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

FINAL TECHNICAL REPORT

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RESEARCH SUMMARY

Title: Detection of Unauthorized Construction Equipment in Pipeline Right-of-Ways

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Objective:
The objective of this program was to develop and demonstrate the ability of an optical fiber intrusion detection device to prevent outside force damage by detecting and alarming when construction equipment is near a natural gas pipeline.

Technical perspective:
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. The industry currently monitors pipelines with weekly over flights with small aircraft or walking patrols.

An optical fiber intrusion detection device could be used to detect such unauthorized construction equipment. 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 would 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. This same technology could be adapted to monitor critical perimeters at compressor stations and custody transfer points.

Technical Approach:
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, a small amount of light is reflected back to the source from each part of the fiber. When construction equipment is present, the ground above the fiber is compressed and vibrated. This changes the optical properties of the fiber and, therefore, the amount of light 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.) The optical fiber sensor reverts to normal after the equipment leaves. It should be possible to monitor a few miles of pipeline from a single location. A modified OTDR technique was selected as the best approach because of its ability to precisely determine the location of an encroachment and its ability to separately detect and evaluate simultaneously occurring events on the same sensing fiber. A custom instrument is required that is more sensitive and processes the returning light differently than commercially available optical time domain reflectometers (OTDR) used to test fiber optic communication cables. Steps to achieve the project objective were to design and build an instrument capable of detecting construction equipment, to develop methods for distinguishing between potentially hazardous and benign intrusions into a pipeline right-of-way, and to demonstrate the practicability of the approach to NETL and the natural gas industry.

Results:
A high-sensitivity, rapidly responding custom optical time domain reflectometer (OTDR) was designed and built to generate, collect, and analyze the light signals created by encroaching construction equipment. During the evolution of this instrument, the sensitivity was increased by a factor of roughly 1000. In combination with the most sensitive optical fiber, the custom OTDR can detect static loads on the fiber as small as 0.2 pounds. The spatial resolution of the custom OTDR was ± 2 meters or ± 10 meters depending on the diode laser used. The spatial resolution did not affect the proof-of-concept.

A method of collecting a time series of light intensity variations from a selected 2 or 10-meter section of fiber was developed and implemented. This capability is required to distinguish benign from hazardous encroachments. The custom OTDR is capable of detecting changes in the light intensity at frequencies up to 5 Hz. The upper limit on frequency response was caused by limitations in the software package used. Other methods of measuring the frequency response of the technique show that light fluctuations in access of 50 Hz can be detected.

An advantage of the OTDR method is its potential for independently monitoring simultaneously occurring encroachment. This capability was demonstrated.

Optical fibers were evaluated to identify those most sensitive to stress and vibrations. Hergalite® proved to be the most sensitive fiber. Hergalite is made from a standard 50/125-micron multi-mode communication optical fiber that is spirally wrapped with a fine plastic line. The plastic line increases the microbending in the optical fiber when soil stress and vibrations are present. The increased microbending causes greater changes in the light returning to the detector. Selected fibers, including Hergalite were installed along an operating ANR Pipeline (El Paso Gas) transmission pipeline. The fibers were installed at depths ranging from 6 to 24 inches in a 1700-foot long loop. Part of the loop passes over the pipeline.

The method of burying the fiber impacts the sensitivity of the technique. Detection of a small vehicle with the fiber buried 4 inches depth was achieved. Projections show larger vehicles would be detected at greater depth. Ongoing improvements in the method of burial should improve the sensitivity.

Project Implication:
The basic concept of using optical time domain reflectometry with an optical fiber buried above the pipeline to detect encroachment of construction equipment into the right-of-way works. Sufficiently rapid time response is possible, permitting discrimination between encroachment types. Additional work is required to develop the system into a practical device.

ABSTRACT

The leading cause of incidents on transmission pipelines is damage 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 is hit. Currently there is no method for continuously monitoring a pipeline right-of-way. Instead, companies periodically walk or fly over the pipeline to find unauthorized construction activities.

Gas Technology Institute (GTI) is developing a system to solve this problem by using an optical fiber buried above the pipeline as a distributed sensor. A custom optical time domain reflectometer (OTDR) is used to interrogate the fiber. Key issues in the development of this technology are the ability to detect encroachment and the ability to discriminate among potentially hazardous and benign encroachments. Advantages of the reflectometry technique are the ability to accurately pinpoint the location of the construction activity and the ability to separately monitor simultaneously occurring events.

The basic concept of using OTDR with an optical fiber buried above the pipeline to detect encroachment of construction equipment into the right of way works. Sufficiently rapid time response is possible; permitting discrimination between encroachment types. Additional work is required to improve the system into a practical device.

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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 contact the pipeline would greatly reduce third-party damage.

An optical time domain reflectometer (OTDR) monitoring the light reflection properties of an optical fiber buried near the pipeline could 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, a small amount of light is reflected back to the source from all along the fiber. The amount of reflected light is monitored at the source—with the advantage of only needing access to one end of the fiber. When construction equipment is present, the ground above the fiber is compressed and vibrated. This changes the optical properties of the fiber and the amount of the light that is reflected back to the source/detector.

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. The optical fiber reverts to normal after the equipment leaves. Potentially harmful encroachment is rare; therefore, methods of distinguishing harmful equipment from benign interferences, such as pedestrians and mowing equipment, are critical.

Only a small portion of the light is reflected back from each portion of the fiber. Thus, most of the light pulse continues along the optical fiber, so that more than one encroachment event can be detected at the same time. This is critical in busy urban areas where encroachments can occur simultaneously along a long optical fiber. This capability also means that signals from locations at railroad tracks and highways can be distinguished from simultaneously occurring hazardous activities and ignored. In contrast, in some extended optical fiber sensor systems, train and highway traffic dominate the signals and prevent detection of a hazardous encroachment.

This project was to perform proof-of-concept. If successful, development of a commercial system would be developed in follow-on work. Work in this project was to 1) Develop the necessary hardware and demonstrate the ability to detect construction equipment near underground pipelines, 2) Develop methods for distinguishing between potentially hazardous and benign intrusions into the right-of-way, and 3) Demonstrate the ability to detect construction equipment on a pipeline right-of-way and to discriminate among signal sources.

In order to provide sufficient sensitivity to detect the encroachments and to manipulate the data to discriminate among sources, a custom OTDR was required. Commercially available units do not meet our needs in terms of sensitivity and how data is processed. A key to the encroachment detection technique was substantially increased sensitivity and data acquisition speed over conventional OTDRs used to test optical communication fiber. This required special attention to laser power and stability, detector sensitivity and stability, and instrument noise.

GTI designed a custom OTDR using a digital oscilloscope and a combination of commercially available diode lasers, photodetectors, and custom high-speed laser drivers and amplifiers. The instrument underwent several design changes to improve the sensitivity and speed of data collection. The laser diode and high-speed electronics can create the 10-nanosecond long light pulse required for 6-10-foot spatial resolution. The Hergalite® fiber has proven the most sensitive. We have proven that the technique can detect simultaneously occurring events. A series of improvements were made to the technique which have increased its sensitivity from 1) Not being able to detect any load on the fiber, through 2) Detecting a few pounds with signal averaging for 10 seconds, through 3) Detecting fractions of a pound with frequency variations of a few Hertz, to 4) Detecting static weights as small as 0.2 and load variations with frequencies of five Hertz, and to 5) Detecting a small SUV rolling over a section of buried fiber.

As this project progressed, brighter diode lasers were developed and commercialized. Application at brighter lasers requires high-current amplifiers that are fast enough to create 10 nanosecond long pulses. The speed of currently available high-current amplifiers limits the technique and required increasing the pulse width to 50 nanoseconds in order to use the new diode laser. This increased our spatial resolution from 2 to 10 meters. However, this was not a problem for the proof-of-concept measurements because location of the piece of construction equipment was not the issue.

ANR Pipeline, a division of El Paso Gas, supplied a test site along an operating transmission pipeline in the Chicago area. They also donated installation of the fiber. ANR Pipeline and GTI jointly planned the installation of optical fiber distributed sensors at the site. The fiber was installed in a loop of 1700 feet, with fiber buried from 6 to 24 inches deep. Four types of fiber were installed during the week of January 6, 2003.

Tests on the best method of installing the fiber to maximize sensitivity are being conducted at GTI. It is possible to detect one wheel of a 3000-pound SUV at depths greater than 4 inches. Changes in installing the fiber are expected to increase the depth of detection.

A conceptual design of a Phase 2 OTDR was made using currently available components. This OTDR would be close to a unit that could be commercialized. Component costs for the unit are $2000. The costs of the two most expensive components (the diode laser and the photodetector) are expected to decrease with time. This price is less than the original estimate of $15,000 for the OTDR. The estimate does not include the fiber or fiber installation.

Operations Technology Development and the Gas Research Institute cofunded this project. The project completion date for that cofunding is 3 months later than for the DOE NETL portion. An updated report will be written at the completion of the cofunded work covering the entire project.

INTRODUCTION

The overall objective of this project was 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 would 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. Construction companies are required by law to phone a highly publicized number and have the location of the buried utility pipes marked, before beginning construction. 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 injured and 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 more than 30 meters. This type of equipment can damage the pipeline without ever having the above ground portion of the equipment in the right-of-way.

The approach was to combine and improve upon existing technologies in a novel way to achieve the required sensitivity to construction equipment and solve the critical problem of minimizing false positives. An optical fiber had been successfully used in several applications as a distributed sensor. Optical time domain reflectometry (OTDR) is a standard telecommunication industry tool for testing fiber optic cables that are hundreds of kilometers long. The Gas

Research Institute[1] (GRI) demonstrated that a fiber optic system with a commercial OTDR with a long averaging time 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 did not need to be developed, but rather modified and extended into a practical system.

Specifically, the technique uses 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 into the optical fiber. Even though no construction equipment is near the fiber, a small amount of light is reflected back to the source from everywhere along the fiber. Construction equipment creates vibrations and compressions in 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, the amount of the light reflected back to the source it is changed. 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 hit or 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 per year. Every year, many benign 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 a few 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 short section of fiber—e.g. near a slow moving train—and not detect a simultaneously occurring hazardous encroachment at another location.

The largest technical barriers were in developing enough sensitivity to detect encroachment and the ability to discriminate among different signals. The latter is important

[1] The Gas Research Institute and the Institute of Gas Technology combined in April 2000 to form the Gas Technology Institute.

because most encroachments are benign with no possibility of injuring the pipeline. (e.g., mowing the right-of-way, people walking, motorcycle, and ATV traffic). Soil conditions (moisture content and freezing) will vary throughout the year. These variations may affect the signals detected by the optical fiber. Compared to benign encroachments, 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" are 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 2-meter segments, which is approximately the size of a small backhoe.

To keep the data analysis speed and memory requirements manageable for the proof-of-concept, a fiber length of approximately 0.5 kilometer was used. Five hundred data points (segments) are required to monitor each kilometer of fiber and will take five microseconds 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, a 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 construction 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 construction activity history above each segment of the optical fiber.

GTI's technical approach was to purchase and assemble as many commercially available components as possible to construct an OTDR. Many of the components, such as a high-speed digitizer and large memory, and a computer system capable of collecting and analyzing the data, were commercially available.

Components from National Instruments (NI) were selected because of the ease and flexibility of assembly and programming. A digital oscilloscope was 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

The ocilliscope was programmed using National Instruments' LabVIEW 6.1 Professional Software Package. Figure 1 is a schematic of the custom OTDR showing the critical components.

Other components in the custom OTDR included:

1. A stable, repeatable high-speed laser diode light source. Stability was required to eliminate any fluctuations and minimize the amount of normalization to each light pulse, as variations in light intensity could be interpreted as encroachment signals. Many diode lasers have a separate output giving the intensity of the pulse, which can be used to trigger an oscilloscope and normalize input pulse amplitudes.
2. A highly reproducible pulse generator
3. A stable power supply to drive the diode laser and create light pulses of 10-50 nanosecond duration with a timing between pulses of at least ~10 microseconds.
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 amplifiers 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 reflected light in two, permitting its detection.
7. An attenuator at the end of the fiber to minimize the amplitude of the reflected signal
8. Low light-loss optical connectors

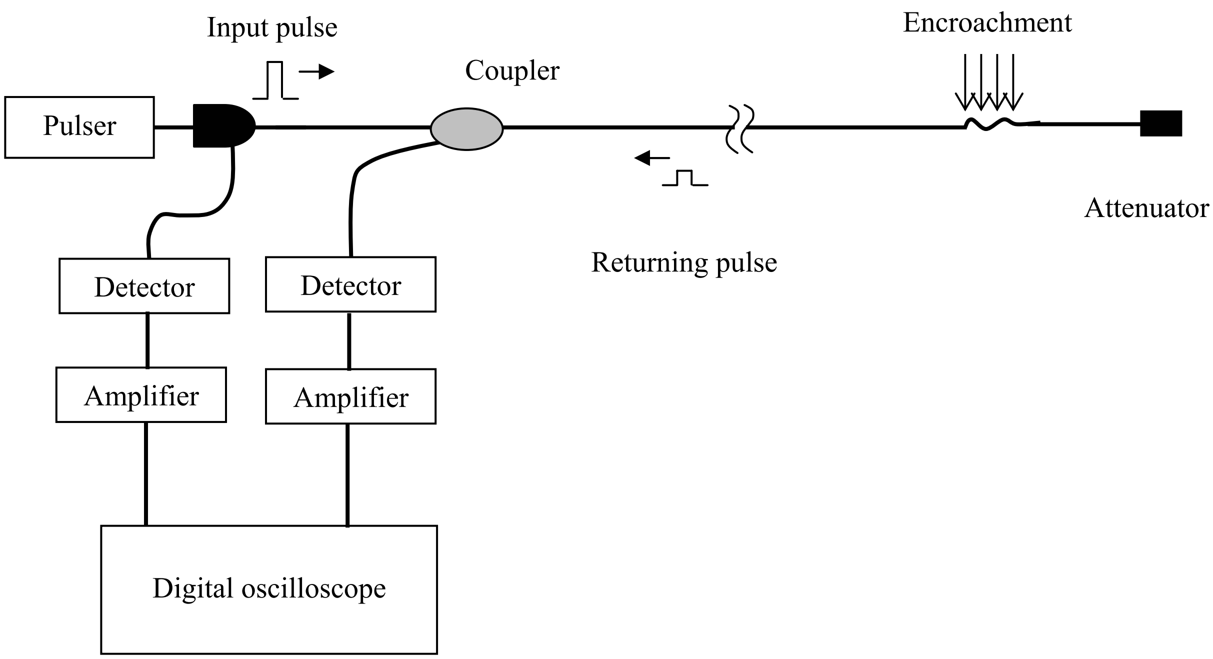

Figure 1. Schematic of the custom OTDR

Laser Diode Driver and Detector Electronics

The final version of the GTI OTDR sends a 10 to 50-nanosecond light pulse into the optical fiber every 40 microseconds and digitizes the returning signal at 100 MHz. A stable, repeatable light source was used to minimize fluctuations in the light pulses that might be interpretated as signals. The original 690 nm diode laser which was capable of delivering 10.5 mW of continuous light power into the fiber was replaced with a 840 nm diode laser capable of delivering 400 mW of continuous light power into the fiber. That required modification of GTI's original circuitry that created repeatable pulses for driving the diode laser. We were not able to find a transistor with both enough current capacity to drive the laser and high enough speed to create 10 nanosecond long pulses. A compromise was made in order to use the new laser—the pulse width was increased to 50 nanoseconds. This meant that our spatial resolution was now 10 meters instead of 2 meters. This was not an issue for the proof-of-concept data collection because the location of the encroaching construction equipment is known. It is the detection of a time varying signal that is important. It is expected that transistor technology will evolve and achieve the higher speed.

Figure 2 shows the latest version of the hardware. The three boxes in the center of the photograph house the custom electronics. The lower box contains the diode laser and its drive circuitry and power supply. The upper box houses the photodetector. Its power supply is on the right-hand side of Figure 2. The optical coupler is in the middle box. Figure 3 is a photograph of the new diode laser.

Figure 2. Photograph of the custom OTDR.

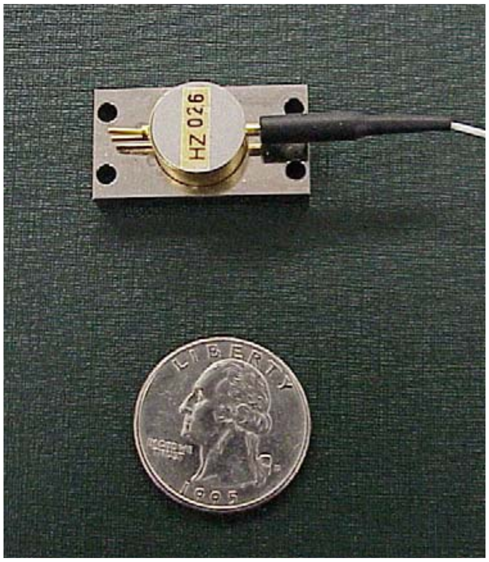

Figure 3. Photograph of diode laser

Near the end of the project, we made a conceptual design of a "Phase 2" custom OTDR that could be commercialized using the latest commercially available parts. The new design included the higher-power diode laser and driver, the photoavalanche detector, a digital signal processor (DSP) to analyze the light signals, a communication module, power supplies, and the fiber optic coupler. The cost of the components including a communication module is $2000. The original estimate made in the Phase 1 proposal was $15,000. The "new OTDR" would fit in one of the three boxes in the center of Figure 2.

OTDR Program

The function of the OTDR is to collect data generated by encroachment from the optical fiber installed in the ground above the pipeline. Conceptually, the fiber is divided into two 10-meter long segments. The resulting time histories from individual segments would be used to detect encroachment, characterize signals created by construction equipment and benign background noise, and discriminate signal sources. In a practical instrument, the returning light would be monitored for changes. When changes are detected for a section of fiber, that section would be monitored to determine the nature of the encroachment. For the proof-of-concept measurements, we could select two positions along the fiber and obtain and record the resulting time-varying waveform. This data is then stored for later analysis.

Optical Fiber Selection

An important component of the detection system was 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 allow the system to remain sensitive to the vibrations and stresses being measured. For the proof-of-concept measurements, sensitivity had priority over durability.

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 over longer and longer distances. Therefore, fibers with less sensitivity to stress, strain, and vibration are desired. 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 admitted to having fiber that was more sensitive to vibrations. A few were thinking of making distributed sensors—but the market size appeared too small for much enthusiasm on their part.

Four fibers were selected as candidates as the optical fiber sensor. The initial goal was 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 their selection are given below.

A version of Hergalite®, a multi-mode optical fiber (50 μm core/125 μm cladding) spirally wound with a "plastic wire," was selected. When stress is applied to the cable, the spiral wound plastic fiber increases the microbending of the optical fiber. Three hundred meters were purchased at a cost of $1.20 per meter. (The actual length delivered was 350 meters.) The manufacturer cautioned 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 plastic wire does not return to its original position when the load is gone. This was not a problem during any of our testing. It is possible that the amount of loading on buried Hergalite was too small to cause a permanent set.

A single-mode fiber was obtained from Fibercore Limited. SM600 has a wavelength design frequency of ~650 nm, meaning that wavelengths of 650 nm or longer will propagate as a single-mode. This feature permitted using a range of wavelengths in single-mode to adjust the amplitude of Rayleigh backscattering (Rayleigh backscattering increases with shorter wavelengths). This fiber has a core surrounded by a cladding (125 μm) and a "single acrylate coating," making the fiber diameter 250 μm. This fiber has a numerical aperture of 0.10 – 0.14. The price for SM600 was $2.36 per meter for lengths of 1.0 kilometer or more, cabling for moisture protection is extra. A source of jacketed Fibercore SM600 was found, however, it was too expensive to be practical. It was not purchased.

The third optical fiber that was tested, Corning® 62.5/125 μm, is part of Corning's line of standard multi-mode fibers for use in indoor applications. It is inexpensive at~$0.15/foot when incased in a 2.9 mm diameter jacket. The jacket contained the optical fiber and a sheath of aramid fibers to provide strength to the cable.

A multi-mode fiber, with a core diameter of 200 μm was also selected. The larger diameter should make this fiber more sensitive to mode conversion during vibration and stress. This feature would permit using a range of wavelengths in multi-mode. The manufacturer was unresponsive in providing pricing and delivery times. This fiber was replaced with Corning® 50/125 μm, which is similar to the optical fiber in the Hergalite. The Corning 50/125 μm was packaged in a similar manner to the Corning 62.5/125 μm fiber.

Corning® PureMode™ HI 980, Corning® SMF-28™, and a polarization maintaining fiber were other candidates that were not selected.

Corning® PureMode™ HI 980 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 was $3.25 per meter in lengths of 1.0 kilometer or more. Water resistant coating and connectors were extra.

Corning® SMF-28™ is a single-mode fiber commonly used in the telecommunications industry. It is optimized for use in the 1310 nm window. Its chief advantages were its low attenuation and low price.

Another possibility was a polarization maintaining fiber. Corning manufacturers a number of them with a range of cutoff wavelengths. Light propagates in two perpendicular polarizations. Polarization maintaining fibers are pre-stressed so that the two polarizations travel independently with minimum cross talk. If the fiber is stressed some conversion from one polarization to the other occurs. If light of a single polarization is used, any light of perpendicular polarization indicates stress. Because of the added complexities of the polarization detection, we elected not to include this type of 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 by surrounding a thin core of index n_1 with 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 thin buffer is often added around the cladding to provide waterproofing and additional strength. Many jacketing materials are available.

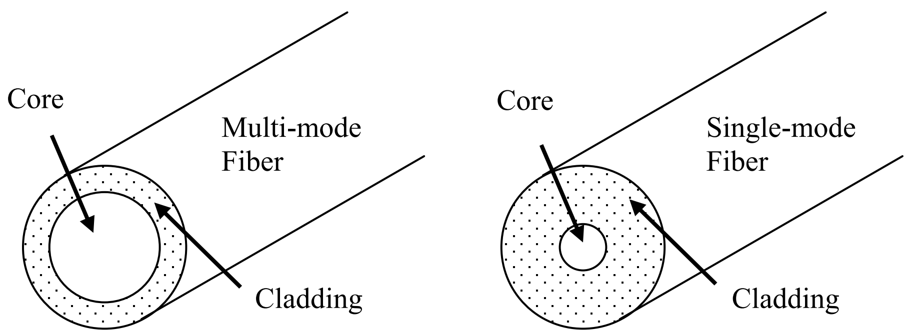

Figure 4. Types of optical fibers are single and multi-mode

There are two general fiber configurations: single-mode and multi-mode. As shown in Figure 4, a single-mode fiber the core is smaller in diameter than a multi-mode fiber core. 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 5). In order to propagate in a single-mode fiber, the light wave must enter the fiber almost 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.

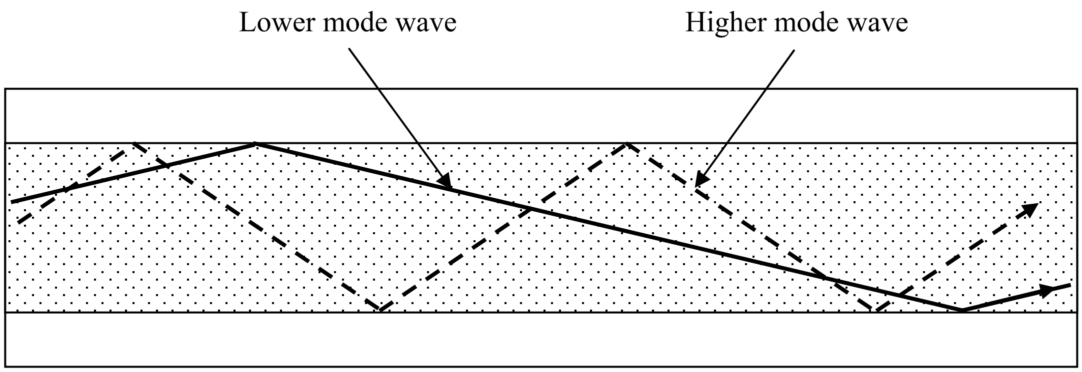

Figure 5. A higher mode light wave travels a longer distance

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. Some of the light is reemitted backwards into the narrow cone of acceptance formed by the fiber core. That light returns to the detector at the light source. More of the light is reemitted at angles to the incoming beam that cause it to be lost into the cladding. Our approach is to use the phenomenon of backscattering (either by detecting the backscattered light or by the decrease in light from succeeding parts of the fiber caused by the loss of light into the cladding) to detect stress to and vibration of 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 unintentionally built into the fiber during its manufacture. These are caused primarily by thermally induced fluctuations in density and variations in the concentration of dopant materials just before the glass transitions into a solid. The main 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 that are 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, λ = wavelength of the light, θ = angle of the scattered light with respect to the incoming light. Note: 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, α, 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 β = isothermal compressibility of the glass, T = temperature. For fused silica transitioning from the liquid to glass state at 1500^{o}C, equation 2 gives an attenuation of 1.7 dB/km for light with a wavelength of 820 nm.

Although equation 2 gives the total attenuation, part of the backscattered light propagates back through the waveguide. The important feature to note is the very strong wavelength dependence, λ^{-4}, of the backscattering. 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 with a cost of ~$130,000 in 2002. Each data trace required two minutes to collect, making it too slow to characterize encroachment signals. Ando Corporation demonstrated this unit at GTI.

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.

GTI used microbending and Rayleigh scattering to detect encroachment because of the extra complexities and cost required to detect Raman and Brillouin scattering.

There are several other phenomenon and measurement techniques (mostly discrete sensors, such as, Bragg gratings) that have the potential of measuring stress and vibrations. As in the case of Raman and Brillouin, the added complexity cannot be justified for our application.

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

A second treatment of Rayleigh scattering was found 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 that 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 (ref 7) 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—

γ_R = Rayleigh scattering coefficient
n = index of refraction of the fiber core [1.46]
p = average photoelastic coefficient [0.286]
β_c = isothermal compressibility at a fictive temperature T_F [7×10^{-11} m^2 N^{-1}]
k = Boltzmann's constant [1.381×10^{-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]
λ = Wavelength of the incident light.

Note: The values in [] are for silica glass.

This scattering is caused by fluctuations in the index of refraction, which in turn is caused by the freezing-in of density inhomogeneities. The inhomogeneities are fundamental and cannot be completely avoided. Substituting the values for silica glass into equation 3 gives:

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

The Rayleigh scattering coefficient is related to the transmission loss factor, ξ

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

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, γ_R =1.199 x 10-3 m^{-1}, ξ = 0.301, and the attenuation, α_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

$$P_o = P_i 10^{-\alpha R/10} = P_i 10^{-5.2 \times 0.002/10} = P_i 10^{-0.00104} = 0.9976 P_i$$

The amount of scattered light in a 2.0 meter section of fiber is (1-0.9976) 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 θ = 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, approximately 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 (light) is reflected back to the source. If the input power is 100 μwatts, 0.024 μwatts (24 nanowatts) will be reflected back. Detectors can measure down to a several hundred nanowatt of light power. This information was used to select the power output of the light sources.

The first diode laser we purchased has a wavelength of 0.69 μm (690 nm) and a light power output into the optical fiber of 10.5 mW. Using the same calculations corrected for the different wavelength of the purchased laser and a 2-meter section of glass fiber, the estimated power reflected back to the source is P_o = 0.000167 P_i. The diode laser has an output power of 10.5 mW, thus the reflected power with no extra stress is ~1.75 μW. Reducing this value for other losses in the OTDR should result in a very detectable signal for the minimum Rayleigh backscattering. Stress related backscatter would be in addition to this value. Because the amplitudes of both the intrinsic and stress/vibration induced backscatter are a function of wavelength, a relatively short wavelength (690 nm) was selected to maximize the signals.

Late in the program a more powerful diode laser became available. It has a wavelength of 840 nm and an output power into the fiber of 400 mW. A similar calculation for the light power reflected back to the source gives 30.4 μW, which is a factor of 17 greater than the 690 nm laser. Another advantage of the 840 nm laser is the attenuation in a fiber is 45% less than the 690 nm laser, meaning the potential range of the 840 nm is greater.

As described above, Rayleigh backscattering is sensitive to wavelength, with more scattering from shorter wavelengths. Shorter wavelengths also mean more attenuation. Therefore we must make trade-offs 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 that can be detected in the optical fiber 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.

Alternate Approaches

Three commercial products are available for measuring the stress/vibrations in an optical fiber. One is Ando Corporation's Brillouin scattering Optical Fiber Strain Analyzer, model AQ8603. It takes two minutes to collect a reading, which is too slow for characterizing encroachment types.

Future Fiber Technologies (FFT) is marketing an optical fiber sensor technology for use in monitoring disturbances to optical fibers. One application under development is for right-of-way encroachment detection. Based on their website, they use an interferometric technique to detect encroachment. Based on FFT's Australian patents, they also have a technique that 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 as a function of time in the frequency range of 0 to 100,000 Hz. The major drawback to each FFT technology is that it does not separate or distinguish simultaneous events. If we monitor kilometers of pipeline in noisy environments from one location, this will be an issue because of the non-hazardous encroachments and passage near railroads and highways. A proprietary technique, requiring three fibers, is used to divide the fiber into long sections and locate the dominant signal in each section. Northeast Gas Association is sponsoring an application of this technique including a test system installed at Public Service Electric and Gas (ref 8).

EDM Services offers products called Trip Wire®. Trip Wire is an optical fiber or conducting wire buried above the pipeline. Any optical fiber can be used. Optical time domain reflectometry for the optical fiber and electrical time domain reflectometry for the metal wire is used to detect breakage or severe damage to the fiber/wire. The damage is detected within a few seconds of its occurrence. Drawbacks to the approach are that the fiber must be damaged or broken for detection and then repaired after the damage has occurred. In the case of third-party damage, the presence of construction equipment is sensed only after the equipment is moved on site, excavation has started, and enough soil has been removed to hit and damage the fiber or wire. At that instant, the construction equipment is in eminent prospect of damaging the pipe in a few more motions.

Commercial OTDR Measurements

During the project a redesigned conventional OTDR was marketed by Agilent Technologies. An Agilent Mini OTDR mainframe with E6009A-850/1300nm multi-mode laser module was obtained and used to test the ability to detect weights on the fiber. Figure 6 shows the results of two measurements, one with a single weight [upper, red curve] and one with a second weight [lower, green curve]. The second weight was placed 11 meters closer to the OTDR. 10-pound weights were used with the edge of the weight resting on the Hergalite. This gives an effective load on the fiber of ~5 pounds. The signals were averaged for 30 seconds to obtain these data. There are two peaks in the curves, one for the initial light pulse and the second reflection from the end of the 275-meter long fiber. With one weight applied as shown in the upper curve, there is a small amount of reflection followed by a sharp drop in signal strength. A second weight was placed on the fiber and another step decrease is seen. The two curves were displaced from each other along the vertical axis to make it easy to compare the features in the curves. As described earlier, measuring signal losses is another method for detecting encroachment. Losses corresponding to both weights are observable, although the second produces a smaller signal loss. When the weight closer to OTDR was removed, the signal loss caused by the remaining weight reverts to that caused by a single weight. When both weights were removed, the fiber returned to normal and no residual signal decrease was detected.

Next, a series of measurements were performed to determinate the length of time required to detect a signal. Measurement times were decreased from 100 seconds to 2 seconds without a noticeable deterioration of the signal loss.

Figure 7 shows the results of the attenuation at one location on the fiber versus the applied static load. The load was applied over a 3-inch long length of fiber. The relationship is linear. A one-pound weight was the smallest used. Signal averaging lasted 30 seconds. It is possible to detect a 1-pound load.

Similar sets of measurements were performed on the Fibercore SM600. We were not able to detect any reflection or attenuation.

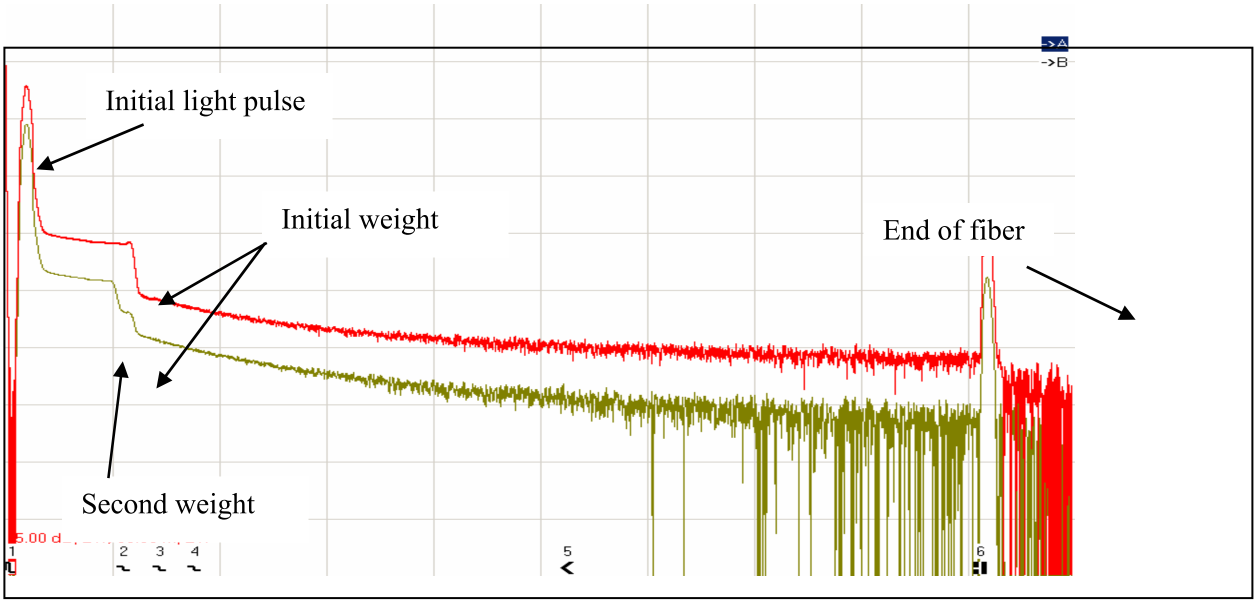

Figure 6. Attenuation versus position in the fiber with one and two weights.

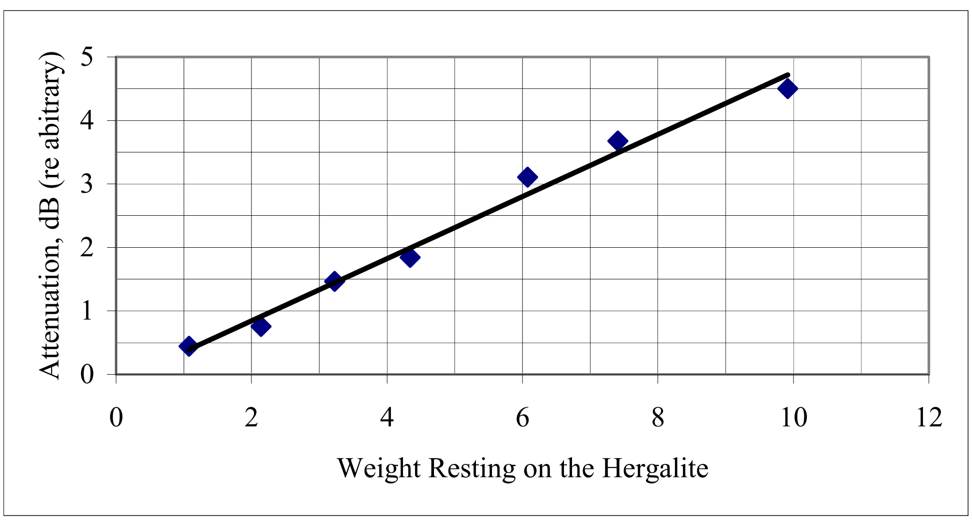

Figure 7. Attenuation as a function of load on the fiber.

GTI OTDR Measurements

The measurements with the Agilent OTDR had the loads applied close to the instrument. The experimental set-up was modified by rewinding the Hergalite fiber on two 10-inch diameter cylinders. The new arrangement permitted loading the Hergalite at 30 meters, at 200 meters, and at the end of the fiber (350 meters). The access at the 200-meter point was long enough to be able to place the fiber in a small soil box.

Using the new Hergalite configuration, the custom OTDR with a 690 nm diode laser was tested to determine the minimum static load it could detect. For these measurements, the output of the photodetector was monitored with a Tektronix TDS 3200 oscilloscope, rather than the National Instruments oscilloscope. Placing a weight on the Hergalite caused a voltage shift in the light intensity versus time trace. Figure 8 plots the voltage shifts as a function of load. We detected static loads as small as 0.2 pounds resting on the Hergalite. The Agilent was not able to resolve the sub-pound loads.

The new high power 840 nm diode laser did not improve the weight resolution. This indicates that the 0.2-pound value is the minimum required to compress the plastic fiber against the Hergalite. However, the new diode laser did increase the amount of returning light and the frequency response of the system—which was a key goal.

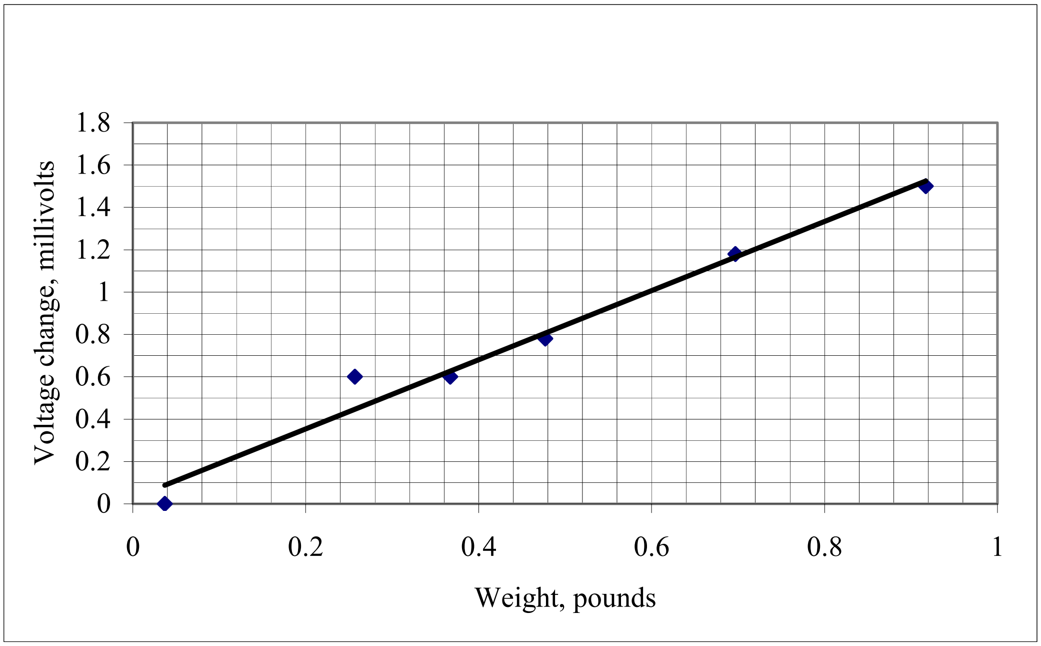

Figure 8. Voltage shift as a function of load on the Hergalite

Test Site

The OTDR and optical fiber system were tested in the field at an operating pipeline. ANR Pipeline, Division of El Paso Energy Corporation, provided the site. Figure 9 is an aerial photograph of the site. The site is along two operating transmission pipelines. One pipeline is 22 inches in diameter; the second is 30 inches in diameter. Overall dimensions of the site were 1430

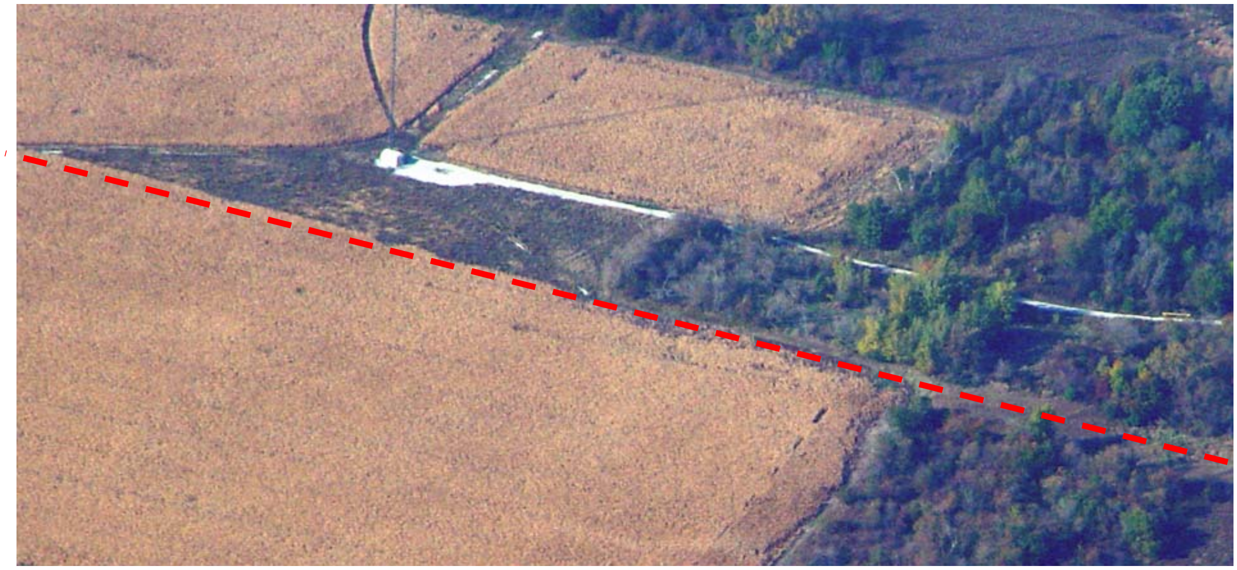

Figure 9. Aerial view of test site

by 2650 feet. Part of site was under cultivation, part was wooded, part was in open field, and part had a stream running through it. The path of the optical fiber sensors was in both the farmed and unfarmed areas. The path of the transmission lines is shown by the red dotted line superimposed on Figure 9. Electrical power is available at the microwave tower located at the end of the gravel road. Instrumentation was attached to each fiber during the testing and removed between test days.

Figure 10 is a schematic of the test site using the distances and depths measured when the optical fiber sensors were installed. The red dots in Figure 10 and the corresponding numbers give a running distance from the fence around the microwave tower. The fibers run in a loop from the tower along the gravel road, across the open area, then back along the pipeline at the edge of the cultivated field and then back across the field to the microwave tower. Two electrical boxes were mounted on the fence surrounding the microwave tower. A Corning® 62.5/125 fiber was installed as a loop, with an end in each of the electrical boxes. A 543-foot section (between points 887 and 1430 feet) is buried 24 inches directly above the 30-inch pipeline. A second piece of Corning® 62.5/125 was installed half of the way around the loop (0 to 887 feet). The latter fiber crossed over the 22-inch pipe, stopping short of the 30-inch pipeline. The fiber was coiled and 100-foot length of bare Fibercore SM600 was spliced to the end. The last 50 feet of the Fibercore was formed into a 6-inch diameter coil and the tail end brought above the ground (near the 826-foot mark). The end coil provides extra distance so that the end of the fiber is not at the

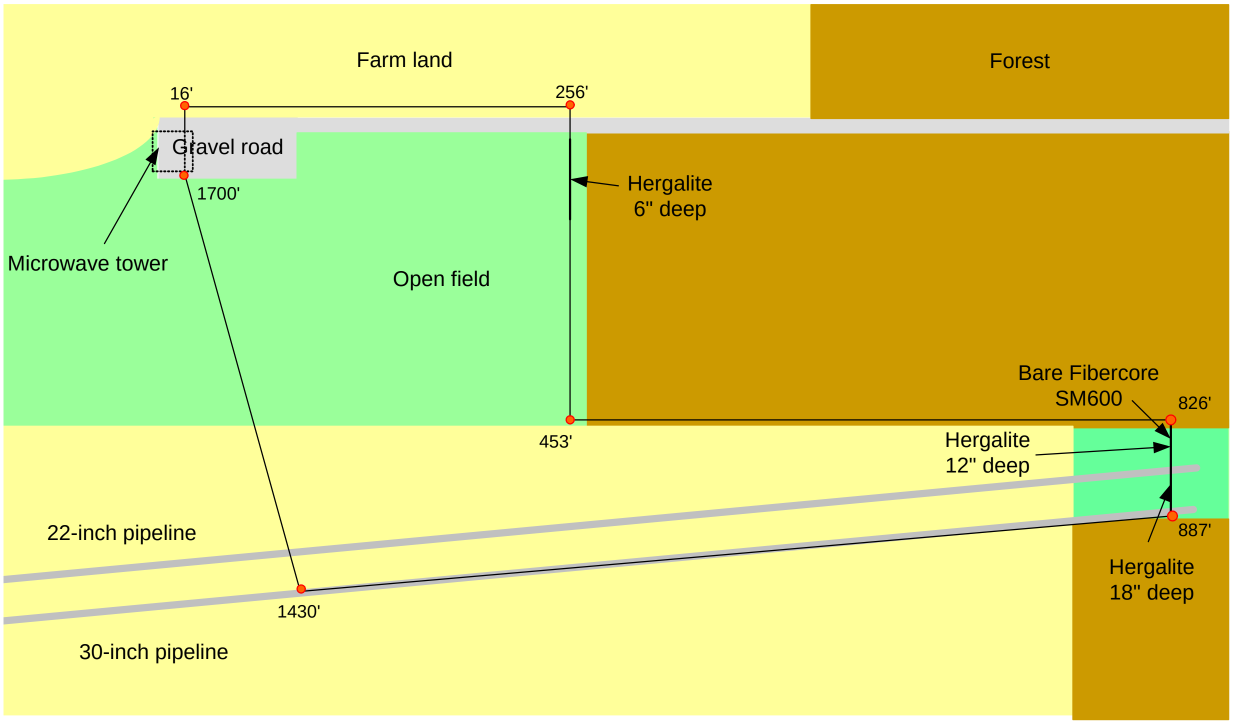

Figure 10. Schematic of the test site

end of the path length. Similarly, 1½ loops of the Corning® 50/125 were also installed. Two sections of Hergalite were spliced into the Corning® 50/125. One 50-foot length of Hergalite was buried 6-inches deep. The second 50-foot length was buried at two depths: half at 12 inches and the remainder at 18 inches. Unfortunately, the Corning® 50/125 fiber that was to be a continuous loop broke between the two sections of Hergalite. Access to the far end of the ½ loop of Corning® 50/125 was provided in an electrical box (at 887 feet). The optical fibers were buried at several depths, ranging from 6 to 24 inches. This arrangement permitted sensitivity tests at a range of depths. The deepest depths permit passage of a plow over the optical fiber without damaging it, thereby minimizing the portion of the field off limits to the farmer.

The emphasis in Phase 1 was on establishing sensitivity to encroachment activities; with durability issues being addressed after the proof-of-concept. In keeping with that approach, we also buried a short section of bare Fibercore SM600 fiber. The Hergalite was packaged in a wax paper sleeve, permitting it to slide. The wax paper sleeve was sandwiched in duct tape. Figure 11 is a photograph of the Hergalite, wax paper/ duct tape configuration.

Because of an unusually mild winter, we were able to install the fibers in early January 2003. Most of the soil backfilling was completed before the soil froze. The exception was over the sensing areas containing the shallowly buried Hergalite, which was completed during a cold

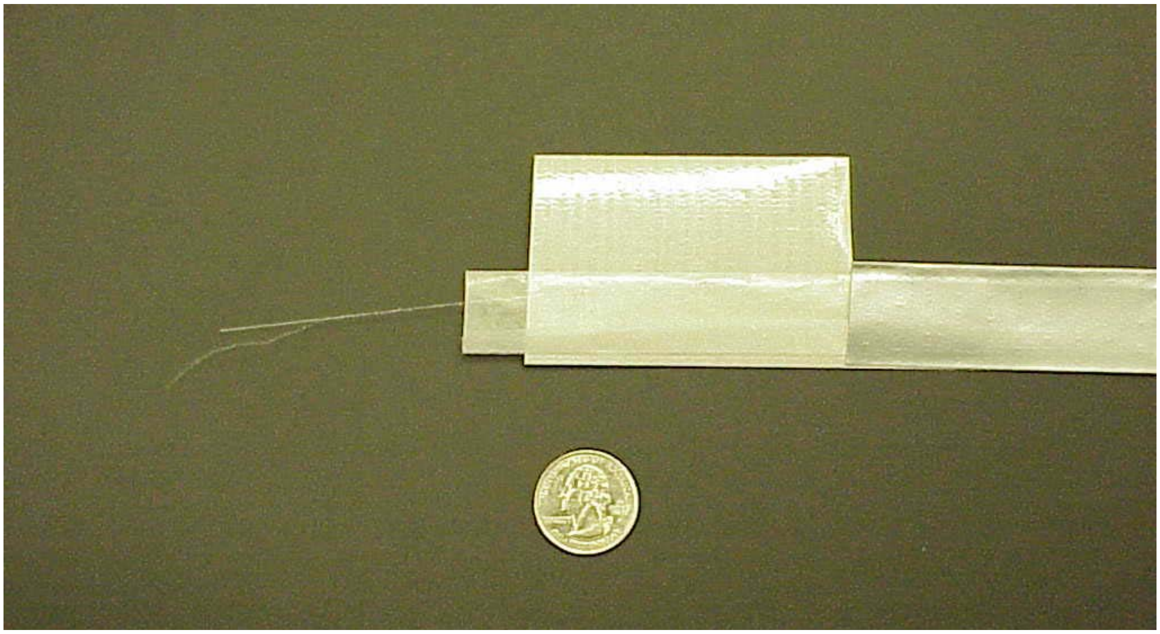

Figure 11. The Hergalite was packaged in a wax paper/ duct tape configuration.

snap that froze the soil to approximately 6-inches deep. Frozen soil away from the fiber path was excavated to expose unfrozen soil. The unfrozen soil was broken up and used to cover the sensing fibers. Then the remaining soil was backfilled, but not compacted. We verified continuous light path from the electrical boxes through each sensing fiber, both during and after the fibers were installed. The soil was left to settle naturally.

Thus we have optical fiber sensors:

- Buried at 4 depths
- Parallel and perpendicular to the gravel road
- Perpendicular to the 22-inch pipeline
- 24 inches above the 30-inch pipeline
- One length with all four fiber types side-by-side.

ANR Pipeline provided access to a range of construction equipment, including an ATV, rubber-tired trucks, backhoe, and cherry picker, track mounted 36,000 and 40,000-pound excavators and track mounted bulldozers-- John Deere 450 (15,000 pounds) and John Deere 750 (25,000 pounds).

Buried Optical Fiber Sensitivity Measurements

GTI tested the custom OTDR at the ANR pipeline on July 12 and 13 on the shallowest Hergalite (6 to 8-inches deep). We were unable to detect any impacts from footfalls, a backhoe driving over the Hergalite fiber, or the backhoe bucket banging on the ground. Although we did not know the precise location of the fiber, at least a few of the events should have been over the Hergalite fiber and therefore detected. These results were surprising because of the high sensitivity obtained in the laboratory, where we detected static loads of 0.2 pounds.

In analyzing the lack of event detection, a few factors emerged. During the testing, the soil was very hard; we could not penetrate the soil more than 2-3 inches with a spade. This section of fiber was the last to be buried when the fiber was installed in January of 2003. The soil was freezing as this section of fiber was being buried and the soil was in clumps rather than fine particles. The fiber was installed close to the edge of the excavation to protect it from breaking during the burial. All of these factors suggest that the fiber was shielded from vibrations/impacts and that soil conditions and burial of the fiber have a large effect on sensitivity.

First Series of Tests: Based on the above considerations, a series of measurements were conducted at GTI's outdoor pipe facility. The approach was to start with exposed portions of the fiber, subject them to various loads, measure the response, and bury the fiber deeper in soil. Sand was used as the first soil. A commercial potting soil was the second soil used. Three sections of Hergalite were used: bare Hergalite fiber, Hergalite fiber in a wax paper/duct tape sandwich, and Hergalite in the 3-millimeter jacket from a 50/125-micron fiber optic cable. For most, but not all of the measurements, the Hergalite was placed on a 6-foot long 2x8-inch board. The thought behind using the board was to provide a hard surface under the Hergalite, increasing compression of the optical fiber by the spiral wound fiber. The loading types included compression using a fingernail, stepping on the fiber with a shoe, a hand truck with 1 or 2 bags of sand, and the front right tire of a Toyota RAV4. These measurements were repeated with the Hergalite/board combination buried under 1 to 14 inches of sand. Some measurements were also made without the board. Hergalite fiber in a wax paper/duct tape sandwich without a supporting board was buried at the ANR Pipeline site in January 2003.

Figure 12 is a schematic of the setup. Figures 13—17 give an overview of the setup, views of the fiber configurations, and methods of loading. The version of the custom OTDR with the 840 nm diode laser, 50/125-micron fiber coupler, and the photo avalanche detector were used to take the measurements. It was the most sensitive version of the instrument. The coils of

Hergalite minimize end affects on both sides of the test section. An FC/FC connector was used to connect the two coils of fiber.

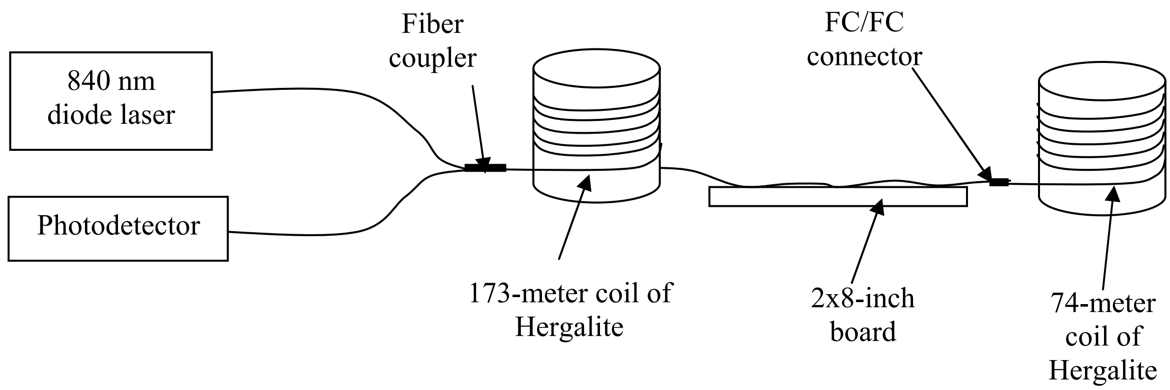

Figure 12. Schematic of the test setup.

Figure 13. Overview of the fiber sensitivity test site. The section of fiber being tested lies on top of a wood support. The soil at this location is not native, rather, sand was brought in and the area was backfilled to a depth of 6 feet.

Figure 14. Close-up of the bare Hergalite fiber on the 2x8-inch plank.
The clear fiber is very difficult to see.

Figure 15. A length of Hergalite was slipped into a 3-mm green plastic jacket.
A hand truck with a damp bag of sand was rolled across the fiber.

Figure 16. Another method of loading was to step on the fiber.

Figure 17. The right front tire of a Toyota RAV4 was used to load the fiber. In this example, the Hergalite fiber is encased in wax paper and duct tape.

Variations in the returning light level due to loading of the Hergalite were analyzed with the "traditional OTDR format" and with the time series analysis[2] developed in this project by GTI. Figure 18 gives the "traditional OTDR format" analysis. The section of fiber being tested was the length of fiber from 193 to 205 meters.

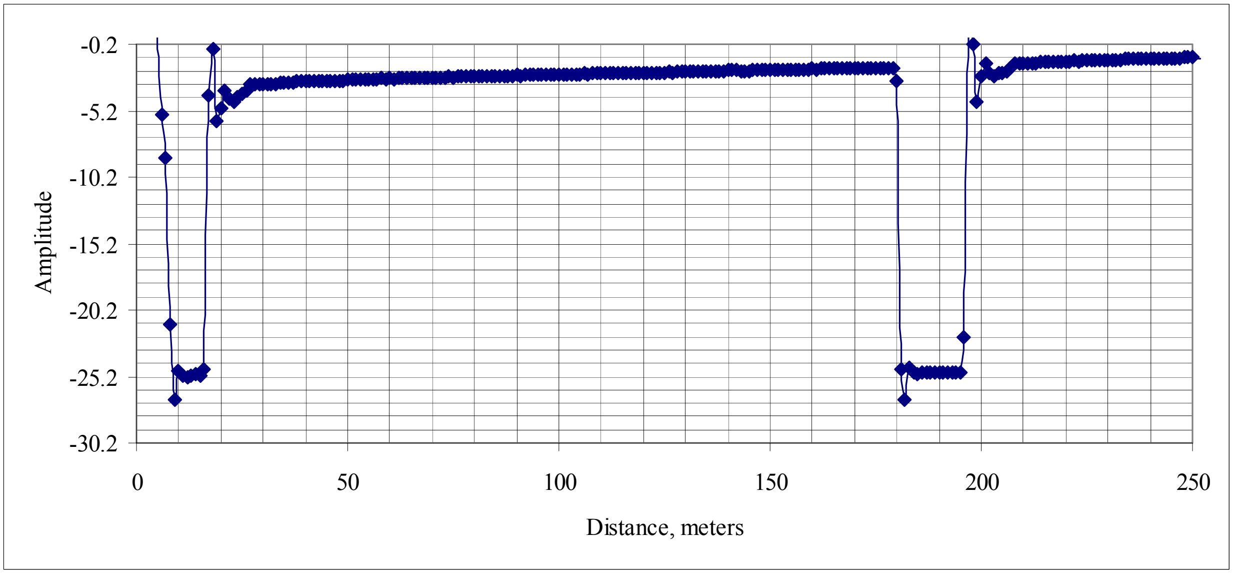

Figure 18. Standard OTDR trace of Hergalite set-up. The section of fiber between 183 and 195 meters was used to collect the time series data.

Figures 19 –27 show the results of the first series of tests in the time series format that monitors a selected location on the fiber as a function of time. It is possible to signal average the time series to improve the signal to noise ratio. This feature was not used for any of the data in Figures 19-26. Figure 27 was signal-averaged 3 times. Without signal averaging, the time series resolution is 0.183 seconds per sample. Figure 19 shows the typical noise. Occasionally, a timing glitch created a sharp spike in the data. Such timing glitches are noted in the figures. In most of the time series data, a time delay occurred between starting the data acquisition and the application of the load. Thus the first part of each waveform is noise. This is especially true for the RAV4 results.

[2] The traditional OTDR format gives the returning light intensity as a function of the distance along the fiber. The time series gives response of a selected short length of fiber plotted as a function of time.

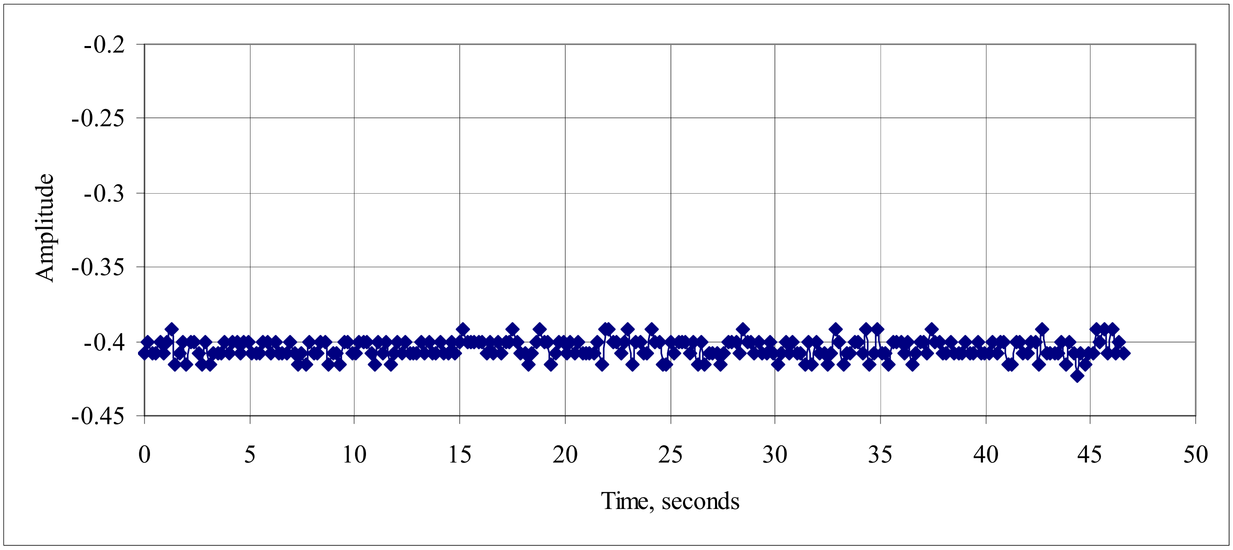

Figure 19. Typical background noise. The noise is the same for all 3 sections of fiber.

Figures 20-22 are for bare Hergalite with no sand cover. Figure 20 shows the response when the fiber is loaded with pressure from a fingernail. Fingernail pressure was slowly varied to extend the response over several tenths of a second. The amplitude and length of force application was varied with some of the loadings close together. All 20 applications of force were detected. Figure 21 gives the results of a 185-pound man standing on the fiber. The shoe spreads the loading over the fiber and the amplitude is smaller, but detectable. The loading in Figure 22 is from a hand truck carrying one bag of damp sand. The combined weight of the hand truck and one bag of sand was 65 pounds. The hard rubber tires concentrated the load, resulting in strong signals. Note the change in vertical scale.

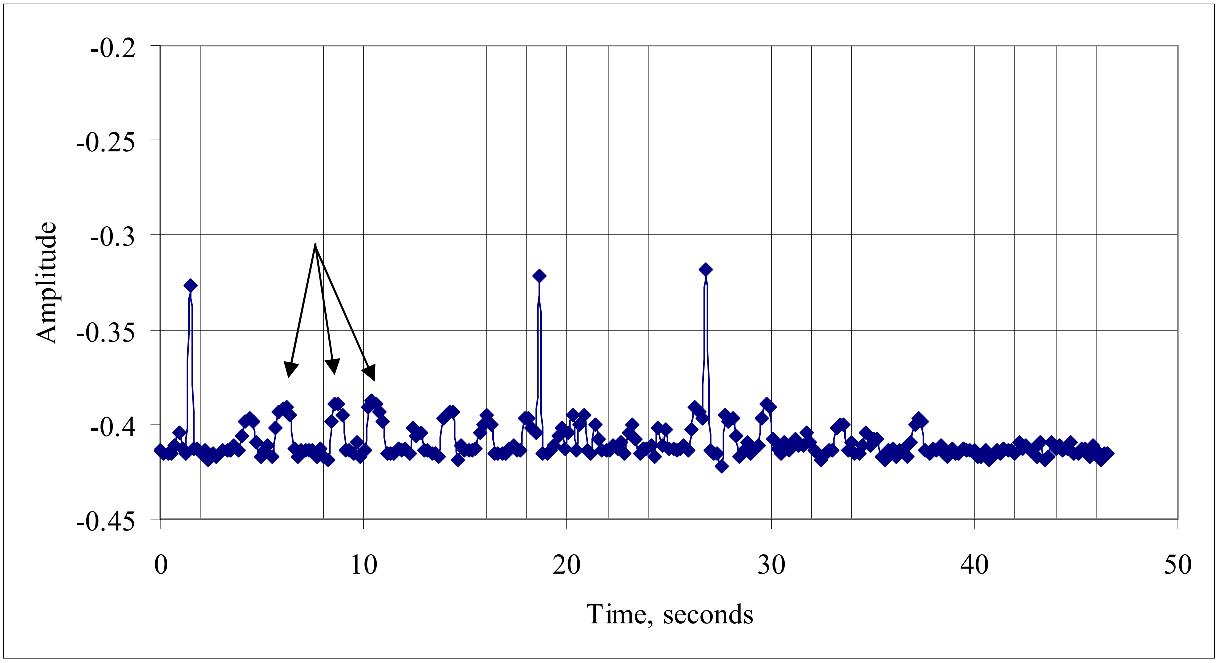

Figure 20. 20 loadings of the bare Hergalite with a fingernail. The arrows indicate some of the responses. The three sharp peaks are timing glitches.

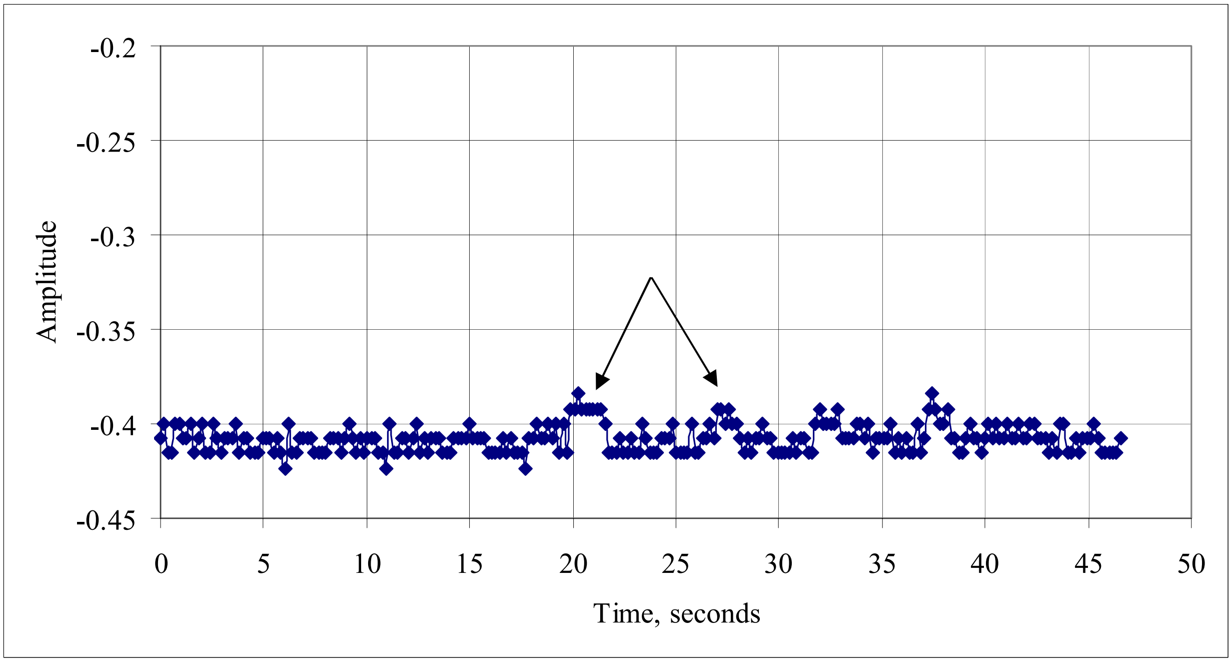

Figure 21. 190-pound loadings with a man standing on the bare Hergalite fiber.

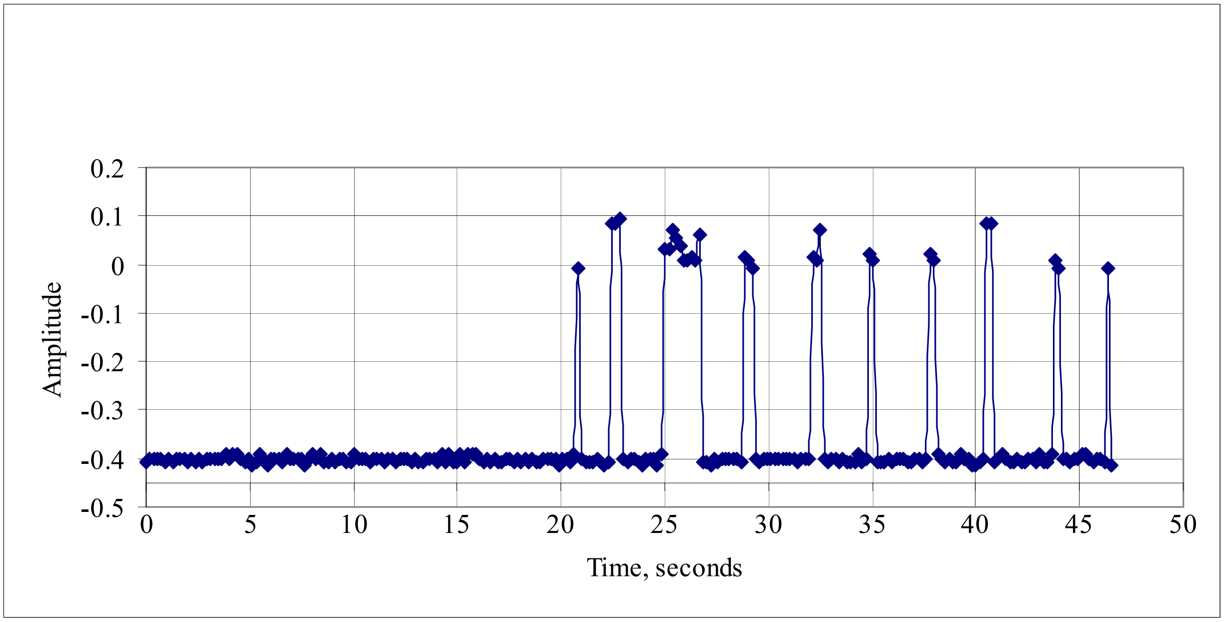

Figure 22. The hand truck with a sand bag created large signals on the bare Hergalite. Note the change in vertical scale from previous graphs.

Figures 23 and 24 give the responses for the Hergalite protected by a 3-mm diameter jacket. The jacket was scavenged from a section of Corning 50/125-micron fiber. In Figure 23, the hand truck was rolled over the jacketed Hergalite several times, giving strong signals. In Figure 24, the RAV4 was driven slowly six times over the jacketed Hergalite. In this case the response was very poor. The jacket helps shield the Hergalite from the soil compressions, reducing its response.

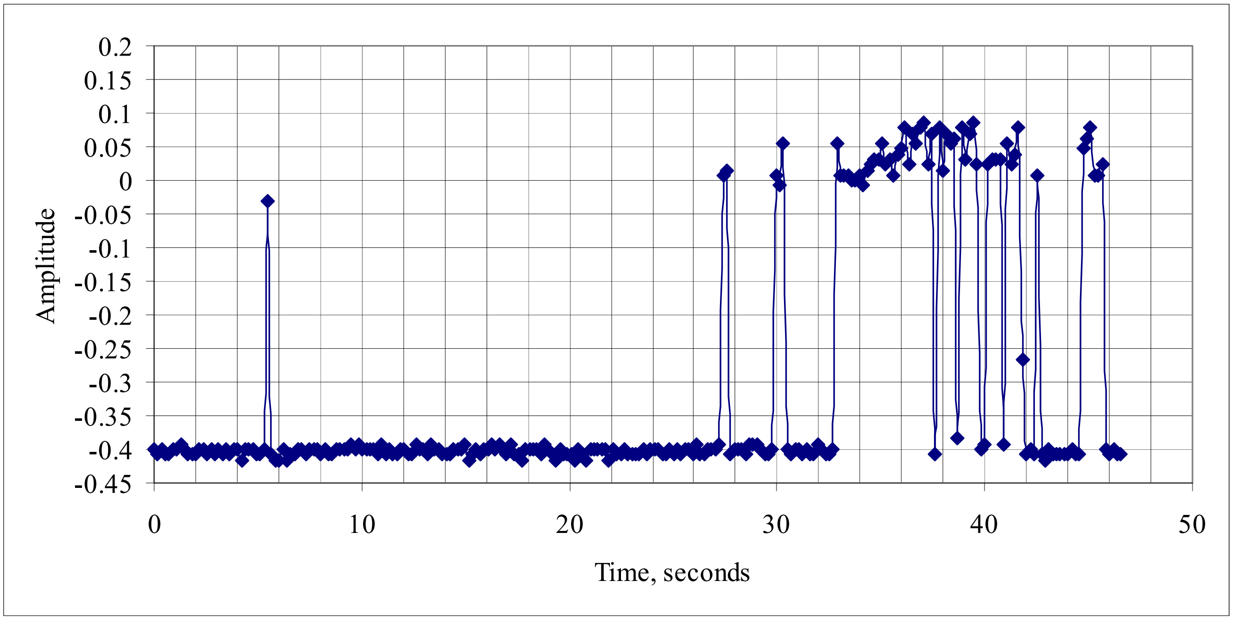

Figure 23. The hand truck with a sand bag created large signals on the jacketed Hergalite. The first peak is a timing glitch.

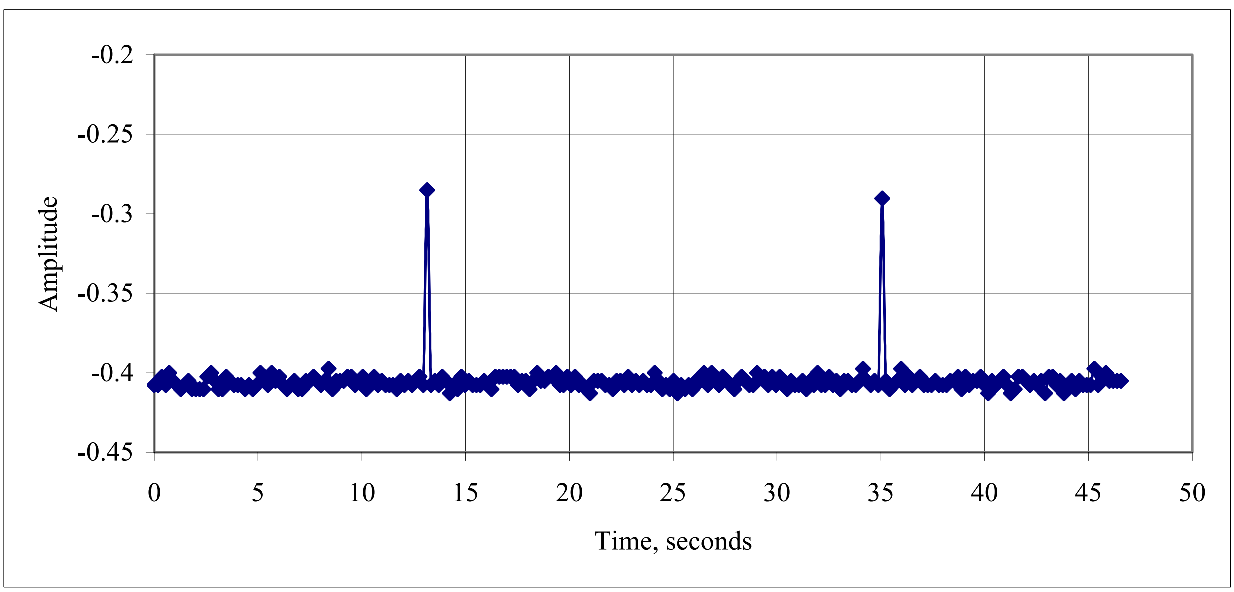

Figure 24. Eight passes with the RAV4 rolling over the jacketed Hergalite did not produce obvious signals. The two peaks are timing glitches.

Figures 25, 26, and 27 give responses of Hergalite protected by a wax paper/duct tape sleeve. The purpose of the wax paper is to permit the Hergalite freedom to shift without breaking. The duct tape protects the wax paper. The goal of this method of packaging was to maximize sensitivity to stress and vibrations. At the risk of breakage, we did not include any typical cable strengthening, such as, aramid fibers. This system was buried at the ANR Pipeline test site. It has survived being in the ground for over 1 ½ years. In Figure 25 the wax paper/duct tape Hergalite was placed on the board and buried 1-inch deep in sand. The RAV4 was driven very slowly over the Hergalite and the resulting large signal lasted 1.4 seconds. The first peak in Figure 25 is a timing glitch. Figure 26 is the same graph with different vertical scale.

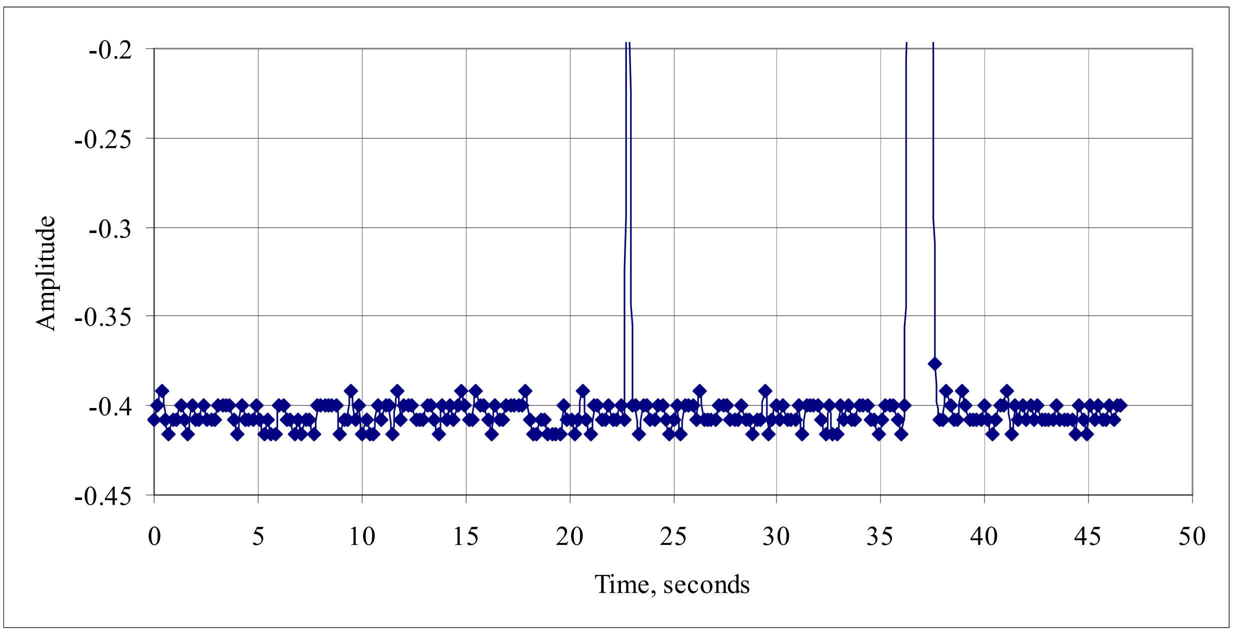

Figure 25. Hergalite protected with wax paper/duct tape and buried 1 inch deep in sand detected a slow passage of a RAV4. The first peak is a timing glitch.

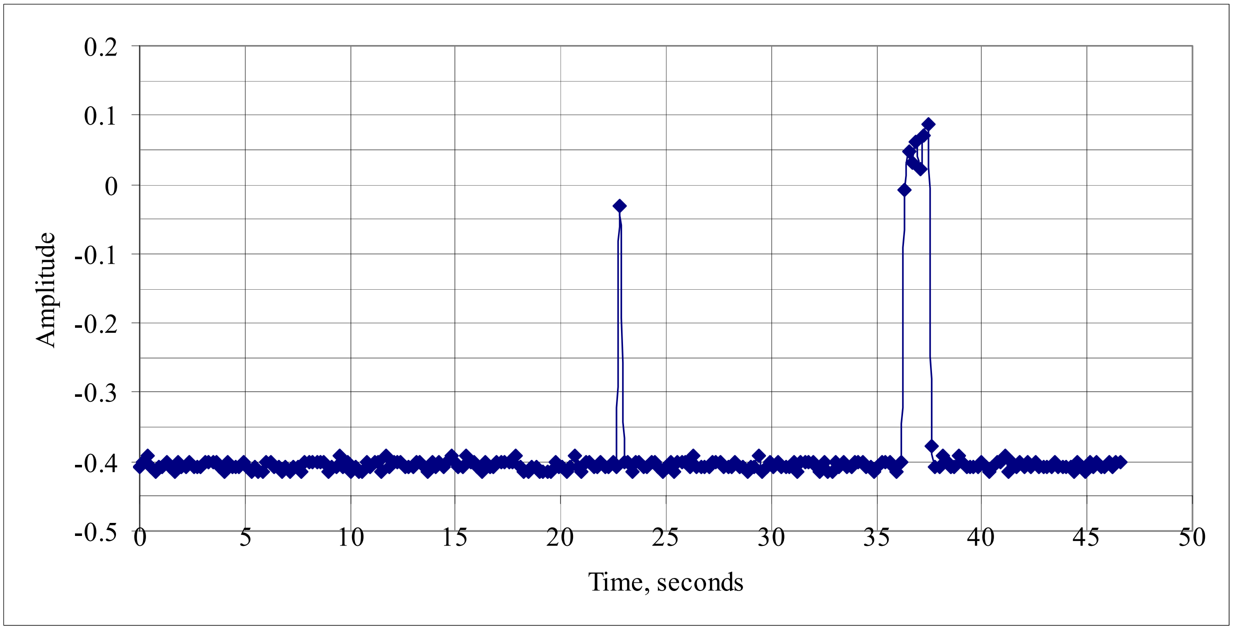

Figure 26. The same graph as Figure 25 with a different vertical scale.

Figure 27 is the same section of wax paper/duct tape Hergalite. However, the board was carefully removed, disturbing the underlying sand as little as possible. The Hergalite placed on the compacted sand and then buried 2 inches deep. Multiple passes of the vehicle were detected.

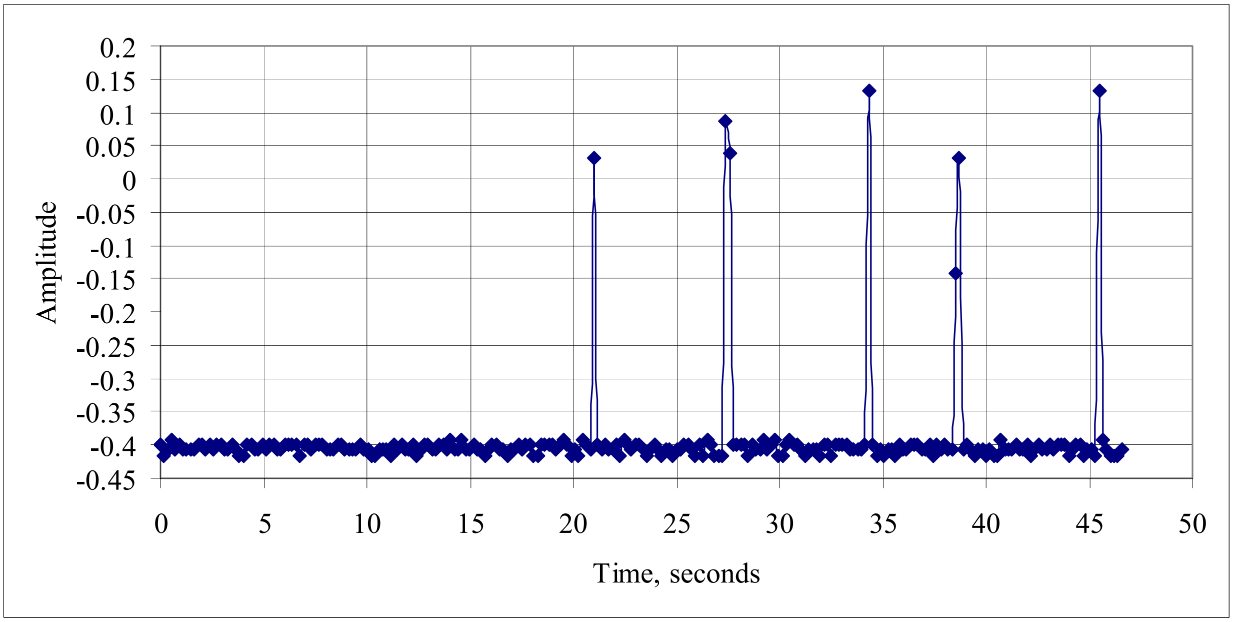

Figure 27. Hergalite protected with wax paper/duct tape and buried 2 inches deep in sand detected multiple passages of a RAV4. In this case the 2x8 board was not present.

Second Series of Tests: At this point in the testing, the fiber broke at a location away from the section being tested. The fiber was spliced together again and a new series of data was collected at deeper depths of burial. Figures 28 and 29 show the selected results of the second series of 16 tests in the time series format with the Hergalite/wax paper/duct tape system backed by the 2x8 board. An averaging of 5 signals[3] was used for the data in Figures 28 and 29. The sand was very dry. 7 inches of lightly compacted sand covered the Hergalite. Figure 28 shows that it was barely possible to detect the RAV4. Figure 29 was a repeat of the same conditions to verify that the results in Figure 28 were not a fluke. We were not able to detect the RAV4 when the Hergalite was buried 14 inches deep.

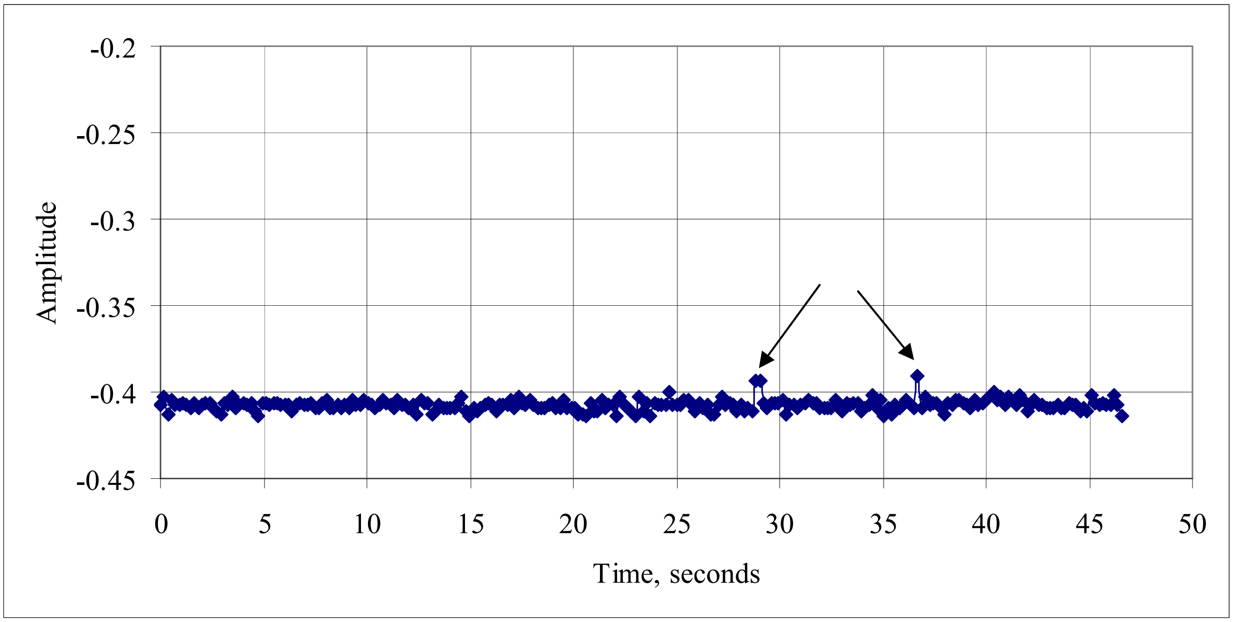

Figure 28. Hergalite protected with wax paper/duct tape backed by 2x8-inch board and buried 7 inches deep in sand barely detected passages of a RAV4.

3 Five consecutive samples are averaged, improving the signal-to-noise raio and slowing the frequencies response.

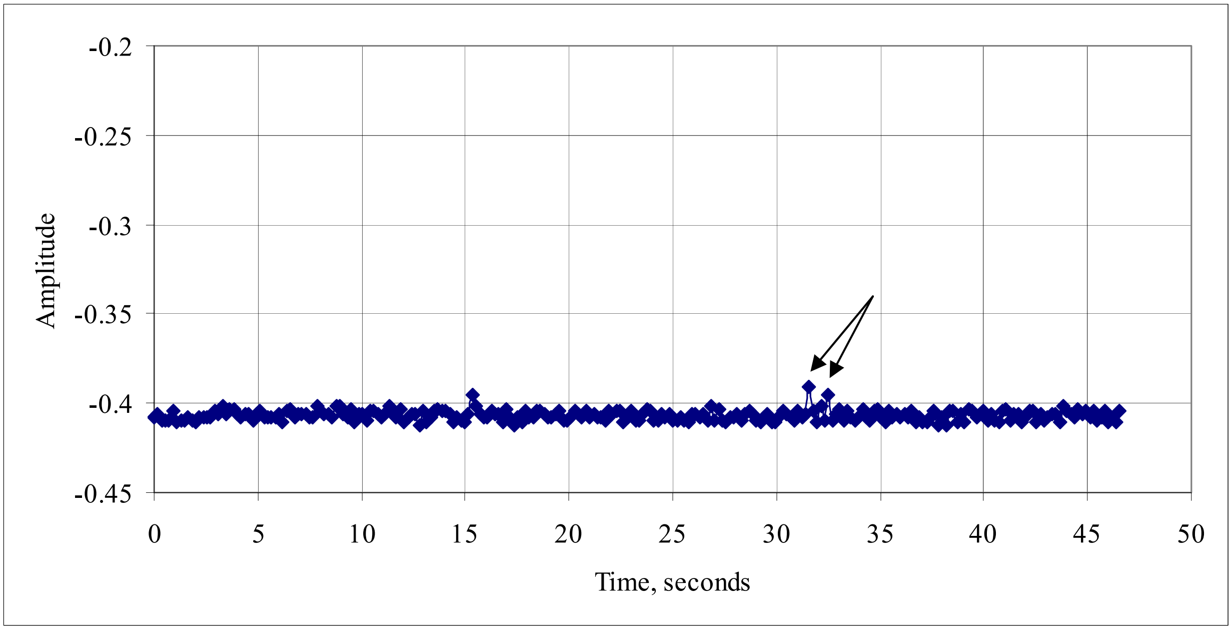

Figure 29. Second attempt on Hergalite protected with wax paper/duct tape backed by 2x8-inch board and buried 7 inches deep in sand also barely detected passages of a RAV4.

Third Series of Tests: The fiber was removed and taken inside. During that process the Hergalite broke in the section being tested. Rather than repairing the fiber, the Hergalite/wax paper/duct tape system was completely replaced. The bare and jacketed sections of Hergalite were eliminated. Figures 30–32 show selected results from the third series of 34 tests. The first tests were performed with the top of the board and the Hergalite buried under 14-inches of sand. Tests were run with the fiber and top of the backing board buried 7-inches deep. A section of the Hergalite was buried in dry sand. Another part was buried in moist potting soil. The responses were weak.

Next, the fiber and board were removed. The fiber was reburied approximately 4-5 inches deep (no backing board) in both kinds of soil. Figure 30 shows the results of the RAV4[4] rolling over the potting soil. The two spikes are probably noise. During the repeat of this experiment, the front wheel spun, loading and compacting the potting soil. Figure 31 shows the very large signals detected. Figure 32 shows the RAV4 passing twice over the same soil/fiber combination. The vehicle was clearly detected. At this point, the time series results became strange, with the peak in the standard OTDR trace disappearing and the noise level shifting. The red diode laser was used to verify that the fiber was not broken.

[4] This particular 3000-pound vehicle is front-wheel drive only.

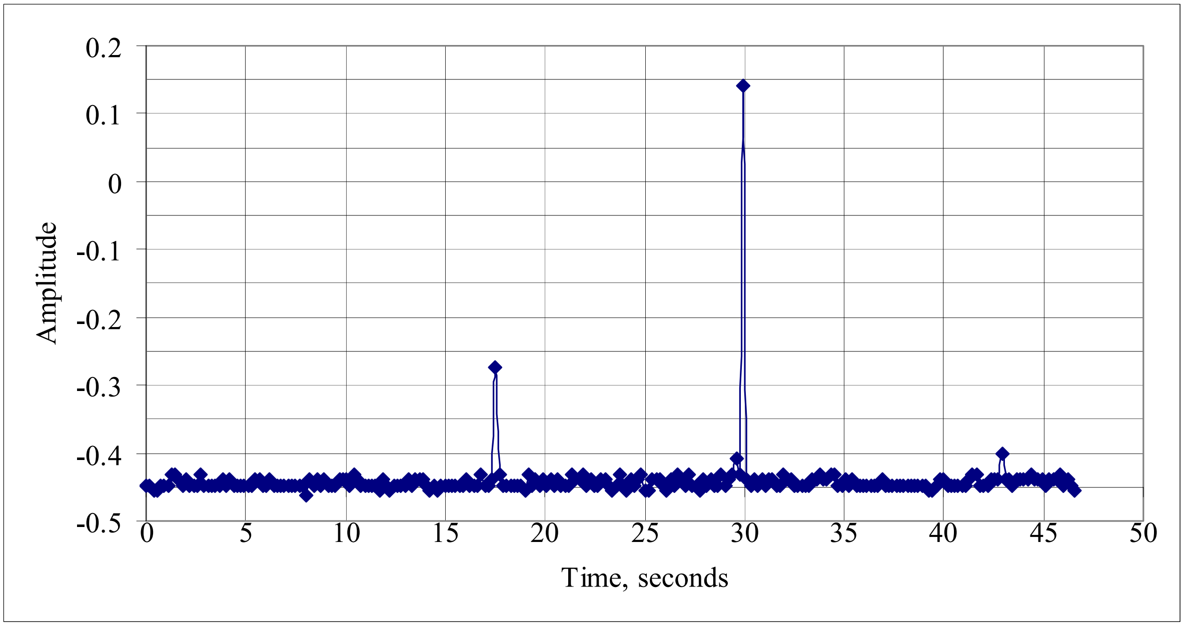

Figure 30. Hergalite protected with wax paper/duct tape without a backing board and buried 4.5 inches deep in potting soil shows no clear detection of the RAV4.
The two peaks are probably timing glitches.

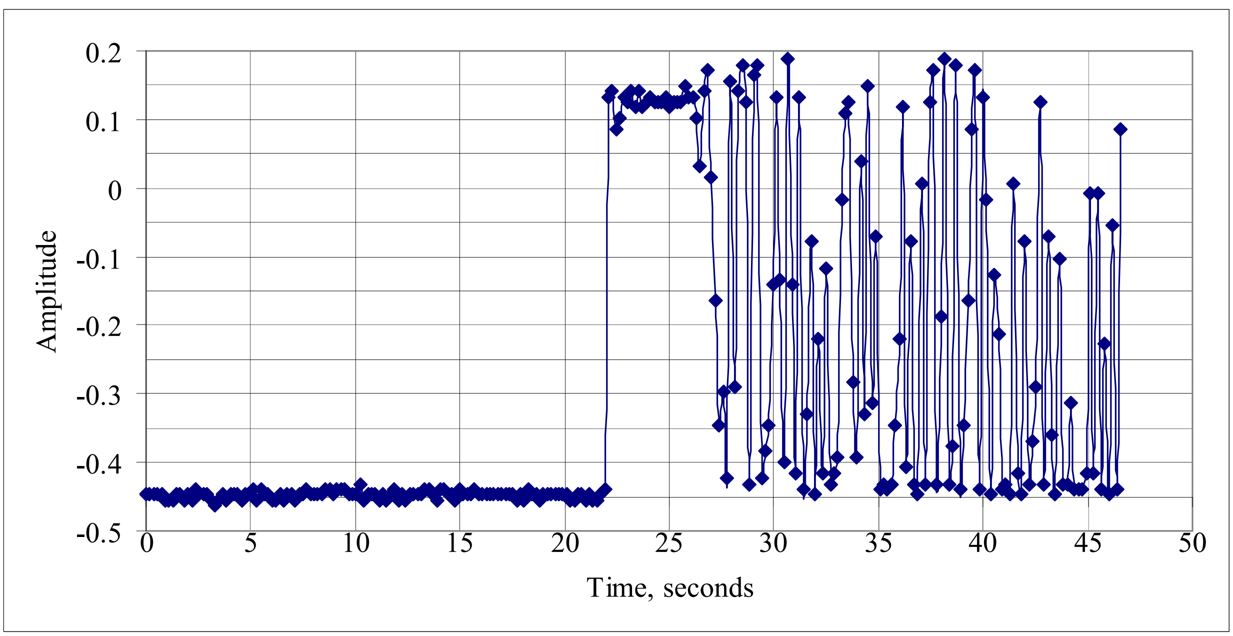

Figure 31. Hergalite protected with wax paper/duct tape without a backing board and buried 4.5 inches deep in potting detected passages of a RAV4.
The tire spun, compacting the soil and giving a large signal.

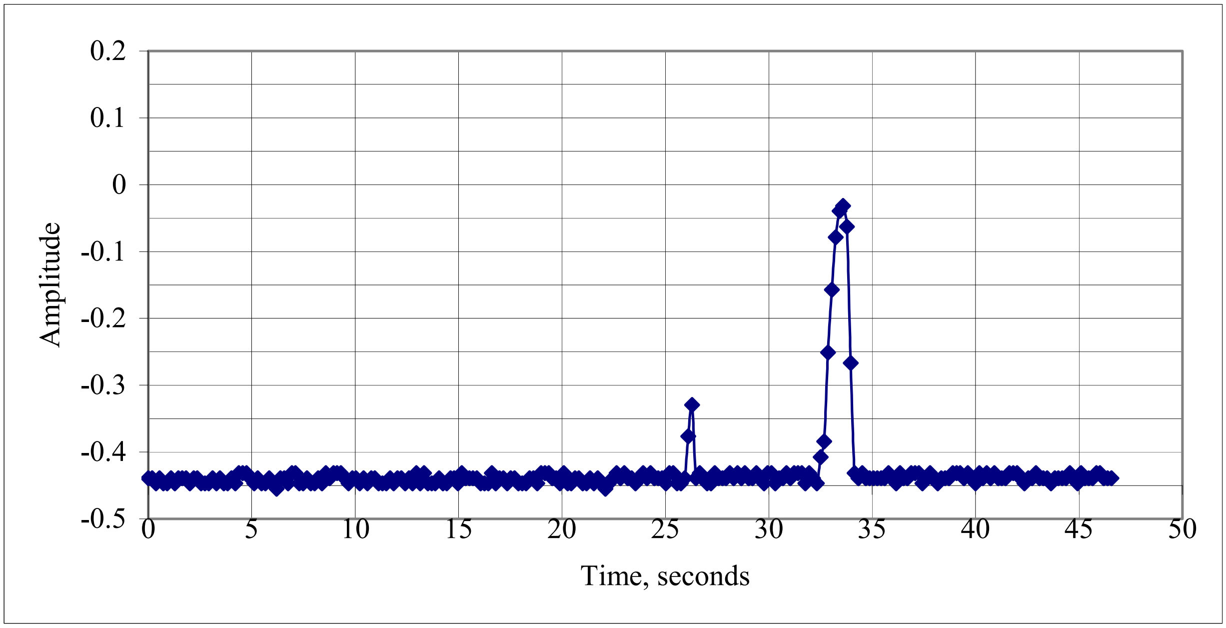

Figure 32. Hergalite protected with wax paper/duct tape without a backing board and buried 4.5 inches deep in sand detected passages of a RAV4. This data was collected after the tire spin.

Extrapolated Depths

The results of the initial soil sensitivity tests (Figures 31 and 32) demonstrate that one tire of a small SUV can create very strong signals at depths of 4 to 5 inches. It is possible to extrapolate these results to estimate the potential range of depths where a detectable signal might be obtained. A Boussinesq equation (ref 9) for predicting the stress in soil from a rectangular load at the surface can be used to estimate the depth at which the technique should be able to detect a rubber-tire backhoe. This equation assumes the stresses are produced in an elastic, homogeneous, and isotropic medium on the surface of an infinitely large half-space for a load at the center of a rectangular footprint. By dividing the load by the estimated contact surface area, it is possible to estimate the stress on the uncovered Hergalite or the soil at the surface of the ground. Estimates of the stress loadings are shown in Table 1. The larger loadings from the hand truck and fingernail correspond with the strong responses in Figures 20, 22, and 23. Two John Deere trucks are available for use at the ANR Pipeline test site. The calculated loading from the Deere 450 and 750 rubber tire backhoes at a depth of 4 inches are larger than those of the RAV4. The Boussinesq equation was used to estimate the depth of burial at which we should be able to detect those machines: 12 and 16 inches, respectively. Developing a better method of installing the optical fiber in soil would increase sensitivity and potential burial depth.

Table 1. Estimated Stress Loadings and Detection Depths

Source of load	Size of load, lbs	Load on one tire, lbs	Footprint, inches	Contact stress at surface, psi	Soil stress at 4 inch depth	Depth of equivalent RAV4 soil stress, psi
Fingernail	5	NA	¼ x ¼	80	NA	NA
Hand truck and sand	65	NA	¼ x 1.25	173	NA	NA
Foot	185	NA	1 x 4.5	41	NA	NA
RAV4	3000	750	4 x 6	31	24	4
John Deere 450	15,000	3750	6 x 12	52	47	12
John Deere 750	25,000	6250	6 x 16	65	61	16

Initial Conclusions from Soil Sensitivity Tests

The soil sensitivity tests demonstrate that it is possible to detect one tire of a small SUV at depths of 4 to 5 inches. The strong signals in Figures 31 and 32, also indicate that

- It is possible to detect light vehicles at greater depths
- The choice of soil and compaction is critical
- It is possible to detect variations in the signal amplitude
- It is possible to detect variations in the time response
- Variations in the amplitude mean that the spiral winding is not simply creating a present or not present signal.

The difficulty in detecting footfalls and the hand truck at modestly shallow depth is both encouraging and discouraging. It would bode well if the sensitivity were great enough to detect minor encroachments. On the other hand, not detecting them reduces the complexity of the discrimination algorithms. So far we seem to be detecting loads directly over the fiber, rather than vibrations off to the side of the fiber. It is too early in the testing to know if this is due to soil type and compaction; depth of burial; or size of the load.

The next step is to continue with the soil sensitivity experiments to better determine the best soil configurations (soil type and compaction).

CONCLUSIONS

The following conclusions can be drawn:

- The basic concept of using optical time domain reflectometry with an optical fiber buried above a pipeline to detect encroachment of construction equipment into the right of way works.
- Simultaneously occurring events can be detected and separately monitored.
- Sufficient time response is possible to permit discrimination between encroachment types.
- The Hergalite fiber is the most sensitive choice of optical fiber cables. The “reset issues” identified by the Hergalite manufacturer are not an issue for our application. The Hergalite can detect static loads as small as 0.2-pounds.
- Method of installing the fiber is critical to the sensitivity of the technique. (Work in the remainder of the co-funded portion of the work will address this issue.)
- Phase 2 instrumentation can be made from commercially available parts for less than $2000; fiber and fiber installation would be extra. Such Phase 2 instrumentation would have greater capabilities than the Phase 1 unit.
- Work remains to improve the system into a practical device.

LIST OF ACRONYMS AND ABBREVIATIONS

DOE – Department of Energy
FOIDS – fiber optic intrusion detection system
GRI – Gas Research Institute
GTI – Gas Technology Institute
IGT – Institute of Gas Technology
NETL – National Energy Technology Laboratory
OTDR - optical time domain reflectometry

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