MINE RESCUE AND SURVIVAL

Final Report

COMMITTEE ON MINE RESCUE AND SURVIVAL TECHNIQUES

NATIONAL ACADEMY OF ENGINEERS

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Washington, D.C. March 1970

This report was prepared under Contract No. S190606, dated 26 February 1969, between the National Academy of Engineering and the U.S. Bureau of Mines of the Department of the Interior.

Available from

National Academy of Engineering
2101 Constitution Avenue
Washington, D.C. 20418

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COMMITTEE ON

MINE RESCUE AND SURVIVAL TECHNIQUES

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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 U.S. 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."

Early in the study the Committee agreed with the Bureau of Mines to conduct its work in three phases. In the first phase, the Committee would define a mine rescue and survival system that could be developed in approximately one year from existing technology. In the second phase, the Committee would plan a more advanced system that could be realized with a 5- to 7-year research and development program. In the third phase, the research and development program would be planned.

In designing the first phase or interim system, much of the basic data necessary to designing the second phase system was found to be unavailable. The interim system was planned with sufficient margin to permit rescue and survival within a wide range of basic parameters. An advanced system, however, could not be planned without more specific knowledge of the conductivity, seismic characteristics, and drill strength of strata overlying coal seams; the metabolism and respiratory rates of men striving to escape or reach chambers, or at rest within refuge chambers; and other basic parameters.

The second phase of the study has been devoted to planning a research and development program to acquire the needed data from which an advanced system could evolve. The Committee strongly urges that the Bureau of Mines, in carrying out this program, strive to improve its competence in the technical disciplines related to mine rescue and survival.

A report describing the interim system was published by the National Academy of Engineering in November 1969. The essential elements of that report, with additional information gained from experiments and further analysis of mine accidents over the past two decades, are included in this publication.

COAL MINING IN THE UNITED STATES

In 1967 the United States consumed 58.8 quadrillion Btu of energy. Both the Atomic Energy Commission and the Resources for the Future, Inc., a private economic forecasting group, predict that the United States energy requirements will reach 135 quadrillion Btu by the year 2000. In 1967 bituminous coal produced 21.4 percent of the energy used in the United States and anthracite coal another 0.5 percent.

Coal Reserves

Coal reserves make up about four-fifths of the United States storehouse of fuel in proven reserves. Seventy-five percent of all fuel, likely to be found and recovered is coal. Electric utilities consume more than half of the bituminous coal mined in the United States in generating 53 percent of the nation's electricity. Atomic Energy Commission analysts have proposed the development of a vast "national energy system" based upon long-distance electrical transmission from abundant untapped coal reserves in the western United States. The study predicts that even if uranium supplies are available and economic breeder reactors developed, coal requirements for electricity generation will more than double by 1980 and increase another 50 percent before the year 2000.

Research and development work is underway to develop new markets for the vast coal reserves of this country. A demonstration plant to convert coal to gasoline at competitive prices is now in operation and its prospects are considered good. Other research shows promise for converting coal into pipeline quality gas to supplement dwindling natural gas supplies.

Coal reserves of the United States as of January 1, 1967, are projected to total 3,210 billion tons based on new estimates determined from mapping and exploration in 17 states by the U.S. Geological Survey. Over 1,560 billion tons, of which over 671 billion tons is bituminous coal, has actually been mapped and explored with bore holes. Eighty-nine percent of this is less than 1,000 ft below the surface, and 24 percent is in beds 28 in. or more thick.

New estimates reveal that 60.0 to 63.5 percent of the coal in place is recoverable and that up to 380 billion tons of known deposits may be recoverable at present prices, with established technology.

Approximately 45 percent, or 171 billion tons, of this is bituminous. Probably 30 billion tons of bituminous coal can be recovered by strip mining and 141 billion tons by underground mining.

In 1967 the United States consumed 480 million tons of coal and exported about 50 million tons. At this rate, readily available reserves will last for hundreds of years. New mining techniques to recover deeper deposits and thinner seams will no doubt be developed before this supply is exausted.

The thickness of coal beds currently being mined in the United States varies from less than 2 ft to more than 50 ft. Over 60 percent of the production is from beds 3- to 6-ft thick. The average thickness mined is 5.3 ft.

The average thickness of coal beds mined has not changed more than a few inches in the past 50 years, and there is no indication of change in the foreseeable future. As coal beds of moderate thickness in the Appalachian Region become depleted, beds of lesser thickness will be exploited. To counteract this, however, thicker, previously untapped beds in the western states will be developed.

Production

As shown in Table 1, approximately 90 percent of the domestic output of underground bituminous coal in 1967 was produced in the following five states: West Virginia (136 million tons), Kentucky (59 million tons), Pennsylvania (56 million tons), Virginia (30 million tons), Illinois (28 million tons). Although there were 3,908 active underground bituminous coal mines in 1967, half of these mines produced 98 percent of the total production. Almost 65 percent of the production came from about 200 mines. The trend has been toward merging of companies and the development of large groupings of mines.

Production from large mines (500,000 tons and over) is expected to continue to increase, while the total number of underground operations will decrease.

Of the 349 million tons of bituminous coal mined underground in 1967, 340 million tons were produced from states east of the Mississippi River; 284 million tons were produced from the northern Appalachian basin, Pennsylvania, Ohio, West Virginia, eastern Kentucky, and Virginia. Therefore, a mine rescue and survival system should be designed primarily for this area with potential for application to other areas.

TABLE 1 - Salient Statistics Concerning Coal Reserves and Underground Coal Mines in the United States

State	Bituminous coal reserves (tons)	Number of mines	Number of miners	Production (tons)	Number of mines producing less than 10,000 tons/year
Alabama	13,518,000,000	91	4,034	9,362,000	58
Alaska	19,415,000,000	0	0	0	0
Arizona	618,000,000*	1	3	1,000	1
Arkansas	1,640,000,000	3	51	45,000	1
Colorado	62,389,000,000	55	1,238	3,574,000	28
Georgia	18,000,000	0	0	0	0
Illinois	139,756,000,000	32	4,881	27,948,000	3
Indiana	34,779,000,000	11	446	1,641,000	1
Iowa	6,519,000,000	5	75	245,000	3
Kansas	18,686,000,000	0	0	0	0
Kentucky	65,952,000,000	1,284	20,566	58,518,000	681
Maryland	1,172,000,000	19	167	381,000	11
Michigan	205,000,000	0	0	0	0
Missouri	23,359,000,000	1	4	1,000	1
Montana	2,229,000,000	9	53	42,000	8
New Mexico	10,760,000,000	5	143	668,000	4
North Carolina	110,000,000	0	0	0	0
Ohio	41,864,000,000	67	3,962	15,172,000	33
Oklahoma	3,299,000,000	1	34	2,000	1
Oregon	48,000,000	0	0	0	0
Pennsylvania	57,533,000,000	312	17,236	56,490,000	137
Tennessee	2,652,000,000	126	1,365	3,954,000	69
Texas	6,048,000,000	0	0	0	0
Utah	32,100,000,000	24	1,238	4,175,000	5
Virginia	9,710,000,000	784	10,977	30,500,000	295
Washington	1,867,000,000	3	39	56,000	2
West Virginia	102,034,000,000	1,070	40,853	136,193,000	489
Wyoming	12,699,000,000	5	67	117,000	4
Total	671,049,000,000	3,908	107,432	349,133,000	1,835

* Includes California, Idaho, Nebraska, and Nevada.

Mining Techniques

There is no best mining system or method for coal mining. The system is dictated by varying geology and geography, unique seam and associated strata characteristics, market requirements, and a highly competitive industry. Contemporary mining systems are the product of a continual, somewhat sporadic, evolutionary process. As new problems were encountered, solutions were found; as labor costs increased, labor-saving devices were developed and utilized; and as the competition from other energy sources increased, coal became more competitive. Although today's systems are not optimal, they have no peer in the production of minerals from inside the earth. Tomorrow's systems will have to meet additional requirements with even more constraints.

Over the past decade (1958 through 1967), the underground average output per man per day has increased from 8.91 to 15.07 tons. Much of this has been made possible by continued improvement in design and application of machinery. The continuous mining machine, introduced in 1948, currently accounts for half of the underground production as shown in Table 2.

TABLE 2 - Underground Production by Mining Methods at Bituminous Coal Mines, 1967

Method	Units in use	Percent of production	Average tons per man-day
Continuous	1,412	47.1	16.40*
Conventional	2,518	45.5	15.60*
Longwall	15	1.0	N.A.
Hand-loading	--	6.4	8.00*

* Estimated.

The large investment of the mining companies in machines and equipment and the restrictions imposed by existing mine configurations will preclude rapid changes in mining techniques. Mine rescue and survival equipment designed to be compatible with today's mining techniques will be useful for many years to come. To be economically feasible, this equipment must be amortized over a number of years of production so that the cost is no more than a fraction of a cent per ton of coal produced.

History of Mine Disasters

Analyses of U.S. Bureau of Mines reports of all 28 major mine disasters (resulting in five or more deaths) due to explosions, fires, or suffocation (from carbon dioxide) were made for the decades 1950-1959 and 1960-1969. A number of questions raised in the Committee following the Interim Report of November 1969 led to additional review and to a similar analysis of minor coal mine disasters. Contacts with principal participants in the rescue and recovery operations served to clarify a number of points that were not sufficiently clear for the Committee's purposes.

Analysis of the 1950 and the 1960 decades is considered pertinent and adequate because:

1. The Federal Coal Mine Code (adopted in 1946 as a part of the labor agreement) was in effect throughout these decades, and 25 of the 28 major disasters occurred in mines that were obligated to comply with provisions of the Code.

2. The Federal Coal Mine Safety Act, Public Law 552, effective July 16, 1952, was in effect most of the 20-year period. However, three major mine disasters involving 19 victims occurred in Title I (small) mines that were not then covered under the enforcement provisions of PL 552. PL 552 was amended in March 1966, thereafter applying to both Title I and Title II mines.

3. The 20-year period was characterized by great expansion of continuous mining, a trend toward larger and fewer mines, extensive mechanization, wide spread application of roof bolting, and updating and strengthening of the state laws in major coal mining states.

Reports on the 28 major disasters reveal that 363 deaths were attributable to flames or violence; 83 to asphyxiation by smoke, carbon monoxide, or both; and 5 to suffocation by carbon dioxide.

Cause of death for 76 of the 78 Farmington disaster victims is not known, although the two who have been recovered were killed instantly by explosive forces and flame.

In the same disasters that caused the deaths of these 529 miners, 27 were rescued injured, 72 were uninjured, and 1,690 were evacuated without aid or incident.

During this period, 115 miners died in disasters statistically classed as minor (resulting in fewer than five deaths). Of these 115, 35 were victims of asphyxiation by carbon monoxide and 3 of suffocation by carbon dioxide.

Of the number of miners for whom the cause of death is known, 126 or 20 percent could have been saved by knowledge of escape routes, training, and use of self-rescuers (assuming sufficient oxygen in the atmosphere, which evidence indicates was present in most cases) or if escape was not feasible by barricading.

In mine accident investigations, the cause of death is determined by the investigator's and a doctor's or coroner's observation of the body rather than by autopsy. Therefore, the number of deaths attributed to either explosive forces or carbon monoxide is not exact. The new coal mine safety act allows for government payment for autopsies. The information that could be gained by autopsies on fire and explosion victims would aid materially in the design of future mine rescue and survival systems.

Fires and Explosions

Unabated coal mine fires create a real hazard from the danger of methane gas explosion, with or without coal dust propagation. As fire disrupts ventilation, accumulations of explosive gas mixtures and sources of ignitions are most likely to come together. Explosive gases are even given off by the fire itself, thus adding to the hazard. Furthermore, heat from unabated fires can cause serious roof deterioration and subsequent falls. This increases fire-fighter's problems and personal danger. It also poses additional hazards to those who have tarried and attempt to escape after the roof has been weakened.

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 initially involved 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 encounter concentrations of lethal gas than miners escaping from a fire. Thus, following explosions, evacuation is more hazardous and the decision whether to attempt escape from the mine or to seek shelter underground is more difficult. In the past, miners have usually erected barricades to protect themselves from poisonous gases only as a last resort after exploring all possible means of escape. Many times miners not equipped with or not using self-rescuers have encountered carbon monoxide and have died while searching for ways out.

Rescue and Survival System

The emergency breathing device proposed as part of the system described in this report would help men trying to escape. If that were not possible, the proposed refuge chambers would provide protection from poisonous gases and some protection from subsequent explosions until the men could be rescued. The chambers could also serve as a temporary haven for men to replace or replenish emergency breathing devices or wait for the air to clear before resuming escape attempts.

The physical disruptions after an explosion may be aggravated by the destruction of the communication 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.

Some have strongly argued that in case of emergencies miners should proceed immediately to a refuge chamber and await rescue. While this would provide almost absolute protection from poisonous gases, there is always the possibility that a subsequent explosion or a roof fall might destroy the chamber and kill its occupants. If an emergency two-way voice communication capability can be developed, a good approach would be for miners to proceed to the chamber to receive information on the extent of damage and whether escape is feasible or they should wait until rescue. In the final analysis, the decision will have to be made by the men underground at the time, and the mine rescue and survival system should maximize their chances for either escape or survival underground.

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.

Two possible training aids for long-term development are an explosion model to demonstrate the effects of explosions and a simulator in which miners could be exposed to simulated conditions of a fire or explosion. A simulator could be equipped with a refuge chamber, smoke generator, and other devices to realistically simulate emergency conditions.

Part 1 of this report describes an interim mine rescue and survival system that could potentially save almost all coal miners who have died from carbon monoxide poisoning following explosions or fires. 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 occurred. Active programs in the Bureau of Mines and in private companies have been underway for five or six years to develop rapid quenching devices. Recently, more companies have begun activities. The potential of this technique is discussed in Part 2 of this report, but it is not believed capable of being developed in time to be a part of the interim system described in Part 1. Therefore, the proposed interim system is limited to saving miners exposed to carbon monoxide or other lethal gases.

A basic rescue and survival system will require some modification for the specific mine and coal seam in which it will be used. The Pittsburgh coal seam, for example, drains methane for a much longer time after initial mining than other seams, creating a much greater danger of secondary explosions. Therefore, in emergencies, miners in this seam should make every effort to escape before erecting barricades or entering refuge chambers.

Some of the equipment recommended in the interim system is applicable to survival and rescue of miners trapped by inundation or cave-ins. However, the greatest potential is related to rescuing survivors of fires or explosion.

PART I - INTERIM SYSTEM

The proposed interim system consists of a survival subsystem using improved emergency breathing devices and refuge chambers, a communications subsystem using seismic or electromagnetic devices to locate and communicate with survivors, and a rescue subsystem 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 owing 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 one hour, and a 45-minute emergency oxygen breathing device has become available. Many coal operators have provided self-rescuers for all men working underground, and the Federal Coal Mine Health and Safety Act of 1969 requires operators to make available to each miner a self-rescue device capable of protecting the miner for one hour or more.

Although hopcalite 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; should provide eye and face protection 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 one-hour oxygen supply. With a rough market estimate of 50,000 to 75,000 units over a two-year period, such a device could possibly 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 it appears to be impossible to escape or imprudent to attempt escape following a fire or explosion, miners are trained to isolate themselves from toxic gases and smoke by erecting barricades of brattice cloth on wood framing. From 1909 to 1961, more than 1,000 coal miners were rescued from behind barricades. In the period under consideration, the past two decades, 62 miners were rescued from behind barricades and 27 died behind inadequately constructed barricades.

Most of the miners who died after initial explosion succumbed to lethal concentrations of carbon monoxide while trying to escape. The emergency breathing device described above should aid escape attempts. When escape is not possible or the risk is considered to be too high, chambers may also serve as waystations for miners escaping from the mine to rest, replace or replenish emergency breathing devices, and communicate with the surface.

Many coal companies provide barricading kits in strategic locations. Instructions are given to all miners that these materials are to be used for no other purpose. As a minimum for underground protection, each section should be provided with barricading kits, including spare emergency breathing devices or cartriges, chemical oxygen generators and carbon dioxide removal agents, food, water, gas detectors, and emergency communications equipment. This material can be mounted on a cart and easily moved to new locations.

Roof falls pose an addition hazard to men remaining underground in an emergency. The central chamber described below provides additional protection against falls, but only roof bolts and posts that are used in mining operations would be practical for sectional shelters.

In any coal mine fire or following an explosion that may leave residual fires or destroy ventilation, there is danger of subsequent explosions. There are three instances of major disasters in the past 20 years in which, through natural cases or human error, multiple explosions occurred. If possible, without creating the hazardous situation inherent in any major underground construction project, some protection should be provided against secondary explosions. Two potential concepts have been identified. A preliminary design has been made of a metal bulkhead and door, two of which could be used to enclose a shock wave. The bulkhead could be anchored by roof bolts into the roof and floor. It would be made in sections that could be easily moved as mining sections are opened and closed. The other concept is an inflatable structure that, if inflation is rapid enough, can be left deflated until actually needed.

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, high-pressure oxygen or air, and possibly potassium superoxide 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. A system using lithium peroxide might be developed in one year, but it is primarily of interest for the longer term system. Baralyme looks most promising and is inexpensive.

Any system using a carbon dioxide removal agent and probably the potassium superoxide system as well 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.

Some coal mining companies have established central refuge chambers to which men can travel if unable to escape. The main disadvantage of these chambers is the distance the miner may be from the chamber, possibly as much as 5,000 ft. The most elaborate of the existing central chambers is a 20 x 40 ft room cut into a coal pillar from a crosscut. The chamber is masonry lined and has a 6-in. hole to an air blower on the surface. Steel cross beams and steel sheeting guard against roof falls. Both ends of the crosscut and the entrance to the chamber are protected by cinder blocks and reinforced concrete bulkheads containing steel doors.

A combination of sectional and central underground shelters may be the most economical method of providing protection. Analysis of the hazards of individual mines should be conducted to aid in selection of types of underground protection.

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.

Communications Subsystem

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

If voice communication is not possible, signal location accuracy requirements will 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 within approximately ± 50 ft.

Telephone Communications

Present telephone lines will most likely fail in the area of an explosion. Also, present systems are by law confined to the main intake airways. It is reasonable to assume that after a major explosion many men could be trapped in working areas or in return airways being used as escape paths. It would therefore be an advantage to have as many direct mine-to-surface circuits as could be arranged. One way to do this would be to use drill holes for mine-to-surface communication circuits.

Since most coal fields are drilled on some pattern for exploration prior to mining, it follows that each of these holes could contain a well-insulated pair of wires that could ultimately become useful as a communication system. The drill plan and mining plan could be coordinated to have as many holes as possible enter on development headings so that maximum time-use could be realized. When the core is removed from the drill hole, a specially devised "wire around a core" could be fed down the hole to the bottom of the coal seam. On the surface, a special cap could be installed and, in effect, buried. Its location would be mapped and marked for future possible need.

Underground, when the hole and wire were reached by mining, a special device would be attached to the wire and protected in a cylinder that could be shoved up into the hole. This location would also be well-marked and made known to all men. Eventually many such locations would be set up.

In the event of a disaster, all the holes on the surface would be opened and manned for possible contact. The men underground would try to get to one of the known "call boxes," screw off the protective cap, and using a keying device, send up signals. A better alternative would be to have a sound-powered phone available in the box so that voice communications would be possible.

Precautions to be taken when installing the wires would be:

1. Good insulation with bottom end sealed until located during mining.

2. Wire (two-conductor) wound loosely around a solid strand. This would provide enough wire to stretch and flex if shifts in the strata would lengthen the hole.

During mining when the cable was found, it would be cut, trimmed, and connected to a keying device or sound-powered phone and properly encased in a cylindrical box, which could be shoved into the hole in the roof for storage. The location would be well-mapped and made known to everyone in the mine.

Electromagnetic Communications

Electromagnetic communications techniques have the advantage that in the long term, they might evolve as a means of operational communications 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 near-term, electromagnetic beacons should be developed even though some recent experiments indicate that emergency voice communication may be possible. Tone-only beacons operating at a very low frequency will have the highest assurance of penetration under all conditions. As additional data on the characteristics of overburden materials become available, voice systems may be developed.

Beacon or voice systems 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.

Appendix B, Part 1, contains a detailed discussion of a possible mine radio communications system and the emergency beacon or voice system.

Seismic Communications

The requirements for a seismic system are the same as for an electromagnetic system: that it be capable of rapid deployment, have sufficient sensitivity to detect the miner-generated signals at distances comparable to the dimensions of the area of possible entrapment, and 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 would consist of four subarrays deployed in a square approximately 1/2 mile across a diagonal. 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 inhomogeneties. 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.

After location, the seismic equipment can be used to communicate with the men below. The miner below ground would use a single seismometer to trigger an audio oscillator connected to an earplug speaker. These devices have been used successfully in personnel intrusion detection. 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 miner's helmet.

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.

Appendix B, Part 2, gives a detailed description of this system.

Rescue Subsystem

The Committee has investigated 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 and rescue teams have not been 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, but 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 and would drill reasonably straight holes in 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 a 1/4-in. wire line 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

At the present, coal operators maintain well-equipped and well-trained rescue teams. These teams have participated in almost every coal mine emergency in the United States and many metalic and non-metalic emergencies. They 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 blowout 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.

A study has been conducted by the Committee on the use of rigid foam for stoppings and other structures during mine recovery operations. The study has shown that a rigid foam with good fire-protective characteristics has the potential to provide significantly improved mine rescue techniques. Rigid foam is widely used in mines for sealing roofs and ribs against deterioration by weathering and for the operational construction of stoppings for ventilation control. However, no truly portable equipment or fire resistant foams, as would be needed for emergency operations, are available. Preliminary investigation has shown the following uses of rigid foam to warrant further study:

1. The construction of temporary stoppings to restore ventilation during recovery operations following a mine disaster.

2. The forming of dams in shafts in entry ways to seal off specific areas of a mine.

3. The lining of refuge chambers for thermal insulation and vapor sealing.

The National Aeronautics and Space Administration has developed a fire-protective foam that appears to offer significant potential as a solution to these problems. The Committee proposes that an evaluation program be conducted to assess the potential of this and other candidate materials. The purpose of the program would be to establish suitable characteristics of the material and the dispensing system, to evolve specific application techniques, and to develop and demonstrate under simulated disaster conditions prototype equipment.

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 where the mine communication system still functioned of the hazard and, if possible, 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 explosion, 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 close enough to the explosion that they may be exposed to carbon monoxide should immediately begin using the breathing devices and proceed out of the mine or to a refuge chamber. If they go to a chamber, they should 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 miners was not known. After the men are accurately located, either by probe holes or by a communication system, a large hole would be drilled. The trapped men would be rescued by pulling them up the hole in a capsule or a harness.

Systems Engineering

The success of the program is dependent upon the integration of the components into a total system. This systems integration or systems engineering effort will make the difference between having a smooth-functioning mine rescue and survival system and having only improved equipment still used in the limited manner of the past.

Systems engineering will reduce costs by assuring that no component or subsystem is made more complex than necessary, by directing the allocation of resources to achieve the most efficient solution to technical problems that arise during the development program, and by preparing plans for testing and procedures for using the total system.

PART 2 - RECOMMENDED RESEARCH AND DEVELOPMENT PROGRAM

The system described in Part 1 of this report is a first step to applying modern technology to the problems of mine rescue and survival. To meet the constraint of a one-year development time, the program must use only technology that is well-developed and whose application is fairly straightforward.

No doubt, a rescue and survival system with a longer development time could take advantage of more recent technological advances and could increase even further the probability of successful rescues. Before this technology can be applied, however, many basic data relative to mine rescue and survival must be gathered. Among these are the conductivity or resistivity and the drillability of strata overlying coal seams, the metabolic requirements of miners in an emergency situation, seismic velocity of coal and overburden, etc. The application of many technological advances can be investigated at the same time these basic data are being gathered.

Survival Subsystem

Although each type of disaster--inundation, cave-in, fire, or explosion--has its own unique problems, an explosion will probably present the most severe conditions for all types of survival equipment. Therefore, survival equipment design would be improved by the development of a physical and/or mathematical explosion analog model capable of indicating the progression and magnitude of shock waves traveling through a mine, the gaseous constituents of the atmosphere after an ignition of primary and subsequent explosions, and the effects of mine configuration on shock wave attenuation, refuge chamber location, etc. Scientists at the Bureau of Mines Pittsburgh Research Center have done some work on modeling mine explosions. Their efforts should be intensified and extended to cover those aspects of explosions unique to the design of survival systems.

In addition to gathering basic data on the conditions under which survival equipment must operate, basic development work should be carried out in areas that will be essential to any survival system. There are, for example, only a few ways to generate oxygen under emergency conditions. These are with chlorate candles, potassium or other superoxides, and stored liquid or gaseous oxygen. Long-term research and development programs should investigate the basic chemistry of candles and superoxides, the storage of oxygen and their application to emergency individual breathing devices, and underground life support systems. Similar investigations should be conducted on the potential carbon dioxide removal agents, chemical light sources, food supplies, and other survival shelter essentials.

Refuge chambers located underground present unique problems. Research and development is needed to produce easily installed, strong, long-life bulkheads or other types of shelters. New materials such as fiber glass and rigid foam may have application.

Appendix A contains a more detailed description of the proposed life support research and development program.

Communications Subsystem

The long-term objective of a research and development program in electromagnetic communications should be development of an operational mine radio communications system, a substantial part of which would survive any predictable explosion or operate as an emergency communication system. A first step in this program should be to determine the transparency of strata overlying coal measures using both loop and grounded wire sources over a large frequency range.

A number of potential communication system concepts have been identified. One of the most promising is a hybrid system using through-the-ground and over-the-surface communication paths. It would combine low-frequency voice communication systems operating essentially vertically with relay stations that would retransmit the signal at standard radio frequencies to the mining office or other communications points. The low-frequency voice systems could be used for emergency communications in case of disaster.

Another approach, which seems less suitable, is the use of high-frequency radio transmissions through the mine openings. In this type of system, the use of repeater stations and the suitability of using the mine openings as wave guides should be investigated.

If the characteristics of the coal and overlying strata are suitable, it might be possible to develop a long-distance, low-frequency, through-the-ground operational radio communications system. This is not a true radio system since an electromagnetic field is generated in the ground and data are transmitted by modulating that field. An experimental system of this type has been developed and has shown considerable promise when tested in a West Virginia coal mine. Additional tests should be conducted in varying types of strata, under varying ground conditions. Appendix B, Part 1, contains a more detailed description of a radio communications research and development program.

In the seismic communications area, as in other areas, a research and development program should be designed to gather basic data on the environment in which the system must operate and to investigate new equipment for emergency and operational conditions. The seismic communications equipment in the interim mine rescue and survival system can be used to gather data for upgrading the performance of the interim system itself and for decisions on development of more advanced systems. Some of the data that can be gathered are measurement of the local seismic velocities and correlation of these with rock composition and geologic structure; measurement of the attenuation rate of seismic energy with depth, horizontal offset, and rock composition; characterization of local ambient seismic noise; identification of seismic noise sources that might degrade system performance and development of techniques for minimizing their affects; and determination of the location accuracy obtainable as a function of geologic structure, rock composition, surface topography, etc.

A number of new techniques for seismic communications have been identified and should be further investigated. These include the resonant transducers that have been developed by the U.S. Army Electronics Command at Fort Monmouth, New Jersey. At present weight and power, requirements would limit the use of these devices to refuge chambers or other semipermanent locations. Further development might, however, permit their integration into the mining equipment.

Bureau of Mines scientists at the Denver Mining Research Center have had considerable success using accelerometers to detect high-frequency seismic pulses from microfractures of rock overlying mines and tunnels. If sufficient high-frequency energy is generated by hammer blows, accelerometers may prove more effective than seismometers for detecting signals from trapped miners. If investigations of the use of accelerometers were conducted at selected mine sites along with other investigations, the cost would be little more than the purchase price of a few accelerometers. Therefore, it is recommended that such an investigation be undertaken, perhaps parallel with the field testing of the interim system.

The Bureau of Mines should consider the development of one or more automatic seismic signaling devices--a number of which appear to be technically feasible. A vibratory transducer that, after being activated by a miner, would continue to transmit continuous wave seismic signal at a unique frequency could act as a beacon for rescue operations. A more sophisticated version could permit programming of messages into the seismic transmitter and perhaps automatic measuring of underground conditions such as air temperature, maximum pressure experienced, and percentage of atmospheric constituents.

Efficient insertion of energy and detection of propagated seismic energy require good coupling of the transducers to the earth. Studies should be conducted to determine the best methods of firmly coupling different types of transducers to the earth.

Studies should also be undertaken of the transmission paths of seismic energy in the coal mining areas. Much of this information can be collected using the interim system. With data on attenuation rates as functions of vertical depth and horizontal offset, it should be possible to model certain selected mines and predict attenuation rates and multipath effects for any given transmission path. The model can be used to assess the feasibility of permanently placing a small number of transducers within or above the mine. Appendix B, Part 2, contains a complete description of the proposed seismic communications subsystem for the interim system and of the proposed research and development program.

Rescue Subsystem

Almost all men rescued from coal mines in the past were brought out by rescue teams wearing breathing devices. Although refuge chambers will increase the number of survivors who can only be reached through drill holes, the majority of men rescued from underground will no doubt continue to be saved by rescue teams. Recognizing the high level of development of rescue operation, the Committee did not feel that significant improvements could be made in rescue techniques in the time allotted for the development of the interim system. For the long-term research and development program, however, a number of improvements in rescue team operations can be envisioned. Infrared and other spectral detectors to search for fires or hot spots within the mine are in use, and new types of rigid foam for construction of temporary stoppings were recommended in the Interim Report. Investigations should be made of the possible use of remote control probe vehicles to complement rescue team operations by sampling the atmosphere and searching for hot spots where physical conditions permit. Much of the research and development work on the generation of oxygen and removal of carbon dioxide for survival is also applicable to rescue team breathing devices. Rescue team operations could probably be enhanced by the development of radio systems for communications between team members and by development of bubble-type helmets to provide better visibility and greater comfort for the wearers of breathing devices.

If a remote control probe vehicle is found to be feasible, it might be equipped with manipulator arms of the type that have been developed by the AEC for remote handling of radioactive material and could have closed circuit television that would be transmitted to the surface through the mine opening by repeater stations dropped from the vehicle at suitable intervals. A vehicle of this type must be fully permissible and must be powered by a self-contained system. Novel power sources such as fuel cells and sophisticated methods of making diesel, natural gas, and other internal combustion engines acceptably permissible should be investigated.

In addition to possible equipment modifications and additions, an operations research type of analysis of rescue team techniques should be conducted to determine if a more efficient method of team operation is possible.

The Interim Report recommended the acquisition of drilling equipment using standard rotary rigs with rolling cutter bits. These drill rigs are versatile and well suited for mine rescue. However, with rotary equipment, the penetration rate is largely a function of the thrust and, therefore, requires large masses of equipment. For the high drilling rates required, this means that the weight of the equipment, its transport, and site preparation may demand more time, better facilities, and greater road clearance than can be provided in a rescue situation. The high thrust requirements of the rotary bits can create roof failure problems when drilling into cavern or chambers containing trapped miners. The last 50 ft above the chamber usually has to be drilled at very low thrust to prevent caving and may take several hours.

Many novel rock disintegration methods are being investigated by the government agencies and independent laboratories throughout the country. The most promising of these methods uses high-pressure water jets. About 20,000 psi can be obtained continuously with high-pressure pumps, but the drilling system requires very special surface and in-hole equipment. Since rescue holes cannot be full of water when they break through without the possibility of drowning the persons being rescued, an ideal drilling system might use a combination of high-pressure water and rotary cutters. With this system the final few feet would be drilled using only the rotary cutters with air circulation for cuttings removal. Appendix C contains a detailed discussion of the research and development requirements for a mine rescue drilling system.

APPENDIX A

SURVIVAL SUBSYSTEM

Three 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, a life support system capable of supporting 15 men for up to two weeks for a small refuge chamber, a self-contained breathing apparatus for rescue team use.

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 are 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 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 1-hour 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 1-hour, 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 1-hour-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 1-hour duration might make this concept excessively cumbersome. Excess oxygen passes out the neck dam of the hood.

Refuge Chambers

If small refuge shelters 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 shelters 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 were 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 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 the 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 superoxide, 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 additonal 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 absorbers 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.

There were only four occurrences of multiple explosions in the past 20 years, and although one investigation is still incomplete, no fatalities have been identifiable to secondary explosions. Nonetheless, such refuge chambers as may be prescribed should provide some protection from subsequent explosions. For the portable chamber, two types of bulkheads are being considered, rigid metal and inflatable.

A study of metal bulkheads has been conducted and a configuration identified that meets refuge chamber requirements.[7] The bulkhead would be made from 2-ft-wide vertical panels attached to the roof and floor of the mine. Enough panels would be used to span the width of the crosscut. Panels 7 ft tall capable of withstanding a 20-psi shock wave would weigh under 200 lb when made of A242 steel. Aluminum panels would be much lighter, but the thermite reaction between aluminum and rusted iron will ignite explosive methane mixtures. Therefore, aluminum bulkheads have been ruled out. The panels could be loaded onto a shuttle car by a few men when the chamber is moved to a new location.

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

The small refuge shelter would be designed to be frequently reestablished as mining advanced or retreated in a given section. The bulkheads could be loaded onto a shuttle car and 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.

Food for Underground Shelters

Since men may be trapped underground for as long as two weeks, stores of food and water must be provided. The minimum caloric intake should be 600 per man per day, and 1800 calories would be much more satisfactory. A satisfactory water provision in daily life, gained in foods and by drinking liquids, is 2 quarts per man per day. The water provision should be increased if a significant amount of protein is included in the diet. If the quantity of water stored is a constraint, the least possible protein should be eaten and the diet should consist almost exclusively of carbohydrates.

Several types of food packaging should be investigated. Two promising developments in the space program are freeze-dried food that has an extremely light weight and long shelf life and food bars individually sealed in foil.

Methods to use the heat given off by the life support system to cook or warm foods should be considered. Chlorate candles particularly have a high operating temperature, and the burning of new candles to replenish the oxygen supply might be made to coincide with meal times.

Self-contained Breathing Apparatus

With few exceptions, mine rescue team equipment has functioned satisfactorily. The history of a low number of mine rescue team fatalities due to apparatus failure or misuse is a tribute to the reliability and care of the apparatus and training of the men. Only 34 lives were lost in apparatus accidents between 1908 and 1940, one in the 1940's, and none in the last two decades.

Most of the self-contained breathing apparatus currently used by rescue teams are updated versions of product designs that are 25 years old. Consequently, though they have proved adequate for team work, the apparatus does impair the efficiency and effectiveness of the rescue teams. Most of these systems are heavy, cumbersome, costly, and uncomfortable if used for long periods. Though there has recently been some effort to develop new apparatus, only one rescue station is currently equipped with a newly developed liquid oxygen apparatus. No apparatus improvements can be foreseen in the time allowed for development of the interim system. The long-term research and development program should contribute improvements to existing equipment and new product designs.

Recommended Research and Development Program

The problems associated with the use of self-rescuers and rescue team self-contained breathing devices have been discussed above. The proposed refuge chamber life support system and emergency breathing device are relatively new concepts using technology developed for aerospace, military, and other portable life support systems. The first systems, therefore, may not be optimum for mine use.

Research and development in the following areas is recommended to overcome deficiencies and improve the life support systems: more rigorous definition of life support requirements; development of new approval schedules; improvement of the methods of delivering the respirable atmosphere to the subject (better mouthpieces, face masks, etc.); and evaluation of the acceptance of the interim life support system.

Definition of Life Support System Requirements

Although the refuge chamber and emergency breathing device described above will reduce the probability of loss of life from inhalation of toxic gases, more complete knowledge of the conditions existing in a mine after an explosion are needed before a truly optimum system can be developed. To obtain this knowledge, the development of a coal mine explosion model is recommended. The model could be a physical and/or mathematical analog capable of indicating: (1) the progression and magnitude of shock waves traveling through a mine; (2) gaseous constituents of the atmosphere after ignition of primary and subsequent explosions; and (3) the effects of mine configuration (e.g., tunnel size, crosscut and spur location, etc.) on shock wave attenuation, refuge chamber location, etc. An experimental program should be conducted to improve and verify the model.

Analysis of the manner by which toxic gases spread throughout a mine following an explosion or fire can be made with the model. Information can be gained on the occurrence and duration of toxic conditions and better requirements established for respiratory protective equipment. The magnitude of explosive forces that the refuge chamber bulkheads may have to withstand could be determined and perhaps in the long term a new method of reducing the forces of the primary and secondary explosions developed.

Previous mine disasters should be simulated to gain additional insight into the causes of death. This knowledge could then be used to develop more effective procedures to search for survivors. In addition, an explosion model could be used as a teaching aid to demonstrate to rescue teams the progression of events in a disaster.

The Bureau of Mines has some work underway in explosion modeling. These efforts should be expedited and expanded to include data relative to rescue and survival.

The metabolic requirements of the miners must be determined more accurately for design of improved emergency breathing devices. Under conditions following an explosion, a miner's oxygen consumption, tidal volume, and respiratory frequency are likely to increase. Each of these parameters affects the emergency breathing device design requirements. A research program should attempt to develop, in the laboratory or in the field, experimental stresses that are similar to those actually experienced during emergency conditions. Because of the difficulty in simulating hazardous conditions in a laboratory environment, considerable care and thought will be required to design meaningful experiments. The subjects should be drawn from the population at risk--the miners themselves. Additional training should not be given to those participating in the experiments; and every possible effort should be made to impose realistic stresses on the subjects.

Development of New Approval Schedules

Self-contained breathing apparatus and emergency breathing devices are covered by the same U.S. Bureau of Mines approval schedules, although their missions--entry into a toxic environment versus escape--are entirely different. The approval schedule in both cases must guarantee the highest possible degree of safety.

Safe use of self-contained breathing apparatus requires high reliability of the apparatus itself, and Schedule 13 is appropriate for this requirement.[8] For emergency breathing devices, however, safety is related not only to reliability of the device, but to its availability and the willingness and ability of the miner to use it. Minimum weight, volume, and comfort when in use may be more important than very strict requirements for operating time, permissible carbon dioxide levels, and inspired gas temperatures. No matter how reliable the device, safety is not provided if it is so bulky and heavy that it is "inadvertently" stashed some place in the mine.

More data are needed before an accurate trade-off can be made. It appears, however, that a new approval schedule reflecting the philosophy of maximum probability of survival should be adopted.

The schedule should not establish inflexible requirements, but should permit trade-offs to achieve a better total design. For example, the present schedule establishes a maximum carbon dioxide level of 2 percent for a 1-hour breathing device. Concentrations of 2 1/2 percent might be permitted if lower weight or operating temperature could be achieved. Trade-offs of this type might be evaluated through the use of a combined index.

Weighting factors could be assigned to each of the parameters. The combined index would be the sum of all the parameters measured weighted by the appropriate factor. This will encourage creative designs and ultimately better equipment. A research and development program should be undertaken to determine acceptable minimum standards and methods for evaluating trade-offs between parameters.

Fees are presently charged by the Bureau of Mines for inspection and testing of new apparatus. These fees may be a deterrent to the development of new equipment and, therefore, consideration should be given to eliminating them.

Atmospheric Generation and Control

Three techniques are used to provide oxygen in portable life support systems: gas stored at high pressure at ambient temperature, liquid stored at low or moderate pressure at cryogenic temperature, and chemical oxygen generators. Cryogenic liquid, high-pressure gas, and some chemical systems require carbon dioxide absorbers. Potassium and other superoxide chemical generators absorb carbon dioxide in the production of oxygen.

Many currently used portable life support systems generate oxygen from potassium superoxide. These units are rated for up to one hour depending on the model. Potassium superoxide beds require 30 to 45 seconds to begin operation in warm weather and are extremely difficult to start in cold weather Many units use small chlorate candles to provide an initial oxygen supply and to aid starting. When humidity of the inlet air is high, as is the case in most respirators, potassium superoxide has a tendency to form potassium hydroxide. Potassium hydroxide, a liquid at bed operating temperatures, causes the bed to cake, severely restricting the air flow and decreasing the utilization efficiency. Additional research is needed in superoxide chemistry to overcome these problems. This work should include the effects on starting and caking of particle size, bed temperature, bed configuration, and the addition of catalysts.

Recent studies have shown lithium peroxide to be promising for carbon dioxide removal, although it has not been used in portable life support systems to date.[9] It has the advantage over other carbon dioxide scrubbers that it also evolves some oxygen, however not in sufficient quantities to be considered a prime oxygen source. Since lithium hydroxide does not cake at bed operating temperatures, its mixture with potassium superoxide and sodium superoxide should be investigated.

Chlorate candles are promising for portable life support systems because of their high oxygen density and indefinite shelf life. However, they produce measurable amounts of chlorine and other trace contaminants and they burn at undesirably high temperatures. New candle formulations may yield lower operating temperatures and purer oxygen. The addition of catalysts to the candle mixtures also may help attain these goals.[10] A reduction in the candle burn temperature either through a variation in candle formulation or through the addition of catalysts also may result in a reduction of the sodium chloride aerosol evolved by the candle.

The chlorate candle ignitors currently in use produce high levels of contaminants.[11] Research is needed to develop clean, gasless, low-energy ignitors. The full potential of chlorate candles cannot be realized until a modulation technique is developed to match the oxygen production rate to the metabolic requirements of the user.

The use of superoxides and chlorate candles in respirators and hopcalite in self-rescuers frequently results in undesirably warm or hot air being inhaled by the user, seriously impairing his performance. In addition, the chemical canisters become hot to the touch, thus distressing to the user. Some portable life support systems use the heat of fusion of water or other chemicals for cooling, but this imposes severe weight penalties on the system. Sublimators or evaporators may prove to be more effective for heat rejection and should be investigated.

Cryogenic systems offer advantages of low volume, weight, operating temperature, and pressures. Even with specially insulated containers, however, cryogenic liquids have a short shelf life, thus requiring new development in insulation before they can be used in emergency respirators. Cryogenic systems still pose problems of supply logistics, though these problems will be reduced through more widespread use of the systems. Cryogenic systems can use either air or pure oxygen. Pure oxygen systems, when used for long periods, present a potential for oxygen poisoning that needs to be better understood.[12]

Research in Facepieces

Currently used self-rescuers and many portable life support systems require mouthpieces or face masks that eliminate all possibility of oral communication. New techniques to deliver the respirable gases to the user and still allow communication need to be developed. Furthermore, research is needed on face mask and mouthpiece design to eliminate leakage of the environmental gases into the portable system. New more comfortable types of face masks for rescue team apparatus should be developed. A plastic helmet might provide more comfort, better visibility, and greater protection than present masks.

Evaluation of the Interim Life Support System

After several mines have been equipped with new emergency breathing devices, a study should be undertaken to determine their acceptance. Information on the percentage of miners carrying the devices versus the number leaving them on machines or in "convenient" places should be provided to those designing equipment so that better designs and more convenient packaging can evolve.

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APPENDIX B

COMMUNICATIONS SUBSYSTEM

PART 1: ELECTROMAGNETIC COMMUNICATIONS

An evolutionary mine radio communication has been planned. Initially, the system would consist of emergency radio beacons, underground for location of and communication with trapped miners. Theoretical and experimental studies are proposed that would permit evolution of the emergency system into an operational mine radio communication system with an emergency location and communications capability.

Emergency Beacon System

The emergency beacon would be provided in refuge chambers, working places, or other locations where miners might congregate in an emergency. In its simplest form, the beacon would consist of a battery, a buzzer, and a key to interrupt the signal. A frequency of 500 to 1000 Hz should assure penetration, even under the most adverse conditions.

Surface searchers would locate a transmitting beacon with direction-finding equipment and would 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 Hertz, which would make the construction simple. Two-way communication could be effected by having voice transmissions downward and keyed code transmission upward. The trapped miners would not need to know code, since the proper response could be indicated by the downward voice transmission.

An alternative type of beacon could be operated at a frequency high enough to act as a carrier for voice communications. At the higher frequency, the field generated by the beacon would become distorted by the conducting overburden, thus sacrificing accuracy with which the beacon can be located.

Either type of beacon must have extremely high reliability, low cost, and sufficiently rugged construction to withstand a 20-psi shock wave.

Operational Mine Radio Communication System

Two approaches to an operational mine radio communication system have been considered. Both should have a high probability of survival for emergency use in a disaster. In both systems, individual miners or mining crews would be equipped with mobile transceivers operating at a low enough frequency to guarantee penetration to the surface or to a repeater located in a protected area underground. Available data indicate that penetration through coal is usually about ten times that through the overburden.

Signals from these transceivers would be either received on the surface and retransmitted to the mine offices at standard radio frequencies or received underground and relayed by telephone wires to the mine offices. The all-radio system is preferred because of its higher probability for survival in a disaster and its flexibility in location.

System Development

The first stage of development would be the design and prototype evaluation of the electromagnetic beacon. Design considerations would include choosing between grounded wire and ungrounded loop antennas, choosing a proper frequency, power, antenna, and other parameters for the system. Tests during evaluation should include studies of the noise background at the surface against which the beacon signal must be recognized and measurements of the actual electrical transparency of rocks over typical mines. Several beacon designs should be tested in a variety of mine conditions. Even if beacon systems that incorporate voice capabilities are available over the same time frame, as it appears they may be, the evaluation of tone-only beacons is strongly recommended. They will almost certainly have a role in mine rescue in view of their simplicity compared with voice systems.

The second stage of development would be the design and prototype evaluation of an emergency voice communication system. The requirement for such a system should be considered as parallel to the requirement for a beacon. Hopefully, a beacon system could be sufficiently portable and reliable that nearly every worker in the mine could be supplied with one. Requirements for voice transmission will be more stringent, and the equipment will probably not be so convenient. In addition to the design considerations for the beacon, a choice must be made between AM signal transmission at low frequencies and FM signal transmission at somewhat higher frequencies.

The third stage in this evolutionary system could be the incorporation of the emergency beacon and voice systems into a operational mine communications system. At present, many mines use either telephone communications or FM signals transmitted along power lines and rails. The system considered here could serve the same role, by transmitting information to the surface at low frequency and retransmitting by standard radio or telephone to the mine offices. The advantage of such a hybrid system would have to be largely economic; the cost of maintenance of a wireless system with the most complicated components on the surface would have to be less than the cost of maintenance of a hard-conductor system underground. The benefits to safety would be large. With a continuously operating system of monitors, conditions prior to a disaster might be recognized, or if not, monitors could detect and locate the site of a disaster more rapidly and accurately than is now done.

Design Considerations

The tightest constraints on the design of a beacon or voice communications system are those related to underground operation during emergencies. The underground transmitter must be capable of operating on its own power supply with a high degree of reliability and with little attention from its human operator for relatively long periods. Constraints are much less severe for the surface-based location or reception equipment.

Past experience with attempts at underground communication indicates that relatively low frequencies must be used. At low frequencies, an electromagnetic field may be generated either by passing an electrical current through a length of grounded wire or by passing the same current through an ungrounded loop of wire. Factors involved in the choice between the two types of antenna are as follows:

1. The size of the signal received at the surface from a grounded wire is proportional to the length of the wire and the intensity of the current flowing in it. In a mine working, it is conceivable that antennas of considerable length could be laid out. However, the current that can be driven through the wire will depend on the quality of the ground connection at either end. In many mines, where the floor is wet clay, this would be no problem; however, in ventilated areas of a mine, the floor and walls may be dried to the point where it is difficult to make contact.

2. The size of the signal received at the surface from an underground loop is proportional to the areas of the loop and the intensity of the current flowing in it. In mine workings, it would be difficult to lay

out a loop with equal dimensions, so loops are not as convenient as grounded wires. However, the current that can be driven through the loop depends only on the size wire used and can be determined during design of the equipment rather than at the time of use as in the case of a grounded wire.

3. If sufficiently low frequencies are used, the magnetic field from a loop source is not distorted by the presence of conductors, such as the overlying rocks, and the location of the source can be determined with good reliability from surface measurements. In the case of a grounded wire source, the current flowing in the earth is detected and the geometry of this current field is quite sensitive to variations in the electrical conductivity. It would be more difficult to locate precisely a grounded wire source using surface measurements.

Aside from these considerations, the most important question is whether a detectable field can be generated. The theory for the behavior of low-frequency fields in the earth has been worked out in great detail in recent years so there is not much uncertainty about this aspect of the problem. For example, the magnetic field from a flat-lying loop in an underground mine working is described by

$$H_R = \frac{M}{2\pi R^3} e^{-ikR} (1 - ikR) \cos \theta \qquad \ldots 1$$

$$H_\theta = \frac{M}{4\pi R^3} e^{-ikR} (1 - ikR - k^2R^2) \sin \theta \qquad \ldots 2$$

where H_R is the magnetic field directed along a radial from the source loop, and H_θ is the magnetic field at right angles, as indicated in Figure B-1. M is the moment of the source, or the product of the current, times number of turns times area of the loop in the mine working; θ is the angle, as indicated on the sketch; and k is the wave number in the rock overlying the mine. The wave number depends on the electrical properties of the rocks and on the frequency. The distance from the underground loop to the magnetic detector on the surface is R.

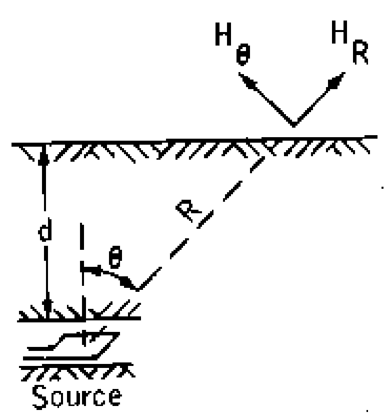

Figure B-1

If the wave number k is very small, as is the case if the operating frequency is made low enough, equations (1) and (2) reduce to

$$H_R = \frac{M}{2\pi R^3} \cos\theta \quad \ldots 3$$

$$H_\theta = \frac{M}{4\pi R^3} \cdot \sin\theta \quad \ldots 4$$

. Thus, at low enough frequencies, the strength of the magnetic field is independent of the properties of the earth. If higher frequencies are used, the magnetic field is attenuated exponentially at higher rates in more conductive ground. In order to specify what frequencies are low and what frequencies are high, typical values for the conductivity of coal and the overlying rock must be known. Figure B-2, from Parkhomenko (Electrical Properties of Rocks, Plenum Press, New York 1968), summarizes values of resistivity reported for coal. The majority of coals mines in the United States are assumed to have electrical resistivities in the range of 10 to 1000 ohm-meters.

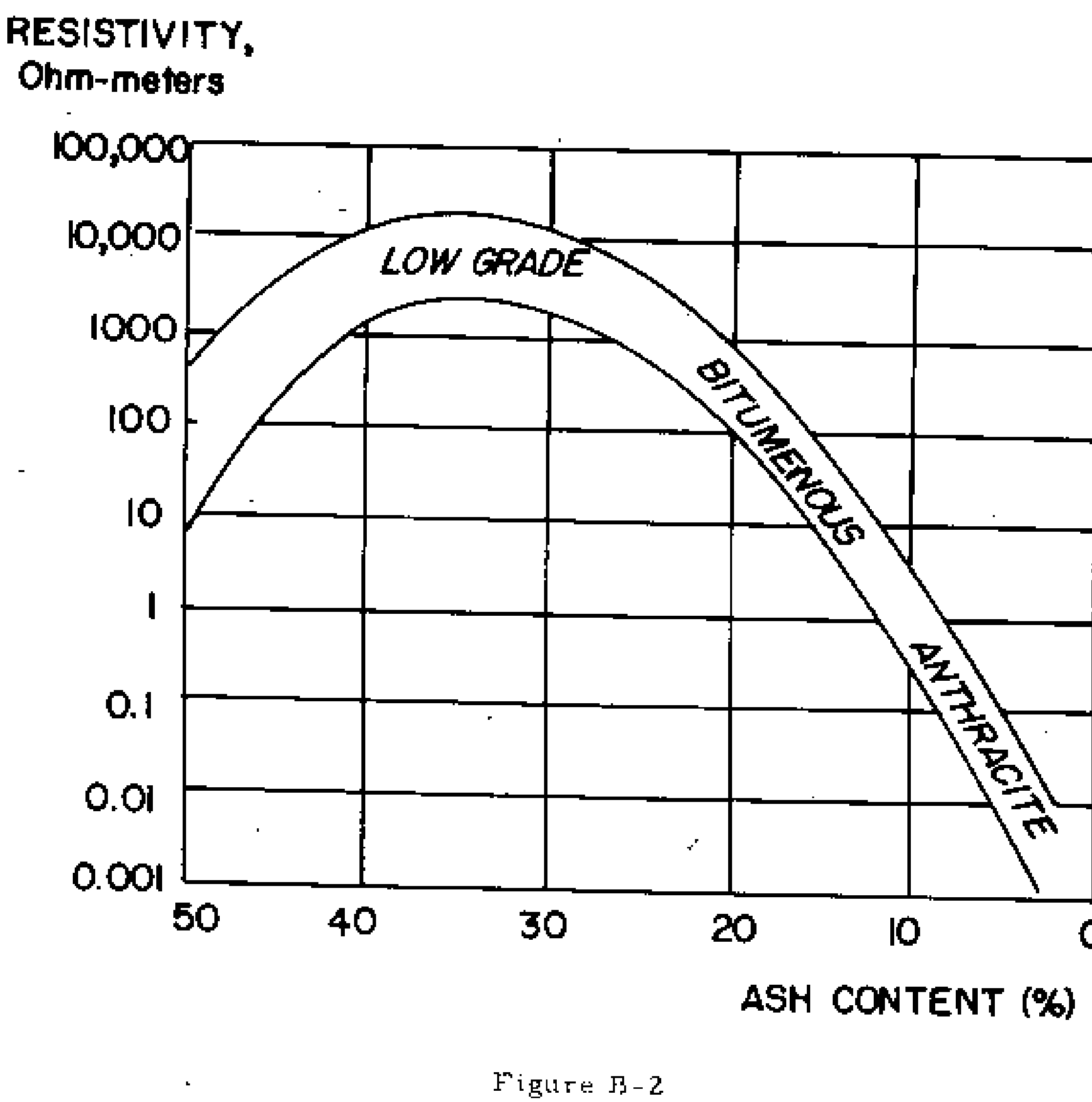

Figure B-2

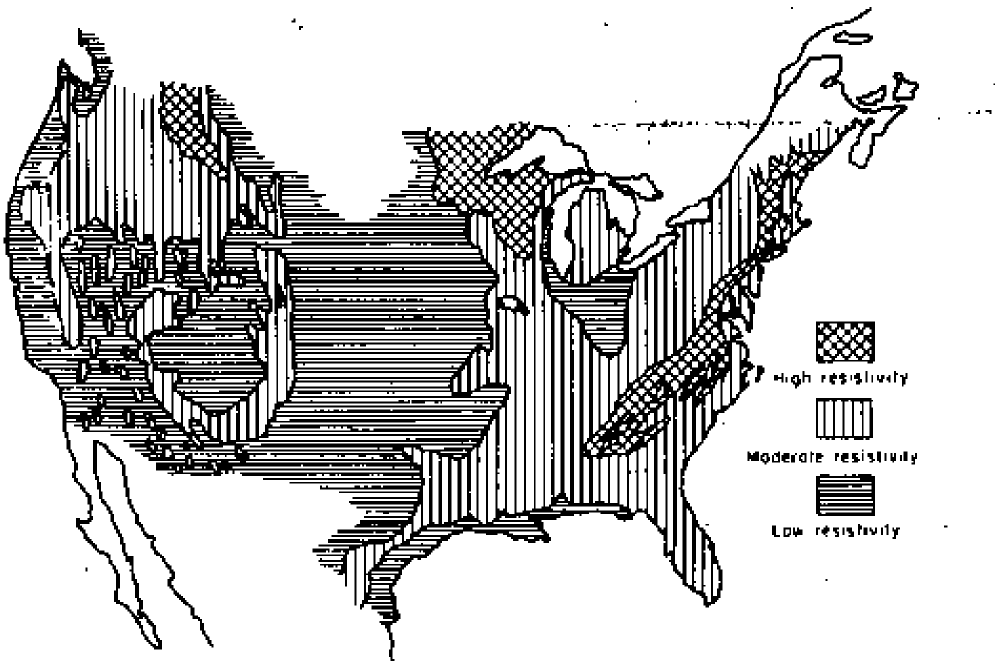

Figure B-3

The rocks overlying coal measures are usually sandstones and shale, which have a moderate resistivity. Figure B-3 shows regions of low, moderate, and high resistivity for surficial rocks. Over most coal measures, the resistivity of rock will lie between 20 and 200 ohm-meters.

Using these numbers, frequencies that are intermediate between high and low can be tabulated as in Table B-1.

TABLE B-1

Frequency, Hz	Conductive overburden (22 ohm-meters)	Resistive overburden (200 ohm-meters)
100	780 ft	2,400 ft
300	440	1,400
1,000	240	780
3,000	140	440
10,000	78	240
30,000	44	140

Given the depth of a mine working and the resistivity of the overlying rocks, these figures then specify the maximum frequency that can be used before the earth begins to attenuate the signal. Thus, for a mine 440 ft deep, with an overburden resistivity of 200 ohm-meters, frequencies as high as 3000 Hz might be used.

For frequencies below which the earth attenuation is significant, the size of the signal from an underground loop transmitter seen at a receiver on the surface can be calculated. The voltage seen with a coil receiver at the surface immediately over the transmitter will be

$$V = \frac{nA_r FM \cdot 12.56 \cdot 10^{-7}}{R^3} \qquad \ldots 5$$

where F is the frequency and n and A_r are the number of turns and the area of the receiving coil, respectively. Assuming a typical frequency of 1000 Hz, the source moment needed at the underground transmitter to provide an easily detectable signal at the surface can be calculated. Assume that the turns-area of the receiver coil is 1,000 square meters (this is typical of geophysical-type coil receivers operating at this frequency). Then, solving equation (5) for the moment required at the underground coil to provide a signal of 10 microvolts at the receiver:

$$M = \frac{R^3 V}{nFA_r \cdot 12.56 \cdot 10^{-7}} \approx 8 \qquad \ldots 6$$

A source moment of 8 amp per square meter is obtained rather easily. Consider a coil that consists of 10 turns of AWG 24 wire, with a 30-ft perimeter. If this is laid out in a loop with dimensions of 3 by 12 ft (to conform to the shape of a mine opening), a current of 0.2 amp would be required to provide this moment. This amount of copper wire would weigh less than a half pound and have an electrical resistance of 8 ohms. The voltage required to power the coil would be about 1 1/2 volts. A small rechargeable battery should be able to provide 10 amp-hours of operation per pound of weight. Thus, a 1-lb battery would operate the beacon for 50 hours.

Even such a simple beacon would weigh about 2 lb. The power requirements can be reduced in several ways. The transmitted tone could be interrupted with signals being transmitted for only 1/5 of each second, reducing the average current by 5, or if the same average current were used, increasing the signal strength fivefold. In addition, the signal could be coded to identify which of several beacons was being detected.

The alternative underground antenna would be a grounded wire. Consider a system such as that shown in Figure B-4. The electromagnetic field is generated underground by passing current through a wire of length L. The voltage at the surface of the earth arising from this wire at low frequency (the frequency requirement is the same as in the case of a loop source) can be calculated from the formula:

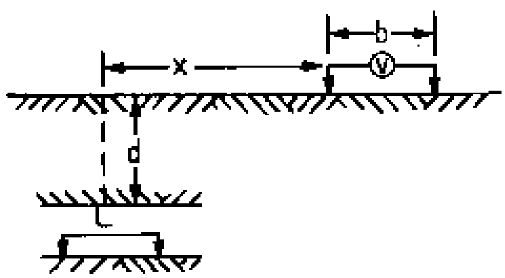

Figure B-4

$$V = \frac{\rho I L b}{2\pi d^3} \left\{ \frac{\left(\frac{x}{L} - \frac{1}{2} \right)}{\left[\left(\frac{x}{d} - \frac{L}{2d} \right)^2 + 1 \right]^{3/2}} - \frac{\left(\frac{x}{L} + \frac{1}{2} \right)}{\left[\left(\frac{x}{d} + \frac{L}{2d} \right)^2 + 1 \right]^{3/2}} \right\} \quad \ldots 7$$

where ρ is the resistivity of the overburden and x is the horizontal offset of the receiver from the transmitter.

To calculate the source moment required to provide a measurable signal at the surface, assume a resistivity of 10 ohm-meters, a length of the surface wire of 300 ft, and a required signal level of 100 microvolts. The moment of the transmitter (product of current and length) would have to be 0.6 amp meters. A signal level of 100 microvolts is comparable to the 10 microvolts specified for the loop detector in the previous calculation. If the length of the grounded wire in the mine is 100 ft, the current required would be 0.05 amp, or a quarter of that required with the loop. However, normal grounding resistances with the wire will range from 50 to 500 ohms, requiring supply voltage of 2.5 to 25.0 volts. The amp-hour per unit weight of a battery increases with voltage, so the net result is that for the same weight and complexity of the transmitter, a wire antenna provides about the same detectability as a loop antenna. The choice between the two systems thus lies in the factors considered earlier--convenience of operation.

It should be noted that either can be converted to a voice system by increasing the moment of the source and by providing appropriate electronics to convert signals to sound. With a beacon system, the moment of the source would need to be increased by a factor of about 100 to provide the bandwidth to transmit voice in an AM form. For an underground transmitter, this would reduce the life expectancy of the power supply by the same factor or from a nominal 50 hours to 30 minutes. If voice transmission is not attempted until after a beacon has been located and the beacon is of no further use, the shorter life would not be important. There is, of course, no practical limit on the intensity of the source that may be used from the surface to transmit voice downwards.

A further factor to be considered in comparing loop and grounded wire sources in the precision with which the location of the source can be mapped from the surface. The obvious field parameter to measure if the source is a loop is the dip angle of the resultant magnetic field at the surface. Directly over the transmitter, the dip angle will be vertical, and as one moves away from the transmitter, the magnetic field will tilt toward the horizontal, as indicated in Figure B-5. The measurement of dip angle of an electromagnetic field is a standard method in geophysical prospecting. For the frequency and signal level being considered here, the dip angle may usually be measured with an accuracy of 1 or 2 deg. This means that a source 300 ft below the surface could be located with a precision of 5 to 10 ft. At greater depths, the accuracy of location would be decreased proportionately.

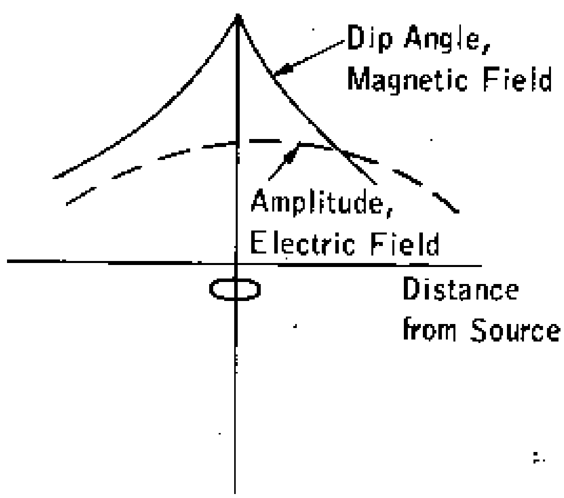

Figure B-5

Once the general area of the signal from a grounded wire source has been located, a more exact determination can be made by measuring the direction of current flow at several spots. The intersection of projections of these current flow lines would indicate the location of the source. The degree of uncertainty would be comparable to the length of the underground antenna, probably of the order of 50 to 100 ft.

To summarize, essential considerations in the design of a beacon are as follows:

1. The frequency should be low enough that attenuation of the signal is minimal. This means that frequencies as low as 200 Hz might have to be used for deep mines in conductive ground or that frequencies as high as 3 to 10 kHz could be used in shallow mines in resistant ground.

2. A loop source and a grounded wire source require about the same current capacity to provide detectable signals at the surface. However, the power requirements for a loop can be specified ahead of time, while those for a grounded wire will depend on how well the grounding is done.

3. A low-frequency loop transmitter will provide a field that is highly diagnostic of the location of the source. A grounded wire will provide a field that is less diagnostic.

4. The magnetic field can be detected with a coil that can be moved around rapidly. The electric field in the earth must be detected with a grounded wire on the surface, which is a much slower process.

5. Either system can be converted to a voice system by providing the appropriate electronics and increasing the moment; however, this will increase both the weight and cost of the beacon.

If voice communications are to be considered, they may be best considered separately, at least at first. The principal reason for using very low frequencies for a beacon system is that at sufficiently low frequencies, the electromagnetic field is not distorted by the earth and the source can be located accurately. If this were not a consideration, more efficient communications could be obtained at somewhat higher frequencies. The reason for this is twofold. First, the natural noise levels decrease gradually with increasing frequency, as shown in Figure B-6. The frequency bandwidth required for voice communications is the same 500 to 1000 Hz whether high frequency or low frequency is used. At higher frequencies up to the point where attenuation becomes too great, more and more sensitivity can also be used.

A second factor favoring higher frequencies when a loop receiver is used is that such a receiver becomes more efficient in direct proportion to the frequency.

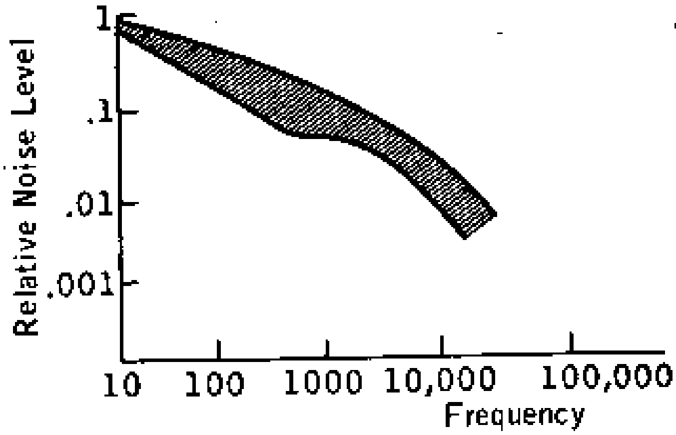

Figure B-6

To estimate the most effective frequency for voice communications; the factors given in Table B-1 must be weighed against the frequency dependence of the antenna. For a grounded wire source, the optimum frequency for voice communications would be one and a half to two times the frequency cutoff indicated in Table B-1. For a loop source, the optimum frequency would be four to six times higher. In a mine in which the cutoff frequency for beacon operation was 3 kHz, the optimum frequency for voice communication using a loop transmitter would be 12.0 to 18.0 kHz.

Recommended Research and Development Program

The following research and development program is recommended for the evolutionary development of an operational mine radio communication system.

1. Experiments should be carried out to measure the transparency of the rock overlying typical mines as a function of frequency. The experiments should use both loop and grounded wire sources over a frequency range of 20 to 20,000 Hz. These data would provide more precise values for the conductivity of rocks over typical mines, and better design criteria for both beacon and voice communications systems. Measurements at six to twelve mines in a variety of geological environments would require three to four months. This program should also include measurements of the noise in the vicinity of the mine, to better specify the detection program.

2. A number of prototype beacons and voice communications systems should be developed and tested. The tests should be carried out in a few specified mines so that performance of the systems can be compared, and they can be evaluated absolutely in terms of the studies made under (1) above. The hardware costs of a beacon should be no more than \$350 to \$1,000. An underground voice communications transceiver may be expected to cost three to ten times more. The surface equipment might cost a hundred times as much.

3. One or more systems should be selected for industrial use.

4. A system based on a hybrid through-the-earth and over-the-surface communications path should be field tested. This can be done by combining the beacon and voice systems selected under (3) above in one or more cooperating mines. The purpose would be to compare the utility and cost of such a system with current hard-conductor systems and to evaluate the concept of continuously monitoring a number of sensors distributed through the mine. The cost of such a program would probably be of the order of \$50,000 to \$100,000 to install the monitoring and relay systems and \$20,000 per year to evaluate the data obtained.

5. Paper and experimental studies related to other approaches to emergency communications should be carried out. Other approaches that seem less suitable than the low-frequency approach recommended here would be the use of high-frequency line-of-sight transmissions through mine openings and the use of mine entries as wave guides. Other concepts will no doubt result from the development program.

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PART 2: SEISMIC COMMUNICATIONS

Following a mine accident, accurate location of trapped miners and subsequent two-way communication with them is an integral part of the proposed system and is of utmost importance to a successful rescue. A seismic approach appears to be feasible using acoustic waves propagated through the rock and soil between the trapped miners and the surface. 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 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 and long shelf-life
- Dual service for location and communication

- Adaptability to widely varying seismic velocities, topography, and geologic structures
- Minimum maintenance
- Capability of continuous operation for extended periods
- Reasonable cost

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

- High reliability and long shelf 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.

Near-term Development

Feasibility Demonstration

Most crucial to the feasibility of the proposed system is the ability to detect a recognizable seismic signal with surface seismometers when the signals are generated by tapping on mine roof or wall with a hammer. After preparation of the Committee's Interim Report, November 1969, a test of this ability was made at a coal mine at Somerset, Colorado, on December 12 and 13, 1969.

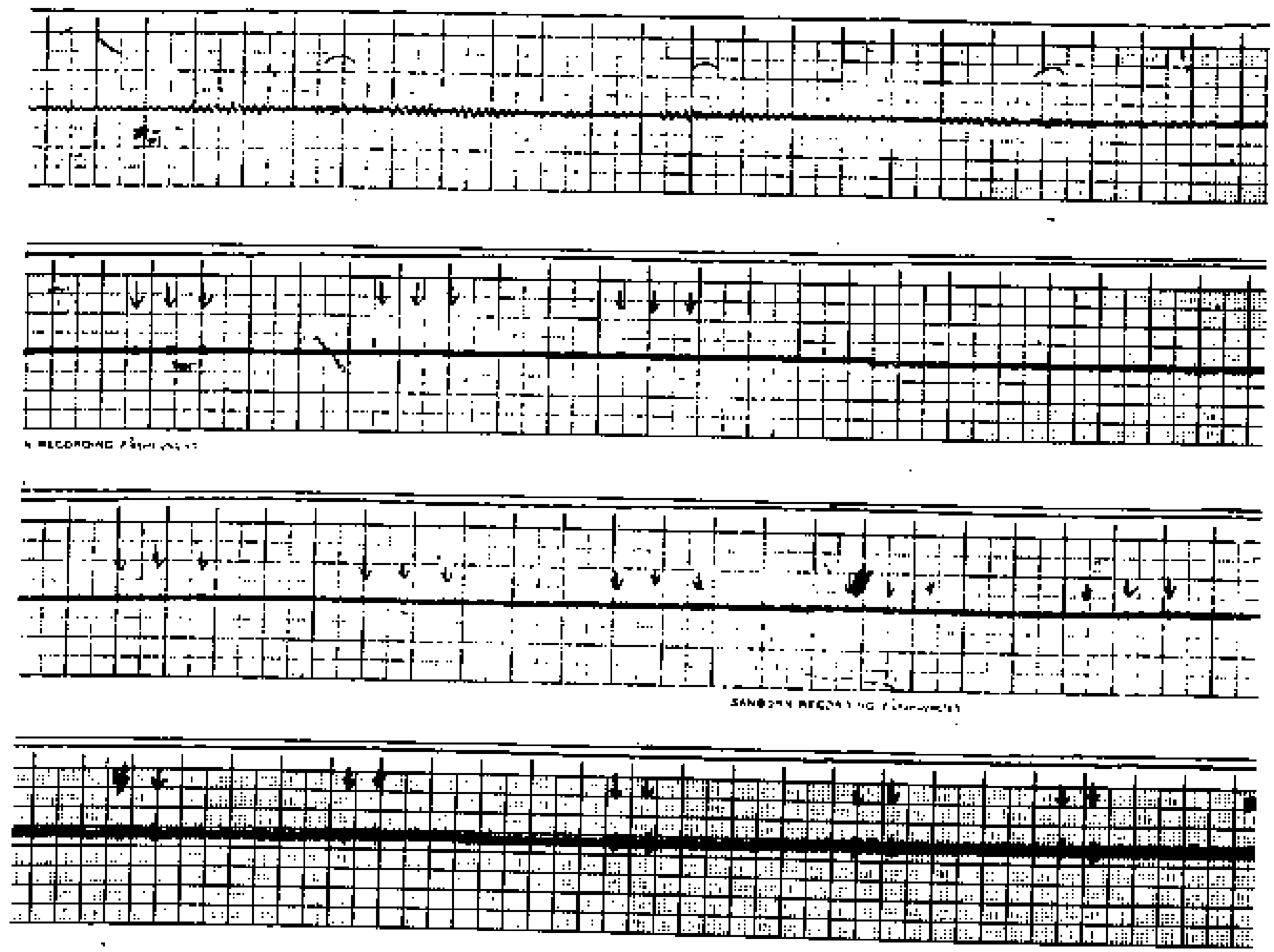
Equipment for this experiment was rather crude, consisting of instruments borrowed for the occasion from Texas Instruments Incorporated and limited in size and weight to what could be carried by air as personal baggage. A single seismometer output was recorded on a pen-recorder after amplification and passage through a 60-Hz notch filter, and a 100-Hz high-cut filter.

Examples of the signals recorded from 3-lb hammer blows on roof timbers at a mine depth of about 210 ft are presented in Figure B-7. The upper strip was recorded at 50 mm/sec, so that each millimeter unit along the horizontal time axis represents 0.02 sec. Remaining strips were recorded at 5 mm/sec, so that 1 mm corresponds to 0.2 sec. In the top three cases, hammer blows were struck in five groups of 3 at 10-sec intervals. In the lower case, there were 2 hammer blows per group. Signals having a signal-to-noise ratio (SNR) of about 2 are easily discerned in most instances.

Examination of these records revealed that the equipment was far from optimum for detection of signals from within a mine. System response had been optimized for surface waves recorded during field tests in Dallas where the predominant signal frequency was about 30 to 35 Hz. The compressional P-waves recorded at Somerset were of much higher frequency. Although the low SNR makes it difficult to estimate signal waveform, it appears that the predominant signal energy is about 65 to 70 Hz. It can be seen from the system response presented in Figure B-8 that such signals are being attenuated by about 20 db relative to the preferred pass-band. Modification of the system frequency response to eliminate frequencies lower than 65 Hz could probably improve the SNR by this 20 db.

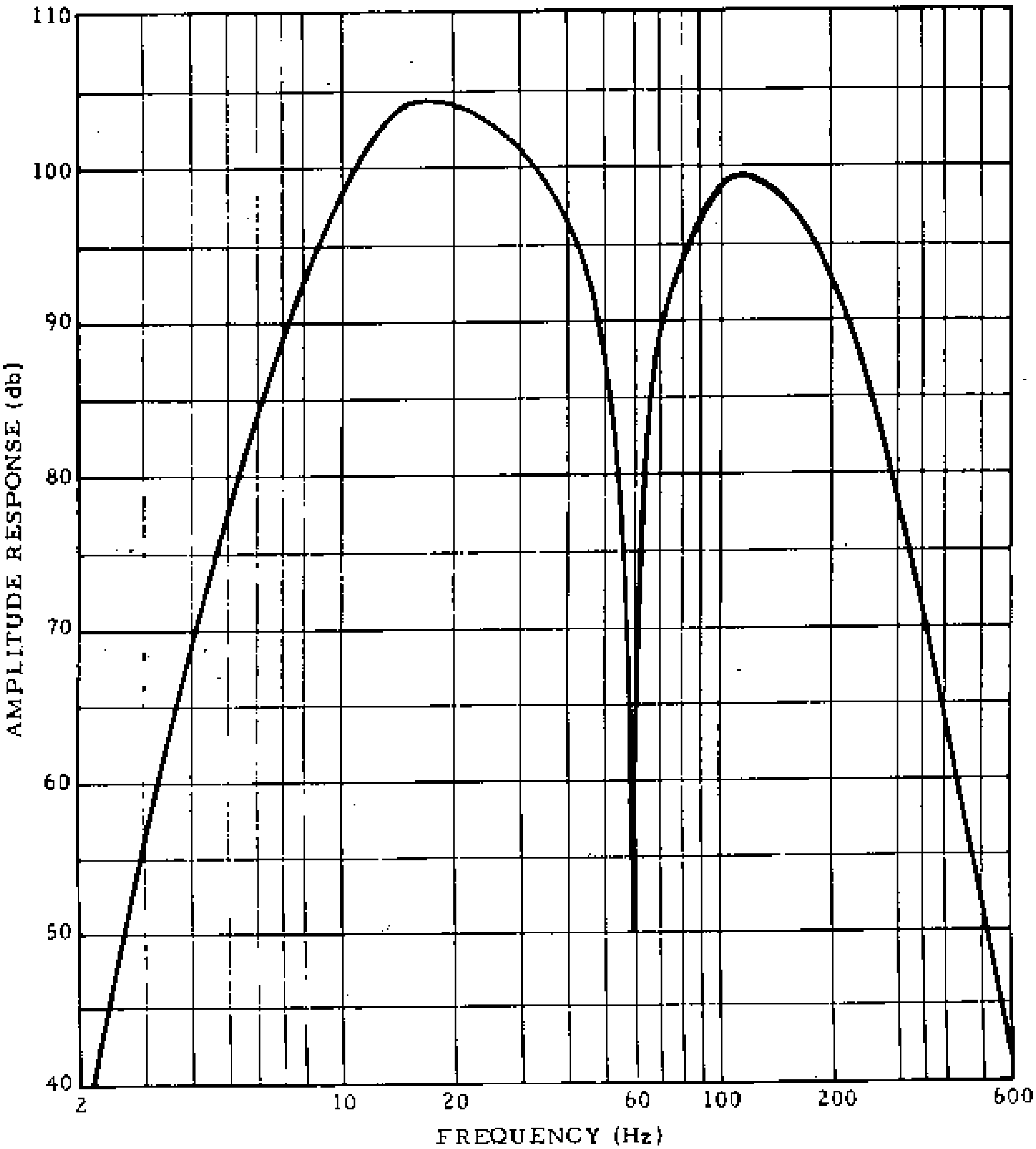
The use of 19-phone geophone patches could theoretically improve the SNR another 13 db, if the seismic signal has the same waveform at each geophone and the seismic noise is spatially random. A 30-db improvement in SNR (in this case an increase from a SNR of 2 to a SNR of 64) would permit the recording of hammer blows at depths or slant distances much greater than 210 ft.

Figure B-7



Examples of seismic signals (marked by arrows) recorded by a single seismometer from hammer tapping at 210-ft depth.

Figure B-8



Amplitude response of experimental system.

The Somerset experiment suggests that the seismic approach will be successful. At the least, it indicates the feasibility of such an approach. Therefore, the Committee recommends that the system development program described in the following section be initiated at the earliest opportunity. It is further recommended that if field testing of the developed seismic system proves it to be the most effective approach (in the context of the total system) to miner location and communication, then production, installation, and inspection of such systems should proceed as described below.

Seismic System Development Program

Configuration Definition

Before design and assembly of a seismic system, it will be necessary to determine the system configuration that will provide the flexibility required to operate optimally under all conditions. This can best be achieved through analysis of seismic data recorded during a field experiment at one or more mines with various system configurations and parameters. About three months will be required for recording and analyzing these data. Objectives of the data-recording operation are:

- To record on multichannel magnetic tape seismic signals generated by hammer blows at a range of depths within a mine.
- To record at a range of horizontal offsets for each depth.
- To record with various system configurations and parameters. Vary the number and pattern of geophones in each patch, the type of geophone (natural frequency), the filter pass-band, and the hum-bucking techniques used to eliminate 60-Hz noise induced by powerlines.
- To repeat at several sites over the mine.

Objectives of the data-analysis operation are:

- To determine frequency content and mode of propagation of all seismic signals observed.
- To determine frequency content, spatial organization, and modes of propagation of principal seismic noise components.

- To determine signal attenuation as a function of mine depth and horizontal offset.

- To specify prototype system configuration in terms of natural frequency of geophones, number of geophones per patch, hum-bucking technique, system gain, filters available, pen-recorder characteristics, and power requirements.

Design, Assembly, and Test

Design and assembly of the prototype system will require about two months. Material costs are estimated at $15,000.

System specifications, in addition to those qualitative specifications listed in "Systems Considerations," should include the following quantitative specifications:

- Ability to detect 3-lb hammer blows on mine roof bolts or timbers at slant ranges up to 1,500 ft and 3,500 ft for mine depths to 500 ft and 2,500 ft respectively.

- Ability to locate within ± 50 ft at depths to 500 ft and to within ± 100 ft at depths from 500 to 2,500 ft.

- Operable near high-voltage power lines.

- Operable in temperatures ranging from -30 to 40°C and relative humidities from 10 to 100 percent.

- Operable for 8 hours on one set of batteries.

The prototype system should be field-tested at three or four geologically distinct regions in order to verify its suitability to each. Field tests and system evaluation will require about five months.

Evaluation of the system will consist of measurement of detection ranges and location accuracy at several sites within each geologic region and comparison to design specification ranges and accuracies.

Surface System

A possible surface system might consist of four subarrays of 19 seismometers each deployed in a square approximately 1/2 mile across the diagonal. Each subarray would be about 40 ft in diameter. Optimum deployment, seismometer type, filtering, etc., would be determined by the experimental program described above. The output of the seismometer arrays would be recorded on a strip chart recorder. Up-to-date mine maps, plotting boards, and other equipment for locating the signal source would be provided at the recording location to permit immediate analysis of the signal received.

Subsurface System

The subsurface system would 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 would be accomplished with a single seismometer, operational amplifier, thresholding circuitry, audio oscillator, and earplug speaker. These devices have been successfully used for personnel intrusion detection. Total weight is about 4 lb and the seismometer would be 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.

Location

The 4-pen recorder would be operated at low speed (5 mm/sec) until a signal is observed. When signals are observed, the operator would switch 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 could operate continuously for 2 hours at low speed with 40 high-speed runs of about 3-sec duration each.

If a signal is observed on three or four of the seismometer subarray outputs, the operator could get a rough location estimate. Since the array would be large with respect to the mine depth, the seismic ray paths would be approximately horizontal in the subweathering rock. A quick computation would 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 azimuth estimates.

Once the rough location estimate is obtained, it would probably be necessary to move the array and reduce its size. Time required to pick up seismometers and cables would be the same as for deployment. With a crew of eight or nine men, the array could be moved and back in operation in about 45 minutes. Reduction in array size (to a 500-ft square) would tend to minimize effects of irregular topography, geologic structure, and inhomogeneities. Since the source would almost surely be within the smaller square array, the intersecting hyperbola method would 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 would probably have one or more subarrays with a signal-to-noise ratio (SNR) that provides good communication capability. If not, the four subarrays could 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 would 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 could also be sent by the surface array crew and picked up by the subsurface system. Information transfer by a pulse-coded system would necessarily be slow and might 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

Long-term Research and Development

High-frequency Seismic Location and Communication

Location

U.S. Bureau of Mines scientists at the Denver Mining Research Center have had considerable success using accelerometers to pick up seismic pulses from microfracturing of rock overlying mines and tunnels.[1,2] Frequencies of interest are 50 to 10,000 Hz. Although high-frequency seismic energy is rapidly attenuated with distance, they have been able to record signals from extremely weak microseisms through 100 to 200 ft of rock and locate the source through analysis of relative arrival times of the signal at four accelerometers.

A hammer blow, being essentially a force impulse, will generate a broad-band seismic signal. If sufficient high-frequency energy is generated to be detectable at ranges of several hundred feet, accelerometers may prove to be more effective transducers than seismometers for detecting tapping signals. Even then, accelerometers probably will be useful only when they can be cemented to solid rock outcrops, since soil or weathered rock will almost totally absorb high-frequency seismic energy.

Since an investigation of the use of accelerometers for miner location could be conducted at selected mine sites along with other investigations, the cost would be little more than the purchase price of a few accelerometers. Therefore, it is recommended that such an investigation be undertaken, perhaps parallel to field testing of the interim system.

Communication

If accelerometers prove to be effective for location, they can certainly be used for communication by a tapping code. It would be most desirable to have voice communication rather than code communication, however, and the voice frequency band, 50 to 3500 Hz, is included in the band now used for locating microseism sources. It is uncertain whether sufficient energy could be imparted to the earth at such high frequencies by some electromechanical device to permit voice communication over distances of 500 ft or more. It is also uncertain whether inhomogenieties and fractures in the rock will prevent transmission of intelligible speech because of frequency-dependent scattering of multipath effects.

In spite of the many uncertainties, the possible gain in system performance if intelligible speech can be transmitted seems worth the cost of investigating the feasibility of construction and testing of an electromechanical transducer to amplify and transmit speech energy as seismic energy. Such an investigation should be pursued only if accelerometers have already proved effective for locating miners.

Resonant Transducers

At the Institute for Exploratory Research, U.S. Army Electronics Command, Fort Monmouth, New Jersey, a group of researchers has developed resonant transducers for research on seismic communication.[3] A large transducer (350 kg and 200 W) and a small transducer (25 kg and 10 W) have been developed, both of which operate at 80 Hz.[4] The large transducer is normally used to transmit and the small transducer to receive, although any combination is workable.

Communications ranges of 2,000 ft with both transmitter and receiver on the surface have been achieved in flat, partially wooded terrain using only 12 W of seismic transmitter power. A depth range of over 1,700 ft to underground locations in a mine has been achieved using about 60 W of seismic transmitter power. Pulse modulation has been the most successful of the techniques investigated (AM, FM, and PM of 80-Hz carrier frequency) for transmission of information.

Recently the same group at Fort Monmouth developed a similar resonant transducer that operates at frequencies over 1 kHz, is much lighter, and requires less power.

These resonant CW transducers could undoubtedly be adapted to use in miner location and communication. At present weight and power, requirements would limit their use to refuge chambers or other semipermanent locations. Further development might eventually permit their integration with mining equipment.

Therefore, a study is recommended of the feasibility of modifying and using one or another of the Fort Monmouth resonant transducers for miner location and communication. If modification of present models does not appear feasible, a program for development and testing of a resonant transducer pair specifically designed for communication between surface and mine entry should be undertaken.

Research Utilizing Interim Seismic System

After several interim seismic systems have been produced and installed, a research program can be initiated to benefit from the periodic training exercises of the rescue-team system operators. First, a group of Bureau of Mines personnel should be formed to design the field experiments, to maintain liaison with the system operation crews, and to interpret experiment results. This group should include a geophysicist with a background in seismology and rock mechanics, a mining engineer, a mechanical engineer, and an electronic engineer.

Experiments designed by the group would be performed by the local system operation crews during their periodic training exercises. Results would be sent to the research group for analysis. Recommendations for minor modification of system components or procedures would be made by the research group to optimize system performance in each region. Experiment results would be analyzed to provide information to aid in making decisions regarding development of more advanced systems. Results would also be beneficial to research and development programs in progress.

Objectives of the data-recording experiments and their analysis, useful both for upgrading the performance of the interim system and for providing data for decisions on development of more advanced systems, are as follows:

- Measure local seismic velocities and correlate with rock composition and geologic structure.
- Measure rate of attenuation of seismic energy with depth, horizontal offset, and rock composition.
- Characterize local ambient seismic noise as to amplitude and spatial coherence during various noise conditions such as normal mine operations, mine shutdown, search and rescue operations, fair weather, rain, or wind.
- Identify seismic noise sources that might degrade system performance; develop techniques for minimizing their effects, e.g., ventilation fans and rescue drilling operations.
- Determine location accuracy obtainable as a function of geologic structure, composition of rock overlying mine, surface topography, ambient seismic noise level, depth of signal source, and horizontal offset from signal source to array.

- Determine optimum frequency bands for system operation for different geologic conditions or tactical operations.

- Determine best seismometer patch size and pattern for different noise conditions and seismic velocities.

Integration of Seismic Systems with Mining Operations

The Bureau of Mines group responsible for continuing development and implementation of mine rescue and survival systems and techniques should consider the following possibilities with regard to integrating the seismic subsystem with mining operations:

1. Mining Equipment

   - Storage of subsurface transducer units in or on continuous mining machines, self-loaders, mancars, or other mining equipment that will be near working sections.

   - Means for storing batteries or other power sources in or on mining equipment.

   - Modification of the design of mining equipment to permit its use as an integral part of the seismic subsystem during emergencies.

2. Refuge Chambers

   - Seismic transmitters and receivers built-in as integral parts of both permanent and portable refuge chambers.

   - Electrical energy sources built into both types of refuge chambers to provide power for seismic transmitters and receivers if electrical power is not already provided for life-support systems.

Automatic Signaling Devices

The continuing research and development program should consider development of one or more of the following automatic seismic signaling devices, all of which appear to be technically feasible.

Miner-actuated Beacon

A vibratory transducer that, after being activated by a miner, will continue to transmit a CW seismic signal at a unique frequency could act as a beacon for rescue operations. This device requires the minimum in miner training and interaction with the system. It is essentially the panic-button seismic system. In cases where the miners are injured or otherwise unable to continue to operate the system, it could signal the rescue team the miners' location as long as its power supply held out.

Miner-actuated and -programmed Beacon

A more sophisticated version of the seismic beacon could permit a miner to program a message into the transmitter. A series of buttons or switches would be provided to allow selection of one of several messages that would be automatically repeated by the device as long as power supplies lasted. Information would be transmitted by pulse-coding at a carrier frequency unique to each device. Only certain predetermined messages could be selected. These would grossly describe the underground situation, e.g., quality of air, barricades up or not, awaiting rescue, or attempting exit. Provision could also be made for selecting one or two numbers to be transmitted with the message code. Such numbers might give the number of miners accounted for, the location of the barricaded area, the number of the refuge chamber occupied, the portal number for which the miners are headed, etc.

Seismic devices for receiving and automatically decoding the signals could be permanently located on the surface where they could receive from one or more beacons. Or a portable seismic receiving system could be used to search all the points on the surface over the beacon positions in the affected part of the mine.

Automatic Air-sampling Devices

The beacon concept can be further refined to include devices for automatically measuring such underground conditions as air temperature; maximum air pressure experienced; and percentage of oxygen, carbon monoxide, carbon dioxide, and methane.

Such a device could include all the features of the previous two devices. The device could be automatically actuated by excessive air pressure, temperature, or percentage of carbon monoxide or methane.

In such case, information would automatically be transmitted to the surface by all beacons in the affected mine area. Only that beacon or beacons programmed by surviving miners would transmit a selectable message. Obviously such information would be invaluable for guiding rescue teams or for allowing surface rescue personnel to select an escape route and transmit it to the barricaded miners.

Transducer-Earth Coupling Studies

Efficient insertion of energy into the earth and detection of seismic energy, which has propagated through the earth, require good coupling of the transducers to the earth. In reflection seismograph survey, coupling is achieved by using geophones with spikes attached to the bases. Earthquake seismologists situate their seismometers on concrete slabs poured in direct contact with solid rock outcrops whenever possible.

A study should be conducted to determine the best method of firmly coupling to the earth each type of transducer used or considered for use with the seismic subsystem. Table B-2 shows some possibilities for the various combinations of transducer types and modes of use. The coupling methods listed should not be considered as recommendations, but merely as illustrations of the combinations that must be considered and some possible methods.

Transmission Path Effect Studies

Much information about the effects of rock composition and geologic structure on transmission of seismic energy can be obtained through the research program using the interim systems. Attenuation rates can be described fairly well as functions of vertical depth and horizontal offset for different geologic sections and structures. When this is done, it should be possible to model certain selected mines and predict attenuation rates and multipath effects for any given transmission path. Then the model can be used to assess the feasibility of permanently placing a small number of transducers above or within the mine, taking advantage of the particular geologic structure to achieve seismic energy transmission to and reception from any location within the mine. Appropriate field tests should then be performed to verify the model and the predictions based upon it.

TABLE B-2

Possible Transducer-Earth Coupling Methods

Mode of Use	Transducer Type: Geophone	Transducer Type: Accelerometer	Transducer Type: Resonant Transducer
Surface, portable	Spike	Placed in quick-setting cement and throwaway base	Augered to soil
Surface, permanent	Concrete slab vault	Cemented to concrete slab in vault	Bolted to concrete slab
Underground, portable	Spike	Placed in quick-setting cement	
Underground, permanent	Cemented to roof rock	Cemented to roof rock	Bolted to roof

If such an approach were successful, it would make permanent placement of transducers more attractive since fewer would be needed for complete mine coverage. It would eliminate the need for a portable surface system, provide for location and communication with miners instantly after an accident, and provide the highest degree of assurance that no signals were going undetected. Control of surface transmitters and outputs from surface receivers could both be located in the mine superintendent's office building, greatly simplifying coordination of rescue operations.

References

1 Blake, Wilson, and Fred Leighton, "Recent Developments and Applications of the Microseismic Method in Deep Mines" (presented at the Eleventh Rock Mechanics Symposium, June 16-18, 1969, Berkeley, California).

2 Blake, Wilson, and Wilbur Duvall, "Some Fundamental Properties of Rock Noises" (presented at fall meeting of Society of Mining Engineers of AIME, September 6-8, 1967, Las Vegas, Nevada).

3 Ikrath, Kurt, et al., "Seismic Communications to Underground Sites," Technical Report ECOM-2919, December 1967.

4 Johnson, R. F., et al., "Continuous Seismic Wave Communication Experiments at 80 Hz in Diverse Terrains," Technical Report ECOM-2921, January 1968.

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 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:

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:

- 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.

- Be transported in military aircraft.

- Drill reasonably straight holes with no more than 6-in. deviation per 100 ft depth.

- Drill 12,000-psi rock at the rate of 100 ft per hour (or more) and strong quartzite at 20 ft per hour.

- Have maximum traveling dimensions of 8-ft width and 10-ft height.

- Have a hoist with a capacity of 2,500 ft of 1/4-in. wire rope. (This can be a separate unit.)

- Drill with air circulation.

2. Provide a rescue drill capable of:

   - Drilling an 18- or 28-in. hole to 1,500-ft depth with a desired capacity of being extended to 2,500-ft depth.

   - Drilling with air circulation.

   - Setting casing for either hole size to a 500-ft depth.

   - 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).

   - A 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 rescued 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 to 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:

- The hole walls are stable.
- The hole walls are fairly smooth and straight.
- There is not a large volume of water flowing into the hole.
- 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. If 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 man 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, or 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 shipstock 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 taking 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.

Recommended Research and Development Program

Drills capable of drilling both the 6- to 8-in.-diameter probe holes and the 18- to 28-in.-diameter holes to 2,000-ft depths are commercially available. In general, large rigs capable of drilling these rescue holes are too slow and too cumbersome for transport and require too much space to provide adequate rescue capabilities. Research should be directed at improving their mobility and increasing their drilling rates, either by improving the present equipment and practices or by using new exotic drilling methods.

Two commercially proven methods to drill the discovery holes are with rotary drills or with percussion drills. Rotary drills must use rolling cutter bits because hard bands of formation would dull drag cutters. Percussion rigs are lighter than rotary drills for the same size and drilling speed but could cause a roof caving problem if used to drill into a weak-roofed refuge chamber. Percussion drills may also become inoperable where heavy water flows are encountered.

The only proven method to drill the 24- to 30-in. rescue holes is to use a rotary drill with rolling cutter bits. Churn drills and calyx drills will work but are too slow. Clusters of solid-head percussion drills are fast but are too undependable and have just about been taken off the commercial market.

Drilling rates are faster when air, rather than water or mud, is used as a circulating medium to remove cuttings. Enough air can be circulated to remove the inflow of water expected above most coal seams.

Any novel drills used for mine rescue must not require water in the hole or at least be convertible to such a system approximately 50 ft above the coal seam to avoid flooding the rescue chamber.

Over 30 novel drilling methods are currently being research by private industry, government agencies, and independent laboratories throughout the world. Novel disintegration methods include:

1. Thermal (spalling, fusion, and vaporization)
2. Chemical
3. High-pressure water jets

Although thermal spalling drills are widely used to drill taconite iron ore, they are not suited for rescue because many of the rocks above coal will not spall. Thermal drills that fuse and vaporize rock are being considered, but, in general, their drilling rates are too low because of the high-energy requirements for heating rock to its fusion temperature.

Chemical rock softeners in some kinds of rock show some promise but at best are means to supplement rather than replace other drilling means. Their application is limited and has been used only in the laboratory except for limited test with tunneling machines. Most of them basically are no more than wetting agents such as detergents and in some rock could cause more harm than good.

High-pressure water jets show most promise of the "exotic" methods of rock disintegration. These jets require pressures ranging from 10,000 to 100,000 psi to drill most rocks. Pressures up to about 20,000 psi can be obtained continuously with high-pressure pumps but require very special surface and in-hole equipment. Pressures in excess of 20,000 psi are usually obtained intermittently using water "cannons" that may be "fired" by a mechanically actuated piston. The high-pressure pulses from cannons get their best results when the drilling surface is not covered with water. This is difficult to accomplish in a vertical hole when the process adds water even though the addition may be only at the rate of 6 to 7 gal per minute. The "cannons" are massive, so that the "barrel" may be ten times as large as the area of rock on which it is effective in any one of its some 120 shots per minute. Continuous erosion drills appear to have more potential in a mine rescue operation than cannon drills.

The high thrust requirements for rotary bits can create roof failure problems when drilling into caverns or chambers containing the trapped miners. The last 50 ft above the chamber usually has to be drilled with low thrust on the bit to prevent caving the roof; consequently, the drilling rate is very low over this interval (i. e., it may take several hours to drill this last 50 ft). Research is needed to reduce this hazard, either by the development of rotary bits requiring less thrust or by the use of novel drills that require little or no thrust on the drill.

It should be acknowledged that the Academy of Engineering has, in a 1968 report, Rapid Excavation, recognized the need for a research effort on the part of the government for more rapid underground excavation methods, including drilling. This is a broad need of the government including such areas as underground transportation facilities, civil defense, and low-cost sewage and water movement. Accomplishments in the field of mine rescue could contribute to these fields. At the same time, mine rescue drilling has some unique problems, including the need for mobility and speed where costs may be secondary. In most other government needs, speed is secondary to cost. The principal need of other agencies is also for horizontal openings. Such vertical drilling as is necessary for rescue is only a means of access to horizontal openings in most cases. Mine rescue drilling, therefore, does deserve research attention to its unique problems. This research will, no doubt, contribute to and receive contributions from research in related fields.

There is considerable drilling research being done that may eventually have application for mine rescue. The Bureau of Mines research group needs to be staffed with personnel who can monitor and evaluate all available drilling research sponsored by industry and other agencies. Millions of dollars are currently being spent annually to develop improved drills for both blasthole drilling and oil well drilling. Some laboratories are doing fundamental research in rock mechanics. Others are working on material transport problems that could affect cuttings removal. Still others are doing research on soil stabilization. Any developments from this research should be quickly incorporated onto the rescue drilling equipment.

Additional work will be required by other laboratories under the Bureau's guidance and sponsorship.

The individual parts of the system that must be studied and improved are:

1. Rock disintegration for:

   - Speed
   - Size of hole
   - Reduction of equipment mass
   - Safety of miners and rescuers

2. Cuttings removal including:

   - Compatibility with wet and dry holes
   - Compatibility with disintegration techniques
   - Compatibility with requirement for compactness and portability
   - Reliability
   - Safety for miners and rescuers' environment

3. Wall support and its installation, which may involve:

   - Plastic pipe
   - Site-formed pipe
   - Quick-setting grout

4. Surface support equipment that are compatible with the above requirements and that will:

   - Be rapidly transportable (perhaps easily assembled modules)
   - Require a minimum of access construction
   - Require a minimum of site preparation
   - Require a minimum of auxiliary services from the mine community
   - Consider reelable pipe

5. Surveying equipment for:

   - Locating drilling sites
   - Orienting directional drilling
   - Exploring holes for near-missed cavities or sounds (preferably with drilling equipment in the hole)

Horizontal drilling through rubble in the mine should be considered as a separate project will less likelihood of success or application.

Methods should be studied for providing miners with the capability of supporting the roof for protection against damage from vibrations or entrance of rescue drills. In fact, very little knowledge is available on the effects of drills breaking through the roof of caverns. A research program should be undertaken to determine the dangers and to propose solutions.

APPENDIX D

ACKNOWLEDGMENTS

The Committee wishes to express its appreciation to the following companies and individuals for their cooperation and contributions to the study:

AVCO Corporation
Consolidation Coal Company
C. Richard Dunrud, U.S. Geological Survey
R. D. Ginter, National Aeronautics and Space Administration
Claude Goode, U.S. Bureau of Mines
Goodyear Aerospace Corporation
Jones and Laughlin Steel Corporation
Mid-Continent Coke and Coal Corporation
Martin Mikulus, National Aeronautics and Space Administration
Mine Safety Appliances Company
Old Dominion University
Puritan Equipment Company
SAR-ASSIST, Inc.
G. T. Schjeldahl Company
Scott Aviation
United States Steel Corporation, Coal Operations
James R. Wait, Environmental Science Services Adminstration
Weston Components Division