IN-MINE EVALUATION OF UNDERGROUND FIRE AND SMOKE DETECTORS

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ABSTRACT

The current state of the art of fire and smoke detection technology is reviewed from the standpoint of suitability for use in underground metal and nonmetal mines. Detection modes, fire signatures, and environmental considerations are included. Preliminary results of long-term, in-mine tests are presented.

INTRODUCTION

Classification of the various smoke and fire sensors into three categories--optical view field, direct contact, and products of combustion (POC)--requires some explanation since most off-the-shelf devices (systems) have more than one principle of response and may respond to more than one parameter. Hybrid sensors may include heat detectors as well as photoelectric- and/or ionization-type product of combustion (POC) detectors, thus classification is according to the primary intended use. For the nonconventional fire detectors that have been developed for gas analysis and detection, the classification may be less obvious. Most of the nonconventional detectors are described in this report under POC types of sensors, even though they may depend on optical or filament-type principles. A further distinction of detector types divides them into point (or local) source, as opposed to the extended-area-type sensor.

For more detailed information on the types of fire detectors available, there are good survey articles (5) and National Fire Protection Association (NFPA) reference books (6), as well as manufacturers' sales literature.

FIRE SIGNATURES

Any product of a fire that changes the ambient conditions is called a fire signature (5) and is potentially useful for detection. To be practical for detection, a fire signature must cause a measurable change in some ambient condition. With other factors being equal, such as hardware costs and detection times versus hazard level, the preferred fire signature is one that generates the highest signal-to-

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

noise ratio in the earliest period of fire development. The principal fire signatures used in the detectors discussed herein are aerosol, energy release, and gas signatures.

Aerosols

Aerosols are particles suspended in air. The process of combustion releases large quantities of solid and liquid particles into the atmosphere ranging in size from 5×10^{-3} to 50 µm.
Aerosols resulting from a fire represent two different fire signatures. Particles less than 0.3 µm do not scatter light well and are classified as invisible. Those larger than 0.3 µm do scatter light and are classified as visible. The invisible aerosol signature is usually referred to as "products of combustion," and the visible aerosol signatures, as "smoke." Invisible aerosol is the earliest appearing fire signature in most cases. (Coal can evolve CO before particulates--PVC materials evolve HCl quite easily).

Energy

Fire also constantly releases energy into the environment and this energy release provides some useful fire signatures. The earliest energy signatures detectable with available hardware are the infrared (IR) and ultraviolet (UV) portions of the electromagnetic spectrum. With the exception of highly unsaturated hydrocarbons such as acetylene, infrared emissions from hydrocarbons are particularly strong in the 4.6-µm region owing to carbon dioxide and in the 2.7 µm region owing to water vapor. This radiation signature can be used effectively for detection but there is the possibility of noise from manmade IR sources. UV fire signatures appear in flames as emissions from OH, CO_2, and CO in the 0.27- to 0.29-µm region. They have been used effectively for flame detection, especially in cases where magnesium or its alloys may be involved.

Gases

Many gases are added to the atmosphere during a fire and these changes are called evolved gas signatures. A related change is the reduction of oxygen content (the oxygen depletion signature). These gases may include CO, CO_2, HCl, HCN, HF, H_2S, NH_3, and NO_x depending on the type of material burning. The most useful gas for detection is CO, since it is present in almost all fire situations. Slow burning and smoldering fires in particular produce large quantities of CO.

OPTICAL VIEW FIELD FLAME DETECTORS

Fire detection devices of the optical view type respond to radiant energy portions of the electromagnetic spectrum generated during flaming combustion of materials. The principal sensing elements used include solid-state detectors--junction type and bulk effects type, vacuum or gas-filled tubes, and thermocouples and thermistors for special applications. The photodetector family type fills a large part of the solid-state category.

Ultraviolet Sensing Detectors

The variety of UV detectors (wavelengths less than 0.4 μm approximately) is small compared with those in the IR region because of the basic problems associated with UV detection. Ordinary glass windows cut off radiation below 0.3 μm and quartz and UV grade sapphire become opaque below 0.18 μm. Below 0.1 μm there is essentially no suitable window material.

Infrared Sensing Detectors

Infrared detectors have the problem of background radiation at ambient temperatures (25°C) being entirely in the IR region (wavelengths greater than 0.8 μm). A common method of discriminating against this background is that of chopping the incident radiant flux so that the detector receives only a fixed radiant frequency, typically 4 to 30 Hz.

Infrared detectors are classified according to their method of response to heat and photon flux: thermal detectors and quantum detectors.

Thermal detectors respond to energy absorbed by a temperature-sensitive material or an absorbing film in contact with the temperature-sensitive material. Included in this category are such devices as thermocouples, metals or semiconducting layers with resistance a function of temperature (bolometers and thermistors), pyroelectric detectors whose polarization is temperature dependent, and gases with pressure being temperature dependent.

Quantum, or energy, detectors respond to photon flux falling on a sensing element and exciting electrons in a bound state to a free or conducting state.

Within these broad classifications the IR spectrum is divided into three divisions: near infrared (0.8-1.4 μm), intermediate infrared (1.4-7 μm), and far infrared (>7 μm). Near infrared requires conventional silicon and germanium detectors; intermediate infrared uses special IR detectors; and far infrared calls for thermal detectors such as thermocouples and thermistors. In some cases there is an overlapping spectral area of response. PbS is one of the most versatile photoconductors and responds to IR from approximately 1 to 4 μm. Doping Ge with Hg and Cu extends its response to 8 to 14 μm. Sensitive areas range from 0.01 mm^2 to 10 mm^2, with time constants shorter than 1 ns. (InSb may be more useful than PbS since it covers the CO and CO_2 bands).

Pyroelectric-type detectors are a more recent development (1-2). These consist of a slice of ferroelectric material sandwiched between electrodes to provide a sensing cell. Typical materials include triglycine sulfate, tourmaline, Rochelle salt, barium titanate, and polyvinyl flouride. Electrically, the material behaves similarly to a capacitor dielectric with a strong temperature-dependent polarization of the magnetic domains. One of the electrodes is transparent to IR radiation which causes a small temperature increase producing a polarization charge on the pyroelectric material and a corresponding voltage change across the two electrodes of the cell.

HEAT SENSORS (DIRECT CONTACT DETECTORS)

There are two general types of heat sensors; those that employ the fixed temperature principle, and those that employ the rate-of-rise principle (6). With the fixed temperature approach an appropriate temperature level setting is selected. When the active element is heated to its operating temperature the active element will bend, expand rapidly or maximally, fuse (change its electrical conductivity and physical state), or produce an electromotive force (emf) which can be amplified to actuate an alarm. Commercially available devices include temperature-sensitive ampoules or pellets, bimetallic elements, eutectic solders and salts, snap discs, thermocouples, and thermistors as point sensors. There is a subcategory of continuous line or wire types using thermistor material, eutectic salt, pressurized gas, or twisted insulated wires under tension. Excluding specially prepared rapid response thermocouples, a major disadvantage of these fixed-temperature types of sensors is slow response time because of thermal inertia. Another disadvantage is their inability to detect low level incipient combustion in its early stages. Commercial fire detector thermocouples have response times on the order of a few tenths of a second. Advantages of direct contact detectors are low cost, reliability, freedom from maintenance, and insensitivity to vibration and dust-laden atmosphere. Continuous line heat sensors have been tried in underground mines.

PRODUCTS OF COMBUSTION DETECTORS

Products of combustion in fires include solid particulates and liquid mists (including invisible and visible particle sizes), ionized species gases, and radiant energy. Combustion product detectors sense one or more of these constituents including heat or flame.

Ionization-Type Detectors

Ionization-type detectors constitute one general class of POC detectors. The most common source of ionization is an alpha emitter such as $Ra_2^{226}SO_4$, or Am^{241}. Beta emitters are sometimes used but not as often since stronger sources are needed to create ionization currents similar to those produced in alpha detectors. Kr^{85} is one beta emitter that is used. The radioactive emitter ionizes the air in a chamber between two electrodes. Current measurable in picoamperes is produced from production and transport of positive and negative ions to the opposite poles of the plates. A decrease in current, relative to clean air, is obtained when combustion products enter the chamber because the combustion particles become ionized and, being larger and heavier than the air molecules, move much more slowly toward the end of the chamber. An electric circuit detects the drop in current and initiates the alarm.

which is a function of gas concentration. The adsorption of a gas molecule on the surface of a semiconductor generally results in the transfer of electrons due to the differing energy levels of the gas molecule and the semiconductor surface. Oxygen, which can accept electrons is adsorbed on the surface of n-type semiconductor. The transfer of electrons from the donor level of the semiconductor to the layer of adsorbed gas results in decreased conductivity of the semiconductor material.

When a TGS that has adsorbed oxygen in this manner comes into contact with reduction or combustible gases such as CO, hydrocarbons, etc. the molecules of these gases are adsorbed and the transfer of electrons is in the opposite direction to the oxygen reaction, releasing the electrons to the semiconductor space charge layer and causing a large increase in the conductivity of the sensor. The sensor output is sufficiently large to allow gas detectors to be designed using a minimum number of components, thus allowing the production of low-cost detectors.

Significant advantages of these solid-state electrolytic cells are the very long lifetimes expected, usually several years, the low cost and simplicity inherent in its design, and the relatively simple electronics needed to utilize the sensor output. Other features include not being permanently poisoned by the toxic gases, resistance to vibration and shock, and having no loss of sensitivity even at gas concentrations so high that air (oxygen) is displaced.

A severe disadvantage is its ease of alarming in areas containing engine combustion products, and its sensitivity to a wide variety of easily oxidized gases not necessarily associated with products of combustion.

For fire detection use the TGS responds readily to CO, which is one of the principal gases given off in the early stages of fire. However, because of the sensitivity of TGS to gases other than POC and exhaust gases, its practical use may be limited to a hybrid system involving ionization or photoelectric detectors. TGS detectors can be calibrated within the range of 200 to 1,000 ppm CO and to a limited extent can be made selective to CO.

Electrochemical Detectors

Electrochemical (fuel cell) techniques for CO sensing depend on the electrochemical reaction of the detected gas, oxidized or reduced (depending on the sensor) at an appropriate electrode potential, producing an electric current that, because of membrane diffusion controlled conditions, is directly proportional to the gas concentration. These devices are subject to interference from gases other than the desired one for detection, but are capable of precision calibration, making them useful as an analytical device. They tend to be expensive and not too rugged for the mine environment but are useful for establishing alarm levels and personnel monitoring.

Photoelectric-Type Detectors

Photoelectric fire and smoke detectors constitute another general type POC detector. The requirements are a source of light and a detector of that light to measure its radiant power. Four different modes of operation are possible depending on the amount of light transmitted or absorbed by the medium, the amount reflected, scattered, or refracted. Most, if not all, commercially available units possibly suitable for mine use are of the light scattering type. A beam of light from a source travels across a light-tight chamber to a light trap or collector opposite the source. A photocell positioned at right angles to the beam senses no light as long as the air inside the chamber is clean. The chamber is open to its surrounding atmosphere through baffling, and if smoke (POC) enters the chamber, light from the beam is reflected or scattered in all directions. Some of this scattered light reaches the photocell, changing its resistance and via suitable electronics initiates an alarm. The alarm level is adjusted to actuate at a given smoke concentration level (normally 3.3 to 6.6 pct $-m^{-1}$ or 1 to 2 pct per foot). In a few models the electronics are also designed to give an alarm if the rate of rise of smoke obscuration exceeds a given value (commonly 0.33 pct $-m^{-1}-min^{-1}$ or 0.1 pct per foot per minute). Auxiliary or backup heat detection is often provided with these detectors.

Photoelectric detectors, like ionization detectors, may respond to particulate matter from sources other than fire. A dusty mine environment might cause some false alarms and would also require periodic cleaning of the sensor chamber internal surfaces. In a wet mine, aerosol forms of fog and mists might cause some false alarms. These detectors are also somewhat dependent on airflow velocity (good chamber design) and location because of the tendency for smoke to stratify in airstreams. They are also less sensitive to black smoke compared with white or grayish smoke.

Solid-State Detectors

Solid-state devices for detecting and sometimes sampling the gaseous components of products of combustion are a third general type of detector that can function as a fire detector.

A promising new development in POC gas detection is the semiconductor cell detector known as the Taguchi gas sensor (TGS). This device uses a selection of bulk n-type metal oxides such as SnO_2, ZnO, and Fe_2O_3 impregnated in a solid-state matrix material supported by conductive filaments. Variation of the chemical formulation allows the cell to be made sensitive to a particular gas or group of gases, and insensitive to others.

A heater electrode imbedded in the cell provides sufficient increase of cell temperature above ambient to allow the cell to operate by diffusion, eliminating the need for a sampling pump arrangement. A collector electrode provides for measurement of cell conductivity,

Optical Gas Detectors

Optical gas sensors are generally confined to laboratory use, although recent prototype models have been developed for personnel hazard monitoring. These use the strong adsorption band of CO at 4.65 µm (infrared). Radiation from an infrared source is passed through a cell through which the sample gas flows and is adsorbed by the CO molecule. A filtered infrared detector responds to this change in radiation and its output is compared with a reference cell, conditioned by suitable electronics and read out on an appropriately marked meter.

A technique useful with different POC detectors is the use of tube bundles (7). With these, air samples can be drawn from different sections of the mine and sequentially monitored at a central location. This procedure provides protection and stability for the detector systems and can add to the flexibility of the mine fire protection system. Slow response times and wall-diffusion losses for submicrometer particles provide inhibitions to its use.

ENVIRONMENTAL CONSIDERATIONS

There are reaily two environmental problems to be faced in designing a reliable fire detection system: Will it continue to operate, and if it does, can it discriminate against the normal mine ambient parameters?

The latter problem can possibly be dealt with by the use of combinations of detector types in the system to provide detection of cellulosic and hydrocarbon fires, spontaneous combustion, and electrical fires. Ambient parameters will differ in various parts of the mine. Occasionally air ventilation networks can improve a POC detector's sensitivity and effectiveness. Sampling tube networks or remote detectors with telemetry can monitor several locations individually. A detector type useful in one location may be quite unsuitable for use in another location; therefore, if conditions change with time, the sensor system should be reevaluated.

Ability to discriminate against normal mine ambient parameters is an important consideration in the design of reliable fire detection systems. Mine Safety Appliances Research Corporation (MSAR) under a Bureau of Mines contract (9) provided CO, CO_2, NO_X, and NO concentration data for shot firing and diesel operations in selected mines and sampling sites, within the mine. Table 1, taken from their report, summarizes much of their data in the form of ratios of contaminants measured in connection with various mine operations. The report suggests that a duel sensing system involving contaminant ratios may provide an approach to minimizing or eliminating false alarms. The CO/CO_2 ratio of diesel exhaust is quite comparable to that of the combustion products of a metal mine fire. Similarly, the CO/NO_X ratios for shot firing and a leaking bulkhead, where a hot spot was thought to exist, are also quite similar. The CO_2/NO_X ratio is significantly different for shot firing and diesel operations compared with the ratio for a fire and/or the leaky bulkhead with a hot spot. This much higher latter ratio may

TABLE 1. - AVERAGE CONTAMINANT RATIOS FOR VARIOUS UNDERGROUND ACTIVITIES

Activity	CO/CO_2	CO/NO_x	CO_2/NO_x
Shot Firing........	0.38(0.44)	6.35(4.58)	11.6(12.4)
Diesel.............	0.04	6.9	97
Fire...............	.025	100	4,000
Leaking Bulkhead... (4,200')	.03	--	--
Leaking Bulkhead... (3,600')	.001	12	8,000

provide a reliable means of fire detection. The report also suggests that studies of the time-distance behavior of the NO/NO_x ratio be made if the CO_2/NO_x ratio were to be employed as a means of incipient fire detection.

In an early Bureau contract study by the Gillette Research Institute, two different types of battery powered ionization detectors were taken underground for a short-term performance evaluation. One, taken into the Bunker Hill mine, Kellogg, Idaho, performed poorly after a few hours of operation in areas contaminated with high concentrations of aerosols and in regions of high ventilation airflows. It did operate satisfactorily in regions supplied by low-velocity intake air.

The other detector, a dual-gate reference type, performed reliably at Central Rock Company, Lexington, Ky. The latter device was not necessarily superior to the former because the Bunker Hill mine presented far greater extremes of environment. What the experiment tended to demonstrate was that state-of-the-art ionization sensors, developed for normal industrial or residential use, military or commercial aviation fire protection, have questionable reliability or, in this case, are inappropriate for use in a mine environment.

It is fair to say that there is no universally applicable fire and smoke detector--one that responds equally well and consistently to all types of fires. The various detector types have been discussed along with some of their advantages and disadvantages. Long-term evaluation of the various detectors' sensitivity and reliability under the extremes of ambient conditions just described are underway and may lead to viable, cost-effective detection and suppression systems for underground mine fires. Until such systems have been developed and environmentally and operationally reliable detectors of various types have been found through long-term testing, it is best that unreliable fire detectors not be installed in mines.

Another important consideration involving mine environment is the spacing and positioning of fire and smoke detectors in the mine. Little is known about optimum detector positioning and spacing in mines. NFPA installation standards do not offer any criteria directly useful in a mine because their codes deal with residential and commercial situations. Mines vary so widely in distribution of combustibles, ventilation patterns, and roof support systems that an installation code may not be feasible or even desirable. Complicated ventilation patterns, random ceiling obstructions, and a variety of tunnel shapes would not allow general applicability of such a code.

Because of the fuel-to-air ratio influence, a knowledge of the relationship between fire and mine ventilation is essential for the proper selection and location of sensors and detectors and also for the correct interpretation of information provided by them. Mine fires can be categorized into two distinct types--oxygen rich (overventilated) or fuel rich (underventilated). The fuel-to-air ratio determines which type occurs; the oxygen-rich type can evolve into the fuel-rich type by spontaneous growth. Timber fires (fuel rich) represents an extreme toxicity hazard because of low O_2 concentrations and high CO and CO_2 concentrations. Fuel-rich conditions also produce more smoke, increasing toxic species exposure and obscured vision.

The greatest hazards of mine fires are caused by toxic and sometimes explosive products of combustion being carried through the mine by the ventilation system and unexpected airflow reversals carrying toxic fumes to intake air ventilation areas, such as fire escape routes, hoist areas, and other areas usually thought of as safe in the event of a fire. The analytical prediction of airflow reversal in a mine, even under ideal conditions, is a very difficult task and beyond the scope of this report. However, Greuer (4) has compiled a large number of references and provided a detailed accounting of the influence of mine fires on the ventilation of underground mines for those who wish to pursue the problem in detail.

Greuer (4) makes a few quantitative predictions of ventilation disturbances that may be useful in interpreting the indications seen when monitoring a fire detection system. These include the following:

Throttling and natural draft changes can cause changes in the quantity of ventilating air currents and sometimes a reversal of their direction. Similar changes can occur in neighboring connected airways as well as that of the fire scene.

Air (oxygen) quantity reductions (O_2 pct) in non-gassy mines can be neglected. In gassy mines air reductions can lead to explosive mixtures which may be carried back through the fire zone.

Ventilation disturbances can also cause smoke layering, which may affect the ability of a detector to operate effectively.

BUREAU OF MINES EXPERIENCE

Shaft Installations

To work toward an answer to the major problem of fire hazard and contaminated air resulting from fire, the Department of the Interior, U.S. Bureau of Mines, contracted with the FMC Corporation, San Jose, Calif. (Contract H0252016 "Mine Shaft Fire and Smoke Protection System"), to evaluate mine shaft fires and their hazards (10). The contract also called for the development and demonstration of a low-cost, reliable mine shaft fire protection system that could be adapted to a majority of metal and nonmetal mine shafts, raises, and winzes, especially in deep mines. Results of this contract have been published elsewhere (10) and so need not be extensively detailed here. However, as an example of a proven system, sensor and detector components that performed successfully in underground tests with controlled fires will be highlighted here.

As part of the background preparation for designing the systems produced, it was found that approximately 67 pct of shafts in metal and nonmetal mines are of wooden construction, and contaminated air was responsible for about 77 pct of fatalities from fires. Causes of fires in mines were predominantly electrical (35 pct) and welding (18 pct). Most fire-connected fatalities occurred in or near shaft stations, the gathering point to normally leave the mine.

Four major needs were brought out for providing effective mine fire and smoke protection:

1. Reliable sensors are necessary for early fire and smoke warning.

2. Isolation barriers (vent doors) would stop the flow of contaminated air.

3. Available water supplies could assist with fire extinguishing.

4. Recording sensor systems and control ventilation doors and extinguishing systems from the surface would be preferable to sending fire-fighting teams underground.

The possibility of a fire starting somewhere in the mine is always present because combustibles and ignition sources are usually close together. In addition to constant fire prevention efforts, provisions should be made to detect and extinguish fires as soon as possible. Sensors and detectors are needed because fires can occur spontaneously in abandoned workings or accidently in unattended areas. Furthermore, depending on detection by persons working in or passing through an area is not realistic.

Besides simply detecting a fire, systems should be made to alert an attended area that fire exists, and where it exists; to alert people underground that a fire has been observed or reported; to take some action to isolate the fire area; and to extinguish the fire if possible. The contract showed that meeting these requirements was possible with existing equipment integrated into a functional protective system consisting of sensors, extinguishing agents, isolation barriers, and appropriate controls.

The harsh environmental conditions that exist underground have already been mentioned. Because labor and maintenance efforts are expensive underground, all components used in this detection-alarm system must be extremely rugged to limit repair needs or they may be out of service at just the wrong times, and reliable to instill confidence in their ability to perform and alarm only in a fire situation.

The first prototype mine shaft fire and smoke protection system was tested at an inactive silver mine in the Coeur d'Alene district of Idaho. The system was installed 3,000 feet below the shaft collar to protect 50 feet of shaft, the shaft station, and 100 feet of drift in two directions.

Environmental conditions in the mine were 100° F and essentially 100 pct humidity. Because the mine was inactive, there was little or no dust present during the 2-week test period. Ventilation was not typical of that found in a working mine because the mine was used exclusively for ventilation and as an alternate escape route for an adjoining working mine. Airflow was temporarily modified for the test.

The sensors installed included thermal wire, CO gas, and ionization types. The thermal wire provided backup reliability for the other two early warning types. CO gas and ionization sensors were placed in sections of the shaft and shaft station areas. A pair of each was placed near the shaft crown plate to sense air entering the area, which was downcast intake air. Others were located near the ventilation barriers towards the mine workings (away from the shaft station area).

Sensors were selected to respond to health hazard levels of fire or contamination by fire (gas/smoke), while being available off-the-shelf, reasonably priced, and compatible with metal/nonmetal mine environments as previously described. Sensors consist of smoke (ionization) detectors, Becon Mk II, manufactured by Anglo American Electronics, Republic of South Africa; two carbon monoxide (gas) sensors, Model CO-181 manufactured by Dynamation Enterprises, Inc., Ann Arbor, Mich., and Model MSD-1 manufactured by Emmet Co., Ann Arbor, Mich.; and thermal wire, type WPP, 155° F manufactured by the Protectowire Company.

The ionization detectors are referred to as smoke detectors in the system even though they primarily sense invisible submicrometer particles (as distinguished from the second detector type, labeled CO, which responds to CO and other gaseous components of smoke).

During extensive factory tests, the ionization detectors performed well. They consistently detected wood fire smoke within habitable levels. Test data indicate the detectors alarmed at smoke density levels of 2 to 6 pct obscuration per foot. This compares favorably with industry standard set points for commercial and residential smoke detectors. A poor response to burning plastic produced smokes appears to be characteristic of ionization-type detectors, and the Becon unit is no exception. On the other hand, the Becon unit is designed for mine environments and does not readily exhibit problems from corrosive environments, dust, humidity, and very high air velocities.

The CO detectors in the system used the Taguchi gas sensor (TGS). They were used at factory settings of 200 ppm CO on the Enmet unit and 75 ppm CO on the Dynamation units. These levels were felt to be realistic for the conditions expected in the test shaft. There was no blasting or diesel equipment operating to increase the CO level at the demonstration site. On the other hand, a CO concentration of 150 ppm may be encountered with some regularity in active mines where blasting and diesel equipment are present. A level of 150 ppm is tolerable without hazard for up to 3 hours so setting alarm points of CO monitors above 150 ppm would represent a realistic alarm level within the limits of safe habitation for short periods, but an extended 200 ppm concentration could be a valid indication of a fire, especially if combined with other indications.

A surface control unit was installed in the hoist room and connected to an underground control unit in the shaft station at the 3,000-foot level. The latter was the junction point of the sensors and related components and provided the interface between them and the surface control unit. The two control units were connected by a single pair of wires with a second pair for redundancy. Multiplexing the signals allowed the surface control unit to handle 16 inputs from the underground control and process 8 outputs for transmittal back to the underground unit.

A fire fueled by wood cribbing was built in a steel pan 3 feet square, about 18 inches deep, with a lid that was raised and lowered to adjust smoke density and products of combustion.

Smoke and CO sensors responded to contaminants in the fire area, all system commands were remotely operated from the surface control unit and performed as designed. The fire was extinguished by the installed sprinkler system during a 6-minute discharge. The thermal wire was located too high above the controlled pan fire to reach its alarm temperature and did not respond.

The first prototype system was installed for only 2 weeks in the Idaho mine, which was not sufficient to test the long-term reliability of the system and components. A second mine was found where the system could be installed and given a longer test. This mine was the Union Carbide Corporation's Pine Creek mine in Bishop, Calif.

Several modifications were made to adapt the system to the particular mine location and it was installed and continuous monitoring began on December 19, 1975. A second prototype system, based on recommendations derived from developing, installing, and monitoring the first prototype, was built and installed at a second level in the second mine as an add-on unit to the first prototype using the same interconnecting wires, and monitoring began during April 1976. The latter system included a new micro processor controlled surface unit, replacing the original prototype surface unit. System testing was concluded in July after controlled fire test demonstrations were performed in each of the two underground areas. Final results include 3 months operation of the first prototype system, providing 87 days of 24-hour-per-day monitoring. The second prototype system was installed $3\frac{1}{2}$ months, providing a combined total of 105 additional days of monitoring for both levels.

The surface control unit was installed on the surface at a guardhouse where it was monitored 24 hours per day. The fire and smoke protection systems were placed at two locations deep within the mine--one in a large compressor station 14,000 feet in the mine at the 9,400-ft level, and the second 14,000 feet in the mine at a shaft and shaft station area at the 11,271-ft level. Because the mine is inverted, deeper operations are at higher elevations.

Three types of sensors were used at each of the two test sites as in the initial test setup. Thermal wire was strung throughout the drift and machinery space of the compressor station and around and down the shaft at the 11,271-ft level.

Ionization sensors and CO sensors were used in pairs except none of the CO sensors were used in the compressor room. An ionization sensor was located above the compressor machinery, one located on each side away from the compressor station, in intake air, beyond remotely controlled vent doors, and one in the upcast exhaust airflow from the shaft at the 11,271-ft level. An additional ionization sensor was placed in the diesel maintenance area, three fans were monitored, one fan was controlled, and air lock doors were monitored.

During the monitoring period, the smoke (ionization) detector in the diesel maintenance bay regularly alarmed during vehicle activity, requiring an adjustment of its sensitivity. Also the smoke detector in the compressor station was readjusted because of alarms. The sensors responded to various known mine activities--diesel exhaust, blasting, and gas and electric welding and cutting vapors.

After the monitoring period, each location was subjected to a test fire using a pan and cribs identical to those used in the Silver Summit test. At the 11,271-ft level it was allowed to burn for nearly 12 minutes before the surface control unit was used to turn on the installed sprinkler system. During the fire the sensors detected over 100 ppm gas, and smoke, and alerted surface personnel that they were in alarm. All alarming and control functions performed satisfactorily through the surface control unit operated by surface personnel.

At the 9,400-ft level a similar fire was allowed to burn for 13 minutes before the surface control unit turned on the sprinkler system there. Again, alarm and control functions operated satisfactorily through the surface control unit, responding to the buildup of smoke.

Other Underground Tests

Among the recommendations coming from this contract testing was that continued laboratory and in-mine tests should be conducted to learn more about gas and smoke detectors. Responses to fires from different fuels, nonfire stimuli, effects of air velocity variations, dust buildup, and effects of mine environments would be of interest over long-term testing.

Based on the recommendations, the Bureau's Twin Cities Mining Research Center entered into a purchase contract with the FMC Corporation to obtain a sensor package suitable for long-term, in-mine testing. A cooperative agreement for locating and testing the package was also negotiated with the Hecla Mining Company, Lakeshore mine near Casa Grande, Ariz.

A three-sensor package containing a Becon Mark II smoke sensor, and Enmet ISA-33 CO gas sensor and two Pyrotector 30-2013-9 flame detectors were assembled An additional CO gas sensor (Dynamation CO 181) was supplied for additional testing at a different location in the Lakeshore mine.

The three-sensor package was installed in the underground diesel fuel storage area located at the end of the 500 East Exhaust Crosscut. The single CO gas sensor was installed in the south decline near the mine's existing Ecolyzer gas sensor. Each sensor is connected by telephone wire pairs to a 9-channel recorder on the surface. These packages were installed in late March 1976 and have been undergoing long-term testing.

Periodic visits to the mine to observe the sensors have shown some problems. The interface electronics and the CO sensors are packaged in NEMA IV electrical enclosures and well protected from the mine environment. The TGS sensors that are part of the CO monitors are not stable in that their base level output drifts over time and with temperature variations. They are also quite sensitive to diesel exhaust emissions and blasting residue gases in the mine.

The flame detectors have remained operational but they do become dust covered with time since they are in an exhaust crosscut where the air velocity is quite high and dusty.

The smoke sensor has remained operational but after several months was not alarming as it should. Blowing accumulated dust away from its baffle entrances caused it to go into alarm, and we were able after some trials, to get it to alarm by checking its trigger level adjustment. Dust does build up in the baffle area in this location to the extent it needs to be cleaned out every few months. The alarm level was adjusted later so it would not respond to the exhaust fumes from standing, idling load-haul-dumps in the passageway to the fueling area. Additional long-term testing continued in this mine as well as others with differing environmental conditions.

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