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## Hybrid Fiber-Optic Electrochemical Carbon Monoxide Monitor

By J. E. Chilton and C. R. Carpenter

UNITED STATES DEPARTMENT OF THE INTERIOR



BUREAU OF MINES

**Report of Investigations 9423**

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### UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	μA	microampere
dB	decibel	μA/ppm	microampere per part per million
dB/km	decibel per kilometer	min	minute
dBm	decibel referenced to 1 milliwatt	mL/min	milliliter per minute
fpm	foot per minute	mm	millimeter
ft	foot	μm	micrometer
h	hour	mm Hg	millimeter of mercury
Hz	hertz	ms	millisecond
in	inch	nm	nanometer
kHz	kilohertz	ppm	part per million
km	kilometer	s	second
m	meter	V	volt
mA	milliampere		

# HYBRID FIBER-OPTIC ELECTROCHEMICAL CARBON MONOXIDE MONITOR

By J. E. Chilton<sup>1</sup> and C. R. Carpenter<sup>2</sup>

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## ABSTRACT

The U.S. Bureau of Mines has developed an intrinsically safe carbon monoxide (CO) monitoring system for mines by coupling a fiber-optic data telemetry (FODT) system with a prototype electrochemical CO monitor. The CO monitoring system can be used in a coal mine as one component of an early fire warning system. This system may be used in belt haulage entries when the entries are used for supplying ventilation air to working places. The FODT accepts a 0.1- to 1.1-V analog signal from the monitor and converts it to pulses (0 to 5 V) at frequencies from 1.1 to 11 kHz that drive a light-emitting diode (LED). An electrically nonconducting fiber-optic cable carries the LED signal to a remote receiver. The receiver analyzes the incoming light signal and displays the measured CO concentration in parts per million. This report discusses the performance of the FODT system and characteristics of the CO monitor such as response times, linearity, and temperature and pressure effects.

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## INTRODUCTION

Carbon monoxide (CO), a toxic and odorless gas, is present in many underground mines. Sources include diesel exhaust; explosives fumes; fires involving coal, wood, brattice cloth, or conveyor belting; and air oxidation of pyrophoric coals. The ambient concentrations in coal mines in Pennsylvania and West Virginia are 0 to 4 ppm CO and for some coal mines in Illinois and Colorado are 12 ppm CO.

Often, CO monitors are used in underground coal mines for fire detection on conveyor belt entries (1).<sup>3</sup> More than 112 coal mines have installed CO monitoring systems to test the air traveling in belt haulage entries to ensure that it can be safely used to ventilate the active workings (2). In these instances Mine Safety and Health Administration (MSHA) guidelines require these systems to have CO monitors at the beginning and end of each belt flight and allow a maximum of 2,000 ft between additional monitors. The monitors are set for alert alarm at 10 ppm CO above ambient and for full alarm at 15 ppm CO above ambient. MSHA has now proposed new ventilation standards for underground coal mines. These standards would reduce the spacing intervals for CO monitors to a maximum of 1,000 ft and set alarm levels to 5 and 10 ppm CO above ambient in belt haulage entries with air velocities less than 300 fpm (3). CO monitors in mines must be stable and accurate at least to 1 ppm CO for effective alarm service.

The CO monitors placed on belt haulage entries must detect fires but could, in addition, be used to verify the quality of the belt haulage ventilation air with regards to CO (4). The average concentration of CO in the belt haulage ventilation air must be below both the exposure limits for miners and the lower fire alert value.

Commercial in-mine CO monitors that transmit monitoring data by electrical signals over copper wires (5-6) depend on power from underground electrical stations. Both four-wire systems—two for power and two for data transfer—and three-wire systems—one for power and one for data transmission with one wire common to

both—are used. Data transmission is either analog, using 4- to 20-mA current loops, or digital, using frequency shift keying. Although the approved CO monitors are intrinsically safe, the power supplies are not. In the event of a fire or explosion, all mine power may be disconnected. Without electricity, the monitors operate on standby batteries for up to 4 h, but after the batteries discharge, the gas monitors are inoperative. Thus, in mine emergencies when information on mine gas concentrations could help determine fire status and location, no information would be available. As part of its goal to improve the health and safety of underground coal mining, the U.S. Bureau of Mines is working to create improved CO monitoring systems.

There are several properties of fiber-optic cables that make them advantageous for use in mines: The fiber is electrically nonconductive and thus, cannot ignite methane by sparking. Silica fiber is immune to radio frequency or electromagnetic pulse interference from electrical sources. The cable is lightweight, and communication-grade fiber is inexpensive compared with copper wire.

Several researchers have announced the development of prototype fiber-optic methane sensors based on the differential absorption of infrared energy. Silica fiber has excellent light transmission characteristics at wavelengths from 850 to 1,800 nm. For example, the 100- $\mu$ m-core-diameter silica fiber used in our tests has a light loss of only 2.5 dB/km at 1,550 nm wavelength. Methane, absorbing at 1,668 nm wavelength, is thus a prime candidate for measurement by differential absorption of infrared light transmitted by silica optical fibers. CO, however, has no strong absorption bands in the silica transmission range. Its strongest absorption is at 4,700 nm wavelength, which is above the infrared transmission range for silica. Therefore, direct estimation of CO by ordinary light absorption measurements is not possible with silica fiber-optic cable. Other schemes can be devised for measurement of CO, such as solid-state oxidation or chemical reaction with color change. However, only the electrochemical CO sensor has the required properties of sensitivity, reversibility, and stability necessary for a mineworthy CO monitor.

<sup>3</sup>Italic numbers in parentheses refer to items in the list of references at the end of this report.

## ACKNOWLEDGMENT

The authors thank Robert S. Zirkle, physical science aid, for conducting the chamber tests of the CO monitors,

carefully recording the data, and performing statistical analyses of the data.

## CARBON MONOXIDE MINE MONITOR

The Bureau has developed a CO monitoring system that couples a prototype electrochemical CO monitor with a Bureau-developed fiber-optic data telemetry (FODT) system. Many publications have described the operation of electrochemical CO sensors (7-9). The CO is oxidized at the working electrode or anode to form carbon dioxide. The counter electrode or cathode reduces oxygen from air. The current from this cell is proportional to the CO concentration. In all these sensors, the CO diffuses to the cell through a membrane, capillary tube, or diffusion chamber.

### ELECTROCHEMICAL SENSOR

For this effort, a CO monitor that has very low electrical power requirements was specifically designed and fabricated for the Bureau (10). This monitor uses a cell with an ion-exchange membrane solid electrolyte with a three-electrode structure (working, counter, and reference electrodes). The current measured between the working and counter electrodes is approximately  $0.4 \mu\text{A/ppm CO}$ . This solid-membrane electrolyte cell was selected for this application because of its long life (units have operated for more than 9 years) and its low working current ( $64 \mu\text{A}$  at 0 ppm CO).

The Giner, Inc., model WMCO100 CO monitor has a range of 0 to 100 ppm CO with an output of 0 to 1 V. As

noted, in the electrical circuit (fig. 1), a constant voltage source sets a fixed voltage between the reference electrode and the working electrode. The current between the working electrode and the counter electrode is converted to a voltage, and amplified to give an output of 1 V for 100 ppm CO. For our application, the voltage was offset to 0.1 V for 0 ppm CO and 1.1 V for 100 ppm CO. With this offset, a 0-V output would signify sensor system failure. The CO monitor uses a 9-V transistor battery, which powers the sensor for more than 2 months. The sensor has a reservoir containing water to keep the membrane hydrated. Both the sensor battery and the water supply would have to be checked, and replaced if necessary, during each 30-day calibration. This monitor is housed in a 7.5- by 7.5- by 5-in fiberglass NEMA 4X enclosure. The enclosure is coated inside with flame-sprayed nickel metal to protect from both radio frequency and electromagnetic interference.

### FODT TRANSMITTER

The FODT transmitter (Tx) board (fig. 2) is housed in the same enclosure as the CO monitor. Four C cells power the Tx board for up to 2 months. The data signal (0.1 to 1.1 V) from the CO monitor is fed to the voltage-to-frequency (V/F) converter on the Tx board through a

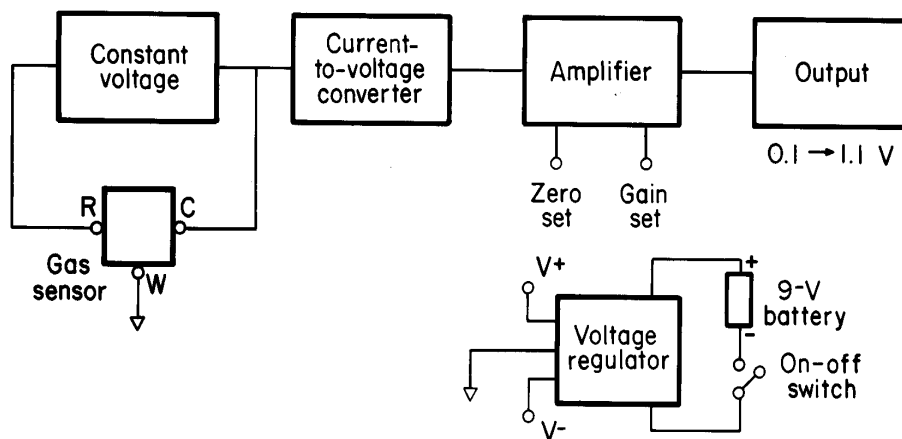


Figure 1.—Giner, Inc., CO monitor system diagram. Gas sensor includes reference (R), counter (C), and working (W) electrodes.



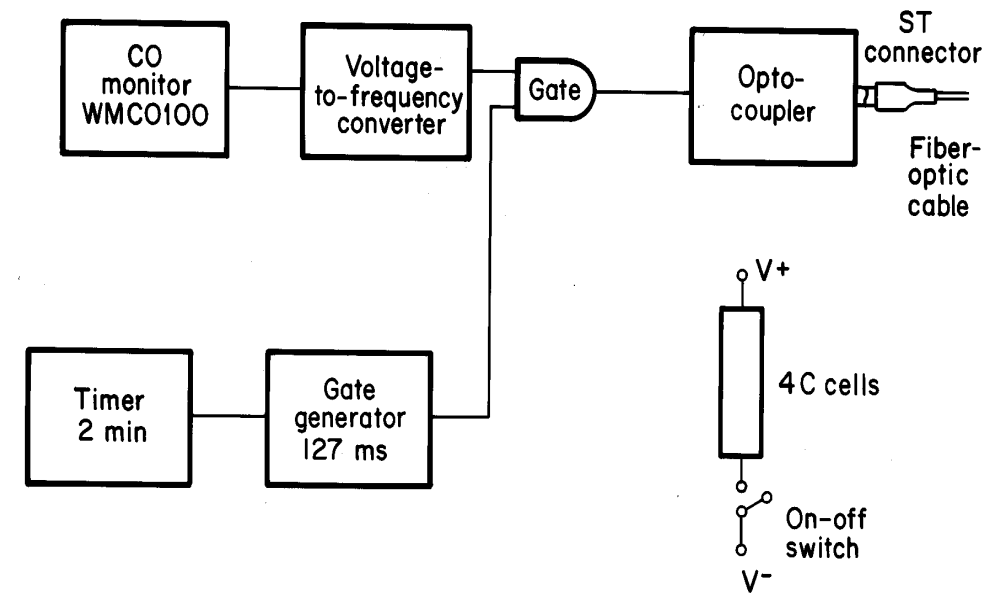


Figure 2.—CO monitor-optical transmitter diagram.

voltage limiter circuit. The voltage limiter prevents over-range data signals (as high as 2.5 V) from exceeding the maximum allowable input signal of 1.5 V to the V/F converter. The output signal from the V/F converter is a 1- to 11-kHz square wave, swinging from 0 to 5 V. The Tx board has a 2-min timer that sets the output repetition rate. The 2-min interval is about twice the response time of the CO monitors. The timer initiates a 127-ms gating signal. This signal and the output from the V/F converter are the inputs to the gate circuit. The output from the gate is a 127-ms burst of 1- to 11-kHz pulses occurring every 2 min. This burst of pulses drives the optocoupler containing an 850- $\mu\text{m}$ -wavelength light-emitting diode (LED), which converts the electrical energy to light. ST-type connectors were used on 100/140  $\mu\text{m}^2$  silica fiber-optic cables to connect the Tx to a remotely located receiver (Rx). The enclosure containing the CO monitor and Tx would be placed at a given location in the mine (fig. 3). The Rx unit would be located and electrically powered on the surface.

For safety, the CO monitor and the Tx were designed to work from low-voltage sources. Such a design helps to minimize the potential for methane ignition in case of electrical or mechanical failure. However, MSHA must

<sup>4</sup>This designation refers to 100- $\mu\text{m}$ -core-diameter fiber with 140- $\mu\text{m}$ -diameter cladding.

evaluate this system before it can be used in areas where permissible equipment is needed.

The Tx and Rx are configured with a CO sensor for this application. It is apparent, however, that the Tx and Rx units could be attached to any sensor with a 0- to 1-V output. Thus mine sensors, such as temperature, pressure, airflow, oxygen or methane gases, or binary switches, such as belt haulage on-off switches, could be used with these fiber-optic-connected Tx and Rx units.

#### FODT RECEIVER

The Rx (fig. 4) detects the light pulses from the fiber-optic cable with an optoreceiver. The pulses are counted and displayed as ppm CO. The Rx unit accurately displays CO concentrations from 0 to 100 ppm CO. Above 100 ppm, the indication is nonlinear, showing 150 ppm CO for atmospheres containing 250 ppm CO or greater concentrations. Below 0 ppm CO (voltages below 0.1 V), the Rx shows a numerical value of 999.9 or less. Audible and visible alarms indicate loss of light signal, underranging, and overranging conditions. The Rx is powered by 115-V ac 60-Hz mains that are separate from the mine's underground power system. Thus, the CO monitor will continue to operate after a mine emergency or fire for at least 1 month using the built-in batteries.

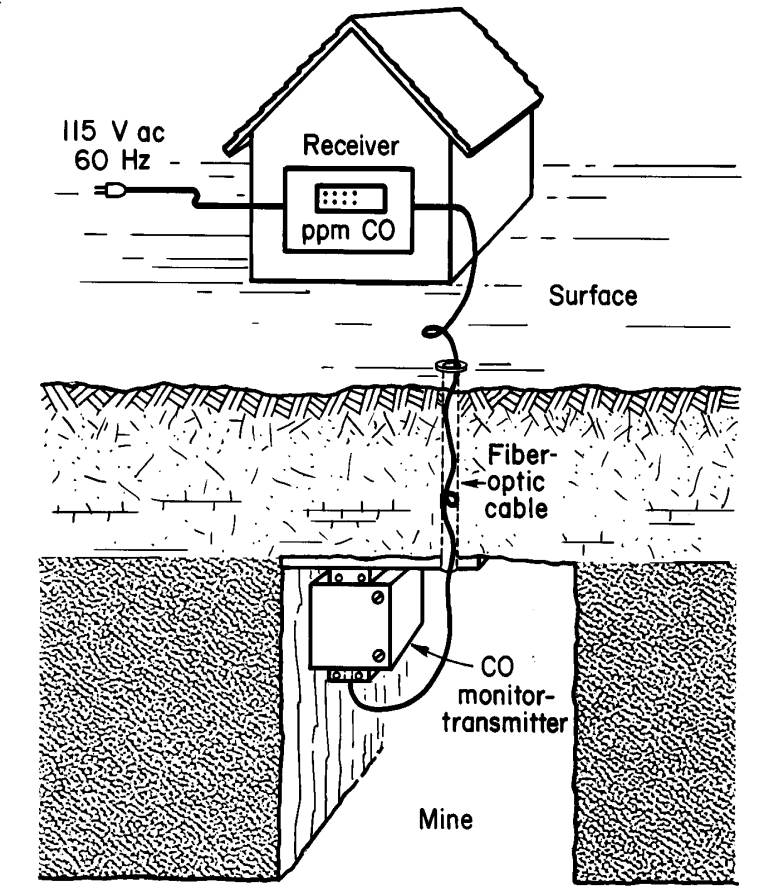


Figure 3.—CO mine monitor telemetry system using fiber-optic cable.

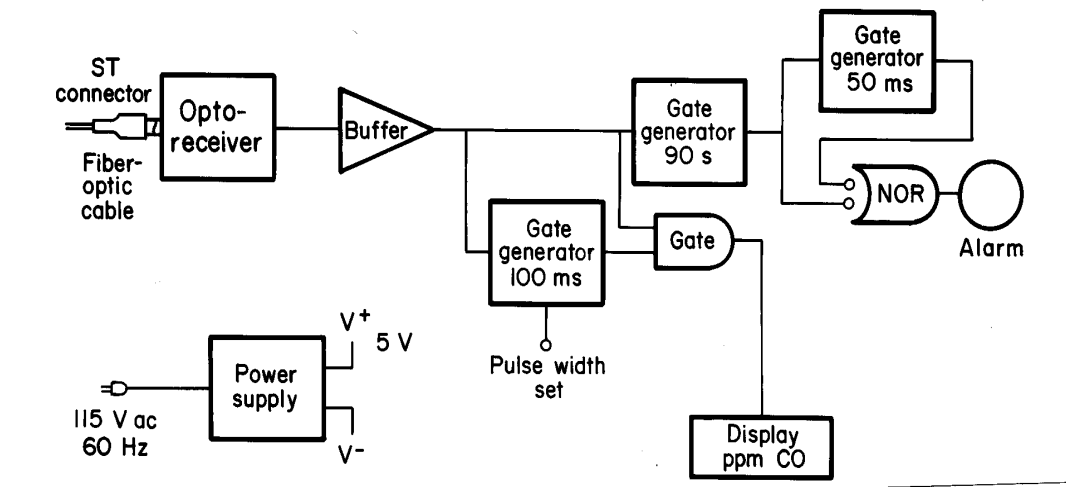


Figure 4.—Fiber-optic receiver diagram.

## TESTS OF MONITOR-FODT SYSTEM

Bureau researchers tested the CO monitor-FODT system with 400 m of optical fiber cable and four ST-type connectors joining the Tx and Rx sections. The system gave equal response as when connected to 1 m of fiber-optic cable. An optical average power meter measured a loss of 9 dB light power through the 400 m of fiber-optic cables with four ST-type connectors. The system uses a Tx LED yielding -17 dBm light power and an Rx sensitive down to -32 dBm. These test data are used to calculate that a maximum distance of 2.5 km between Tx and Rx units is possible using the 100/140  $\mu\text{m}$  silica optical fiber with a stated loss of 4.5 dB/km (at 850 nm wavelength).

In addition, underground tests were conducted by placing the CO monitor and Tx unit in a drift in the Bureau's experimental coal mine. The Rx unit was in the mine supervisor's office, 200 m from the Tx unit. Two miners secured the optical fiber cable to the roof and ribs with wire loops placed every 2 m. The lightweight fiber-optic cable was easy to deploy and recover. Applying a calibration standard test gas of 60 ppm CO from a portable gas cylinder to the sensor produced a reading of 57.9 ppm CO back at the Rx. In laboratory tests, this standard gas produced an indication of 55 ppm CO.

## CARBON MONOXIDE MONITOR RESPONSE TESTS

CO monitors used in mines have many performance requirements. Accuracy must be within 1 ppm CO at 10 ppm CO. Drift must be minimal so calibration is necessary only every 30 days. Response times must be under 2 min. Low electrical power usage, minimum interference from other mine gases, and minimum effects of temperature and pressure changes are all required or recommended features. Many of these requirements are described in another publication (11).

The Bureau tested the performance of three Giner, Inc., model WMCO100 CO monitors (fig. 5). Figure 6 shows a monitor with the fiber-optic Tx. These three monitors, labeled PT-1, PT-2, and PT-3, were tested initially using the manufacturer-supplied calibration fixtures to apply the test gases. The calibration fixtures (figure 7-upper) were 15/16-in-diameter, Lexan<sup>5</sup> plastic holders threaded to fit the gas diffusion port at the bottom of the case. The test gas flowed into the fixture through a 1/16-in-diameter tube. A 1/16-in hole was drilled into the fixture for a gas exit. The modified calibration fixture (figure 7-lower) was designed to give minimum test gas pressure but was not used in the tests. During the first tests, the case doors were open to accommodate electrical leads connecting the monitor to a digital multimeter. Another set of tests was run in a controlled-temperature chamber with the case closed. Small-diameter wires running through the door gaskets served as electrical leads to the multimeter.

### RESPONSE TESTS

Tests were conducted to examine the effect of sample gas flow on the response of the CO monitors. Pressurized

cylinders supplied test gases, and mass flow controllers set the flow. The mass flow controllers are part of a dynamic gas-mixing system designed at the Bureau (12). Response changes of the monitors were measured as a function of gas flow. The monitors were initially at equilibrium with air. At the start of the test, CO was fed by tube into the calibration fixture. Figure 8 shows the effect of test gas

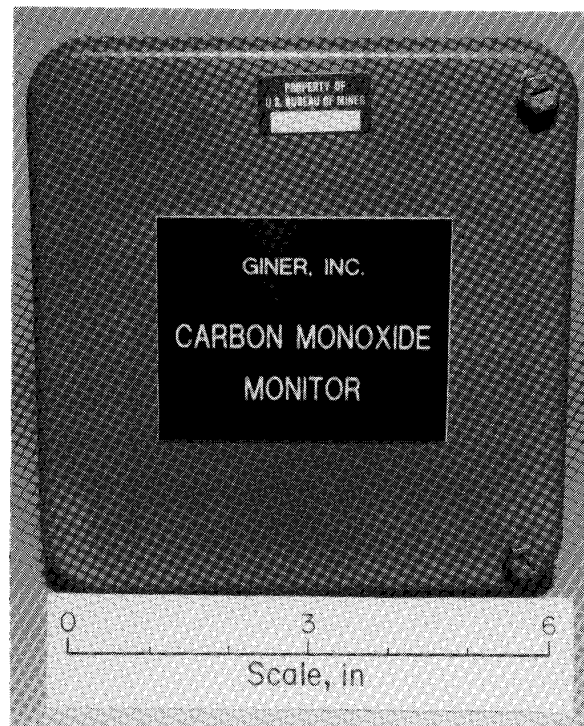


Figure 5.—Giner, Inc., CO monitor.

<sup>5</sup>Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

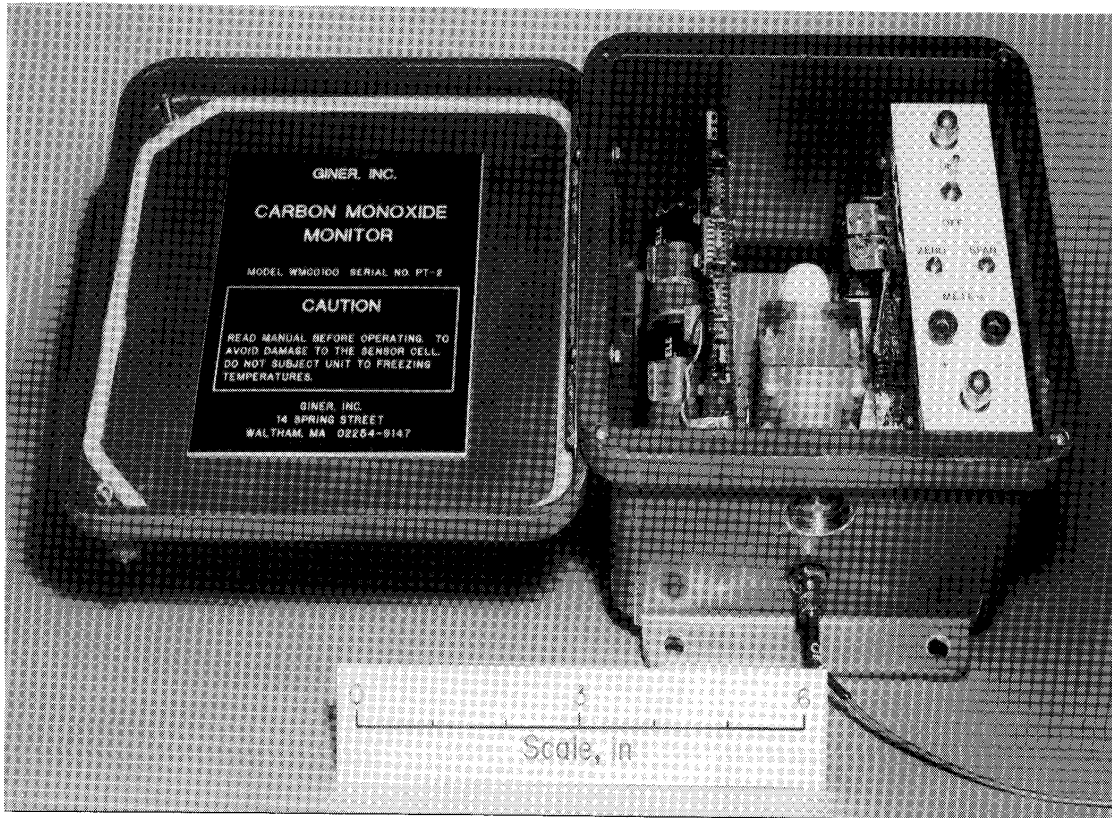


Figure 6.—Giner, Inc., CO monitor with transmitter.

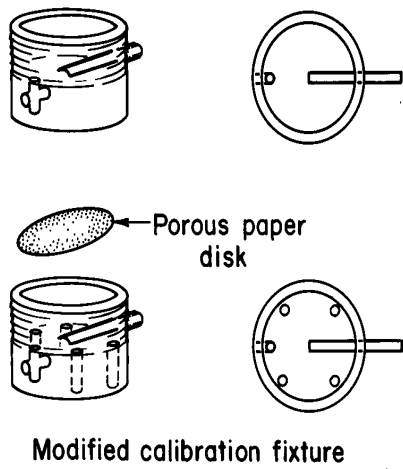


Figure 7.—Calibration fixture for CO monitor depicting plastic holder and metal inlet tube.

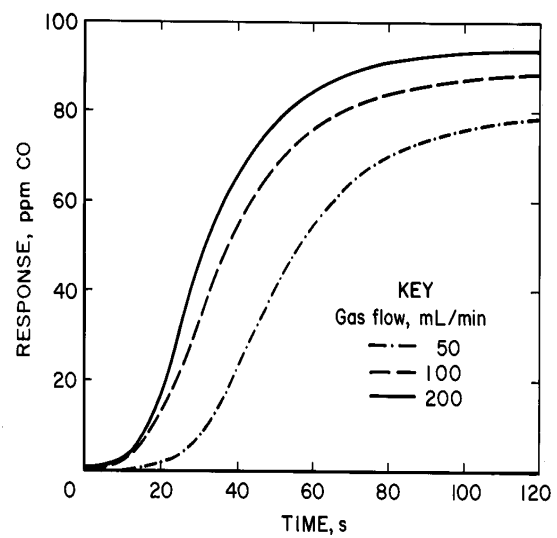


Figure 8.—Effect of gas flows with 82 ppm CO test gas on CO monitor response.

flow rates from 50 to 200 mL/min on the rise times<sup>6</sup> and on the final response values for monitor PT-1. Table 1 lists rise times measured with the three monitors for different test gas flow rates.

Response recovery times<sup>7</sup> were measured for each monitor by feeding air at a flow of 100 mL/min through the calibration fixture after the monitor was at equilibrium in the test gas. A graph of the responses (fig. 9) shows that the recovery times were 67, 82, and 80 s. These recovery times are the same magnitude as the rise times whenever test gases are fed through calibration fixtures.

Table 1.—Rise times for each CO monitor, seconds

Flow, mL/min	PT-1	PT-2	PT-3
50 .....	89	98	96
100 .....	67	81	71
200 .....	62	67	66

Response times of these monitors were also measured in a controlled-temperature chamber. Each monitor was placed in the air-filled chamber with tape placed over the monitor's gas port. The chamber was filled to 40 ppm CO by mixing 990 ppm CO with air in the chamber. A fan circulated this mixture, moving the gases from the bottom of the chamber to the top at about 40 fpm. The rise time test was started by pulling the tape off the port, using the chamber gloves to avoid upsetting the atmosphere. After the rise time tests, recovery time tests were then run by opening the chamber door, allowing the chamber gases to be replaced by air. Figure 10 shows both rise and recovery curves for PT-3. Table 2 lists the average of these values for each monitor.

Table 2.—Chamber test response times, seconds

Unit	Rise	Recovery
PT-1 .....	50.5	76.9
PT-2 .....	56.7	72.9
PT-3 .....	55.6	73.4

The overall average rise time for 3 monitors was 53.8 s with a 95% confidence interval of 51.6 to 55.9 s for 13 measurements. The overall average recovery time for three monitors was 75.0 s with a 95% confidence interval of 66.2 to 83.8 s for eight measurements. For the rise time tests, the change in gas concentrations was a step function,

<sup>6</sup>Rise time is the time for the response to reach 90% of the final value.

<sup>7</sup>Recovery time is the time for the response to fall to 90% of the final value.

but for the recovery time tests, it was not. The chamber required a finite time for room air to dilute the 40 ppm CO to 0. Furthermore, the chamber door was opened only partially (4 in) to control the temperature.

Figure 11 shows the results of single response time tests, run at different temperatures. The rise times were a weak function of temperature, while recovery times appeared to depend more on temperature. In reality, much of the time dependence for the recovery measurements resulted from the gas temperature affecting how fast air replaced the gas in the chamber.

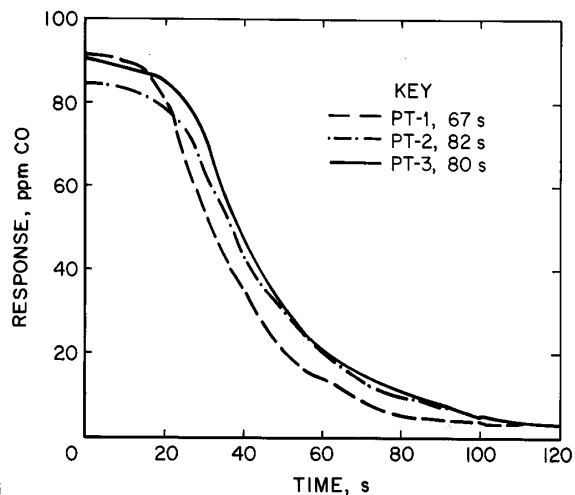


Figure 9.—CO monitor recovery measurements with zero air.

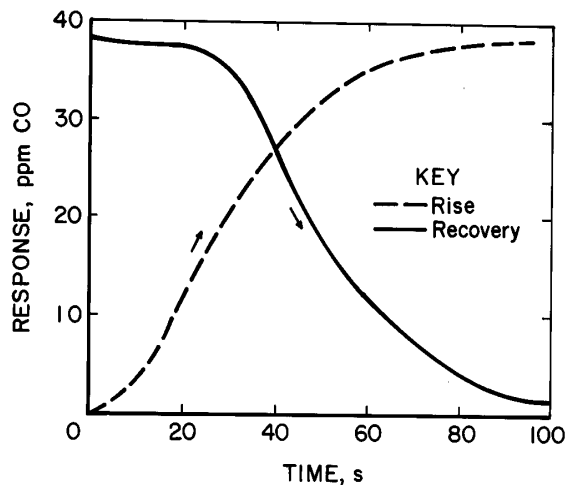


Figure 10.—Chamber test of rise and recovery times with 40 ppm CO test gas.

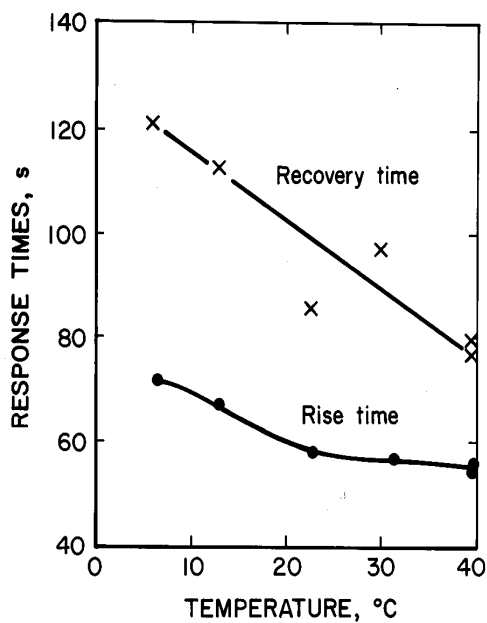


Figure 11.—Effect of temperature on response times with 40 ppm CO test gas.

For both the rise time and the recovery time tests, the response times were well under the 2 min recommended in reference 11.

### LINEARITY TESTS

The three monitors were tested for linearity of response to gases from 0 to 94 ppm CO. Test gases were supplied through the calibration fixtures at a flow rate of 100 mL/min. Figure 12 shows a plot of the data (response versus gas concentration) used to calculate the linear regression equation. In the linear equation  $Y = A + BX$ ,  $Y$  is the monitor response,  $X$  is the gas concentration,  $A$  is the  $Y$ -axis intercept, and  $B$  is the slope. Table 3 gives the estimates for  $A$ ,  $B$ ,  $S_{yx}$  (the standard deviation of the errors of response from the universal line of regression), and  $r^2$  (the coefficient of correlation). The coefficient of correlation is a measure of the amount of variation in the dependent value (monitor response) that results from variation in the independent value (gas concentration).

The responses in ppm CO for PT-1, PT-2, and PT-3 were determined from the monitor output voltages corrected for the 0.1-V offset. PT-2' is the response of PT-2 in ppm CO, obtained from the display on the Rx. The Rx was connected to the CO monitor and Tx by a 1.5-m length of fiber-optic cable. The intercepts,  $A$ , were approximately 1 ppm CO, and the slopes approached unity.

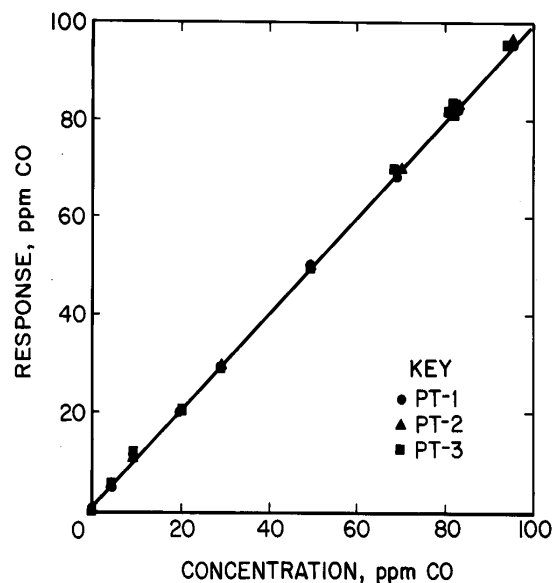


Figure 12.—Linearity of CO monitor response to gas inlet with calibration feature.

The  $r^2$  values indicated that more than 99.9% of the variance in all of the monitor responses resulted from changes in the test gas concentrations.

Table 3.—Regression statistics

Y	A	B	$S_{yx}$	$r^2$
PT-1 . . . .	1.0959	0.9926	0.4476	0.9998
PT-2 . . . .	1.1101	.9938	.7058	.9996
PT-2' <sup>1</sup> . . .	.9382	.9989	.6694	.9997
PT-3 . . . .	1.1257	.9967	.8245	.9995

A Intercept.  
 B Slope.  
 $r^2$  Coefficient of correlation.  
 $S_{yx}$  Estimate of standard deviation of the error of response from the universal line of regression.  
 Y Monitor label.  
<sup>1</sup>PT-2' is response of PT-2 in ppm CO obtained from the display on the receiver.

These linearity tests using the calibration fixture were run with the case doors open, using electrical leads to connect to the voltmeter to measure response. Other tests were run in the environmental chamber without calibration fixtures with the monitor case doors both closed and open. Figures 13 and 14 give the responses of monitors PT-1 and PT-3. With the case doors closed, as they would be in mine use, the responses are linear. A referee CO monitor inside the chamber measured the test gas concentrations.

**TEMPERATURE TESTS**

Temperature tests (fig. 15) were run using the calibration fixtures to supply zero air or calibration gas to each monitor. Test gases were fed through 0.3 m of tubing to each monitor in an environmental chamber at a flow rate of 100 mL/min. The response increased by 6 ppm CO when the temperature increased from 25° to 40° C. The response decreased by 10 ppm CO when the temperature decreased from 25° to 5° C. In many mine applications,

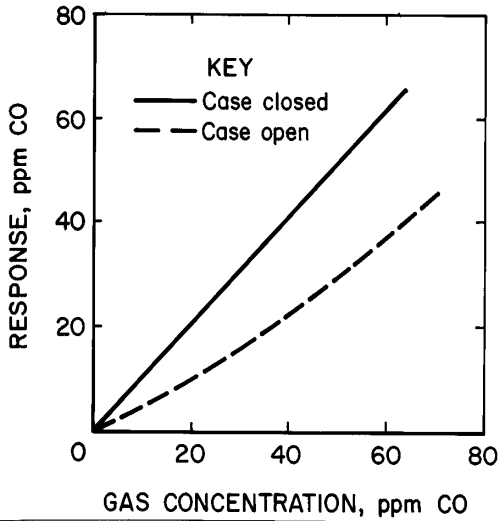


Figure 13.—Linearity of PT-1 monitor response to gas in chamber with monitor case doors open and closed.

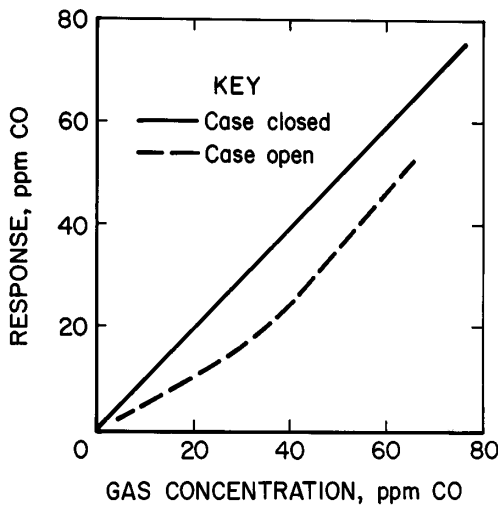


Figure 14.—Linearity of PT-3 monitor response to gas in chamber with monitor case doors open and closed.

the temperature does not change significantly from the average of 12° C. These monitors could be used unmodified in such mines. Nonetheless, the manufacturer has added a temperature compensation circuit to the amplifier in some monitors to reduce variations in monitor response.

The combined CO monitor-Tx section was tested in the chamber for temperature effect. The Rx was placed outside the chamber. Figure 16 shows the same voltage response for the monitor but a reduced temperature range for the Tx. The V/F converter in the Tx has a low-temperature limit stated to be 0° C; however, the component operated only at temperatures above 10° C. A

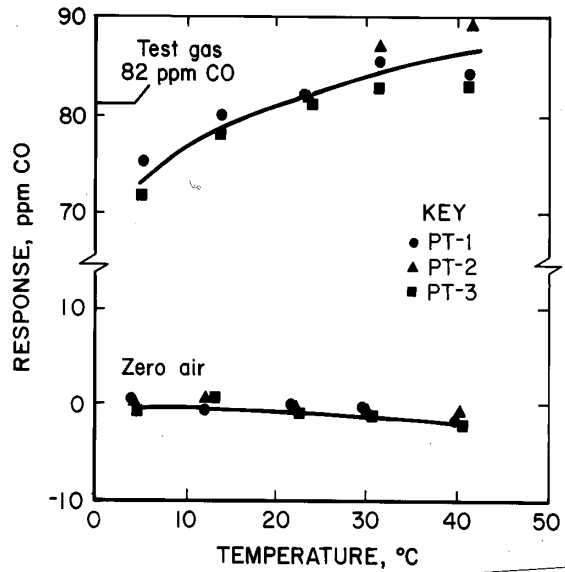


Figure 15.—Effect of temperature on CO monitor response to 82 ppm CO test gas and zero air.

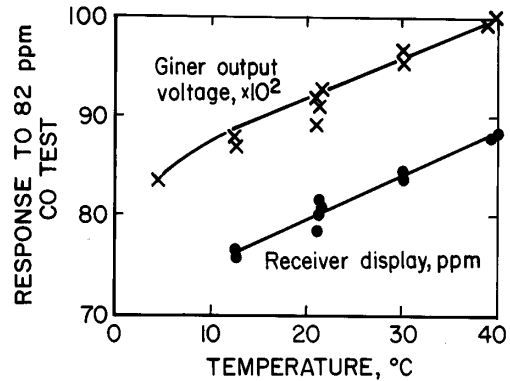


Figure 16.—Effect of temperature on CO monitor-transmitter response to 82 ppm CO test gas.

different converter is available with a low-temperature limit of  $-21^{\circ}\text{C}$ .

Monitor PT-3 was tested in the environmental chamber with a closed case and without calibration fixtures at different temperatures with gases ranging from 35 to 40 ppm CO. Figure 17 shows that the effect of temperature on response has the same general characteristic shape as the other tests run with calibration fixtures and open cases.

### PRESSURE TESTS

The dependence of the CO response on atmospheric pressure was measured by placing a monitor in a vacuum jar and reducing the pressure by a vacuum pump. Test gas flowed to the monitor through the calibration fixture. A mass flow controller held the gas flow to 100 mL/min. Figure 18 shows the monitor response from 737 mm Hg (the pressure at the laboratory elevation of 1,000 ft) to 239 mm Hg for both 82- and 40-ppm CO gas mixtures. The ratios of the average percent change in response to the percent change in pressure are 0.44 for both concentrations. The monitor's response depends on atmospheric pressure and thus altitude. Monitors must be calibrated at the elevation of use to minimize the bias due to change of ambient pressure. Figure 19 shows an interesting comparison of the pressure dependence of different sensors. The Giner cell, with a solid-membrane electrolyte and a tubular diffusion chamber, had much less pressure dependence than did a cell with liquid electrolyte and a capillary gas entrance. The membrane cell with enclosed liquid electrolyte had the greatest response to pressure changes.

For this study of the low pressure response of the CO monitors, the test gas was fed in succession into each monitor's calibration fixtures with the gas flow set to a 100-mL/min rate by a mass flow controller. Each unit was placed in a vacuum jar, with calibration fixture in place, and the pressure within the jar was maintained by adjustment to the airflow from the jar to a vacuum pump. The pressure within the jar was measured with a mercury manometer. In this dynamic pressure test the test gases were continually flowing, and thus the responses involved

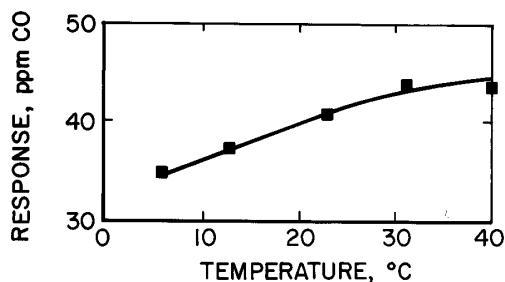


Figure 17.—Effect of temperature on CO monitor-transmitter response to 40 ppm CO test gas.

both the effects of pressure and of gas flow on the CO monitors. These dynamic pressure tests were performed as a laboratory evaluation of different types of CO sensors, and the test has no relation to the monitors' operation in a mining environment. It should also be emphasized that these tests were performed on laboratory monitors and not on fixed point monitors approved for use in mines.

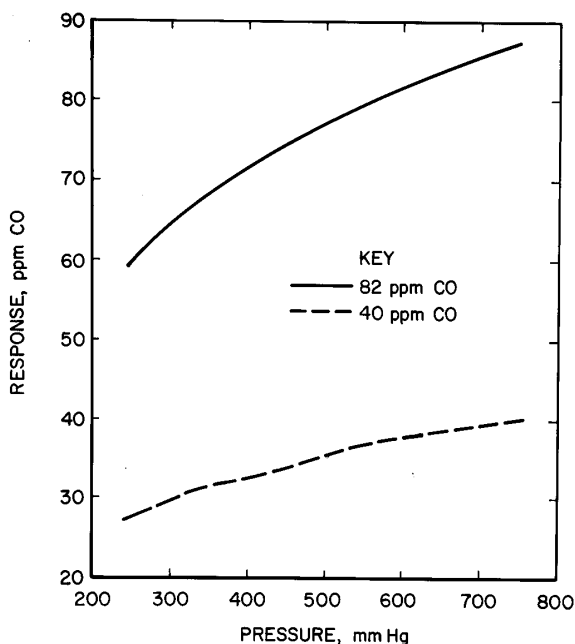


Figure 18.—Effect of pressure on CO monitor response.

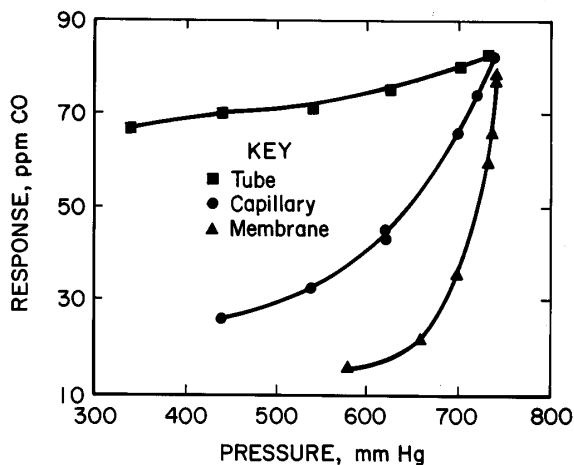


Figure 19.—Effect of pressure on response of different types of CO monitors. (Tube = solid-membrane electrolyte and tubular diffusion chamber; capillary = liquid electrolyte and capillary gas entrance; membrane = enclosed liquid electrolyte.)



**DRIFT TESTS**

Drift tests were conducted with the monitors for 1 month. The test gases flowed into the monitors through the calibration fixtures for each measurement. Neither the temperature nor the atmospheric pressure was controlled. Graphs of the responses of the monitors (fig. 20) and of

the atmospheric temperature and pressure during each measurement (fig. 21) suggest that environmental conditions have a small effect. During the month, the monitors exposed to 82 ppm CO gas fell an average of 2 ppm CO. During the same period, the response to zero air fell less than 1 ppm CO.

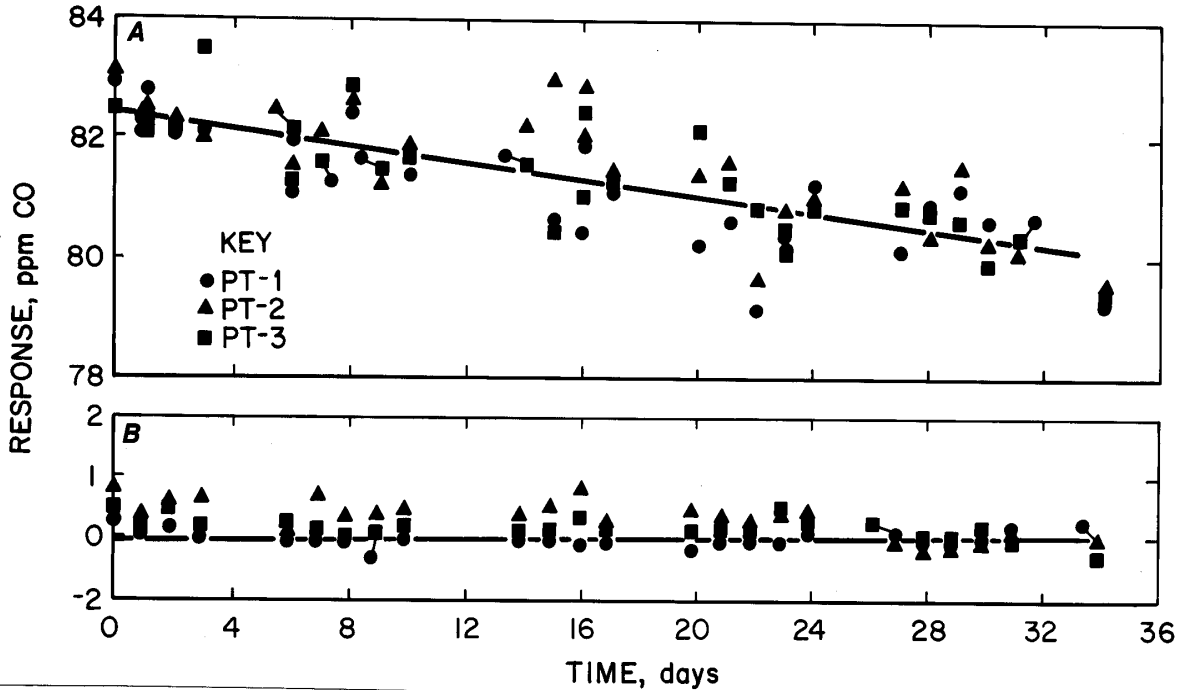


Figure 20.—CO monitor drift test. A, Span 82 ppm CO in air; B, zero air.

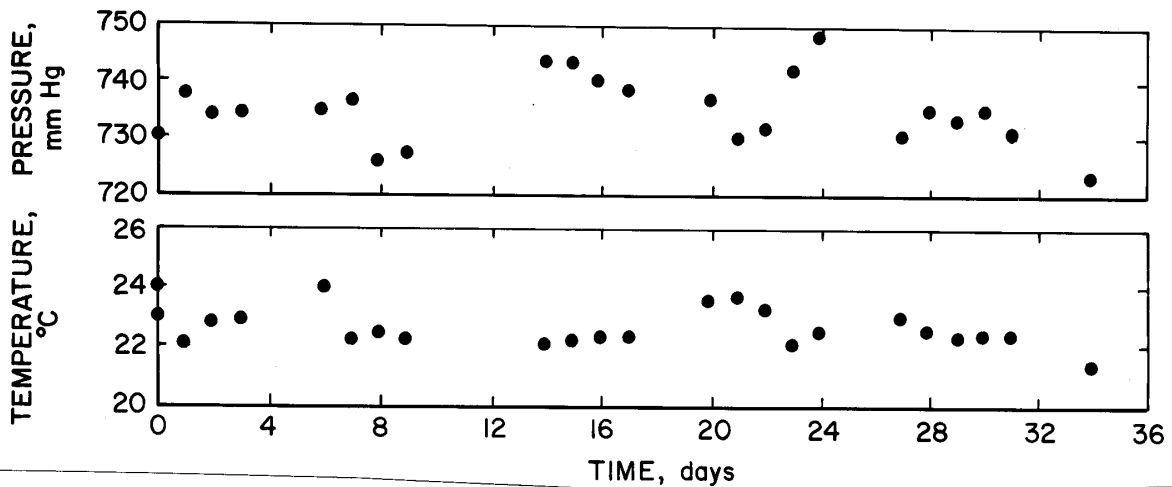


Figure 21.—Drift test environment.

## SUMMARY

- The Bureau has designed, fabricated, and tested a fiber-optic data telemetry system that can transmit a 0- to 1-V analog signal from a mine sensor via fiber-optic cable to a remote receiver.
- A battery-powered CO monitor with range of 0 to 100 ppm CO has been integrated with the fiber-optic telemetry system for use as an intrinsically safe CO monitoring system.
- Characteristics of the Giner, Inc., CO monitor have been measured, including response times, linearity, and the effects of temperature and pressure on monitor response.

The results of these tests demonstrate that the CO monitor would perform as well as or better than other commercial membrane or capillary CO sensors.

- The Bureau's fiber-optic telemetry system will operate with any type of sensor that has an output signal of 0 to 1 V (or preferably 0.1 to 1.1 V). Such a system would be useful for measurement of many parameters, such as temperature, pressure, airflow, or the concentration of other gases. The system also could be used with binary output devices, such as conveyor belt or electrical power on-off indicators.

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