Information Circular 8907

# Postdisaster Survival and Rescue Research

## Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa., November 16, 1982

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# PREFACE

This Information Circular summarizes recent Bureau of Mines results covering postdisaster research. The papers are only a sample of the Bureau's total effort to improve mine health and safety through its Health and Safety Technology program, but they represent the major research effort in the area of postdisaster research. Those desiring more information on the Bureau's Mining Research program in general, or information on specific research, should feel free to contact the Bureau of Mines, Mining Research Directorate, 2401 E Street, NW, Washington, D.C. 20241, or the appropriate author listed in the following proceedings.

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# POSTDISASTER SURVIVAL AND RESCUE RESEARCH

Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa., November 16, 1982

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ABSTRACT

These proceedings consist of papers presented at a Bureau of Mines Technology Transfer Seminar on postdisaster survival and rescue research. Several seminars are held each year to bring the latest results of Bureau research to the attention of the mining industry as quickly as possible.

# INTRODUCTION

By Sidney O. Newman[1]

The postdisaster research program is directed toward research and development of technology and equipment that increases the chances of a miner surviving or being rescued after an underground mine disaster. A disaster is an accident of major proportions, and it may result in the entrapment of miners whose normal egress from the mine is cut off. This often necessitates a rescue operation and a means of keeping the trapped miners alive while they await rescue. The Bureau is currently pursuing research to develop the technology that will enhance the ability of miners to survive such an occurrence. The research is divided into two basic problem areas, survival and rescue. Both areas are concerned with the inability of miners and rescue teams to cope with the postdisaster environment, such as toxic gases, unstable roof conditions, water flooding, and lack of oxygen. In addition, research is also conducted to find ways of locating and quickly reaching trapped miners. Most of the research conducted by the Bureau has been directed toward the postdisaster problems associated with coal mines. However, most of the research results are also applicable to noncoal mines as well.

The papers presented in these proceedings address some of the recent research conducted by the Bureau of Mines that has been directed toward the postdisaster problems outlined above. The topics covered range from an overview of the technology developed for oxygen self-rescuers to training programs for mine rescue. Any questions or comments pertaining to this research are encouraged and appreciated.

Open file report (OFR) references in the proceedings listed as available from NTIS may be obtained from the National Technical Information Service, Springfield, Va. 22161, and are also available for reference at Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Bruceton and Pittsburgh, Pa., and Spokane, Wash.; the Department of Energy facility in Morgantown, W. Va.; the National Mine Health and Safety Academy, Beckley, W. Va., and the National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.

Throughout the proceedings, mention of trade names is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

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# AN OVERVIEW OF OXYGEN SELF-RESCUER TECHNOLOGY

By John G. Kovac[1]

## ABSTRACT

Federal regulations require that every person who goes into an underground coal mine in the United States be supplied with a self-contained self-rescuer (SCSR), a device capable of providing at least 60 min of oxygen regardless of ambient atmosphere. The development of oxygen self-rescuer technology suitable for in-mine use was a complicated engineering research and project management problem. The purpose of this paper is to trace the role that the Bureau of Mines played in the development of this technology from 1969 to the present.

## INTRODUCTION

When a mine disaster occurs, the basic survival technique for a miner is to escape from the mine. Following a mine fire or explosion, the atmosphere inside a mine sometimes becomes oxygen deficient or filled with toxic gases. Under these circumstances, escape is nearly impossible unless a miner is equipped with a self-rescue device that supplies oxygen without the need of breathing mine air.

Federal regulations (30 CFR 75.1714) require that every person who goes into an underground coal mine in the United States must be supplied with an SCSR. An SCSR is an emergency breathing apparatus designed for the purpose of mine escape. It must be capable of providing at least 60 min of oxygen, regardless of the ambient atmosphere. Only SCSR's approved by the National Institute of Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) can meet the provisions of the regulations.

These regulations became effective on June 21, 1981, about 2.5 yr after they were promulgated by MSHA. Their successful implementation depended crucially on two factors: (1) the commercial availability of approved SCSR's and (2) acceptance by mine operators and mine workers that SCSR's were rugged enough to survive deployment underground and function reliably in the event of a mine disaster.

The purpose of this paper is to examine the role the Bureau of Mines played in the development of SCSR technology. The development process, translating a conceptual design for an oxygen self-rescuer into a workable SCSR technology, was a complicated engineering research and project management problem. This paper will describe how the Bureau of Mines successfully developed prototype SCSR's approved for in-mine use. These prototypes, because they derived from proven, available technology, demonstrated the feasibility of the SCSR concept, encouraging manufacturers to adapt and modify this technology for commercial production.

## SCSR DESIGN CONCEPTS

In 1969 the National Academy of Engineering (NAE) established a Committee on Mine Rescue and Survival Techniques at the request of the Bureau of Mines. The purpose of this committee was to conduct a study program to assess technologies that could improve significantly a

[1]Supervisory mechanical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

miner's chances for survival following a mine fire or explosion.[2]

Based on a survey of underground coal mine disasters from 1950 to 1969, the NAE committee believed that a miner's chances for survival following a mine disaster could be significantly improved if he or she were equipped with a new type of emergency breathing apparatus, one that supplied oxygen without the need for breathing ambient mine air. Such a device, they argued, was well within the reach of existing technology. Thus, the NAE committee recommended that the Bureau of Mines develop SCSR technology and described how an SCSR should optimally perform for mine escape purposes.

The SCSR design requirements that emerged from the NAE committee's recommendations defined how an SCSR should optimally perform for mine escape purposes. There were nine design requirements, as follows:

1. Provide respirable atmosphere, regardless of environment.

2. Permit intermittent voice communications between miners.

3. Supply 1 hr of oxygen at a work rate defined by 30 CFR 11, NIOSH Man Test 4.

4. Should be lightweight and compact.

5. Should be reliable and simple to operate, providing immediate safe oxygen levels at startup.

6. Should be acceptable to miners.

7. Should be rugged.

8. Materials and design should be within present state of the art.

9. Target costs should be less than $50 per unit (in 1969 dollars) for 50,000 to 70,000 units produced within a 2-yr period.

Besides defining how an SCSR had to optimally perform for mine escape purposes, the NAE committee also described two conceptual designs for SCSR's, which they felt could potentially meet all nine design requirements.

There are two ways to obtain oxygen in SCSR's: by storing oxygen physically as a compressed gas or a cryogenic liquid, or by generating oxygen chemically. From the start, liquid oxygen SCSR's were ruled out because such a storage system represented a high development risk. Chemical oxygen sources were favored over compressed oxygen because available bottled oxygen technology could not meet the compact size and weight requirements. Another reason for favoring chemical oxygen sources was that even if a compressed oxygen SCSR could be built, it was believed that a chemical oxygen SCSR would have fewer moving parts and, as a result, have lower maintenance requirements and higher reliability.

Both NAE designs used chemical oxygen sources, and, in order to meet the requirements of a 1-hr oxygen supply and compact size, both used a closed-loop breathing circuit. In a closed-loop breathing apparatus, all inhaled and exhaled air is kept within the breathing circuit, conserving the available oxygen for reuse while requiring that the carbon dioxide produced by the body be absorbed. The NAE committee suggested that two different oxygen sources be considered, a sodium chlorate candle plus a carbon dioxide scrubber, and potassium superoxide.

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[2] Committee on Mine Rescue and Survival Techniques, National Academy of Engineering. Mine Rescue and Survival. Final Report (Contract S0190616). BuMines OFR 4-70, March 1970, 81 pp.; NTIS PB 191 691.

## SCSR'S DEVELOPED BY THE BUREAU OF MINES

The Bureau of Mines successfully developed five different SCSR's through research contracts with private industries.

In the order in which they were developed, the five SCSR's are

1. Westinghouse Electric Corp., Personal Breathing Apparatus (PBA), 1971.

2. Mine Safety Appliance Co., 10-min SCSR, 1973.

3. Lockheed Missiles and Space Corp., PBA, 1974.

4. MSA 10/60, 1978.

5. U.S. Divers Self-Contained Emergency Breathing Apparatus 60 (SCEBA 60), 1981.

All five devices are shown in figure 1. The size, weight, and operating characteristics of each device are listed in table 1.

TABLE 1. - Specifications of Bureau-developed SCSR's

| SCSR | Duration, min | Carrying weight, lb | Volume, cu in | Oxygen source |
|---|---|---|---|---|
| Westinghouse PBA | 60 | 8.7 | 525 | Chlorate candle. |
| Lockheed PBA.... | 60 | 4.5 | 200 | Potassium superoxide. |
| MSA 10-min SCSR. | 10 | 2.4 | 100 | Do. |
| MSA 10/60[1]...... | 10 | 4.2 | 170 | Do. |
| | 60 | 8.5 | NAp | |
| SCEBA 60........ | 60 | 6.2 | 354 | Compressed oxygen. |

NAp Not applicable. [1]Deployed together.

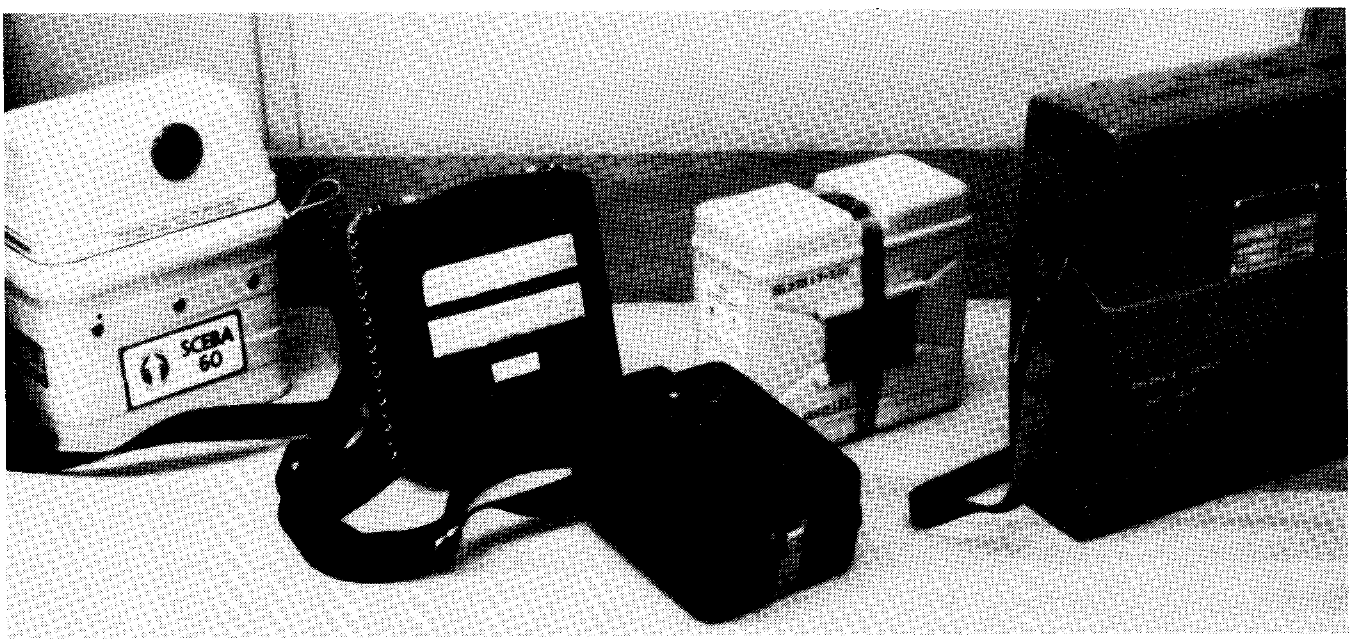


FIGURE 1. - Bureau-developed SCSR's. Left to right: SCEBA 60, MSA10/60, MSA 10-min SCSR, Lockheed PBA, Westinghouse PBA.

FIGURE 2. - Westinghouse PBA as worn by a miner for escape.

Westinghouse Electric Corp., PBA

The Bureau of Mines funded Westinghouse Electric Corp. to develop a 1-hr, sodium chlorate candle SCSR.[3]

The Westinghouse PBA was a straightforward feasibility demonstration of the SCSR concept using available technology as a starting point. It met most of the optimum design requirements. While the Westinghouse PBA was made as small as possible within the state of the art for sodium chlorate candles, its overall size and weight made it impractical for miners to carry this SCSR constantly. Figure 2 shows the Westinghouse PBA in use on a miner.

Since the Westinghouse PBA was a closed circuit breathing apparatus, it used pure oxygen as the breathing medium, generating oxygen by burning a sodium chlorate candle. The sodium chlorate candle was ignited automatically when the SCSR was pulled from its carrying container.

The flow path through the Westinghouse PBA is shown in figure 3. The wearer breaths oxygen to and from breathing bags. Exhaled gas passes through a canister containing a carbon dioxide absorbent---lithium hydroxide. Fresh oxygen from the sodium chlorate candle is constantly added to the breathing circuit. The amount of oxygen added will support a person working at the hardest work possible. Therefore, more oxygen is generated than is normally used by a person not working at maximum effort. The oxygen not used is vented through a one-way relief valve in the right breathing bag. This relief valve vents at a very low pressure buildup, and therefore, normally vents most of the time the apparatus is in use.

Separate tubes provide for inhalation and exhalation. Breathing check valves in the mouthpiece maintain one-way flow of the oxygen, preventing the wearer rebreathing gas from which carbon dioxide has not been removed. Rebreathing does not occur until the exhaled gas has been passed through the lithium hydroxide.

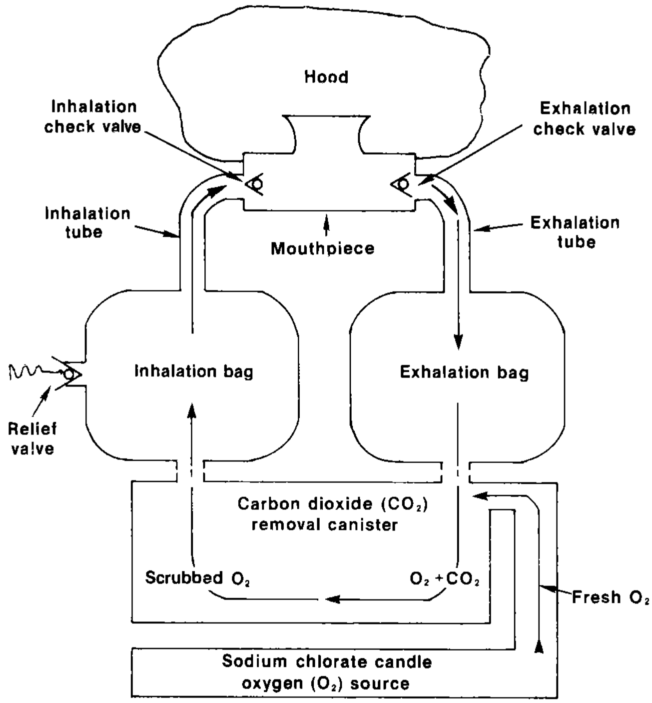


FIGURE 3. - Flow path through the Westinghouse PBA.

A plastic hood with a rubber neck seal and antifogging goggles is sealed around the mouthpiece to provide eye protection to the miner, to permit the miner to remove the mouthpiece without admitting contaminated air, and to ensure universal fit of the apparatus. A nose clip on the eyepiece holds the nose shut to prevent breathing from the hood.

MSA 10-Min SCSR

Because of the size of the Westinghouse PBA, the Bureau of Mines funded two separate contracts for the development of a 10-min, belt wearable SCSR and a 1-hr SCSR using potassium superoxide as the oxygen source. The development of the MSA 10-min SCSR will be discussed first.[4]

[3]Westinghouse Electric Corporation. Coal Mine Rescue and Survival. Volume 1. Survival Subsystem (Contract HO101262). BuMines OFR 9(1)-72, September 1971, 113 pp.; NTIS PB 208 266.

[4]Buban, E. E., and R. E. Gray. Short Duration Self-Rescue Breathing Apparatus (Contract HO220071, Mine Safety Appliance Co.). BuMines OFR 6-75, Apr. 1, 1974, 120 pp.; NTIS PB 240 471.

FIGURE 4. - MSA 10-min SCSR as worn by a miner for escape.

Figure 4 shows the MSA 10-min SCSR deployed for use. In order to meet belt-wearability requirement, this SCSR was designed to use a pendulum breathing circuit.

Figure 5 is a drawing of the flow path through the MSA 10-min SCSR. The exhaled air goes through the potassium superoxide bed where oxygen is produced and carbon dioxide is absorbed; then the exhaled air goes into the breathing bag. On inhalation, the gas from the bag returns by way of the same route. The split potassium superoxide bed design was chosen to make maximum use of the potassium superoxide while keeping overall breathing resistance low. The pressure relief valve on the breathing bag is necessary because the potassium superoxide produces slightly more oxygen than is needed. For safety, the potassium superoxide bed is designed to absorb all carbon dioxide, and thus, overproduces oxygen. The relief valve is a one-way valve so that no toxic gases can enter the breathing bag.

Because potassium superoxide does not provide oxygen instantly, a supply of oxygen is provided by a sodium chlorate candle for the first 45 sec. This helps inflate the breathing bag and provides the oxygen the wearer would need for the first minute or so. By that time enough breath moisture will have reacted with the potassium superoxide so as to provide the oxygen needed.

Inside the plastic carrying case, the MSA 10-min SCSR is packed in a double-sealed vapor bag. After the sealed bag is opened, the SCSR is donned by putting the bag strap over the neck. The sodium chlorate candle is started automatically by pulling a firing pin that is attached to the goggles used to protect the eyes from smoke. The entire donning operation can be accomplished in less than 30 sec.

The results of personnel tests of the MSA 10-min SCSR showed that the device would last at least 10 min or longer depending on work rate.

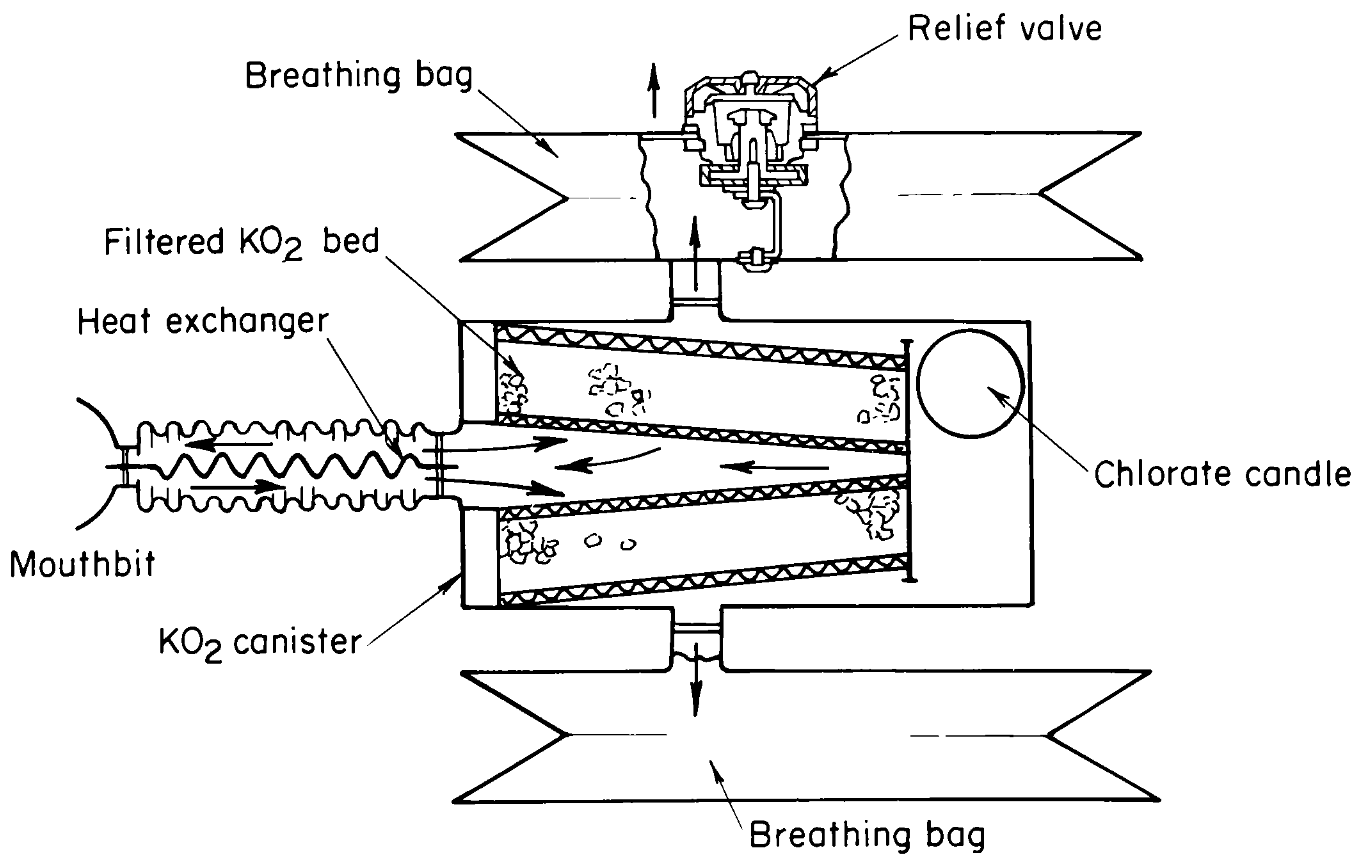


FIGURE 5. - Flow path through the MSA 10-min SCSR.

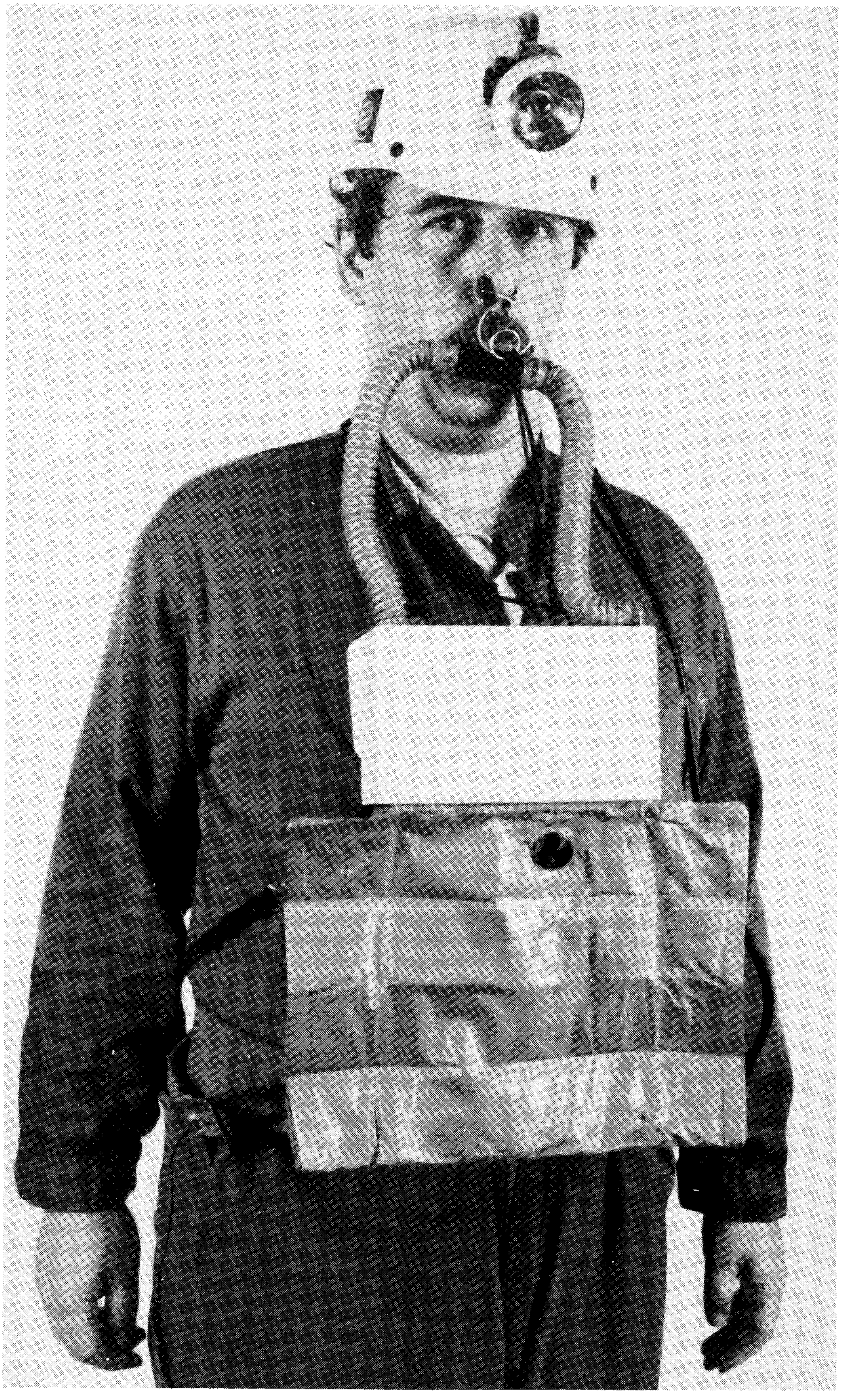

FIGURE 6. - Lockheed PBA as worn by a miner for escape.

## LOCKHEED PBA

In a parallel effort, the Bureau of Mines funded a contract with Lockheed Missiles and Space Corp. to develop 1-hr potassium superoxide SCSR.[5]

The Lockheed PBA is shown in figure 6 and a flow path diagram is shown in figure 7. In this SCSR the wearer exhales through the exhalation breathing tube down through the potassium superoxide bed and into the breathing bag. On inhalation, oxygen enriched air scrubbed of carbon dioxide bypasses the potassium superoxide bed by way of the return duct, then enters the inhalation breathing tube and passes into the mouthpiece; check valves at the mouthpiece assembly control the inhaled and exhaled direction of flow. Again, a relief valve on the breathing bag is needed to vent excess oxygen.

In order to keep inhaled air temperature within NIOSH requirements (<115° F), the heat generated by the chemical reaction of potassium superoxide is removed by gas flow routed through the breathing bag by internal baffles. The large surface area of the breathing bag exchanges heat with the ambient mine air.

A small sodium chlorate candle provides instant oxygen, similar to the MSA 10-min SCSR. This candle supplies 2 liters of oxygen in the first 15 sec and 8 to 10 liters during the 90 sec that follow. Pulling the mouthpiece towards the wearer automatically fires the sodium chlorate candle.

The top and bottom covers on the Lockheed PBA are held in place with "O" ring seals and a band strap. The outer case and cover provide moisture and shock protection for the SCSR. The moisture indicator in the upper cover allows a wearer

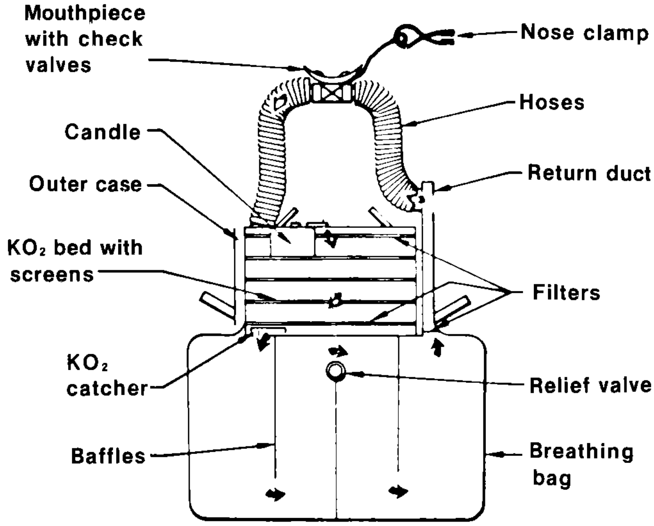


FIGURE 7. - Flow path through the Lockheed PBA.

to determine if the outer case has leaked moisture.

When the latch mechanism is opened, the bottom cover falls away, and the breathing bag deploys from the bottom. The top cover is placed between the wearer and the unit in order to keep the hot outer cover from touching the wearer. This also allows mine air to surround the apparatus and keep it cool.

During a demonstration wear test of the Lockheed PBA, one unit had the breathing bag catch fire. This was caused by potassium superoxide escaping from the chemical bed and bypassing the potassium superoxide catcher, falling into the breathing bag. The combination of thermally hot potassium superoxide with a silicon-fiberglass breathing bag in the presence of about an 80-pct oxygen atmosphere was enough to start the fire.

Despite this serious problem and other design flaws, such as the need for protective goggles to be packaged inside the unit, the Lockheed PBA became the prototype for commercially available, NIOSH-MSHA approved SCSR's. Both MSA and Draeger refined and successfully commercialized Bureau developed SCSR technology, producing the MSA 60-min SSR and the OXY SR 60B, respectively.

[5]Shengli, Y., and E. N. Perry. One-Hour Self-Rescue Breathing Apparatus (Contract HO220040, Lockheed Missiles and Space Corp.). BuMines OFR 8-75, October 1974, 123 pp.; NTIS PB 240 420.

FIGURE 8. - MSA 10/60 SCSR as worn by a miner for escape.

## MSA 10/60

The necessity of discarding the MSA 10-min SCSR in order to don a 1-hr SCSR in a contaminated environment was considered by the Bureau of Mines to be a design drawback. To overcome this limitation, it was decided that an optimum system would combine a 10-min, belt-wearable SCSR with a stored, larger, 1-hr duration oxygen supply that could be plugged into the 10-min unit without removing the mouthpiece. This 10/60 design concept was developed into a workable technology by Mine Safety Appliance Co., under contract to the Bureau of Mines.[6]

Figure 8 shows the MSA 10/60 SCSR as used by a miner for escape purposes. The 1-hr oxygen supply is plugged into the 10-min unit.

For the 10-min unit, a breathing circuit was developed in which the air is passed through the potassium superoxide bed twice per respiration. The 1-hr oxygen supply differs from the 10-min unit in that air is drawn only once through the chemical bed per respiration. In other words, after connecting both components together, the breathing circuit is switched from a pendulum system to a simple closed loop system. This was necessary to keep the inhaled air temperature within NIOSH approval requirements.

A 6-cm finned aluminum cylinder located in the breathing tube acts as a heat exchanger in the 10-min device. Location of the heat exchanger in the breathing tube also prevents the breathing tube from closing. The breathing bag and the manifold in the 1-hr oxygen supply are used as the primary heat exchanger when both components of the MSA 10/60 are assembled together. These heat exchange mechanisms lower inhalation air temperature to less than 115° F, meeting NIOSH certification requirements. Both potassium superoxide canisters have a felt cover to protect the user from burns.

Operation of the MSA 10/60 SCSR involves connecting the 10-min and 1-hr components together. Figure 9 shows the flow path through the assembled system.

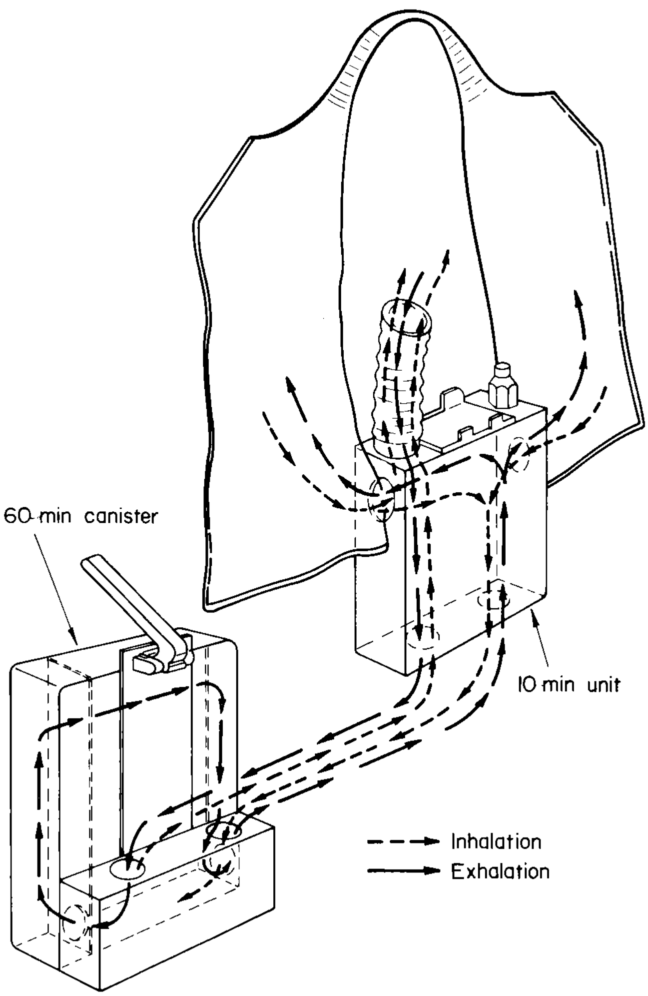


FIGURE 9. - Flow path through the MSA 10/60 SCSR.

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[6]Mine Safety Appliances Co. Combined Short and Long Duration Rescue Breathing Apparatus (Contract HO252079). July 1976; available for consultation at Bureau of Mines Pittsburgh Research Center, Pittsburgh, Pa.

The manifold system is designed to limit the inhaled concentration to less than 50 ppm of carbon monoxide if the coupling is performed in a mine atmosphere contaminated with 2.5 pct carbon monoxide. The potassium superoxide canisters have hermetic seals over their coupling ports. When the 1-hr oxygen supply is pressed against the 10-min unit, a metal-to-metal seal is made between the ducts prior to opening of either of the individual hermetic seals. Initial rotation of the handle on the latch assembly secures the metal-to-metal seal between the two components. Further rotation punctures the hermetic seals and activates the shutoff valve for the 10-min unit.

The results of breathing machine and personnel tests indicated that the MSA 10/60 SCSR will last 60 to 270 min, depending on work rate.

## SCEBA 60

Given the experience and technology of the late 1960's and early 1970's, the development of compressed oxygen SCSR's held little promise of success. This is the chief reason why the Bureau of Mines invested research and development resources in developing chemical oxygen SCSR technology.

In the late 1970's, however, it became clear that the state of the art in compressed gas breathing apparatus had improved considerably over the past 10 yrs. This technology had advanced to the point where a compressed oxygen SCSR could be offered as a viable alternative to potassium superoxide SCSR's. Therefore, the Bureau of Mines awarded a contract (J0100092) to U.S. Divers to develop a 1-hr compressed oxygen SCSR suitable for mine escape use.

The SCEBA 60 as used by a miner for escape is shown in figure 10. The apparatus includes a mouthpiece, nose clip, breathing hose and bag, a lightweight, single-use high-pressure oxygen vessel (115 liters at 3,000 psi), lithium hydroxide absorbent canister, and a pressure reducing on-off valve.

The SCEBA 60 uses a pendulum flow circuit shown schematically in figure 11, which provides a push-pull action through the carbon dioxide absorbent bed. Just as in the case of chemical oxygen SCSR's, to minimize size, the SCEBA 60 is a closed circuit breathing apparatus with an external breathing bag being used for gas storage. A compressed oxygen vessel and associated regulating valves control the addition of oxygen to the system.

In addition to these major components, the SCEBA 60 includes an easily reliable pressure gage, a volume sensing relief valve, and a sealed carry case with quick donning waist and neck straps.

At present, the SCEBA 60 is undergoing NIOSH certification trials.

Based on Bureau-developed technology, MSA and Draeger refined the design of the Lockheed PBA into commercial products; the Draeger OXY SR 60B and the MSA 60-min SSR. The SCEBA 60 SCSR will probably be commercialized once it receives NIOSH approval for in-mine use.


FIGURE 10. - SCEBA 60 as worn by a miner for escape.

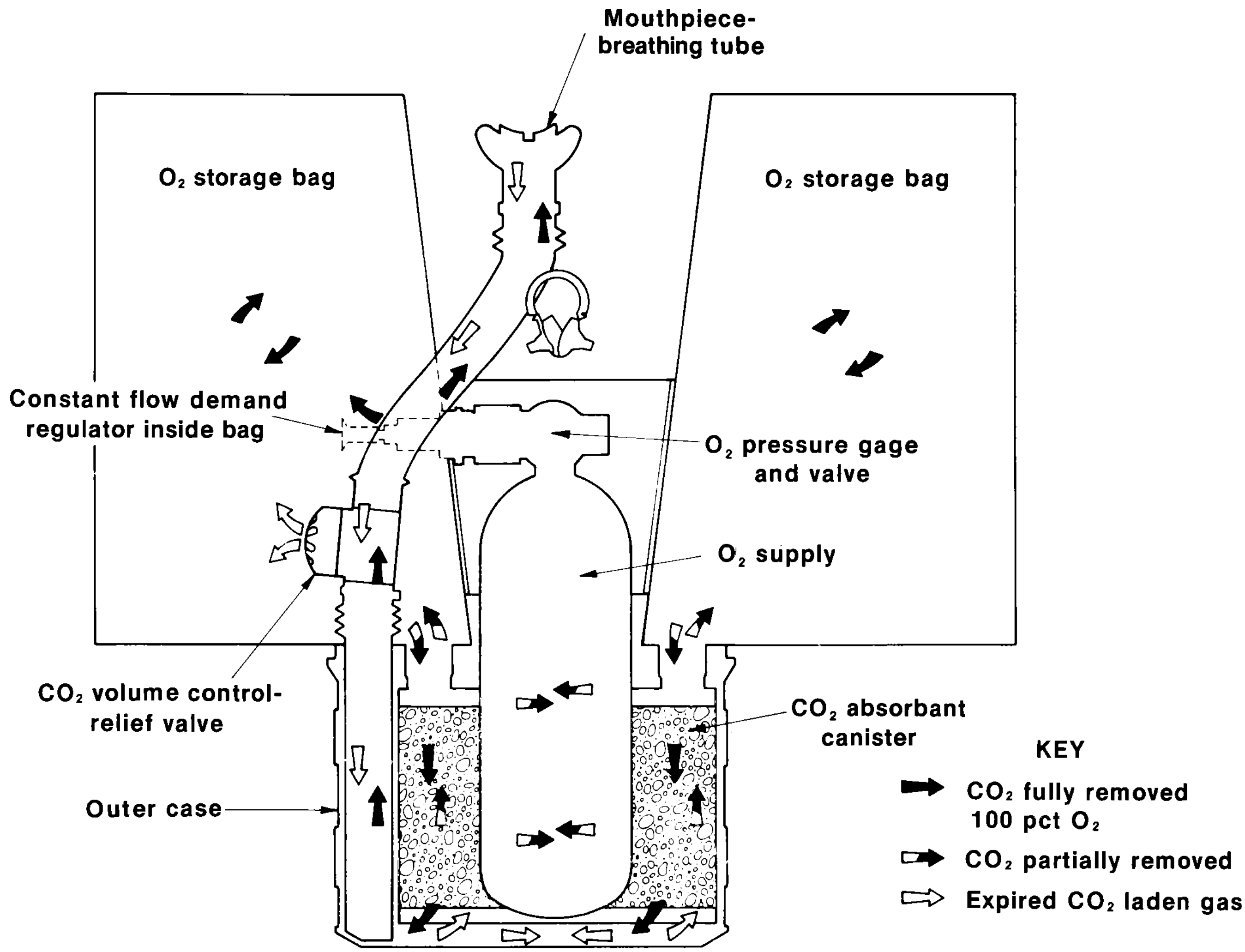


FIGURE 11. - Flow path through the SCEBA 60.

## STATE OF THE ART IN SCSR TECHNOLOGY

Five models of NOISH-MSHA approved 1-hr SCSR's are commercially available--CSE AU9-A1, Draeger OXY SR 60B, MSA 60-min SSR, OCENCO EBA 6.5, and PASS 700E. All five devices are shown in figure 12. The size, weight, and operating characteristics of each SCSR are listed in table 2.

TABLE 2. - Specifications for commercially available, approved 1-hr SCSR's

| SCSR | Weight, lb | | Volume, cu in | Oxygen source |
|---|---|---|---|---|
| | Carrying | Deployed | | |
| CSE AU9-A1.............. | 11.0 | 9.5 | 354 | Compressed oxygen. |
| Draeger OXY SR 60B...... | 8.4 | 7.4 | 366 | Potassium superoxide. |
| MSA 60-min SSR.......... | 9.1 | 6.7 | 360 | Do. |
| OCENCO EBA 6.5.......... | 7.7 | 6.8 | 452 | Compressed oxygen. |
| PASS 700E............... | 19.0 | 14.5 | 757 | Do. |

FIGURE 12. - Commercially available approved SCSR's. Left to right: (top) Draeger OXY-SR 60B, PASS 700, SCEBA 60; (bottom) CSE AU9-A1, MSA 60-min SSR, OCENCO EBA 6.5.

In order to meet the 1-hr duration requirement, all of the SCSR's are closed circuit breathing apparatus. Both the Draeger OXY SR 60B and the MSA 60-min SSR use potassium superoxide to generate oxygen and remove carbon dioxide. The CSE AU9-1, OCENCO EBA 6.5, and PASS 700E store oxygen as a compressed gas and use lithium hydroxide to absorb carbon dioxide. With the exception of the PASS 700E, all of the SCSR's can be worn by the miner as personal protective equipment; the PASS 700E must be carried or stored.

In 1982 the cost of an approved SCSR is about $500. Taking inflation into account, the target cost of $50 per SCSR projected by the NAE in 1969 becomes about $150 per SCSR in 1982. So the projected actual SCSR costs differ by about a factor of three.

## CONCLUSIONS

The Bureau of Mines successfully pursued the development of SCSR technology, cooperating with private industry to produce three prototype SCSR's approved for in-mine use.

Manufacturers refined and adapted Bureau-developed SCSR technology for commercial production.

# LABORATORY ENVIRONMENTAL TESTING OF CHEMICAL OXYGEN SELF-RESCUERS FOR RUGGEDNESS AND RELIABILITY

By Nicholas Kyriazi[1]

## ABSTRACT

The Bureau of Mines subjected two manufacturers' chemical oxygen ($KO_2$) self-rescue breathing apparatus to a series of laboratory environmental treatments designed to simulate various conditions in underground coal mines. The environmental treatments consisted of extremes of temperature, shock, and vibration. The tests were designed to be used as predictors of the ability of the self-rescuers to survive those environmental insults with no degradation in their protection to the wearer.

Based on the severity of the treatments, simulating conditions more severe than offered by the mining environment, the two apparatus tested should be able to withstand the abuse offered by the mining environment and still function as intended in an emergency. Correlation of these tests with results of long-term field evaluations is needed to provide confidence in the laboratory tests as predictors.

## INTRODUCTION

On June 21, 1981, coal mine operators were required to make available to each underground coal miner in the United States a self-contained oxygen self-rescuer (OSR). The regulations, 30 CFR 75.1714, require that each person in an underground coal mine wear, carry, or have immediate access to a self-rescuer that provides an oxygen source. The OSR will replace filter self-rescuers (FSR) as primary escape equipment. FSR's protect only against low levels of CO.

In December 1980 the Bureau began laboratory environmental testing of the two chemical oxygen OSR's that had been approved by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA), the Draeger OXY-SR 60B[2] and Mine Safety Appliances (MSA) 60-minute self-contained self-rescuers (SCSR); no other self-rescuers had NIOSH-MSHA approval at that time. The purpose of this series of environmental tests was to attempt to project the effects of the underground mining environment on OSR's. Such studies are not always done on new equipment before large-scale deployment, but because OSR's are used for life support, it is critical that they be maintained in operable condition. These laboratory tests were planned to give further knowledge and assurances about the readiness of OSR's to operate when needed.

There is no implication that either NIOSH, MSHA, or the manufacturers have conducted less than thorough testing of these devices. There is a high level of confidence that they are dependable devices. However, the need to study environmental effects arises owing to the gradual deterioration that all equipment and materials are expected to experience. Environmental testing can help estimate equipment lifetime. For OSR's, the questions of concern are related to expected lifetime in various modes of section (container) storage, placement on mining equipment, and wear or carry.

The assured answers to these questions can come only from experience, and the Bureau intends to perform a long-term field evaluation after actual deployment

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[1]Biomedical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[2]Reference to specific products does not imply endorsement by the Bureau of Mines.

of the OSR's. In lieu of this experience, the laboratory tests offer the following benefits: (1) If the test is severe enough, one can directly observe the failure mode for a particular environmental assault on the equipment; and (2) the laboratory test results can be used as indicators of areas where attention should be focused during the field evaluations.

The test results should not be applied to other OSR's or breathing apparatus, since they are specific to the two chemical $O_2$ devices evaluated.

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS PAPER

| | | | | | |
|---|---|---|---|---|---|
| bpm | breaths per minute | kg | kilograms | min | minutes |
| cu in | cubic inches | lb | pounds | mm | millimeters |
| ° C | degrees Celsius | lpb | liters per breath | mph | miles per hour |
| ft/sec | feet per second | lpm | liters per minute | sec | seconds |
| hr | hours | m | meters | yr | years |

## DESCRIPTION OF SELF-RESCUERS

Basically, a closed circuit, self-contained breathing apparatus of any type is composed of a mouthpiece or facepiece and breathing hose, an oxygen source, a carbon dioxide absorbent, and a breathing bag. In the case of chemical oxygen apparatus, $KO_2$ is both the oxygen source and the carbon dioxide absorbent, satisfying human physiological needs with a little excess oxygen. This excess oxygen has the effect of continually purging the system of nitrogen, which may exist in the breathing loop.

As can be seen from figures 1 and 2, the MSA 60-min SSR and Draeger OXY-SR 60B apparatus have different flow paths and arrangements of components. Their functions, however, are the same--to provide a portable life-supporting atmosphere. The oxygen self-rescuers differ from the filter self-rescuers (fig. 3) in that they are bigger and heavier. Inhalation temperatures for SCSR's may be high towards end of apparatus life, but this is unrelated to ambient conditions, whereas the FSR may heat up to unbearable temperatures and actually burn the lips of the user if ambient CO concentrations are high. Duration is determined in FSR's by ambient CO concentrations, humidity, and physiological demand; in SCSR's the physiological demand of the user alone determines duration, and an SCSR may last as long as 5 hr if the user is sedentary (NIOSH man-test 5).

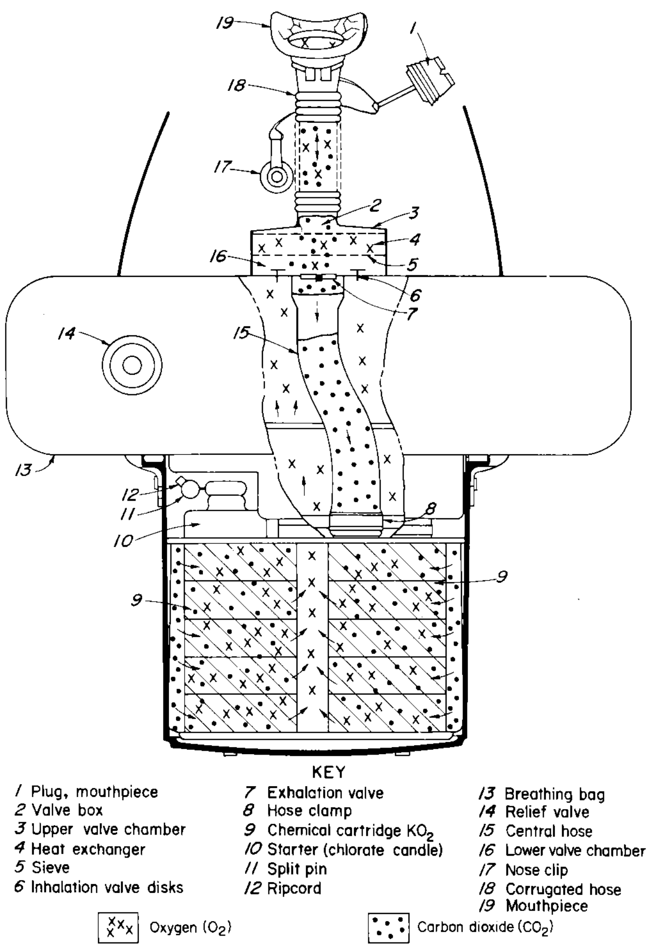


FIGURE 1. - Draeger oxygen self-rescuer.

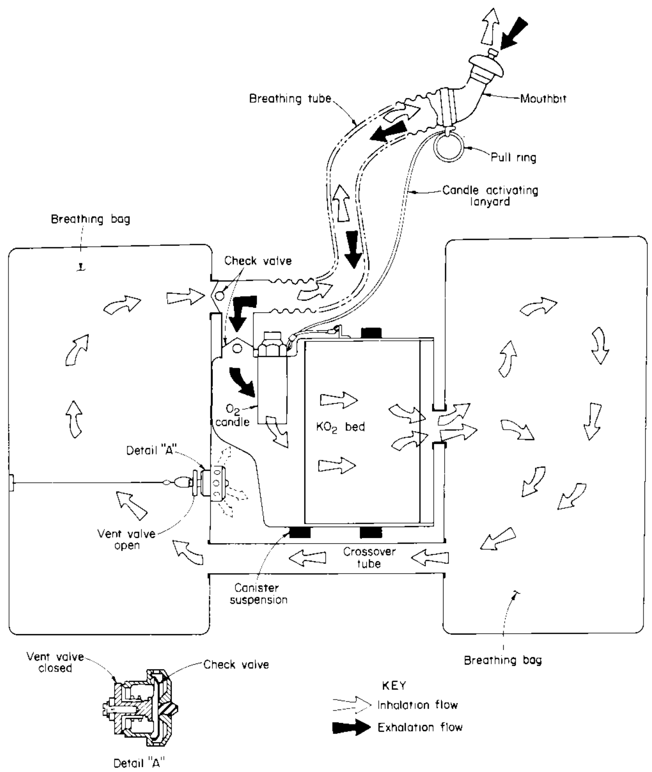


FIGURE 2. - MSA oxygen self-rescuer.

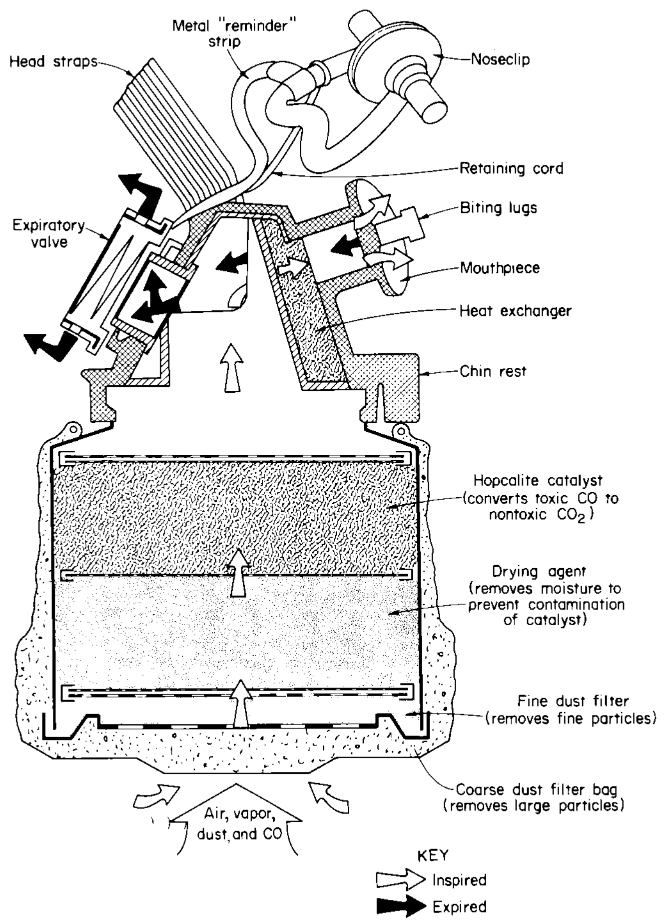


FIGURE 3. - Filter self-rescuer (FSR).

## EXPERIMENTAL DESIGN AND TEST METHODS

Laboratory testing consisted of (1) determining baseline performance for untreated, new OSR's, (2) performing environmental degradation treatments, and (3) measuring the effects of the treatments on OSR operational lifetime. The treatments performed were temperature extremes (71° C, 48 hr; 100° C, 4 hr; and -45° C, 16 hr) and shock and vibration. Both human subject tests on a treadmill and machine tests using a breathing and metabolic simulator (BMS) were used to measure the effects of the environmental treatments on OSR performance. Human subject testing provided relevant human factors information, while the BMS tests provided a more reproducible method for quantifying the duration of respiratory protection. Duration of respiratory protection is necessarily a function of the workloads performed during testing. The BMS, unlike a human subject, can be programmed to precisely reproduce a given demand (work load) from test to test.

An apparatus could fail in two ways: Measured parameters could exceed predefined limits, or the apparatus could cease to support life completely. In other words, even though an apparatus may be very hard to breathe through, for example, and may exceed the predefined limits, it could still be used in a life and death situation to escape from an irrespirable atmosphere. The difference between these two definitions was recognized and noted in some cases in this study.

## TREADMILL TESTING

The human subject test used was the treadmill equivalent of NIOSH man-test 4 for 60 min (table 1). The treadmill simulation of the test was based on the published studies of Kamon.[3] Treadmill testing permitted continuous monitoring of $CO_2$ and $O_2$ measured in the breathing bag, and temperature and pressure measured in the mouthbit. At the end of 60 min, a constant speed chosen by each subject was maintained until apparatus failure. Three human subjects were used for the treadmill testing. Characteristics of untreated, new OSR's were measured during human subject and machine tests to establish the normal range of performance. These tests were used as controls for comparison with the treated OSR's. Since each subject would put a different demand on the apparatus, owing to differing weights and end-run speeds, these factors were normalized by comparing the duration of each subject's treated units only with his or her own control unit. Normalization consisted of dividing each duration for a treated unit by the duration of the control unit. This was done for each test subject so that each control apparatus would have a normalized duration value of 1.00 with the treated units having normalized duration values varying around 1.00. Weights of the subjects and their end-run speeds are given in table 2. Duration was defined by the termination time. Factors determining termination were inhaled gas concentrations of $CO_2$ greater than 1.5% or of $O_2$ less than 21%, inadequate gas volume (bag bottoming on inhalation), any subjective intolerable discomfort such as breathing resistance or high temperature of inhaled gas or of apparatus surface, or an excessively high heart rate (greater than 90% of maximum). If a treated unit reached the duration of a control test, the test was usually stopped for the benefit of the test subject.

[3]Kamon, E., T. Bernard, and R. Stein. Steady State Respiratory Responses to Tasks Used in Federal Testing of Self-Contained Breathing Apparatus. Am. Ind. Hygiene Assoc. J., December 1975, pp. 886-896.

TABLE 1. - NIOSH man-test 4 and treadmill equivalent

| Time, min[1] | NIOSH man-test 4[2] | Treadmill equivalent |
|---|---|---|
| 2 | Sampling and reading.............................. | Stand. |
| 2 | Walk at 3 mph...................................... | Walk at 3 mph. |
| 1 | Climb vertical treadmill (1 ft/sec)............... | Walk at 4.5 mph at 15% grade. |
| 2 | Walk at 3 mph...................................... | Walk at 3 mph. |
| 5 | Pull 45-lb weight to 5 ft (60 times in 5 min)...... | Walk at 4.2 mph. |
| 3 | Walk at 3 mph...................................... | Walk at 3 mph. |
| 8 | Carry 50-lb weight over overcast (4 times in 8 min) | Walk at 2.7 mph. |
| 2 | Sampling and reading.............................. | Stand. |
| 4 | Walk at 3 mph...................................... | Walk at 3 mph. |
| 1 | Run at 6 mph....................................... | Run at 6 mph. |
| 9 | Carry 50-lb weight over overcast (6 times in 9 min) | Walk at 3.6 mph. |
| 3 | Pull 45-lb weight to 5 ft (36 times in 3 min)...... | Walk at 4.2 mph. |
| 2 | Sampling and reading.............................. | Stand. |
| 6 | Walk at 3 mph...................................... | Walk at 3 mph. |
| 5 | Pull 45-lb weight to 5 ft (60 times in 5 min)...... | Walk at 4.2 mph. |
| 3 | Carry 45-lb weight and walk at 3 mph............... | Walk at 4.2 mph. |
| 2 | Sampling and reading.............................. | Stand. |

[1]Overall test takes 1 hr. [2]30 CFR 11-H.

TABLE 2. - Human subject weights and end-run speeds

| Subject | Weight, kg | Constant end-run speed, mph |
|---|---|---|
| A.......... | 49 | 3 |
| B.......... | 68 | 6 |
| C.......... | 73 | 6 |

More than one test for each treatment and control per person were not run for several reasons. Additional testing on the BMS of the treated units was planned and, taken with the treadmill testing, was felt to be sufficient. The treadmill testing results cannot be considered definitive if taken alone, however. More control tests per person were not run since previous experience with laboratory testing of the OSR's showed our control tests to be typical. Also, the physiological demand for a human subject varies with changes in running style, weight, fitness, and diet. This would preclude any reliance on human subject testing for providing reproducible physiological demand. This was the purpose of the BMS testing.

## BREATHING METABOLIC SIMULATOR TESTING

A prototype breathing metabolic simulator built by Reimers Consultants, Falls Church, Va., was used in the machine-testing part of the study (fig. 4). The metabolic state used in the machine testing represented the average work rate that would be exhibited by a 50th percentile miner (87 kg) performing man-test 4 for 60 min.[4] The physiological parameters at standard temperature and pressure, dry, follow:

$V_{O_2}$ - Oxygen consumption - 1.35 lpm

$V_{CO_2}$ - Carbon dioxide production - 1.30 lpm

$V_E$ - Ventilation - 31.89 lpm

$V_T$ - Tidal volume - 1.21 lpb

RF - Respiratory frequency - 26.5 bpm

Termination factors were inhaled gas concentrations with more than 1.5% $CO_2$, or less than 21% $O_2$, or inadequate gas volume. For a treatment to be considered to have had no impact on an apparatus, the chlorate candle must function and there must be no significant degradation in the duration compared to the control tests. A discussion of the various environmental treatments and methods follows.

## SHOCK AND VIBRATION TREATMENT

There is no specific NIOSH or MSHA requirement in the Code of Federal Regulations for shock or vibration testing of breathing apparatus. At present, however, NIOSH requires that self-rescuers survive 40 hr of shock and vibration on a Rotap sieve shaker. The two chemical OSR's tested by the Bureau had successfully passed this test during NIOSH and/or MSHA approval testing.

The Rotap machine subjects the OSR to vibration from rotary motion and an impact from a hammer blow (2.5 impacts/sec). The OSR is rigidly mounted to avoid excessive accelerations and monitored to maintain accelerations within 15 g, peak to peak, for the entire test period. The test's origin is from experience with FSR's and simulates the extent of damage suffered in worst case tests of harsh mining environments, including carrying and mounting on machines for 1 yr. The Rotap test itself, though, does not simulate vibration spectra and types likely to be seen on mining machinery. To resolve this problem, we devised a composite test based on the reported vibration levels experienced on portable equipment, on underground mining machines (long-wall, continuous) measured on the frame, and on underground and surface

[4]Work cited in footnote 3.

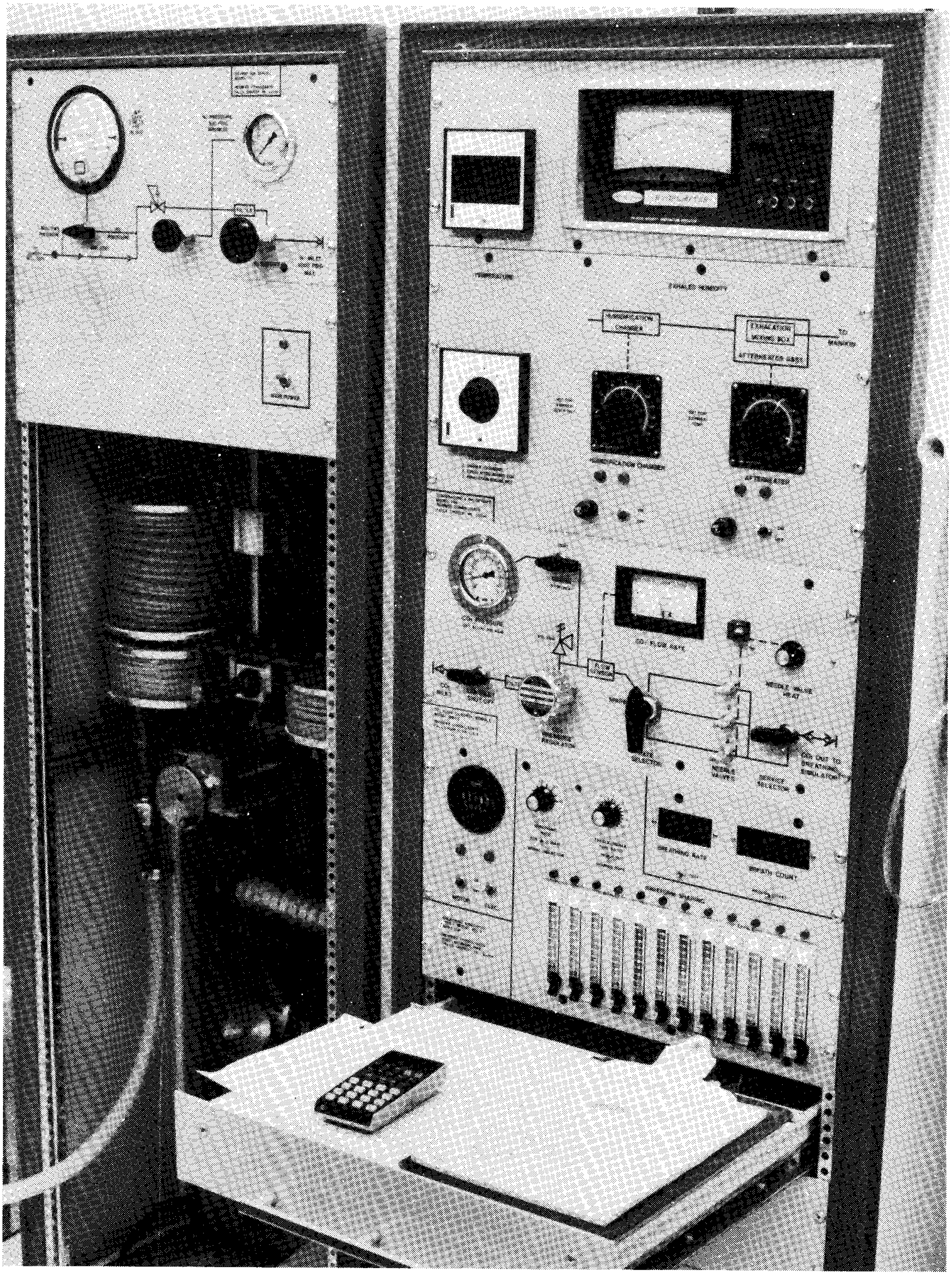

FIGURE 4. - Breathing metabolic simulator.

haulage vehicles.[5] A shaker table of the type used in military standard (MIL-STD) vibration tests was used in the vibration treatment with motion along the vertical (Z) axis only (fig. 5). The test conditions are as follows:

| Frequency, Hz | Acceleration, g(± peak) |
|---|---|
| 5 - 92 | 2.5 |
| 92 - 500 | 3.5 |
| 500 - 2,000 | 1.5 |

There is no consensus on what constitutes an appropriate vibration treatment simulating the mining environment. MIL-STD 810B, which specifies a frequency range of 9 to 500 Hz at an acceleration of 4 g (± peak), has been recommended,[6] but others recommend MIL-STD 810C,[7] which specifies 1.5 g (± peak) from 5.5 to 30 Hz, increasing to 4.2 g (± peak) at 5 to 500 Hz, as being a more appropriate test.

[5]Dayton T. Brown, Inc. Environmental Test Criteria for the Acceptability of Mine Instrumentation. USBM Contract J0100040, June 1980; available for consultation at the Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[6]Bolt, Beranek and Newman, Inc. Shock and Vibration Tests for Mining Machinery Instrumentation. BuMines Contract H0155113, Addendum to Report No. 4033. January 1979; available for consultation at the Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[7]Berry, D. R., and D. W. Mitchell. (Foster-Miller Associates). Recommended Guidelines for Oxygen Self-Rescuers--Volume 1, Underground Coal Mining. BuMines Contract J0199118; available for consultation at the Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

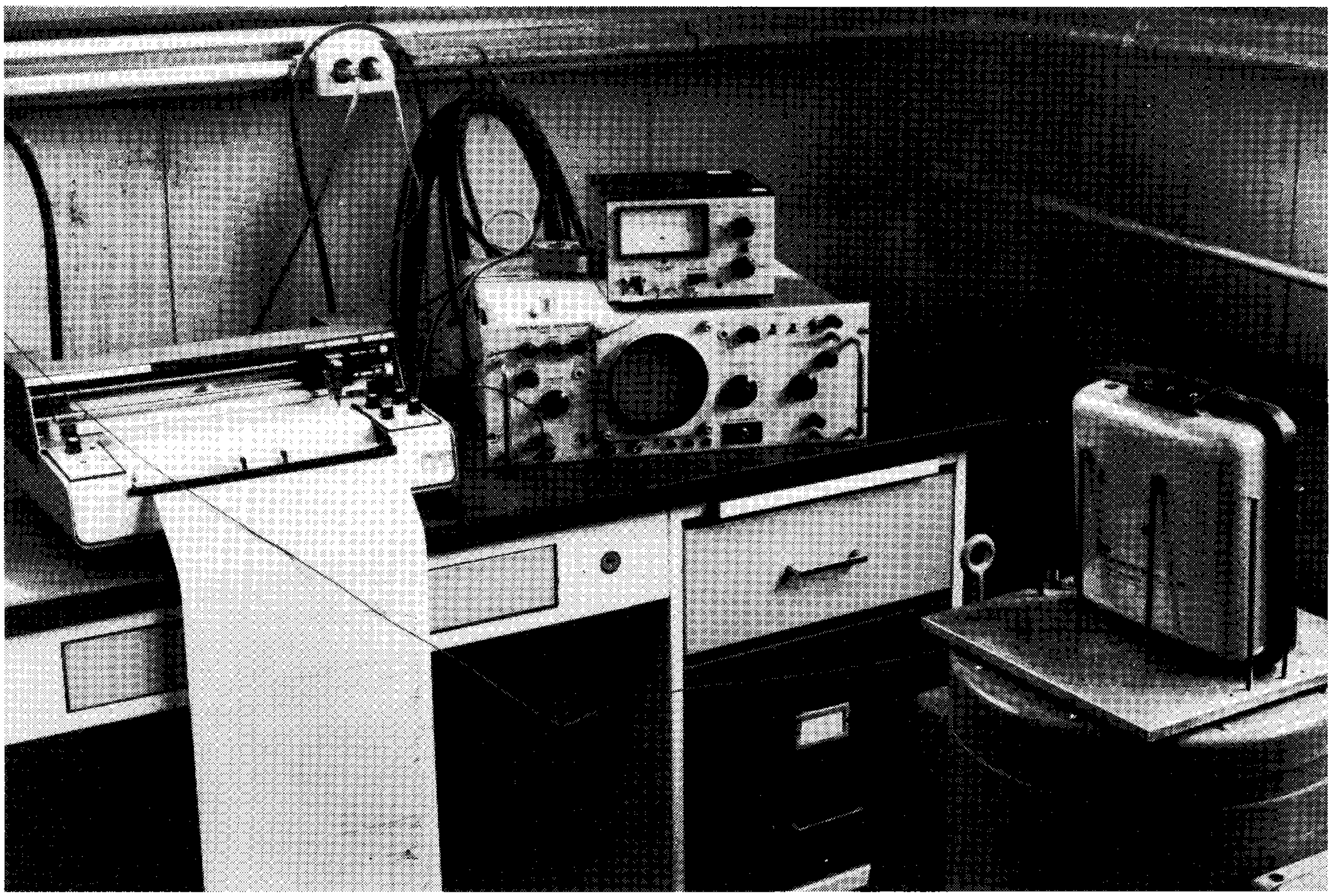

FIGURE 5. - Vibration treatment equipment.

One variation on vibration tests which we made was to vibrate the self-rescuers loose rather than strapping them down as is usually done. We felt that, based on European experience,[8] the self-rescuers would not be strapped tightly to machines, but, rather, simply placed in unpadded holders if not just thrown on the floor or other surface, unrestrained. We restricted their lateral motion (±1 cm) with pegs screwed into the 1.3-cm aluminum table. While at first inspection it would seem that the bouncing of the apparatus at lower frequencies would make individual treatments vastly different in terms of vibration and shock insult, we believe that the cumulative effect of the unclamped vibration treatment over an entire test is similar and reproducible.

The control accelerometer was screw-mounted as close to the OSR on the table as possible without any danger of contact with it. With another accelerometer glue-mounted on top of the self-rescuer so as to be sensitive to motion in the Z-axis, we did resonance searches at an input of 1 g (± peak). At most three resonances, but usually fewer or none, were noted. A resonance was defined as being consistent regardless of self-rescuer orientation and greater than 2 g (± peak). For each resonance, the self-rescuer was vibrated at the appropriate g level for 30 min. The remaining test time was spent sweeping the frequency range with a sweep time of 20 min for a total test time of 3 hr. This procedure was performed for each axis for a total vibration test duration of 9 hr (fig. 6).

[8]Work cited in footnote 7.

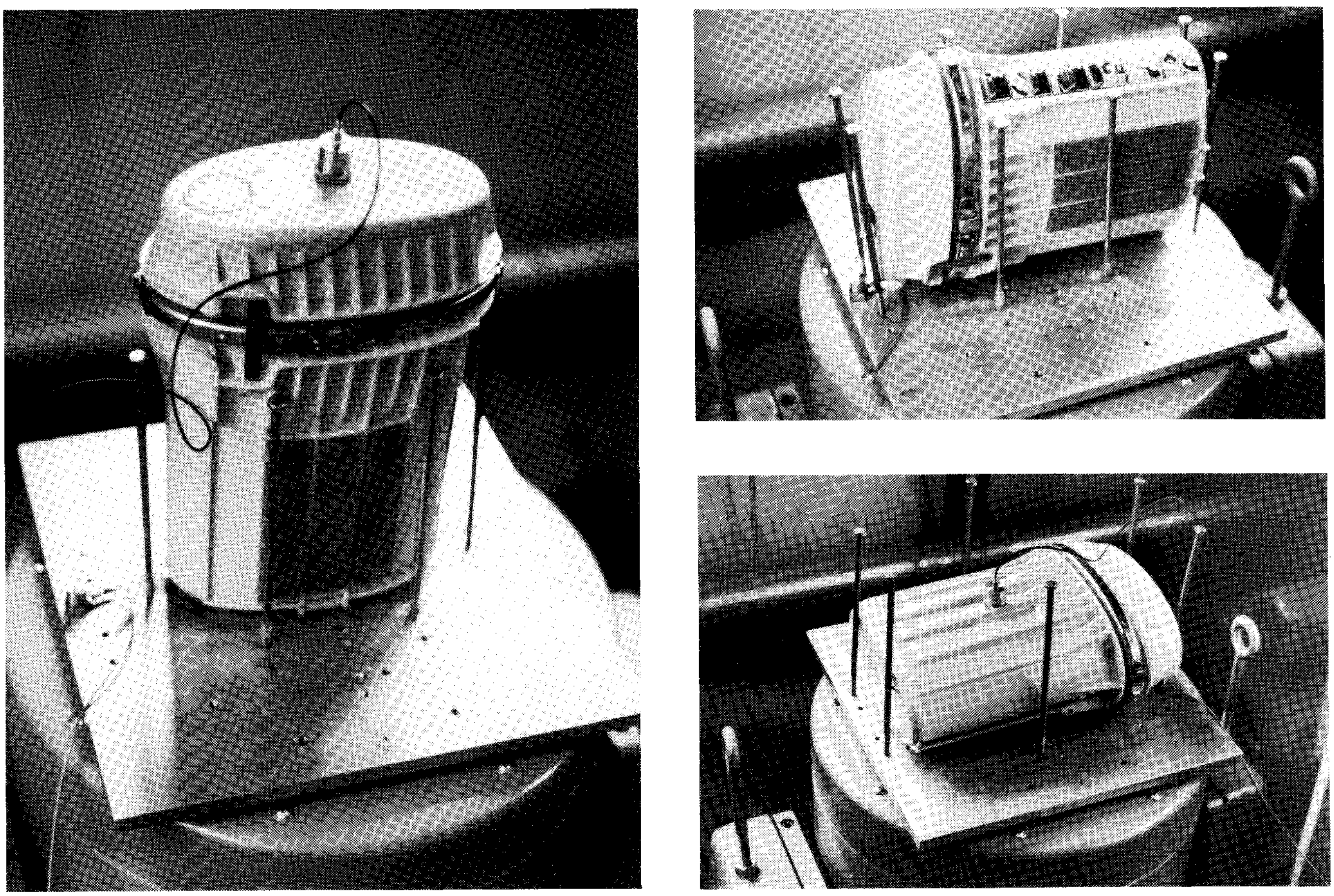

FIGURE 6. - Draeger OXY-SR 60B, showing the three orientations used in the vibration treatment.

The shock portion of the treatment was a drop of 1 m (belt-height) onto a concrete floor. This was performed on each axis also. We consider this to be a worst case, realistic expectation for in-mine use.

## HIGH- AND LOW-TEMPERATURE TREATMENTS

71° C, 48 Hr.--This treatment was conducted according to procedures described in MIL-STD 810C, Test Method 501.1, March 10, 1975, except that the oven was preheated.

100° C, 4 Hr.--This treatment was performed not out of any anticipation of similar in-mine conditions, but as a research probe to study failure modes for the apparatus under unrealistically high temperatures. If the apparatus were, however, not affected by this treatment, a higher degree of confidence would be gained in their performance ability. A convection oven was used in both heat treatments.

-45° C, 16 Hr.--This was arbitrarily determined to be a worst case condition.

## RESULTS AND DISCUSSION

### Treadmill Tests

The results of the treadmill tests (fig. 7) are presented in table 3. Included are the test subject codes, the duration of the tests, and the failure modes for each test. Because control test durations varied considerably owing to the different physiological demands placed on the SCSR's, control durations were normalized to unity for the sake of analysis and comparison. Also, owing to scheduling problems, cases arose where one test subject ran a treated unit in place of another subject. Again, normalization takes this into account. Failure modes were high $CO_2$ and low bag volume.

TABLE 3. - Treadmill test results

| Draeger | | | MSA | | |
|---|---|---|---|---|---|
| Subject | Duration, min | Failure mode | Subject | Duration, min | Failure mode |
| CONTROL | | | | | |
| A.......... | 118 | Low bag volume. | A.......... | 119 | High $CO_2$. |
| B.......... | 66 | High $CO_2$. | B.......... | 63 | Do. |
| C.......... | 64.5 | Do. | C.......... | 68.5 | Do. |
| 71° C, 48 HR | | | | | |
| B.......... | 66 | Exceeded control. | A.......... | 120 | Exceeded control. |
| C.......... | 66 | Do. | B.......... | 63 | Do. |
| C.......... | 67 | Do. | C.......... | 69.5 | Do. |
| 100° C, 4 HR | | | | | |
| A.......... | [1]71 | Candle failure; high $CO_2$; low $O_2$. | B.......... | 63 | Exceeded control. |
| B.......... | [1]64 | Do. | B.......... | 63 | Do. |
| C.......... | ([2]) | Do. | C.......... | 69.5 | Do. |
| -45° C, 16 HR | | | | | |
| A.......... | 118 | Exceeded control. | A.......... | 119 | Exceeded control. |
| B.......... | 66 | Do. | B.......... | 63 | Do. |
| C.......... | 64.5 | Do. | C.......... | 65 | High $CO_2$. |
| SHOCK AND VIBRATION | | | | | |
| A.......... | 120 | Exceeded control. | A.......... | 120 | Exceeded control. |
| B.......... | 64.5 | High $CO_2$. | B.......... | 62 | High $CO_2$. |
| C.......... | 64.5 | Exceeded control. | C.......... | 63 | Do. |

[1]Technical failure at start. [2]Life support failure.

FIGURE 7. - Treadmill testing.

The most severe treatment for the Draeger unit was heating to 100° C for 4 hr. Inspection of the apparatus showed bulging of the plastic case (fig. 8). An average volumetric increase of approximately 4% was measured. Other noted changes were cracked and warped lenses on goggles in some cases (fig. 9) and warping of the three inhalation valves at the breathing bag-breathing tube interface (fig. 10). During treadmill testing, it was apparent that the chlorate candles were not working. Manual startings of the apparatus were necessary in all cases. The three inhalation valves, which were warped, permitted exhaled gas to flow into the breathing bag where we measured gas concentration continuously. All the Draeger tests for this treatment were considered technical failures owing to candle failure, sporadic high $CO_2$, and initially low oxygen. Two test subjects were able to start their units manually and finish man-test 4; a third was unable to continue owing to lightheadedness. The third subject also experienced $O_2$ concentrations of as low as 15.1% before the $KO_2$ bed started. While the tests were technically failures, they would have successfully protected a person in an irrespirable atmosphere in two cases and with some physiological side effects in the third case. Cold treatment, shock and vibration, and heating at 71° C did not affect the Draegers to any significant degree.

The most severe treatment for the MSA unit was the shock and vibration. A coughing problem was noted in both control and treated apparatus and became more severe for the vibrated units. This led to taking outside breaths and exhaling through the unit to clear it of

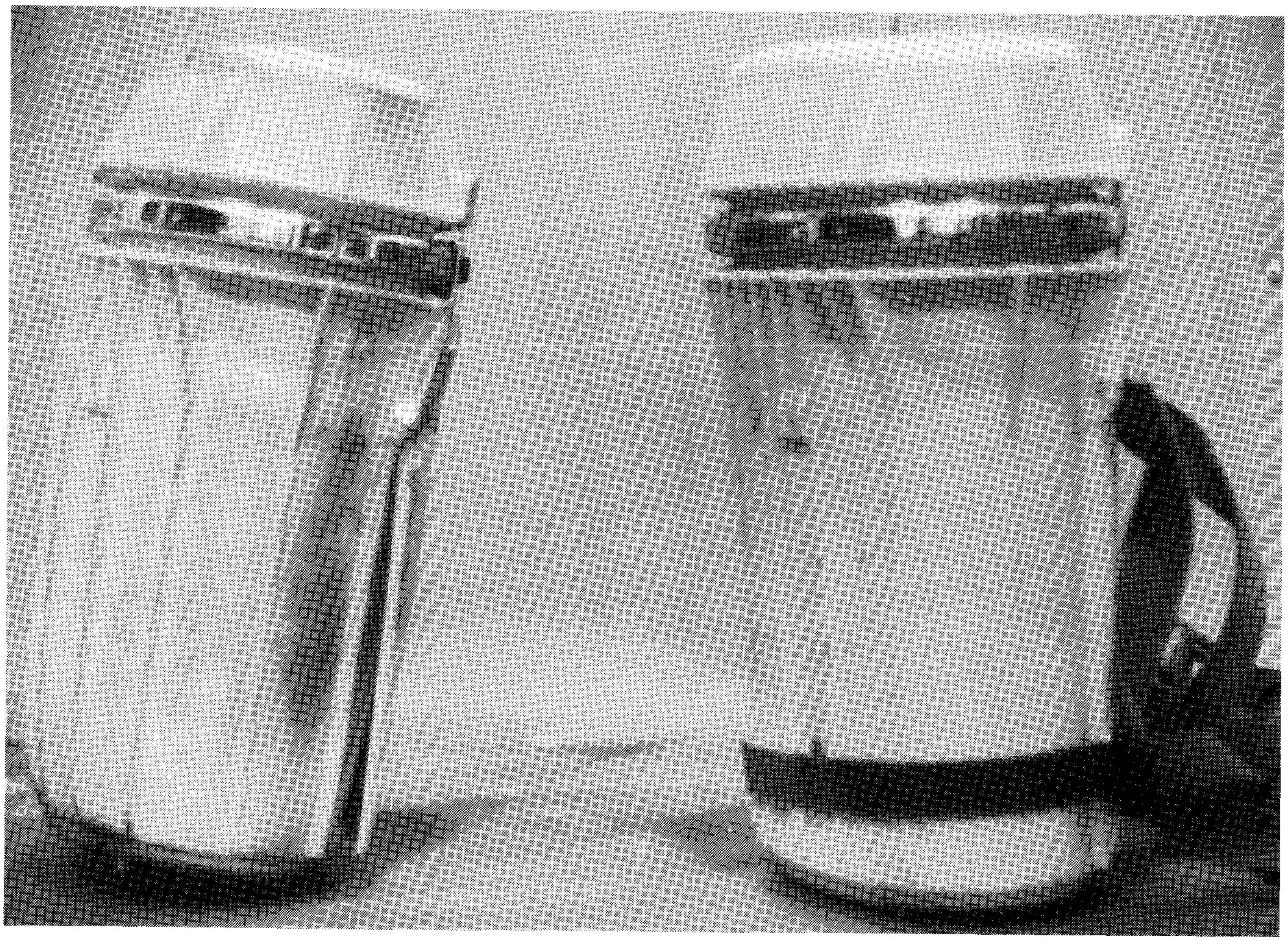

FIGURE 8. - Draeger unit after 100° C, 4 hr.

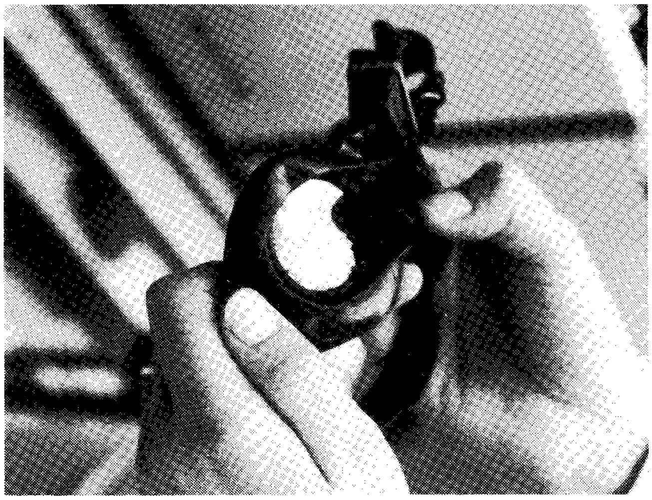

FIGURE 9. - Draeger goggles after 100° C, 4 hr.

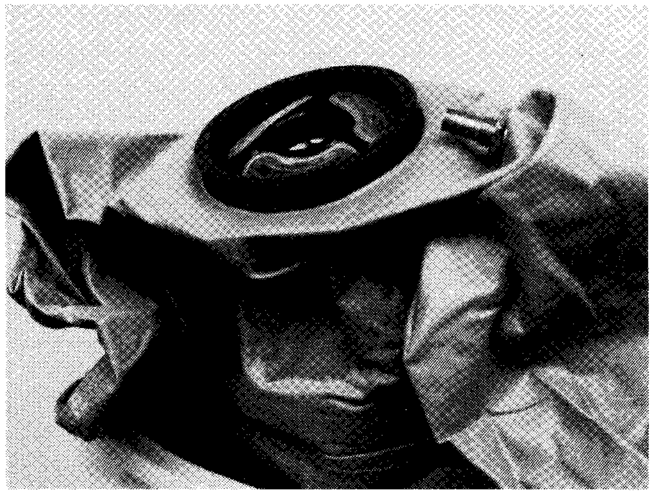

FIGURE 10 - Draeger inhalation valves after 100°C, 4 hr.

what we believe to have been $KO_2$ dust. Coughing occurred upon initial donning in all cases and any time the apparatus was jostled during the first 5 min. Suspecting $KO_2$ dust as the cause, we disconnected the bag-hose assembly from the $KO_2$ canister of a new MSA OSR. Inhaling from the bags and hose did not cause coughing, whereas inhaling from the $KO_2$ canister directly did cause coughing. A more effective filter on the $KO_2$ bed would easily solve this problem.

Coughing was experienced in some tests of the MSA units previously at NIOSH and in the MSHA field evaluation, but not to the degree that we have experienced it. We postulate that those test subjects who have not been subjected to a dusty coal mine environment are more likely to experience coughing since their lungs would have more sensitivity to irritating particulates. We conclude that while the coughing necessitated outside breaths in some cases, the problem was not serious enough to consider the tests in which it occurred failures; this problem will be remedied by MSA in production models of the units.

The shock portion of the treatment apparently caused the canister assembly portion of several of the MSA apparatus to become disconnected from the frame onto which they were secured with rubber shock mounts. It was necessary to tie the canister assemblies to the frame with wire in some cases. The heat and cold treatments did not affect the MSA's to any significant degree.

## BMS Tests

The results of the simulator tests are presented in table 4. The normalized test times for both treadmill and simulator tests are given in table 5. Durations and failure modes are given. We discarded one vibrated MSA unit that accidentally was vibrated more than the others. Temperature and breathing resistance limits as defined by NIOSH (maximum inhaled temperature, 46° C; maximum peak-to-peak resistance at a 120-lpm flow rate, 100 mm $H_2O$) were exceeded in some cases, but were not used as termination factors since NIOSH standards apply specifically to NIOSH testing, which is different from the simulator test. Failure modes included low bag volume, high $CO_2$, and low $O_2$. As with the treadmill testing, the two Draeger units heated to 100° C suffered candle failure and had to be manually started. They were both technical and life support failures owing to candle failure, low oxygen (12%), and high $CO_2$ (5.8%), all of which occurred at the start of the test. The other treatments did not affect the Draegers to any significant degree. None of the treatments affected the MSA's to any significant degree.

TABLE 4. - Simulator test results

| Draeger | | MSA | |
|---|---|---|---|
| Duration, min | Failure mode | Duration, min | Failure mode |
| CONTROL | | | |
| 52 | Low bag volume. | 82.5 | High $CO_2$. |
| 59 | Do. | 75 | Do. |
| 76 | Low $O_2$. | 61 | Low bag volume. |
| 61.5 | Low bag volume. | 76 | High $O_2$. |
| 58 | Do. | 53 | Do. |
| 71° C, 48 HR | | | |
| 65 | High $CO_2$. | 68.5 | High $CO_2$. |
| 54.5 | Low bag volume. | 79 | Do. |
| 100° C, 4 HR | | | |
| ([1]) | Candle failure; high $CO_2$; low $O_2$. | 65 | High $CO_2$. |
| ([1]) | Do. | 57 | Do. |
| -45° C, 16 HR | | | |
| 60 | Low bag volume. | 61 | High $CO_2$. |
| 64 | Do. | 74.5 | Do. |
| SHOCK AND VIBRATION | | | |
| 58 | Low bag volume. | 78 | Low bag volume. |
| 66 | Do. | 74 | High $CO_2$. |
| 60 | Do. | | |

[1]Life support failure.

TABLE 5. - Normalized test times

| Treatment | Draeger | MSA |
|---|---|---|
| TREADMILL TESTS | | |
| 71° C, 48 hr | 1.00 | 1.01 |
| | 1.02 | 1.00 |
| | 1.04 | 1.01 |
| 100° C, 4 hr | ([1]) | 1.00 |
| | ([1]) | 1.00 |
| | ([2]) | 1.01 |
| -45° C, 16 hr | 1.00 | 1.00 |
| | 1.00 | 1.00 |
| | 1.00 | .95 |
| Shock and vibration | 1.02 | 1.01 |
| | .98 | .98 |
| | 1.00 | .92 |
| SIMULATOR TESTS | | |
| 71° C, 48 hr | 1.06 | 0.99 |
| | .89 | 1.14 |
| 100° C, 4 hr | ([2]) | .94 |
| | ([2]) | .82 |
| -45° C, 16 hr | .98 | .88 |
| | 1.04 | 1.07 |
| Shock and vibration | .95 | 1.12 |
| | 1.08 | 1.06 |
| | .98 | |

[1]Technical failure. [2]Life support failure at start.

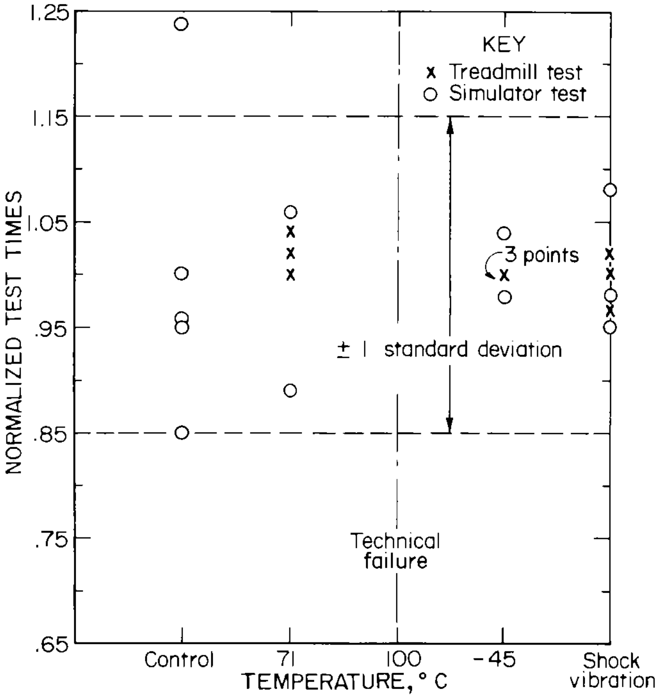


FIGURE 11. - Normalized treadmill and BMS test data, Draeger.

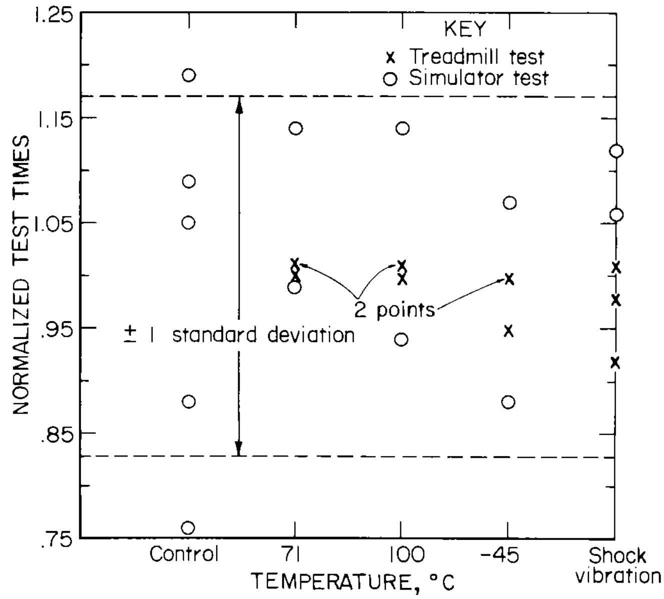


FIGURE 12. - Normalized treadmill and BMS test data, MSA.

Figures 11 and 12 show plotted results of the treadmill and BMS tests for the Draeger and MSA SCSR's, respectively, in normalized form with treadmill control tests having a value of 1.00. Only the 100° C treatment on the Draegers had much effect on duration of the units. For comparison, the control test durations of the simulator tests were averaged and standard deviations computed, normalized with respect to the average, and plotted. This shows that the variation of the treated units compared with that of the untreated units is similar.

## CONCLUSIONS

The results of this study show that the Draeger OXY-SR 60B and the MSA 60-min SSR chemical oxygen self-rescuers approved by NIOSH will successfully withstand the mining environment in the areas of temperature extremes and physical abuse likely to be encountered when the apparatus are either mounted on mining machines, carried, or transported.

The Draeger OXY-SR 60B experienced candle failure when heated to 100° C for 4 hr. It is recommended that the unit be kept below its approved maximum storage temperature (70° C). The MSA 60-min self-rescuer evidenced problems with coughing upon initial donning with most units, treated and untreated. This problem was magnified when the apparatus was vibrated and shocked. A simple modification of the exit filter in the $KO_2$ canister can be made to increase its effectiveness, and MSA plans to make this modification in production models.

# CHEMICAL OXYGEN SELF-CONTAINED SELF-RESCUER ESCAPE STUDY

By John G. Kovac,[1] D. Randolph Berry,[2] Diane M. Doyle,[3] Elizor Kamon,[4] and Donald W. Mitchell[5]

## ABSTRACT

An underground escape study evaluating the performance of chemical oxygen self-contained self-rescuers (SCSR's) was conducted by the Bureau of Mines. Six volunteer coal miners, ranging in age from 24 to 61, were the test subjects. All six subjects traveled along a special escapeway which was 7,825 ft long and had seam heights ranging from 30 in to 7 ft. Average escape speeds ranged from 96 ft/min crawling to 264 ft/min for head-bent walking. Average life of the chemical oxygen SCSR's was 60.8 min. The total distance traveled before the exhaustion of a chemical oxygen SCSR was independent of travel speed. The average breathing rate was 41 l/min, and the average oxygen consumption was 1.38 l/min.

## INTRODUCTION

In May 1981, the Bureau of Mines conducted an underground escape study on the performance of chemical oxygen SCSR's. Specifically, the purpose of this study was to obtain detailed, quantitative information in the following areas:

1. Escape speeds in different mine conditions.

2. Evaluation of chemical oxygen SCSR's in actual escape conditions.

3. Miner physiology in actual escape conditions.

The Draeger OXY SR 60B and the MSA 60-min SSR were the only SCSR's evaluated in this study.[6] Both emergency breathing apparatus are chemical oxygen SCSR's, using potassium superoxide to generate oxygen and remove carbon dioxide. Figures 1 and 2 show the two SCSR's as worn by a miner. The size and weight of these two units are given in table 1. Since both the design, function, and overall performance of the Draeger and MSA SCSR's are similar, the results of the escape study are reported without identifying either apparatus.

TABLE 1. - Specifications for approved 1-hr chemical oxygen SCSR's

| | Carrying wt, lb | Deployed wt, lb | Volume, cu in |
|---|---|---|---|
| Draeger OXY SR 60B..... | 8.4 | 7.4 | 366 |
| MSA Model 60-min SSR. | 9.1 | 6.7 | 360 |

[1]Supervisory mechanical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.
[2]Technical staff consultant, Foster-Miller Associates, Inc., Waltham, Mass.
[3]Pittsburgh Division staff engineer, Foster-Miller Associates, Inc., Waltham, Mass.
[4]Professor of applied physiology and ergonomics, Pennsylvania State University, University Park, Pa.
[5]Pittsburgh Division Manager, Foster-Miller Associates, Inc., Waltham, Mass.
[6]Reference to specific products does not imply endorsement by the Bureau of Mines.

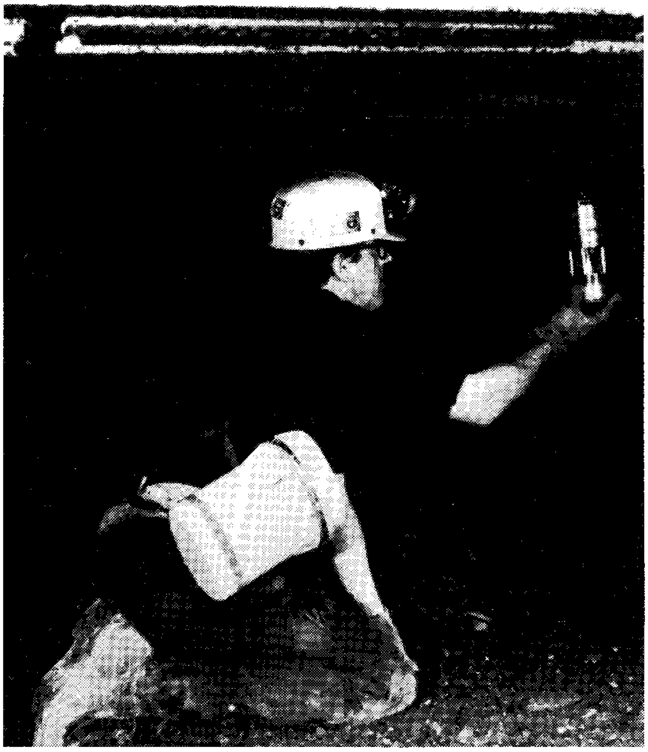

FIGURE 1. - Draeger OXY SR 60B worn by a miner.

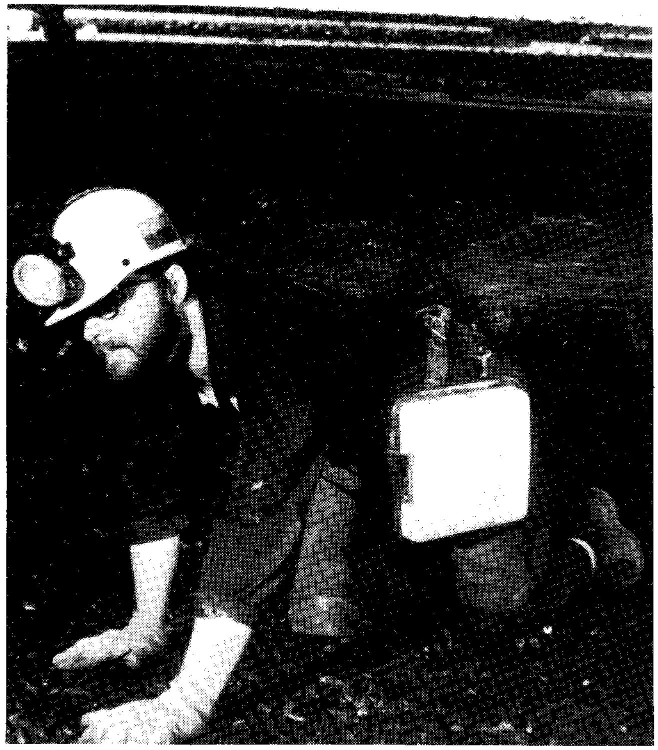

FIGURE 2. - MSA 60-min SSR worn by a miner.

## TEST PROCEDURE

The underground escape study was conducted in the Rochester and Pittsburgh Coal Co.'s Emilie No. 4 Mine. The escape route is shown schematically in figure 3. This route was not a designated escapeway for the mine. Instead, the route of travel was specially selected to meet the following requirements:

1. Must be at least 1 hr long for the fastest miner.

2. Different segments of the route must have different seam heights.

3. Different segments of the route must have different ground conditions such as wet and dry, level and sloping, and smooth and irregular roof and floor.

As shown in figure 3, the escape route was divided into seven segments according to the travel height in each segment. The total length of the escape route was 7,825 ft with seam heights ranging from 30 to 78 in. Escapeway conditions included such factors as irregular roof, loose material on the floor, water, and an uneven or pitched roof. To complete the escape route, test subjects were required to crawl, duckwalk, and walk upright.

### Test Participants

Employees of the Rochester and Pittsburgh Coal Co. volunteered for this study. The six men and their job classifications are listed in table 2.

TABLE 2. - Test participants

| Miner | Age | Job description | Underground experience, yr |
|---|---|---|---|
| A.... | 61 | Superintendent-mine foreman. | 41 |
| B.... | 54 | General assistant. | 35 |
| C.... | 49 | Section foreman... | 6 |
| D.... | 49 | Shift foreman..... | 10 |
| E.... | 34 | Safety inspector.. | 10 |
| F.... | 24 | Maintenance foreman. | 6 |

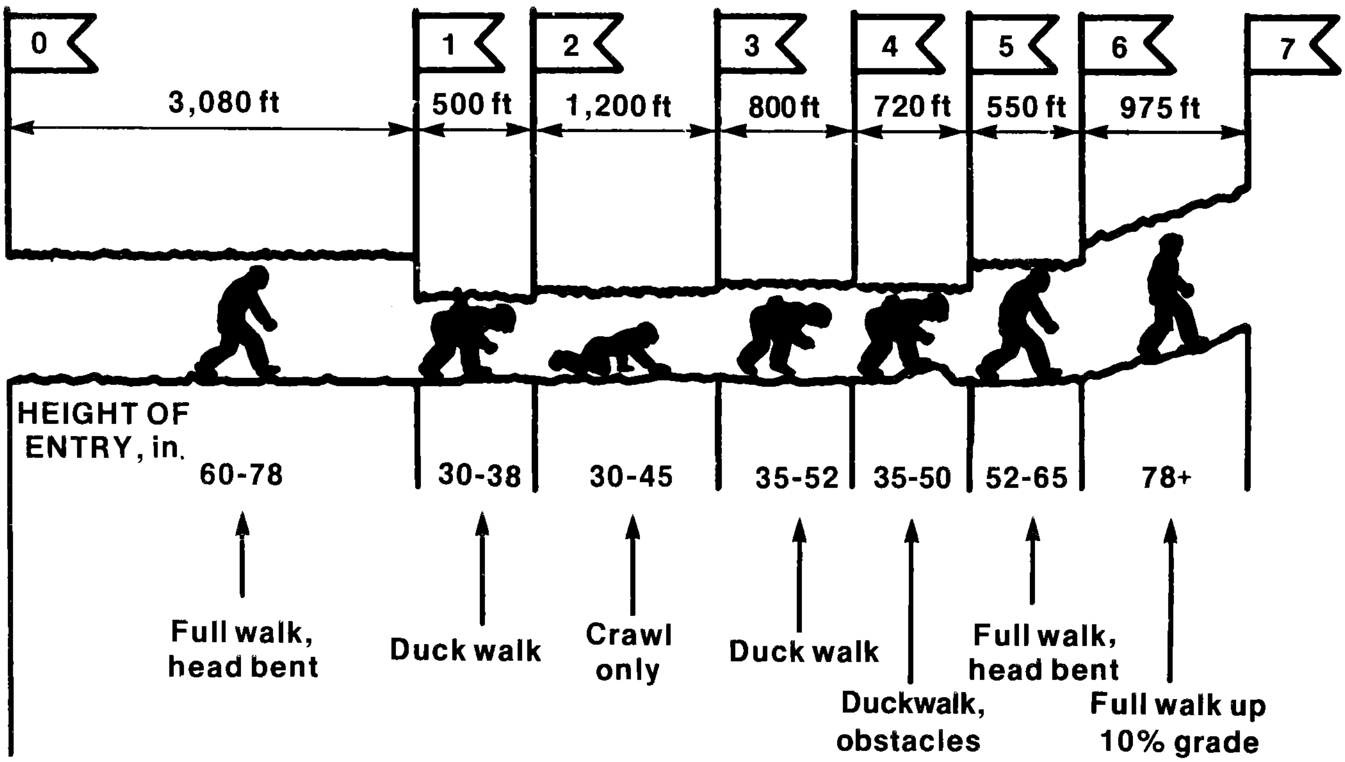


FIGURE 3. - Escape route.

The test participants were chosen from company management[7] to represent a broad cross section of the mine population in good health. For legal and ethical reasons, it was not possible to involve in these tests persons having respiratory, circulatory, coronary, or ambulatory deficiencies.

Before any underground testing, the six volunteers were trained in the use of SCSR's, including how to recognize when an SCSR becomes depleted. Also, the six volunteers were given a thorough stress test by a physician.

The purpose of the stress test was to measure the physiological response of each volunteer to physical exercise. The stress test involved step increases in uphill walking either up to exhaustion, or until the supervising physician found it necessary to terminate the test. Towards the end of the test, at the peak of exertion, the test subjects expired air was collected for the measurement of maximum rate oxygen uptake ($\dot{V}_{O_2\ max}$), which is also called maximum aerobic capacity. Since the cardiograms were continuously monitored during the stress test, the maximum heart rate ($HR_{max}$) at $\dot{V}_{O_2\ max}$ was also available. Other data was also collected including age, weight, and height as well as the resting and maximum values of ventilation rate ($\dot{V}E$), rate of oxygen uptake ($\dot{V}_{O_2}$), and heart rate (HR) for each tested miner. All of this information is shown in table 3.

---

[7]A nationwide coal strike precluded the involvement of union miners during the period that these tests were conducted.

TABLE 3. - Age, physical characteristics, resting and maximum heart rates (HR, beats/min), minute $O_2$ uptake ($\dot{V}_{O_2}$), and pulmonary ventilation ($\dot{V}_E$) for each miner

| Miner | Age, yr | Ht, cm | Wt, kg | Resting | | | | Maximal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | HR, beats/min | $\dot{V}_{O_2}$ | | $\dot{V}_E$, l/min | HR, beats/min | $\dot{V}_{O_2}$ | | $\dot{V}_E$, l/min |
| | | | | | l/min | ml-kg/min | | | l/min | ml-kg/min | |
| A.... | 61 | 185 | 71.2 | 76 | 0.28 | 3.93 | 10 | 156 | 1.60 | 22.5 | 33 |
| B.... | 54 | 160 | 77.6 | 69 | .37 | 4.77 | 14 | 155 | 2.39 | 30.8 | 64 |
| C.... | 49 | 166 | 78.0 | 72 | .37 | 4.74 | 12 | 168 | 2.87 | 36.8 | 54 |
| D.... | 49 | 172 | 80.7 | 84 | .39 | 4.83 | ND | 200 | [1]2.70 | [1]33.5 | ND |
| E.... | 34 | 166 | 81.3 | 96 | .36 | 4.43 | 12 | 200 | 3.17 | 38.9 | 97 |
| F.... | 24 | 183 | 82.9 | 74 | .30 | 3.62 | ND | 182 | 3.48 | 42.0 | 86 |
| $\bar{X}$.... | 45.2 | 172 | 78.6 | 78.50 | .35 | 4.39 | 12 | 176.8 | 2.47 | 34.1 | 62.3 |
| SD... | 13.6 | 10 | 4.1 | 9.95 | .04 | .50 | 1.63 | 20.4 | 0.88 | 10.2 | 25.5 |

ND No data.

[1]Estimated by extrapolation to the $HR_{max}$ from $\dot{V}_{O_2}$ -HR relationship during the escape.

Test Sequence

Each of the six miners traveled the escape route once per day for 4 consecutive days. The first day was a practice run for preliminary observations and to acquaint each man with the route. On each day of the following 3 days of time trials, two miners traveled the escape route without wearing an SCSR, two miners escaped wearing SCSR's, and two miners escaped wearing a recording respiration meter with face mask, called an Oxylog, which is shown in figure 4. These assignments were rotated daily so that after 3 days each miner had escaped without an SCSR, wearing an SCSR, and wearing the Oxylog, as shown in table 4. The miners' instructions were to travel as fast as possible, yet complete the trial.

TABLE 4. - Test sequence

| Miner | Day 1 | Day 2 | Day 3 |
|---|---|---|---|
| A................ | Normal | Oxylog | SCSR |
| B................ | Normal | SCSR | Oxylog |
| C................ | Oxylog | SCSR | Normal |
| D................ | SCSR | Oxylog | Normal |
| E................ | SCSR | Normal | Oxylog |
| F................ | Oxylog | Normal | SCSR |

Other mine employees were located at stations 0 through 7 to record the times of each test subject and to measure and record heart rate and blood pressure. Each of these measurement personnel was a certified emergency medical technician.

FIGURE 4. - Miner wearing an Oxylog.

At station 0, test subjects were started on the route individually at 15-min intervals and departure times were recorded. The SCSR wearers activated their units, and the time was recorded. In addition, the miners wearing SCSR's recorded the time and location when their SCSR's were no longer usable. An SCSR was judged to be exhausted when its breathing bag became deflated or when breathing resistance increased.

## RESULTS

### Escape Speed

The average travel speed for each segment along the escape route is given in table 5. Based on these data, figure 5 was constructed, giving a curve of escape speed as a function of escapeway height. As expected, the lower the seam height, the slower the escape speed.

TABLE 5. - Average travel speed

| Route segment | Mode of travel | Speed, ft/min | | |
|---|---|---|---|---|
| | | Normal | With SCSR | With Oxylog |
| 0 to 1.. | Head bent | 264 | 212 | 220 |
| 1 to 2.. | Duckwalk. | 103 | 100 | 97 |
| 2 to 3.. | Crawl.... | 96 | 85 | 79 |
| 3 to 4.. | Duckwalk. | 123 | 94 | 100 |
| 4 to 5.. | Duckwalk. | 105 | [1]85 | 86 |
| 5 to 6.. | Head bent | 236 | 174 | 220 |
| 6 to 7.. | Upright.. | 244 | [2]234 | 217 |

[1]3 of the 6 SCSR's exhausted during phase.
[2]The other 3 SCSR's exhausted during this phase.

Wearing an SCSR or the Oxylog had a definite influence on travel speed, as shown in table 6.

TABLE 6. - Travel speed while wearing a respiratory device

| Travel mode | Average speed over entire route, ft/min |
|---|---|
| Normal............... | 161 |
| Wearing SCSR......... | 135 |
| Wearing Oxylog....... | 136 |

It is not surprising that Oxylog and SCSR produced the same decrease in speed because the two units weigh about the same, are carried on the body in a similar manner, and require breathing through a mouthpiece or mask.

This decrease in travel speed while wearing a respiratory device was fairly consistent in each segment of the travel route.

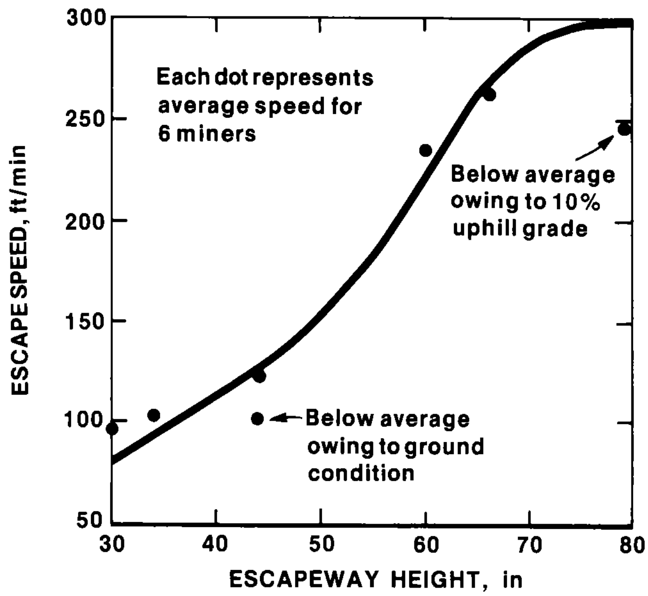


FIGURE 5. - Test results.

Life of Chemical Oxygen SCSR's

Six chemical oxygen SCSR's were tested during this study, one by each of the six test subjects. The results are summarized in table 7.

In general, the faster the miner traveled, the sooner the SCSR was consumed. As can be seen in the last column of table 7, chemical oxygen SCSR's seem to provide enough oxygen for a constant amount of work regardless of the speed at which the work is carried out.

TABLE 7. - Life of chemical oxygen SCSR's

| Miner | Escape time (travel + wait), min | Life of SCSR | | Distance traveled × body weight, million ft-lb |
|---|---|---|---|---|
| | | Time, min | Distance, ft | |
| A............. | 70+13 | [1]77 | 6,850 | 1.07 |
| B............. | 62+10 | [1]61 | 6,215 | 1.06 |
| C............. | 51+14 | [1]60 | 6,850 | 1.18 |
| D............. | 64+14 | [1]60 | 5,640 | 1.00 |
| E............. | 51+14 | [2]49 | 5,700 | 1.02 |
| F............. | 50+ 9 | [2]58 | 7,340 | 1.34 |

[1]Includes 2-min wait (after donning SCSR) before starting escape.
[2]Includes 1-min wait (after donning SCSR) before starting escape.

Physiological Data

The physiological response of five of the six miners during escape is summarized below:

| | |
|---|---|
| Average breathing rate. | 41 l/min. |
| Average oxygen consumption. | 1.38 l/min. |
| Average heart rate. | 143 beats/min. |
| Oxygen consumption (walking). | 0.35 ml per meter traveled per kilogram body weight. |
| Oxygen consumption (crawling). | 0.70 ml per meter traveled per kilogram body weight. |

Instrumentation malfunctions during the underground test program resulted in the loss of some data, no oxygen consumption data for miner F, and no ventilation rates for miners D and F.

SCSR's used in U.S. underground coal mines must be jointly approved by the Mine Safety and Health Administration (MSHA) and the National Institute for Occupational Safety and Health (NIOSH) according to 30 CFR 11. The major performance requirement in 30 CFR 11 is the 60-min man-test 4. Specific activities in man-test 4 include walking, running, climbing a vertical treadmill, and carrying and pulling weights. All of the travel speeds and carried weights are prescribed for a total of 52 min, interspersed with 8 min of rest for samplings and readings.

In this escape speed study, the oxygen consumption (1.38 l/min) was the same and the respiration rate (41 l/min) was 30% higher than the rates of miners during the performance of the corresponding element of man-test 4.[8]

SUMMARY

The main points of this study are summarized below:

1. Wearing an SCSR decreased travel speed.

2. The duration of chemical oxygen SCSR's ranged from 49 to 77 min with an average duration of 60.8 min.

3. For the escape route in this study, the duration of a chemical oxygen SCSR (as measured in minutes) seems directly related to the speed of the escape, whereas the total work effort allowed by the SCSR (as measured by miner's body weight × distance traveled before the SCSR expires) is remarkably constant, regardless of the speed with which the work effort is performed.

4. The physiological cost of the escape route in this study was greater than the physiological cost of man-test 4.

In terms of future research, the Bureau of Mines plans to conduct a similar study evaluating the performance of commercially available NIOSH-MSHA-approved compressed-oxygen SCSR's.

[8]Kamon, E., T. Bernard, and R. Stein. Steady State Respiratory Responses to Tasks Used in Federal Testing of Self-Contained Breathing Apparatus. Am. Ind. Hygiene Assoc. J., 1975, pp. 886-896.

# MEDIUM FREQUENCY RADIO COMMUNICATION SYSTEM FOR MINE RESCUE

By Harry Dobroski, Jr.,[1] and Larry G. Stolarczyk[2]

## ABSTRACT

Theoretical and experimental work sponsored by the Bureau of Mines indicated that medium frequency (MF) signals (300 kHz to 3 MHz) propagate through natural media (water, rock, coal, etc.) and down the passageways of the underground mine. Existing passageway conductors in the "wire plant" such as track, wire rope, telephone cable, electrical power distribution systems, etc., cause a low-loss transmission line signal propagation mode to exist. This paper describes sytem concepts as well as the new MF radio equipment that has been developed for communications in the underground mining complex. The new equipment includes a lightweight vest transceiver that is potentially useful for rescue personnel to establish emergency communication links to the rescue team communications center. This paper also describes the most recent field test results.

## INTRODUCTION

In the event of a mine disaster such as an explosion where miners may be trapped underground, efficient rescue efforts are essential. Rapid and efficient operations not only enhance the possibility of achieving a successful rescue, but also reduce the risks to the rescue teams. In many instances, rescue teams have risked their lives in areas where there were no trapped miners only to learn later that if the rescue effort had been directed into other areas of the mine, lives could have been saved.

The traumatic event of a mine disaster poses problems that few people comprehend. It is an event that takes place in a confined area where toxic gases, oxygen deficiency, poor visibility, and the danger of a recurring disaster are ever present. If miners actually survived the initial event, the question exists as to their condition and location. Obviously survivors are not likely to be found where expected because they would move to safer locations, seek out alternate escape routes, or as a last resort, barricade. In any event, rapid communications with, and rescue of, these trapped miners is essential. The difference between life and death can often be measured in minutes.

The Bureau of Mines has developed through-the-earth seismic and electromagnetic (EM) location and communication systems that enhance escape and rescue to a large degree. The first system is presently operational and the second is still in the research and development stage. Nevertheless, even if fully implemented, there will never be any assurance that all miners have truly been located. Injury or other factors may make it impossible to utilize the features of either the seismic or electromagnetic systems. The keystone of any rescue effort is, and will remain, the rescue team.

Rescue team communication is second in importance only to the life support system. Without it, the rescue effort goes slowly, increasing the danger to both the team and the trapped miners they hope to rescue.

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## RADIO PROPAGATION IN MINE ENVIRONMENTS

Although radio transmission on the surface of the earth is well understood, transmission in an underground environment generally is not. Complex interactions occur between the radio wave and the environment. Characteristics of the geology (stratified layering, boundary effects, conductivity, etc.) and the mine complex (entry dimension, conductors, electromagnetic interferences, etc.) had to be measured and understood before any practical mine radio system could be built.

In a confined area such as a mine, a radio wave can propagate a useful distance only if the environment has the necessary electrical and physical properties. The "environment" takes into account the natural geology and fabricated perturbations such as the mine complex itself. As an example, if the wavelength ($\lambda$) of a radio wave is small compared with the entry dimensions, a waveguide mode of propagation is possible. Attenuation depends primarily upon the physical properties of the entry such as cross sectional area, wall roughness, entry tilts, and obstacles in the propagation path. Secondary effects such as the dielectric constants and earth conductivity also influence attenuation.

Mine radio systems based upon this waveguide effect are available commercially and have been successfully used by rescue teams for short-range coordination. These radios operate in the UHF band of the radio spectrum and are small and convenient to carry and use. Under line-of-sight high coal conditions, transmission ranges in excess of 300 m (1,000 ft) are often possible. However, in low coal, or when going around obstacles and corners, the range is severely reduced. Clearly a system is needed that would permit long-range radio communications not only among team members, but also with other teams and the surface command center. MF radio provides not only this capability, but also that of communicating with trapped miners from within the mine.

## GENERAL IN-MINE MEDIUM FREQUENCY RESULTS

Considerable research has been conducted within the last 8 years in the area of underground MF transmissions. This research showed that MF signals could propagate for great distances in most geologies and offered the hope of a whole-mine radio system. The Bureau of Mines and the South African Chamber of Mines (SACM) pursued research independently.

Around 1974, SACM introduced a new single-sideband system and followed up later with another designed especially for rescue team use. Performance in South Africa was reported to be good (13, pp. 87-102).[3] The evaluation of these units in U.S. mines showed them to be inadequate. The type of modulation used [single sideband (SSB)] made them sensitive to electromagnetic interference (EMI). In addition, power level was far too low and inefficiencies in both circuit and antenna designs produced short-range performance.

The Bureau's approach to the problem was more fundamental. A program was designed (1-4, 9-10) and executed to study in-mine MF propagation and learn how it interacted with the complex environment. This environment consists of various geological factors such as stratified layers of different electrical parameters, entry size, local conductors, EMI, etc.

Figure 1 is a simplified geometry of an in-mine site that illustrates one of the most important findings of

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

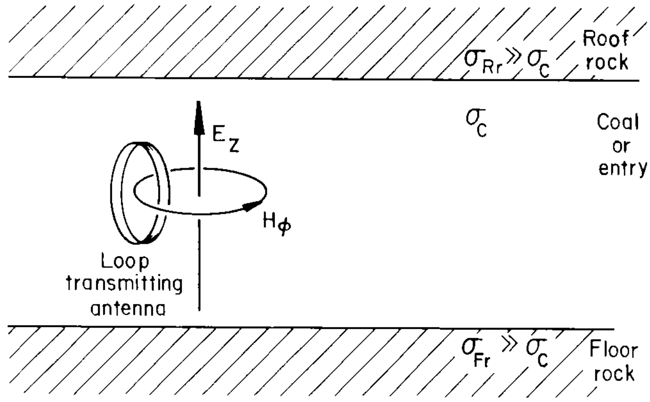


FIGURE 1. - Coal seam mode.

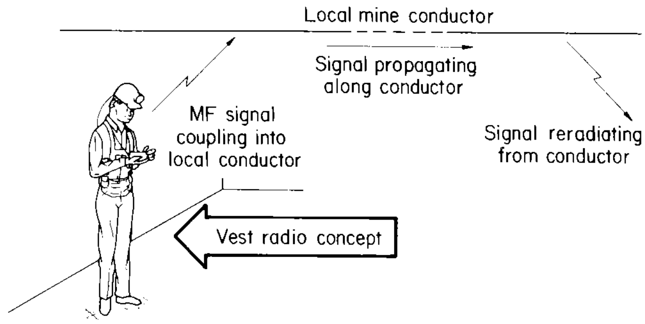


FIGURE 2. - MF parasitic coupling and reradiation.

the measurement program--the "coal seam mode." For this mode to exist, the coal seam conductivity ($\sigma_c$) must be several orders of magnitude less than that of the rock ($\sigma_r$). A loop antenna that is at least partially vertically oriented, produces a vertical electric field ($E_Z$) and horizontal magnetic field ($H_\phi$). In the rock, the fields diminish exponentially in the Z-direction. In the coal seam, the fields diminish exponentially at a rate determined by the attenuation constant ($\alpha$) which in turn depends upon the electrical properties of the coal. An inverse square-root factor also exists because of spreading. The effect is that the wave, to a large degree, is trapped between the highly conducting rock layers and propagates long distances within the lower conducting coal seam. The fact that the coal may have entries and crosscuts is of minor consequence.

In the presence of conductors, the picture changes considerably. In this case, the effects of these conductors can totally dominate over the effects of the geology. In general, the presence of conductors (rails, trolley lines, phone lines) is advantageous.

MF signals can couple into, and reradiate from, continuous conductors in such a way that these conductors become not only the transmission medium but also the antenna system for the signals. Figure 2 illustrates this concept. The most favorable frequency depends to some extent on the relationship between the geology and existing conductors. The frequency effects are quite broad. Anything from 500 to 800 kHz is usually adequate.

## SPECIFIC APPLICATION OF MF COMMUNICATIONS TO RESCUE TEAMS

The low attenuation of MF signals in many stratified geologies, such as coal mines, can be of great benefit to rescue teams. If existing mine wiring (like powerlines or belt lines) are present, the range is even greater. This permits a rescue team member to stay in communication with other members, the fresh air supply, and outside disaster control centers.

To date, MF technology has not been specifically applied to rescue team communications. Such application is the second step in the Bureau's overall MF communications program. However, there is no basic difference between operational MF systems and postdisaster MF systems. By October 1982, the Bureau's operational MF systems will be in place in several cooperating underground mines. By October 1983, performance evaluation of the systems will be completed. As the performance proceeds, emphasis will be directed to specific postdisaster-rescue applications.

## SYSTEM CONCEPTS

The main advantage of MF communication is simplicity. Figure 3 shows a rescue team member equipped with an MF vest radio. This vest radio permits rescue team members to maintain local communications (fig. 4).

In most cases, rescue teams will utilize a lifeline for rapid retreat in case of smoke when visibility is limited. The lifeline offers interesting possibilities for MF radio communications. Some rescue teams actually use the line already to carry communications via sound-powered telephones. Such a scheme is both archaic and ineffective.

Since this line is a continuous conductor back to the fresh air base, it provides a convenient parasitic path for MF communication as shown in figure 5. To assure even more reliable communications, physical audio links could be made with the lifeline as shown in figure 6. Such an approach provides redundancy via simultaneous audio and radio links.

Figure 7 illustrates a total MF base station for rescue team use. At the fresh air base, the briefing officer (as the individual is sometimes called) is equipped with a standard intrinsically safe base station or repeater; the officer could also be equipped with a vest. With such an arrangement, communications are possible not only between rescue team members, but also with the surface and with other distant rescue teams. In addition, it also provides a possible link to the trapped miners.

Since existing mine wiring is extensive and minewide, it is easily seen that it provides yet another redundant link for the rescue team members. Since other rescue teams are also in the vicinity of mine wiring, interteam communications are possible if desired. This concept of interteam communications is a radical departure from existing procedures. It will permit one rescue team, in one part of the mine, to modify the ventilation in such a manner that it does not degrade the ventilation in the vicinity of another rescue team. Equally important is the fact that trapped miners are also probably in the vicinity of existing mine wiring.

## LOCATION AND COMMUNICATIONS SYSTEMS FOR THE RESCUE OF TRAPPED MINERS

So far this paper has primarily addressed the application of MF communication to rescue teams. However, the ultimate objective of the rescue operation is to reach trapped miners in a timely manner before they succumb to the effects of injury, exposure, or toxic atmospheres. To this end, rescue team communications is but a part. The key to successful rescue lies in the rapid location of the trapped miners. Without this, valuable time can be wasted in diverting rescue efforts to the wrong area, often with tragic results.

Bureau research in the area of location has been addressed by through-the-earth seismic and EM systems. In the seismic system (5, 11-12), trapped miners pound on the roof or ribs of the mine to generate seismic vibrations. These vibrations travel through the overburden to the surface where they can be detected by sensitive transducers called geophones. Computer analysis of the arrival times of the seismic signals at the various geophones permits the source to be accurately located. This system is operational and is kept in readiness by MSHA Mine Emergency Operations. Present Bureau research in EM means to locate and communicate with trapped miners is shown in figure 8. The system consists of two parts, a transceiver that is normally carried on the miner's belt and a surface system for detection and communications.

FIGURE 3. - Rescue team member with MF vest radio.

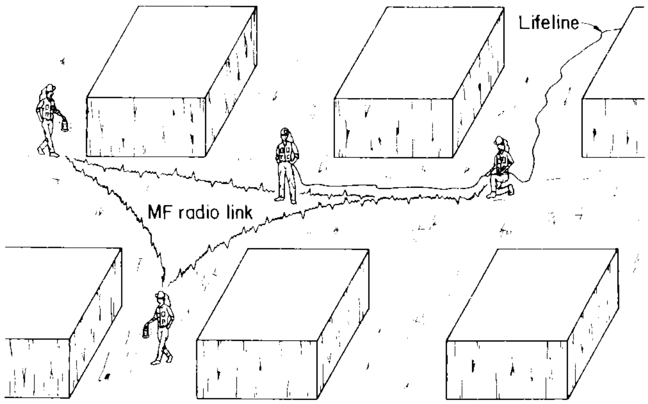


FIGURE 4. - Basic MF communications among rescue team members.

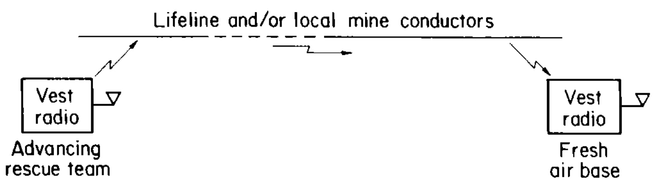


FIGURE 5. - Lifeline as a parasitic MF path.

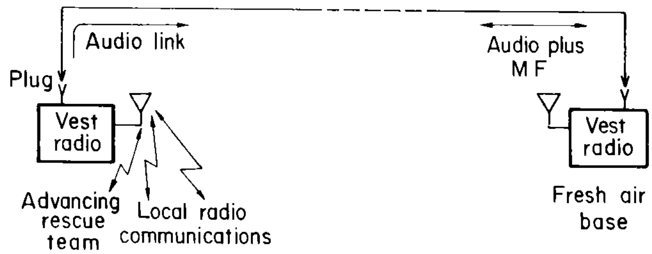


FIGURE 6. - Lifeline as a redundant communications line for MF and audio communication.

In operation, the trapped miner removes the transceiver from the belt, deploys a self-contained loop antenna, and attaches the transceiver to a special cap lamp battery. This antenna consists of 90 m (300 ft) of No. 18 wire that must be deployed in the largest area possible to be effective. A location signal is transmitted directly through the earth.

On the surface, sensitive receivers detect the signal and locate the source. Once detection and location are made, a large surface transmitter is deployed above the trapped miner. This transmitter is powerful enough to send voice messages by radio, directly down through the earth.

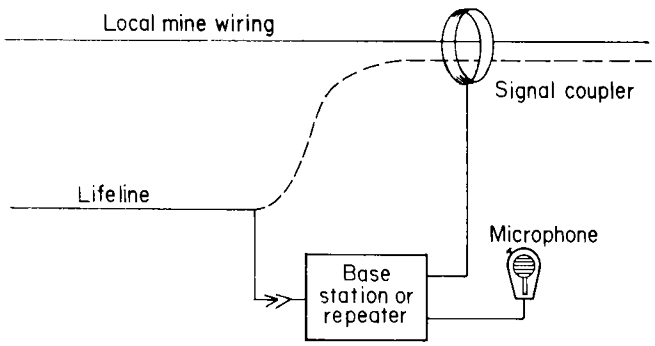


FIGURE 7. - Total MF base station for rescue teams.

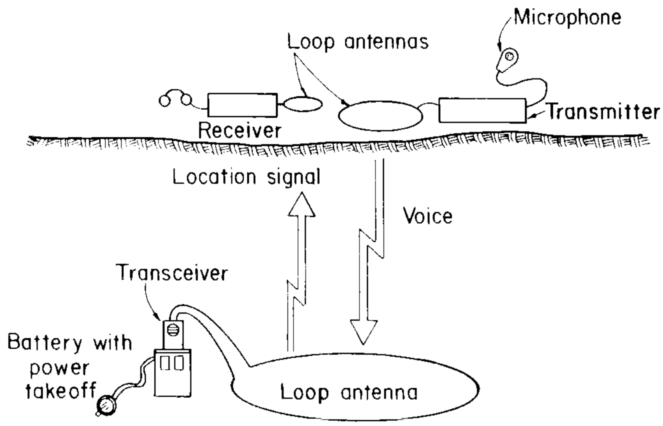


FIGURE 8. - Voice frequency electromagnetic system for location and communication with trapped miners.

The trapped miner's transceiver receives this voice. The surface personnel then ask the miner "yes-no" questions concerning his or her condition and that of the mine. The miner responds by simple on-off keying of the transceiver. In this manner a two-way communications link is established, entirely through the earth, and rescue operations can start in the most efficient manner.

Details of this EM system can be found in numerous reports (6-8, 13-15). This is known as a voice frequency (VF) system because all communications take place in the VF band of 300 to 3,000 Hz.

The seismic system is very effective in mines up to 700 m (2,200 ft) deep, and does not require the miner to be equipped with any special devices. However, it does require the miner to be able to pound. Injury or lack of a sufficiently heavy object with which to pound may render the system ineffective. The most serious drawback is that of time. The surface receiver station (geophones, field truck with computer, etc.) may take too long to set up. Bad weather and terrain can further delay the surface station deployment.

The EM-VF receiver system is less affected by adverse conditions on the surface because it is lighter and more easily transportable. However, it has its own disadvantages. The trapped miner must be equipped with a special transceiver, and must be able to deploy the antenna in a sufficiently large area. Injury or confined quarters may prevent deployment. In addition, under the best of conditions, the system has a range limit of about 300 m (1,000 ft). Although a new system is under development that will increase the range to 1,000 m (3,000 ft) (3), this improvement comes about only with complex, slowly deployed surface equipment. Therefore, it will be subject to the same delays as the seismic system.

MF communication offers advantages over through-the-earth approaches by permitting in-mine communications to the trapped miners. This could be in addition to, or in place of, through-the-earth schemes that may fail because of excessive overburden or the inability of the trapped miner to deploy his or her end of the system successfully. Figure 9 illustrates this concept.

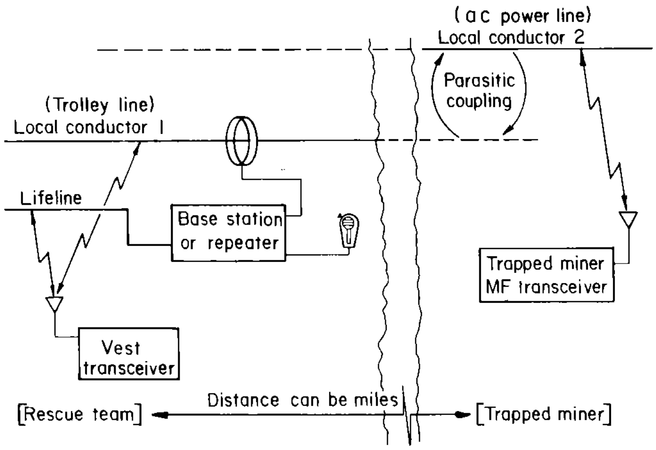


FIGURE 9. - MF in-mine location and communication system.

In this illustration, the trapped miner is equipped with a small MF transceiver built into the top of the cap lamp battery or worn on the belt. Note that this is exactly the same packaging concept used for the VF through-the-earth system shown in figure 8. The intent, however, is not to send a signal through the earth, but rather to induce a signal onto local mine wiring. If this is accomplished, the in-mine rescue team also is likely to be in the vicinity of mine wiring and can receive the signal. It must be pointed out very clearly that mine wiring does *not* mean that one continuous assembly of wiring is involved. If the trapped miner is near a power cable and not near a trolley line, and the rescue team is near a trolley line and not near a power cable, this does not mean that a communications link between the two cannot exist. An induced MF signal on one type of conductor will parasitically couple to all others, even if there is no physical connection. This is the uniqueness of MF communication.

In operation, the trapped miner would deploy an MF loop antenna or coupler, preferably onto available local wiring. The coupler could be a small device of small volume similar to a current transformer. The loop could be a coupler that was unwound. In either case, the antenna is small. If nearby wiring does not exist, the loop could be deployed in hope of coupling to distant wiring. When so deployed, the transmitter sends out MF signals of narrow bandwidth that parasitically couple onto mine wiring, and are widely distributed. This can be received by the in-mine rescue team. If this occurs, they will use their more powerful MF equipment (vests or base stations) to establish a voice link to the trapped miner. By asking the trapped miner yes or no questions, his or her location can be learned. However, direct location via MF communication is impossible. The parasitic coupling characteristics of MF signals do not permit the through-the-earth VF type of location; the signal could be on many conductors.

Obviously VF and MF systems could be combined such that the benefits of both VF (fig. 8) and MF (fig. 9) could be obtained. Equally important is the fact that the MF trapped miner device could be used in nonemergency situations as a page receiver and thereby be a cost effective addition to a general mine communication system. Table 1 lists MF communication system specifications.

TABLE 1. - MF communication system specifications

| | |
|---|---|
| Emissions, narrowband FM: | |
| Occupied bandwidth................kHz.. | 10 |
| Rf frequency......................kHz.. | 60-1,000 |
| Peak deviation....................kHz.. | ±2.5 |
| Modulated frequency................Hz.. | 200-2,500 |
| Receiver, superheterodyne: | |
| Sensitivity........................... | 1.0 µV (12-db sined) |
| Selectivity........................... | 8-pole crystal filter |
| IF 3-db bandwidth (minimum).....kHz.. | 12 |
| IF 70-db bandwidth (maximum)....kHz.. | 22 |
| RF bandwidth......................kHz.. | 60-1,000 |
| Squelch............................... | Noise operated and tone |
| Transmitter, push-pull, class B: | |
| Output power, W: | |
| Vest................................. | 4.0 |
| Vehicular............................ | 20.0 |
| Antenna magnetic moment ($ATm^2$): | |
| Vest.................................. | 2.1 |
| Vehicular............................. | 6.3 |
| RF line coupler, transfer impedance ($Z_T$): | |
| 1-in coupler, ohms: | |
| 350 kHz.............................. | 10.0 |
| 520 kHz.............................. | 11.2 |
| 820 kHz.............................. | 17.8 |
| 4-in coupler, ohms: | |
| 520 kHz.............................. | 10.6 |

## PERFORMANCE DATA

In order to evaluate the potential of MF signals as a means to locate and communicate with trapped miners, and to provide communications for the actual rescue team operation, a test was conducted at the York Canyon Mine near Raton, N. Mex., in June 1982. This mine is a coal mine located in the York seam of the Raton Basin. The terrain is hilly such that the mine overburden varies from about 150 to 300 m (200 to 800 ft).

The mine has four main drift entries that are about 2,500 m (7,000 ft) long. Off these entries, submains were driven and longwall mining occurs. A borehole is located at about the 2,500 m (7,000 ft) mark. This borehole contains a twisted pair cable that is associated with the fire monitoring system on the longwall panels.

This is an ac mine that transports the coal by belt. Rubber-tired vehicles provide transportation for personnel and supplies. The distance from the portal, down the main entries to the longwall faces, can be nearly 5,500 m (15,000 ft).

At the mine portal, a MF signal coupler was attached to the mine telephone lines. This coupler was controlled by a standard MF base station. A second coupler and base station were placed at the top of the borehole. The coupler was clamped around the cable that went down the borehole.

Two personnel entered the mine and, by vehicle, traveled down the main entries to the vicinity of the borehole [2,500 m (7,000 ft)]. These personnel were equipped with MF vest transceivers that had a magnetic moment of 2.1 $ATm^2$ and a sensitivity of 1 V at 52 kHz. The intent of the test was to ascertain whether or not these personnel could communicate with the base at the portal, or the base at the top of the borehole. If so, it would demonstrate that MF-equipped rescue teams could communicate with the outside command center without deploying their own communications line, or relying on the integrity of the mine phone line that may, or may not, be intact. In addition, it would demonstrate that if a trapped miner was equipped with a MF transceiver of similar specifications, he or she could directly communicate with rescue teams in the mine, or search crews on the surface who were monitoring any conductors egressing the mine.

The result of the test showed that communications were possible from almost anywhere in the haulage and belt entries to either base station. It was even possible for the base at the portal, on the telephone line, to communicate with the base atop the borehole, on the fire monitor line, even though there was no physical connection between the two. Whenever a vest was within a few feet of mine conductors, there was an obvious improvement in clarity and signal strength.

Although this test was preliminary, it clearly highlights the potential of using MF communications for search and rescue operations. Much more work is necessary to measure range from mine wiring whenever the mine is not operating as would be the case during search and rescue operations. An operational mine produces considerable levels of acoustic and EM noise which reduces MF system range.

## CONCLUSIONS

The Bureau of Mines has developed a whole-mine MF communication system consisting of vest transceivers, base stations, and repeaters. The primary use of the system is for operational mine communications via parasitic coupling onto existing mine conductors. The system is directly applicable to rescue team and trapped miner communications.

When applied to a rescue scenario, rescue team members can maintain local communications and communications with the fresh air base. Communications with other rescue teams and with the surface operations-command center is also possible.

A test was conducted at the York Canyon Mine (New Mexico) that demonstrated the potential of MF communications in the location, search, and rescue scenario. In this test, simulated trapped miners and rescue team personnel were able to communicate with two outside base stations that were monitoring signals coupled onto mine wiring that egressed the mine.

Because rescue team members are equipped with life support hardware, the existing vest concept will have to be modified to account for this. The present physical configuration of the vest is in conflict with the physical configuration of the life support system. This, however, is a minor problem.

Transceivers will have to be developed for mining personnel to have on their persons for emergency use. Such a device would be functionally similar to the vests. A convenient packaging arrangement would be as part of the cap lamp battery.

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# FINDING AND COMMUNICATING WITH TRAPPED MINERS

By S. Shope,[1] J. Durkin,[1] and R. Greenfield[2]

## ABSTRACT

The Bureau of Mines has performed research and developmental work on methods to locate and communicate with miners trapped underground following a mine disaster. This work has evolved two major systems to accomplish the objective: (a) the seismic system and (b) the electromagnetic (EM) system.

The seismic system detects, at the surface, vibrations generated by the trapped miner pounding on the roof of the mine with any implement at his or her disposal. The vibrations can be used to determine the location of the miner. Tests have shown that the system is effective in locating the miner at depths to 2,000 ft. The seismic system is presently operational and maintained in a state of readiness by the Mine Safety and Health Administration (MSHA).

The EM system makes use of a belt-worn radio-type transmitter that the miner activates when trapped. The signals from the transmitter are sent to the surface where surface personnel can detect them and locate the miner's position. Once location is determined, surface personnel can transmit voice signals to the miner to establish communication. Tests have shown the system to be effective in locating the miner at depths to 1,000 ft. Studies are continuing to improve the performance of the system.

## INTRODUCTION

Mine disasters continue to have a major impact on underground mining from both an economic and psychological perspective. Disasters are usually caused by explosions, fires, cave-ins, or floods. The time period immediately following a disaster and up to the point when the mine is again secured is the focus of the Bureau's postdisaster program. Some disasters are so violent and widespread that they immediately kill all underground personnel; however, it is not uncommon for a disaster to be confined to a small underground locale. Even small confined events have the potential to so disrupt the mine that aftereffects can contribute greatly to the death toll. A prime example of this is disasters caused by explosions. The miners not immediately killed by the fire and blast have the potential of succumbing to toxic gases produced by the explosion. Studies have shown that miners that do not have access to immediate evacuation stand the best chance for survival if they barricade themselves. Barricading limits the amount of poisonous gas that the trapped miners are exposed to. However, once barricaded, the miners cannot leave until rescued and may be considered prisoners of the mine. Usual means of communication may be destroyed, prohibiting members of the rescue team from communicating with the trapped personnel. Without this communication, the rescue team knows little about the number, condition, or location of the barricaded miners. The last factor is regretable, since reliable knowledge on the location of the entombed miners could lead to the prompt arrival of the rescue team and could prevent unnecessary deaths. In addition, the rescue team itself would be exposed to less hazard by knowing directly where to search.

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Following the 1968 Farmington Mine disaster, the Bureau contracted the National Academy of Engineering (NAE) (5)[3] to recommend means to increase the probability of survival and rescue of miners in mine disasters. The report recommended that the Bureau develop new communication techniques to detect and locate trapped miners. The Bureau considered these recommendations as the starting point for a continuing concentrated research effort to improve survival and rescue capability.

The condition following a mine disaster is unpredictable; cables may be severed and passageways blocked. A hardened communication system that advances with the face would be prohibitively expensive and could not be considered 100 pct reliable. It became apparent that the best approach would be a technique that would allow communication directly through the mine workings or overburden strata.

Two major areas of detection and location communications were recommended by NAE and continue to be investigated: (a) seismic and (b) electromagnetic (EM). This paper describes the concept of both techniques, the present status of each, and the program plans for future research in these two areas of postdisaster communication and location.

## THE SEISMIC LOCATION SYSTEM

In the 1970 NAE report, it was suggested that a seismic technique might be capable of detecting and locating trapped miners. It was proposed that the miner would strike a part of the mine with any heavy object that could be found. The resulting vibrations would then be detected on the surface by the use of seismic transducers (seismometers) which will be referred to as geophones. The geophones convert seismic signals to voltages that are then amplified, filtered, and recorded. By comparing the relative arrival times at several geophone locations, the trapped miner's location can be readily determined. This concept may be visulaized in figure 1.

In 1971 Westinghouse Electric Corp. (23) built and tested such a system. From 1972 until the present, Westinghouse, in cooperation with the Mine Safety and Health Administration (MSHA) and the Bureau of Mines, has modified and tested the system at a variety of mines.

Presently, the seismic location system is operational and deployed as one element of MSHA's Mine Emergency Operations (MEO) facility located near Aliquippa, Pa. This facility is maintained and operated by Westinghouse under MSHA contract. Following a mine disaster in which it is believed personnel are trapped underground, and it has been determined that the seismic location system may be necessary, the system is driven overland or transported by cargo aircraft to the mine disaster site. The system is then positioned over the suspected underground entrapment area.

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

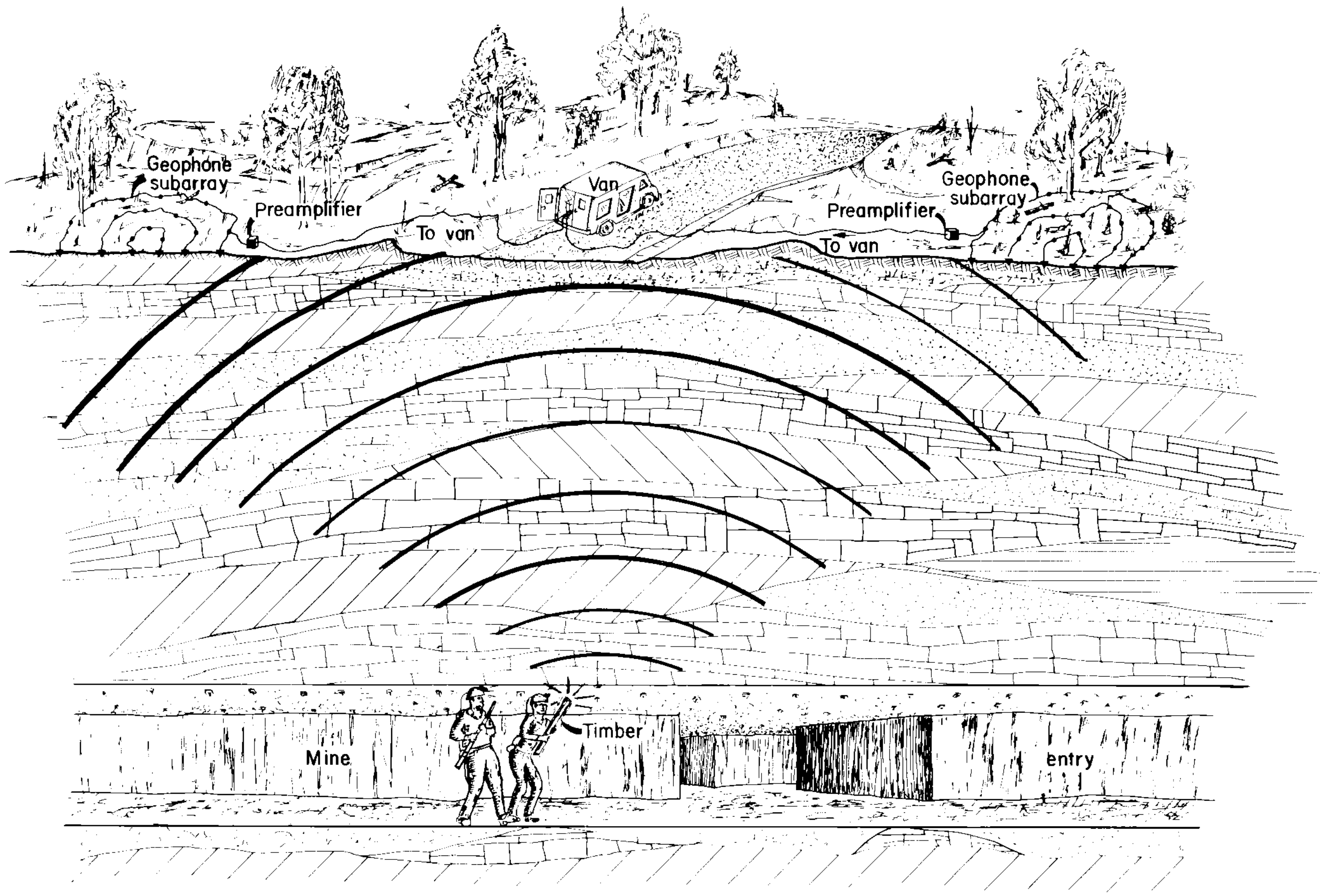


FIGURE 1. - Seismic system for locating trapped miners.

Figure 2 shows the van housing the seismic location equipment; in this case the van is mounted on a flat-bed vehicle. Hopefully, the deployment area is clear and readily accessible, but if not, it can be cleared by bulldozers and the system transported to the site by tracked vehicles or, if necessary, by helicopter. It is recommended that in order to provide the best possibility of detecting and locating any trapped miners, the geophones be placed surrounding their most likely location. If the trapped miner is not in the area covered by the geophones, he or she may still be detected and located, but accuracy in the calculation of his or her location may suffer (6). However, it is not necessary for the van to be placed in this immediate area owing to the large lengths of cable available to link geophones to the van; also, there exists the option of connecting the geophones to the van via a wireless frequency modulated (FM) telemetry link.

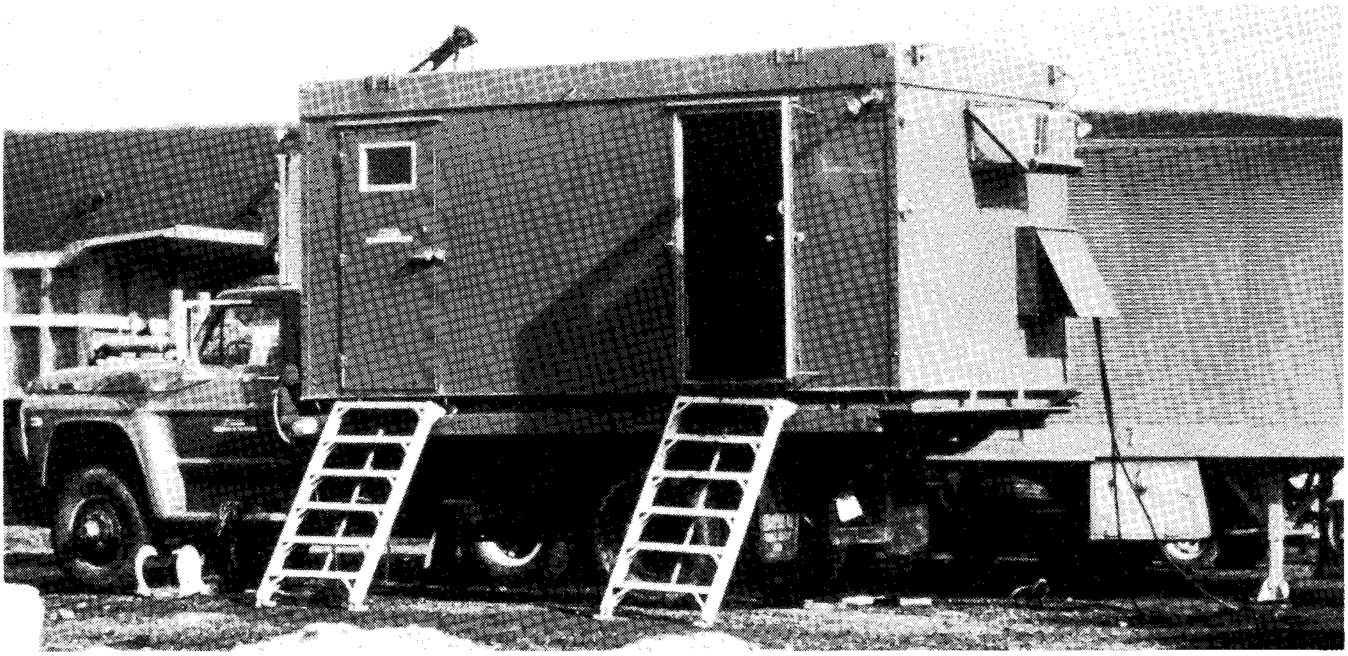

FIGURE 2. - Seismic van.

In fact, it is recommended that the van or any other vehicle or personnel activity be positioned far enough away from the geophones so that this activity would not interfere with the reception of any trapped miner seismic signals.

After a site is chosen, the seismic array is deployed in a configuration that will cover the area to be monitored. An ideal array configuration is shown in figure 3. The array geometry is adjusted to the geometry of the mine and to surface conditions. The array consists of seven subarrays; each subarray is composed of either 7 or 24 geophones configured as shown in figure 4. Detailed discussion of these subarrays is given in a later section. While the array is being deployed, a survey of the subarray locations is made using surveying equipment maintained with the seismic system.

MSHA maintains a continuing effort to explain to the mining community the operation of the seismic location system. The miner is instructed to do the following in the event he or she is trapped underground:

1. When all possible escape is cut off, the miner is to barricade for

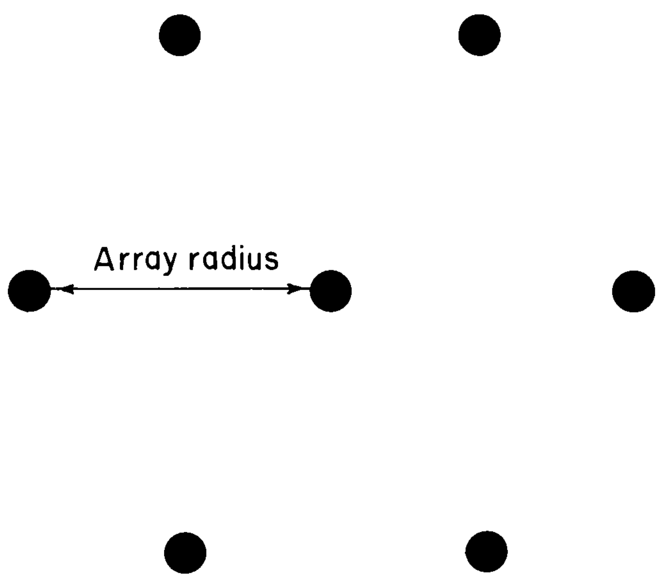


FIGURE 3. - Ideal array configuration.

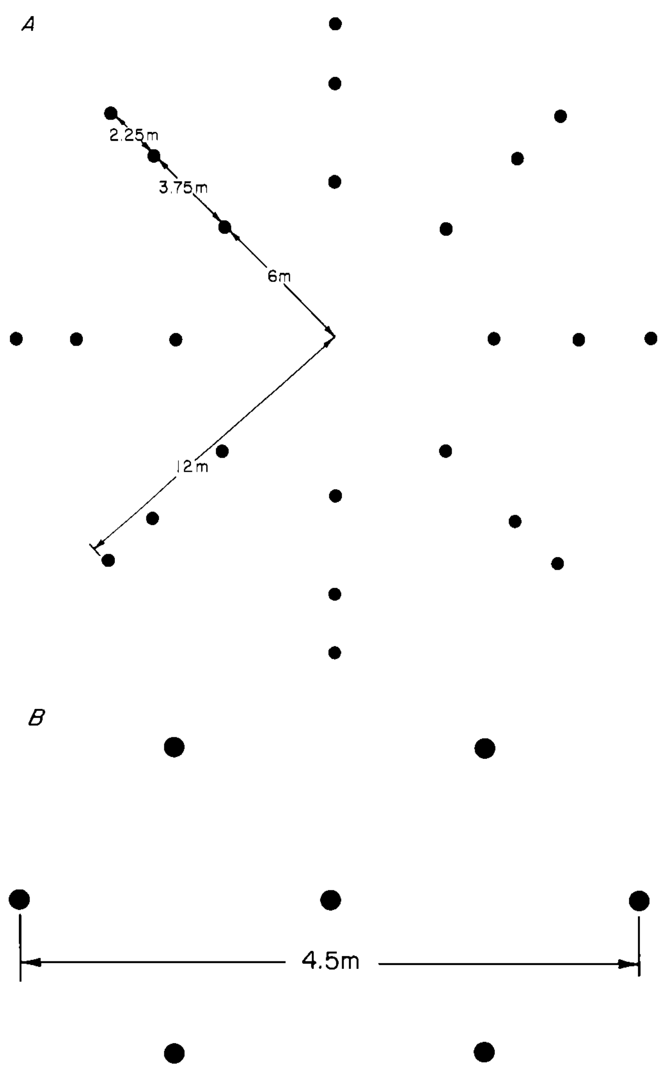


FIGURE 4. - Subarray configurations of (*A*) 24 and (*B*) 7 geophones.

protection from possible toxic gases and wait for a signal from the surface before beginning to signal the seismic system.

2. As soon as the system is in a state of readiness, the surface crew detonates three explosive charges that can be easily heard by the trapped miner.

3. After hearing these three shots, the miner is to pound 10 times on any hard part of the mine, preferably the roof or a roof bolt, with any heavy object that can be found; a heavy timber is best. (Figure 5 shows a miner pounding while an operator in the seismic van observes the geophone signals.)

4. Following this, the miner is to rest for 15 min and then repeat the pounding. While resting, if the miner hears five shots from the surface he or she knows the signaling has been detected and help is on the way.

5. If the miner hears no shots, he or she repeats signaling every 15 min.

The above instructions are summarized in a hardhat sticker (fig. 6) that MSHA distributes.

During the expected signaling period, attempts are made to reduce surface activity while the seismic system is in use to optimize the chances of detecting the miner's signal. The system operates continuously, but this quiet period should enhance the chances of detection during the expected signaling sequence.

Once the signal is detected and the miner's location has been determined, directions are given to the rescue team members to guide them in their rescue efforts. If a rescue team is unable to reach the trapped miner, a drilling rig is positioned over the site of the miner's location and a rescue borehole is drilled for his or her evacuation.

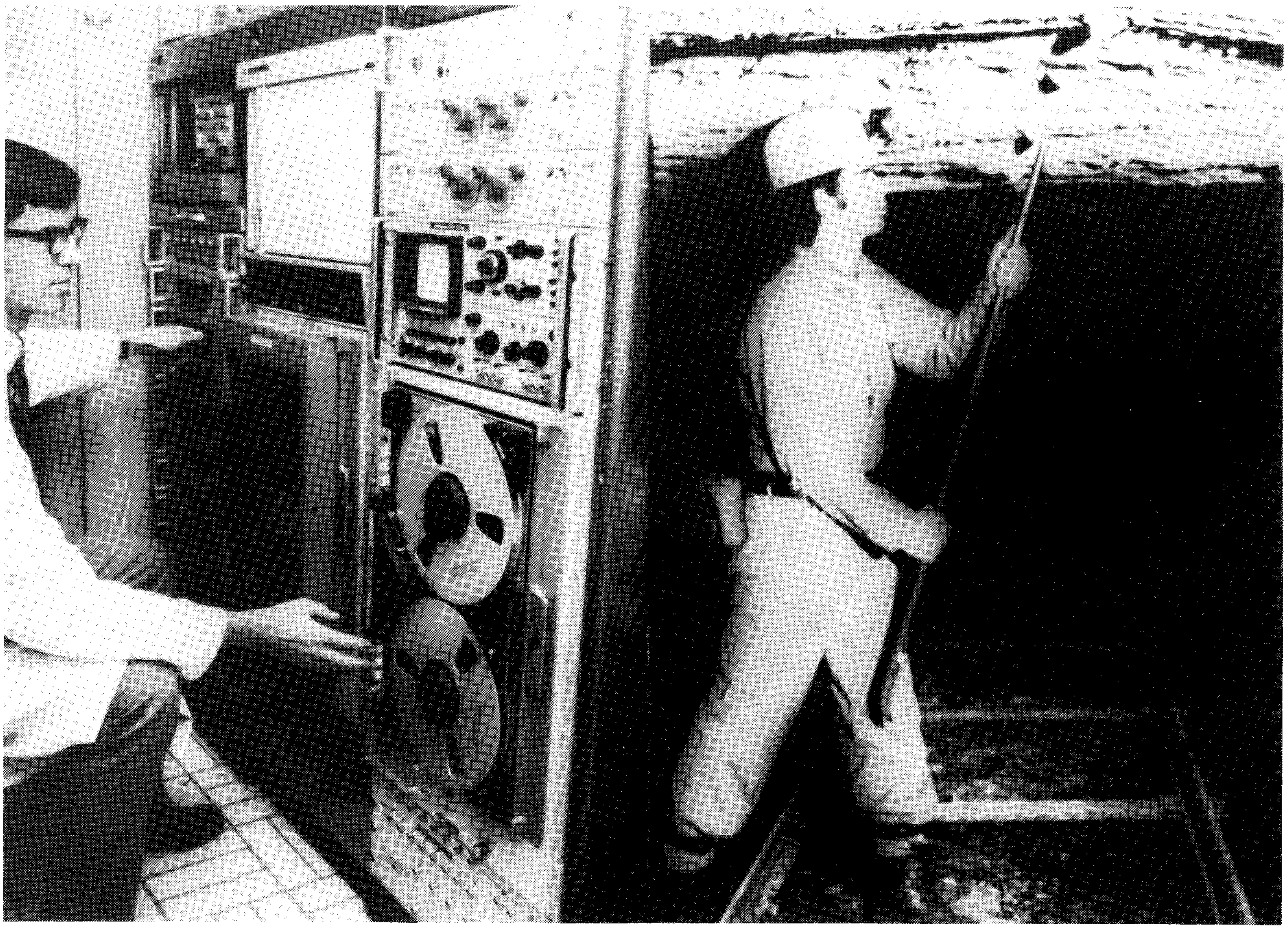

FIGURE 5. - Surface personnel listening while a miner pounds.


FIGURE 6. - MSHA hardhat sticker.

System Instrumentation

The operation of the system may be best described by referring to the system diagram as shown in figure 7. The heart of the system is the electronic instrumentation contained in the van, as seen in figure 8 in block diagram form. An interior view of the operating panel may be seen in figure 9. The geophone used is the Geospace GSC-11D model M-3,[4] having a natural undamped frequency of 14 Hz. At each subarray, a preamplifier increases the signal level before transmitting it to the van via a cable or telemetry link. At the van, the signals are each passed separately through a tracking digital notch filter. This filter removes narrow-band manmade interference such as

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[4]Reference to specific equipment is for identification purposes only and does not imply endorsement by the Bureau of Mines.

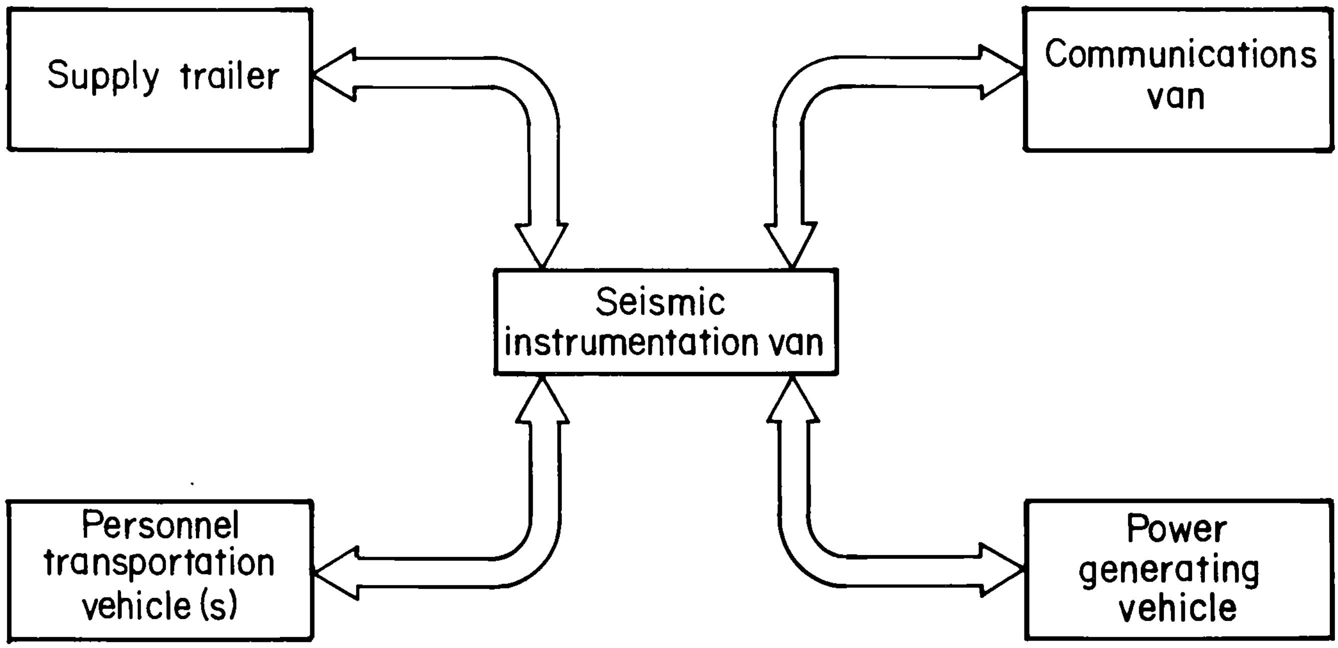


FIGURE 7. - System block diagram.

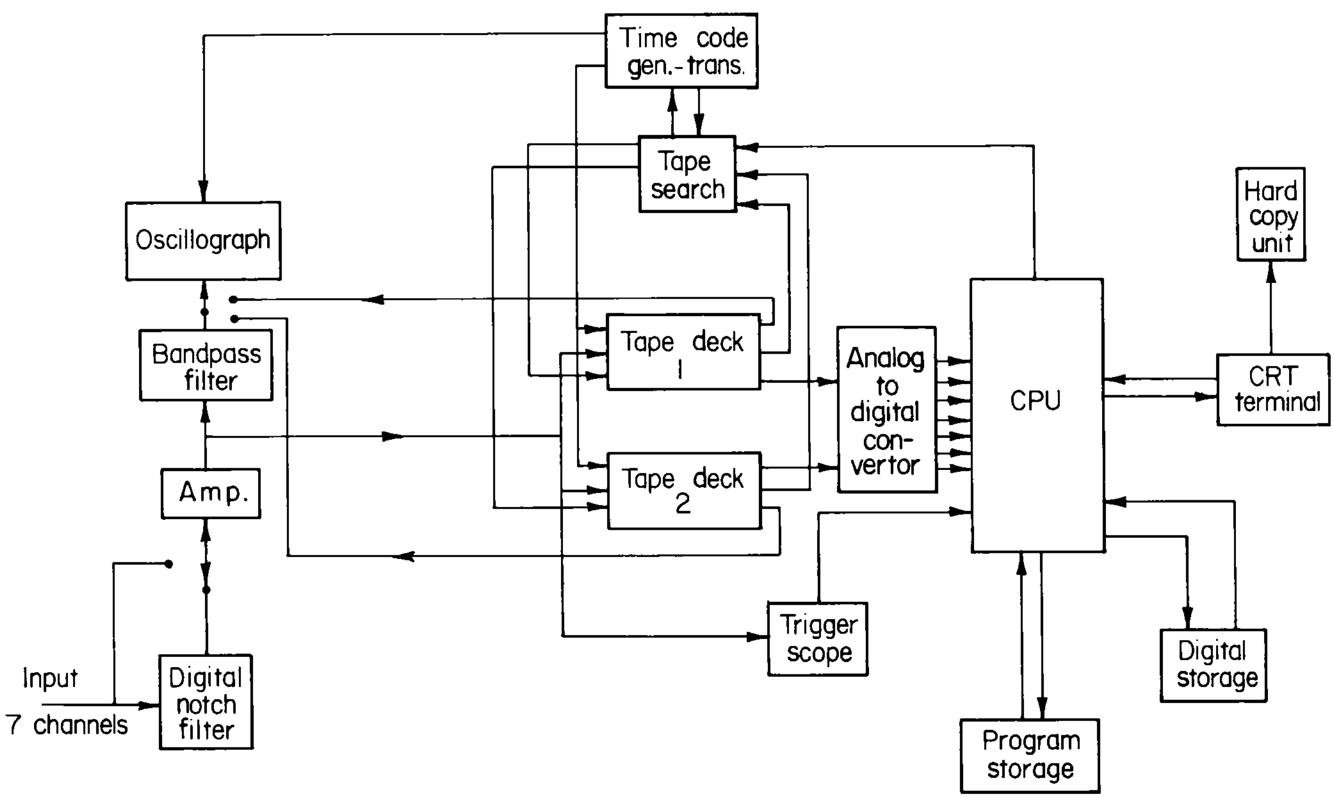


FIGURE 8. - Block diagram of van instrumentation.

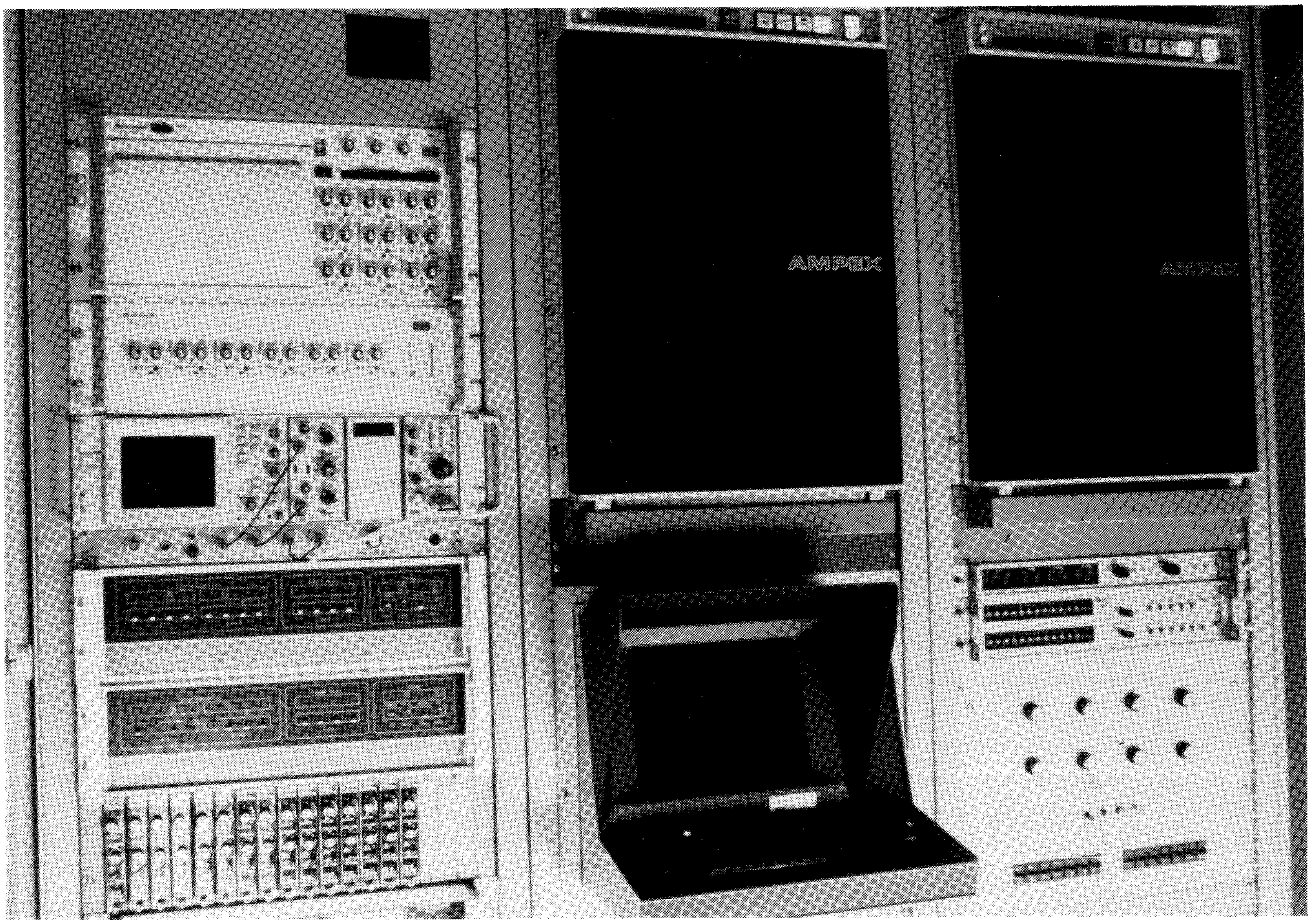


FIGURE 9. - Interior view of van.

powerline pickup or seismic disturbances caused by local machinery. This filter operates by latching onto the fundamental frequency of interference and tracking it if slight variations in frequency occur. This initial processing step eliminates interference that would, in some instances, limit system performance.

An example of the performance of the filter may be seen in figure 10. Figure 10*A* shows a seismic record heavily contaminated with a 60-Hz interference. Figure 10*B* shows the same record after passing through the notch filter and illustrates how a miner's signal is easily seen after filtering, whereas prior to filtering it would have been impossible to detect the signal.

After notch filtering the signals are amplified and then recorded on analog tape. The signals are band-pass filtered from 20 to 200 Hz and are displayed on an oscillograph record for recordkeeping purposes. By visually monitoring the oscillograph record, the operator can determine whether a signal has occurred.

When the operator detects a signal, the analog tape containing the event is replayed into a PDP 11/34 computer via an analog-digital converter. The computer performs interactive signal processing on the data and displays the results on the computer's CRT terminal. A permanent record may be obtained using the hard copy unit.

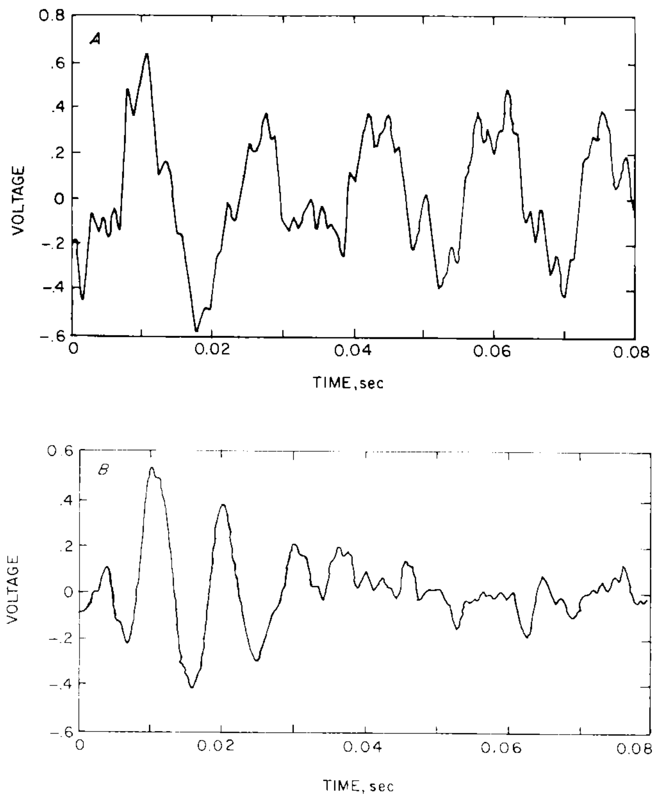


FIGURE 10. - Seismic record showing signal and noise before (*A*) and after (*B*) digital notch filtering.

When processing has been completed, the relative arrival times of the signals from each channel are determined. These data, together with information on the location of the subarray and the velocity of seismic waves obtained by the refraction surveys, are submitted to the computer location program to determine the trapped miner's location.

The present system relies on the operator's ability to determine when a signal has occurred. Manual detection of the signal can be unreliable due to the low signal-to-noise ratio (SNR) often encountered and the inability of the operator to maintain peak performance over extended periods of time. At present a contract effort is underway that will implement an automatic detection capability into the seismic system. The automatic system will provide equal performance to that of the human observer by allowing a computer to search the data for suspected signals. There will always be manual interaction even with the automatic detection system.

## Seismic Noise

Seismic noise can at times be a major problem when detecting small-level seismic signals. Since the signal from a trapped miner can be on the order of a few microinches per second (μips), a normal background noise can obscure the signal. Thus information is needed on the types of noise sources, the expected amplitude ranges, and the amplitude variation with frequency and time.

Three common noise sources are typically encountered in the field: (a) natural seismic background noise, (b) manmade seismic noise, and (c) manmade electromagnetic interference (EMI) coupled into the field equipment. Narrow-band manmade noise may be readily eliminated by use of the digital notch filtering techniques previously discussed.

Since natural seismic noise tends to vary widely as a function of time, geographic location, and frequency, it is not possible to make precise predictions of the noise at the site of some future mine disaster; thus the noise must be treated in statistical terms. For some purposes, however, it is sufficient to know the noise characteristics within fairly broad limits.

Study of the miner-induced frequency spectra indicates that most of the signal energy is in the frequency band between 20 and 200 Hz. These studies have also shown that the amplitude of the envelope of the seismic noise is often Rayleigh distributed (3-4).

## Theoretical Seismic Waveform Modeling Procedure

An analysis was performed to understand the factors that affect the seismic signal amplitude, waveshape, and spectra. Based on this analysis, a waveform modeling procedure (WMP) was developed to model seismic signals generated from impacts on the surface of mine workings. The output of the WMP is the predicted voltage waveform produced as sensed by a geophone. A block diagram of the WMP may be seen in figure 11. The computations for each of the boxes are convolved to give a final theoretical waveform that is then compared with actual field test measured waveforms.

A major factor that determines the seismic waveform is the time-dependent force that the miner's implement (timber, pick, etc.) applies to the mine roof or floor. It can be shown, based on the work of Sung (21) that if the wavelengths are long, compared with a length characterization of the surface area of the implement that is in contact with the surface of the mine opening, the force the implement exerts on the surface is proportional to the amount the surface is displacing.

To include the effect of the mine tunnel or cavity, the theory described by Greenfield (12) is used. The geometric spreading is given for the present situation by a I/R dependence. The effect of anelastic attenuation (often called Q-dampening) on the wave as it propagates is included by using the Futterman operator (9). The effect of geological layering and the free surface of the earth is included by the method developed by Haskell (13), using a modification of the program described by Lablanc (17). The transfer function between the ground displacement and the voltage output of the seismic sensor was calculated based on the description of a seismometer given by Bollinger (1). The seismic system's 20- to 200-Hz filter response was obtained by recording the impulse response of the filter.

The waveform given by the WMP gives extremely good fit to records observed at various field tests of the system. Both the waveshapes and the absolute amplitudes are well fit. The first example is from the Orient No. 6 mine; figure 12 shows the actual seismogram as compared with a seismogram predicted by the WMP.

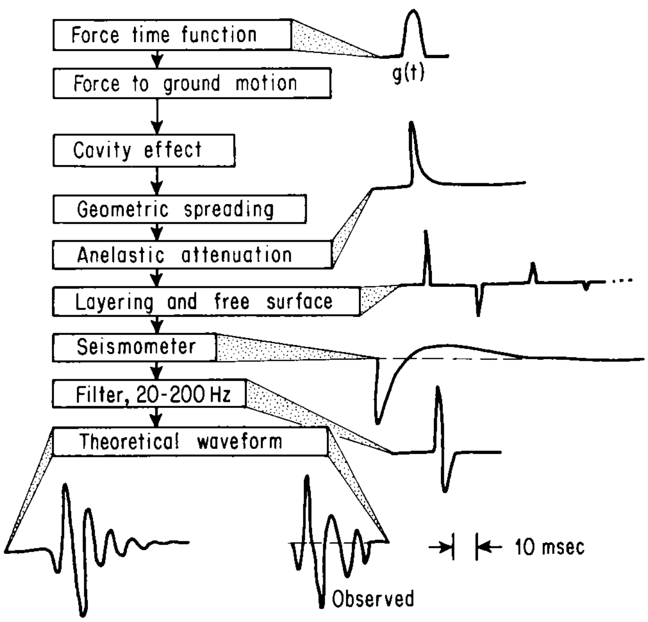


FIGURE 11. - Theoretical waveform modeling procedure (WMP).

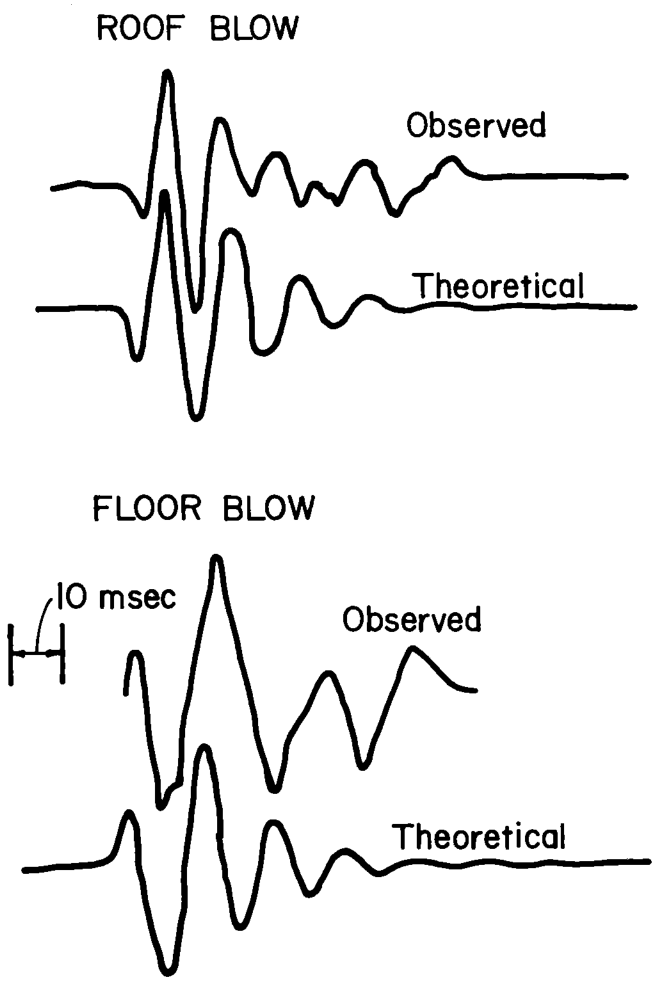


FIGURE 12. - Comparison of actual and theoretical waveforms.

Figure 13 shows the effect on the waveform of soil thickness (d). For no soil (d = 0 m), the waveform is a single simple pulse. For a thick soil layer (d = 20 m), the waveform is a series of pulses of decreasing amplitude. These represent the successive bounces of the pulse owing to multiple internal reflections in the soil layer. The time between pulses is the two-way traveltime in the layer. As the layer thickness decreases, the time between pulses decreases; when d is reduced to 10 m the pulses overlap in time.

The exact form of the signal is quite dependent on d. For this reason, the earth at any particular site is considered as being comprised of a homogeneous rock region and a soil layer near the surface. Recent work has indicated a need to compensate for this effect. Preliminary setup of the system now includes a refraction survey that is usually conducted at every subarray location. The results of this survey determine the soil layer thickness, soil layer velocity, and rock velocity. These parameters are later used in the location algorithm.

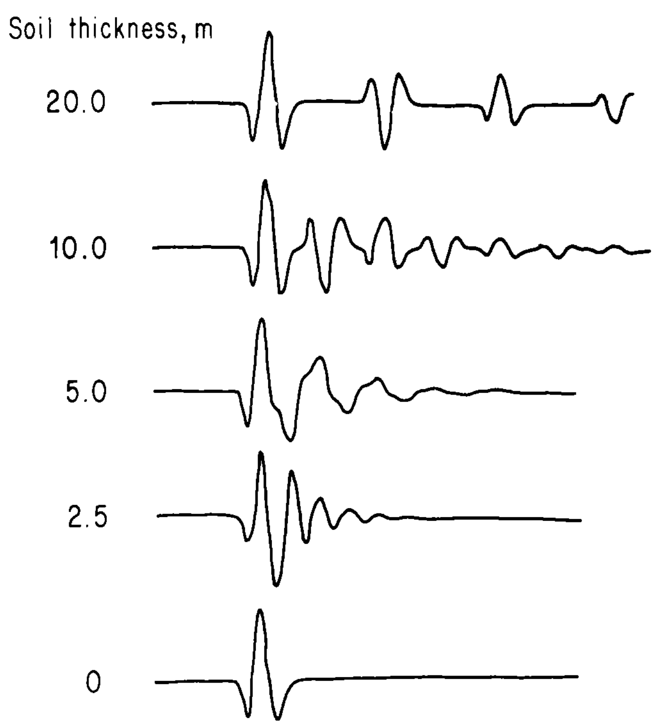


FIGURE 13. - Effect of soil layer thickness on vertical waveforms.

## Signal Amplitude Model for Various Sources

In this section, signal sources are compared with the best-source type. This is done by relating the signal amplitude from other sources to that of the best-source type. From the data, an average difference in decibels (db) between each of the source types and the best-source type is determined. This difference is called the adopted value.

In the majority of tests the best signal source was a large timber applied to a roof bolt (denoted as source type S1). There are exceptions to this; for example, it was noted that at the Staufer Mine a large timber on the roof (there were no roof bolts) created weak signals owing to the height of the roof, which made it difficult to use the large timber effectively. However, in general, the large timber on the roof was either the best or within a few decibels of being the best-source type. Thus for the S1 source, a value of 0 db is adopted. Table 1 gives the adopted value for a variety of sources.

## Subarray Performance

The seismic rescue system uses an array composed of seven subarrays rather than seven individual geophones to receive seismic signals, the reason is that a subarray will give a better SNR than a single geophone. This improvement is achieved principally in three ways. First, noise that is uncorrelated between the geophones will be reduced in amplitude by the cancellation that occurs when zero mean random numbers are averaged. Second, noise that is propagating at a slow horizontal velocity will be reduced on the output of the subarray because, if the subarray is thought of as an antenna, the noise will be outside of the antenna's main beam. Finally, any adverse effects that would result if a single badly planted geophone was used will be alleviated by the averaging of all the subarray geophone outputs.

As mentioned before, two subarray configurations have been developed and used

TABLE 1. - Signal amplitude of various sources relative to signal amplitude of a large timber on a roof

| | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| Source type | Large timber. | Small timber. | Sledge. | Large timber. |
| Application point | Roof bolt. | Roof bolt. | Roof bolt. | Floor. |
| Orient #6 Mine.....db.. | NAp | -7 | -8 | -14 |
| Peabody Mine.....db.. | NAp | -3 | ND | -12 |
| Peabody Mine.....db.. | NAp | -1 | -3 | ND |
| Concord Mine.....db.. | NAp | ND | -3 | -4 |
| Staufer Mine (no roof bolts)..db.. | NAp | 0 | -1 | +2 |
| Value adopted for C[2].....db.. | 0 | -3 | -3 | -8 |
| | S5 | S6 | S7 | S8 |
| Source type | Small timber. | Hard hat. | Sledge. | Rock pick. |
| Application point | Floor. | Roof bolt. | Floor. | Roof bolt. |
| Orient #6 Mine.....db.. | ND | -19 | ND | ND |
| Peabody Mine.....db.. | -16 | ND | -14 | ND |
| Peabody Mine.....db.. | ND | ND | ND | ND |
| Concord Mine.....db.. | -4 | ND | ND | -7 |
| Staufer Mine (no roof bolts)..db.. | ND | -11 | ND | ND |
| Value adopted for C[2].....db.. | -10 | -15 | -15 | -7 |

NAp Not applicable. ND No data.
[1]No roof bolts.
[2]Approximate average difference between amplitude from source type and amplitude from large timber hitting roof bolt.

extensively. The first is a seven-geophone subarray (25) with a 4.5-m diameter, having the geophones wired in parallel. The second is a larger 24-geophone subarray with a 24-m diameter. This large subarray uses two series-connected strings of 12 geophones with the two strings connected in parallel (8). The subarrays are shown in figure 4. The electronic configurations of both subarrays are such that the sensitivity of the subarrays is well below even low levels of natural seismic noise. Thus the ability to detect and identify signals from an underground miner is determined by the seismic noise level.

The use of a subarray will normally result in some loss of amplitude compared with using a single geophone in measuring a signal from a miner hitting below ground. This signal loss is due to the fact that the signal is not exactly the same on each subarray geophone. For a miner directly below the subarray, the the signal is in phase at all geophones and the signal loss will be minimal. However, for sources horizontally offset from the subarray there is a phase shift (or, equivalently, an arrival time difference) between the geophones.

The noise reduction for incoherent noise results in a gain of 13.8 db for the 24-geophone subarray and 8.5 db for the 7-geophone subarray. Seismic noise that is completely incoherent is not the normal situation but occurs during rain. In this situation the noise level is high and thus the subarray gain is especially important. Field test results have verified that this gain occurs during rain. In areas with brush or high grass ground cover, the noise generated by the wind may also be essentially incoherent between geophones. The larger spacing between geophones of the 24-geophone subarray compared with the 7-geophone subarray enhances the possibility that the noise will be incoherent.

In many situations the seismic noise may be highly coherent between the subarray geophones; however, the subarray can still give noise reduction because the noise is not in phase between the geophones (2).

The source of coherent noise may be wind acting on trees outside of the subarray, distant traffic, machinery, or airborne noise. Much seismic noise at frequencies of 20 to 200 Hz is of low horizontal phase velocity, since it travels at an acoustic velocity (330 m/sec) or at seismic surface wave velocities, which are usually below 1,000 msec.

From theoretical considerations of SNR improvement by the 24- and 7-geophone subarrays, it is to be expected that the 24-geophone subarray would offer a significant SNR gain over the seven-geophone subarray. In an extensive series of field tests this was often the case (8). Typical gains were 5 db for the 7-geophone subarray and 10 db for the 24-geophone subarray. There were, however, some mines where the SNR of the two subarray types were comparable. The seven-geophone subarray, however, may offer practical advantages in terms of deployment, where a clear area cannot be found to deploy the larger 24-geophone subarray.

## Probability of Detection

It is desirable to determine the probability that a surface array will detect an underground source. In the configuration normally used, seven subarrays are placed on the surface to monitor a portion of the subsurface. A method has been developed to calculate the probability that m subarrays or more, with $1 \leq m \leq 7$, will detect a miner's signal. The detection of a signal by one subarray may be sufficient to identify the signal as coming from an underground miner. However, identification can be more certain if several subarrays can detect the signal. To locate, at least three subarray detections are required, and five or more are desirable for accuracy.

In the following three examples, the substrata volume being monitored is a right-rectangular prism with top at $h_1$--200 ft and bottom at $h_2$--1,200 ft as seen in figure 14. This depth range is consistent with the fact that the majority of mines lie in this range.

Figure 15 is the first example of the results of the calculations. This view shows an array containing seven subarrays with a 500-ft radius. The subsurface being monitored is a square having sides of 2,000 ft. For the large timber on a roof bolt source with no subarray SNR improvement, one looks at the 0-db position on the abscissa to get the probability of

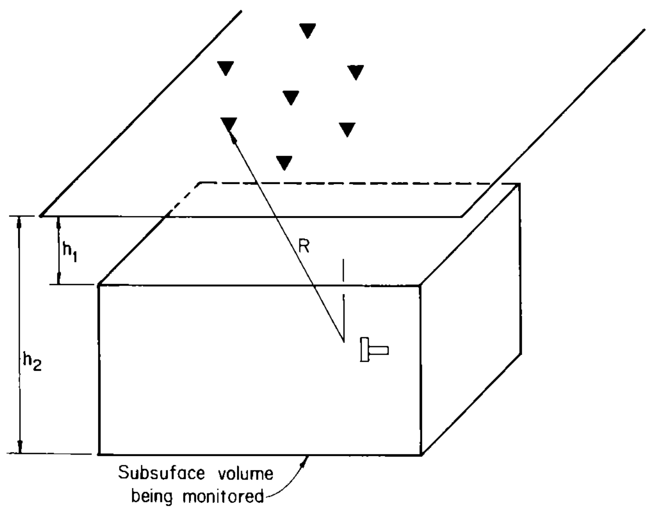


FIGURE 14. - Substrate geometry for calculation probability of detection; triangles indicate subarray locations.

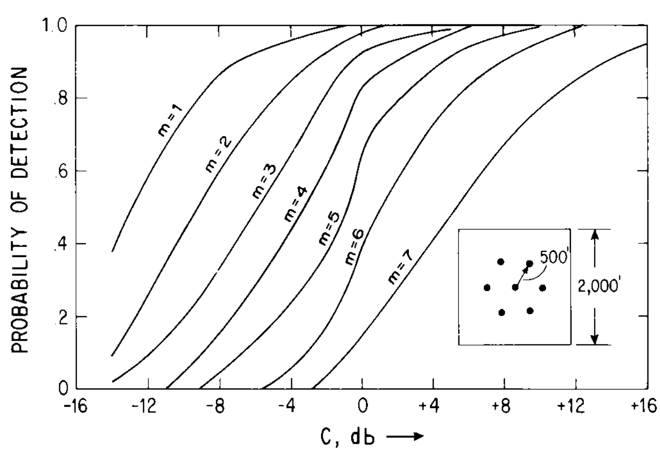


FIGURE 15. - Probability of detecting m or more subarrays for 500-ft array radius and 2,000-ft monitored square.

m or more subarrays detecting the signal. For example, the probability of m = 5 or more detecting the signal is 0.62 (index base 1.000).

From table 1, the signal for a small timber on a roof bolt (S2) has C = -3 db. Thus one looks at the -3 db abscissa value for a S2 source. Note that for any source type, the use of the subarrays gives approximately a +5-db improvement in SNR compared with the single sensor values. After a single subarray has detected a signal, the stacking of successive blows will also improve the SNR. If 10 blows are stacked, a 10-db improvement is commonly obtained. Thus, for the case of locating the source using stacked traces from the subarrays, the C = +15 db value applies for the large timber on the roof bolt.

Thus, for large-timber sources for the figure 4*A* configuration, it is very likely that at least one subarray will initially detect the signal; after stacking, signals should be seen on the five or more subarrays that are desirable for accurate location.

Figures 16 and 17 show corresponding results for the monitoring of a square having sides of 4,000 ft for array radii of 500 ft and 1,000 ft. Since a large area is being monitored, the detection

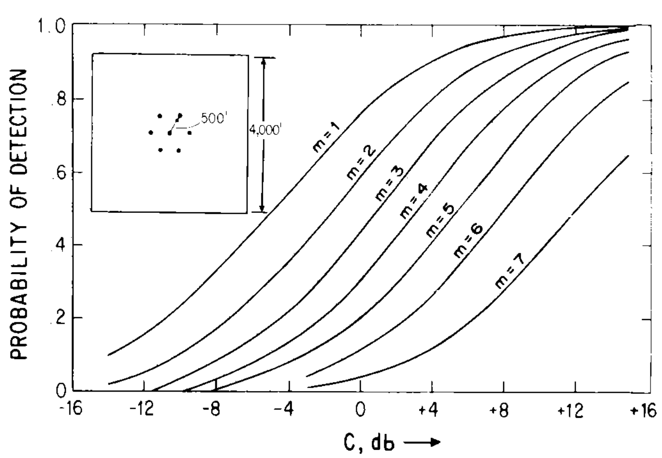


FIGURE 16. - Probability of detecting m or more subarrays for 500-ft array radius and 4,000-ft monitored square.

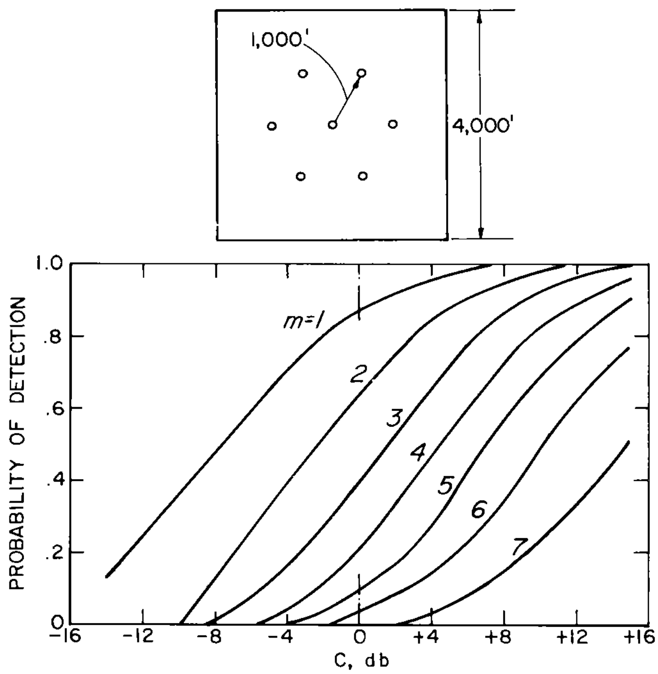


FIGURE 17. - Probability of detecting m or more subarrays for 1,000-ft array radius and 4,000-ft monitored square.

probabilities are lower than for the 2,000-ft square.

For the monitoring of the 4,000-ft square with an array centered at the center of the square, the effect on the detection probabilities of the array radius was examined. This was done for the value C = 0 db; that is, for the best source with no array gain or stacking. Results are shown in figure 18. To obtain a signal from at least one subarray, the use of the larger radius arrays is somewhat better. The reason for this is that for the 500-ft-radius array points on the boundary of the square will be a minimum of 1,500 ft horizontally removed from the nearest subarray. Thus, to have the maximum probability of detection, it is suggested that before a signal is found it might be best to use a 1,000-ft-radius array when monitoring such a large area. If conditions allow, after detection on a single subarray, it would then be desirable to move some of the distant subarrays to the vicinity of the detecting subarray and signal the trapped

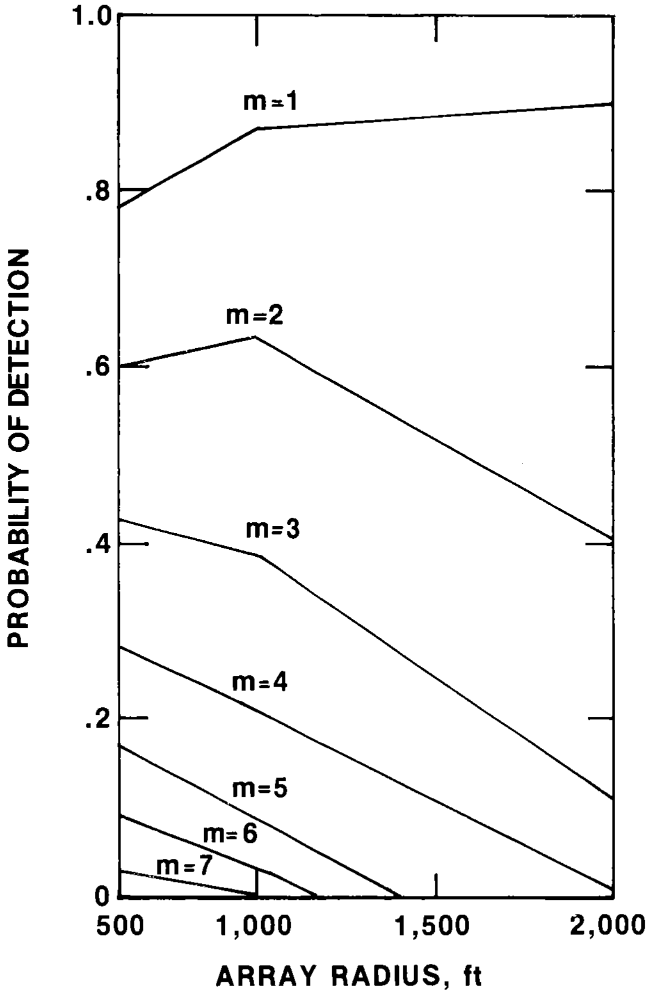


FIGURE 18. - Probability of detection with m or more subarrays versus array radius (C = 0 db), and 4,000-ft monitored square.

miner to repeat his or her signal to allow improved location.

Next, the situation will be examined where the trapped miner is believed to be below a particular point. One subarray would be set directly above that point. The probability of detecting the miner can be calculated by fixing the subsurface region to be monitored as a very small area directly below the central subarray of a 1,000-ft-radius array. For a source 500 ft deep, even a weak source with C = -10 db will be detected with 0.85 probability. Noting that a 24-geophone subarray gives a 5- to 10-db SNR improvement, it is expected that a subarray would probably detect the signal even for sources down to 2,000 ft. This high probability of detecting a source directly below a subarray is consistent with the fact that in field tests signals from sources directly below a subarray were consistently detected.

It is instructive to observe the variation in the probability of detection as depth is varied. These results are shown in figure 19. The probability of detecting a miner's signal was determined when using an array of a 1,000-ft radius over square areas of 0.5 and 1.0 mile on a side, for varying depth. Probabilities were determined for weak and strong sources with and without processing. This processing takes the form of stacking. Also considered was whether detection is probable on one or more subarrays ($m < 1$) or five or more subarrays ($m < 5$).

The detection probabilities discussed have all been based on the use of subarrays made of geophones that measure the vertical particle velocity of the ground. Geophones that measure the horizontal particle velocity are also manufactured and have been used in a limited number of experiments. The results of these experiments indicated that most often the vertical geophones outperform the horizontal geophones. There have been exceptions to this where the horizontal geophones have given better performance. To employ horizontal geophones, two extra channels (one for north-south and one for east-west polarization) at each subarray location must be employed. When using horizontal geophones each geophone must be carefully oriented. The signals from horizontal phones are often more difficult to interpret. Therefore, the logistics of the operations suggest that for the surface seismic location system the present vertical geophone system should be maintained rather than a mixed vertical and horizontal system.

## Location Accuracy

To guide the efforts of the rescue team or to determine where to site the rescue drill, it is necessary to determine the location of the trapped miner. For the

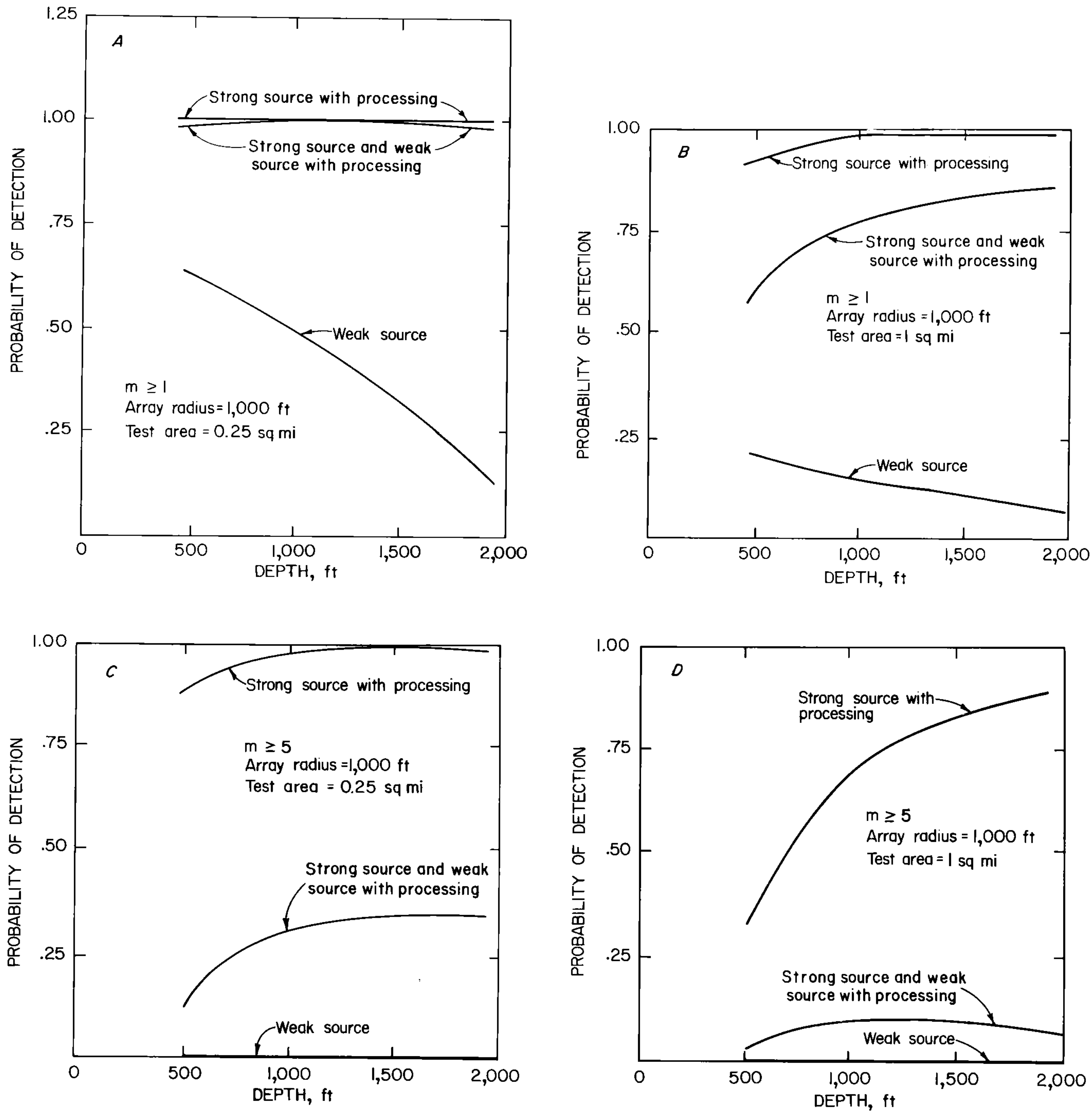


FIGURE 19. - Probability of detection versus depth, array radius 1,000 ft. *A*, m ≥ 1, test area 0.25 square mile; *B*, m ≥ 1, test area 1 square mile; *C*, m ≥ 5, test area 0.25 square mile; *D*, m ≥ 5; test area 1,000 ft.

rescue team, an accuracy of 100 ft or less would appear desirable. For positioning the drill an accuracy of a few feet would be desirable. However, as discussed below, accuracies of a few feet do not appear feasible. Thus, the positioning of a rescue drill so as to intersect a mine entry near the estimated location of the trapped miner could best be done using a mine map, if available.

The seismic system presently uses the "MINER" program (11) to calculate the location from arrival times measured on stacked seismograms. This program combines the individual subarray arrival times, either three or four at a time, to determine a location. The MINER program can use a known depth for the source or can fit for the source depth. Alternate methods of location based on the least squares principle are often used in seismic location work; this principle is the basis of work done by Ruths (19).

Westinghouse (25) compiled estimates of location errors obtained for a limited number of locations at 12 mines. Table 2 gives these results. This table indicates that horizontal location errors are usually below 100 ft. However, it should be understood that these results are generally for the better SNR events and that the majority of the sources were located near the center of the array where location accuracy is best.

TABLE 2. - Number of mines with average horizontal error in four ranges

| Error range, ft | Number of mines within error range |
|---|---|
| 0-50............. | 4 |
| 50-100........... | 6 |
| 100-200.......... | 2 |
| Over 200......... | 0 |

Two of the mines discussed by Westinghouse had average errors of approximately 150 ft. In addition, extensive work by Ruths (19) showed errors of this order of magnitude for Island Creek's Hamilton No. 1 Mine. The mines at which the larger errors occur tend to have topographic relief and geologic conditions that vary with position. Ruths' work (19) indicates that the presence of very low velocity solid layers that are different between the subarrays is among the most serious sources of error.

Three techniques have been used to decrease the location error resulting from soil layer variations. Results to date with these techniques indicate that soil-layer-related errors can be reduced to 100 ft or less. Ruths (19) studied the first of these techniques both by computer simulations and by study of data from an earlier Island Creek Mine field test (24).

In technique 1, called the reference-correction method, it is necessary to get a source to within several hundred feet of the suspected position of the trapped miner. This might be impractical in a disaster situation. As an alternative method of employing technique 1, a receiver in a drill hole near the level of the mine might be used to measure travel-times from shots near each subarray. The reference-correction method appears to greatly improve the probability that location errors will be below 100 ft even in mines with highly variable near-surface conditions. In technique 2, a short refraction measurement is made at each subarray and used to make an arrival time correction. In technique 3 an arrival time is measured at each subarray from a blast at a known position outside the seismic array. Recent work at the Hamilton No. 1 Mine (March 1980) gives an indication that the errors from soil layer variations can be greatly decreased by use of technique 2 or 3.

## THE EM LOCATION SYSTEM

Parallel to the seismic location program, the Bureau has maintained an EM location research effort. The EM technique offers the potential of providing a superior location method along with the capacity for voice communications. During the past 12 yrs, the Bureau has directed this program to the point of developing hardware prototypes and conducting performance evaluation, implementation assessment, and reliability studies. In addition, existing research projects include alternate EM techniques involving computerized signal processing. These alternate methods would make significant improvements in performance, which would allow implementation of EM location devices in very deep mines where the present EM or seismic methods are not feasible.

### Concept

The premise on which the EM system would be implemented is that the trapped miner would deploy a small transmitter that would be powered by a cap lamp battery. This transmitter would be connected to a length of wire, forming a magnetic antenna. The resulting magnetic field would then be detected on the surface and the trapped miner's underground location ascertained. The surface personnel could then establish voice communications to the miner (downlink); however, limited power underground would preclude the use of voice uplink communications. This concept may be seen in figure 20.

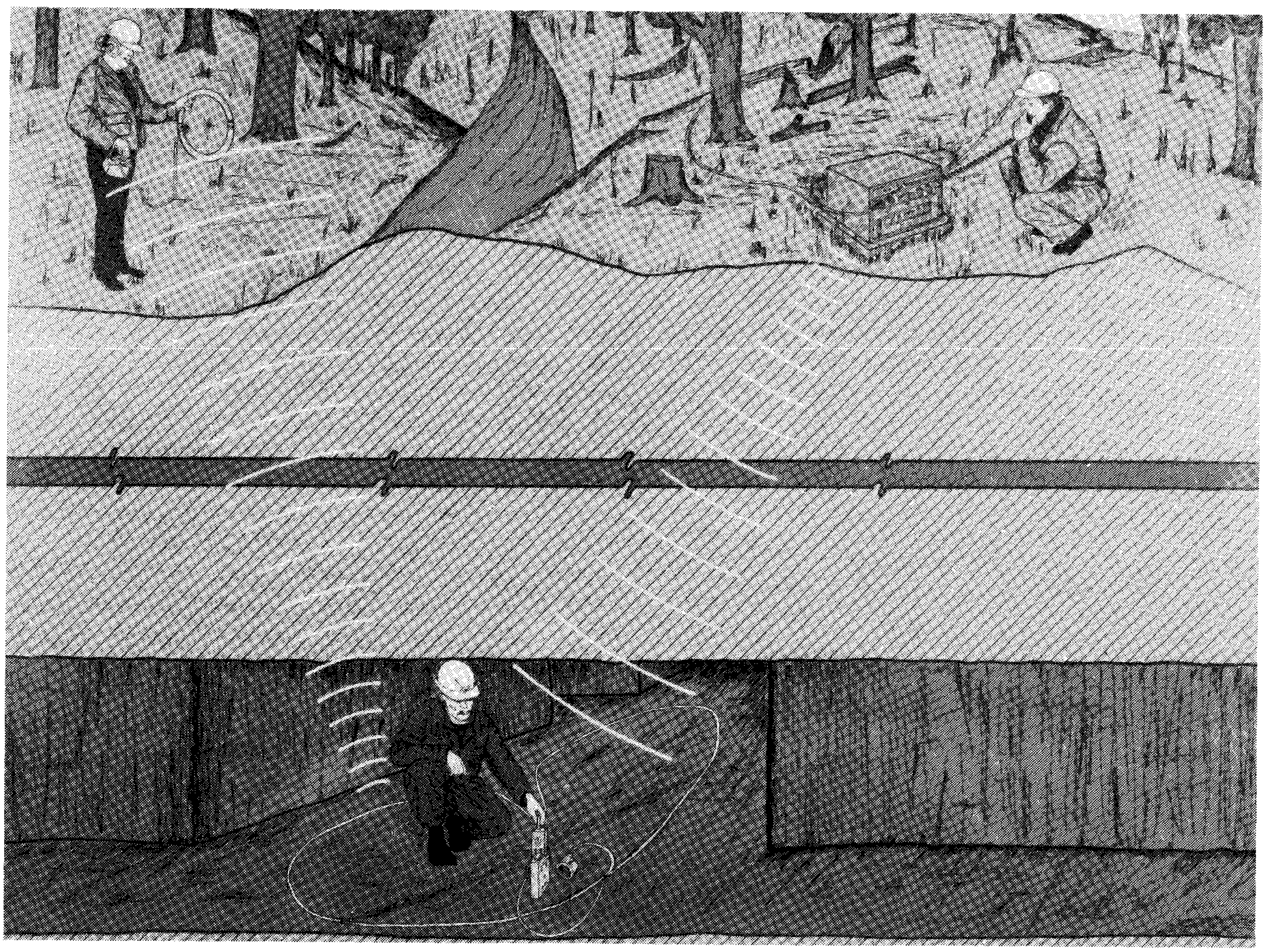

FIGURE 20. - Through-the-earth transmission system.

Early in the EM research program theoretical and experimental studies have shown that the best chance for success was in a system comprised of a narrow-band transmitter and receiver. Initial units of this type were developed by Collins Radio (4), with an improved version built by General Instrument Corp. (20), as shown in figure 21 connected to a modified cap lamp battery. The majority of these units were constructed in the belt-worn configuration, as shown in figure 22; a few were constructed directly into a cap lamp battery. The antenna is included in this package and consists of 300 ft of No. 18 copper wire. Four frequencies have been chosen and are 630 Hz, 1,050 Hz, 1,950 Hz, 3,030 Hz. Included in several of the units are baseband receivers capable of receiving voice communications from the surface.

The surface equipment consists of narrow-band, personnel-carried receivers in conjunction with hand-held antennas. The narrow-band receivers and antennas exist in helicopter-borne versions also. Aerial searches are performed to determine the general locale of the signal and are used when the mine presents large surface areas to be searched. Surface crews are then used to provide a more accurate location. A high-power audio

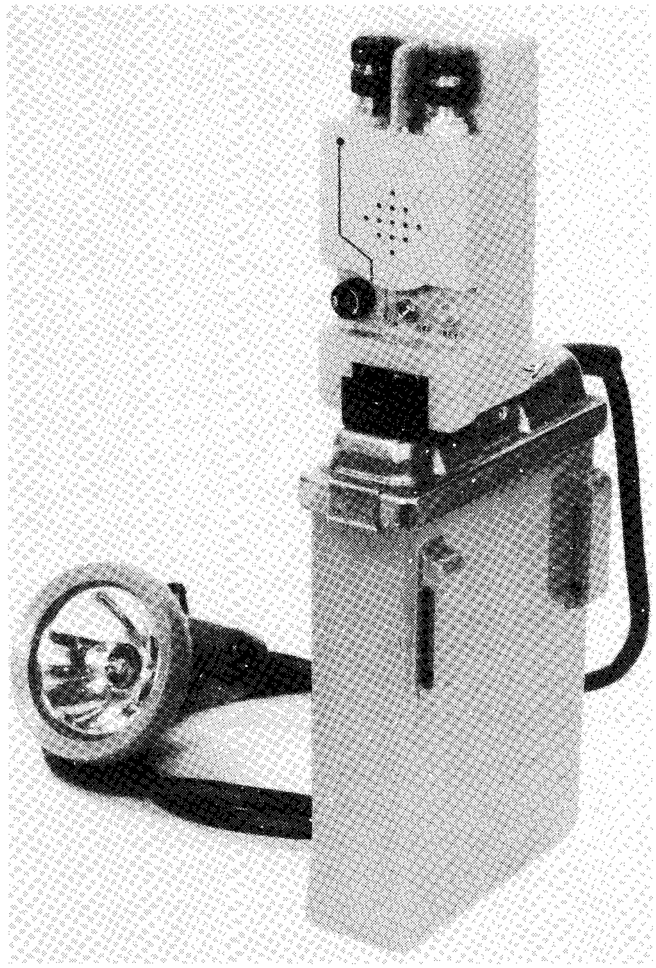

FIGURE 21. - General Instrument transmitter mounted on a modified cap lamp battery.

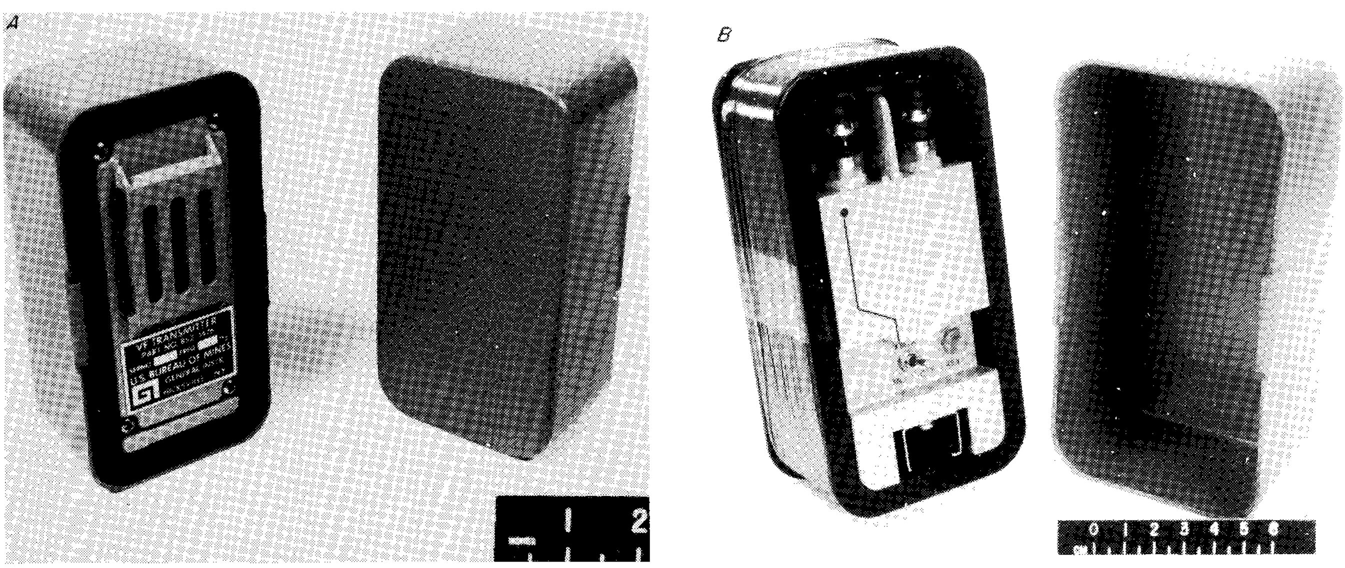

FIGURE 22. - General Instrument transmitter. *A*, packaged belt-worn configuration; *B*, package cover removed exposing antenna spool.

amplifier and large loop of wire are included in the surface equipment. The amplifier provides the capability of voice downlink communications.

Although the trapped miner cannot respond with voice communications, the transmitter is equipped with an on-off key. This key may be used for responding to the downlink voice communications in a coded fashion. In this configuration and with the cap lamp turned off, the transmitter will continue to operate for a period of 2 to 4 days, depending upon the state of discharge the battery was in when the miner became trapped. Figure 23 shows the life expectancy of the cap lamp battery when operating the transmitter. The range of values were obtained using an old battery with an 8-hr discharge to an upper bound of an undischarged new battery. A 2-ohm resistor was used to simulate the antenna load.

As mentioned previously, the prototype units built by General Instrument were mainly in the belt-worn configuration, even though the method of eventual implementation into the mining community has not yet been fully assessed. Other methods of deployment are being considered; a few examples are fixed-position deployment at strategic locations, mounting units on vehicles, having only foremen carry them, and building them directly into the cap lamp battery.

## EM Experimentation

Early in the EM research program, theoretical efforts were undertaken to investigate the surface fields created by a subsurface buried magnetic antenna (14). These formulations assumed a homogeneous earth of conductivity. The conductivity serves to attenuate the signal as it propagates through the earth. Additional theoretical work has been done to include the effects of a stratified earth. However, at these wavelengths, the homogeneous half-space model is usually sufficient.

The research also included an extensive field testing program. The objective of the 94 field tests was twofold. First, the tests were to define a signal transmission and analysis program to obtain a reliable data base for characterizing the signal transmission properties of overburdens in the U.S. coal fields and, second, to use this data base to predict

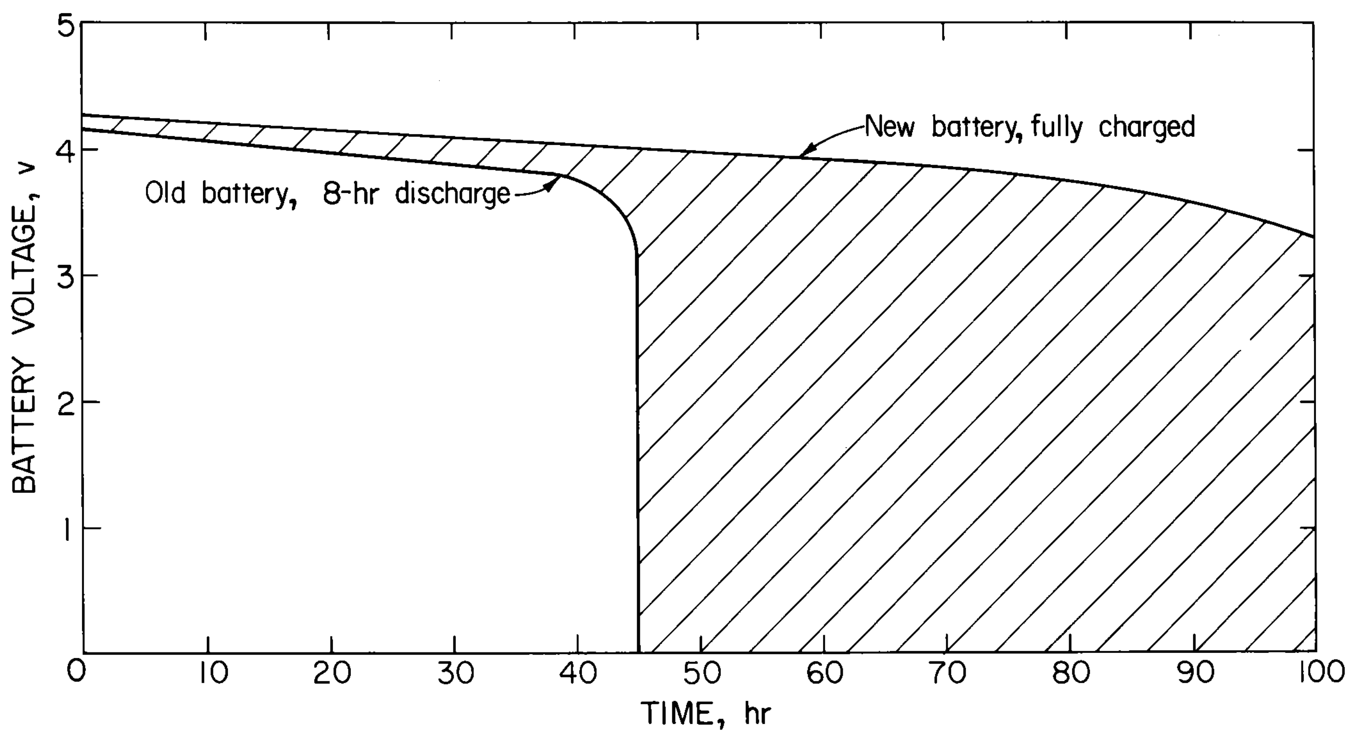


FIGURE 23. - Cap lamp voltage variation with time while operating trapped miner transmitter.

the likelihood of successful performance of the EM trapped miner location system.

The mines sampled for these tests were selected from a population of all coal mines on the basis of both the overburden depth and number of miners employed in the mine. The sample reflected concern both for the physical dependence of signal penetration on depth and the number of miners exposed to potential disasters within each depth interval. Figure 24 shows the cumulative distribution of mines as related to maximum depth and demonstrates that approximately 90 pct of all U.S. coal mines are less than 1,000 ft deep.

The field testing was conducted by Westinghouse (10) and Bureau personnel. Data analysis was performed by Arthur D. Little, Inc. (16). These data are presently still being analyzed by the Bureau attempting to more accurately assess through-the-earth EM propagation by utilizing more complicated mathematical models to describe the data. The Bureau also regularly conducts EM field tests to further supplement this data.

The two most important factors that indicate how well a signal will propagate through the earth are the overburden bulk conductivity and the mine depth. Unfortunately, the geological structure of the overburden above coal mines differs from mine to mine, which causes the

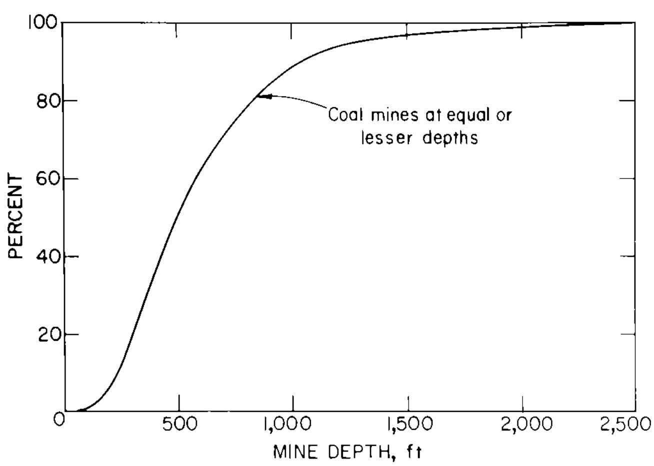


FIGURE 24. - Cumulative distribution of coal mine depths throughout the United States.

electrical conductivity to vary also. Therefore, for a given mine depth, one would expect the signal transmission characteristics to vary from one mine to the next. In order to predict the signal strength at any mine, one must rely on a statistical assessment of the data and then to use this statistical data to determine signal strengths at any mine based on depth alone.

The root mean square (RMS) values of the vertical magnetic field, H, of all of the data taken were normalized to a transmitter magnetic moment of M = 1 amp$^{-2}$. Following this normalization, statistical studies were performed to relate the surface field strength and mine depth at each frequency tested.

Each normalized data point can be denoted as $S_{ij}$, where the subscript i represents the specific frequency and thus the subscript j represents the specific depth of test for each mine. Thus, each surface measurement, $S_{ij}$, taken can be considered as a single observation of the signal strength at a predetermined frequency and overburden depth level at a particular mine. The selection of the mines tested was done on a statistically based random sample to assure that $S_{ij}$ could be described by a common normal probability law.

Several linear regression models were hypothesized and tried. The model found to best fit the behavior of the data is one in which the mean value of the normalized signal strength, $S_{ij}$, is linearly related to the logarithm of overburden depth. This is shown in equation 1.

$$S_{ij} = \alpha_i + \beta_i \log(\text{depth}) + \varepsilon_{ij}. \qquad (1)$$

Here $S_{ij}$ is the normalized vertical magnetic field signal strength (expressed in db re 1 μamp/m-RMS for the ith frequency and depth j for a transmit moment of M = 1 amp-m$^2$).

The parameters $\alpha_i$ and $\beta_i$ are parameters to be estimated from the data, where depth is known in meters. The parameter $\varepsilon_{ij}$ represents a random variable that is normally distributed, with expected value zero and variance which is the same for all values of j.

The derived regression lines for each of the four frequencies are plotted in figure 25. It is visually apparent that the log-linear relationship is an appropriate one and the $R^2$ statistic, a measure of goodness of fit, supports this observation.

Two types of intervals have been estimated from the data. One is known as a confidence interval, which is defined as a range of values computed from the sample that can be expected to include the true (but unknown) mean value with a known probability. Figure 26 displays 95-pct confidence intervals with dashed lines. To illustrate this concept using figure 26*A*, it follows from the field experiment that the probability is 95 pct that the interval from -6 to -12 db includes the true mean normalized signal strength for a transmitter of magnetic moment M = 1 amp-$m^2$ at 630 Hz and an overburden depth of 190 ft.

While the confidence interval represents a probability statement about a mean value over many trials it is also of interest to quantify the expected outcome of a single trial. For example, what signal strength could be expected if a test were conducted at a predetermined frequency and overburden depth? This situation is depicted by prediction intervals also plotted in figure 26. To illustrate this concept, again using

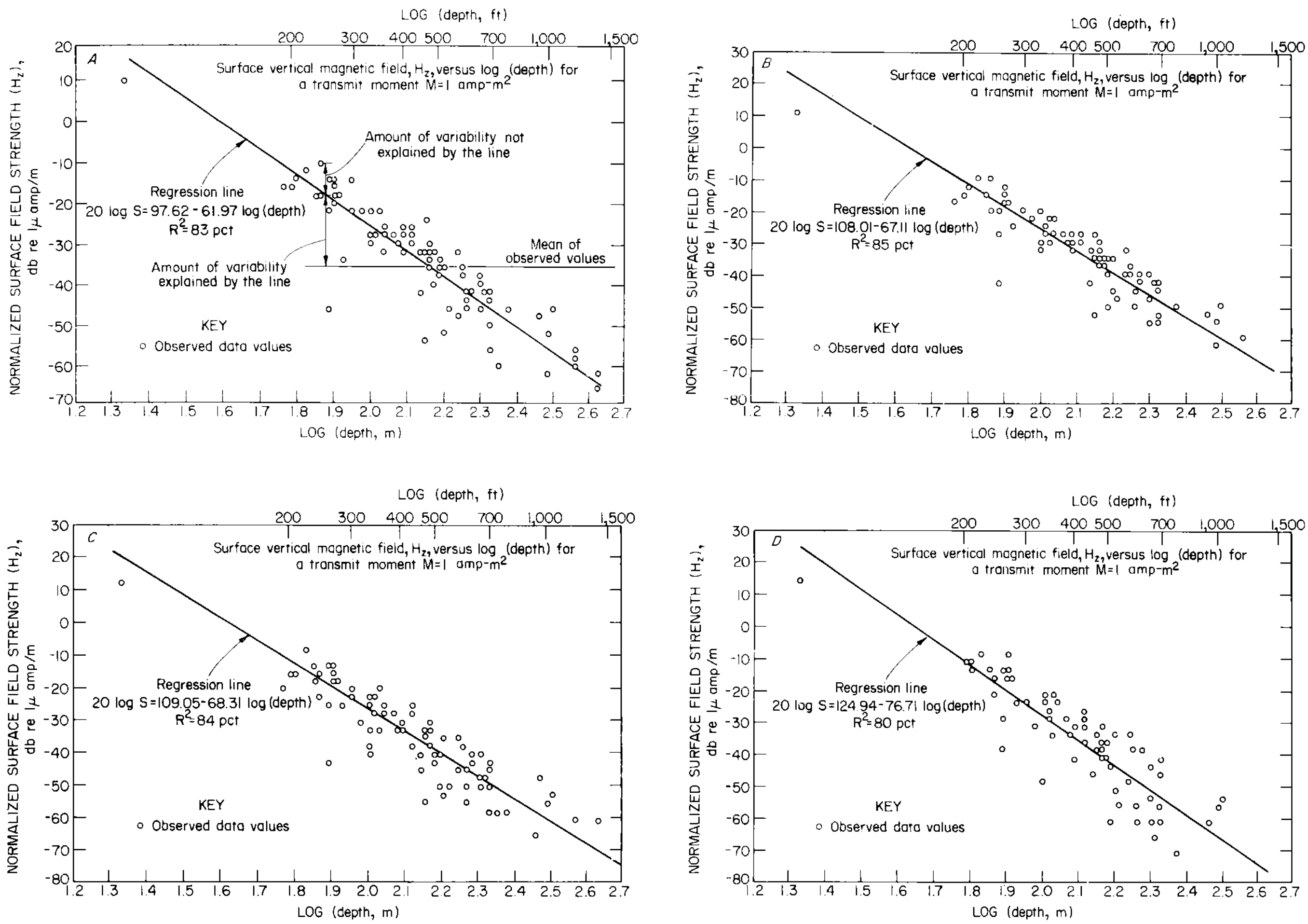


FIGURE 25. - Uplink normalized overburden signal response data and linear regression log (depth) model. *A*, at 630 Hz; *B*, at 1,050 Hz; *C*, at 1,950 Hz; *D*, at 3,030 Hz.

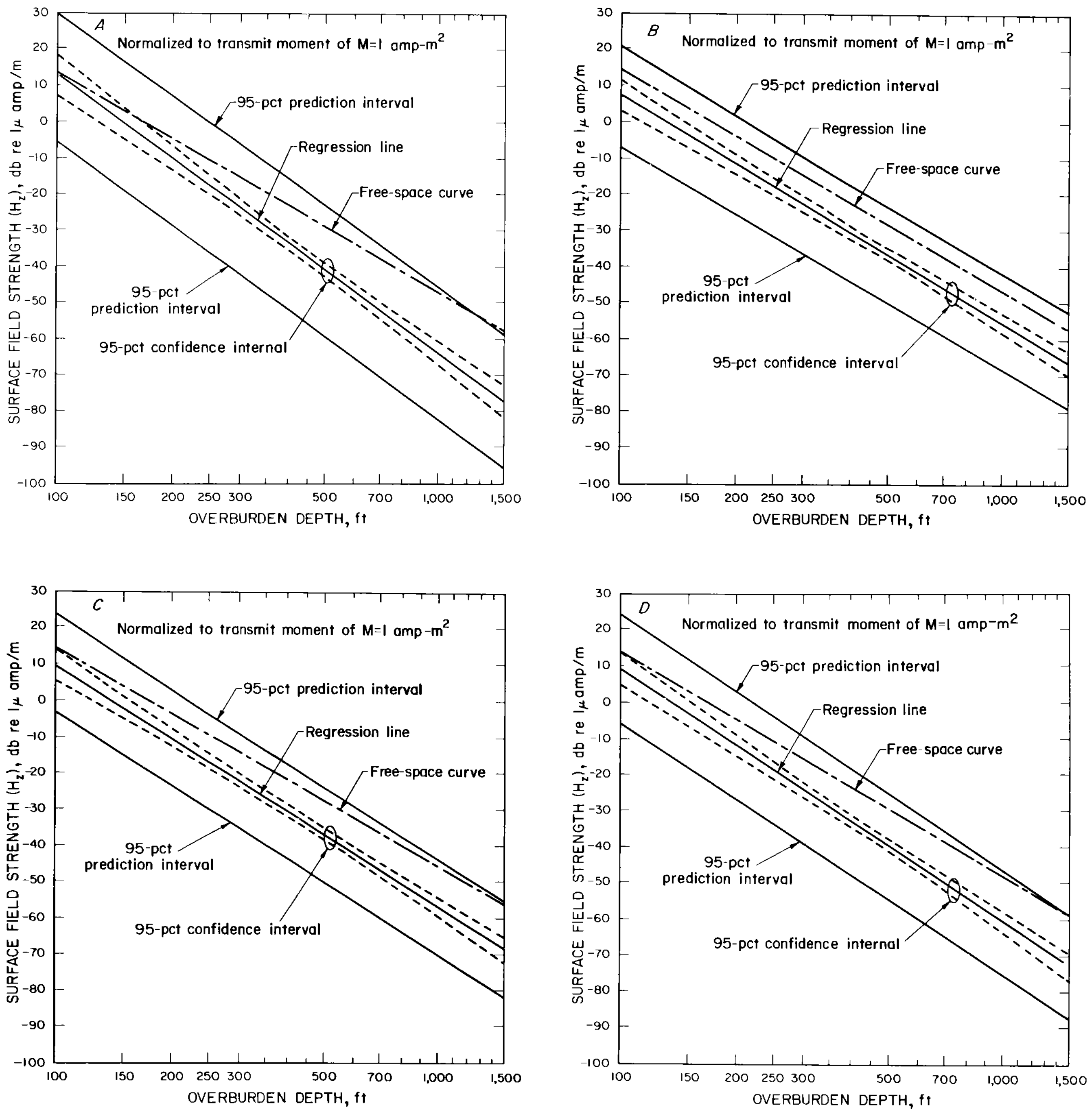


FIGURE 26. - Uplink regression results, normalized vertical signal strength, hertz versus depth. *A*, for 630 Hz; *B*, for 1,050 Hz; *C*, for 1,950 Hz; *D*, for 3,030 Hz.

figure 26, the probability is 95 pct that another test performed at 630 Hz at a depth of 500 ft would yield a signal strength between -49 and -22 db. Also plotted in figure 26, for comparison, is a curve of the free space vertical field strength that would be measured on the surface in the absence of the lossy overburden media.

Figure 27 summarizes the normalized average overburden response as a function of depth and frequency by plotting the four regression lines and the free space curve on the graph. This figure shows that the frequency dependence of signal strength is relatively insignificant for depths less than 500 ft, and that the change across the band is only about 10 db even at the maximum depth of 1,500 ft.

These summary normalized overburden response plots, together with the confidence and prediction levels of this section, can be used to generate estimates of signal strength produced on the surface above coal mines as a function of overburden depth and operating frequency for transmitters having any prescribed magnetic moment versus frequency characteristics in the 630- to 3,030-Hz band.

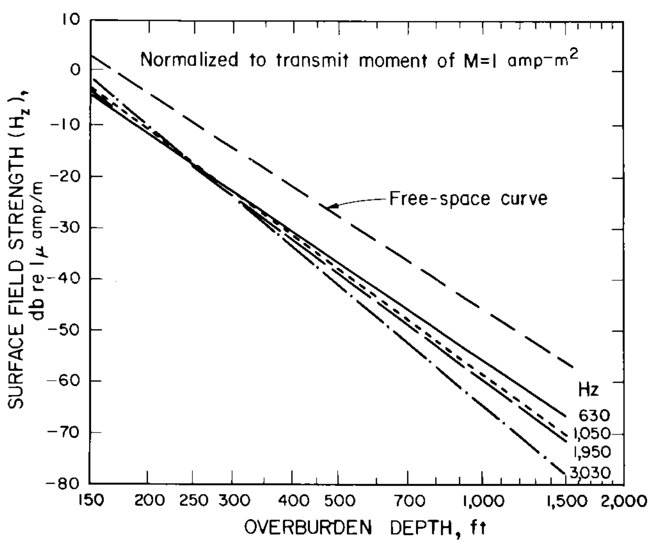


FIGURE 27. - Normalized overburden response curves. Uplink regression results, average surface vertical signal strength, hertz versus overburden depth by frequency.

## EM Noise

Magnetic field noise measurements were obtained during the course of the measurement program. This set of data was obtained by a Bureau team performing noise analysis of 27 of the 94 mines tested. The Bureau's data were gathered on tape and later analyzed in the laboratory. For purposes of signal detectability, the RMS value of the vertical magnetic field is of interest. The statistical distribution of this noise, using the Bureau data base, at each frequency for a receiver bandwidth of 30 Hz is shown in figure 28.

## Surface SNR

In previous sections, the behavior of signal data and noise data obtained in this study have been characterized by statistical relationships. To develop an understanding of detection probability it is necessary to characterize the probability distribution of the surface RMS SNR at each frequency.

The indepencence of signal and noise distributions, in addition to the property of normality exhibited by each distribution, permit straightforward combination of the two distributions to generate SNR probability estimates. By the central limit theorem, the sum (or difference) of two normally and independently distributed variables is also normally distributed.

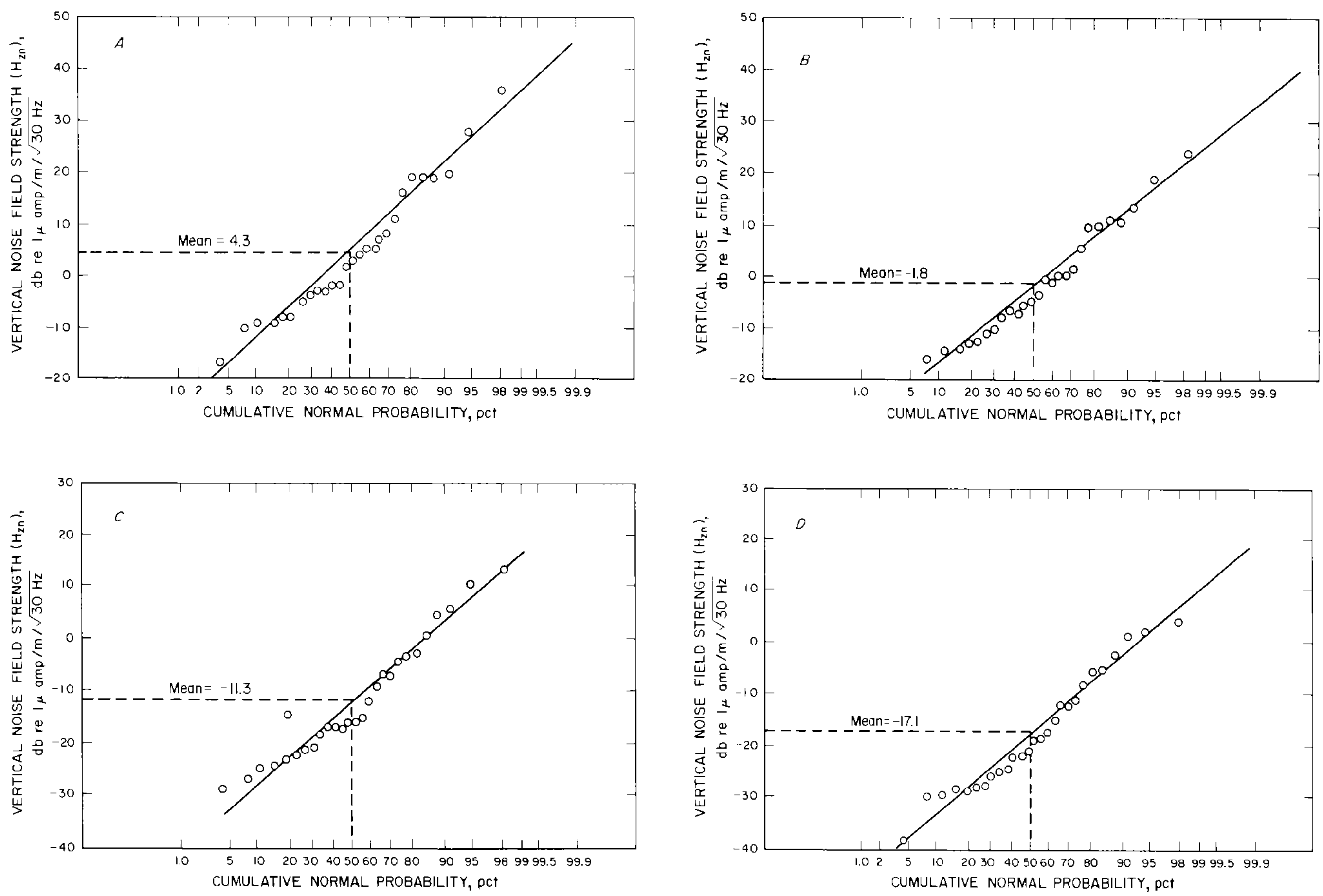


FIGURE 28. - Statistical distribution of RMS surface noise at (*A*) 630 Hz; (*B*) 1,050 Hz; (*C*) 1,950 Hz; (*D*) 3,030 Hz.

The SNR distributions are conveniently plotted using normal probability paper. Such normal probability plots derived are given in figure 29 for five different overburden depths at each of four frequencies.

These four graphs provide a straightforward method to estimate the probability of having various SNR's in actual practice. The vertical axis represents the area under the normal curve from minus infinity to some SNR, $R_o$, and provides the probability of achieving a SNR less than or equal to $R_o$.

It is instructive to observe the behavior of probability estimates associated with exceeding a given SNR as a function of overburden depth and frequency. Figure 30 gives the the probability of the RMS signal being at least greater than RMS noise. Note that the best performance occurs in the upper part of the frequency band even though more loss occurs through the earth at the higher frequencies and the magnetic moment is smaller at the higher frequencies. This can be explained owing to the rapid decrease in surface noise levels as frequency increases.

## Signal Detection Criteria

The success of rescue effort when using a trapped miner transmitter rests on the ability of surface personnel to confidently detect the signal from the underground transmitter. The pulsed signals from the underground transmitters are detected by searchers carrying rescue receivers equipped with a hand-held loop antenna and headsets. The mode of detection is aural, based on the headset

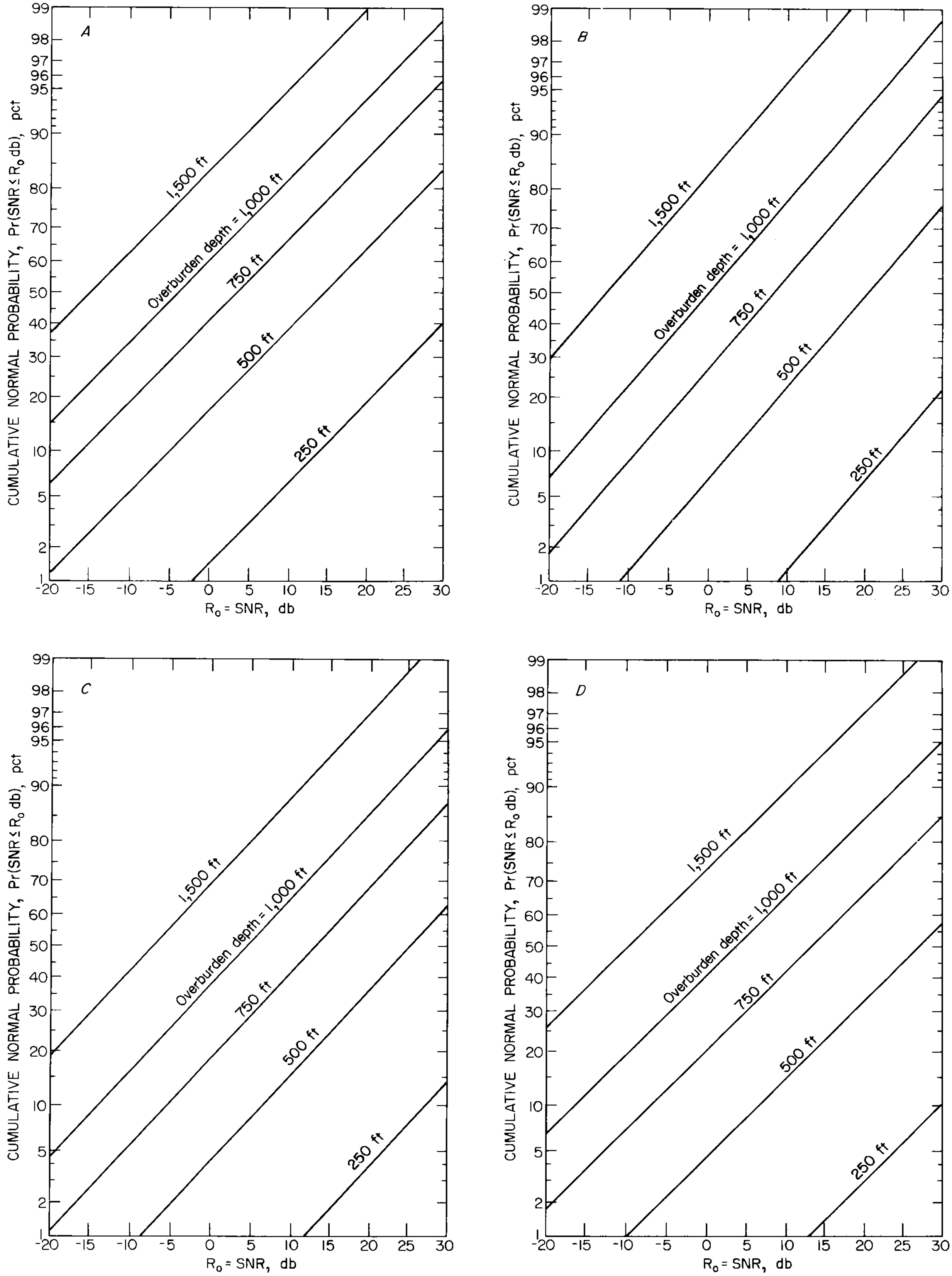


FIGURE 29. - Cumulative probability distribution of SNR's expected above U.S. underground coal mines at (*A*) 630 Hz; (*B*) 1,050 Hz; (*C*) 1,950 Hz; (*D*) 3,030 Hz.

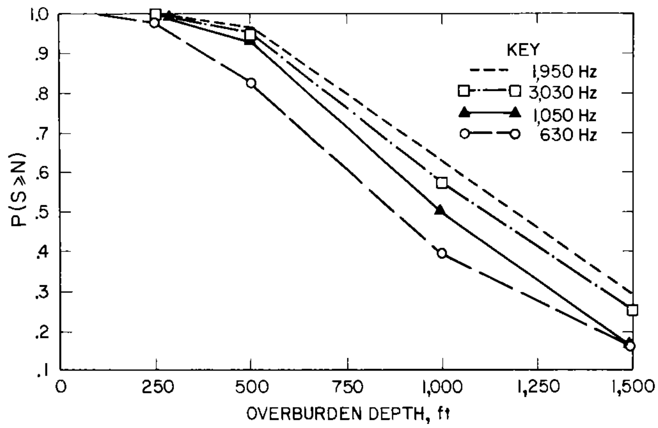


FIGURE 30. - Probability that mean RMS signal is greater than or equal to RMS noise +9 db for General Instrument transmitter.

signals perceived by the ear. It is then necessary to establish a relationship between the nature of the signal, SNR, and the probability of aural signal detection.

The aspects of the signal that influence detection are (a) frequency, (b) signal length, and (c) signal repetition. The primary aspect of the noise for detection considerations, besides the level of the noise, is the noise bandwidth. How each of these parameters affects the signal detection capability must be understood, then their results can be combined to generate a probability of detection curve as a function of SNR.

The present receiver mixes the received signal with an internal oscillator to a higher frequency for purposes of narrow-band filtering, then mixes the filtered signal again to present a listening signal of 978 Hz to the operator. The ability to detect a tone masked by broad-band noise as a function of frequency has been studied by Urick (22).

When the ear listens for a tone, it acts as a narrow-band filter centered at the signal frequency. The bandwidth of this apparent narrow-band filter is known as the critical bandwidth. The bandwidth is approximately 60 Hz at the 978 Hz listening frequency of the rescue receivers.

The pulse length is also an important aspect of signal detectability. Psychoacoustic data taken by a number of investigators determined the "recognition differential" required versus pulse length for a 50-pct probability of detection. The recognition differential is the amount in decibels by which the signal level needs to exceed the measured noise spectrum level (noise level in 1 Hz within critical band of interest) to provide a 50-pct probability of detection. The General Instrument (GI) transmitters have a fixed pulse duration of 100 msec which prescribes a recognition differential of 23 db to achieve a 50-pct probability of detection. To determine the significance of the 23-db recognition differential in terms of required SNR, a bandwidth must be chosen. The bandwidth used in the receiver is 30 Hz, one-half of the critical bandwidth of the ear at the listening frequency.

Studies (18) have shown that systems with bandwidths approximately one-half the critical bandwidth will behave in the same manner detectionwise as those having a system bandwidth equal to the critical bandwidth. Therefore, for purposes of the trapped miner system, a SNR of 23 $-10 \log 30 = 8$ db is needed to yield a 50-pct probability of detection.

A final factor affecting detection is the signal repetition rate. Garner (10) provides data on the effect of the repetition of a pulsed tone on signal detectability. According to this work the 1-Hz repetition rate of the trapped miner transmitter should require 2 db less SNR. The 50-pct probability of detection SNR criterion of (8 - 2) db or 6 db, will be used.

This work quantifies the necessary SNR to establish a 50-pct detection probability. It is also necessary to extend this work to determine detection probabilities at any other SNR. The results of this extension are shown in figure 31. This plot can be used with the earlier established expected SNR for the underground transmitter to establish signal detection probabilities.

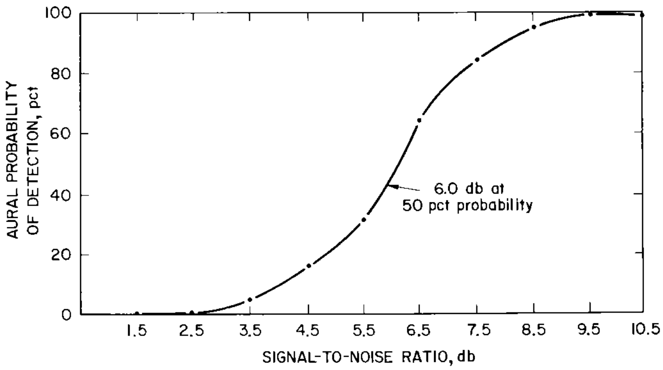


FIGURE 31. - Aural probability of detection versus RMS SNR for trapped miner pulsed continuous-wave signals in background Gaussian noise.

## Probability of Detection Estimates

In an actual mine emergency situation many factors will influence the actual ability to rescue the miner. Time of arrival of the rescue team, life expectancy of the miner, search times, and operation time of the underground transmitter are only a few of the factors that have a bearing on the success of the rescue effort. This report has not discussed these points but rather has investigated the detection probability for an existing signal as being measured by a rescue team in an area which in general is directly over the trapped miner. Even within this measurement there are factors such as geology, noise, and depth that influence the probability of success. However, though these factors may not enable the success of this measurement to be stated in a deterministic manner, the chances, as outlined in this paper, can be quantified in a probabilistic framework.

The probability of detection curve in figure 31 actually represents a conditional probability; that is, the likelihood that detection will occur given the presence of a fixed RMS SNR. As a consequence, the chance of detecting a signal transmitted through the earth can be calculated according to

$$P\ \{D \text{ and } R_k\} = P\ \{R_k\} \times P\ \{D|R_k\}, \quad (2)$$

where $\{D \text{ and } R_k\}$ represents the probability of achieving a SNR of size $R_k$ and also detecting the signal embedded in the noise. $P\ \{R_k\}$ is the probability of the occurrence of a SNR of the size $R_k$ and $P\ \{D|R_k\}$ is the conditional probability of detecting a signal given a SNR of size $R_k$.

The results of these calculations present, as shown in figure 32, the expected property of detection estimates for GI transmitter signals as measured over all the U.S. coal fields.

## SUMMARY

A system based upon seismic techniques as envisioned by the NAE in 1970 has proven to be an effective means for detecting and locating miners trapped underground following a mine disaster.

Expected signals from miners pounding on the roof of a mine are of sufficient strength to enable detection over a large area of the mine. Estimations of the location of the trapped miner are of sufficient accuracy to aid the rescue team or the positioning of a rescue drill.

The seismic system, as discussed in this report, is presently operational and in a state of readiness in the event of a mine disaster. It should prove to be an invaluable aid to future postdisaster rescue efforts. The attractiveness of this technique is that it requires no

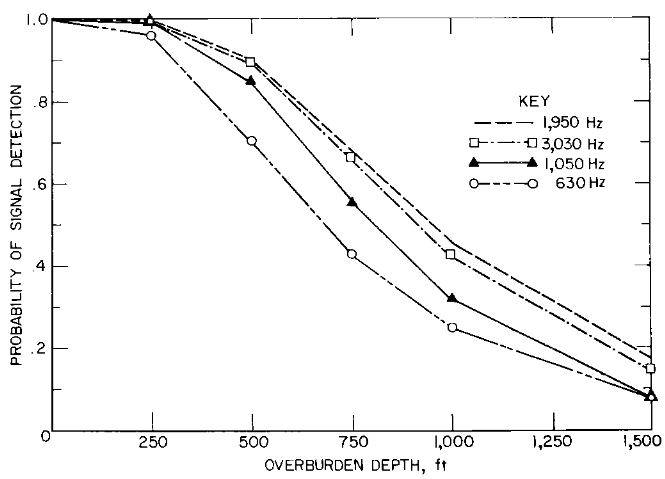


FIGURE 32. - Predicted probability of signal detection versus overburden depth by frequency for the General Instrument transmitter.

active devices to be carried by underground miners. The components necessary for utilizing this method are readily available in any mine. A limitation of the seismic location system is that it provides no communication capability. A detailed technical discussion of the seismic system is contained in a report by Durkin and Greenfield (7).

This paper has also outlined the EM trapped miner communications and location research program conducted at the Bureau's Pittsburgh (Pa.) Research Center. It has also discussed the extensive field testing program to evaluate the transmitter performance. Analysis of this data (15) has enabled one to place into a probabilistic framework the ability to confidently detect the signal from the underground transmitter. Results indicate that the probability of detecting this signal is 45 pct at a depth of 1,000 ft, a depth which exceeds 90 pct of the coal mines in the United States, and a 90 pct probability at a depth of 500 ft, a depth which exceeds 50 pct of the mines. This information is vital for the future formulation and promulgation of new regulations written for the use of the EM system.

Studies are currently underway to improve the detection capability by providing signal processing capability in the receiver. Future work will look at a systems approach when using this technique. This study will investigate each element involved in a successful rescue effort, such as research strategies, life expectancies, etc. Coupled with the results discussed in this paper, a thorough understanding of the effective implementation of the EM system will be obtained.

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# BUREAU OF MINES BOREHOLE PROBES PROGRAM

By James R. Means, Jr.[1]


## ABSTRACT

The Bureau of Mines has developed probes for deployment through boreholes drilled into mines for the purpose of remote information retrieval. Various probes provide closed-circuit-TV monitoring, two-way voice communications, temperature measurements, and batch gas sampling. These probes can provide accurate information about the mine environment when access into the mine is impossible.


## INTRODUCTION

Communication with miners and information about environmental parameters are essential to the safe operation of any mine. However, following a disaster (when information is most needed), the normal paths of communication into the mine are usually disrupted, and obtaining data about the mine and communicating with the miners are impossible. Consequently, the Bureau of Mines has developed several types of borehole probes, each capable of establishing a telecommunications link into the underground environment via boreholes drilled into the mine.

These cylindrical probes are lowered into the mine via a combination strength and communication cable. Although the probes are by nature limited to obtaining information in the immediate vicinity of the borehole, they can reach locations inaccessible by conventional means. To maximize the utility of the probes, care must be exercised in the selection of sites for borehole drilling, and drilling should commence at the earliest possible time since the drilling of a single borehole may take several days.

Applications to data have been in three separate but related categories:

1. Location of trapped miners.

2. Collection of environmental data following a mine disaster.

3. Diagnostic work in mine subsidence efforts.

Capabilities of existing probes include closed-circuit TV, two-way voice communication, remote gas sampling, and remote temperature readout. Currently the closed-circuit-TV capabilities are being upgraded, and additional probes are being considered for high-temperature mine fire applications.

## TV PROBE

The oldest of the Bureau's probes is the TV probe, which was developed for use in trapped-miner detection but has also found use in mine subsidence efforts and even in a shaft inspection. Figure 1 is a drawing of the probe.

The TV probe features a low-light-level TV camera, which was developed for the National Aeronautical and Space Administration (NASA) by Westinghouse. This camera utilizes a silicon-intensified-target (SIT) vidicon, which enables it to function at faceplate illuminations as low as $10^{-5}$ foot-candles. Focusing and iris control are accomplished via a custom remote-controlled lens, and the view orientation of the camera is converted from downward to horizontal via a 45° mirror placed just below the camera lens.

[1]Electrical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

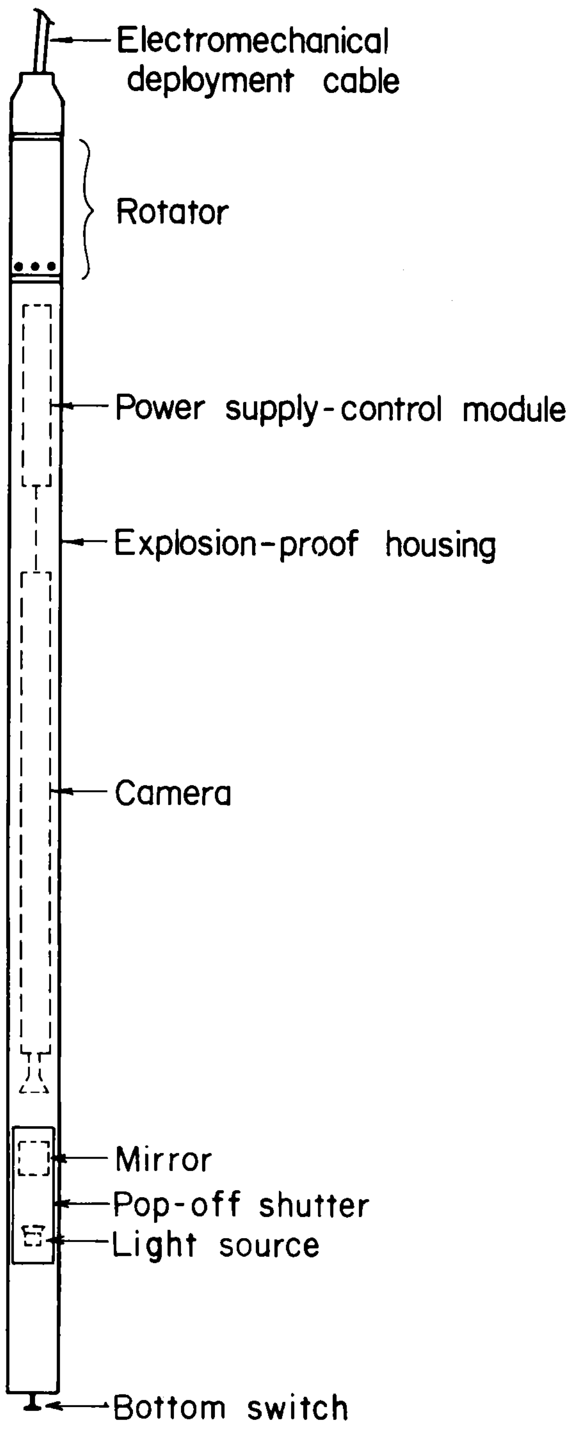


FIGURE 1. - Mark III television probe.

The camera, the remote lens, and an NiCd battery pack to power the probe are encased in an explosion-proof housing to mitigate any potential explosive hazard associated with these components. This configuration has prevented wires from being routed to the bottom section of the probe. Consequently a self-contained light section was designed.

The light section consists of a miner's cap lamp mounted for horizontal illumination and a NiCd battery pack. This arrangement provides illumination suitable for viewing at distances of up to 70 m (220 ft). Focusing of the cap lamp is done manually before the probe is deployed.

The probe can rotate through a full 360° via a rotator section in the top of the probe. This section contains a motor-gear unit which rotates the bottom of the probe with respect to the top section. Double-armored cable, which is used in TV probe applications, prevents the top section from rotating. Thus the bottom section rotates as the top remains stationary.

To minimize dirt in the optics of the system, a spring-loaded pop-off shuttle is placed over the cutaway sections of the main probe housing. When the probe hits the bottom of the mine, a bottom switch activates a screw-drive mechanism which releases the spring-loaded shutter. This removes any dirt from the optical path that has been accumulated during the descent of the probe.

This probe is large, measuring 291 cm (9 ft 6-5/8 in) tall by 8.9 cm (3-1/2 in) in diameter, and weighing approximately 135 pounds. It is deployed via a double-armored cable which has a break strength of several thousand pounds. The cable contains 13 conductors and an RG59 coaxial cable (coax). The probe uses five wires and the coax. Connection of the probe to the cable is done by a machined stainless steel marine-type connector which provides mechanical strength as well as electrical connection.

The TV probe is deployed from a custom-built truck-winch system which was configured to fit on a C-120B airplane (fig. 2). This allows for rapid deployment in emergency situations. The winch was fitted with approximately 2,000 ft (615 m) of cable, and a 6.5-kVA generator was mounted on the truck to provide power for the probe and associated equipment. The truck-probe system has been successfully deployed and was delivered to the

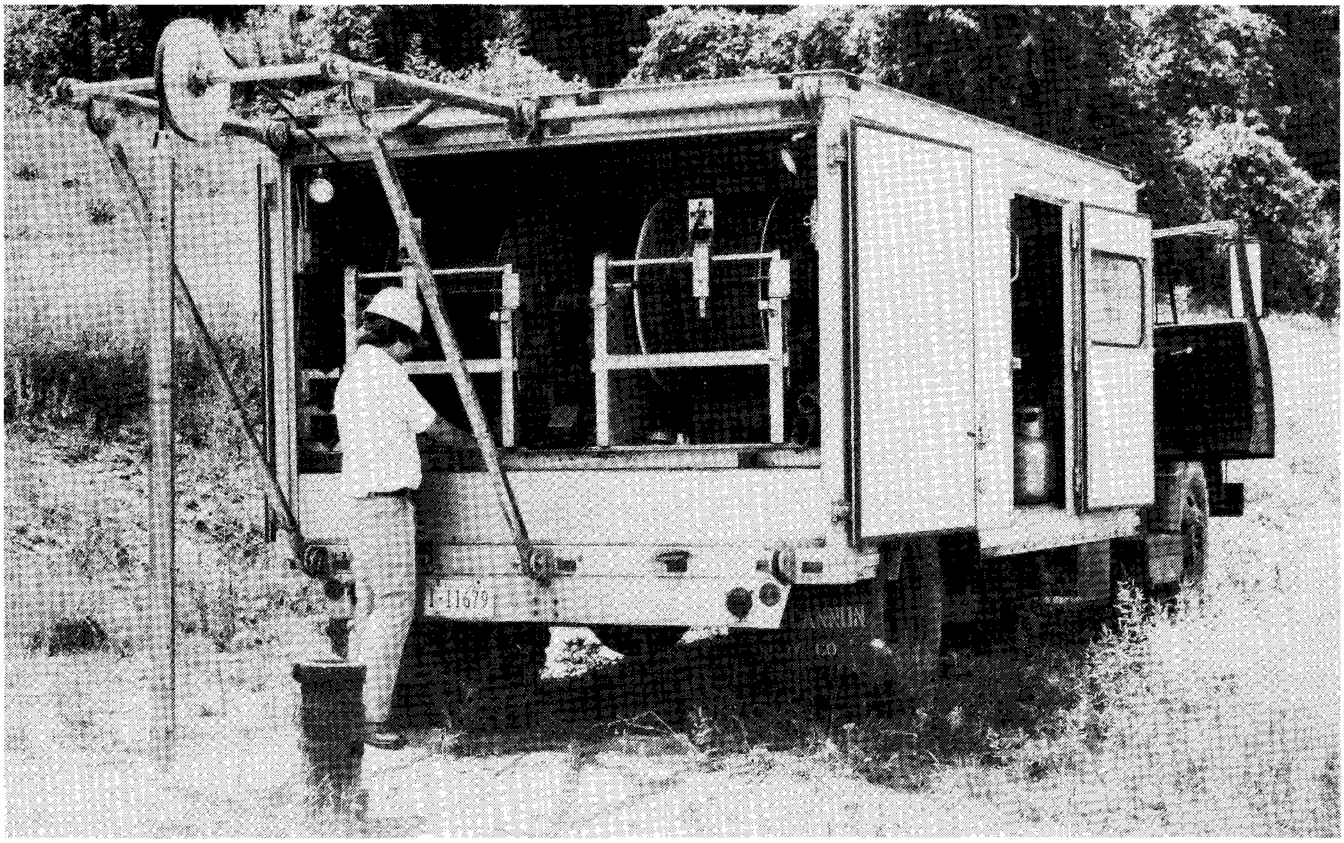


FIGURE 2. - Custom-built truck-winch system.

Mine Safety and Health Administration's (MSHA's) Mine Emergency Operations (MEO) group for use in postdisaster operations.

A new version of the above probe is currently under construction for the Bureau of Mines[2] that will extend the capabilities of the TV probe. This will include the addition of an electronic compass with remote readout, a remote zoom lens, and multiplexing of all control signals onto the video coax. All original probe functions will be retained, and the outside diameter will be increased to 10 cm (4 in).

Additionally, a new section will be provided that will permit downward viewing (fig. 3). This unit will require a 26-cm (10-in) hole and should be useful in shaft emergencies. The new probe should be completed in fiscal year 1983.

## COMMUNICATIONS PROBE

Technical and regulatory constraints on the explosion-proof housing of the TV probe made inclusion of voice communications impossible. Consequently, a separate probe was designed and constructed to meet this need. This probe is much smaller than the TV probe and can be deployed by a hand-operated winch, as illustrated in figure 4.

[2]Design Engineering Laboratories, Torrence, Calif. 90505, Bureau of Mines Contract HO308041, Closed Circuit TV Borehole Probe.

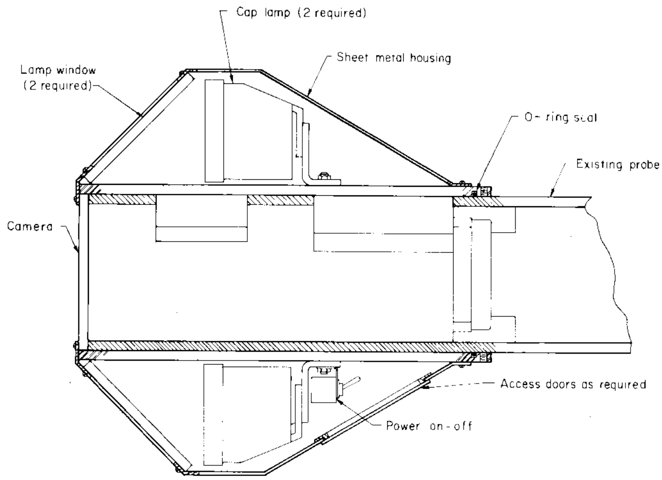


FIGURE 3. - Downhole-viewing module.

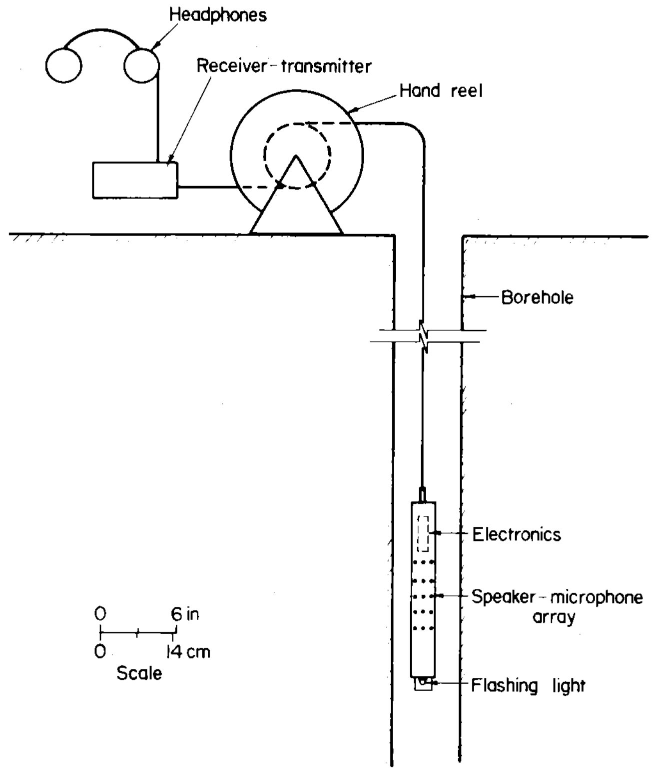


FIGURE 4. - Communications probe.

Circuitry for this probe is simple and intrinsically safe. The transmit circuitry is contained in the uphole control unit, and the speakers are in the probe. Receiver circuitry consists of a microphone with a solid state amplifier which transmits a signal to a receiver in the uphole control unit. Transistor radio batteries (9-V) are located in both the probe and the control box for powering circuitry.

A flashing array of LED's is located at the bottom of the communications probe as a visual indication of the probe's presence. This circuitry is powered by its own 9-V transistor radio battery.

The communications probe operates at voice frequencies and is of the push-to-talk type of operation. No plans exist to improve this probe, which is capable of operation at sufficient depth for use in any U.S. mine. This probe was also delivered to MSHA's MEO group.

BATCH GAS-SAMPLING PROBE

Traditionally, gas-sampling remote areas of a mine following a disaster has been done through a plastic tube lowered into the mine via a borehole. This can be done accurately, but owing to stretching of the tube, the user never is sure of the depth of the end of the tube. It is also good practice to have a redundant reading to verify data. Consequently, a batch gas-sampling probe was developed for MSHA by the Bureau of Mines with a bottom indicator to assure samples are taken within the mine.

Figure 5 shows the batch gas-sampling probe and its control unit. Three separate vacuum bottles are contained in the probe. Each of these can be punctured individually with a hypodermic needle driven by a motor-worm gear unit which will automatically retract. This permits a gas sample to enter the bottle, which can later be analyzed. The sensor on the bottom will give an indication that the probe has reached the mine floor by turning on a light-emitting diode on the control box. These two functions allow batch gas samples to be taken accurately in the mine.

Remote temperature monitoring was also included in this probe. This was done

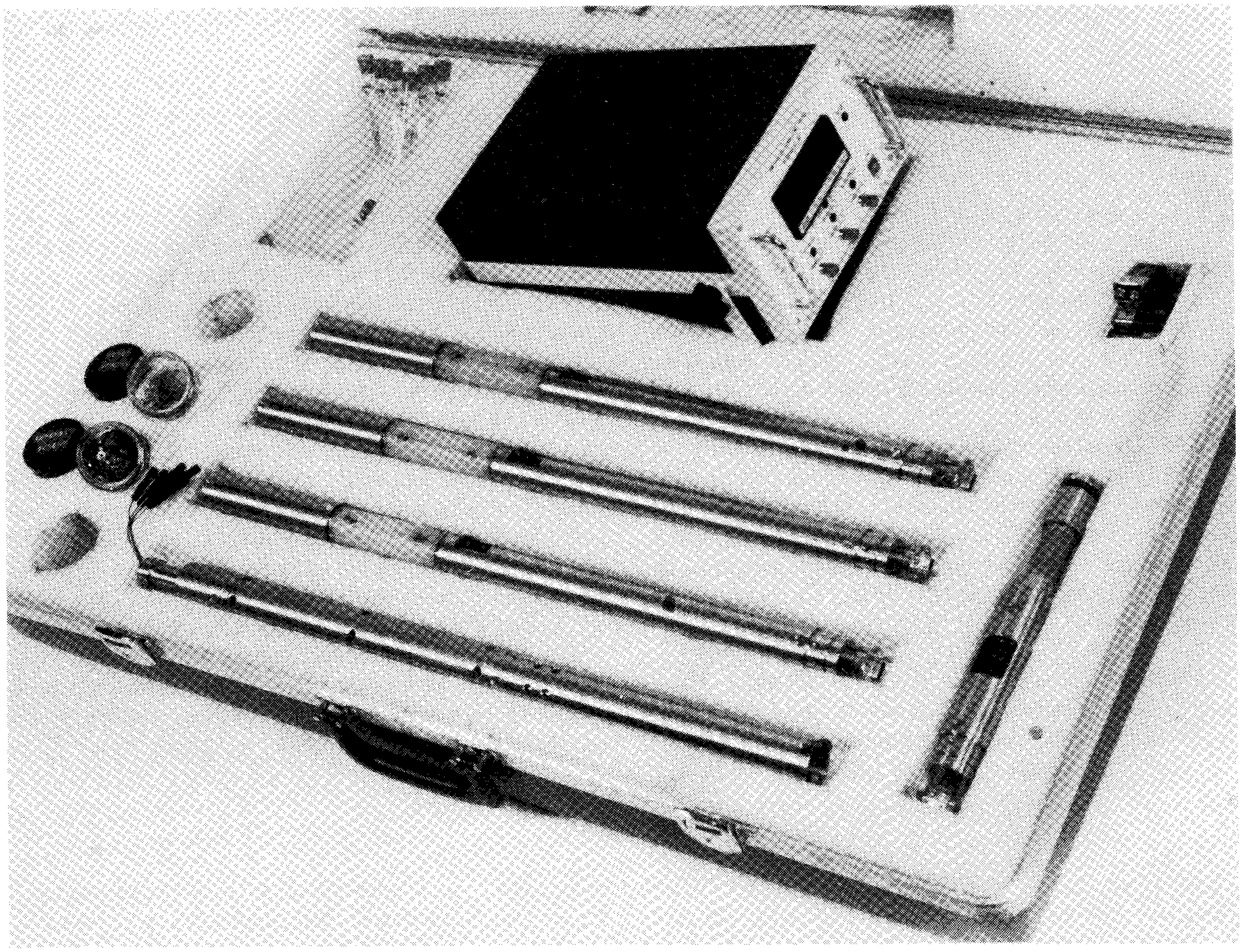

FIGURE 5. - Batch-sampling probe and its control.

with a thermocouple and an electronic ice point reference junction. This allows the reference voltage to be transmitted along copper conductors where it is read out in a digital readout in the control unit.

The probe has been tested in both field and laboratory tests and has been accepted by MSHA. It is currently deployed at MSHA's MEO facility. No plans exist for upgrading this probe at the present time.

## CONCLUSIONS

The Bureau of Mines has developed borehole probes capable of gaining visual information, taking gas samples, indicating temperature, and establishing voice communications through boreholes into a mine. Data gained from these probes can be useful in locating trapped miners or dealing with mine problems if the boreholes are located properly and drilled in a timely manner. These probes are currently under the jurisdiction of MSHA at the MEO facility.

The Bureau is currently upgrading capabilities of the TV probe to include a remote compass, a remote zoom lens, multiplexing of all controls, and downward viewing. These functions will be contained in a new probe scheduled for completion in fiscal year 1983.

# MINE PERSONNEL LOCATOR AND IN-MINE ACTIVITY CONTROLLER

By James R. McVey[1]


## ABSTRACT

The Bureau of Mines, through contract J0205059 with Nelson and Johnson Engineering, Inc., Boulder, Colo., has developed the design for a personnel locator and in-mine activity controller. The new system, when fabricated, will provide mine management immediate access to the location of underground personnel and enable in-mine monitoring and control. The inability to quickly determine the location of underground personnel and control critical underground activities has always been a problem and generally hampers rescue operations in case of disaster.

Although Public Law 91-173 states that each mine operator shall maintain a check-in, check-out system for identifying persons underground, current identification systems provide no means of knowing where a miner is underground. Miners often leave their normal work stations to provide other services. The personnel locator virtually eliminates this change of work station problem with its automatic monitoring capabilities. The system consists of a host (aboveground) computer, strategically located underground remote terminals, and cap-lamp transponders that automatically interrogate the miners any time they pass a remote terminal. Their location change is immediately transmitted to the surface to update the host computer information. The system will monitor personnel and equipment movement and has analog and digital input-output capabilities for measurement and control.


## INTRODUCTION

The inability to quickly determine the location of personnel and control critical underground activities generally hampers rescue operations during and after a mine disaster. Public Law 91-173 states that each mine operator shall maintain a check-in, check-out system for identifying persons who are underground. Nearly all mines today use a large board with numbered hooks and brass tags. When miners go underground, they remove their brass tags from the board and take them along; in some cases, magnetic nameplates are used with two-sided colors which the miners place on a personnel location board to indicate that they are underground. These indicators are returned to an out-of-mine position when the miner exits the mine. A very serious shortcoming exists in this procedure, in that miners often leave their normal work stations and there is no convenient recording method available to notify surface personnel of the change. Post-disaster information on the location of trapped miners has usually indicated that miners were found at locations other than their normal work stations and had not taken expected escape routes.

The mine personnel locator and in-mine activity controller (MPLAC) has been designed to help eliminate this problem. The new system will automatically log the miners into the mine and keep track of their direction of travel and location underground. The system, which has been designed but not built, consists of a host computer, strategically located remote terminals, and cap-lamp transponders (transceivers). Each miner is automatically interrogated as he or she passes or enters the radio frequency (RF) field, which usually extends up to 200 ft from the remote terminal. The miner is identified by an assigned code transmitted

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from the cap-lamp battery transponder to the remote terminal. The remote terminal retransmits this signal to the surface, updating the miner's location and direction of travel in the next polling from the host computer.

The system is also designed as a total mine-monitoring system. The remote terminal not only monitors personnel and equipment locations, but is also equipped with analog and digital inputs and digital outputs for measurement and control. These input-output functions allow measurement of various parameters and activities such as ventilation, toxic gases, smoke or fire detection, and a host of others. The digital outputs allow control of alarms and equipment. An alphanumeric display and keyboard allow sending and receiving of messages between terminals and the host computer. Paging is also provided. A visual page is displayed at the terminal and by a page indicator light on the miner's cap-lamp battery if the miner is within the terminal's transmitting range.

UNITS OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| ft | feet | sec | seconds |
| KHz | kilohertz | tpd | tons per day |
| MHZ | megahertz | V | volt |
| msec | milliseconds | | |

## SYSTEM DESCRIPTION

Though equipment can purchased for monitoring many mine parameters, none can quickly determine the location of underground personnel. The system described in this paper, a combination of available mine-monitoring and computer components, provides a continuous update of personnel location. New features are the cap-lamp transponder and a remote interrogation terminal.

The mine personnel locator (fig. 1) consists of the main host computer and data printer, interconnecting communications data link (coaxial or fiber optics), remote terminals, and cap-lamp transponders. The host computer is a Columbia Products Commander Series 900.[2] The Commander 900 was chosen for its industrial adaptability, memory, and input-output expansion capabilities; many other computers will function equally as well. The data printer is an Okidata u80 and provides a hard-copy output of requested information. The remote terminal, yet to be built, is a microprocessor-based unit that provides automatic transponder interrogation, mine measurements, communications, and control. The transponder, also yet to be built, is a small radio transmitter-receiver that is mini-dip-switch programmed to the miner's identification code. The transponder is located in the hood that covers the top of the cap-lamp battery. Communication between the host and remote terminals is by coaxial or fiber optics cable, user's choice.

## HOST TERMINAL

The Columbia Data Products Series 900 microcomputer is responsible for the general control of all operations. Once programmed, it will continuously poll all underground measurements and cause the remote terminal to produce control functions if programmed to do so. The computer is Z80 microprocessor-based and has 32K bytes of random memory (RAM), expandable to 64K bytes. A dual mini-floppy-disk drive is built into the main frame, providing an additional 320K

[2]Reference to specific products does not imply endorsement by the Bureau of Mines.

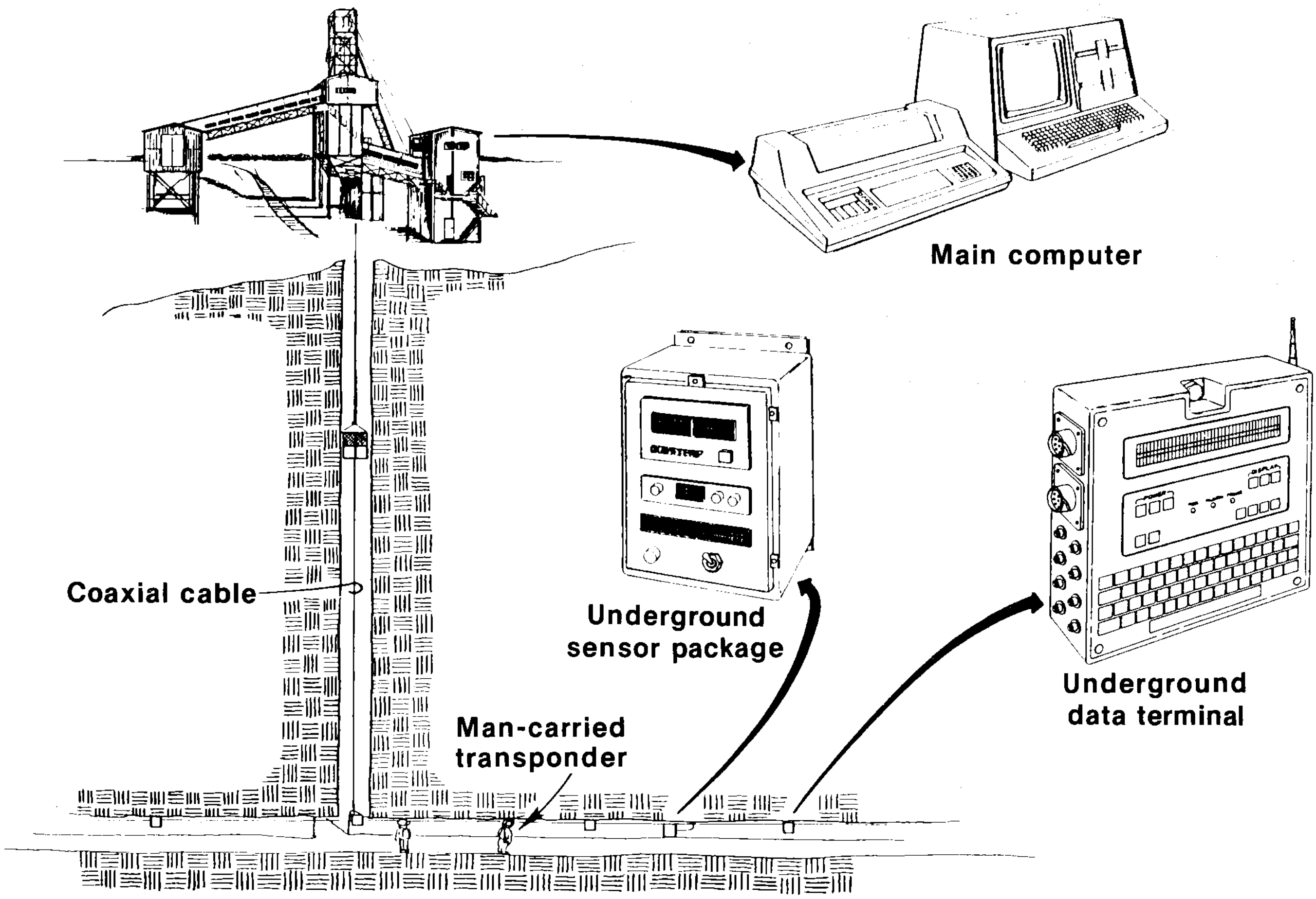


FIGURE 1. - Conceptual view of mine personnel locator and mine activity controller.

bytes. Multiple input-output options are available (fig. 2). The floppy controller can handle two additional external disk drives for further memory expansion. A cathode-ray tube provides visual display of all data requested for viewing by the operator. "Basic" computer language was chosen for the operating system for ease of programming and use by the industry. The computer easily provides control of all functions required for personnel location and underground measurement, plus many management functions such as accounting and maintenance scheduling.

## REMOTE TERMINAL

The remote underground terminal has been designed using an Intersil 87C48 microprocessor and performs the following tasks:

1. Reads and obeys keyboard data input.

2. Displays messages from the host computer and other underground terminals via the host.

3. Provides the host computer with updated transponder data.

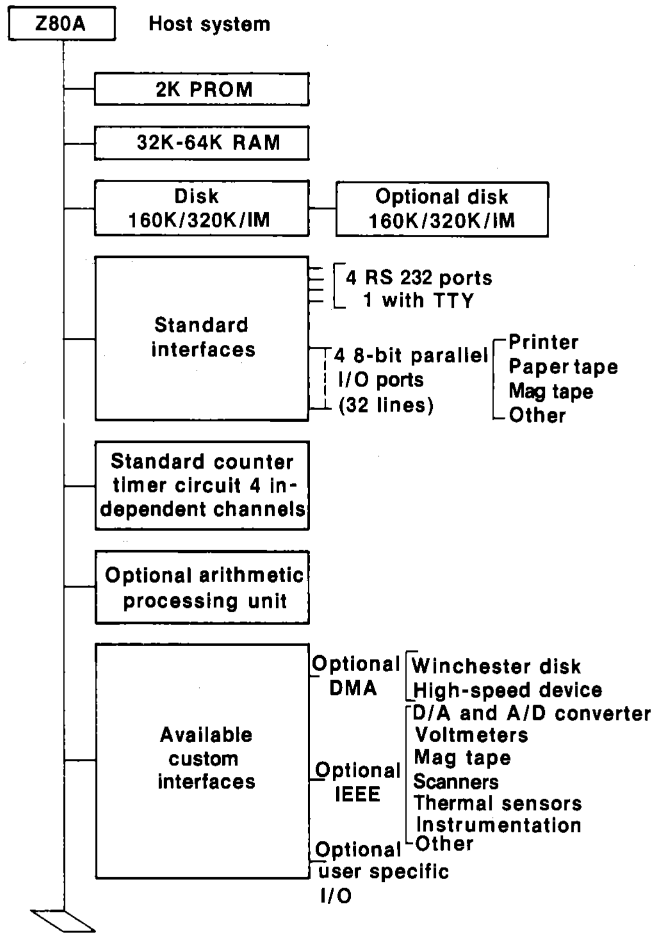


FIGURE 2. - Commander block diagram.

4. Continually interrogates transponders in the area.

5. Measures or interrogates all measurement channels (sensors).

6. Outputs command signals (sets off alarms, etc.).

7. Communicates with the host computer and other terminals via the host.

The remote terminal (fig. 3) is powerful enough to provide multiple functions, thereby relieving the host computer of all underground data retrieval duties. The remote terminal utilizes two 40-character lines for displaying messages readable from 20 ft. Through side-mounted connectors, it can measure up to eight 0- to 10-V differential analog inputs, 12 optically isolated contact closures, and one optically isolated 0- to 100-KHz frequency channel. Four digital output connector channels (contact closures) are provided to set off alarms and control functions. The remote terminal sends out an interrogation pulse (RF signal) to check for miners in the area every 5 sec. This information is stored and polled by the host computer for updating miner location. A full alphanumeric keyboard and special function switches provide data entry and retrieval. Communication between the host computer and terminal or terminal-to-terminal communications can be via coaxial or fiber optics cable. Figure 4 depicts a miner using the remote terminal as a communication device.

## TRANSPONDERS

The miner location transponder (fig. 5) is a small radio frequency transmitter and receiver (transceiver) located in the hood of the miner's cap-lamp battery. The transponder is totally automatic. The miner's recognition code is set into a mini dip switch mounted in the hood of the cap lamp and is a part of a timing circuit. Every 5 sec, a pulse is transmitted from the remote terminal and is received by all transponders in the area. When each transponder (fig. 6) receives a pulse, it starts a countdown to the count set by its own dip switch. When this count is reached, the transponder transmits a code back to the remote terminal, identifying itself within a time window determined by the dip switch. Each timing window (fig. 7) is 20 msec in length. Therefore, 5 sec provides access to 256 transponders (windows). By entering work shift codes into the computer, one can expand the number of total personnel to be monitored. The cap-lamp power cord serves as the antenna, and power is supplied by the cap-lamp battery. A small light-emitting diode, located on the lid of the cap-lamp battery, is turned "on" any time there is a page to be answered. RF transmission frequency has been set at 49.6 MHz.

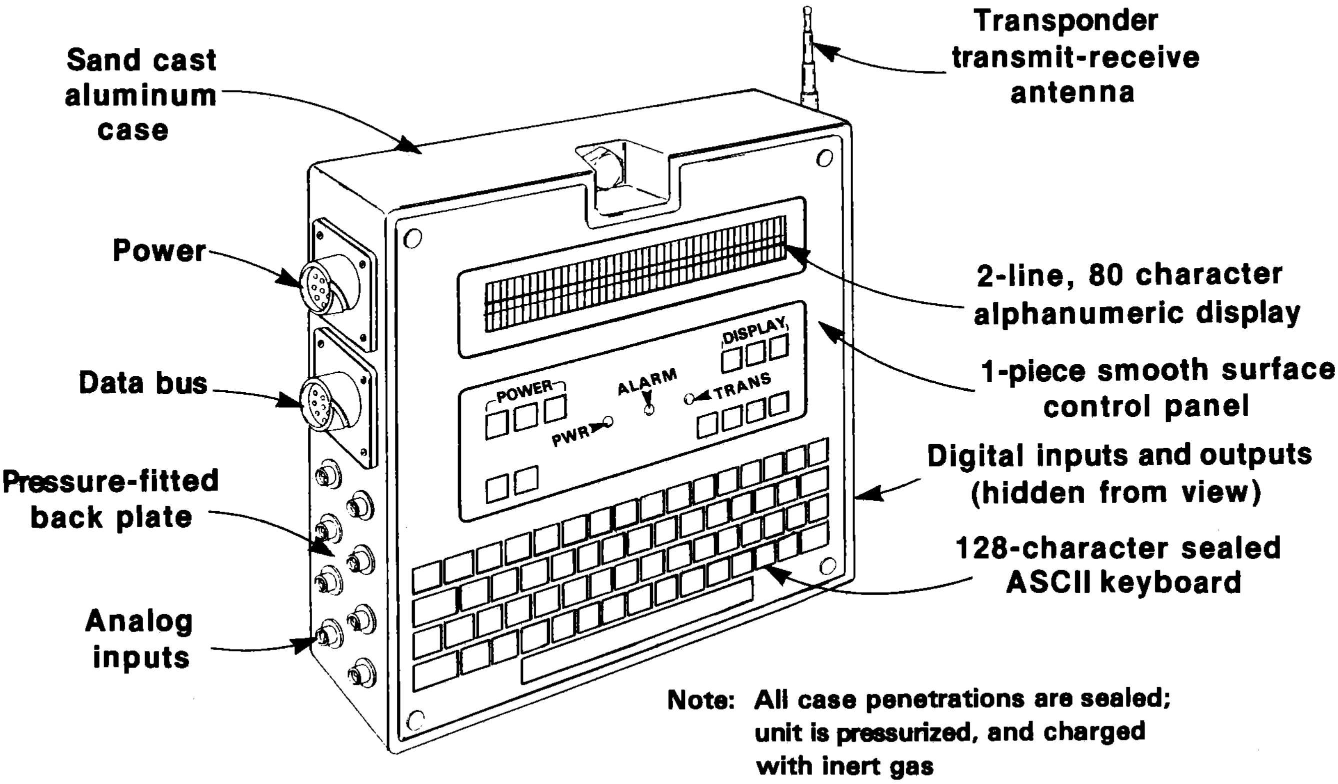


FIGURE 3. - Conceptual drawing of remote terminal.

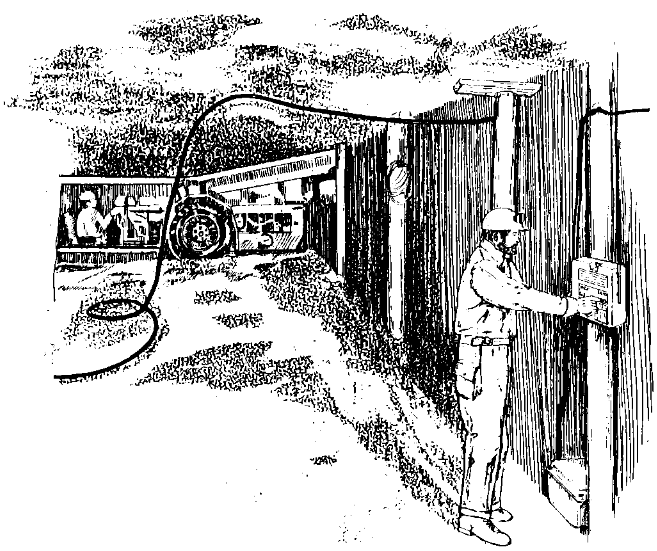

FIGURE 4. - Remote terminal deployment.

COMMUNICATION LINK

The personnel locater can use either coaxial or fiber optics cable for a transmission media. Coaxial cable is much cheaper but it limits band width. Fiber optics transmission gives almost limitless band width for the system. Because fiber optics cable is becoming more cost effective, it will probably be used as the communication link with the first installation.

SYSTEMS UTILIZATION

The MPLAC has been designed to, hopefully, combine the best of two worlds--mine personnel location and underground measurement. The new system will increase safety and emergency capabilities.

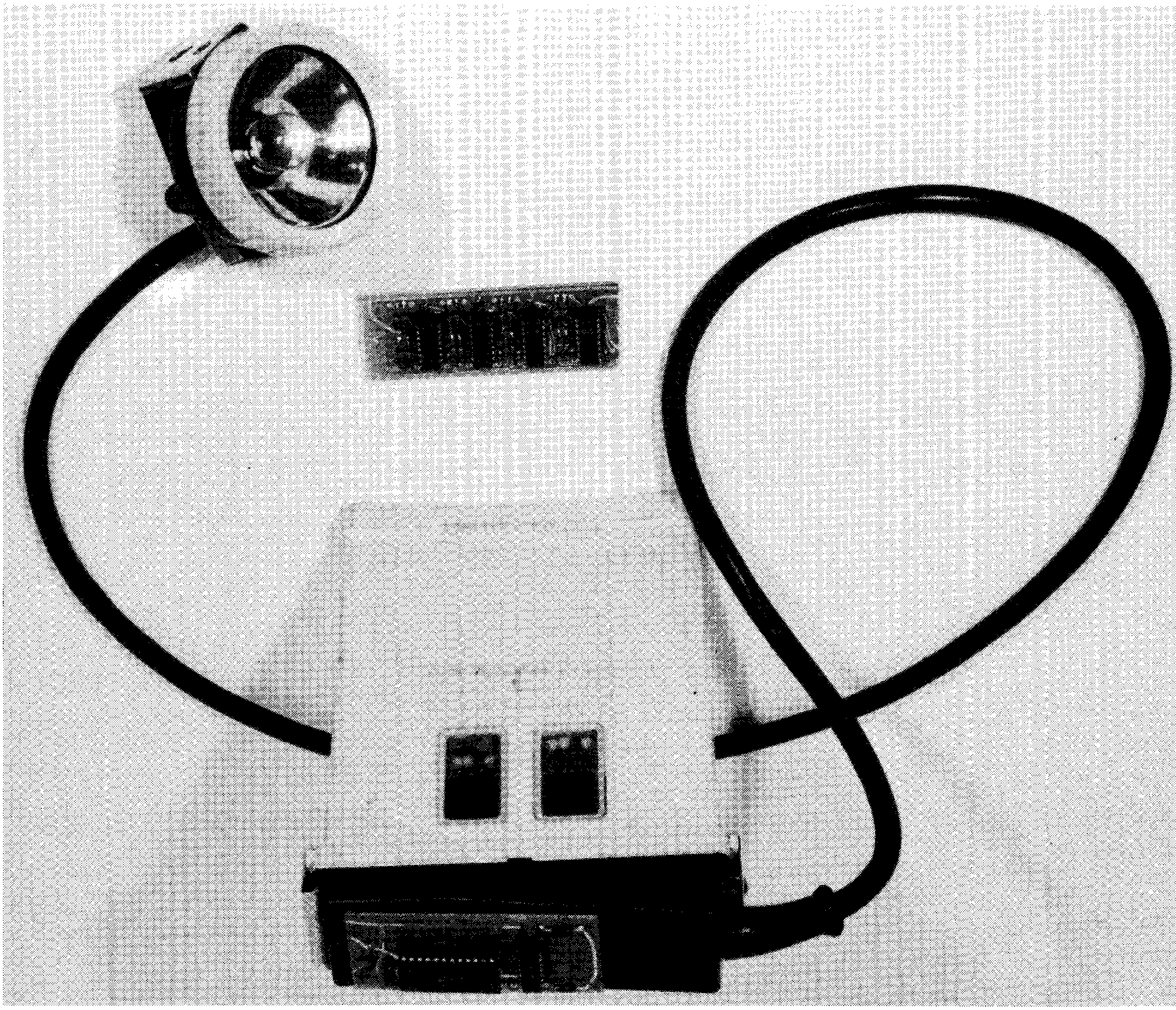

FIGURE 5. - Transponder-cap lamp and battery.

Through proper and multiple use of strategically located underground remote terminals, one can monitor the locations of all underground personnel and mobile equipment. These same terminals can also provide cost savings to the user through their automatic measurement capabilities. The miner can use the MPLAC to monitor conveyor belts, power, power factor, ventilation, methane gas, etc. The monitoring of power and power factor can reduce required feeder and transformer capacities, thereby reducing overall costs. Fire hazards caused by overload or unbalanced loads (creating heat) are also reduced.

The monitoring of belts can reduce maintenance problems and belt downtimes and thus increase production. Many mines have indicated that monitoring belts, alone, has offset the cost of the system the first year of operation. Monitoring power factor, phase loading, and holding down peak power demands during mine startup can bring about reduced power costs and more lucrative power contracts.

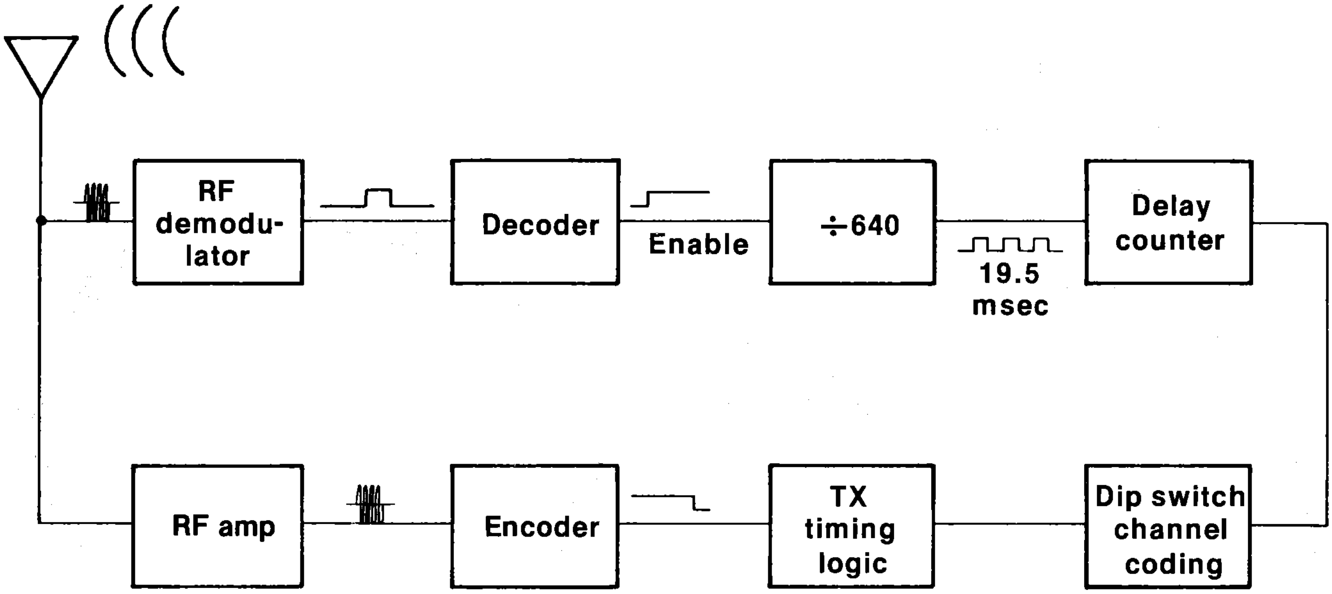


FIGURE 6. - Transponder block diagram.

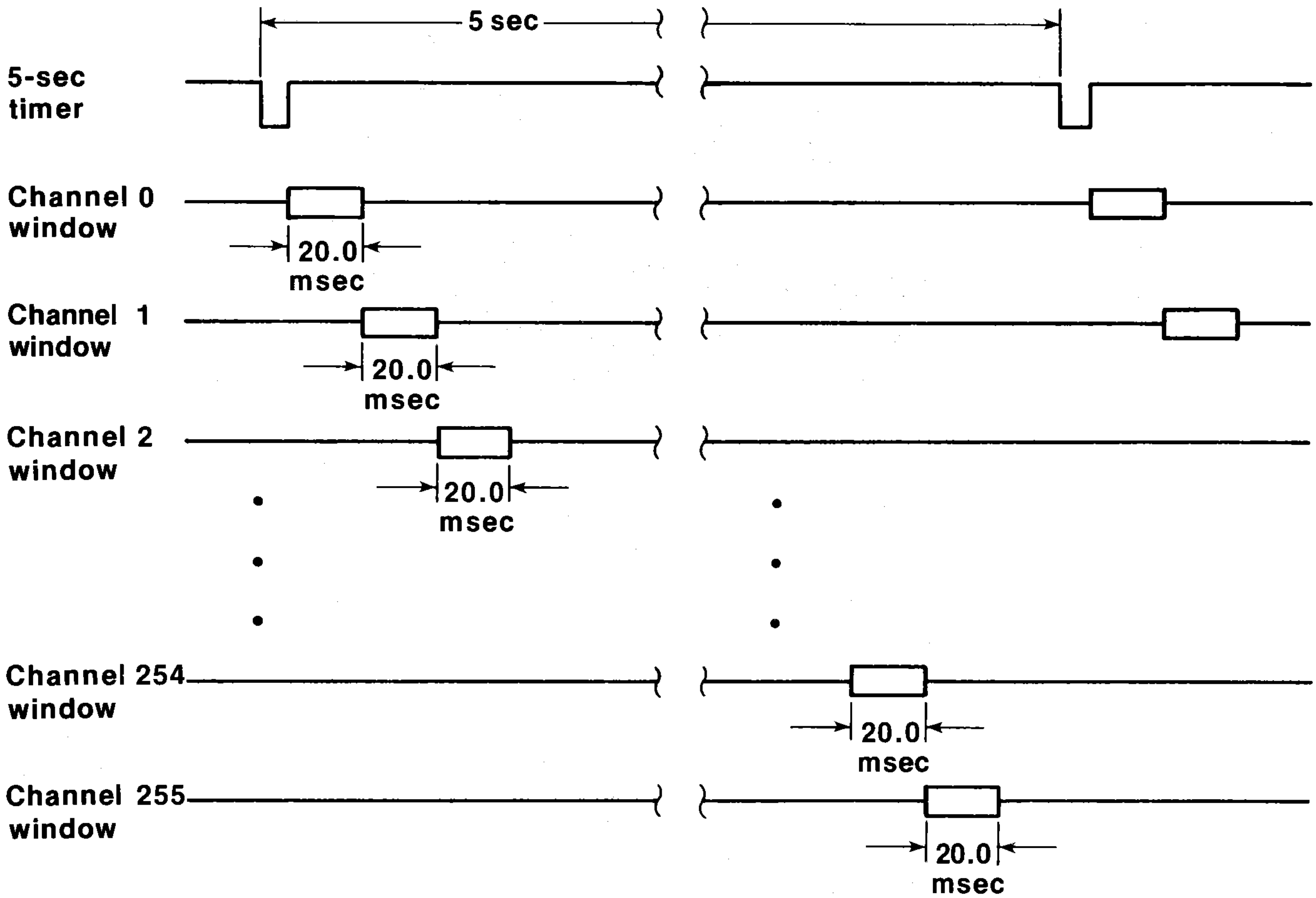


FIGURE 7. - Transponder timing—256 channels.

## CONCLUSIONS AND RECOMMENDATIONS

Present mine-monitoring systems do not monitor miner's location. This conceptual design provides this capacity. It is believed that the Mine Personnel Locator and In-Mine Activity Controller, designed under Bureau of Mines contract J0205059 by Nelson and Johnson Engineering of Boulder, Colo., is a necessary and viable tool for the mining industry. The new system is state-of-the-art in design and versatility. It combines measurement functions and much-needed personnel location into one convenient, easy-to-operate system.

The conceptual design is complete and ready for the hardware construction phase. The mining industry has reviewed the system during the design phase (table 1) and has provided much needed input. Acceptance has been good, and a tentative proposal for a 50-50 cost-share hardware phase has been received from one mine.

TABLE 1. - Mining industry reaction to mine personnel locator and activity controller

| Mine | Type | Estimated size, tpd | Mine monitoring | Digital communications | Personnel locating |
|---|---|---|---|---|---|
| Geneva.... | Coal.... | 1,450 | Neutral....... | Of limited value | Neutral. |
| Sufco..... | ...do... | 9,000 | Very important | .....do......... | Useful. |
| Galena.... | Silver.. | 750 | Useful........ | .....do......... | Useful but difficult to implement. |
| Star...... | ...do... | 1,000 | .....do....... | .....do......... | Do. |
| Highland.. | Uranium. | 3,250 | Very important | Useful.......... | Important. |
| Empire.... | Coal.... | 3,000 | .....do....... | Not needed...... | Very important.[1] |
| FMC....... | Trona... | ([2]) | .....do....... | Neutral......... | Would not buy it. |
| Tenneco... | ...do... | 4,800 | Important..... | Not needed...... | Useful. |
| Texas Gulf | ...do... | 7,000 | Very important | .....do......... | Very important. |

[1]These above respondents indicated that they would probably buy a personnel locator system by itself, if it were offered, and integrate it into their existing monitoring systems.

[2]Tons per day size is proprietary; 6- by 6-mile area.

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