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An Electromagnetic System for Detecting and Locating Trapped Miners

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AN ELECTROMAGNETIC SYSTEM FOR DETECTING AND LOCATING TRAPPED MINERS

by

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ABSTRACT

The theory of electromagnetic fields indicates such fields could be used to detect and locate trapped miners. To be useful, the hardware of the system must meet a number of requirements, including small size, intrinsic safety, and rugged construction. Such hardware has been built, and the system has been tested by the Bureau of Mines and its contractors. These tests indicate that the electromagnetic method provides a practical means to locate miners in emergencies.

INTRODUCTION

Soon after the radio came into common use, the Bureau of Mines recognized its potential as an aid in locating miners trapped by mine fires or explosions. The early experiments[2] indicated that while through-the-earth electromagnetic (EM) communication was possible, the hardware requirements of a practical system could not be met by the technology available at that time. In 1968, however, the Farmington mine disaster resulted in a National Academy of Engineering recommendation[3] that a postdisaster location system be developed.

Thus, in 1970, the Bureau of Mines contracted with Westinghouse Electric Co. (contract H0101262)[4] to develop through-the-earth communication techniques.

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[1]Geophysicist, Industrial Hazards and Communications (now with Sun Oil Co., Houston, Tex.).

[2]Ilsley, L. C., H. B. Freeman, and D. H. Zellers. Experiments in Underground Communication Through Earth Strata. BuMines Tech. Paper 433, 1928, 60 pp.

[3]National Academy of Engineering, Committee on Mine Rescue and Survival Techniques. Mine Rescue and Survival. National Technical Information Service, PB 191 691, 1969.

[4]Westinghouse Electric Corp. Coal Mine Rescue and Survival, Volume 2, Communications/Location Subsystem. BuMines Open File Rept. 9(2)-72, 1971, 258 pp.; available for consultation at the Bureau of Mines libraries in Pittsburgh, Pa., Denver, Colo., Twin Cities, Minn., and Spokane, Wash.; at the office of the Assistant Director--Mining and the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 208 267.

Both seismic and EM methods were investigated. Originally, the EM work concentrated on large, more or less permanently placed units that would permit voice and/or code "conversations" between the mine and the surface. The early tests and theoretical studies carried out by J. R. Wait of the Institute for Telecommunication Sciences (Bureau of Mines contract H0122061)[5] indicated that a location system that used portable "manpack" units was feasible.

In such a system, the miners would carry a small transmitter that would be activated if the men were trapped. A team of rescuers on the surface would detect the transmission and would then approximately locate the point on the surface that was directly above the miners.

Subsequent development work and tests by Westinghouse (Bureau of Mines contracts H0232049, H0242006, and H0220073)[6] and by Bureau of Mines personnel

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[5]Geyer, R. G. Thru-the-Earth Electromagnetics Workshop. BuMines Open File Rept. 16-74, 1973, 217 pp.; available for consultation at the Bureau of Mines libraries in Pittsburgh, Pa., Denver, Colo., Twin Cities, Minn., and Morgantown, W. Va.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 231 154/AS.

[6]Farstad, A. J. Electromagnetic Location Experiments in a Deep Hardrock Mine. BuMines Open File Rept. 28-72, 1973, 54 pp.; available for consultation at the Bureau of Mines libraries in Pittsburgh, Pa., Denver, Colo., Spokane, Wash., and Twin Cities, Minn.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 232 880/AS.

Farstad, A. J., C. Fisher, R. F. Linfield, and J. W. Allen. EM Location System Prototype and Communication Station Modification. BuMines Open File Rept. 68-73, 1973, 107 pp., 44 figs.; available for consultation at the Bureau of Mines libraries in Pittsburgh, Pa., Twin Cities, Minn., Denver, Colo., and Spokane, Wash.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 226 600/AS.

Farstad, A. J., C. Fisher, Jr., R. F. Linfield, R. O. Maes, and B. Lindeman. Trapped Miner Location and Communication System Development Program. Volume I--Development and Testing of an Electromagnetic Location System. BuMines Open File Rept. 41(1)-74, 1973, 181 pp.; available for consultation at the Bureau of Mines libraries in Pittsburgh, Pa., Denver, Colo., Spokane, Wash., Twin Cities, Minn., and Morgantown, W. Va.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 235 605/AS.

Linfield, R. F., A. J. Farstad, and C. Fisher, Jr. Trapped Miner Location Development Program. Volume IV--Performance Test and Evaluation of a Full Wave Location Transmitter. BuMines Open File Rept. 41(4)-74, 1973, 52 pp.; available for consultation at the Bureau of Mines libraries in Pittsburgh, Pa., Denver, Colo., Spokane, Wash., Twin Cities, Minn., and Morgantown, W. Va.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 235 608/AS.

demonstrated that the system worked in both coal and metal mines and contracts H0133045 and H0242010 were let to Collins Radio Co. for the development of preproduction prototypes of system hardware. As of January 1975, no insurmountable problems have been encountered in either hardware development or field testing of the units. This paper provides a survey of all these related developments.

ACKNOWLEDGMENTS

The author wishes to thank Richard Watson, Howard Parkinson, and John Murphy of the Bureau of Mines Pittsburgh Mining and Safety Research Center for their frequent suggestions and assistance. The cooperation of personnel at the many mines where the field tests were made is gratefully acknowledged.

DESCRIPTION OF THE SYSTEM

Figure 1 shows the trapped miner location system. The miner's cap lamp battery powers a small transmitter, which generates a signal in the transmit antenna. This signal is picked up by the receive antenna, amplified and filtered by the receiver, and then detected through earphones. This simple transmission-reception is adequate for detection of trapped miners. To understand how location is achieved, it is useful to consider the fields produced by the transmit antenna.

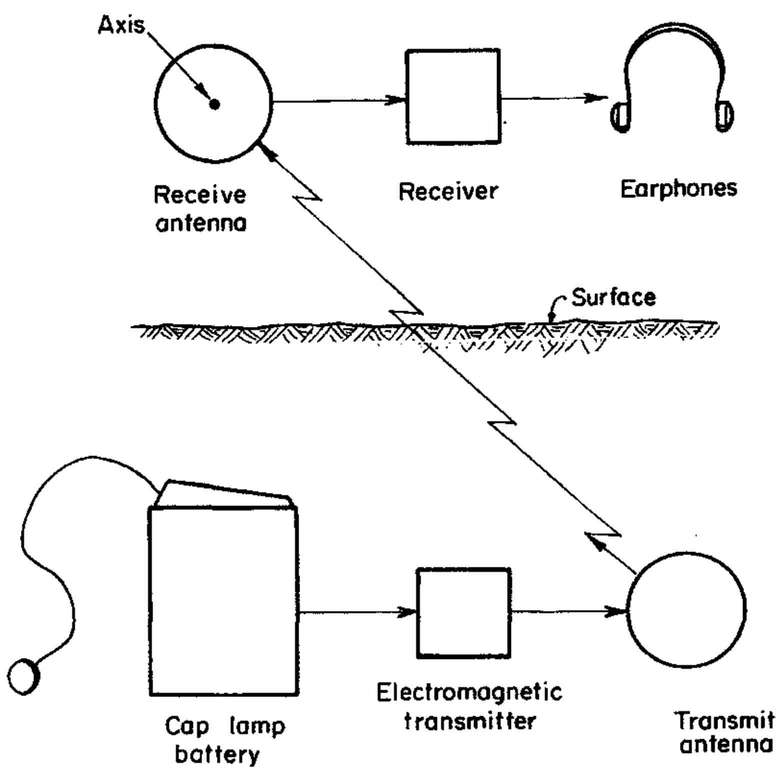

FIGURE 1. - Schematic of EM location system.

THEORETICAL CONSIDERATIONS

This section explains the technical details; less theoretically inclined readers may wish to skip to the "Location Practice" section.

Before proceeding, a definition must be introduced. The "axis" of a circular antenna is a line running through the center of the antenna and perpendicular to the plane of the circle. Hence, in figure 1, the axis of the received antenna is through the center of the antenna and perpendicular to the plane of the figure.

The transmit antenna's field is shown in figure 2A. The solid line represents

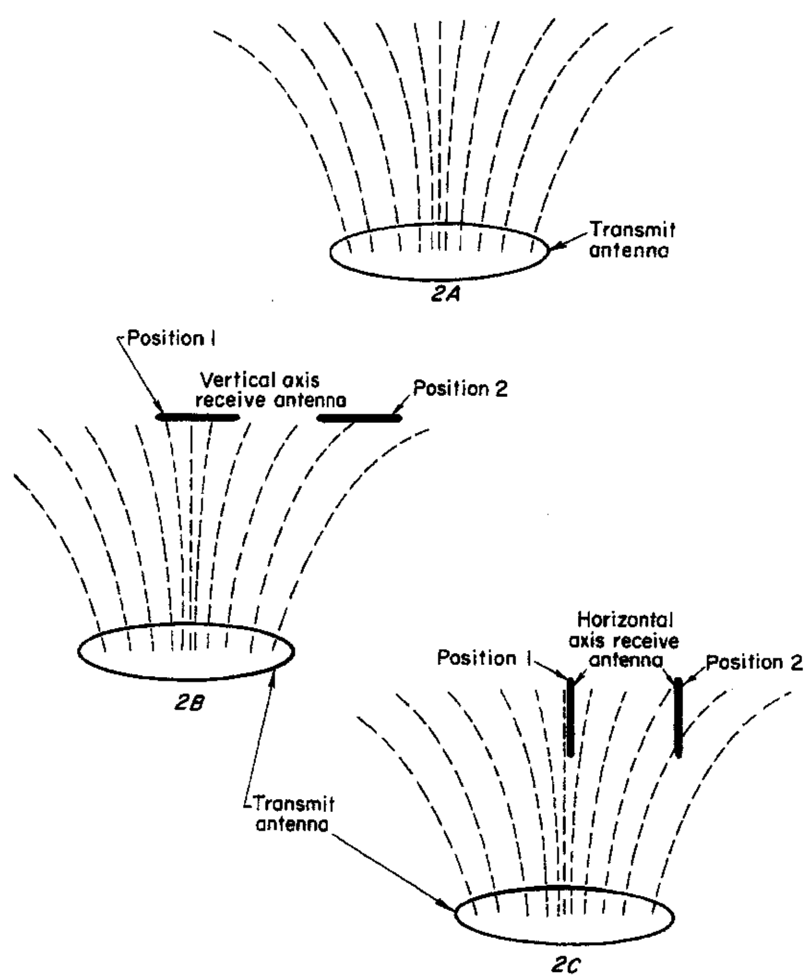

FIGURE 2. - Flux lines and antenna position.

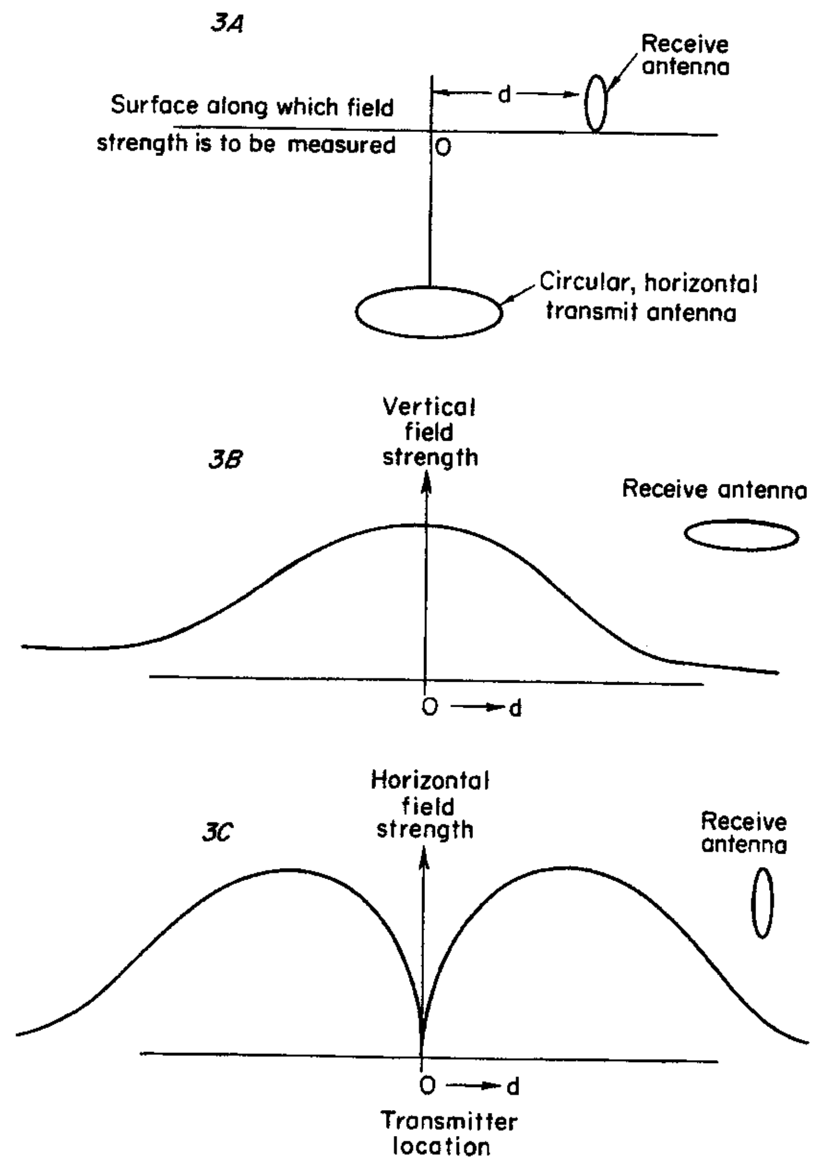

FIGURE 3. - Horizontal and vertical EM fields.

the antenna, which is a circular loop of wire lying in the horizontal plane. The dashed lines, which are referred to as flux lines, represent the field produced by this antenna. The intensity of the signal on a loop receive antenna is proportional to the number of the flux lines that pass through the loop. The flux lines tend to be concentrated directly above the center of the transmit antenna, and to be less dense as distance from this center point increases. Thus, in figure 2B, a maximum signal on the vertical axis receive antenna is expected when that antenna is at position 1; that is, when it is directly above the center of the transmit antenna. As the receive antenna is moved away from the center point, for example, position 2, the signal becomes weaker.

The situation is somewhat different if the receive antenna is rotated 90° so that its axis lies in a vertical plane which passes through the center of the transmit antenna. Directly above the center of the transmit antenna, at position 1 of figure 2C, the receive antenna is parallel to the flux lines. Hence, no flux lines pass through the receive antenna, and no signal is received. At points away from the center point, for example, at position 2 of figure 2C, the flux lines are no longer vertical. The flux lines now pass through the receive antenna, and a signal is received. As the receive antenna is moved still farther away, flux lines become less dense and the signal becomes weaker.

Figure 3 graphically summarizes these phenomena. As figure 3A shows, we again assume the transmit antenna is a circular loop lying in the horizontal plane. Signal strengths are measured along a horizontal surface above the transmitter. The receive antenna is located on this surface a distance d from the surface point directly over the center of the antenna.

Figure 3B shows vertical field strength (which is the strength of the signal detected on a vertical axis receive antenna) versus d. The signal strength peaks directly over the center of the transmit antenna, and then drops off as distance from this point increases. The horizontal field (that detected on a horizontal axis receive antenna and shown in figure 3C) is a minimum at this center point, increases with distance to some critical point, and then decreases.

So far we have assumed that the horizontal axis of the receive antenna was in the plane containing the center of the transmit antenna. In figure 4, which is a top view of the flux lines, the antenna with orientation 1 satisfies this condition. That figure also indicates that an antenna with its axis horizontal and perpendicular to the flux lines (orientation 2) does not cut any flux lines. Hence, no signals are received at such an orientation.

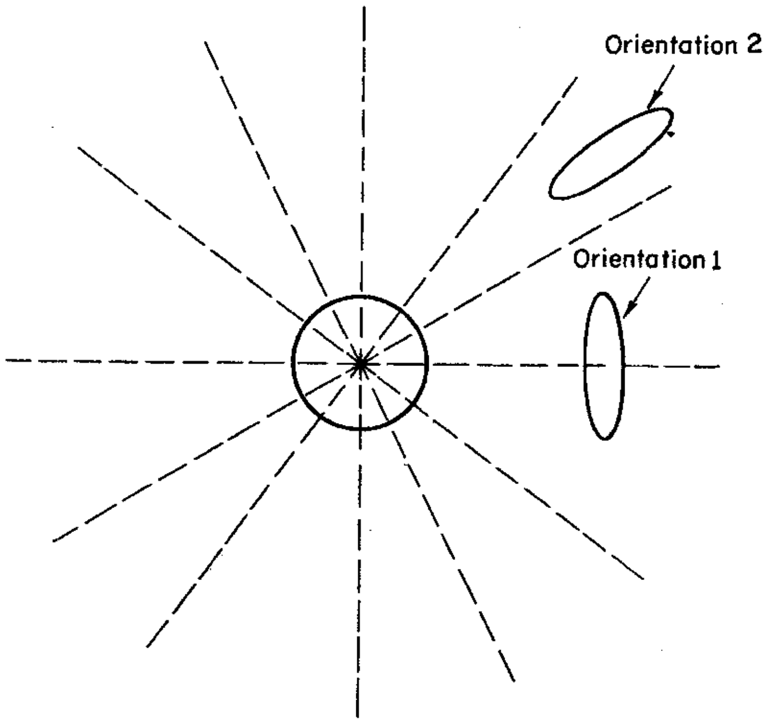

FIGURE 4. - Top view of flux lines.

LOCATION PRACTICE

The first problem in locating the signal source is to detect a signal. At any given point there is an orientation of the receive antenna which gives maximum signal; this occurs when the axis of the antenna is parellel to the flux lines. This most favorable orientation is a function of the location of the transmitter; hence it is unknown. At most points within the range of the system, however, orienting the axis of the receive antenna vertically gives an adequate signal. Hence, when initially searching for a trapped miner, the receive antenna is oriented so that its axis is vertical.

Once a signal is detected, location can begin. The receive antenna is oriented so that its axis is horizontal. Thus, with the axis in the horizontal plane, the receive antenna is rotated. Let us define the vertical plane containing both the transmit and receive antenna as the "critical" plane. When the axis of the receive antenna is in this critical plane, a maximum signal is received; that is, when the antenna is in orientation 1 of figure 4. When the axis of the receive antenna is perpendicular to the critical plane (orientation 2 of figure 4), a minimum signal is received.

Figure 5 illustrates the procedure. In 5A the man is searching for the signal. The 18-inch-diameter loop in his hands is the receive antenna; in figure 5A the antenna axis is vertical. In 5B he has oriented the receive antenna so that its axis is in the critical plane and a peak signal is received. In figure 5C the axis is perpendicular to the critical plane so no signal is received. The lower portions of figures 5B and 5C show the top views at these latter two orientations.

In practice, it is easier to detect the orientation where the signal disappears than the orientation where the signal peaks. Thus, the searcher rotates the antenna to find a minimum signal and determines the critical plane. He sights down the antenna plane with the earth's surface. He then moves about 20 yards perpendicular to the critical plane and repeats the process. The intersection of the two critical planes contains the center of the transmit antenna. On the surface, this intersection of planes is the point where the two imaginary lines cross. Figure 6 illustrates this principle.

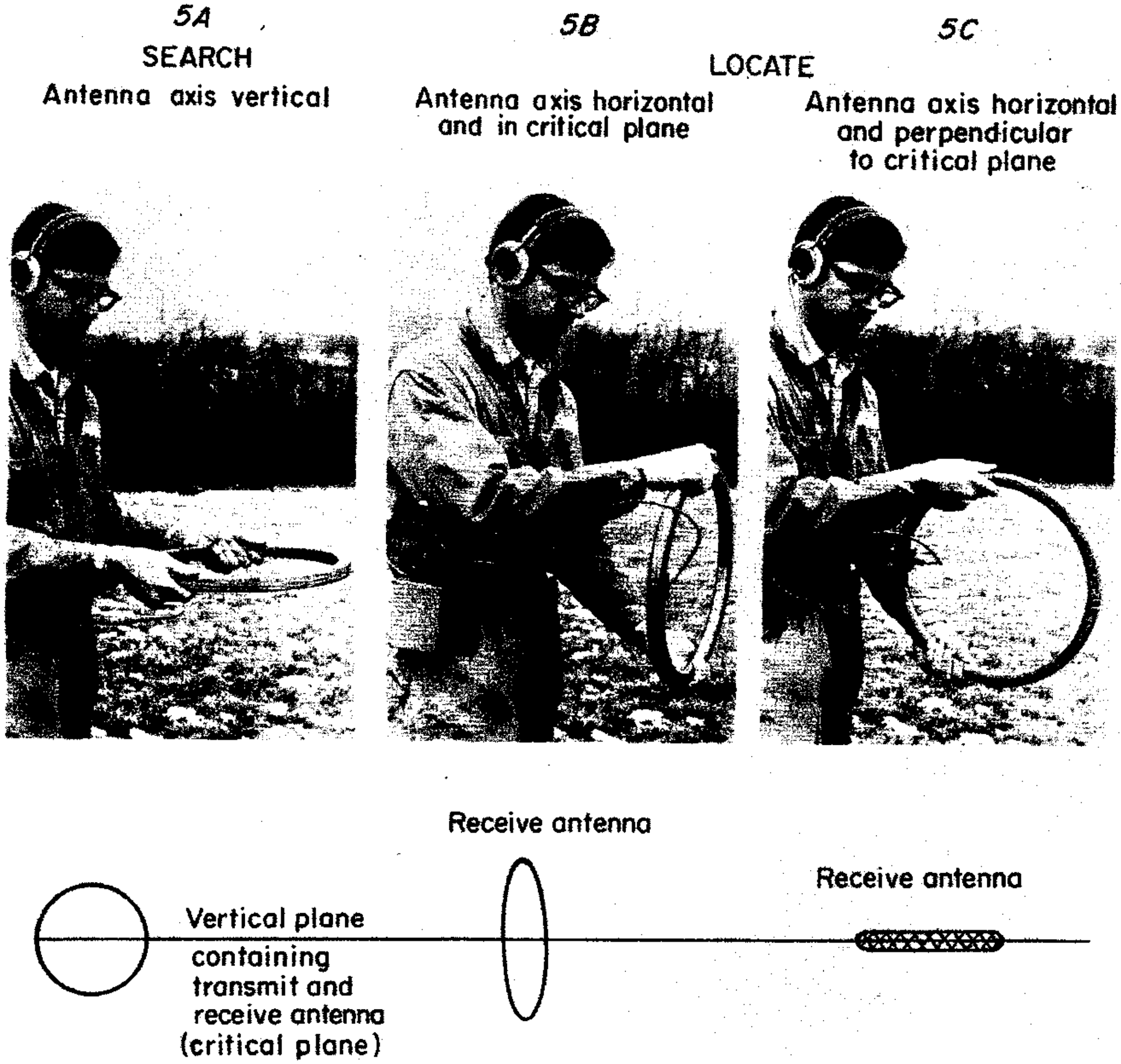

FIGURE 5. - Determining "critical planes."

Directly over the center of the transmit antenna, no signal is received when the axis of the receive antenna is horizontal, because regardless of what horizontal direction the axis is pointing, the receive antenna is always in a critical plane. Thus, to get an exact location, the rescuer searches for the point at which he can rotate his antenna (always keeping the axis horizontal) and receive a minimum signal. He should check this location by verifying that the signal strength on a vertical axis receive antenna is a maximum. The location is the point at which the vertical axis antenna signal peaks and all horizontal axis antenna signals null.

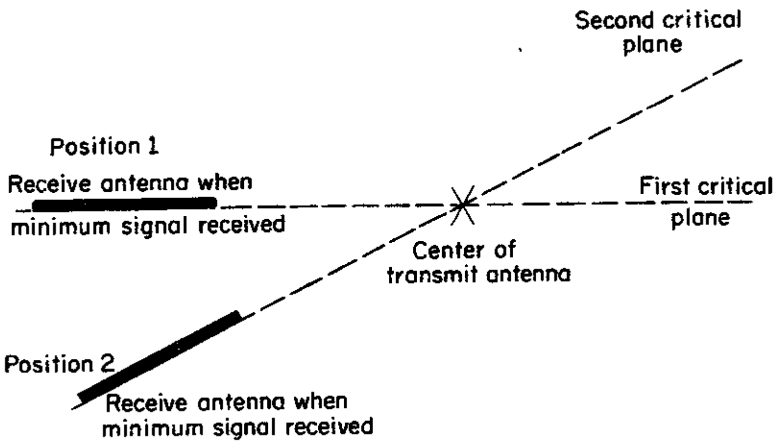

FIGURE 6. - Location procedure (top view).

BASIC EQUIPMENT REQUIREMENTS

Much of the preceding discussion concerns location theory. This section discusses the practical problems of developing useful hardware for the system.

The most demanding hardware requirements are those for the transmitter. This unit must be readily available to a miner whenever and wherever the emergency occurs. Such availability is assured only if the miner carries the transmitter with him at all times. Hence, the unit must be small and lightweight.

Emergencies are uncommon events, so any given unit will be used rarely, if ever. However, the unit must work that one time it is needed. An

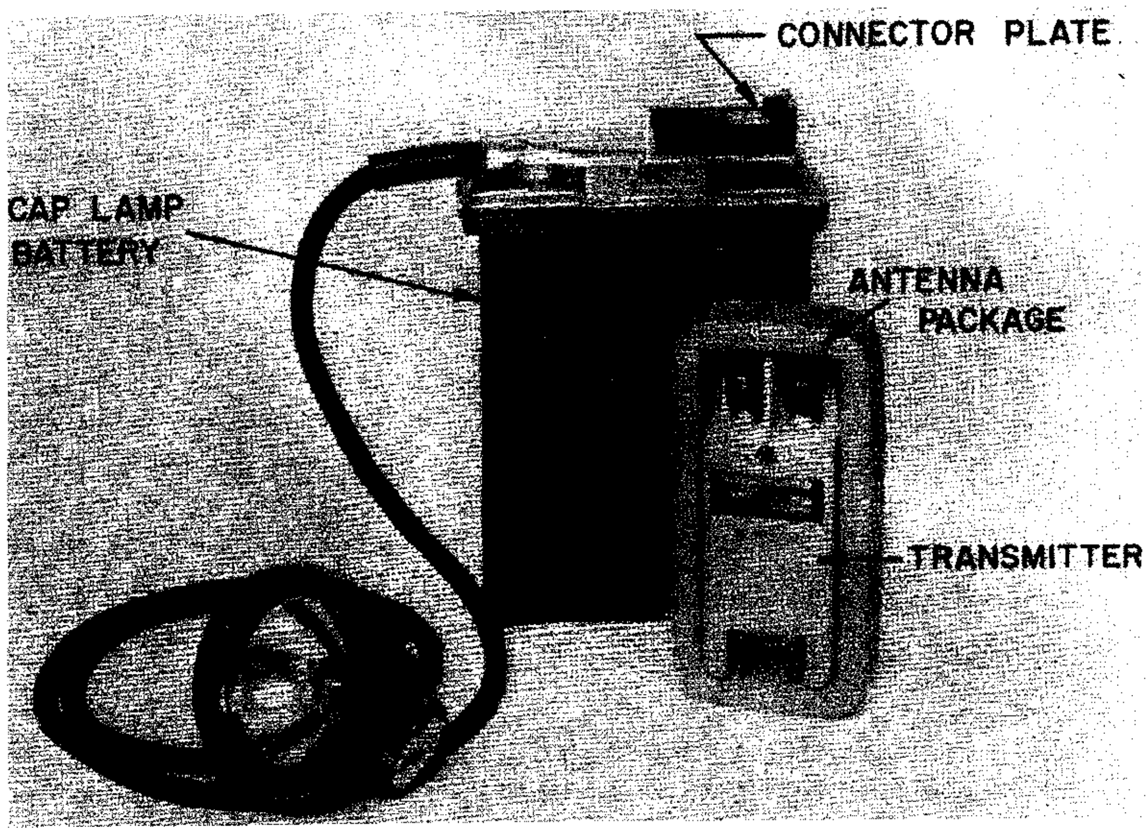

FIGURE 7. - Preliminary version of manpack location transmitter in separate package.

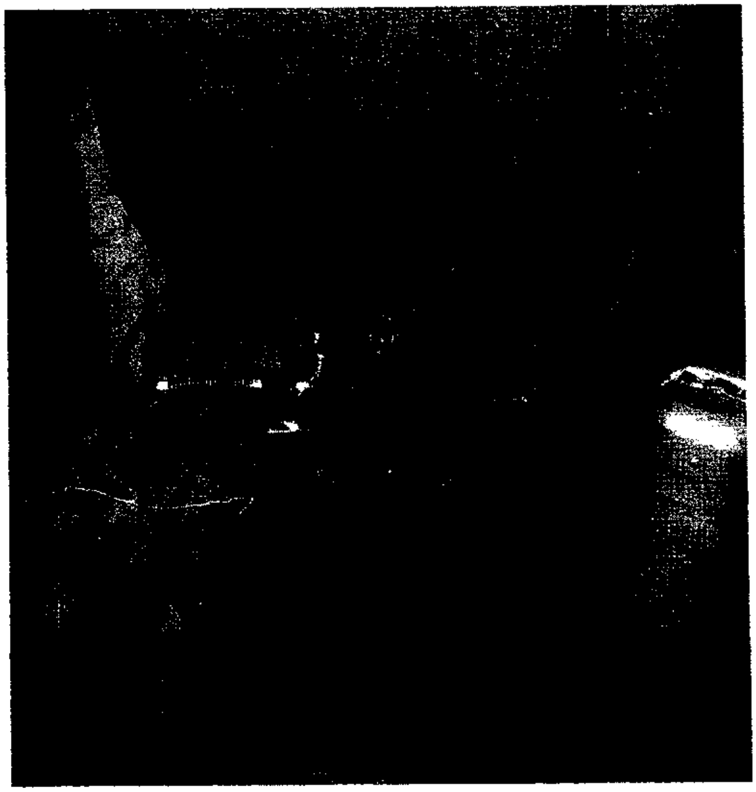

FIGURE 8. - Preliminary version of manpack location transmitter, built into cap lamp battery.

extremely reliable unit is required. Anything carried by a miner is subject to considerable wear and abuse, so the transmitter must be very rugged.

Such a unit exists. The transmitter is intrinsically safe. It can be encased in a 1.4- by 0.35- by 3.45-inch molded package. Thus encased, it can be shocked, immersed in water, subjected to temperature extremes, etc., with no damage.

Two antenna types have been tested. Under favorable conditions that will be defined later, a 90-foot coil of No. 16 wire is adequate. An antenna this size weighs about half a pound; it can be put into an easy-to-carry package.

An alternative is to use a previously installed antenna. In most coal mines this would be several hundred feet of No. 10 or No. 12 wire wrapped around a pillar of coal. In an emergency, any available wire can be used.

A problem that becomes increasingly relevant as we approach implementation of a practical system is the packaging of the transmitter and antenna. We have studied a separate unit (fig. 7) and units packaged in the miner's cap lamp battery (figs. 8 and 9). Considerable attention is given to using sturdy, reliable switches and connectors in these units.

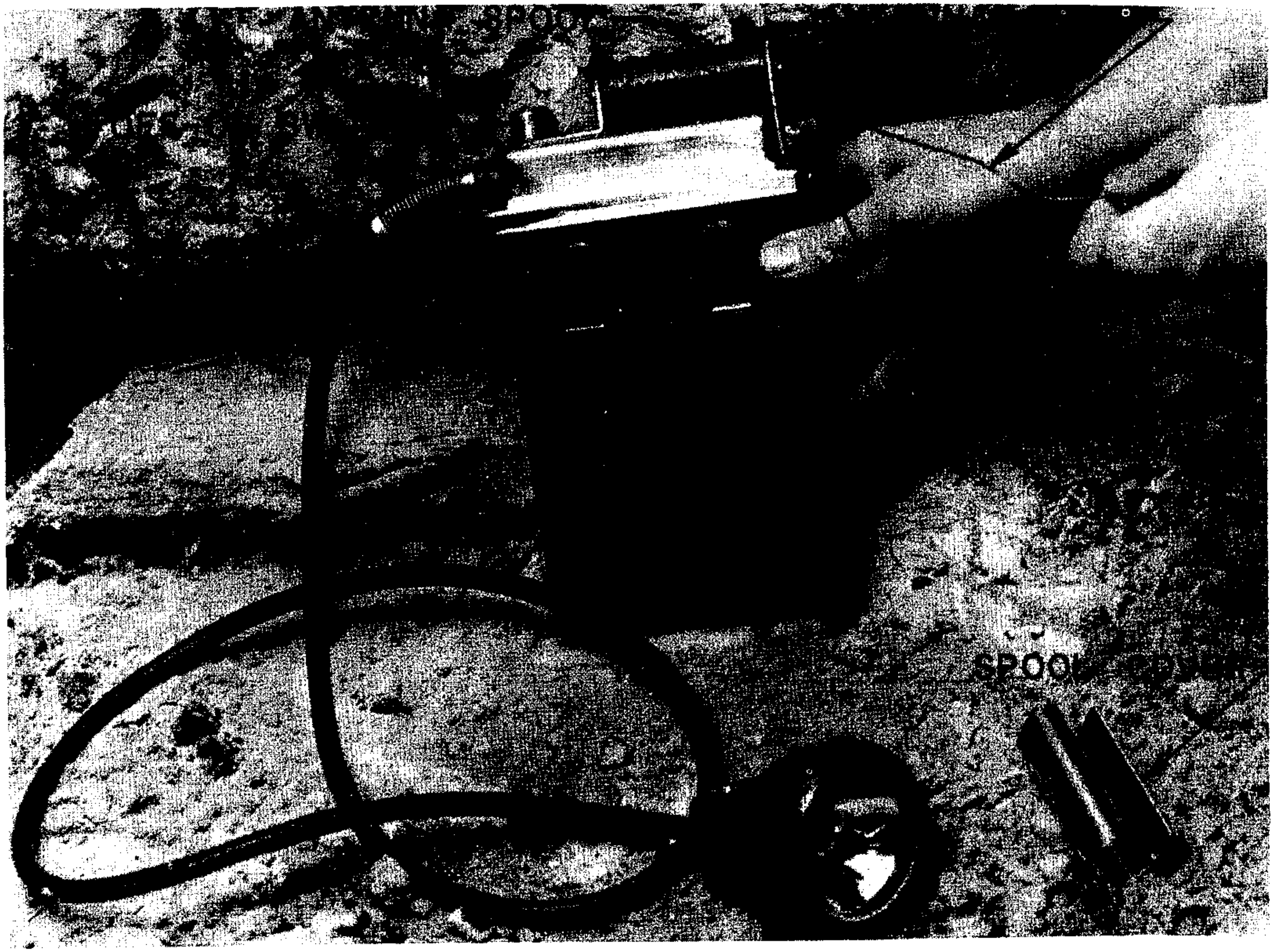

FIGURE 9. - Deploying unit shown in figure 8. Man has removed cover from antenna spool and is pulling antenna wire from spool.

The transmitter is powered by the miner's cap lamp battery. A fully charged battery will power the transmitter for over a day. Even at the end of an 8-hour shift, the battery should have enough power to drive the unit for another 8 hours.

The receiver presents fewer problems. We have developed a sturdy, field-worthy unit. Since it may be useful to take the receiver into a mine, it is intrinsically safe. As shown in figure 10, the total receive system consists of a loop antenna about 18 inches in diameter, a tuning unit which can be carried on the rescuer's belt, and a headset. As figure 11 indicates, the receive unit is easy to carry, even in rugged terrain.

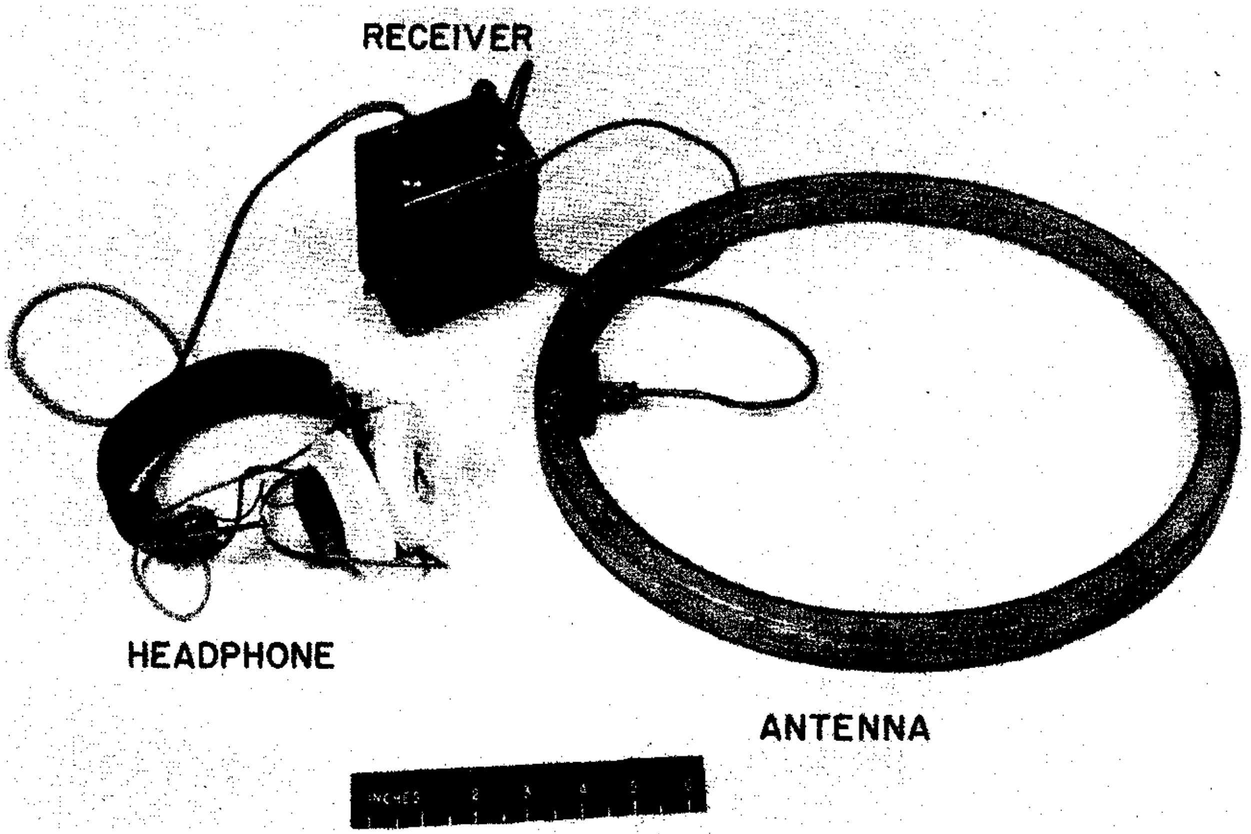

FIGURE 10. - Preliminary version of receive unit.

FIGURE 11. - Using receive unit shown in figure 10.

SYSTEM REFINEMENTS

Previous sections have outlined how the EM location system works and described the basic hardware for that system. In practice, certain problems are encountered with such a basic system, and certain refinements are useful.

For example, consider the situation in which more than one group of miners is trapped. Will their transmitters interfere with one another, making location impossible? This problem can be avoided by assigning each group of miners a different transmitter frequency; generally the best frequencies to use are those midway between 60-Hz harmonics in the 1,000- to 3,000-Hz band; that is, 1,050 Hz, 1,110 Hz, 1,170 Hz, . . . 2,910 Hz, 2,970 Hz. Thus, we have a 33-channel system. Each transmitter is fixed to one frequency. A tunable receiver for surface use is being built.

A second problem is trying to determine if a reception is the signal of a trapped miner, or is just noise. Since the receiver is very sharply tuned, any reception (signal or noise) that passes through the tuning section to the earphone will have the same frequency. However, controlling the rate and duration of the transmitted signal provides a way to distinguish a signal from noise. A pulse about 0.2 second long transmitted every 2 seconds is optimum for location work. This means the receiver earphone will emit a short "beep" every 2 seconds. It is extremely unlikely that a noise source would show such a uniform cycle. The intermittent tone means the transmitter is switched on only 10 percent of the time. This extends the battery life to the 24 hours mentioned above.

So far, we have implied that the rescuer must walk over the trapped men before they can be located. But what happens at a large mine which is spread over tens of square miles and may be covered by heavily wooded mountains? To search such an area on foot could take several days. Thus, we have developed a helicopter-borne receiver (fig. 12). This unit enables us to monitor six different frequencies at once while flying over the area. The final, most accurate location must still be done on foot, but the men can be approximately located from the air.

The location system could be very useful in an emergency, but a true two-way communication system would be even better. For this reason a combination voice receiver-code transmitter is being developed for use in the miner's unit. It will be recalled that the location transmitter is turned on only about 10 percent of the time. With the voice receiver, the trapped miner would listen for voice messages from the rescue crew during the remaining time. A continuous transmit switch will be added to the miner's unit so that he can send coded replies to questions asked by the rescuers. Testing of this system should begin in 1975.

TABLE 1. - Mines where EM location systems have been tested

Mine	Mine type	Location	Overburden, feet
Bureau of Mines Safety Research.	Coal........	Bruceton, Pa........	80
Rainbow No. 7..................	...do.......	Rock Springs, Wyo...	140
Latrobe Construction............	Limestone...	Latrobe, Pa.........	325
Inexco No. 1....................	Fluorspar...	Jamestown, Colo.....	350
Camp No. 2......................	Coal........	Morganfield, Ky.....	375
U.S. Tunnel.....................	Hardrock tunnel.	Idaho Springs, Colo.	390
Copper Queen....................	Copper......	Bisbee, Ariz........	400
Guyan No. 1.....................	Coal........	Amherstdale, W. Va..	400
Robena No. 1....................	...do.......	Waynesburg, Pa......	400
Putnam..........................	...do.......	Elmwood, W. Va......	460
Somerset........................	...do.......	Somerset, Colo......	500
Robena No. 4....................	...do.......	Waynesburg, Pa......	990
Geneva..........................	...do.......	Dragerton, Utah.....	1,500
Grace...........................	Iron........	Morgantown, Pa......	2,400
Galena..........................	Lead, zinc..	Wallace, Idaho......	4,300

These results were obtained under mock-emergency conditions. That is, the transmitter is deployed at an unknown point, and the surface personnel do not require any "hints" to perform the location. No fine tuning, no conversation between trapped miners and rescuers, and no additional adjustments are required.

SUMMARY AND CONCLUSIONS

An EM system has been built and tested that permits the detection and location of trapped miners. The hardware required is compact, sturdy, and in general practical for use in mines. Successful field tests of the system have been conducted at a wide variety of mines.

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