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REPORT OF INVESTIGATIONS/1995

Optically Powered Remote Gas Monitor

By T. H. Dubaniewicz, Jr., and J. E. Chilton

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	mm	millimeter
cm^3/min	cubic centimeter per minute	mV	millivolt
dB	decibel	mV/ppm	millivolt per part per million
dB/km	decibel per kilometer	mW	milliwatt
dBm	decibel referenced to 1 milliwatt	nm	nanometer
h	hour	ppm	part per million
kHz	kilohertz	s	second
km	kilometer	V	volt
m	meter	W	watt
mA	milliampere	µA	microampere
MHz	megahertz	µA/ppm	microampere per part per million
MHz·km	megahertz kilometer	µm	micrometer
min	minute		

Reference to specific products does not implyu endorsement by the U.S. Bureau of Mines.

Optically Powered Remote Gas Monitor

By T. H. Dubaniewicz, Jr.,[1] and J. E. Chilton[2]

ABSTRACT

Many mines rely on toxic gas sensors to help maintain a safe and healthy work environment. This report describes a prototype monitoring system developed by the U.S. Bureau of Mines (USBM) that uses light to power and communicate with several remote toxic gas sensors. The design is based on state-of-the-art optical-to-electrical power converters, solid-state diode lasers, and fiber optics. This design overcomes several problems associated with conventional wire-based systems by providing complete electrical isolation between the remote sensors and the central monitor. The prototype performed well during a 2-week field trial in the USBM Pittsburgh Research Center Safety Research Coal Mine.

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INTRODUCTION

Canaries alerted the miner to dangerous atmospheric conditions in the early days of mining. Today, many underground mines rely on computerized atmospheric monitoring systems (AMS) to help maintain a safe and healthy working environment. Atmospheric monitoring systems collect data from various types of gas sensors located throughout the mine, and alert mine personnel when a particular gas exceeds allowable levels. These remotely located sensors must have some way of communicating with the central computer, often over very long distances. Reliable communication over these long distances is most important. When properly installed and maintained, AMS operate reliably. However, current trends in the mining industry will make maintaining reliable communications among the remote sensors and central monitor even more difficult. Recognizing this, the U.S. Bureau of Mines (USBM) initiated a program to investigate the application of fiber optics (FO) to the special problems encountered in the mine environment. Most recently, a fiber-optic remote environmental warning system (FOREWARNS) has been developed that uses FO for communications and to deliver power to several remote toxic gas sensors located in the mine.

The prototype system was designed to accommodate sensors for three toxic gases of concern in underground mining: nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Nitrogen dioxide emissions are present in exhaust from diesel-powered machinery; dry atmospheres, such as found in salt mines, exacerbate this problem. Nitrogen dioxide is also a by-product of the detonation of explosives used in underground mines. Sulfur dioxide may be found in the exhaust of diesel machinery using high-sulfur-content fuel. Sources of CO include diesel exhaust, explosive fumes, fires, and air oxidation of pyrophoric coals. Federal mining regulations set exposure limits for these and other noxious gases in underground coal mines (*1*)[3] and underground metal and nonmetal mines (*2*).

Carbon monoxide sensors are also often used for fire detection along conveyor belts because of their susceptibility to fires (coal spilled onto seized rollers, defective motors, etc.). These sensors work well for this purpose because combustible materials in mines such as coal, wood, brattice cloth, conveyor belting, and fuels produce CO gas in the initial stages of fires (*3*). Depending on ventilation rates and other factors, CO sensors may be spaced several hundred meters apart along the belt, often extending many kilometers underground. Highly efficient longwall mining methods, along with depleting reserves, are extending these haulage routes and, therefore, the distance over which the CO telemetry systems must communicate. Distance, coupled with high-power electrical systems of some modern longwall machines, allow telemetry links to be more susceptible to electromagnetic interference (EMI).

Another concern involves the use of conveyer belt air to ventilate working sections of the mine. According to current mining regulations, working sections of a mine may not be ventilated by belt air (*4*). Therefore, an additional entry must be developed to provide fresh air to the working sections. However, a variance to this regulation may be granted allowing the use of belt air for ventilation, provided adequate safety precautions are taken (*5*). One of these precautions is using early-warning fire detection systems like remote CO monitors. If the fire detection system should fail, a fire could quickly send toxic fumes to the working area and block off the remaining escape routes. For this reason, every effort must be made to ensure that early-warning fire detection systems are reliable.

Fiber optics provides reliable long-distance telemetry. The EMI problem associated with wire-based telemetry systems is virtually eliminated in fiber-optic telemetry systems. Fiber optics also eliminates ground loops. Ground potential may vary throughout a mine, which could adversely affect electrical signals. The fragility of optical fiber is a reliability issue with many in the mining industry. However, properly cabled fiber has proven to be surprisingly rugged, as evidenced by the thousands of kilometers of fiber placed on the ocean floor for intercontinental communication systems.

Despite these advantages, FO has not yet made a big impact in industrial applications. One reason is the popularity of the 4- to 20-mA current-loop transmitter. The current-loop transmitters provide a cost-effective solution to grounding problems associated with electrical telemetry systems. This situation will change with the emergence of a fieldbus standard that is intended to facilitate the use of smart sensors in industrial applications (*6*). The fieldbus standard will be based on an all-digital communications protocol to convey information, as opposed to the analog electrical current signal used by the current-loop transmitters. An all-digital communications standard should finally allow the widespread use of fiber-optic cable in applications that are now dominated by current-loop transmitters.

One of the remaining obstacles to widespread use of FO in the mining industry is the need for electrical power at remote sensing locations. Electrical telemetry systems often use the same conductor for power and communication, reducing the number of connections to remote sensors. For this reason, rather than replacing another technology, FO becomes an expensive add-on. However, recent technological

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[3] Italic numbers in parentheses refer to items in the list of references at the end of this report.

developments allow FO to provide communication and power to remote locations in a networked environment as well. Development of FOREWARNS was intended to prove this concept and to familiarize designers with this technology.

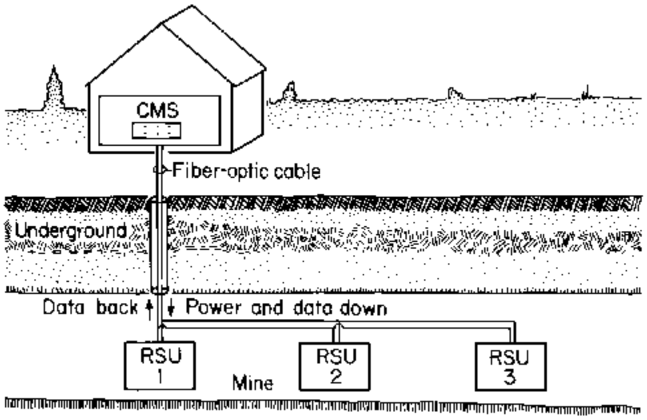
SYSTEM COMPONENTS

A concept drawing of FOREWARNS is shown in figure 1. A central monitoring station (CMS) communicates with and provides power to three remote sensing units (RSU's) via a large-core fiber-optic cable. The CMS consists of a control box with a liquid crystal display, a laser housing, and a laser power supply. The optical signal is distributed to each RSU by a fiber-optic splitter. Each RSU contains a gas sensor, an optical-to-electrical power converter, and telemetry circuitry. The RSU responds to the CMS when polled via standard communications grade, multimode fiber-optic cable and splitters (figure 2).

LASER

A key component of this system is a high-powered, solid-state diode laser. Diode lasers that can launch several watts of power into fiber-optic cable are now available. These solid-state lasers are reliable and require low maintenance compared with other types of lasers. The operating wavelength of the laser should be in the 800-to 850-nm range to efficiently match the power converters at the remote end. The laser selected for this application was a SDL Inc. (formerly Spectra Diode Labs) model SDL-3450-P5 with a center wavelength of 814 nm and a spectral width of 3 nm. The laser consists of an array of diode lasers capable of producing more than 5 W of optical power. The electrical-to-optical conversion efficiency at this power level is 22%. The output of the laser is intensity modulated for simultaneous power and data transmission. The laser diode array couples up to 5 W into a dense, random fiber-optic bundle pigtail terminating in a SMA-type connector. The bundle diameter at the connector is 400 µm, and beam divergence is about 50° full width at half-maximum power.

Figure 1



Communication and power to remote sensors provided by FO.

FIBER-OPTIC LINK

A fiber-optic link distributes the modulated laser power to three RSU's, and provides a return path for communication with the central monitor. A light emitting diode in each RSU transmits information back to the CMS. Fiber-optic connections are shown in figure 3. The fiber bundle coupled to the laser diode array connects directly to a single 400-µm-core-diameter, step index, hard-clad silica, fiber-optic cable. An SMA-type connector is used at this interface; ST-type connectors are used throughout the rest of the link. The numerical aperture (NA) of the single 400-µm-core-diameter fiber is rather large (0.37) to increase coupling efficiency. The laser power is distributed among the three RSU's via two 400-µm-core fiber-optic splitters, with splitting ratios of 3:1 and 1:1. The return path consists of a 62.5-µm-core fiber-optic cable and two splitters with 1:1 splitting ratios. Fiber-optic connectors are used at all interfaces between fiber-optic components for convenience. A substantial savings in the optical power budget can be realized by replacing connectors at the cable-splitter interfaces with fusion splices. One-hundred-meter lengths of cable separate each of the RSU's and the CMS.

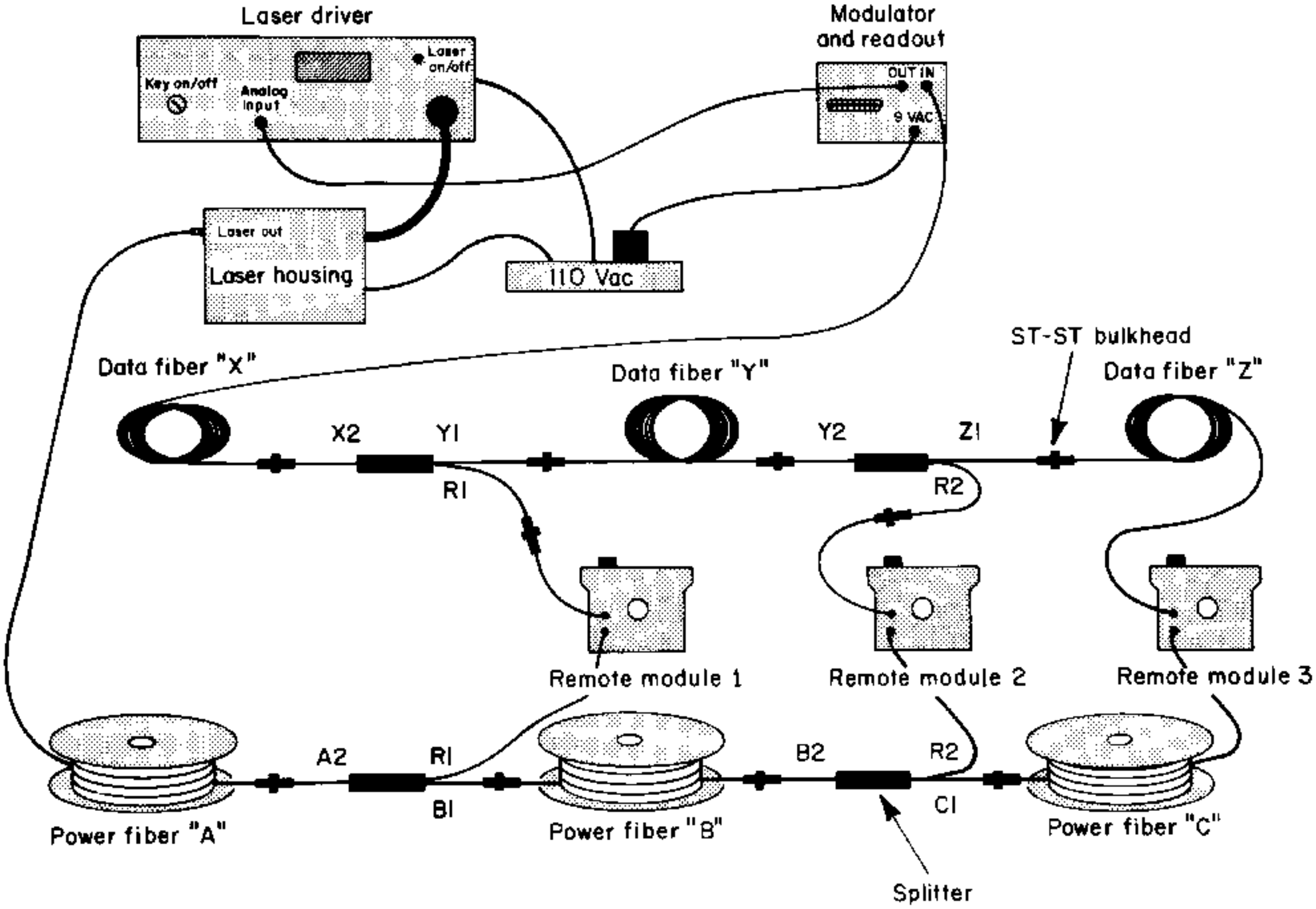
POWER CONVERTERS

An optical-to-electrical power converter in each RSU supplies enough electrical power to operate the sensor and telemetry circuitry (figure 4). These power converters represent another recent technological development. Originally developed by Varian Associates, Inc., and now licensed to Photonic Power Systems, the optical-to-electrical power converters are made of a monolithic gallium arsenide (GaAs) semiconductor device. They convert light into electrical current at voltages appropriate for powering integrated circuits and

Figure 2

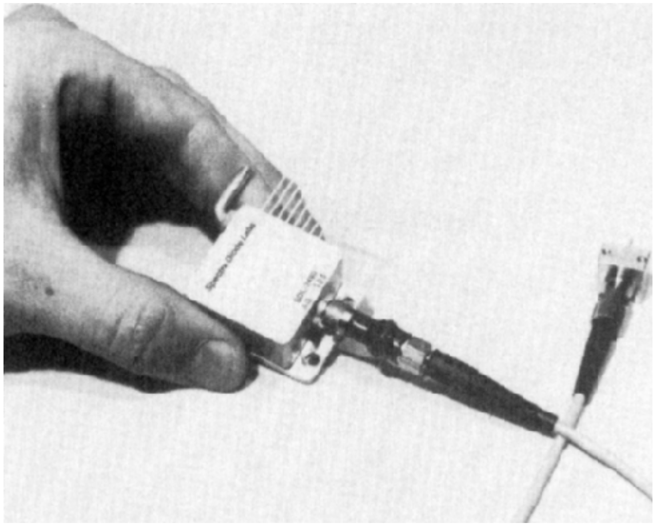
FOREWARNS prototype.

Figure 3



General schematic of FOREWARNS. (Courtesy of Photonic Power Systems)

Figure 4



Optical power supply consisting of fiber-coupled solid-state laser and power converter.

sensors. The illuminated area of the power converter is circular with a diameter of about 3 mm, making it ideal for "power-down-a-fiber" applications. The optical-to-electrical conversion efficiency is approximately 50%, exceeding the efficiency of silicon solar cells. The standard GaAs converter's maximum electrical output power is about 2 W. It can also receive data signals at rates up to 250 kHz for data transmission. Each RSU contains one 6-V power converter.

SENSORS

All the sensors used in FOREWARNS contain electrochemical sensing elements. Electrochemical-type sensors work well for this application because of their extremely low power consumption. Besides the CO, NO_2, and SO_2 sensors used in the current system, there are numerous other gases that can be monitored with electrochemical sensors suitable for use with FOREWARNS.

The USBM tested a total of three Giner, Inc., model WMCO100 CO monitors (*7*). Each CO sensor has a cell containing a solid membrane electrolyte (Nafion TM DuPont). Three electrode structures (working, counter, and reference electrodes) are pressed onto the solid electrolyte. Carbon monoxide concentrations are determined by measuring the working-to-counter electrode current. Oxidation of CO at the working electrode and reduction of oxygen at the counter electrode produces thiscurrent. The cell generates about 0.4 µA/ppm of CO detected, and requires only 64 µA of bias current at 6 V. The sensor provides a 10-mV/ppm output voltage. In addition to low power consumption, the sensor also exhibits unusually long life (similar units have operated for 9 years in the laboratory). The CO cells require periodic water replenishment. The 0- to 1-V output of the sensor corresponds to a range of 0 to 100 ppm of CO.

The USBM also tested a City Technology Ltd. NO_2 sensor (model 3MNDH) and SO_2 sensor (model 3MSH). These sensors also use a three-electrode structure similar to the CO sensors; however, the electrodes are contained within an aqueous solution cell as opposed to being pressed onto a solid membrane electrolyte. The NO_2 and SO_2 sensors also produce about 0.4 µA/ppm internally, and provide a 10-mV/ppm output voltage. Power requirements are 250 µA at 9 V. A voltage multiplier circuit increases the voltage available from the 6-V power converter to ensure proper sensor operation. The NO_2 and SO_2 sensors do not require water replenishment and are less costly than the CO sensors; however, they do need to be replaced more often (expected operating life is 2 years at standard temperature and pressure).

CONTROL AND ALARM

Photonic Power System's Isolated Power and Data Module System controls communication between the RSU's and the CMS. The CMS sequentially polls and displays the identity of each RSU, sensor output, and alarm threshold. The parallel configuration of FOREWARNS is fault tolerant to a malfunction or disconnection of any of the RSU's. Each RSU can be set to alarm at any interval from 1 to 99 ppm, in 1-ppm intervals, by switches located on the remote telemetry board. An 8-bit analog-to-digital converter (ADC) converts the analog sensor signal to a digital signal. When the sensor reading is greater than the set point for that sensor, the remote station generates an alarm signal. Since the alarm signal is generated at the remote location, it could be used to activate a nearby battery-powered personnel alarm. Each RSU has a remote audio alarm powered by a 9-V transistor battery to demonstrate this feature. Long battery life can be expected as the battery is used intermittently, only during an alarm. The battery could also conceivably act as a backup power source for the remote unit and sound the alarm in the event the fiber-optic link was severed. A local alarm at the CMS sounds only when a sensor in alarm status is polled. At the sensor end, the remote alarm sounds continuously when the threshold levels are exceeded.

RESULTS

FOREWARNS was calibrated in the laboratory prior to undergoing a field test in the USBM Pittsburgh Research Center Safety Research Coal Mine (PRC-SRCM). The PRC-SRCM, operational since the early 1970's, is a room-and-pillar operation approximately the size of a working section in a commercial coal mine. It is used for testing new equipment and technology before transferring them to industry.

CALIBRATION TEST

One of the CO sensors was installed in a RSU and tested to determine how accurately FOREWARNS tracked the sensor output. The accuracy of FOREWARNS largely depends on three factors: accuracy of the sensor itself, resolution of the ADC, and resolution of the display. The sensor was exposed to several CO calibration gases at a rate of 95 cm^3/min. In these tests neither the laboratory temperature nor atmospheric pressure were controlled.

Table 1 summarizes the results recorded after 90 s of exposure. Column 1 corresponds to the value indicated on the calibration gas bottle, column 2 shows the voltage output of the sensor, and column 3 is the gas concentration reported by FOREWARNS. Combining the resolution of the 8-bit ADC over the 0- to 1-V output span of the sensors and the display resolution (1 ppm), the displayed measurement should be within ±0.5 ppm of the reading indicated by the sensor (column 2). The results in column 3 fall within this range.

FIELD TRIAL

FOREWARNS was tested for 2 weeks in the PRC-SRCM. Carbon monoxide, nitrogen dioxide, and sulfur dioxide RSU's were placed inside the mine, each separated by 100 m of cable (figure 5). All RSU's and cable were placed in intake air. The CMS was located in the mine office just outside

Figure 5

Underground test of CO remote sensing unit.

mine the portal. A 100-m length of cable was also used to separate the CMS and the NO_2 RSU. The sensors were challenged with a calibration gas twice a day during the first week, and once a day the second week. All sensors responded when exposed to the calibration gas. The RSU's were set to alarm when the sensor reading reached the calibration gas concentration; the longest alarm response time observed was just under 3 min.

Table 1.—Monitor response to CO calibration gas

CO concentration, ppm	Sensor output, mV	Monitor response, ppm
0[1]	8	1
24	249	25
60	620	62
100	988	99

[1] Pure air.

TELEMETRY DESIGN ANALYSIS

The two parameters that tend to be the dominant design criteria for fiber-optic telemetry systems are the transmission rate (how fast) and link length (how far) (*8*). The transmission rate of this system was chosen to be 5 kHz for two reasons: First, at 5 kHz the sensors can be easily interrogated about once every 10 s, which is sufficient for many applications; second, modulating several amperes of laser-diode current becomes increasingly difficult at higher transmission rates. This transmission rate is sufficiently low that bandwidth limitations on the maximum allowable length of fiber-optic cable are negligible (the bandwidth-length product of the 400-µm fiber-optic cable is 13 MHz·km), leaving only the optical power budget to be considered.

The optical power budget of a fiber-optic communication system is usually defined in terms of optical power levels needed to maintain an acceptable bit error rate (digital systems) or signal-to-noise ratio (analog systems). For this system, however, the optical power budget must also be defined in terms of the amount of optical power needed to maintain acceptable voltage and current at the remote sensor. This is the only consideration on the power and data-down link because the sensor will cease to function properly before light levels approach the signal detection limit of the GaAs power converter. Receiver sensitivity on the data-back link must still be considered.

OPTICAL POWER BUDGET: POWER AND DATA-DOWN LINK

Researchers determined the minimum laser power needed to operate the remote sensors experimentally. First, each RSU was exposed to a test gas, then the laser power was decreased gradually until the unit failed to respond. The peak power measured at each RSU input just prior to sensor failure was about 70 mW for each. The average optical power at cutoff is about half of this value, as the laser output fell below the lasing threshold at minimum signal modulation. The losses associated with the fiber-optic components in the power and data-down link are listed in table 2 (refer to figure 3).

Table 2.—Optical losses in power and data-down link

Component	*Loss, dB*
400-µm core fiber, per kilometer	6.0
ST-ST connections (typical)	0.5
Fiber bundle to single fiber connection	2.3
1 by 2 coupler, 3:1 split ratio:	
A2-R1	5.7
A2-B1	1.5
1 by 2 coupler, 1:1 split ratio:	
B2-R2	3.8
B2-C1	3.4

OPTICAL POWER BUDGET: DATA-BACK LINK

The overall power margin for a single transmitter-receiver pair is about 10 dB. The losses associated with the fiber-optic components in the data-back link are listed in table 3 (refer to figure 3).

Table 3.—Optical losses in data-back link

Component	*Loss, dB*
62.5-µm core fiber, per kilometer	3.0
ST-ST connections (typical)	0.6
1 by 2 coupler, 1:1 split ratio:	
R1-X2	3.8
Y1-X2	3.55
1 by 2 coupler, 1:1 split ratio:	
R2-Y2	3.7
Z1-Y2	3.54

LASER SAFETY ISSUES

HUMAN EXPOSURE

All lasers should be operated in compliance with appropriate safety standards. The American National Standards Institute (ANSI) Standard Z136.1 provides guidance for the safe use of lasers and laser systems in terms of human exposure (*9*). The standard defines control measures for each of four laser classifications. The laser used in FOREWARNS is an ANSI class-4 laser emitting an invisible infrared beam of high power contained within a fiber-optic cable. Under normal operating conditions, the laser beam is enclosed within the fiber-optic cable and terminated in a RSU so as not to pose a skin or eye hazard. Another control measure not defined in the Z136.1 standard can also help reduce the risk of injury due to exposure: The system can be designed to automatically shut off if communication is interrupted due to cable disconnection or breakage.

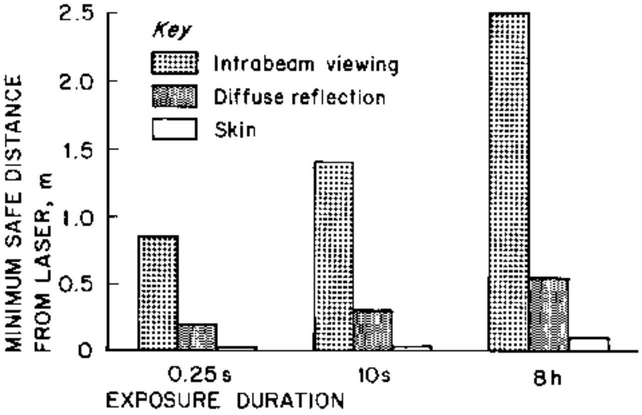
One characteristic of the system is the large divergence of the beam exiting the cable at the cleaved and polished connector interface. The angle subtended by the diverging beam (Θ) can be determined from the NA of the step index optical fiber by the equation $\Theta = 2\sin^{-1}(\mathrm{NA})$.

The NA of the 400-µm cable is 0.37; therefore, Θ is about 43°. With this large divergence, the intensity of the beam weakens dramatically with increasing distance from the emitting surface as compared with other types of lasers. The implications in terms of human exposure are best illustrated by a laser hazard evaluation conducted by Rockwell Laser Industries. Rockwell's LAZAN hazard analysis software calculated the Maximum Permissible Exposure (MPE) limits for various exposure conditions based on the laser operational characteristics listed in table 4. The MPE is defined as the radiant exposure that personnel may receive without adverse biological effects. The MPE was then used to determine the Nominal Ocular Hazard Distance/Nominal Hazard Zone (NOHD/NHZ). The NOHD/NHZ is defined as the distance from a laser at which the radiant exposure is equal to the MPE. Figure 6 shows the NOHD/NHZ for various exposure conditions as determined by LAZAN.

EXPLOSION HAZARD

Another safety concern involves fiber-coupled optical ignition of combustible atmospheres (*10-20*). According to Federal mining regulations, components of AMS installed where permissible equipment is required shall be intrinsically safe (*21*). Currently, there are no standards or guidelines on the safe use of fiber-optic systems in hazardous (classified) locations in the United States. Without these standards, approval agencies are not likely to approve laser-coupled fiber-optic instrumentation as permissible equipment. The International Society for Measurement and Control (formerly the Instrument Society of America) has formed the SP12.21 Fiber Optics subcommittee to establish guidelines and to be a source of information on this subject. The subcommittee is currently working with international organizations with similar interests to establish an international standard for the safe operation of fiber-optic systems in hazardous locations.

Figure 6



Nominal ocular and skin hazard distances for laser characteristics (listed in table 4).

SUMMARY

A toxic gas monitoring system that powers and communicates with three separate remote sensors over fiber-optic cable has been demonstrated. The system performed well during a 2-week trial in the USBM PRC-SRCM. The primary advantage for this particular application is enhanced reliability afforded by fiber-optic telemetry in locations where electrical power may not be readily available. The design is based on state-of-the-art optical-to-electrical power converters, solid-state diode lasers, and FO. The digital approach taken is in line with emerging industry telemetry standards.

Laboratory and field tests led to several observations. Difficulties in modulating several amperes of laser-diode current places a practical limit on the maximum transmission rate of this system. The 5-kHz rate chosen is sufficient for many applications. Remote sensor stations required about 35-mW average optical power. Control measures defined by existing laser safety standards can reduce the risk of injury resulting from physical exposure; however, no such standards exist in the United States regarding explosion hazards. Approval agencies are not likely to approve laser-coupled fiber-optic instrumentation as permissible equipment in hazardous (classified) locations until such standards are established.

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