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Ultra Low Frequency Electromagnetic Fire Alarm System for Underground Mines

By K. E. Hjelmstad and W. H. Pomroy

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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Manuel Lujan, Jr., Secretary

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Library of Congress Cataloging in Publication Data:

Hjelmstad, Kenneth E.

Ultra low frequency electromagnetic fire alarm system for underground mines : by K.E. Hjelmstad and W.H. Pomroy.

p. cm. — (Report of investigations; 9377)

Includes bibliographical references (p. 11).

1. Mine fires—Prevention and control. 2. Fire alarms. 3. ELF electromagnetic fields. I. Pomroy, William H. II. Title. III. Series: Report of investigations (United States. Bureau of Mines); 9377.

TN23.U43 [TN315] 622 s—dc20 [622'.82] 91-10026 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	Hz	hertz
A/m	ampere per meter	m	meter
cm	centimeter	m^2	square meter
dB/m	decibel per meter	mho/m	mho per meter
gal	gallon	min	minute
h	hour	pct	percent
H/m	henry per meter	W	watt

ULTRA LOW FREQUENCY ELECTROMAGNETIC FIRE ALARM SYSTEM FOR UNDERGROUND MINES

By K. E. Hjelmstad[1] and W. H. Pomroy[2]

ABSTRACT

During an underground mine fire, air can be rapidly depleted of oxygen and contaminated with smoke and toxic fire gases. Any delay in warning miners could have disastrous consequences. Unfortunately, present mine fire alarm systems, such as stench, audible or visual alarms, telephones, and messengers, are often slow, unreliable, and limited in mine area coverage.

Recent research by the U.S. Bureau of Mines has demonstrated that ultra low frequency electromagnetic signaling can be used for an underground mine fire alarm. In field tests of prototype equipment at five mines, electromagnetic signals from 630 to 2,000 Hz were transmitted through mine rock for distances as great as 1,645 m to an intrinsically safe receiver. The prototype system uses off-the-shelf components and state-of-the-art technology to insure high reliability and low cost. When utilized, this technology would enable simultaneous and instantaneous warning of all underground personnel, regardless of their location or work activity, thereby increasing the likelihood of their successfully escaping a mine disaster.

This report presents the theoretical basis for through-the-rock ultra low frequency electromagnetic transmission, design of the prototype transmitter and receiver, and the results of in-mine tests of the prototype system.

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INTRODUCTION

Recent research by the U.S. Bureau of Mines has resulted in the design and testing of an electromagnetic fire-warning alarm system for underground mines. Presently used fire alarm systems, such as stench, audible or visual alarms, telephones and messenger, are often slow, unreliable, and limited in mine coverage. The use of the electromagnetic fire-warning alarm system would enable simultaneous and instantaneous warning of all underground personnel. Early warning would increase the likelihood of miners successfully escaping a mine disaster, and the safety of miners and improved mining efficiency are stated objectives of the Bureau.

Evacuation of personnel from underground mine fires can require considerable time. Evacuation time from noncoal underground mines is strongly correlated with depth of the shaft and can range to nearly 1-1/2 h (*1*).[3] In deeper mines, the evacuation time can exceed the rated capacity of the presently used filter-type self-rescuer, which is approximately 60 min operating time in a mine environment of 1 pct carbon monoxide (*1*). Any delay in warning miners of the necessity of donning their self-rescuers can be disastrous (*2*), thus the benefit of a warning alarm system capable of quickly sending a fire alarm signal to miners is obvious.

DEFICIENCIES OF PRESENT MINE FIRE ALARM SYSTEMS

Because of the need for rapid evacuation, it is clear that reliable and timely fire-warning systems are essential. In typical above ground occupancies (factories, apartment buildings, hospitals, commercial buildings, etc.), conventional fire alarms such as bells, gongs, lights, whistles, public address announcements, telephones, and even word-of-mouth are sufficient. However, in underground mines, these methods are generally not suitable, and are therefore seldom used.

Workers in underground mines are often widely dispersed over very large areas with little or no means of communication between groups or individuals. Even a short separation between the worker and a visual or audible alarm could render the alarm useless, if the worker was not in direct line-of-sight of the alarm or the worker was using or near noisy equipment. In many mines, working areas are completely isolated, without links to any other part of the mine by telephone, power cable, compressed air line, conveyors, rail, or any other continuous or semicontinuous conductor over which a warning signal could be transmitted. Most mines are so large that the cost of installing a conventional fire alarm system (bells, lights, etc., and the associated wiring) would be prohibitive. Also, since the mine workings are constantly advancing, a fixed fire alarm system would likewise need to be constantly extended, but would seldom, if ever, actually reach the working faces. Finally, any alarm system that relies on a power or signaling cable can be too easily disabled by a rockfall or other cable damage. The principal disadvantages of the prior art of underground fire alarm systems are inherent slowness, vulnerability to damage, and limited mine coverage.

The most common fire alarm system in hard-rock mines, the stench system, utilizes the ventilation system to transport the fire-warning signal. It operates by releasing an odoriferous chemical (the same chemical used to odorize natural gas) into the mine's ventilation and/or compressed air streams. When the miners detect the odor, they immediately begin to act according to a prearranged evacuation plan (*2*). The principal disadvantages of the stench system are the time required for the odor to reach the remotest workplaces and the tendency for some parts of a mine to be consistently missed altogether (*6-8*). These problems are particularly acute in mines with openings having large cross-sectional areas, and therefore, extremely slow ventilation velocity. Under certain conditions, a fire can even generate its own ventilation forces that are counter to the mine's ventilation and further slowdown or reverse the stench flow.

The deficiencies of the stench system are well known. However, because of the lack of a superior alternative, it is still the most commonly used fire alarm system. Considerable research effort has been directed toward the development of fire alarms utilizing wireless radio frequency signaling systems; however, each has inherent disadvantages that have prevented their widespread use in mines. Ultra-high frequency (UHF) systems, have negligible through-the-rock transmission capabilities and are limited to line-of-sight applications. When a miner travels around a corner and the pocket pager type receiving antenna is not in a direct line-of-sight with the transmitting antenna, the wireless communication link is broken. To achieve mine-wide coverage for the warning system, it would be necessary to install transmitting antennas throughout virtually the entire mine. In large mines, that might comprise

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

several hundred miles of workings. The cost of such an installation would therefore be prohibitive.

Another type of radio frequency system operates in the medium frequency (MF) spectrum (*7-10*). It has limited through-the-rock transmission capabilities, and has an advantage over UHF systems in that specialized transmitting antennas are not required. Transmission signals can parasitically couple into any continuous or semicontinuous metallic conductors present. Thus, a receiver need only be within line-of-sight of any such conductor (power line, rail, compressed air pipe, etc.) for the system to operate. The disadvantages of the MF system are that the receiving antenna are quite large and cumbersome (worn like a vest with large batteries in the pockets), and many modern mines which utilize diesel-powered trackless mobile equipment do not require continuous or semicontinuous metallic conductors installed throughout the mine. They may be present in certain locations, but too many areas would be left unprotected, and the miners working in remote parts of the mine may not be made aware of the existence of a mine fire.

In summary, the use of stench in the ventilation system in high-back, room-and-pillar mines where air movement is slow can result in excessive time delay in sending a fire alarm to underground miners. A fire alarm system using wire for carrying the signal transmission can be disabled by a broken wire. Conventional fire alarm systems are usually expensive to install in a mine; therefore, the mine company may only install them where the majority of miners are working. Those miners working in remote parts of the mine may not be close enough to a fire alarm and, as a result, would fail to be alerted to the existence of a mine fire. MF, and to a lesser extent, UHF radio systems have the potential to act as a good fire-warning system for most underground mines. However, they are entirely dependent on the quality of underground conductors which are often inadequate or nonexistent.

ULTRA LOW FREQUENCY (ULF) ELECTROMAGNETIC FIRE ALARM SYSTEM DESIGN

The electromagnetic fire alarm system described in this report combines the transmission and reception of ULF electromagnetic fields through mine rock to send a fire-warning signal to underground miners. A magnetic field, generated about the transmitting loop antenna, is the means of signal transmission. The field emanates from the transmitting antenna in a somewhat spherical manner, that can be described by the following equation (*5-11*):

$$H = INA[G]/2\pi Z^3$$

where H = magnetic field strength, A/m,

I = antenna current, A,

N = number of turns,

A = area of antenna, m^2,

G = attenuation constant,

π = constant 3.14 (pi),

and Z = distance through transmitting medium, m.

The transmitter can consists of a small signal generator, a 1,000-W audiofrequency amplifier, and a transmitting antenna (fig. 1), all located either at the surface or underground in the mine. If the mine is very deep, the transmitter could be located at a midpoint in the mine and transmit in all directions. For initial tests of the system, a 30-m-diam transmitting loop antenna was used, formed from 6 or 10 turns of No. 10 or No. 12 insulated copper wire. In later tests, a 12-strand unshielded power cable was used to form a 106-m-diam loop antenna. (Line configuration antennas might also be used for transmitting.) The transmitting unit is of simple design, without significant size limitation on antenna configuration or transmitter power.

The uniqueness of the system is the easy mobility of the receiving unit, which utilizes a high-permeability wound ferrite core antenna for reception of the through-the-rock signal. The small (15 cm long) antenna allows for mobility of the receiver wearer and increases the likelihood of survivability of the warning receiver, because it has no long connecting wire that would be exposed to damage from fire, rockfalls, or explosions (fig. 2).

Tuning of both transmitter and receiver antenna to a common resonant frequency allows for maximizing transmitting antenna current (and power), while maintaining a sensitive small-sized receiver antenna for the convenience of the receiver wearer. Tuning of both antennas to a common resonant frequency also creates a system that discriminates against electromagnetic noise, while still accepting the signal in the warning frequency range. By choosing frequencies that avoid harmonics of the power frequency (60 Hz), and by using pass band filters and pulse modulation, the receiver can be made unresponsive to electromagnetic noise effects, and responsive only to the encoded fire-warning signal. Input to the receiver is from

Figure 1.—Fire-warning system transmitter.

Figure 2.—Fire-warning system receiver.

a high-magnetic-permeability ferrite core wound with hundreds of turns of enameled copper wire to form an antenna which can be tuned to the carrier frequency of the transmitting antenna. The receiver can be designed to function from 300 to 10,000 Hz; however, tests of the system were conducted with the system tuned to 1,950 or to 630 Hz. Tuning is accomplished by placing capacitance of appropriate size in series with the antenna to achieve a resonant frequency of choice.

The receiver is powered by a small battery, therefore, it is very portable and convenient to carry. For use as a fire alarm system for underground mines, the receiver could be powered by the caplamp battery usually worn by an underground miner or by a vehicle battery if mounted on a vehicle. The use of the caplamp battery as a power source for the receiver would insure that the receiver would always have an adequate power supply because the caplamp batteries are recharged each 24-h period and checked daily. To insure that the receiver functions properly, a routine check of it could be made by exposing it to a ULF pulse emitted by a test fixture near the mine entrance.

The high-magnetic-permeability ferrite core receiving antenna has exceptional magnetic flux gathering capabilities. This makes it possible for the antenna to be very sensitive and capable of capturing even the weakest electromagnetic signal. Through amplification, the generated antenna voltage can be used to initiate a blinking of the miner's caplamp in a manner that is recognizable to the miner as a fire-warning signal. When the miner is certain of the warning, he or she can prevent further blinking by pushing a button on the battery. Research has determined that the risk of ULF initiation of electric blasting caps is negligible. Research also has shown that the signal does not have any detrimental effect on the storage of information on computer diskettes.

INITIAL FIELD TEST RESULTS

Initial field tests of the electromagnetic fire alarm system were made at a local Minneapolis sandstone mine which had 15 m of overburden made up of sandstone, limestone, and glacial till. The transmitter and a 30-m-diam six-turn loop transmitting antenna were located on the surface, and the receiver unit was carried underground.

For the initial tests, an 8-ohm speaker was used with the receiver to allow the operator to hear signal reception. The first tests were made at low power levels (2 W). The results of these tests are shown in figure 3. The area of reception is about 10 times the area of the transmitting loop antenna. The signal was received through about 15 m of overburden. The results of this first test were encouraging enough to justify additional field tests of the system (*3-4*).

A second series of tests were made in the Tower-Soudan underground iron mine located in northern Minnesota. Unlike the first test, the transmitting antenna was placed underground in a stope located 762 m from the main shaft above the 27th level. The transmitting antenna was made up of 10 turns of No. 10 copper wire formed into a 30-m-diam loop. The transmitter (fig. 1) and receiver (fig. 2) were the same as used in previous tests.

It is possible to establish the voltage generated in a ferrite core receiving antenna by measuring across its leads. This was done while the receiving unit was placed at the center of the transmitting loop antenna. It was established that the ratio of the power in the receiving antenna to the power in the transmitting antenna, in decibels, was a constant value regardless of the transmitting power levels, provided distance between antennas was constant.

Receiving antenna power levels were then established at various points throughout the mine at various

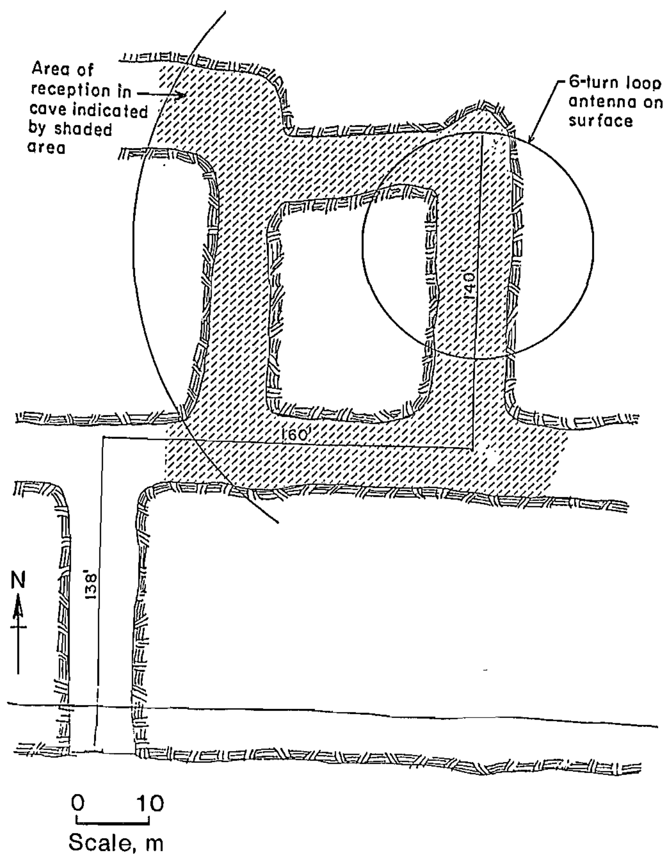

Figure 3.—Reception area of first field test.

transmission power levels. The ratio of the power level in the receiving antenna to the power level in the transmitting antenna, in decibel loss, is the basis for establishing power loss at various distances. The results of these measurements are shown in figure 4 and indicates that the through-the-rock electromagnetic signal decays with distance in a manner similar to an inverse cubic function. The graph also indicates maximum signal reception through-the-rock at this minesite was in excess of 762 m. Maximum transmitter power level was 53.3 W.

Another in-mine test of the electromagnetic fire alarm system was conducted at The New Jersey Zinc Co., Sterling mine near Ogdensburg, NJ. A 10-turn, 30-m-diam transmitting antenna was positioned at two different locations on the surface. At one site, the antenna was positioned on overburden of water saturated saprolite (a claylike residuum of limestone dissolution). At the other site, the antenna was positioned on marble (fig. 5). For this test, a handheld 30-cm-diam 500-turn loop antenna was used to measure the magnetic field strength at depth. The measured magnetic field strength at depth was compared with the theoretical (free space) value of magnetic field strength at the same distance. The ratio of the two values of field strength permitted determination of the attenuation constant. When compared, it was determined that the marble had lower attenuation characteristics than saprolite and was correspondingly more transparent to electromagnetic waves.

Tests at the Sterling mine and the two sites in Minnesota were conducted at a frequency of 1,950 Hz. Theory predicts that if lower values of frequency are used, the signal attenuation will be less, because skin depth of the signal (the depth at which the signal equals 1/e or 36 pct of its original value) is inversely proportional to both frequency and rock conductivity as shown by the following equation:

$$\delta = \left[\frac{2}{\omega \mu \sigma}\right]^{1/2}$$

where δ is the skin depth, ω is frequency, and σ is rock conductivity.

If μ is assumed to be $4\pi * 10^{-7}$ H/m for a nonmagnetic material this equation can be reduced to the following:

$$\delta = \frac{503.3}{(f\sigma)^{1/2}}.$$

Through measurement and further calculations, the value of σ can be established. The two types of overburden at the Sterling mine had values of conductivity slightly greater than 10^{-1} mho/m, which is a value greater than the value of conductivity for most mine rock (*10*). A high-conductivity material retards penetration by a magnetic field, but since the signal was still detectable on the 563-m level, the tests suggest that through-the-rock signaling is a viable means of warning miners of the presence of a mine fire, and that the system is likely to function well in a great many mines.

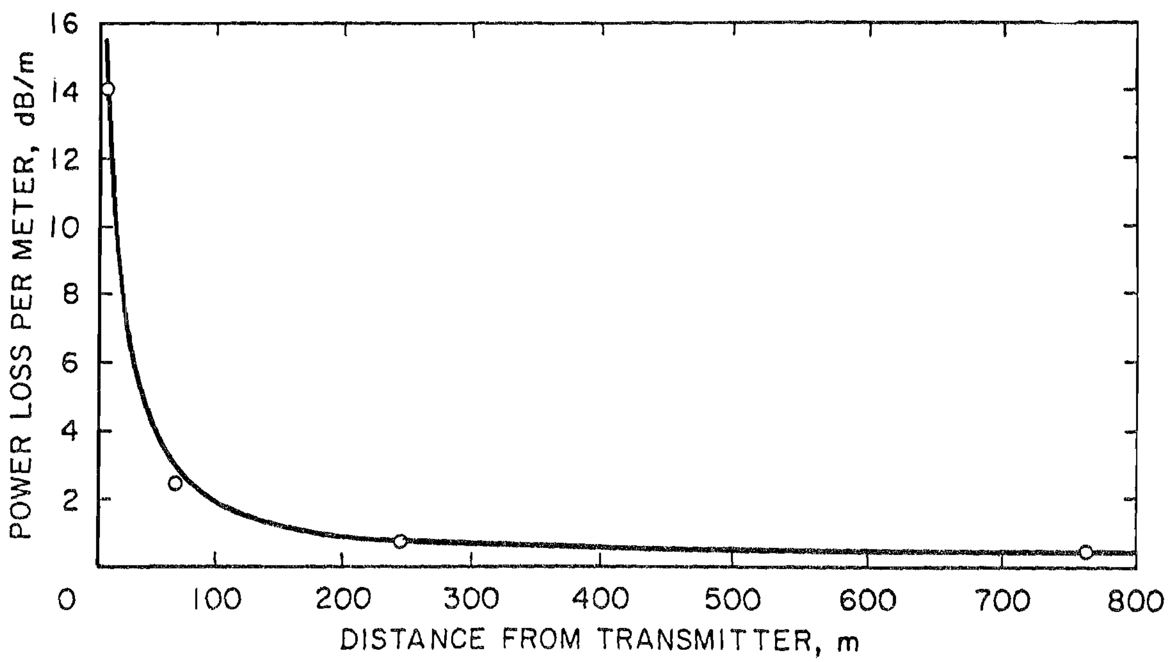

Figure 4.—Signal attenuation at various distances.

Electromagnetic theory predicts that the electromagnetic wave skin depth is greater at lower frequencies (*5*). Therefore, mines that were known to present problems associated with high-conductivity overburden, were chosen for tests conducted at a frequency of 630 Hz instead of the 1,950 Hz frequency used in earlier tests.

Tests of the electromagnetic fire alarm system were made at two Louisiana salt mines where the overburden was known to be made up of salt water saturated rock and mud. The highly conductive overburden is believed to present a very difficult condition for electromagnetic signal transmission, and this proved to be true even at a lower transmission frequency of 630 Hz.

The transmitter and 93-m-diam loop antenna of 12 turns were deployed on the surface above the workings of a salt mine (fig. 6). The transmitted electromagnetic signal penetrated to the 365-m level and was received at sites in the mine which indicate that full mine signal coverage of the fire-warning signal was possible (fig. 7). In reaching to the 365-m level, the signal passed through two levels of the mine in which the Department of Energy had stored 95 million gal of petroleum, and also through 45 m of salt water saturated overburden and 320 m of cap rock and rock salt.

Tests conditions at the second salt mine with 260 m of salt water saturated overburden made surface to in-mine signal transmission more difficult. With the antenna and transmitter placed on the surface (fig. 8), signal reception was obtained at the 426-m level within the mine, but reception at sites underground indicate that mine-wide coverage was not as complete as desirable and that underground deployment of the transmitter would give more satisfactory performance. When the transmitting antenna was placed underground around mine pillars in fresh air near the shaft, it was possible to transmit a fire-warning signal and receive it at sites that indicated full mine coverage was feasible (fig. 9). A transmitter power level of 350 W was used in tests with the transmitter placed underground. The overburden electrical conductivity at the salt mines was the greatest found thus far, exceeding $1.5*10^{-1}$ mho/m making it the least transparent to electromagnetic signals of any of the test sites; however, this problem was overcome with increased transmitter power or with the transmitter antenna placed underground.

Figure 5.—Transmitting antenna on surface.

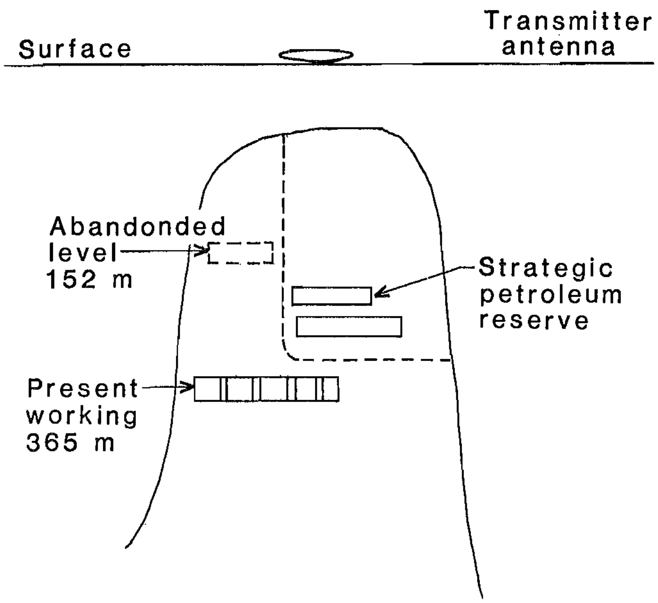

Figure 6.—Cross section of salt mine.

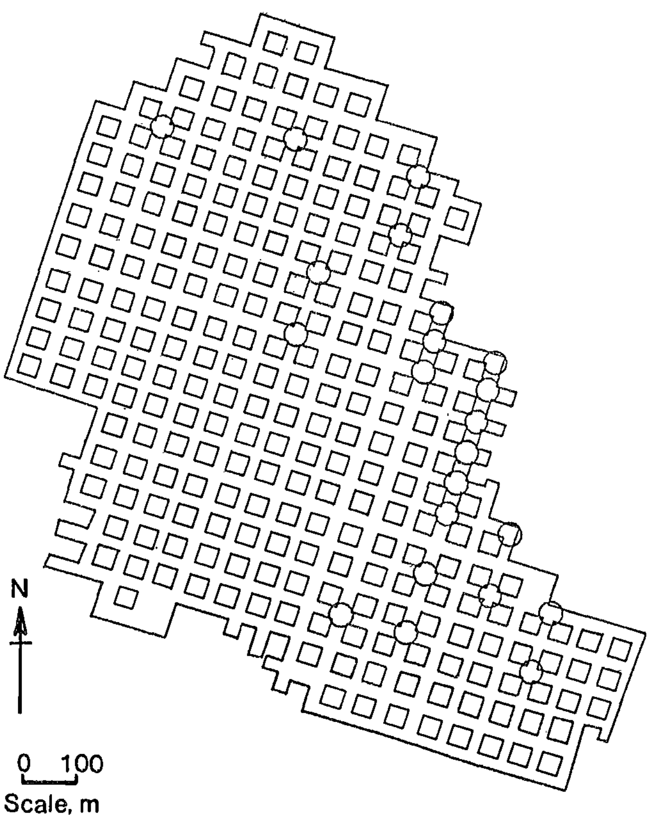

Figure 7.—Salt mine with transmitter on surface.

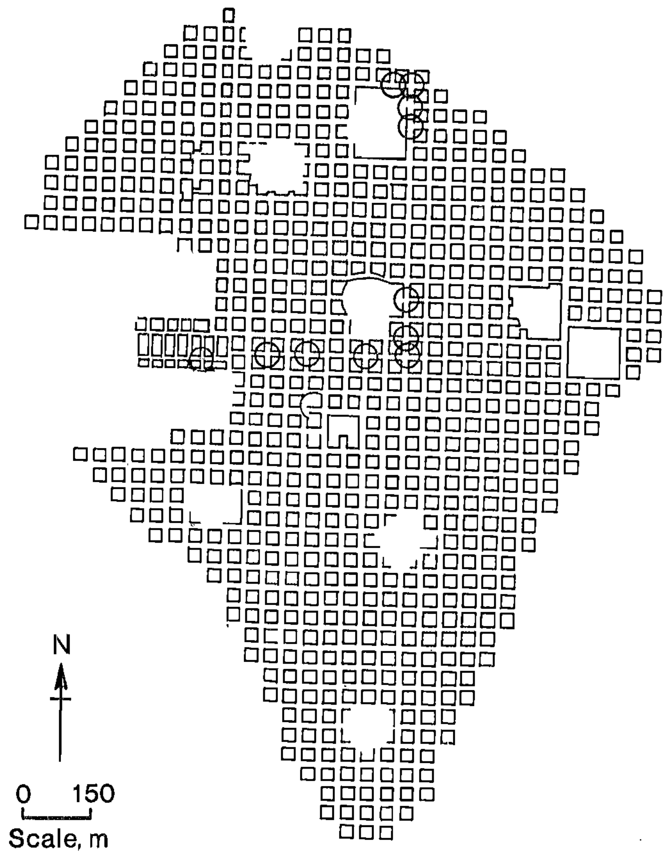

Figure 8.—Second salt mine with transmitter on surface.

The gypsum mine in Iowa was a site at which tests were made to determine the effects of antenna design on the performance of the fire alarm system. This mine has 188 m of overburden made up of 60 m of limestone above the gypsum ore body, 60 m of shale, and about 60 m of glacial till. Like the salt mines, this was a room-and-pillar mine and perhaps more typical of the many room-and-pillar mines in the United States. The mine underlies farmland, which was not accessible for deploying an antenna. Thus, transmitter antenna was placed underground around mine pillars. Electromagnetic signal transmission from a surface transmitter and antenna would encounter the same rock strata and therefore approximate the conditions of the test. Two antennas were used to gain information on electromagnetic signal transmission characteristics as a function of antenna design. One antenna was a 93-m-diam loop of 12 turns, the other, a 48-m-diam loop of 8 turns. Field strength meters were used to evaluate reception on the surface.

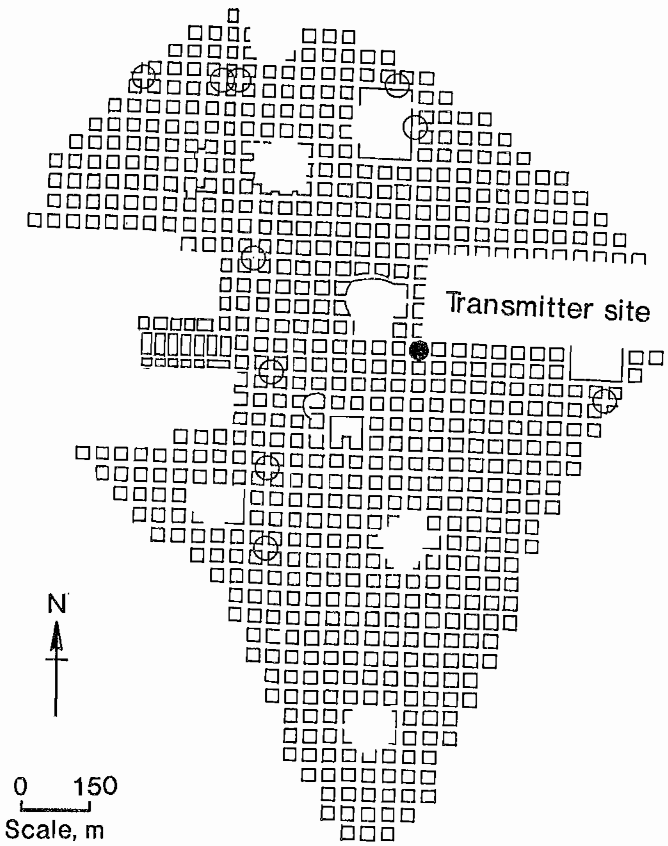

Figure 9.—Second salt mine with transmitter underground.

Field strength measurements were made from surface roads overlying the mine. Reception at the surface was good and the electromagnetic signal was detectable at a distance over 1 mile from the center of the underground transmitting loop antenna.

The limits of the surface reception area had an elliptical shape for transmission from both types of antennas. The major axis of the ellipses is thought to correspond to a preferred orientation of joints in the limestone overlying the ore body, because flat surfaces which exist on mine pillars have a similar east-northeast orientation in space. This test suggests that transmitting from within a mine and measuring the electromagnetic field strength on the surface, may be a useful means of establishing preferred orientation of overburden joint systems.

It is known that the energy of an electromagnetic signal may be somewhat attenuated in crossing an interface in rock, however the area encompassed by the limits of signal reception from the large transmitting antenna is great enough to provide full mine coverage of a fire-warning signal if the transmitter and antenna were placed on the surface above the center of the mine. Two aquifers exist in this area of the overburden, but signal reception was very good, due in part to improved sensitivity of the receivers used in the tests (*4*).

The area of surface reception as determined from plotting of reception sites on a map (fig. 10) indicates that the reception area on the surface is directly proportional to the strength of the magnetic moment of the transmitter antenna. Test results indicate that a 12-turn antenna with a magnetic moment of $129*10^3$ A*t*m^2 (ampere-turns-meter squared) produced an area of reception of $2.3*10^6$ m^2, while an 8-turn antenna with a magnetic moment of $60*10^3$ A*t*m^2 produced an area of reception of $1.2*10^6$ m^2. These results indicate that when the magnetic moment is doubled, the area of reception on the surface is also doubled. Interestingly, the large antenna powered at 25 W produced an area (one square mile) of reception that is twice as great as the area of reception of the small antenna transmitting at 125 W of power. These findings indicate that the magnetic moment of the loop antenna increases as a square of the radius of the loop and therefore has more effect on the size of the reception area than does the magnitude of transmitter power expressed in watts. Again, the test results indicate that if the antenna were located on the surface of the ground above the center of the mine, full-mine coverage by the fire-warning signal could be achieved. The use of a transformer to match the impedance of transmitter and antenna could make it possible to achieve 90-pct efficiency of the transmitter system and produce a magnetic moment which is much greater than the magnetic moment used in the above mentioned test.

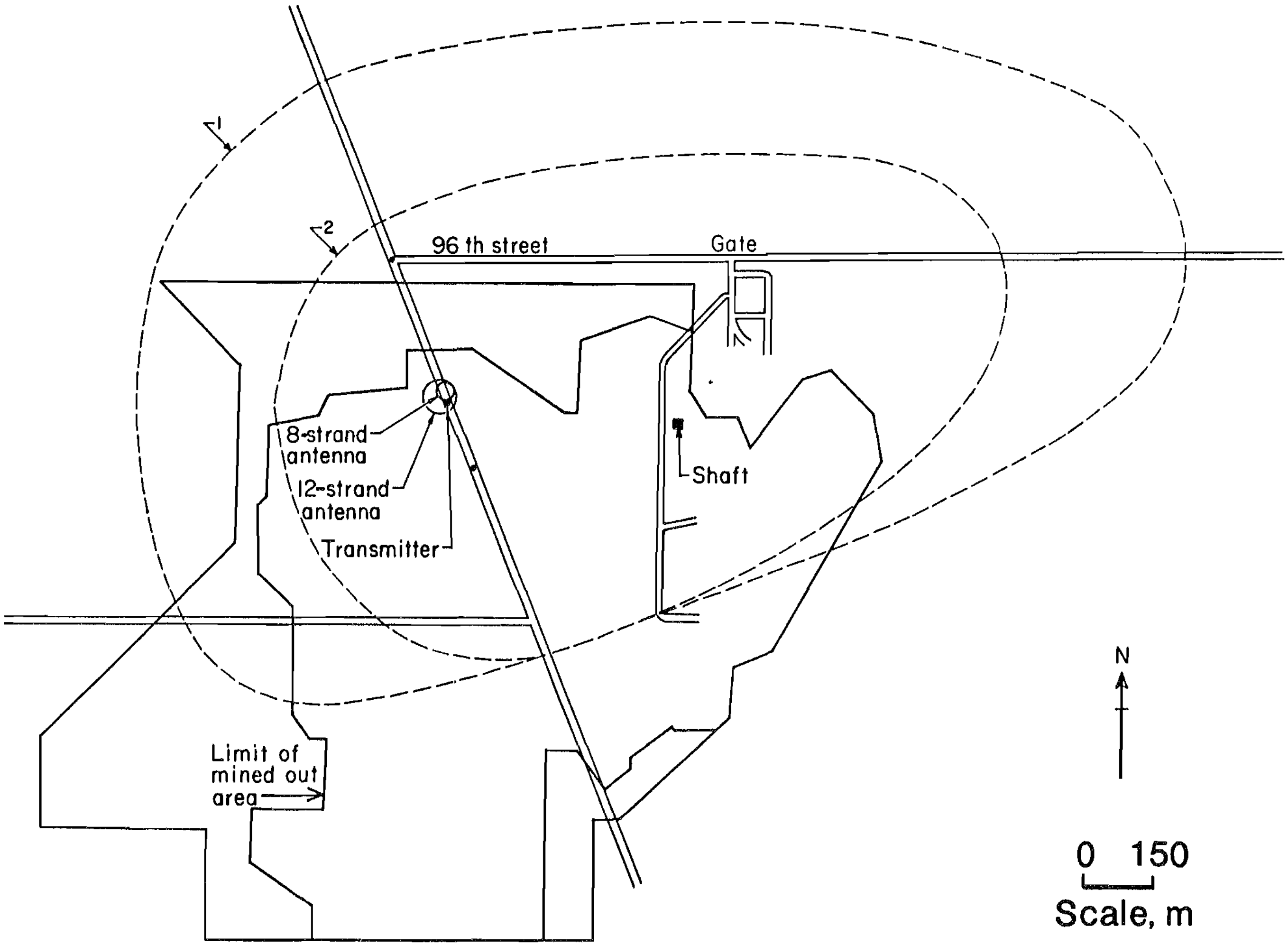

Figure 10.—Reception limits at gypsum mine. (1) Magnetic moment of 129,000 A*t*m² yields 2.3 × 10⁶m² area of reception; (2) magnetic moment of 60,000 A*t*m² yields 1.2 × 10⁶m² area of reception.

CONCLUSIONS

A fire-warning alarm system has been developed which functions by transmitting an encoded ultra low frequency electromagnetic field through mine rock to underground workings where miners equipped with personal pagers can receive the fire warning signal. A prototype of the system has been successfully tested at two underground metal mines, two salt mines, and one gypsum mine. The signal transmission distance achieved during these tests, was greater than 1,645 m through overburden at a gypsum mine. Since 90 pct of the metal and nonmetal mines and nearly all of the coal mines in the United States are less than 900 m deep, it is believed that the electromagnetic fire-warning system with a transmitter on surface would be able to function well in most of the domestic mines in the United States. Using underground transmitters, the system would be expected to perform even better in underground mines.

The Bureau has filed patent applications on this invention and is actively promoting commercial development of the system for in-mine use.

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☆ U.S. GPO: 1991—511-010/42,010

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