ONE-WAY FIRE WARNING ALARM SYSTEM FOR UNDERGROUND MINES

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Abstract - An ideal fire warning alarm system for underground mines would be low cost, convenient, fast, reliable, and able to warn all underground workers. Present warning systems, such as phones, messengers, and stench, fail one or more of these criteria. The U.S. Bureau of Mines may have devised the ideal system. The one way communication system employs a large loop antenna and transmitter to create a 630 hertz (Hz) electromagnetic field to send information through-the-earth to cap lamp battery mounted micro-receivers worn by underground miners. Field tests of prototype equipment in 1986 resulted in through-the-rock signal transmission of over 762 m (2500 ft). Subsequent hardware upgrades for more recent tests resulted in transmissions of over one mile.

Recently developed receiver circuitry employs phase-locked-loop detection circuitry responsive only to a specific series of pulses of given time duration, that eliminates false alarms from electromagnetic noise emitted by mine equipment, power lines, or lightning. A multichannel system can relay standard messages to miners.

I. INTRODUCTION

The ideal fire warning system for underground mines would be capable of instantly warning all miners of an emergency regardless of their location in the mine. A fire warning system that is capable of alerting the miners quickly would allow them to don self rescue breathing apparatus [1] for protection against toxic fire gases and save precious time needed for a successful escape from the mine fire [2]. The ideal fire warning system would also have low installation and maintenance costs, be reliable, able to withstand rough treatment, and tolerate the harsh mine environment.

Currently used underground mine fire warning systems such as telephones, ultra high frequency (UHF) and medium frequency (MF) radio, visual or audible alarms or the most commonly used "stench" system all have their limitations and shortcomings.

Telephones are commonly used in coal mines where the miners are closely grouped at the working face and not dispersed as they often are in metal or nonmetal mines. The noise of a ringing telephone or other audible alarm can be masked by the noisy mine environment, or its ring becomes so familiar a sound that it is ignored by the miner. This form of communication can be rendered dysfunctional when the wire is severed by rock falls, fire, or explosion.

UHF radio and visual alarms require line-of-sight for signal reception and miners in remote parts of the mine will not be made aware of the warning signal. MF radio requires an extensive electrical conductor system for signal transmission [3]. In modern mines where diesel equipment is used, conductors such as power, air, and water lines might be absent, and the cost of installing wire conductors throughout the mine for MF radio would be very costly.

The most commonly used fire warning system in underground metal and nonmetal mines is the stench system [4-5]. It employs the injection of a stench into the ventilation system or compressed air lines for carrying the fire warning signal to the underground miner. However, in high back room and pillar mines where air movement can be slow, the time required for the stench warning to reach miners can be excessive. Existing fire warning systems have not been universally able to provide full mine coverage for all underground miners. A properly designed electromagnetic fire warning system would provide the fire warning instantly and simultaneously to all miners regardless of their location in the mine.

II. ELECTROMAGNETIC FIRE ALARM WARNING SYSTEM

The electromagnetic fire warning system described in this paper combines the transmission and reception of ultra-low frequency electromagnetic through-the-earth fields as a means of sending a fire warning signal to underground miners [6]. The electromagnetic field generated by the 100 meter diameter loop antenna together with its accompanying electric field is the means of signal transmission. The fields emanate from the transmitting antenna in a somewhat spherical manner, while the field along the antenna axis can be approximated by the following equation [7-8].

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

where H = the magnetic field strength, A/m
I = the antenna current, A,
M = the number of turns,
A = the area of the antenna, m^2,
G = an attenuation constant,
π = the constant 3.14 (pi), and
Z = distance through the transmitting medium, m.

The transmitter system consists of a low frequency audio signal generator operating at 630 Hz coupled with a high power audio amplifier (fig. 1) which

Fig. 1. Fire warning system transmitter.

drives a large loop antenna (fig. 2). The electromagnetic field generated by the large loop antenna penetrates the mine rock to underground workings where miners equipped with micro-receivers mounted in and powered by their cap lamp batteries are made aware of the fire warning when the signal initiates a blinking of their cap lamps (fig. 3).

Fig. 3. First generation ULF receiver.

In initial trial tests of the fire warning system a transmission frequency of 1950 Hz was used, however a transmission frequency of 630 Hz was ultimately chosen because it is low enough to more easily penetrate overburden, while still operating within constraints of our power amplifier and loop antenna system. Since 630 Hz lies between the tenth and eleventh harmonics of the standard 60 Hz power line frequency used in the United States, it also offers some immunity to electrical noise, although the ambient noise level is less at higher frequencies. Further research is needed to determine the optimum operating frequency for the warning system.

In order to further reduce the effects of electrical noise on the system the low frequency warning signal can be encoded to discriminate between the actual signal and noise sources. The Bureau developed system uses a pulse modulation technique to eliminate false triggering of the system. This type of modulation switches the signal between on and off states at predetermined intervals. The prototype system uses a signal modulated at 1 Hz (the signal is on for one-half second and off for one-half second). To further insure against false alarms, the receiver must receive four consecutive cycles of the modulated signal before the system recognizes it as a valid warning signal.

Although the recently developed receiver circuit operates on a 630 Hz frequency, other ULF frequencies may be suitable for a specific mine. The selection of the optimum transmission frequency would be based on four basic criteria: 1) the ULF electromagnetic noise spectrum of the underground mine, 2) maximum required signal transmission distance, 3) the electrical properties of the mine rock through which the signal must pass, and 4) cost of the required fire warning system components.

Choosing a frequency where the ambient electromagnetic noise level is at a minimum would be essential in maximizing the signal-to-noise ratio of the system, an important consideration in designing an effective warning system. The transmission frequency would also have to be selected so that the through-the-earth signal transmission distance is maximized while amplifier and antenna costs are minimized. The optimum frequency selected would maximize the signal-to-noise ratio of the system while operating within the constraints of the power amplifier and antenna.

A. Receiver

In order to detect the transmitted signal and warn the miner of a possible emergency the Bureau has developed a prototype receiver circuit which will eventually be integrated into the miners cap lamp battery unit. The system will detect the pulse modulated signal from the transmitting system and flash the cap lamp until the miner acknowledges the warning and returns the lamp to normal operation.

The receiver circuit consists of four major sections: 1) the receiving antenna, 2) the amplifier, 3) the phase-locked-loop detection system, and 4) the cap lamp flashing system. Each section is described in detail below.

The receiving antenna consists of a 17 cm (7 inch) long and 0.635 cm (1/4 inch) diameter ferrite core wrapped with several hundred turns of #30 AWG enameled copper wire. The receiver antenna, is capacitively coupled to the input transformer of the receiver and tuned to operate at the 630 Hz resonant frequency. The transformer steps up the voltage by a factor of ten, after which a selective bandpass amplifier filters the received signal and drives two gain stages designed to amplify the filtered signal to the desired level for detection by the phase-locked-loop (PLL) detector circuitry. The prototype receiver has the amplified signal fed to a pair of PLL signal detectors. The first PLL detects the 630 Hz carrier signal. The output of the first PLL drives the input of a second PLL for detection of the 1 Hz modulation frequency. Four cycles of the 1 Hz modulated signal must be received by the counter before the system recognizes it as a valid warning and activates the cap lamp flasher to warn the miner of an emergency. A reset button allows the miner to acknowledge the warning and return the cap lamp to its normal operation. Additional PLL stages could be added to provide multiple warning signals or digital data transmission capabilities if desired.

B. Transmitter

The Bureau's prototype ultra-low frequency transmitter for encoding signals consists of a pair of signal generators, a power amplifier, a transformer, and loop antenna. The primary signal source generates a 630 Hz sine wave output that is triggered by the second signal source operating at the 1 Hz modulation frequency. The output of the primary signal source feeds the input section of the 1000 watt audio frequency range power amplifier.

In order to provide the maximum power to the multi-turn loop antenna a set of matching capacitors is used to cancel the effect of the antenna's inductive reactance on the system. By measuring the inductance of the loop antenna using a inductance meter, the capacitance value needed to maximize power transfer can be obtained from the following formula:

$$C = \frac{1}{4 \times \pi^2 \times f^2 \times L}$$

where f = frequency, Hz,
L = antenna inductance, Henries (H), and
C = matching capacitance in Farads (F).

After selecting the approximate series capacitance required to tune the antenna, the system is fine tuned to the resonant frequency by adding or removing capacitors as necessary. The use of a transformer to match impedance of the transmitting antenna to that of the amplifier can improve efficiency of the system when the impedance of the large transmitting antenna is higher than the optimum output impedance of the amplifier.

III. 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 diameter 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 in conjunction with an audio frequency receiver to allow the operator to hear a continuous tone signal. The first tests were made at low power levels (2 w). The signal was received through about 15 m of overburden with an area of reception about 10 times the area of the transmitting loop antenna. The results of this first test were encouraging enough to justify additional field tests of the system.

A second series of tests was 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 above the 27th level drift, located 762 m from the main shaft. The transmitting antenna was made up of 10 turns of #10 copper wire formed into a 30 m diameter loop. The transmitter (fig. 1) and receiver (fig. 3) were used in the tests.

It is possible to establish the current generated in a ferrite core receiving antenna by measuring the voltage 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 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 rock at this mine site was in excess of 762 m. Maximum transmitter power level was 53.3 w.

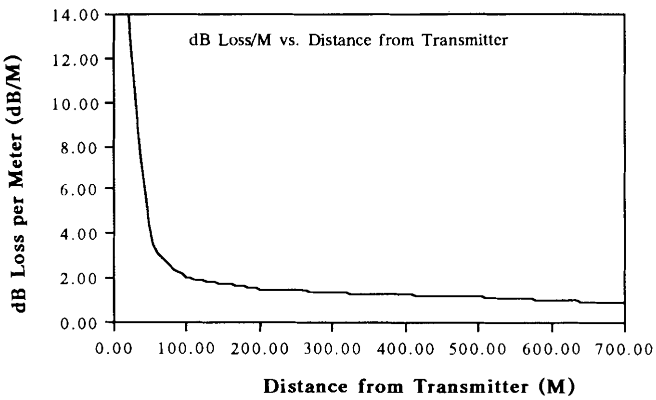

Fig. 4. Graph of signal attenuation at various distances.

Another in-mine test of the electromagnetic fire alarm system was conducted at a 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. 2). For this test a hand held 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 depth. 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 mine and the two sites in Minnesota were conducted at a carrier wave frequency of 1950 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 conductivity as shown by the following equation:

$$\text{Skin depth (m)} = \delta = \left(\frac{2}{\omega\mu\sigma}\right)^{1/2}$$

where ω is 2π x f (frequency), and σ is 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:

$$\text{Skin depth (m)} = \frac{503.3}{(f\sigma)^{1/2}}$$

Through measurement, and further calculations the value of σ can be established. The two types of overburden at the mine had values of conductivity slightly greater than 10^{-1} mhos/m, which is a value greater than the value of conductivity for most mine rock). A high-conductivity material retards penetration by an electromagnetic 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.

As stated above electromagnetic theory predicts that the electromagnetic wave skin depth is greater at lower frequencies. Therefore, mines that were known to present problems associated with high conductivity overburden, were chosen as tests sites suitable for determining if lower frequency signals penetrated more effectively. Thereafter more recent tests were made using a frequency of 630 Hz instead of the 1950 Hz frequency used in earlier tests.

IV. RECENT FIELD TESTS RESULTS

The following field tests of the electromagnetic fire warning system were made using the high gain receivers (6000 and 12000 gain) that can be equipped with phase lock loops for receiving pulse modulated 630 Hz signals. For gathering test data on EM signal-to-noise ratios, a voltmeter or portable oscilloscope were used to monitor voltage output of the receiver circuit.

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 earth material. The highly conductive overburden is believed to present a most difficult condition for electromagnetic signal transmission, and this proved to be true even at a the lower transmission frequency of 630 Hz.

The transmitter and 93 m diameter loop antenna of 12 turns was deployed on the surface above the workings of the first mine (fig. 5). The transmitted electromagnetic signal pulsed on/off for 30 second intervals 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. 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 gallons of petroleum, and also through 45 m of salt water saturated overburden and 320 m of cap rock and rock salt.

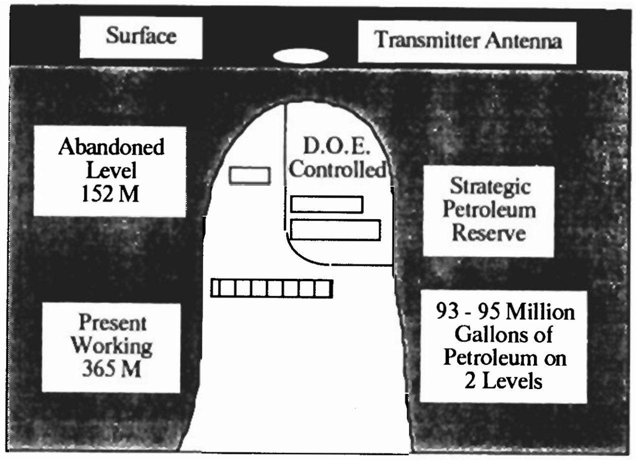

Fig. 5. Cross section of first salt mine.

Test conditions at the second mine which has 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, 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 completely satisfactory and therefore underground deployment of the transmitter would likely give more satisfactory system 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 indicate full mine coverage is feasible. 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 of mine rock tested thus far, exceeding $1.5*10^{-1}$ mhos/m making it the least transparent to electromagnetic signals of any of the test sites, however this problem can be overcome with increased transmitter power or with the transmitter antenna placed underground.

A 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 and to simplify test conditions the transmitter antenna was placed underground around mine pillars. Two antennas were used to gain information on electromagnetic signal transmission characteristics as a function of antenna design. One antenna was a 93 m diameter loop of 12 turns, the other 48 m diameter loop of 8 turns. Field strength meters were used to evaluate reception on the surface. Electromagnetic signal transmission from a surface transmitter and antenna would encounter the same rock strata and therefore approximate the conditions of the test.

Field strength measurements were made at sites on intersecting surface roads overlying the mine. Reception at the surface was good and the electromagnetic signal was detectable at over a mile away 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. A procedure of transmitting from within the 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 the redesigned narrow bandwidth, high gain receivers used in the tests.

The area of surface reception as determined from plotting of reception sites on a map (fig. 6) indicates that the reception area on the surface is directly proportional to the strength of the magnetic field emitted by the transmitter antenna. Test results indicate that a 12 turn antenna with a magnetic moment of $129*10^3$ ATM^2 produced an area of reception of $2.3*10^6$ m^2, while an 8 turn antenna with a magnetic moment of $60*10^3$ ATM^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. As expected, the large antenna powered at 25 w produced an area (one square mile) of reception twice as great as the small antenna transmitting at 125 watts of power, since the magnetic moment of the loop antenna 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% efficiency of the transmitter system and produce a magnetic moment of $.9*10^6$ ATM^2 which is about 4 times greater than the magnetic moment used in the above mentioned test.

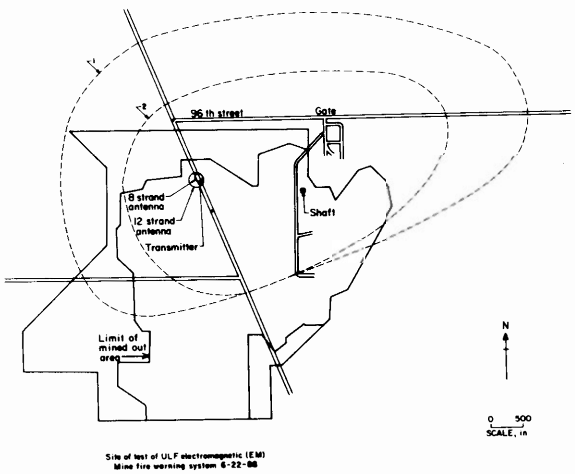

Fig. 6. Map of reception limits at gypsum mine
(1) Magnetic moment of $129*10^3$ ATM^2 yields $2.3*10^6$ m^2 area of reception;
(2) Magnetic moment of $60*10^3$ ATM^2 yields $1.2*10^6$ m^2 area of reception.

V. 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 warning devices 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 1645 m through overburden at a gypsum mine. Since 90 pct of the metal and nonmetal mines in the United States are less than 900 m deep, it is believed that the electromagnetic fire warning system described has the capacity to function well as a fire warning alarm system for most mines and could therefore find widespread use in the domestic mining industry. During field tests with more improved versions of the receiver units, full mine signal coverage was achieved at three of the mines. With improved equipment designs and proper transmitting antenna design and placement, it is reasonable to assume that the electromagnetic fire warning system could be capable of instantly warning miners in remote parts of a mine at distances of over a mile from the transmitting antenna and serve to alert them to the existence of a mine fire.

The use of pulse modulation detection circuitry in the receiver allows it to reject all electromagnetic noise and false alarms and act only on the pulse modulated 630 Hz fire warning signal; only when a series of four 1 Hz pulses are passed to the counter will the flasher activate the blinking of the cap lamp which signifies a fire warning.

The Bureau of Mines has filed patent applications on this invention and is actively promoting commercial development of the system for in-mine use. It is planned that a prototype system will soon be installed in a mine and refinements in system operation finalized and the system made commercially available.

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