Fiber Optics for Atmospheric Mine Monitoring

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Abstract—**Fiber optic (FO) technology is progressing rapidly, including the development of FO sensors for a wide variety of applications. These sensors have the advantage of high sensitivity, light weight, small size, high bandwidth, and freedom from electromagnetic influences. The U.S. Bureau of Mines is investigating the application of FO technology to monitoring mine atmospheres. This paper describes work done to address methane, carbon monoxide, and distributed temperature monitoring. A review is made of the potential and problems of using FO's for mine monitoring systems. Methane detection is based on differential absorption of infrared light. A methane monitor that can detect concentrations as low as 0.2% as far away as 2 km via FO cable is described. The upper range is 100% volume methane. Since the system requires no electrical power within the mine, it is intrinsically safe. A carbon monoxide monitoring system that combines a low-powered electrochemical cell with FO telemetry is described. Testing has shown that the system can operate maintenance free for several months. Finally, a distributed FO temperature-monitoring system is being investigated for possible application in mine fire detection. Performance of this system at the Bureau's Lake Lynn Laboratory is reported. The sensor employs optical time domain reflectometry techniques that allow the entire length of fiber (up to 2 km) to function as a distributed temperature sensor. Distributed temperature sensors have considerable potential for monitoring areas such as conveyor beltways.**

I. INTRODUCTION

TODAY'S MINES are more efficient than ever. However, these advances have placed an additional burden on the systems that are relied on to ensure a safe work environment, particularly atmospheric monitoring systems (AMS's). These systems monitor such things as hazardous levels of explosive gas (primarily methane (CH_4)) and evidence of combustion such as high levels of carbon monoxide (CO) or sudden increases in temperature. Examples of problems associated with high productivity are numerous. Highly efficient longwall operations liberate CH_4 more quickly into the atmosphere [1]. Longwalls, along with the promise of computer-assisted mining, will mean deeper mines and longer haulage routes. More operations will seek variances to allow beltways to be used as fresh air intakes [2]. Knowing that beltways are susceptible to fires (seized rollers, defective motors, etc.), early detection of combustion is critical. Since it is the Bureau's goal to see that AMS technology keeps pace with production technology, a program was initiated to investigate the application of fiber optics (FO) to monitoring such variables as CH_4, CO, and temperature in the mine environment.

Over the last several years, there has been much research in the area of FO sensing, although little of this work has impacted the mining industry. This is due in large part to the small return on investment in the limited mining market, despite the potential safety benefits of this technology. A well-known characteristic of optical fiber is intrinsic safety. Conventional fiber is made with silica or plastic and sometimes both. Since these materials are nonconductors, sparking is not a problem. Another reason optical fiber has not made a big impact on the industry is the perception that it is unable to withstand the hostile mine environment. FO cable is proving to be rather sturdy, as evidenced by the thousands of miles of fiber placed on the ocean floor. Fiber is becoming increasingly easier to maintain. Connectors that require no epoxy or polishing have recently been introduced. Manual splicing employing some kind of epoxy is sufficient for most fiber repair. Cost is becoming another attractive feature as production technology is perfected. The abundance of silica will ensure the availability of fiber well into the future. Other advantages of fiber include high data capacity and extreme light weight compared with copper cable.

One application of FO that is receiving some attention is a totally passive, intrinsically safe CH_4 sensing system that exploits the light-absorbing properties of the gas. A literature search was conducted to determine the extent of progress made by researchers in other countries such as Japan, England, Norway, and Australia [3]–[7]. Although working models were reported, attempts to obtain units for independent testing were unsuccessful. Since no commercial units were available, it was necessary to develop an engineering system for research.

FO is also an integral part of the design of an intrinsically safe CO monitoring system. Atmospheric mine monitoring was initiated as a technique to provide early fire warning in coal mines. Combustible materials in these mines such as coal, wood, plastics, and fuels produce CO in the initial stages of fires. Properly installed and maintained CO monitors can reliably detect these fires in their early stages [8]. However, the power supply for the monitors is not as reliable. Mine electrical systems are not intrinsically safe and therefore must be turned off during emergencies. Data from the monitors is soon lost, just when the need for this information may be critical. The objective of the CO work is to develop an intrinsically safe system that will operate on its own power supply for up to several months.

The absorption technique used in the detection of CH_4 cannot be applied to CO because CO has no absorption bands within the optical bandpass of standard silica fibers. Instead,

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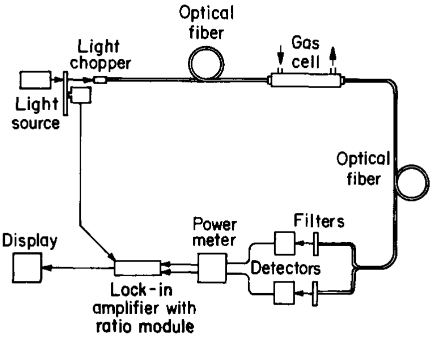

Fig. 1. FO methane sensor.

a system that combines a low-powered electrochemical cell with FO telemetry was chosen.

Rising temperatures as well as increasing CO levels can be indicators of impending disaster in a mine. A commercial system that employs several kilometers of optical fiber as a distributed temperature sensor was recently introduced. Several fibers can be monitored simultaneously. Temperature changes as small as 1° C can be detected, to within a few meters of its actual location, anywhere along the entire length of fiber. In the event the original hot spot should develop into a fire, the system can indicate how far the fire has progressed, even if part of the cable is destroyed. This kind of information would be invaluable to rescue-and-recovery operations. Results of a test conducted at the Bureau of Mine's Lake Lynn Laboratory are reported.

II. METHANE

Fig. 1 shows the components that comprise the FO CH_4 monitor assembled at the Bureau's Pittsburgh Research Center. White light and optical bandpass filters are used to measure CH_4 concentrations using differential absorption techniques. A light beam chopper forms pulses from a tungsten halogen lamp, and a condensing lens focuses the light pulses onto an optical fiber. The fiber then guides the light into the mine to the remote site to be monitored. The light exits the fiber, passes through a 50-cm open-air cell where CH_4 gas may be present, and then re-enters another fiber, which guides the light back out of the mine. A splitter directs the light to two bandpass filters. Detectors behind each of the filters convert the light into electrical signals that are processed to calculate the concentration of CH_4 present in the gas cell.

The CH_4 monitor takes advantage of the optical properties of the gas. CH_4 absorbs infrared energy at two spectral regions within the optical "window" of conventional silica fiber. One spectral band lies near 1666 nm and the other near 1330 nm (Fig. 2). By observing the amount of light returning to the detector at one of these absorption lines, the concentration of CH_4 can be determined. The system was designed to monitor the peak near 1666 nm, primarily because it absorbs much more infrared energy than the 1330 nm peak. A differential detection technique compensates for wavelength-independent fluctuations caused by lamp dimming, lens dust, etc.

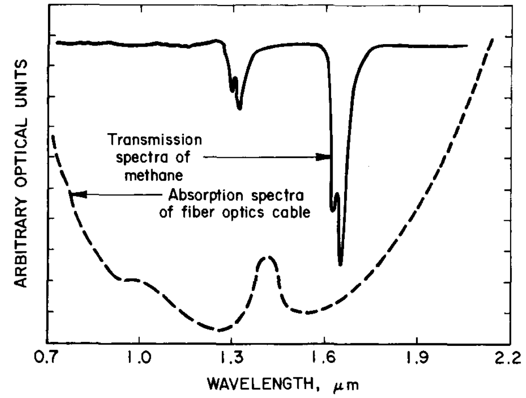

Fig. 2. FO window and methane absorption peak.

A tungsten halogen lamp was chosen for the light source. One of several evaluated proved to meet the requirements of the system. This was a high-output, miniature lamp with a color temperature of 2800° K. (The sensor requires infrared energy at a wavelength of 1666 nm. This wavelength corresponds to a color temperature of approximately 2200° K.) The lamp coupled over 400 nw of power into a lensed 100-m-diameter fiber core and through a 1670-nm center wavelength dielectric interference filter with a half width of approximately 3 nm. The life of the 8-W lamp is rated at 3000 h, which is equivalent to over 4 mo of continuous use.

The CH_4 interacts with the light in the gas cell. A gas cell was constructed using 20-power microscope objectives to couple light between the emitting and receiving fiber. Less than 5-dB loss was measured over a 50-cm optical pathlength. A custom-made field version of the cell was obtained based on these results that had an attenuation of about 6 dB.

Once the light returns from the remote site, a number of different instruments can be used to separate the absorption and reference wavelengths from the broadband beam. One alternative is to split the light and send each beam through a dielectric interference filter. A filter with a center wavelength of 1670 nm and bandwidth of approximately 3 nm was placed in the light path and then tuned to the absorption wavelength of 1666 nm by tilting. An optical powermeter using a cooled germanium detector with a sensitivity of −80 dBm converted the light to an electrical signal. This signal was processed by a lock-in amplifier and other electronics to indicate the actual CH_4 level.

The combination of these components led to the successful detection of CH_4 gas below the lower explosive limit. The minimum detectable concentration of CH_4 as a function of fiber length is illustrated in Fig. 3. There are two primary factors limiting the sensitivity of the monitor. For relatively short lengths of fiber, the sensitivity is limited when the fractional change in power caused by CH_4 absorption is roughly the noise equivalent power (NEP) of the detector. An additional limitation occurs in longer lengths of fiber as the maximum power received at the detector approaches the NEP. This effect is responsible for the sharp upturn in Fig. 3 after 2 km.

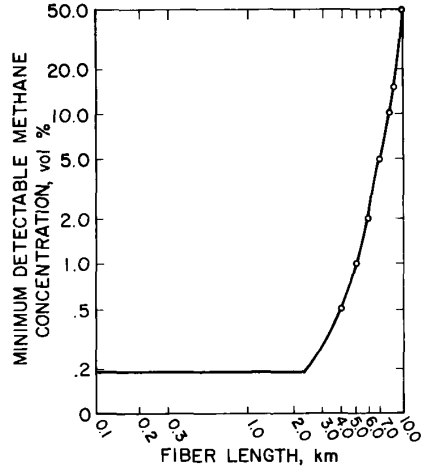

Fig. 3. Minimum detectable methane concentrations.

Modifying different components of the system will have an effect on the performance curve of Fig. 3. To increase the sensitivity in the short range, one can increase the pathlength of the gas cell or use a narrower bandpass filter. This would shift the horizontal portion of the curve downward. These changes also would decrease the optical efficiency of the sensor, tending to shift the vertical portion of the graph to the left. Alternately, increasing the light power or using a more sensitive detector would greatly improve performance in the long range while providing moderate improvement in the short range.

Other hydrocarbons similar in molecular structure to CH_4 were introduced into the gas cell to investigate their effect on the monitor. The response to ethane (C_2H_6) was about one third of the response to CH_4. An unexpected result was observed when propane (C_3H_8) and butane (C_4H_{10}) were introduced into the gas cell. Light levels actually increased for both of these gases, and the increases were proportional to their respective indices of refraction [9].

During a series of in-mine tests, changes in environmental temperature caused a noticeable drift in the output of the monitor. These effects have been seen by other researchers and attributed to the temperature-sensitive optical filters [6].

Light losses from macrobends in the fiber are significant in the 1666-nm region (macrobending refers to bending the fiber into loops with a diameter that is much larger than the fiber diameter) [10]. Macrobend losses in silica fiber become apparent around 1500 nm and increase with wavelength. Choosing a reference wavelength within a few nanometers of the absorption line will minimize the errors caused by this effect. However, excessive bending must be avoided to maintain an acceptable signal-to-noise ratio. Light losses of 20% were observed when 100/140-μm fiber contained in a 3-mm jacket was looped around a 1-cm dowel. Losses decreased to less than 0.1% for loop diameters greater than 6 cm.

One way to avoid macrobending losses is to choose the CH_4 absorption region located near 1330 nm. This is a particularly good spot in the silica fiber "window" as far as attenuation and bending losses are concerned. However, this absorption line is considerably weaker than the 1666-nm line and requires a much stronger light source to obtain an acceptable signal-to-noise ratio.

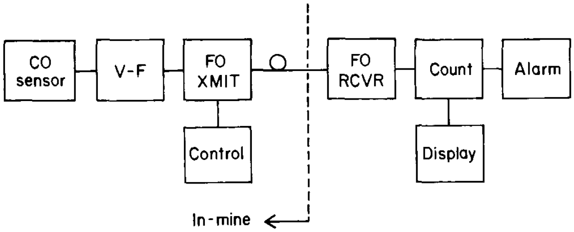

Fig. 4. Carbon monoxide monitor.

III. CARBON MONOXIDE

The CO monitoring system is comprised of a sensing unit located within the mine, which transmits light signals to a receiver (Fig. 4). An electrochemical sensor housed within the sensing unit is powered by a 9-V transistor battery. The transmitter and timing circuitry located in the same enclosure are powered by a 4-C cell, 6-V battery. The sensing unit is designed to operate for up to 2 mo on a single battery charge while meeting Mine Safety and Health Administration (MSHA) intrinsic safety requirements. The electrochemical sensor was designed and fabricated by Giner Inc., Waltham, MA. This sensor uses a cell with an acid form, solid membrane, electrolyte (Nafion TM DuPont) with a three-electrode structure (working, counter, and reference electrodes). To determine the CO concentration, the working to counterelectrode current is measured. The current is derived from oxidation of CO at the working electrode and reduction of oxygen at the counter electrode. This cell was designed to generate 0.4 μA per ppm of CO. The solid membrane electrolyte cell was selected for this application because of its long life (units have operated for 9 yr) and low current consumption (64 μA). The cell requires water that must be replenished periodically.

The 0-to-1-V output of the sensor represents a range of 0 to 100 ppm CO. This output voltage range was offset by 0.1 V to provide a live zero, which is a fail-safe feature that accounts for signal loss from power failure, loss of transmitter, or break in the fiber. Tests were first run on three of the electrochemical units without connection to the transmitter or receiver. Concentrations of CO in air from 0 to 82 ppm were introduced into the units. The average error as expressed as a percentage of full scale (100 ppm) was 1.6% for all readings from the units. At a 10-ppm CO level, the actual errors averaged 0.5% of full scale or 5% of reading. These units were not temperature compensated and yielded an average change of +4 ppm CO response per 10° C increase in temperature at 82 ppm CO. There was no change in response to pure air (zero) over the temperature span of 5 to 40° C. A decrease of ambient pressure of 16% yielded a decrease in response of 7.4% for 82-ppm CO. Response drift measurements taken over 32 days on the three units indicated no change to air without CO and −1.2, −12, and −7.3% change per month to the 82-ppm CO test gas.

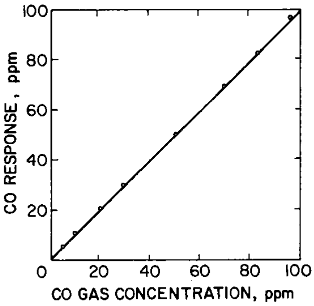

Fig. 5. CO monitor output linearity.

Most of the drift occurred during the first two weeks of test. The times for 90% response to a step increase in concentration from 0-to-82-ppm CO were 67, 81, and 71 s for the three units. After the units were turned off for 48 h, each took 3 min after turnon to indicate zero response (0.1 V). These monitors are also sensitive to other oxidizable gases such as hydrogen, acetylene, nitric oxide, hydrogen sulfide, sulfur dioxide, and nitrogen dioxide. Chemical filters are available for the removal of all of these gases except hydrogen. The hydrogen sensitivity of these monitors was an average of 12.1-ppm hydrogen per ppm CO reading for the three units.

One electrochemical monitor was wired to the digital transmitter with both units housed in a single plastic enclosure and the combined monitor-transmitter unit connected to the digital receiver through a 1-m length of 100/140-μm-diameter silica fiber cable using ST-type connectors. Tests at CO concentrations from 0 to 94 ppm yielded a linear function of CO concentration versus receiver display with an average error of 1.7% full scale indication (100 ppm) (Fig. 5).

A test of system operation with 500 m of FO cable using six ST-type connectors was successful with a measured 9-dB loss in light power. This system uses a light-emitting diode transmitter (Honeywell HFE 4201-015) yielding -17 dBm light power and a receiver (Honeywell HFD 3201-002) that is sensitive to -32 dBm. The use of 100/140-μm-diameter fiber with a loss of 4.5 dB/km (@ 850 nm) would permit a minimum distance of 2.5 km between transmitter and receiver.

IV. TEMPERATURE

Recently, a system that uses a several kilometer length of fiber as a distributed temperature sensor was demonstrated at the Bureau of Mines Lake Lynn Laboratory. The Bureau's Lake Lynn Laboratory, which is a converted limestone mine in southwestern Pennsylvania, is used to conduct underground fire and explosion research under controlled conditions. The system tested was provided by York Technologies, Inc., as a research tool to determine whether or not FO-distributed temperature-sensing technology would be effective in an actual in-mine fire situation. In addition, we needed to know how different FO cables performed compared with more conventional fire-detection techniques. The system was computer-based and included a laser source, time domain reflectometer, optical filters, data analysis electronics, video display, and disk storage capability. Spatial resolution was 7.5 m, and temperature resolution was 1° C.

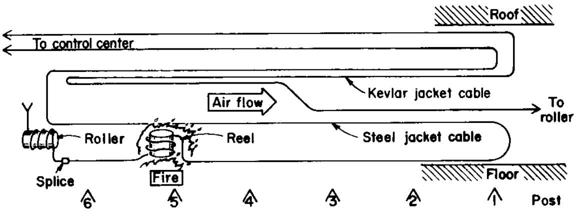

Fig. 6. Test arrangement at Lake Lynn.

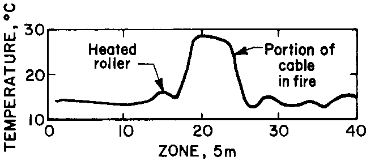

Fig. 7. Temperature versus zone.

The system is based on the Raman effect. When light of any wavelength passes through optical fiber, some photons will be scattered at slightly greater or lesser wavelengths. This phenomenon, which is known as the Raman effect [11], takes place at the quantum level. The scattered (or, more correctly, the re-emitted) wavelengths are called the Stokes and anti-Stokes sidebands. Although orders of magnitude are weaker than the central wavelength, these sidebands are extremely temperature sensitive, and therein lies the mechanism for measuring temperature with this system [12].

Two different fiber cables were chosen for the test. The first was a stainless steel-clad polyamide-coated fiber, and the second was a standard communications-grade Kevlar-reinforced PVC cable. Each test cable was 100 m long since the fire zone was designed to be small. However, to make the test more realistic, two 450-m reels of additional fiber were connected to the ends of the test cable for a total cable length of 1100 m.

The fire zone was in a section of the mine that was about 2.5 m high and 5 m wide (Fig. 6). The fire was fueled by a small volume of coal contained in a steel trough on the floor and ignited by electric resistance heaters. An airflow of 38 m/min was established by distant exhausting ventilation fans. Six posts from ceiling to floor were installed to hold the FO cables at different locations in the fire zone. The distance between the first and sixth posts was approximately 15 m. The PVC and steel-clad fiber were connected in series and strung at various heights above the steel trough. The PVC section was doubled back to follow the same route as the steel-clad fiber. A few meters of FO cable was wound around a conveyor belt roller as part of the test. Although no roller would ever be monitored by wrapping a FO cable around it, this technique could easily be used on electric motors or gearboxes along conveyor lines or on the support structure of the belt line. The conveyor belt roller was heated by a separate electric heating element. In order to test the stainless-steel FO cable in the most severe manner possible, a portion of it was left on its reel and placed directly in the coal.

The computer displayed the data in two formats. The first showed temperature versus time for each zone. A zone was defined as a 5-m length of fiber. The second format showed temperature versus distance (zones) along the entire length of test cable for different times after the separate electric heaters were applied to the coal and roller. Fig. 7 is a sample of the second format at 17 min into the test. The heated roller was in zone 15, the section of cable placed directly in the fire was in zone 22, and the sections of steel-clad fiber directly above the fire were in zones 29, 34, and 40.

Test results showed that a few of the sectors slightly downwind of the coal pile responded to a 2° C increase above ambient within a few minutes of applying power to the resistive heaters in the coal pile. When ignition did occur, all downwind sectors responded. The section of cable placed in the fire continued to operate up to at least 510° C with no apparent degradation. This was the highest temperature the processing electronics could handle without saturation; therefore, the actual temperature it withstood was above this. Results also showed that the Kevlar cable reacted more slowly to rising temperature than did the stainless steel cable at the same location. This was to be expected since the Kevlar jacket provided a degree of insulation to the heat.

Other sensors were included in the test for comparison. The first was a thermal wire cable deployed along the roof of the entry, which was designed to activate at 68° C. It did not respond. A single thermocouple sensor mounted at the roof 3 m downstream of the fire showed a maximum temperature of 44.5° C. A CO sensor deployed 16 m downstream near the roof alarmed at a 10-ppm threshold at 6 min. A smoke sensor at the same location alarmed at about 4 min.

The fire itself was never very vigorous in nature. There was a slowly increasing smoking phase, an ignition after about 10 min, a smoky burn for about 20 min, and a decrease in flame and smoke.

The FO system was such that any zone could be set to alarm at any temperature desired. It was arbitrarily decided to set every zone to alarm at a temperature increase of 2° C above ambient. Under these conditions, certain zones reached the alarm levels in about 4 min, and all were alarmed within about 20 min. If desired, each zone could have been assigned its own alarm level.

V. SUMMARY

The status of the Bureau of Mines research into the application of FO technology to atmospheric monitoring systems is discussed. Accomplishments to date are encouraging, but more research is required before FO technology can make major contributions to atmospheric monitoring systems. A passive, intrinsically safe CH_4 monitor can detect concentrations below the lower explosive limit up to several kilometers away via FO cable. More work, however, is required to compensate for temperature and fiber bending-induced errors. Furthermore, some method of monitoring multiple sites is needed to make the system economical. A unique CO monitoring system, combining a low powered electrochemical cell and FO telemetry, was designed to be intrinsically safe and operate on a single battery charge for several months. Measurements can be made remotely up to several kilometers via FO cable. A single point system has been field tested. Here, the design must be expanded for multipoint monitoring. Finally, a report on a demonstration of a commercial distributed FO temperature monitor is presented. The intrinsically safe fiber sensor can give early warning for equipment that is prone to over heating, such as belt rollers or motors, and can locate the trouble area continuously over several kilometers. Further tests are planned in a working mine conveyor beltway to examine mine worthiness.

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