. The final version was approved by the COR. With the exception of updates, Task 2 is complete.

Technical Problems Encountered

No technical problems that will impact the ability to perform the project or project schedule have been encountered.

Project Management Problems Encountered

With the loss of the subcontractor, new arrangements must be made for a test site in the Chicago area. GTI expects to have a new arrangement made next quarter and there should be no impact on the project.

As stated in the proposal, GTI plans to hire an electrical/electronics engineer to help with the construction of the custom OTDR, data collection, and associated signal processing. Two highly qualified candidates were identified. Each expressed great interest in the project, but subsequently accepted other jobs. The search continues. With the large number of people laid off in the Chicago area, GTI expects to hire a highly qualified person soon. We still expect to meet all project due dates. However, without the additional engineer the spending rate has been lower than planned this quarter. The work accomplished is commensurate with the expenditure.

Action Requested of Doe NETL Project Manager

There are no action items requested of the DOE COR.

Work Planned For The 1st Quarter Of 2002

The following items are planned for the next quarter:

- Obtain a transmission pipeline site in the Chicago area
- Complete selection and ordering of the optical fibers
- Begin programming the digital oscilloscope to collect successive waveforms, store the data, and create waveforms corresponding to a specific distance along the fiber
- Construct LED/laser diode light source
- Construct light detector.

CONCLUSION

Although the project is in the very early stages, the following conclusions can be drawn:

- The initial assessment of backscattering mechanisms indicates that any of several choices of optical fiber cables and light sources should be suitable for detecting encroachment.
- Although the parts of the project are proceeding more slowly than initially planned, all of the milestone dates will be met.

LIST OF ACRONYMS AND ABBREVIATIONS

COR –	Contracting Officer’s Technical Representative
DOE -	Department of Energy
DSLP –	Digital Sonic Leak Pinpointer
FERC –	Federal Energy Regulatory Commission
FOIDS -	fiber optic intrusion detection system
GPS –	global positioning system
GRI –	Gas Research Institute
GTI -	Gas Technology Institute
IGT –	Institute of Gas Technology
IRNG –	Infrastructure Reliability of Natural Gas
LED –	light emitting diode
NETL -	National Energy Technology Laboratory
NT -	Nicor Technologies
OTDR -	optical time domain reflectometry

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