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

QUARTERLY TECHNICAL REPORT

(January 1 through-March 31, 2002)

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Report Issue Date: April 26, 2002

DOE Contract #: DE-FC26-01NT41160

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Submitted to

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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 would be prevented if potentially hazardous construction equipment could be detected, identified, and an alert given 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 encroachments.

The work performed in the second quarter of the project includes design of the instrument, selection of the key components, and beginning programming of the custom optical time domain reflectometer. Work included an assessment of two other approaches to measuring strain and vibrations in an extended optical fiber sensor.

## TABLE OF CONTENTS



## LIST OF GRAPHICAL MATERIALS

## EXECUTIVE SUMMARY

Natural gas transmission companies mark the right-of-ways 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 a small portion 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.

Because only a small portion of the light is reflected back, most of the light pulse continues along the optical fiber. This means that more than one event (encroachment) can be simultaneously detected. This is critical in busy urban areas where encroachments can occur simultaneously along a long optical fiber. This capability also means that the signals from locations close to railroad tracks and highways can be detected and ignored. In contrast, in some extended optical fiber sensor systems, train and highway traffic dominate the signals and prevent detection of hazardous encroachment.

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. Next a Technology Status Assessment describing the state-of-the art in 3rd-party damage detection and right-of-way-encroachment for use by NETL 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 should be selected in the Chicago area by the end of April 2002 for installing the test fibers. GTI

considers this to be a minor set back and anticipates little difficulty in obtaining a site along a transmission line. During the second quarter of this project (this reporting period) discussions were held with Nicor Gas on their willingness to participate under a different agreement. A meeting will be held April 19 at Nicor Gas. GTI will make a presentation on how Nicor Gas and GTI can work together. We anticipate an answer one week after the meeting.

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 was being used to select candidate optical fibers for initial screening.

This quarter GTI continued the detailed design process and selection of components and optical fibers for the sensors. Programming of the high-speed, digital oscilloscope forming the heart of the Optical Time Domain Reflectometer (OTDR) began. This process is required because of the requirement to characterize encroachment signals. The data and signal processing required is different from that attainable in commercially available OTDRs.

# 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 could 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.

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 encroachment 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.

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. This is especially true in urban areas where the pipeline passes under railroads and highways. Techniques that monitor the optical fiber as a whole (for example interferometric), can be dominated by signals from a slow moving train and not detect hazardous encroachment.

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 $2 \times 10^8$ 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 approximately 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 of the optical fiber.

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, 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 64 MB flash memory
- 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, Hi-Q mathematics package, and 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.

Delivery time on the digital oscilloscope was part of the critical path on the OTDR. Programming the OTDR is now the critical path. One of the project deliverable due dates is for the custom OTDR. We expect to meet this June 13 due date.

Other components in the OTDR include:

1. A stable, repeatable high-speed light source such as a laser diode or LED. Stability is required to eliminate any fluctuations and minimize the amount of normalization to each light pulse. Variations in light intensity would be interpreted as signals. Many diode lasers have a separate output giving the intensity of the pulse which can be used as trigger for the oscilloscope and to normalize input pulse amplitudes.
2. A highly reproducible pulser (10 nanoseconds or shorter)
3. A stable power supply to drive the light source
4. A stable, high-speed detector with a dynamic range large enough to detect backscattered signals from the stressed portions of the fiber
5. Low noise amplifier and band-pass filter to amplify the signals from each detector
6. An optical coupler to inject the pulse from the light source into the optical fiber with minimal light transferring directly to the returning pulse detector. The coupler also splits the returning light pulse in two, permitting its detection.
7. Attenuator at end of fiber to minimize the amplitude of the reflected signal
8. Low-loss connectors

Figure 1 is a schematic of the custom OTDR showing the critical components. The requirements for each component are known. Specific parts are being selected and ordered next quarter.

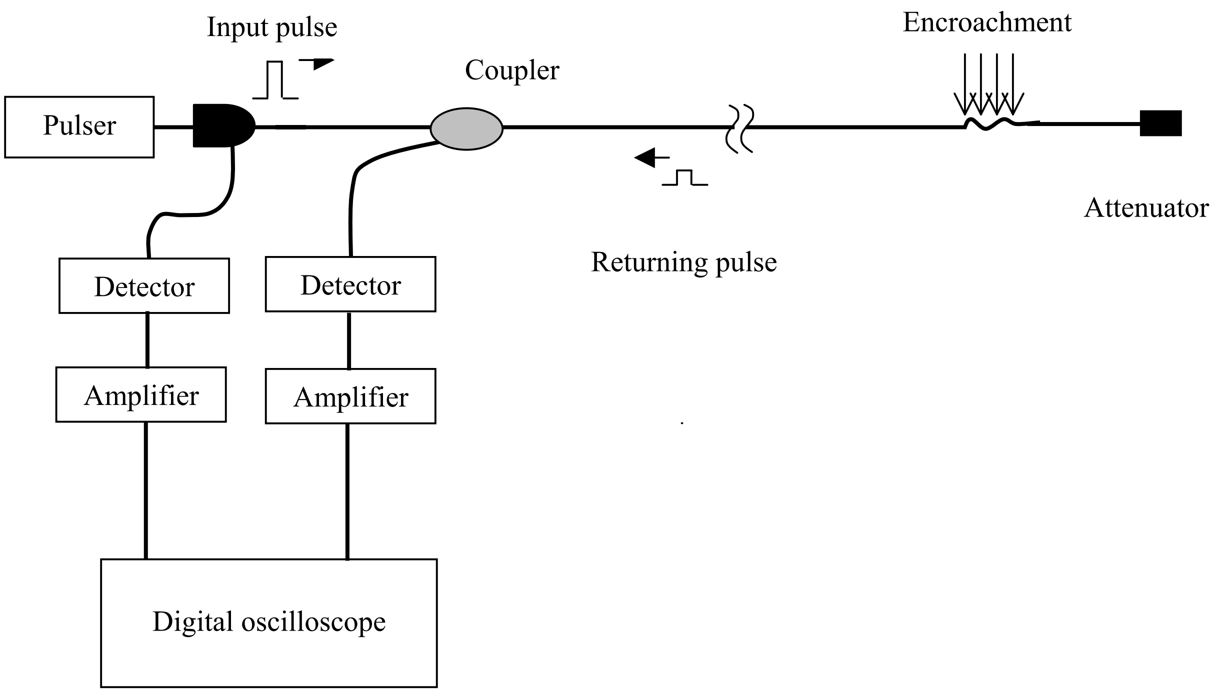


Figure 1. SCHEMATIC OF THE CUSTOM OTDR

Optical Fiber Selection

An important component of the detection system is the choice of the optical fiber used as the sensor 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. Part of the project is to evaluate optical fiber sensitivity and durability.

Cable lengths above the transmission pipeline site will be approximately 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.

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 step was to compare our needs to commercially available products.

Optical fibers are commercially available because of the telecommunication market. The focus of that market is faster data transmission rates and, therefore, fibers with less sensitivity to stress, strain, and vibration. The optical fiber manufacturers work hard to minimize sensitivity to vibration and stress. They prominently mention this in their advertising. Our application calls for fiber that is sensitive to vibrations. The knowledge of how to minimize sensitivity to stress and vibration implies the knowledge to make a better sensor. This issue was discussed with several fiber manufacturers and suppliers at the Optical Fiber Conference in Anaheim the week of March 18, 2002. No one admits to having fiber that is more sensitive to vibrations. A few are thinking of making distributed sensors—but the market size appears too small for much enthusiasm on their part.

Four fibers have been selected as candidates as the optical fiber sensor. The initial goal is to demonstrate the ability to detect encroachment. Choices of fibers were made primarily on the prospects for good sensitivity. The fibers and the reasons for there selection are given below.

A version of Hergalite has been purchased and should be delivered near the beginning of May. A wire is spirally wound around a multi-mode optical fiber. When stress is applied to the cable, the spiral wound wire increases the microbending in the optical fiber. This type of fiber was used in the project that detected a rubber-tired backhoe with a low-cost OTDR. Three hundred meters has been purchased at a cost of $1.20 per meter. (The manufacturer cautions against its use in areas where easy access to the cable is difficult, such as buried pipe, because the wire can be permanently deformed. When the set is permanent—the wire doesn't return to its original position when the load is gone. It is possible that the amount of loading of buried Hergalite is too small to cause a permanent set.)

A single mode fiber will be ordered from Fibercore Limited. This fiber has a core surrounded by a cladding (125 μm). It has a "single acrylate coating" making the fiber diameter 250 μm. This fiber has a numerical aperture of 0.10 – 0.14. It has a wavelength design frequency of ~650 nm, meaning that wavelengths of 650 or longer will propagate as a single mode. This feature will permit using a range of wavelengths in single mode to adjust the Rayleigh backscattering. The price for SM600 is $2.36 per meter for lengths of 1.0 kilometer or more. Cabling for moisture protection is extra. The SM600 is in stock. We are waiting for pricing on the cabling.

A multimode fiber, H-PCF sub code HS-20/06 will be ordered from Sumitomo Electric. This fiber has a larger core diameter (200 μm) surrounded by a hard polymer cladding (230 μm), which in turn is surrounded with a protective coating (0.5 mm diameter). The larger diameter should make this fiber more sensitive to mode conversion during vibration and stress. This feature will permit using a range of wavelengths in multi-mode. We are waiting for pricing and delivery times. This fiber has a numerical aperture of 0.4.

The fourth optical fiber under consideration is Corning® PureMode™ HI 980. This is a single mode fiber at wavelengths of 980 nm and longer. It has a numerical aperture of 0.20. Corning advertises this fiber as "offering reduced bend attenuation due to its high core index of refraction." It has the least attenuation of the fibers under consideration. This fiber is $3.25 per meter in lengths of 1.0 kilometer or more. Water resistant coating and connectors are extra. We will obtain pricing and delivery times for the coated fiber.

## 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. 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.

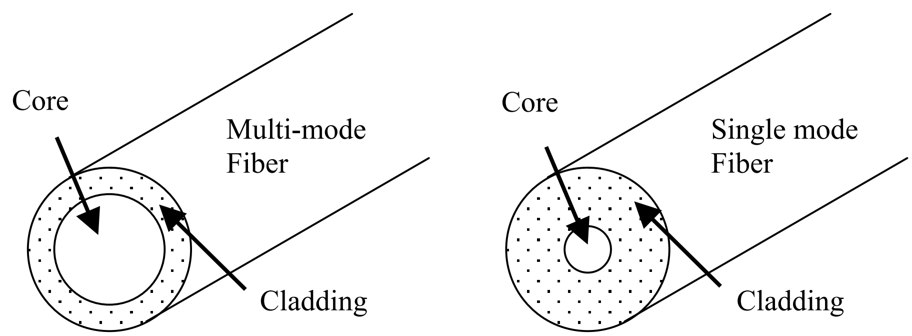


Figure 2. TYPES OF OPTICAL FIBERS

There are two general fiber configurations: single mode and multi-mode. As shown in Figure 2, 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 cladding 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. See Figure 3. 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, both attenuating and 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.

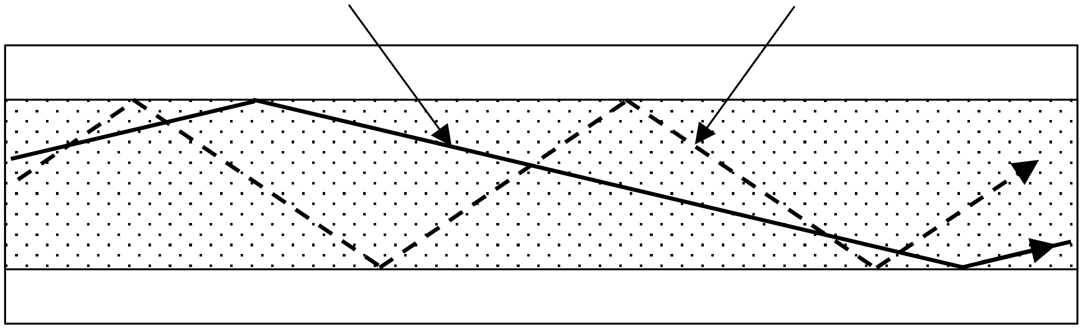


Figure 3. A HIGHER MODE LIGHT WAVE TRAVELS A LONGER DISTANCE

Mode conversion can be effective as a sensing mechanism. 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 outputs 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. 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 #1

Light is attenuated as it travels down a fiber by several mechanisms. 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. Unintentional 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. The predominant use of optical fibers is in telecommunication. Thus, the fiber manufacturer tries to minimize scattering losses 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 often refers to the scattering of light by air molecules. However the term 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.) It is elastic because energy of the scattered wave is the same as the incident wave. Lord Rayleigh modeled the air molecule as an electric dipole driven by the electric field of the light wave. The scattered intensity from dipole scatterers much smaller than the wavelength of light (ref 5) is:

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

where N = number of scatterers, p = polarizability, R = distance from the scatterer, $\lambda$ = wavelength of the light, $\theta$ = 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.

Equation 1 is for air molecules. Changing the geometry to backscattering in an optical fiber, the attenuation, $\alpha$, caused by Rayleigh scattering is given by (ref 6)

$$\alpha = 8\pi^3\, (n^2\text{-}1)\, k\, T\beta/(3\lambda^4) \qquad \text{eq. 2.}$$

where $\beta$ = 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, $\lambda^4$. 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. Brillouin scattering can be used to measure stress in the optical fiber. Ando Corporation makes an Optical Fiber Strain Analyzer, model AQ8603. It is a sophisticated OTDR and costs ~$130,000. Each data trace requires 2 minutes to collect, making it too slow to characterize encroachment signal. Ando has offered to demonstrate this unit at GTI once the optical fiber is installed.

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. The 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 Raman and Brillouin scattering, GTI will use microbending and/or Rayleigh scattering to detect encroachment.

There are several other phenomenon and measurement techniques (mostly discrete sensors) 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.

Scattering Mechanisms #2: Minimum Rayleigh Scattering in a Glass Fiber.

This quarter we found a second treatment of Rayleigh scattering that gives the theoretical minimum possible amount of Rayleigh scattering in glass optical fibers. Many commercial optical fibers are close to this limit. The advantage of this analysis is it gives the minimum signal level we must be able to detect. Which in turn provides guidance on the light source wavelength and power level and on the detector sensitivity.

John M. Senior, Optical Fiber Communications, Prentice/Hall International 1985, pp 69-70 gives an equation giving the minimum Rayleigh scattering coefficient as:

$$\gamma_R = 8\pi^3 n^8 p^2 \beta_c k T_F / 3\lambda^4 \qquad \text{eq. 3}$$

where—

| | |
|---|---|
| $\gamma_R$ = | Rayleigh scattering coefficient |
| n = | index of refraction of the fiber core [1.46] |
| p = | average photoelastic coefficient [0.286] |
| $\beta_c$ = | isothermal compressibility at a fictive temperature $T_F$ [$7 \times 10^{-11}$ m$^2$ N$^{-1}$] |
| k = | Boltzmann's constant [ $1.381 \times 10^{-23}$ J K$^{-1}$] |
| $T_F$ = | The fictive temperature, which is the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature. [1400 K] |
| $\lambda$ = | Wavelength of the incident light. |

This scattering is caused by index fluctuations caused by the freezing-in of density inhomogeneities. The inhomogeneities are fundamental and cannot be avoided. The values given in [ ] are for silica. Substituting the values in brackets into equation 1 gives:

$$\gamma_R = 1.895 \times 10^{-28}/\lambda^4 \ \ \text{m}^{-1} \qquad \text{eq. 4}$$

The Rayleigh scattering coefficient is related to the transmission loss factor, $\xi$

$$\xi = \exp(-\gamma_R L) \qquad \text{eq. 5}$$

where L = length of the fiber. The attenuation due to Rayleigh scattering in dB km$^{-1}$ is given by:

$$\text{Attenuation} = 10 \log_{10} (1/\xi) \qquad \text{eq. 6}$$

For example at a wavelength of 0.63 µm, $\gamma_R$ =1.199 x 10-3 m$^{-1}$, $\xi$ = 0.301, and the attenuation, $\alpha_R$, = 5.2 dB km$^{-1}$

The attenuation can also be expressed as $\alpha_R$ = 10 log10 ($P_i$/ $P_o$). $P_i$ is the input light power (watts) and $P_o$ is the output light power at the end of the fiber. For 2.0 meters of fiber and a wavelength of 0.63 µm

$$P_o = P_i 10^{-\alpha R/10} = P_i 10^{-5.2 \times 0.002/10} \ P_i 10^{-0.00104} = 0.997608 P_i$$

The amount of scattered light in a 2.0 meter section of fiber is (1-0.997608) $P_i$ = 0.0024 $P_i$. This value gives the upper limit on the minimum backscattered light because only part of the light is scattered into the fiber. For a fiber with a core index of n= 1.46 and a cladding index of 1.40, the critical angle is $\theta$ = arcsin(1.40/1.46) = 73.5 degrees as measured from the normal to the core/cladding interface.  90 – 73.5 degrees = 16.5 degrees.  Using the angular dependence in equation 1, about 10% of the Rayleigh scattering is reflected back to the source.

Therefore, for a fiber with the lowest loss Rayleigh scattering at 0.63 μm and a 2-meter section of glass fiber, 0.00024 of the input power is reflected back to the source.  If the input power (light) is 100 μwatts, 0.024 μwatts (24 nanowatts) will be reflected back.  Detectors can measure down to a few nanowatts of light power.  This information will be used to select the power output of the light sources.

As described above, Rayleigh backscattering is sensitive to wavelength, with more scattering from shorter wavelengths.  Shorter wavelengths also mean more attenuation. Therefore we will have to make tradeoffs between sensitivity and range.

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.

Demonstration of Alternate Approaches

Two commercial products will be demonstrated and evaluated at GTI.  There are Ando Corporation's Brillouin scattering Optical Fiber Strain Analyzer, model AQ8603 and Future Fiber Technologies third party interference detection system.

Future Fiber Technologies is marketing an optical fiber sensor technology for use in monitoring disturbances to optical fibers.  One application is for right-of-way encroachment detection.  Based on FFT's Australian patents, the technique monitors the entire fiber by injecting a continuous light source into the fiber and utilizing mode conversion of light at locations where there is a disturbance.  Disturbances to the fiber cause some of the light to change modes.  Different modes travel at different velocities.  When recombined at the detector, the modes interfere causing voltage fluctuations related to the vibrations.  The total amplitude is monitored at as a function of time in the frequency range of 0 to 100,000 Hz.  The major drawback to this technology is it does not separate or distinguish simultaneous events.  If we monitor many kilometers of pipe in noisy environments, this will be an issue because of the nonhazardous encroachments and passage near railroads and highways. A second technique, requiring access to both ends of the fiber is used to locate the dominant signal. GTI is in the process of signing a non-disclosure agreement so the equipment and technique can be demonstrated at GTI.

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 is 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 Issues

With the loss of the subcontractor, new arrangements must be made for a test site in the Chicago area. GTI had hoped to have an agreement in place with Nicor by the end of March. 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 planed to hire an electrical/electronics engineer to help with the construction of the custom OTDR, data collection, and associated signal processing. This process took longer than anticipated. A highly qualified person with much experience in programming and digital signal processing was hired February 18. He will be part-time until the middle of May. He will come up to speed in programming in LabVIEW and in the use of the new digital oscilloscope with most of his time charged to other projects. We still expect to meet all project due dates. However, without the additional engineer the spending rate has been lower than planned. The work accomplished is commensurate with the expenditure.

GTI attended the Optical Fiber Conference 2002 in Anaheim the week of March 18, 2002. All expenses were charged to the GTI cofunding portion of the project. Several relevant optical fibers, light sources, and other components were identified. Because of this conference, several purchasing decisions were delayed into the early part of the 2$^{nd}$ quarter of 2002. The knowledge gained was well worth the slight delay.

Action Requested of Doe NETL Project Manager

There are no action items requested of the DOE COR.

Work Planned For The 2$^{nd}$ Quarter Of 2002

The following items are planned for the next quarter:

- Obtain a transmission pipeline site in the Chicago area
- Install optical fibers at the test site
- Complete selection and ordering of the optical fibers
- Complete 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
- Complete assembly of the OTDR.

# 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 should 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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