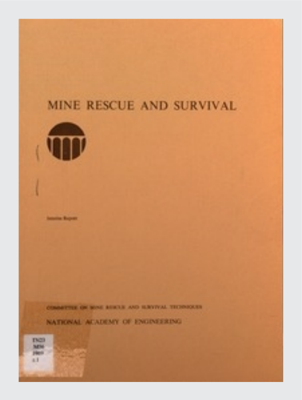

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Mine Rescue and Survival

Interim Report

Committee on Mine Rescue and Survival Techniques

NATIONAL ACADEMY OF ENGINEERING

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FOREWORD

The National Academy of Engineering Committee on Mine Rescue and Survival Techniques was established in March 1969, at the request of the Bureau of Mines to "conduct a study program to assess the technological capabilities that can be applied to survival and rescue techniques following mining disasters." The Committee was further charged with giving consideration to "improving the effectiveness of new devices and to describing the technological possibilities of new devices or equipment that may make it possible to improve significantly workers chances of survival in the environments that prevail following disasters."

The study is being conducted in three phases: (1) to describe a rescue and survival system that can be developed from existing technology in approximately one year, (2) to describe a system that can be realized with a five-year research and development program, and (3) to plan a research and development program to assure that the latest technological advances are continuously integrated into the operational mine rescue and survival system.

This Interim Report, describing a system that can be developed from existing technology, concludes the first phase of the study. The Final Report of the Committee will be submitted to the Bureau of Mines by March 15, 1970.

INTRODUCTION

This Interim Report describes a mine rescue and survival system that could be developed from existing technology in about one year. The system could potentially save all coal miners who have died of carbon monoxide poisoning following explosions or fires.

Bureau of Mines' statistics show that 436 coal miners died in disasters (defined as single accidents causing 5 or more deaths) due to explosions or fires between January 1951 and October 1968. Three-hundred thirty-five of these deaths are attributed to forces of the explosions and 101 to carbon monoxide poisoning. During this period more than 100 additional miners died in fires or explosions that killed less than 5 men. Probably at least 25 of these died of carbon monoxide. The cause of death of the 78 men who died in the explosion at Farmington, West Virginia, in November 1968, is not yet known.

In mine accident investigations, the cause of death is determined by the investigator's observation of the body rather than by autopsy. Therefore, the number of deaths attributed to either explosive forces or carbon monoxide is only approximate; and it is likely that more are killed by carbon monoxide than attributed to this cause.

Coal mine explosions propagate so rapidly that the only protection against explosive forces is prevention of ignition or rapid quenching of explosions once ignitions have occured. Rapid quenching techniques are being investigated for an advanced mine rescue and survival system, but cannot be developed in time to be a part of the system described here; and ignition prevention is beyond the scope of this study. Therefore, the system proposed in this report is aimed at saving miners explosed to carbon monoxide and other lethal gases.

Some of the techniques under review by the Committee are applicable to survival and rescue of miners trapped by inundation. However, the greatest potentials are related to fires and explosions. The physical disruptions after an explosion are aggravated by the destruction of the communications system locally or, in extreme instances, throughout the mine. Miners who are near but not in the immediate explosion area may suffer from shock and some injuries, although they are most often ambulatory. Others more distant may suffer no injuries whatsoever and may not realize that an explosion has occurred.

Unabated fire makes the danger of methane gas explosion, with or without coal dust propagation, a real hazard. As fire disrupts ventilation, accumulations of explosive gas mixtures and sources of ignitions are more likely to come together. Explosive gases are even given off by the fire itself, adding to the hazard.

Fortunately the foregoing does not occur rapidly. The smoke and carbon monoxide follow the ventilating current; and in the early stages of the fire, the location and direction of travel of the gases are known. In the vast majority of fires, miners have been evacuated around the fires and gases. The improved emergency breathing device, discussed later as part of the proposed system, should aid miners in evacuating during the early stages of fires.

In explosions the gases are very rapidly forced throughout the affected part of the mine. The force of the explosion destroys stoppings and disrupts ventilation. Miners attempting to evacuate the mine are much more likely to walk into concentrations of lethal gas. Thus, following explosions, evacuation is more hazardous; and unless an obvious escape route is available, barricades should be erected or the proposed refuge chambers used.

There is strong evidence that, in addition to proper equipment, proper training is essential to survival and rescue. Each mining crew should be organized for and drilled in behavior that would maximize their chances for survival. They should be taught the specific hazards associated with different types of emergencies and the best way to meet them. The records of coal mine disasters show very clearly that many more miners would have survived had they known the proper course of action to follow.

The proposed system consists of a <u>survival subsystem</u> using improved emergency breathing devices and refuge chambers, a <u>communications subsystem</u> using seismic or electromagnetic devices to locate and communicate with survivors, and a <u>rescue subsystem</u> of large- and small-hole drilling equipment and rescue teams. Except for providing them with location information, the operation of rescue teams can be only marginally improved upon in the first phase system.

SURVIVAL SUBSYSTEM

The survival subsystem consists of a lightweight, portable emergency breathing device that a coal miner can carry on his person and two types of refuge chambers--large chambers centrally located and small chambers for individual sections.

Emergency Breathing Device

The present device for protection of individual miners in an emergency is the self-rescuer, which uses the catalyst hopcalite to convert carbon monoxide to carbon dioxide as the mine atmosphere is breathed through the self-rescuer. In a 1 1/2 percent carbon monoxide atmosphere, which is not unusual in areas close to a mine explosion, temperatures at the mouthpiece of the self-rescuer can reach 185°F due to the exothermic reaction of the conversion of carbon monoxide in the catalyst. The self-rescuers presently in use are rated by the Bureau of Mines for 30 minutes in a carbon monoxide atmosphere. A new model recently introduced has been rated for 1 hour. Most coal operators now provide self-rescuers for all men working underground.

Although self-rescuers have saved the lives of many miners, they are only marginally adequate for the job for which they are intended. An emergency life support device for underground workers should provide a respirable atmosphere, regardless of the environment, should permit intermittent voice communication to allow miners to communicate in areas of high dust and smoke concentrations, should be of the longest possible duration, and should be light and compact enough that miners will not object to carrying them continuously. The Committee believes that a device meeting the above criteria can be developed from existing technology to provide a 45-minute oxygen supply. With a market estimate of 50,000 to 75,000 units over a two-year period, such a device could be sold for under $50 per unit. This compares very favorably with the price of the improved model of the self-rescuer that provides substantially less protection at a slightly lower cost.

Refuge Chambers

When unable to escape following an explosion or fire, miners are trained to isolate themselves from poisonous gases by erecting barricades of wood, brattice cloth, and other materials.

Many miners have been saved by well-sited and well-constructed barricades. However, analysis of the disaster reports from 1951 to 1968 shows that the majority of miners who erected barricades died behind them.

This high fatality rate is not wholly attributed to poor barricading methods or lack of materials. Many coal companies have placed barricading kits at strategic locations in their mines. Instructions have been given that these materials are not to be used for any other purpose. When materials have been available, fatalities have occurred for a variety of reasons; poor training in erecting barricades, failing to enclose sufficient air volume behind the barricade, or waiting until the air was contaminated with carbon monoxide before erecting the barricade. Some gas will leak past even a well-constructed barricade and delays in rescue have proved fatal.

To overcome the weaknesses of barricades, two types of refuge chambers are being proposed; large central chambers that could support all of the men that might be in the mine and small chambers that would be located near each working section and would support the men employed in that section. Although there are many possible designs for both types of chambers, a typical large chamber might be a room cut into a coal pillar from a crosscut. The room would be lined with concrete blocks or bricks and would have substantial roof support. The chamber itself and both ends of the crosscut in which it was located should have masonry and steel doors that would withstand the forces of a subsequent explosion. Communications and forced fresh-air ventilation would be through a 6- to 8-in. hole to the surface.

A typical small chamber would be a crosscut with steel or inflatable bulkheads anchored to the coal at both ends and a self-contained life support and communications system inside. Holes to the surface from the small chambers would not be economically feasible. The bulkheads would be designed to withstand a 20-psi shock wave. When the chamber was not in use, doors in the bulkheads would be left open to provide ventilation from the normal mine ventilation system. The bulkheads and the cart housing the life support and communication subsystems would be designed for portability. The chamber could be easily advanced or retreated in the section or moved to a new section.

The choice between the two types of chambers should be based on a hazard analysis of the mine and on the duration of the emergency breathing devices available. Some mines may most efficiently and inexpensively provide protection by using chambers of both types. The Committee is considering computer simulation methods of hazard analysis to assist in determining the requirements for refuge chambers. For example, any mining crew should be able to reach a portal or refuge chamber without passing a potentially dangerous area such as the edge of a caved area that might contain explosive mixtures of methane or entries leading directly to another mining section that might be an ignition source.

Possible oxygen sources for small chambers are chlorate candles, high-pressure oxygen, and potassium superoxide, which, in addition, removes carbon dioxide. Hydrogen peroxide was considered, but rejected because it is toxic and its vapor in high concentrations is explosive.

Chlorate candles and high-pressure oxygen or air require carbon dioxide removal agents. Potential agents are lithium hydroxide, lithium peroxide, and baralyme (a mixture of calcium and barium hydroxide). Lithium hydroxide is very irritating but not toxic. Lithium peroxide has not been used extensively in life support systems, but has the advantage of evolving oxygen while removing carbon dioxide. Its use might be developed in one year, but it is primarily of interest for the longer term system. Thus baralyme looks most promising and is inexpensive. A 15-man, 14-day supply costs about $800.

Any system using a carbon dioxide removal agent and possibly even the potassium superoxide system would require a hand-cranked blower to circulate the air through the chemical bed. A chart would be provided with the system giving the length of time the blower should be operated each day as a function of the number of men in the chamber of the number of days they have been there.

The small refuge chambers would be located in each working section and moved as mining advanced or retreated. Miners would never have to travel more than a few thousand feet to reach a chamber and receive immediate protection from the gases of an explosion or fire. The life support equipment includes--in addition to the oxygen-generating and carbon dioxide removal systems--food, water, chemical light sources, medical supplies, methane detectors, carbon monoxide detectors, oxygen level detectors, and a limited number of 45-minute breathing devices to permit those in the refuge chamber to egress to aid others who may be injured reach the refuge chamber. This equipment would be mounted on a wagon that could be easily pulled by a shuttle car to the new location.

A detailed discussion of survival systems is contained in Appendix A.

Although there have been few occurrences of multiple explosions in mines, it would be desirable to provide in any refuge chamber some protection from subsequent explosions. For the portable chamber, two types of bulkheads are being considered, rigid metal and inflatable. For metal bulkheads, trade-off studies are being conducted of aluminum versus steel, type of stiffening, weight versus size, weight versus pressure, and convex versus flat configuration. Actual design of the bulkhead, construction, and testing of a prototype are beyond the scope of this study.

Inflatable bulkheads would be more portable than metal and, if inflation is rapid enough, can be left deflated until actually needed. Their more complex construction will make them higher priced.

COMMUNICATIONS SUBSYSTEM

"Communications," as used in this report, means locating and communicating with workers trapped underground either behind barricades or in refuge chambers. Electromagnetic and seismic communication techniques are being investigated.

Signal location accuracy requirements depend upon whether the mine is equipped with refuge chambers at the working sections. If chambers are used, only sufficient accuracy to determine the section signaling will be required. The exact location of the chamber can be found from the mine map. If refuge chambers are not used, the signal source must be located to within ±50 ft.

Electromagnetic Communications

Electromagnetic communications techniques have the advantage that, in the long term, they might evolve as a means of operational communication within the coal mine. If properly designed, enough of the operational system could survive an explosion to provide emergency communications. Moreover, electromagnetic or radio communications is the only technique that would permit emergency voice contact between men on the surface and those underground.

For the short-term system, electromagnetic beacons are proposed. Beacons would be located in refuge chambers, near the working faces, or in locations where miners would be likely to construct barricades if they were unable to egress from the mine. The beacon would operate at a low frequency, 500 to 1000 Hz, to ensure penetration to the surface even under the most adverse conditions. It would consist of a battery, a buzzer, and a key to interrupt the signal. Power would be applied to either a grounded wire or to a coil of wire. With the beacon underground would be a low frequency receiver. Surface searchers could locate the source of the field radiating from the beacon then communicate with the trapped individuals by laying out a large coil on the surface and transmitting downward at a higher frequency with very high power levels. The underground receiver would have a band width of only a few hundred Hertz which would make the construction simple. Two-way communication could be effected by having voice transmission downward and keyed code transmission upward. (The trapped individuals would not have to know code because the proper response could be indicated by the downward voice transmission.)

A detailed discussion of both the possible mine radio communications system and the emergency beacon system is contained in Appendix B, Part 1.

Seismic Communications

The requirements for a seismic system, as for an electromagnetic system, are that it be capable of rapid deployment, that it have sufficient sensitivity to detect the miner-generated signals at distances comparable to the dimensions of the area of possible entrapment, and that it be capable of locating the miners with sufficient accuracy that they can be reached by holes drilled from the surface or that fairly exact direction can be given to rescue teams. Although generally desirable, the ability to establish two-way communication between the miners and the surface is of secondary importance.

An interim system consisting entirely of currently available instruments has been described by the Committee and its performance predicted. This system is not expected to be optimum but will be adequate to provide a location capability that does not now exist during the time required for development of a more advanced system.

The interim system is based on miner location and communication by means of seismic pulses generated by striking the mine roof or walls with a hammer. The source of the signal is located by an analysis of the relative arrival times of seismic signals at the various elements of a large seismometer array. Two-way communication is by simple coded messages based on sequences of hammer blows.

The surface system for initial location consists of four subarrays of 19 seismometers each deployed in a square approximately 1/2 mile across a diagonal. Each subarray is recorded on a strip-chart recorder. Analysis of the arrival time of the P-waves at each of the subarrays will give approximate location, after which the array size will be reduced to a 500-ft square to minimize the effects of an irregular topography, geologic structure, and other inhomogeneities. With the smaller array, knowledge of the depth of the mine at this location, and knowledge of rock velocity in this area, it should be possible to locate the signal source within ±25 ft.

The smaller array will probably have one or more subarrays with a signal-to-noise ratio sufficient to provide good communication capability. If not, the four subarrays may be moved to a point above the best location estimate and their outputs combined to give an improved signal-to-noise ratio. The miner below ground will have a single seismometer, an operational amplifier, thresholding circuitry, an audio oscillator, and an earplug speaker. These devices have been successfully used in personnel intrusion detection. Their total weight is about 4 lb and the seismometer is equipped with a spike that can be driven into the roof of the mine for best reception. Any tool can be used for hammering--a 10 lb hammer would be preferable if available. The signaling code and instructions for using the system could be pasted inside each miners helmet.

When ready to communicate, a series of hammer blows on the ground surface will tell the miners that they have been located and that they should stop sending their location signal and start sending the prearraged coded messages regarding their condition. With this system it would be possible to determine the number of miners trapped, their physical condition, the condition of the air in their vicinity, and perhaps an estimate of their survival time to provide the rescue team guidance on priorities with which they should explore various areas of the mine.

RESCUE SUBSYSTEM

The Committee is investigating drilling and rescue-team techniques to save coal miners who, because of physical injury or gases in the mine atmosphere, have not been able to egress following an explosion or fire.

Drilling

There have been a limited number of times in the past when miners have not been able to egress nor rescue teams able to enter mines and the only means of rescue was through holes drilled from the surface. If refuge chambers are constructed in coal mines, there will be more occasions when miners will survive subsequent explosions and rescue holes will have to be drilled.

The principal interest of this Committee is in the rescue of trapped coal miners; however, the same drilling equipment can be used to rescue miners in salt mines, potash mines, or tunnels. The drilling systems described here have been optimized for rescue from rather flat-lying bituminous coal seams less than 1, 500 ft below the surface with overlying rock of relatively low strength. The highest strength rock expected to be encountered will be quartzite of approximately 25, 000-psi compressive strength, which in a very few areas may be as thick as 60 ft. Appendix C contains a detailed discussion of the drilling system and the assumptions made in arriving at the design.

The recommended drilling system would consist of a highly mobile probe and search drill that could drill a 6- to 8-in. hole to depths of 1, 500 ft with capability to go to 2, 500 ft. This drill would be air-transportable by military aircraft, drill reasonably straight holes with no more than 6-in. deviation per hundred feet of depth, drill 12, 000-psi rock at a rate of 100 ft per hour or more and strong quartzite at a rate of 20 ft per hour or more. It would have maximum traveling dimensions of 8 ft wide and 10 ft high. It would have a 1/4-in. wire hoist with the capacity of 2, 500 ft and would use air circulation for removal of cuttings from the hole.

The system would also include a rescue drill capable of drilling an 18- to 28-in. hole to a depth of 1, 500 ft with the capability of being extended to 2, 500 ft. This rig would also drill with air circulation for cuttings removal and would be capable of setting casing for the

28-in. hole to a 500-ft depth. It would drill 12,000-psi and weaker rock at the rate of 17 ft per hour and 25,000-psi quartzite at 6 ft per hour. It would have a hoist drum capacity of 2,500 ft of 3/8-in. wire rope.

To assure the availability of highly experienced and skilled drilling crews, the Bureau of Mines may want to contract with a drilling company to guarantee the availability of experienced drilling crews at times of emergency. It would be necessary for these crews to familiarize themselves with the Bureau of Mines equipment and maintain this familiarity by drilling a few holes each year.

Rescue Teams

Many coal operators maintain well-equipped and well-trained rescue teams that have participated in almost every coal mine emergency in the United States. These teams deserve high commendation for their bravery and efficiency of operation. They have been greatly handicapped, however, by lack of knowledge of the location of survivors. In a number of instances miners could have been saved if rescue teams had known their location.

Either the seismic or the electromagnetic communications system described previously could provide information that would permit rescue teams to direct their efforts to recovering the areas in which the miners are trapped.

Rescue efforts are also slowed by the time required to explore for fires or "hot spots" and to replace stoppings blow-out by the explosion. The Bureau of Mines is investigating the use of infrared spectrometers to detect fires or "hot spots" at distances up to 1,000 ft. An infrared spectrometer is being used in the recovery of the Consol No. 9 mine at Farmington, West Virginia.

Studies are now under way by the Committee to determine if high-expansion ratio, quick-setting, rigid foams can be used for the construction of stoppings under emergency conditions. Rigid foam is now used in mining operations but the size and speed of the foam-making equipment render it unsuitable for emergency use. If this study shows the technique to be feasible, development should proceed through selection of the optimum foaming materials, development of the best techniques, and construction and testing of a number of stoppings.

A typical rescue operation, using the proposed equipment, might be carried out as follows:

> As soon as the men on the surface are aware that an explosion or fire has occurred, they would notify workers in the areas of the mine still having communications of the hazard and, if it could be determined, of the best escape routes. They would notify company, state, and federal mining officials and, from available evidence, determine the locations in which survivors would most likely be trapped. Thus far, this is the procedure now in use. Next, an area should be located on the surface above the places in which survivors are expected to be found.
>
> The Bureau of Mines would immediately dispatch electromagnetic or seismic location and communication equipment and drilling rigs to the site. Other drilling rigs in the area would be requisitioned if needed.
>
> Rescue teams would begin immediately to determine if danger of subsequent explosions exists and, if not, to restore ventilation and to explore the affected areas of the mine. If there is danger of additional explosions, the Bureau's drilling crews should move to the approximate location and prepare to drill.
>
> The location and communication equipment would begin searching in the most likely areas immediately upon arrival.
>
> Meanwhile, workers underground in the unaffected areas should proceed out of the mine, carrying with them emergency breathing devices and carbon monoxide detectors. The atmosphere should be tested frequently for carbon monoxide because prior emergencies have shown that men frequently succumb before realizing that carbon monoxide is present in dangerous concentrations.

If carbon monoxide is detected, the workers must don the emergency breathing devices and decide whether to continue to the portal or proceed to a refuge chamber.

Workers in the affected area should immediately being using the breathing devices and proceed to a refuge chamber unless an obvious escape route is available. Once in the chamber, they would activate the oxygen-generating and carbon dioxide removal equipment and start sending seismic or electromagnetic beacon location signals.

Direction finding equipment on the surface would locate the source of the signals and establish communication with the men below. Directions and priority for rescue, if more than one group is trapped, would be furnished rescue teams or drillers.

If rescue teams can be used, they would restore ventilation up to the refuge chamber and evacuate the men. If some men are critically injured, they could be evacuated using oxygen breathing equipment before restoration of ventilation.

If rescue teams cannot enter the mine, probe holes would be drilled if the exact location of the miners was not known. After the men are accurately located, either by probe holes or a communication system, a large hole would be drilled. The trapped men would be rescued by pulling them up the hole in a capsule.

SYSTEMS ENGINEERING

The Committee recommends a substantial systems engineering effort as a part of this development program. The overriding consideration must be for the total system. A systems engineering effort will prevent the optimization of individual subsystems or components beyond the requirements of the total system, resulting in shorter development time and lower costs. Should technical problems arise in the development of any of the components, trade-off studies will be conducted to determine whether additional resources should be committed to overcoming the problem or if it is more efficient to improve another part of the system to overcome the degraded performance of the component in difficulty.

The most important function of the systems engineering group would be to prepare plans for testing the total system and procedures for its use. Components which individually function satisfactorily may require some modification for use with the total system. A well-planned testing program is essential to assuring the system will perform satisfactorily when needed. Well-thought-out procedural guidelines are essential to efficient use of the system during an emergency.

APPENDIX A

SURVIVAL SUBSYSTEM

Two life support systems are required for the proposed coal mine rescue and survival system: a lightweight individual emergency breathing device that can be carried continuously by a coal miner and a life support system capable of supporting 15 men for up to two weeks for a small refuge chamber.

Emergency Breathing Device

The present emergency breathing device for individual miners is the self-rescuer. This device uses the catalyst hopcalite to convert carbon monoxide to carbon dioxide as the mine atmosphere is breathed through the self-rescuer. The name hopcalite refers to various mixtures of the oxides of manganese, copper, cobalt, and silver. In "four-component hopcalite" all of these oxides are present, and the catalyst is precipitated as hydrous oxide. In the two-component catalyst only oxides of manganese and copper are present; the copper is precipitated as a carbonate. Both of these hopcalite catalysts are very effective for low-temperature oxidation of carbon monoxide, although the four-component catalyst rapidly loses its activity at elevated temperatures.[1] Hopcalite is relatively immune to the effects of water vapor at elevated temperatures, but at lower temperatures the catalyst must be protected from water vapor by the addition of a drying agent. It must also be protected from organic materials that can poison the catalyst.

In a 1 1/2 percent carbon monoxide atmosphere, temperatures at the mouthpiece of the self-rescuer may reach 185°F because of the exothermic reaction of the conversion of carbon monoxide in the catalyst. At concentrations higher than about 1 1/2 percent, the temperature of the inhaled air becomes greater than can be tolerated by the man wearing the self-rescuer.

In addition to the disadvantage of the high temperature of the inhaled air, the percentage of carbon dioxide in the air breathed by the wearer is increased by three factors. First, following a mine fire or explosion, the concentration of carbon dioxide in the air is substantially increased. Second, the carbon monoxide is converted to an equal percentage of carbon dioxide by the action of the self-rescuer.

Third, some of the wearer's exhaled breath, which contains carbon dioxide as a body waste product, is rebreathed. Carbon dioxide is a powerful respiratory stimulant causing an involuntary increase in the minute volume (the volume of air inhaled each minute) even though there is no change in the work rate. Thus, although a few percent of carbon dioxide would not of itself be harmful, the effect of the gas is to increase the breathing rate of the wearer (possibly causing fatigue), reducing the lifetime of the self-rescuer.

Two models of the self-rescuer are now currently available. One is rated by the Bureau for 30-minutes duration and the second is rated for a 1-hour duration in an atmosphere containing carbon monoxide. The 1-hour device has a heat exchanger built into the mouthpiece to reduce the temperature of inhaled air. For either device there is no way the wearer can determine whether the catalyst is functioning properly.

In many instances following an explosion, the miners must pass through heavy smoke and dust concentrations to egress from the mine or to reach an area where barricades can be erected safely. Occasionally the smoke and dust concentrations are so heavy that the miners cannot see each other and can communicate only by touch or by voice. An emergency escape device should take this into consideration and should provide the capability for intermittent voice communication. Following is a description of two concepts that the Committee believes might overcome the disadvantages of the self-rescuer in providing emergency respiratory protection. Although these two approaches appear promising, there are no doubt many other concepts that should be considered. A relatively short-duration study (three to six months) would bring many of these to light.

Both concepts considered here use a plastic hood to completely enclose the head of the wearer. The preferred material is polyimide, which was used in the FAA development of a proposed protective passenger smoke hood for aircraft.[2] Polyimide was selected because of its nonmelting property when exposed to extreme heat and because it is transparent and nonflammable. It reportedly does not begin to char until temperatures exceed 1472°F. Other desirable features include high tensile strength, folding endurance, low shrinkage, insolubility in inorganic solvents, and inertness to fungi. It is conceivable that a coal miner wearing this hood could pass quickly through a relatively high temperature flame without suffering severe burns.

The first system being considered uses a potassium superoxide canister to generate a 45-minute oxygen supply. The wearer would inhale air through the potassium superoxide from the hood or from the hood and a small supplementary breathing bag. If the circulation system can be so designed that there is no build-up of high carbon dioxide concentrations within the hood, the wearer can temporarily remove the mouthpiece and breath the air trapped in the hood while talking with other miners. Returning to breathing from the mouthpiece would flush the carbon dioxide from the hood, again permitting voice communication. It is believed that the physiological effects of the build-up of carbon dioxide when breathing directly from the hood would provide sufficient warning to the miner that he would resume breathing through the mouthpiece before becoming anoxic.

This system could be carried on the miner's belt, and additional devices and potassium superoxide canisters could be stored in strategic locations within the mine; then should the miner be trapped in an irrespirable atmosphere for longer than 45 minutes, he would locate an additional device or replace his potassium superoxide canister.

The second concept is quite similar, except that it uses a chlorate candle for the oxygen source. A 45-minute-duration candle is connected by a small tube to a mouthpiece inside the hood. The air exhaled by the wearer passes through a filter to remove the carbon dioxide and then into the hood. The filter might be built into the mouthpiece; however, sufficient filtering materials for a 45-minute duration might make this concept excessively cumbersome. Excess oxygen passes out the neck dam of the hood.

Refuge Chambers

If small refuge chambers are established near each working section and advanced or retreated as the mining advanced or retreated, it would not be economically feasible to provide a hole from the surface to the chambers. Therefore, the chambers must be equipped with self-contained oxygen-producing and carbon dioxide removal systems. In the concept under consideration, all life support equipment--oxygen supply, carbon dioxide removal agent, chemical light sources, food, water, blankets, oxygen level detectors, methane level detectors, carbon monoxide detectors, medical supplies, and perhaps a chemical toilet--would be mounted on a wheeled cart or "red wagon." This wagon could easily be moved by a shuttle car as the refuge chamber was advanced or retreated.

Three possible oxygen sources are being considered for the refuge chambers: potassium superoxide, chlorate candles, and high-pressure air or oxygen. Hydrogen peroxide also was considered, but was rejected because of its toxicity and the potential of its vapor becoming explosive in high enough concentrations.[3] Potassium superoxide has the advantage of absorbing carbon dioxide in the production of oxygen. The systems using chlorate candles or compressed air or oxygen would require carbon dioxide scrubbers.

Potassium superoxide will theoretically produce 33.8 percent oxygen by weight with approximately 90 percent of the potassium superoxide actually available for conversion. The density of potassium superoxide is approximately 41 lb/cu ft, and it generates 415 BTU's per pound of oxygen produced. Potassium superoxide has been used in breathing systems for many years. Numerous long-term tests have been run: in 1960 the Air Force ran a 1-man, 168-hour test using potassium superoxide[4]; in 1960 the Navy ran a 6-man, 8-day test using potassium superoxide[5]; and in 1964 the Boeing Company, under contract to NASA, performed a 5-man, 30-day sodium superoxide test.[6] Currently potassium superoxide is used for oxygen production and carbon dioxide removal in several small research submersibles.

The crew could be expected to have an oxygen consumption of 2.0 lb per man-day with a respiratory quotient of 0.82, requiring a carbon dioxide removal rate of 2.25 lb per man-day. This would require about 7 lb of potassium superoxide per man-day, which would absorb 0.17 lb of water per man-day. Thus, for a 200 man-day system, 1,400 lb of potassium superoxide would be required.

It might be possible to purchase potassium superoxide in these quantities for about $3 a pound, or about $4,200 for a 200 man-day supply. Building this into a system might double this price.

Chlorate candles theoretically produce 48 percent oxygen by weight with approximately 90 percent actual availability. The density of candles is 141 lb/cu ft, and they produce approximately 422 BTU's per pound of oxygen generated.

Candles made of alkali metal chlorates have been used in submarine oxygen supplies for years and are currently planned for emergency oxygen systems in the C-5A military transport and the new generation of commercial jet liners. The standard submarine candle is approximately 12 in. long and 7 in. in diameter, weighs 25 lb, and burns for 45 minutes liberating about 10.2 lb of oxygen, an equivalent of 5 man-days. This candle is presently available for about $15. A 200 man-day supply, therefore, would cost $600.

Chlorate candles, like superoxides, have essentially an infinite shelf-life. There are, however, disadvantages to the candles when used in a mine system. First, they decompose at 1300 to 1500°F and would ignite any methane that leaked into the candle container. Second, they are not self-regulating, as is potassium superoxide, and require frequent monitoring of the oxygen level to determine when an additional candle should be ignited. Third, chlorate candles would have to be supplemented with a carbon dioxide removal system.

Another possibility for refuge chamber oxygen is compressed air or oxygen tanks. A 2,400-psi tank containing 1,500 cu ft of oxygen--sufficient for 60 man-days--costs approximately $225 when purchased in lots of 100 or more. Regulators and oxygen would slightly increase the total cost. One disadvantage is the difficulty of storing high-pressure gases for long periods of time without leakage. Leakage rates during long-duration storage would have to be determined, as would the effects of the shock waves generated by an explosion on the regulators, valves, and seals. A high-pressure oxygen system, like a chlorate candle system, would require a carbon dioxide scrubber.

Potential carbon dioxide removal systems could use lithium hydroxide, baralyme, or lithium peroxide. Lithium hydroxide has the disadvantage of being very irritating, although it is not toxic. It would cost about $10 per man-day, or $2,000 for a 15-man, 14-day supply.

For a system to evolve from existing technology, baralyme is probably the most attractive carbon dioxide removal agent. Although on a weight basis twice as much baralyme is required as lithium hydroxide, it does not have irritating properties and thus is easier to handle. In addition, it is considerably cheaper at about $4 per man-day, or $800 for a 15-man, 14-day supply.

Lithium peroxide has not been used extensively in life support systems; however, it has an obvious advantage over other carbon dioxide absorbors in that it evolves oxygen. Lithium peroxide is very promising if its use could be developed in time for the near-term system.

Any of the systems using a carbon dioxide removal agent and possibly even the potassium superoxide system would require a hand-cranked blower to circulate the air through the chemical bed. A chart would be provided with the system giving the length of time the blower should be operated each day as a function of the number of men in the chamber of the number of days they have been there. With this type of system, an activated charcoal bed could be added to aid in removing undesirable odors, although this would not be absolutely necessary.

The small refuge chamber would be designed to be frequently reestablished as mining advanced or retreated in a given section. The bulkheads which would be used to enclose the crosscut forming the chamber would be made of sections capable of being loaded onto a shuttle car by 2 or 3 men. The life support system and all other equipment would be mounted on a cart that could easily be pulled by a shuttle car. The chamber should always be within a few thousand feet of the working face so that miners in the section could travel rapidly to it and receive almost immediate protection from the gases generated by the explosion or fire. Depending on the type of system chosen, cost for the cart would range from $10,000 to $15,000. Trade-off studies should be conducted to select the optimum system, which should then be developed and tested.

REFERENCES

1 Emmett, Paul H., ed., Catalysis, Vol. VII, Reinhold Publishing, New York, 1960.

2 Office of Aviation Medicine, Department of Transportation, Federal Aviation Administration, A Protective Passenger Smoke Hood, April 1967.

3 Fabuss, Bela M., et al., "Self-Contained Generator for Shelter Use," Montsanto Research Corporation, 1964, AD 616 639.

4 Keating, Donald A. and Konrad Weiswurm, "KO_2 Passive Air Regeneration Studies for Manned Sealed Environments," WADD TR 60-707, Wright Air Development Center, December 1960.

5 Mancinelli, D. A. and E. L. Michel, "Environmental Requirements of Sealed Cabins for Space and Orbital Flights," NAMC - ACEL - 418, May 24, 1960.

6 "Manned Environmental System Assessment," The Boeing Company, NASA Contract NASw 658, May 1964, N65-12076.

General Reference

Charanion, T. R., A. J. Glueckert, R. G. Barile, and J. D. Zeff, "Environmental Control Systems for Closed Underground Shelters," General American Transportation Corporation, Contract Report, Contract No. OCD-OS-62-56, April 1963, AD-413416.

APPENDIX B

COMMUNICATIONS SUBSYSTEM

PART 1, ELECTROMAGNETIC COMMUNICATIONS

Two approaches to underground communication should be considered: one in which a radio communications system would be set up for ordinary conversation during routine mining operations and which would have some possibility for surviving for emergency communications after a disaster; and one in which electromagnetic beacons would be provided to working crews so that they could signal their survival if all else failed.

Standard Radio Communications

A practical system might consist of mobile radio transmitters for use by individuals or working crews. The signals from these transceivers would be relayed by telephone wire to the surface after being converted from the transmitted frequency to a phone line frequency by one or several relay stations underground. To be practical, the relay stations would have to have a range of 1,000 to 2,000 ft over which they could receive the transmissions from the portable transceivers. It would in fact be preferable to have several shorter-range repeaters rather than a single long-range repeater, because several would provide overlapping coverage and a greater chance of partial survival of the system in case of a disaster.

The critical question in the use of such a system is whether a portable transceiver can be built that has a range adequate to meet the purposes. On the basis of published results of attempts at radio communications in mine openings, it is not clear if this might be possible. Further careful studies of radio transmissions, particularly as a function of frequency and antenna orientation, will be required to evaluate this.

One approach might be to use high enough frequencies that the radiated energy would travel through the mine openings as a guided wave. Typical mine openings have dimensions of the order to several meters; and therefore, the wavelengths would have to be of the order of several meters--corresponding to frequencies in the 100- to 200-MHz range. It is believed there is no experience with the use of such frequencies underground. At such frequencies, there are a number of practical problems, such as a difficulty in refracting waves around corners in the mine openings and scattering caused by the variable cross section of the wave guide. However, in view of the lack of experience with these frequencies, some experimental work should be done, particularly since standard transmitters in this range are available.

The other approach is one of brute force, in which the radio communication is done through the material between the transmitter and the repeater. In the extreme, if the range becomes great enough, this reduces to the problem of communicating directly to the surface with electromagnetic waves. Ordinarily, though, the range of a radio transmitter along the seam being mined should be considerably greater than the range to the surface. Range of radio transmissions is determined largely by the so-called skin depth, which is the distance over which the radio signal is reduced by a factor of about 2/3 because of heat loss in a conducting medium. Bituminous coal seams are reported to have a conductivity range from 10^{-2} to 10^{-3} mhos per meter, whereas the rock overlying a bituminous coal seam normally has a conductivity of 10^{-1} to 10^{-2} mhos per meter. Removal of coal and backfilling of mined-out areas with rock rubble probably decreases the overall conductivity by a factor of 2 or so. The net result of these probable electrical properties for coal and overburden is that radio range in a coal seam is probably three to ten times greater than the range through the overlying structure.

At frequencies around 1 MHz, where it may be possible to use standard portable transceivers, a skin depth will be of the order of 300 ft in coal and 50 ft in the overburden. In a distance of seven skin depths, a radiated signal is reduced by a factor of 1,000 by attenuation, and this constitutes a practical limitation for detection with a sensitive receiver. Thus, it might be possible to transmit at MHz frequencies through a coal seam, if the field can be radiated in such a way that it sees only the electrical properties of the coal, and not the combined properties of the coal and the surrounding rock. Perhaps it would be feasible to generate horizontally polarized waves with the transmitter to accomplish this.

If experimentation shows that the effective conductivity is too high to permit operation at MHz frequencies, consideration might be given to ELF transmissions in the vicinity of 10 kHz. The attenuation at this frequency is lower by a factor of 10, allowing about ten times the distance of transmission for the same radiated power as at 1 MHz. However, antennas such as might be used on a portable transceiver in a mine opening are very inefficient at these lower frequencies. There is probably an optimum frequency not too far from 1 MHz where the increasing inefficiency of antennas at lower frequencies offsets the increasing penetration obtained.

The costs of such a communication system are as follows: Standard transceivers in the 1- to 10-MHz range or in the 100- to 300-MHz range cost from a few hundred to a thousand dollars. If a nonstandard frequency range is to be used, and particularly if it is to be a low frequency, a portable transceiver could cost from $2,000 to $5,000, for small quantities. The repeater station will cost about $10,000 to about $35,000, depending on how standard the ultimate system would be. Installation of armored telephone cable in existing ventilation shafts would cost about $1 per foot, or about $3 per foot if new holes had to be drilled. There would also be operating costs involved in maintenance of the surface-based switchboard.

Careful consideration should be given to the feasibility of such a system, even if initial experiments seem to be negative, inasmuch as the system would provide continuous underground communication for standard operations, as well as emergency communications. A very important advantage of a continuous system is that monitors could be placed in the mine to record the levels of carbon monoxide and methane (and possibly temperature) with warnings transmitted instantaneously to the surface switchboard. This would provide the operator a chance to prevent a disaster if explosive gases build up in an unoccupied part of the mine, and it could give surface personnel the information they need to guide survivors to the surface after an explosion.

The radio relay system does not, of course, provide the full answer, even if it works in some mines. Other mines will be too small to warrant the use of such a permanent system, and if such a system is available, it is too complex to assure that after an explosion, everyone underground will have communications. The system should be backed up with an emergency beacon system.

Emergency Beacon System

The requirements for this system would be a high degree of reliability in all respects, even with the compromised channel capacity. It must be rugged, reasonably inexpensive, and utterly reliable. The use of an audio-frequency electromagnetic beacon has been suggested and seems quite feasible. An electromagnetic field would be generated with either a grounded wire or an induction coil by the trapped miner, and then, surface personnel would search for such beacons. A frequency between 500 to 1,000 cps would assure penetration, even under the most adverse conditions. The beacon would consist of a battery, a buzzer, and a key to interrupt the signal. Power would be applied to either a grounded wire or to a coil of wire. Surface searchers would spot the source of the field and then communicate with the trapped individuals by laying out a large coil on the surface and transmitting downward with high power. The underground receiver would have a bandwidth of only a few hundred Hz, which would make the construction simple. Two-way communication could be effected by having voice transmissions downward, and the keyed code transmissions upward (the trapped individuals would not need to know code, because the proper response could be indicated by the downward voice transmission).

Preliminary computations indicate that a coil antenna would be preferable in the mine to a grounded wire antenna. With a current of 0.1 amp applied to a 500-turn 50-ft periphery coil (which could be unspooled from a small reel and which would weigh about 10 lb), the field would be readily detectable with sensitive equipment on the surface at distances of about a half mile from the spot over the beacon. A 60-ft grounded wire in the mine would provide about the same electric field at the surface for the same power consumption, but it suffers from several disadvantages.compared to the coil source:

1. Electric fields are detected with electrodes driven in the earth, so the search would be slower.

2. The electric field will be shorted out in the mine if the opening in which the wire is laid has rails in it.

3. The laying out of a grounded wire requires more participation by the trapped individual than does laying out the coil; for example, in a ventilated area of the mine, the wall rock may be locally dried so that it provides poor contact. The individual would have to choose a spot with good contact properties, and it may be necessary to provide some sort of meter on the equipment to assure that sufficient current is being driven into the ground to be seen by surface searchers.

Surface search equipment would consist of a search coil, if the source is a coil, connected to a sensitive turned voltmeter. Search is simplified if it can be assured that the frequency being sought is known within a few percent. If several beacons are being sought, there may be confusion from overlapping signals; and it would be desirable to have each beacon in a mine provided with a distinct frequency, perhaps separated by as much as 5 percent. The search equipment should best be operated by experienced personnel, to avoid confusion and save time. It is obvious that dry runs are essential to provide experience in locating underground beacons.

A beacon should have a life of at least 48 hours; at a current of 0.1 amp, a power supply with a capacity of at least 5 ampere-hours would have to be provided. A weight of a pound or two per ampere-hour is reasonable, so the full weight of the coil, the transmitter/receiver and the batteries would be in the neighborhood of 20 lb, with a volume of 1/2 to 1 cu ft. The equipment is obviously not man-portable, but would have to be placed at strategic locations in the mine or hung on mine cars. The possibility of an 8-oz 10-cu-in. beacon that would be man-portable is not foreseen at this time.

The cost of a beacon system might be up to $200, without a receiver, and possibly $50 more with a receiver. The cost of the search equipment could be high, depending on how many sets are developed and who operates it. Estimates are the receiving and location equipment would cost between $10,000 and $50,000. The voice transmitter would cost about $2,500 to $10,000.

A program should be carried out to evaluate the desirability of various modifications of a beacon from the human and mine engineering aspects.

After this evaluation, parametric trade-off studies, development of prototype beacon and surface equipment, and tests of the prototype should be conducted. Tests of the prototype system should be conducted in all major coal producing areas of the United States to assure penetration of the different overlying formations with sufficient strength that the signal can be detected from a point over the beacon.

None of this can be done currently with off-the-shelf equipment. It all could be done with existing components on an experimental basis, but not much of the available equipment could be operated with assured safety in a mine. In particular, great care must be taken that any radio transmitter used underground will not detonate explosives.

PART 2, SEISMIC COMMUNICATIONS

Accurate location of and subsequent two-way communication with trapped miners following a mine accident is an integral part of the proposed system and of utmost importance to a successful rescue. A seismic approach using acoustic waves propagated through the rock and soil between the trapped miners and the surface appears to be feasible. An interim system consisting entirely of presently available instruments is described and its performance predicted. The system is not expected to be optimum, but will be adequate to provide, during the anticipated five-year research and development program, a capability that does not now exist.

System Considerations

One prime consideration is that the system have sufficient sensitivity that it can detect the miner-generated seismic signals at distances comparable to the dimensions of the area of possible entrapment. Another prime consideration is that the system be capable of locating the source of the signals with a precision commensurate with the requirements for safe and efficient rescue operations. Accuracy of only a few hundred feet will be required if each section of the mine is equipped with refuge chambers. The mine map can be used for exact location of the chambers and seismic signals will be used only to determine which of the chambers are occupied. If the mine is not equipped with chambers, location accuracy of approximately ±50 ft will be required. Although highly desirable, the ability to establish two-way communication between the miners and the surface is of secondary importance.

Other important features of the surface system should include:

- Quick and simple deployment
- Portability
- Battery-powered operation
- All-weather operation
- Computational simplicity and speed
- High reliability--long shelf-life

- Dual service for location and communication
- Adaptability to widely varying seismic velocities, topography and geologic structure
- Minimum maintenance
- Capability of continuous operation for extended periods
- Reasonable cost

The subsurface part of the system should have the following features:

- High reliability--long storage life
- Nonexplosive and spark-proof design
- Lightweight and rugged construction
- Capability of being operated by one man
- Requirement of little or no training for operation
- Availability at multiple key locations in the mine
- Minimum maintenance requirements
- Capability of continuous operation for extended periods
- Unit cost that makes storage of multiple units below ground economically feasible

System Description

The interim system is based on miner location and communication by means of seismic compressional pulses (P-waves) generated by striking the mine roof or walls with a hammer. Location is accomplished by an analysis of the relative arrival times of seismic signals at various elements of a large seismometer array. Two-way communication is achieved through a simple code based on sequences of hammer blows.

Surface System

Four subarrays of 19 seismometers each are deployed in a square approximately 1/2 mile across the diagonal. Each subarray is approximately 40 ft in diameter. All seismometers are permanently connected in parallel by shielded, polyurethane-jacketed cable. Seismometers are 28-Hz natural-frequency instruments weighing about 2 lb each. Each seismometer subarray is laid out on a hexagonal grid with approximately 5-ft spacing between instruments. A battery-powered preamplifier in watertight case is located at the subarray center. This single channel output is transmitted by 1, 320 ft of 2-conductor shielded cable back to the recording equipment at the center of the large square array. Cables are laid out and picked up using portable breast-reels commonly used for seismic exploration work in areas not accessible by trucks.

The four cables from the seismometer subarrays are plugged into an aluminum suitcase-mounted instrument package consisting of:

- 60-Hz notch filters
- 36 db per octave high-cut filters (variable gain in 6 to 12 db stops for up to 10 steps)
- Power inverter and batteries

Another aluminum suitcase contains a 4-channel strip-chart recorder. Paper speed is variable from 5 mm/sec to 200/sec.

A plotting board with necessary straightedges, templates, and compasses is provided. Up-to-date maps of the mine workings on a scale of 1 in. = 200 ft are provided and can be mounted on the plotting board beneath a transparent worksheet. Specially constructed circular slide rules may be necessary to speed the computations when topography is rough and to allow for widely differing seismic velocities in different geographical regions.

The array commandpost (CP) should also be provided shelter in case of bad weather--the back of a covered truck or simply a canvas tent. Battery-powered lamps must be provided for array deployment and computational work at night. Walkie-talkie radio or sound-powered phone communication will be required between the array CP and the rescue operations CP. A magnetic compass will be necessary for array orientation and location when array sites have not been previously selected and surveyed in. Spare batteries, extra rolls of strip-chart paper, and certain spare parts should be available at the array CP.

Subsurface System

The subsurface system will consist of an instrument for conversion of seismic motion to audible acoustic energy, a hammer, and a code chart and instructions for its use. The conversion of seismic energy to audible acoustic energy has been accomplished with a single seismometer, operational amplifier, thresholding circuitry, audio oscillator, and ear-plug speaker. These devices have been successfully used for personnel intrusion detection. Total weight is about 4 lb and the seismometer is equipped with a spike that may be driven into the mine roof for best reception.

Any tool could be used for hammering. If available, a 10-lb hammer would be preferable. The signaling code and instructions for using it should be pasted inside each miner's helmet.

System Operation

Deployment

A station wagon, 3/4-ton truck, or similar vehicle can transport the entire surface system. All elements of the system are portable and can be hand-carried into rough country if necessary.

When the vehicle reaches the array CP at the center of the square array, several operations should be carried out simultaneously. The four cables should be laid out their full 1,320-ft length at right angles to one another. If sufficient help is available, these cables can be laid and the seismometers carried to the subarray locations simultaneously. This operation requires 8 men and about 10 minutes; fewer helpers will increase the time proportionately. Each subarray can be laid out and connected in about 10 minutes. Subarray size and configuration are not critical, and pacing off distances between seismometers will provide sufficiently accurate subarray layout.

While the subarrays are being laid out, another man can be setting up the CP equipment and checking continuity of cable connections as they are connected at the subarrays. After array deployment, all personnel should return to the array CP because their movement within or near the subarrays would constitute a major noise source.

Ideally, array positions would have been surveyed-in for all likely locations over the mine workings when the system was installed. Tests could then be quickly performed to determine the proper subarray size and configuration for maximum noise rejection. Subarray velocities could also be accurately measured at that time by hammering at selected points in the mine.

Although such site selection and calibration prior to an accident is desirable, it is not essential. Rough asimuth setting at the array center and the use of cables cut to the correct length (1,320 ft) will permit rapid array deployment with enough configuration control to permit signal detection and a preliminary rough estimate of the miners' location. It is expected that after signal detection and rough location, the array would be moved so as to be centered over the estimated location and substantially reduce in size.

Location

The 4-pen recorder is operated at low speed (5 mm/sec) until a signal is observed. When signals are observed, the operator switches to high speed (200 mm/sec) in order to permit accurate (±0.001 sec) measurements of relative arrival times. With a 200-ft paper roll, the recorder can operate continuously for 2 hours at low speed with 40 high-speed runs of about 3 seconds duration each.

If a signal is observed on three or four of the seismometer subarray outputs, the operator can get a rough location estimate. Since the array is large with respect to the mine depth, the seismic ray paths will be approximately horizontal in the subweathering rock. A quick computation will tell the operator whether the source is inside or outside the square array. If it is inside the array, the method of intersecting hyperbolas must be used for source location. If it is outside the array, an assumption of plane waves may be used and the outputs used in pairs to find the intersection of two straight lines along the two asimuth estimates.

Once the rough location estimate is obtained, it will probably be necessary to move the array and reduce its size. Time required to pick up seismometers and cables will be the same as for deployment. Thus with an 8- to 9-man crew, the array could be moved and back in operation in about 45 minutes. Reduction in array size (to a 500-ft square) will tend to minimize effects of irregular topography, geologic structure, and inhomogeneities. Since the source will almost surely be within the smaller square array, the intersecting hyperbola method will be used to obtain the best location estimate. Knowledge of mine depth and rock velocities in the area should give location precision of ±25 ft.

Communication

The smaller array will probably have one or more subarrays with a signal-to-noise ratio (SNR) that provides good communication capability. If not, the four subarrays may be moved to a point above the best location estimate and combined to give a single output with an improved SNR.

When ready to communicate, a series of hammer blows on the ground surface will tell the miners that they have been located, that they should stop sending their location code and start sending the prearranged coded message regarding their condition, etc. Messages may also be sent by the surface array crew and picked up by the subsurface system. Information transfer by a pulse-coded system will necessarily be slow and may require repetition to ensure correct reception. A fairly good description of the following subsurface conditions could probably be transmitted in about 15 minutes:

- Condition of air
- Condition of barricades
- Number and seriousness of injuries
- Adequacy of food and water supplies
- Adequacy of first-aid supplies
- Adequacy of breathing or other survival equipment
- Number of survivors in that location
- Estimate of survival time

The prearranged code, taped inside every miner's helmet, would permit a selection of up to about six different messages to report on each category.

After the general description of their situation, a more detailed but slower communication could be conducted by morse code (also inside the helmet). The miners could be advised to start walking out and given a route to follow.

System Sensitivity

Although no experiment has been conducted to measure the signal amplitudes obtainable at the surface with a hammer source in a mine (and vice versa), the signal amplitudes obtained in exploration seismology indicate that hammer blows should be easily detectable at ranges of 5,000 ft or more. Seismic signals have been recorded by down-hole seismometers with a very high SNR at depths of 5,000 ft. An experiment in shallow refraction seismology has shown good signal amplitudes from hammer blows obtainable with single seismometers at ranges of 250 meters.[1] Since this energy is refracted twice at the base of the low-velocity weathered layer and must penetrate that very absorbent layer twice, this range is very encouraging.

Another experiment using a hammer source for shallow reflection exploration has demonstrated a good SNR for reflections from depths of 450 ft recorded at 300 ft offset with single seismometers.[2] Since even the strongest reflections usually correspond to reflection coefficients of 0.1 or less, under the assumption of energy loss through spherical spreading only, the same signal level should be observed at a distance of 10,000 ft when the direct wave, rather than a reflected wave, is recorded. Scattering and absorption (especially of the higher frequencies) will reduce this range. The elimination of one of the two passages through the weathered layer when recording a mine-to-surface or surface-to-mine transmission should tend to increase the effective range.

Use of seismometer array can greatly enhance the SNR if the arrays are properly sized and configured. By connecting all 19 seismometers in each subarray in parallel, the output is simply the sum of the 19 seismometer outputs. A uniform hexagonal array, such as the one recommended, has the property that its sum response is very low for plane waves whose (apparent) wavelength is equal to or less than the array diameter.[3] Since most of the coherent noise recorded by the array will be propagating in the low-velocity weathered layer, it will exhibit relatively short (40 to 100 ft) wavelengths. The signals from within the mine will propagate almost horizontally (except, of course, when a subarray is almost directly overhead) at the prevailing subweathering rock velocity. Thus signals will exhibit apparent wave lengths of 300 to 700 ft. A 19-element array can give roughly an 18-db SNR improvement through simple summation when the noise is isotropic and propagating at apparent wavelengths equal to the array diameter.

Any spatially random noise will increase in RMS by a factor of $\sqrt{N}$. Thus, a 19-element array will give about a 13-db SNR improvement if the noise is spatially random.

Most seismic noise in the signal band (25 to 50 Hz) is expected to appear spatially random even over the very small dimensions of the subarrays. However, strong coherent noise may appear, which results from coupling of acoustic waves in the air with the earth. The recommended subarray size is designed to attenuate such coherent noise energy.

With the extrapolation from hammer-reflection seismic experiments and the improvements in SNR available through use of seismometer arrays, it appears that detection ranges of 5,000 ft or more can be expected. This range will depend on the ambient seismic noise level and the types and conditions of the intervening rocks and soils.

Measurements of seismic velocities and characterization of the ambient noise field in the 25- to 50-Hz band at each mining region prior to emergency use of the system is recommended. Optimum subarray size could be determined, signal velocity more accurately measured, and detection range determined. Then in an emergency, better SNR and better location precision could be obtained.

The single seismometer used in the subsurface system will be the same type as that used in the surface system. It is expected that ambient noise levels in the signal band will be much less in the mine and use of arrays unnecessary. Range for surface-to-mine signal transmission will never exceed the mine depth--usually 400 to 600 ft. Good transmission can probably be achieved to much greater depths.

There are three considerations when estimating the cost of this system. First is the cost of acquiring the instruments. Second is the cost of installing the system including training of mine personnel and operators. Surveying and measurements of seismic velocities are also installation expenses. The third system cost is the annual cost for inspection and maintenance.

System Deployment and Ownership

Surface System

It is anticipated that the surface system be owned by the Bureau of Mines. It is important that the system can be quickly transported to the site of a mine accident. But because of the system cost, as few systems should be constructed as needed to give a quick reaction capability. Systems might be located in areas of high-density mining activity so that no mine is more than 50 miles from a system.

All installation, training, inspection, and maintenance might be performed by a section of the Bureau of Mines specially set up for that purpose. All trained system operators and instructors for miners' classes could be Bureau of Mines personnel where feasible--mine safety engineers where not.

Subsurface System

The number of subsurface devices required for adequate protection will depend on the size of the mine, the number and distribution of underground crews, and the number and distribution of shafts and refuge chambers. The Bureau of Mines should set the requirements for the number, distribution, and type of subsurface devices.

REFERENCES

1 Gough, D. I., "A New Instrument for Seismic Exploration at Very Short Ranges," Geophysics, Vol. 17, No. 2, April 1952.

2 Meidao, Tsvi, "Hammer Reflection Seismics in Engineering Geophysics," Geophysics, Vol. 34, No. 3, June 1969.

3 Graebner, R. J., "Seismic Data Enhancement - A Case History," Geophysics, Vol. 25, No. 1, February 1960.

APPENDIX C

MINE RESCUE DRILLING SUBSYSTEM

The purpose of this subsystem study is to design a drilling system for rescuing trapped coal miners in conditions most likely to be found in the United States. The same system can be used to rescue men trapped in other underground workings. In the past six years, men have been trapped in salt mines, potash mines, and tunnels.

Although coal mines probably have the highest safety standards of all underground workings, the hazards are greater because most coal seams produce explosive methane gas; coal dust suspended in air is explosive; the coal will burn; coal naturally occurs in fairly weak sedimentary formations in which roof falls are common; and more tons of coal are produced than any other mineral. Thus more men are employed in producing coal, creating a greater exposure to accidents than other underground work.

The rescue drilling system should be designed for the characteristics of the greatest volume of coal, recognizing that conditions may occur that fall outside the system capability.

A study probably would show that 90 percent of the United States coal production comes from areas having the following characteristics:

1. Rather flat-lying bituminous coal seams less than 1, 500 ft below the surface.

2. Overlain with moderately low-strength rock in a multitude of relatively thin layers (a few inches to a few tens of feet) of varying strength. (The highest strength rock will be quartzite of approximately 25, 000-psi compressive strength, which in a very few areas may be as thick as 60 ft.)

3. Overlying formations that will produce a relatively low volume of water (less than 100 gal/min).

4. Mountainous areas making access to some drilling sites difficult.

5. Served by secondary highways where limited bridge capacity or underpass clearance may restrict movement of massive machinery.

6. Where rescue volunteers, mechanically skilled and unskilled, are abundant in time of emergency. The skills currently do not include large-hole drilling ability.

7. Where cuttings disposal from drill rigs is not problem.

8. Where massive earth-moving machinery is likely to be available from surface mining operations.

9. Unconsolidated surface material (which will require surface casing) of less than 40-ft thickness.

Mines in these areas will have the following characteristics:

1. Be within 100 miles (two-hours driving time) from commercial airports.

2. Be well surveyed and mapped and staffed by skilled engineers who can, in a reasonably short time, locate a surface site directly above any point underground.

3. Employ miners that are trained, if escape seems impossible, to enter refuge chambers if provided or to seek refuge in a deadend entry, barricade themselves, and wait for rescue.

RESCUE DRILLING SYSTEM

Given the above conditions, the mine rescue drilling system should:

1. Provide a highly mobile probe and search drill that would:
   a. Drill a 6- to 8-in. hole (probably 6 3/4 in. to take advantage of commercial technology in this size range) to 1,500-ft depths with a capability of being extended to 2,500-ft depths.
   b. Be transported in military aircraft.
   c. Drill reasonably straight holes with no more than 6-in. deviation per 100 ft depth.
   d. Drill 12,000-psi rock at the rate of 100 ft per hour (or more) and strong quartzite at 20 ft per hour.
   e. Have maximum traveling dimensions of 8-ft width and 10-ft height.
   f. Have a hoist with a capacity of 2,500 ft of 1/4-in. wire rope. (This can be a separate unit.)
   g. Drill with air circulation.
2. Provide a rescue drill capable of:
   a. Drilling an 18- or 28-in. hole to 1,500-ft depth with a desired capacity of being extended to 2,500-ft depth.
   b. Drilling with air circulation.
   c. Setting casing for either hole size to a 500-ft depth.
   d. Drilling 12,000-psi and weaker rock at the rate of 17 ft per hour and 25,000-psi quartzite at the rate of 6 ft per hour (penetration rates).
   e. Have hoist drum capacity of 2,500 ft of 3/8-in. wire rope.

RESCUE PROCEDURE

The rescue drilling subsystem can be used independently of the total system and will improve the chances of rescue when drilling is required. Use of the total system, however, greatly increases the chances for survival and rescue.

In a mine equipped with refuge chambers and seismic or electromagnetic location and communication beacons the exact location in which to drill can be easily determined. If the mine is equipped only with beacons, it will be possible to locate a drill within 50 ft of the survivors, in most cases close enough for rescue.

As soon as it is recognized that the emergency situation will require the drilling apparatus, a report should be made to the Bureau of Mines in the normal manner.

If the mine is equipped with location beacons, Bureau of Mines equipment will locate the survivors. If the mine does not have beacons, the mine management would be instructed to select the most likely areas where men may be trapped or barricaded. Survey crews would be dispatched immediately to locate a drill site on the surface.

Since the drilling rigs described here are available and can be in use prior to the rest of the proposed system, the following discussion applies to mines without refuge chambers or location beacons. The simplification or elimination of the steps below if the other subsystems are in use is obvious.

Bulldozers would clear a trail to the drilling site. In inclement weather, a supply of rock aggregate would be needed for the road.

If the trapped men are in a refuge chamber, a rescue hole can be drilled immediately. Even when beacons are in use, but not chambers, it may be prudent to drill a probe hole to confirm that the workers can be rescue from this location. If neither beacons or refuge chambers are in use, trapped men must be located by probe holes.

Meanwhile, if needed, the small exploratory drill rig would be sent to the site. If the men must be located by probe holes, a search would be conducted in an area of about 50-mile radius for other mine exploration drill rigs that would be requisitioned to supplement the Bureau's rig. These could be small diamond drills, truck-mounted rotary exploration or blasthole drill rigs, or (for mines less than 200 ft deep) down-the-hole percussion drills from nearby quarries, road jobs, or mines.

Until most mines are equipped with location beacons, an inventory or census of drill rigs and how they are equipped could be maintained by divisional offices of the Bureau of Mines.

It is assumed that the Bureau's rig could be on site drilling within three or four hours. Perhaps three or four holes requiring three to six hours each would be needed to make contact with miners. It is also assumed that in a well-planned operation miners may be contacted within 25 hours.

Electric heaters, food, blankets, lights, telephones, medical supplies, and barricading materials would have been packaged to be inserted through a 6-in. hole. Instructions on survival and communication would have been prepared. It should be noted that the discovery hole may have to be resealed except for a few hours each day to protect the men from dust created by the rescue drill.

Pumps and high-pressure air ventilation lines may have to be lowered into the discovery hole to maintain a respirable atmosphere for men below.

The discovered miners would be asked for information on mine conditions and locations where others may be found. Their advice would be sought for precise location of the bottom of the discovery hole and for suggestions on the relative position of the rescue hole to follow.

The heavier rescue rig would have been dispatched to the drilling site. It may start drilling even before the exploratory hole has found men on the chance that a hundred feet or so of hole may be drilled in a location to which the men may be able to travel. In any event, there is no reason for the rig to stand idle. The drillers could be improving their techniques, and should a short move be necessary, it would require less than two hours. Such preliminary drilling would also give data on drillability, wall stability, and in-situ water conditions that may be helpful at another location.

The large-hole rig would be equipped to drill either an 18- or 28-in. hole below the surface casing. By the time the men are located, it would have been decided whether they will be brought up in a harness or in a capsule. Harness recovery can be made through an 18-in. hole if indications are that:

1. The hole walls are stable.
2. The hole walls are fairly smooth and straight.
3. There is not a large volume of water flowing into the hole.
4. No men are injured requiring that they be strapped to a stretcher.

The hole wall condition could be examined by a down-hole still camera taking pictures every 5 ft or by continuous inspection with a remotely controlled television camera.

The large hole would be drilled in one pass. It the men are in a rather confined area, the last 10 ft of drilling must be done very slowly, particularly if the coal is overlain by a weak formation. This slower drilling rate, where required, would be at 2 ft per hour.

Equipment for hoisting men out of the hole is also required. For the 18-in. hole, a harness system that holds a men upright if he loses consciousness, protects him from falling rocks, and maintains him in a position of minimum cross-sectional area (one arm above the head) is required. A coat of grease prior to beginning the ascent would also be helpful.

A capsule should be designed for use in the 28-in. hole. It should be pointed at each end to prevent catching on rock shelves or "dog-legs" in the hole. The capsule should be capable of completely enclosing an injured man strapped to a stretcher. Both the top and bottom of the capsule must be jettisonable so that the passenger can be raised or lowered independently if the capsule gets caught.

Both the harness and the capsule should be equipped with a microphone and speaker for communication and a mask and fresh-air line in case the air in the hole is not respirable.

For safety reasons the men would be pulled to the surface by hand.

THE EXPLORATORY DRILL RIG

The exploratory drill rig would be truck-mounted. It would be capable of applying 30, 000 lb pulldown and gravitational thrust, not including the weight of the drillstring in the hole, on the bit. This probably would require a ballast box because the rear end of truck rigs is not that heavy. It would be capable of lifting another 10, 000 lb of drillstring weight.

It would drill a 9-in. surface hole to about 75 ft maximum depth and set 7 5/8-in. casing to rock at that depth or as required. It would drill a 6 3/4-in. hole below the casing to coal or about 1, 500 ft maximum.

It would have a 5-in. flush OD drillpipe approximately 30 ft long. Flats would be milled at the tool joints to accommodate breakout wrenches and provide a means to suspend the pipe during trips.

The derrick should have a magazine to accommodate three pieces of pipe and the other can be stored on the ground or a horizontal rack. Help will be available to load pipe into and out of the derrick magazine as required.

The rig should also be able to handle three 30-ft-long sections of 7-in. pipe to be used for the 9-in. surface hole. This will keep the air requirements to less than 1, 000 CFM for the surface hole for 3, 000-fpm annulus velocity.

All of the air can be at 40 to 50 psi. The only time higher air pressure may be desired is to blow water from the hole. In any event, even with the air pressure at 100 psi, this would have to be done in stages as the bit is lowered.

Fifty horsepower should be provided for the rotary drive. It should have four forward rotary speeds of about 25, 50, 75, and 150 rpm and one reverse speed of about 30 rpm.

There are approximately ten manufacturers of truck-mounted rotary drill rigs and many of them make rigs that would require very little modification to do the exploratory work. These include:

1. Winter Weiss Division of Smith Intl. (Porter Drill)
2. Schramm
3. Bucyrus Erie
4. Robbins
5. Ingersoll-Rand
6. Joy Manufacturing
7. Davy
8. Gardner-Denver (Mayhew)
9. Chicago Pneumatic (Reich Drill)

Hole deviation will be difficult to avoid. An Eastman multishot survey tool can be run into the hole at completion to locate the bottom of the hole with reasonable accuracy.

Most coal mines are laid out on a room and a pillar or a panel mining plan. The exploratory hole will be aimed at a mine entry about 20 ft wide between two coal pillars that may be 30 to 80 ft wide. If the entry is missed, it will probably be by not more than a few feet. The miss will be known immediately on the surface because the depth to the coal will be known. If the drillstring does not fall into the cavity or if coal comes out with the air circulation, obviously the drill has deviated into (or has been directed into) the pillar.

If there are miners in the entry, they will hear the drill. The depth into the pillar (or distance from the entry) will be so slight that unless the miners are injured they may dig their way into it.

If the drill penetrates a coal pillar, it may be possible to withdraw the bit and use a whipstock to bend the drillstem into the entry.

All of these drilling and survey tools should be maintained by the Bureau of Mines and used periodically. This will keep the tools in shape and train the crew.

THE RESCUE DRILL RIG

The rescue drilling rig must be able to handle large-diameter bits through the rig floor. The drillpipe would be 8-in. diameter either with oil-field-type threaded connection or with flanges. Pipe will be in 15- to 20-ft lengths.

The swivel should have an opening of sufficient size to pass 4-in. cuttings.

Reverse air circulation would be used. A 10- to 15-ft-deep cellar would be dug by hand. A 36-in. casing set and grouted in this cellar.

A rotating seal must be developed, which would be attached to the top of this cellar casing. The lid must be removable for trips. The rotating center part must be designed to pass the pipe and tool joints or flanges as they pass into the hole. Air would be introduced into the annulus through the stationary part of the lid.

An air flow of 2,000 CFM would provide more than 5,000-fpm velocity up through the drillpipe, which would be adequate. At this volume, the flow across the bottom of the 28-in. hole may not be as high as would be desired. However, the velocity through the pipe must not be too high or it would cause erosion or damage to the swivel. Three 1,500-CFM, 100-psi air compressors at $60,000 each would provide a flow rate of up to 4,000 to 5,000 CFM. The 100-psi air pressure is higher than would be needed for drilling but could be useful in removing up to 200 ft of water head that could build up while drilling is shut down.

Planning of the drilling must not overlook the fact that all surface equipment must be stopped when the life support (6-in.) hole is open for supplying the men below and talking to them. The noise and dust of drilling would interfere with these operations and cause a hazard to them.

The rescue rig would have speeds of approximately 3, 8, and 15 rpm forward and 5 rpm reverse.

The hoist on the rescue rig should be capable of lifting 10,000 lb.

Baskets with a 16-in. outside diameter to surround the lower section of the drillstring should be provided as drill collars. These would be 10 ft long and be filled with lead shot for a weight per collar of about 15,000 lb. Four collars would be required. The additional drilling thrust would be provided by weight of the bit, drillstring, and swivel and by rig pulldown.

All rigs, for probe and rescue, should have roller stabilizers for each bit size.