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Evaluation of a Signaling and Warning System for Underground Mines

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	min	minute
H	henry	mm	millimeter
Hz	hertz	mV	millivolt
kg	kilogram	s	second
kHz	kilohertz	V	volt
km	kilometer	W	watt
km^2	square kilometer	μF	microfarad
kW	kilowatt	μV	microvolt
m	meter	Ω	ohm
m^2	square meter	%	percent
mH	millihenry		

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EVALUATION OF A SIGNALING AND WARNING SYSTEM FOR UNDERGROUND MINES

By Ronald S. Conti[1] and Robert G. Yewen[2]

ABSTRACT

Underground mines rely on alarm systems, such as stench gas, audible or visual alarms, pager phones, telephones, and messengers to warn miners of a fire or other emergency. These systems are often slow, unreliable, and limited in mine coverage. This report describes the evaluation of a wireless signaling and warning system for underground mines. This system is applicable to both coal and noncoal mines. The work was conducted by the National Institute for Occupational Safety and Health[3] in cooperation with TeleMagnetic Signalling Systems (TSS) under Cooperative Research and Development Agreement No. BOM-CRDA-6200-0119.

A TSS wireless ultra-low-frequency electromagnetic signaling system was installed at the Experimental Mine at Lake Lynn Laboratory near Fairchance, Fayette County, PA. A commercial smoke sensor was interfaced to a remote portable transmitter, and the alarm of the sensor was used to trigger the central evacuation and paging transmitter system during experimental mine fires. The underground/surface receivers flashed cap lamps and activated remote devices, such as strobe lights, within 30 to 40 s after the encoded signal was received. Evaluation results showed full-mine coverage of the electromagnetic field and that the encoded signal was received at the farthest point underground and on the surface perimeter.

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[2] Director of research, TeleMagnetic Signalling Systems, Unionville, Ontario, Canada.

[3] This research originated under the former U.S. Bureau of Mines prior to transferring to the National Institute for Occupational Safety and Health in 1996.

INTRODUCTION

Mine Safety and Health Administration (MSHA) statistics[4] indicated that 107 underground fires occurred in coal and metal/nonmetal mines from 1990 to 1995 in the United States, causing 32 injuries. Historically, mine fires have resulted in fatalities, injuries, and economic losses totaling hundreds of millions of dollars. A primary research thrust of the National Institute for Occupational Safety and Health's (NIOSH) Pittsburgh Research Center is to enhance the safety of the mine personnel by preventing disasters, such as fires and explosions.

Federal regulations [30 CFR[5] 57 and 75 (1994)] require that each mine have (1) a program of instruction to include location and use of fire-fighting equipment, escapeways, exits, and routes of travel; evacuation procedures; and fire drills; and (2) automatic fire-warning devices that upon activation would provide an effective warning signal to all work locations, or at a manned location where personnel have an assigned post of duty and have telephone or equivalent communications with all personnel who may be endangered.

A fire occurred on a belt drive roller on March 7, 1988, [Strahin et al. 1990] in the Marianna No. 58 Mine, Washington County, PA. During the developing fire, the following sequence of events occurred:

- At approximately 7:00 p.m., the belt stopped and was restarted.
- At 9:08 p.m., a high carbon monoxide warning in the tailpiece cleared and was never investigated.
- At 10:35 p.m., a miner smelled smoke, which was immediately followed by light smoke, which quickly changed to a heavy black smoke. Upon investigation, this miner observed fire coiled around the belt drive roller. Fire-fighting attempts with fire extinguishers were unsuccessful, water was not readily available, and the belt drive deluge system had been turned off.
- At 10:50-10:55 p.m., miners were notified to evacuate the mine. During this period, 27 miners donned their self-contained self-rescuers and began their escape. It required almost 80 min for the miners to reach the surface. Four miners were treated for possible smoke inhalation.

All three working sections were equipped with a telephone at the time of the fire. No one was present to answer the telephone on two of the sections, and a telephone call was ignored on the other section. A carbon monoxide warning light was energized near the belt feeder; however, no one was present to see it. Approximately 10 min passed before all miners received an evacuation message [Stowinsky 1996]. This delay in evacuating the mine could have been catastrophic had the fire been further developed and escape routes blocked. The mine eventually had to be sealed and abandoned.

Survival for an underground miner during a fire or other emergency can be measured in terms of minutes. An emergency warning that arrives late can result in tragedy. Existing warning systems for underground mines, such as horns, sirens, stench gases through the ventilation system, or messengers (other miners), can be slow and ineffective. This prompted the development of wireless, ultra-low-frequency electromagnetic signaling technology for warning and paging systems for the mining industry.

As early as 1899, Nikola Tesla suggested the use of what is today described as extremely low frequencies for worldwide communication using an earth medium [Wheeler 1961]. Pioneering research was conducted by the former U.S. Bureau of Mines (USBM) on the propagation of radio waves through the earth and detection of trapped miners [Dobroski and Stolarczyk 1982; Shope et al. 1982; Geyer et al. 1974; Anema 1976; Lagace et al. 1980; Westinghouse Georesearch Laboratory 1973; Lagace et al. 1982]. Subsequent USBM research [Hjelmstad 1990; Hjelmstad and Pomroy 1991] showed that ultra-low-frequency electromagnetic signals from 630 Hz to 2 kHz could be transmitted through mine rock for distances as great as 1,645 m to an intrinsically safe receiver. The prototype wireless system of the previous research used off-the-shelf components and state-of-the-art technology to ensure high reliability and low cost. The technology enabled simultaneous and instantaneous warning of all personnel, regardless of their underground location or work activities, by flashing their cap lamp.

An Australian mining industry research initiative resulted in the commercial availability of a "paging" system for under- ground mines [Zamel 1990]. The Personal Emergency Device communication system is a "through-the-earth" transmission system that enables communication of specific messages with individuals underground, no matter what their location and without dependence on cables or wiring underground. This system consists of a personal computer, low-frequency transmitter, surface loop antenna, and portable receiving units integrated with the cap lamp battery. It functions with a carrier wave frequency of 1,000 Hz and employs a frequency-modulated signal for transmitting messages entered to the transmitter from a personal computer. Specially designed software makes it possible to send a message up to 32 characters long for readout on the person-wearable receiver with its liquid crystal display (LCD). Messages can be directed to an individual, to a group, or to all underground personnel. When a message is received, the cap lamp flashes and the miner can then read the message from the LCD on top of the

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[4] Mine fire statistics were obtained from files maintained at MSHA's Denver Safety and Health Technology Center, Injury and Employment Information Branch, Denver, CO.

[5] *Code of Federal Regulations.* See CFR in references.

lamp battery. A message is displayed for 1 min. For example, with a surface loop antenna approximately 2 km long, a signal was received 1 km in depth and laterally for a 1- to 2-km radius.

The first demonstration of the system in the United States was conducted at our Lake Lynn Laboratory near Fairchance, Fayette County, PA, in November 1990. An approximately 1.6-km-long copper wire formed a surface loop antenna above the mine. Several messages were typed into the computer and clearly received throughout the underground mine workings 50 to 100 m below the surface.

TELEMAGNETIC SIGNALLING SYSTEMS AND TECHNOLOGY OVERVIEW

Under a Cooperative Research and Development Agreement (CRADA) with TeleMagnetic Signaling Systems (TSS), Unionville, Ontario, Canada, a research effort at Lake Lynn Laboratory was established to further develop the signaling system. Initial meetings were held during the summer of 1992 to develop a research plan and formalize the working agree- ment. The research plan included a simple and inexpensive system using a small surface transmitting antenna (less than 2 m in diameter), an underground receiver/transmitting antenna (15 to 50 m in diameter), and underground/surface person-wearable receivers for full mine coverage. Once the system was designed, it must be easily integrated with existing fire detection and warning systems, turn devices such as strobe lights on or off, and its frequency cannot initiate electric blasting caps. Lastly, it can alert all miners of an emergency.

The first-generation product produced by TSS [Yewen 1987] is aimed at mine evacuation and paging. This underground signaling system transmits an emergency warning that can quickly reach the underground worker. The low-frequency electromagnetic field has a distinct advantage because it can penetrate kilometers of soil and rock to reach the most remote shaft or tunnel, which makes it ideal for underground signaling and paging systems. This system consists of a low-frequency transmitter that can be strategically placed to create an electromagnetic signal that can completely envelop most mines without the use of repeater systems. However, some mines may require a repeater system for complete mine coverage. Figure 1 shows a typical configuration of the wireless system for a mine. The transmitter loop antenna is on the surface, and a receiver/transmitter loop antenna is underground. The person-wearable receivers are small, lightweight modules incorporated into the miner's cap lamp assembly. Upon receiving an emergency or paging signal, the cap lamp begins to flash, which in turn alerts the miner to evacuate the mine or call the surface for a message, depending on which signal is received. To discriminate between the two signals, the miner would observe the "on" status of the red light-emitting diode (LED) mounted in the lamp assembly receiver module. For example, for a paging signal, the miners' cap lamp would flash and the red LED would illuminate; if the red LED is not illuminated, the miner is alerted that an emergency may exist.

Further coverage can be provided by installing receivers on vehicles or in refuge stations and work areas. Due to the high level of electrical noise (electromagnetic interference/radio frequencies) generated by some vehicles, specialized low-noise antenna receiver systems are used. The system has the potential for special receivers with the ability to relay gas sensor alarms, seismic alerts, and addresses to control fans and pumps. Remote emergency wireless paging stations are available as a standard "Fire Pull Station." They can be installed at any strategic location in the mine or on the surface. During an emergency event, the station can activate the warning signal.

The system is designed to produce a low-frequency electromagnetic field with a programmable carrier output frequency about 2 to 3 kHz. Operating the system at this low frequency enhances the ability to penetrate through most geology of sand, soil, water, and rock with little difficulty. The carrier is modulated with low-frequency tones from 4 to 40 Hz using a unique signaling protocol to address individual receiver units.

The transmitter and antenna system is usually installed on the surface of the mine using a loop antenna. A custom-designed loop antenna at the point of installation is engineered around environmental and geological influences on the electrical characteristics of the loop. For example, if the loop antenna is lying on an overburden that is high in various salt contents, then at times of heavy rain or melting snow, the earth beneath the loop antenna can become very conductive. This drives the impedance up, thus reducing the effective ampere-turns. Low-lying areas of overburden with this characteristic should be avoided.

Influencing geologies such as sulfide ore bodies can also affect the impedance of the loop antenna. When possible, the loop antenna should be installed strategically at a comfortable distance from the influence. A recommended distance, depending on the size of the ore body, is 200 to 600 m.

Other influences, such as diabase dikes, have a different effect. The diabase dike is magnetic and deviates the field. These dikes effectively form a magnetic wall. If possible, the loop antenna should be placed where the electromagnetic field does not have to penetrate the dike directly, but will still reach its target radius to the mine.

A microprocessor-based center controls the operation of the system. It encodes the through-the-earth transmitted signals in such a way that the desired in-mine receivers turn on. The system paging capability can be programmed to contact up to eight individual person-carried receivers in the mine, such as supervisors and maintenance personnel. A control station is

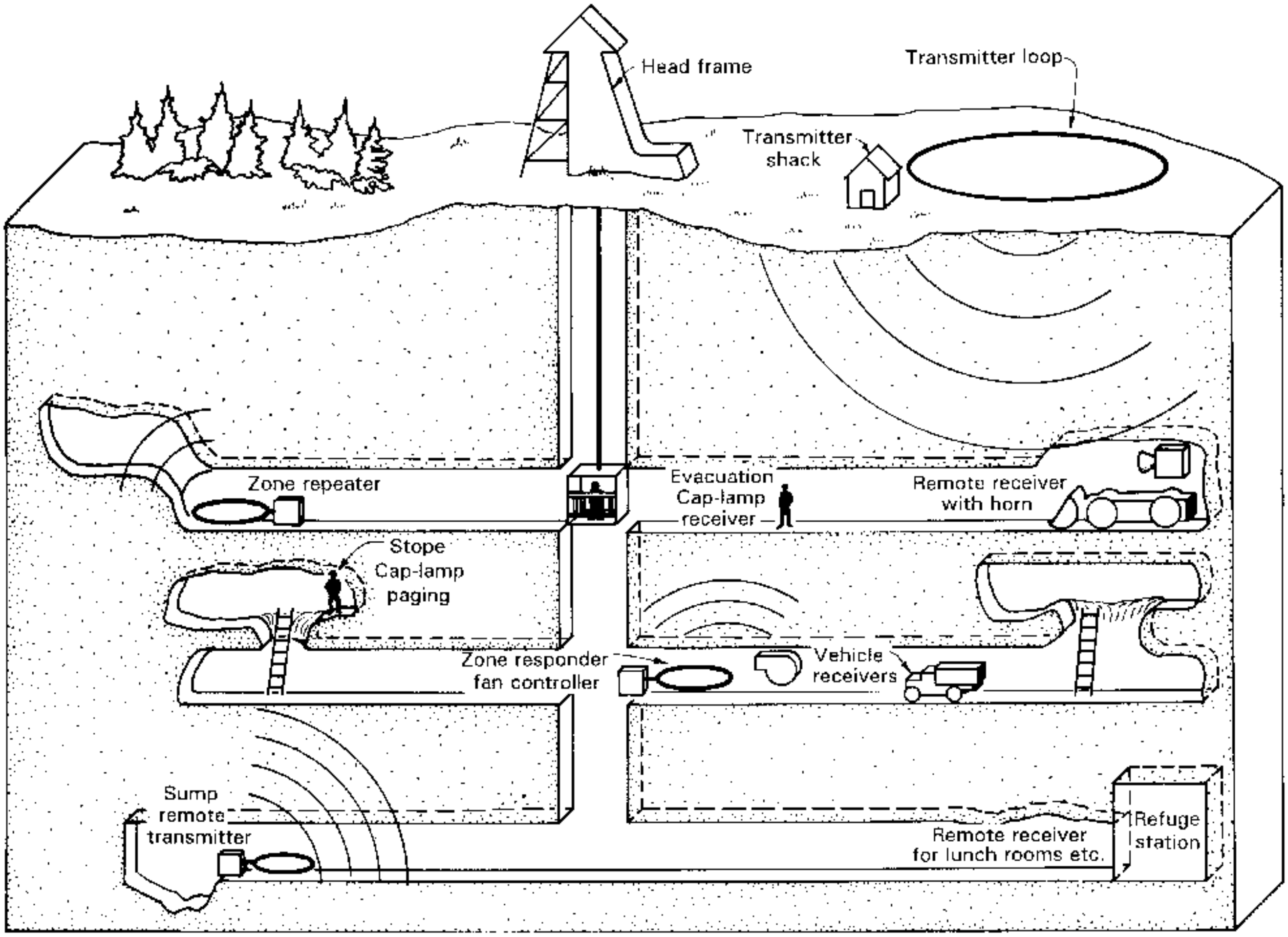

Figure 1.—Conceptual representation of a mine, depicting capabilities of the communication and signaling system.

also available as a system remote module that can be mounted at the surface transmitter location and can be addressed and controlled from existing personal computers or programmable logic control systems.

The TSS receiver technology has been designed to a module format to retrofit existing cap lamps. The receiver module technology is encapsulated to protect it from harsh environments in an injection-molded, impact-resistant plastic case. Cap lamp manufacturers are not opposed to the retrofits. TSS is currently seeking MSHA approval for use in U.S. underground coal mines.

The receiver circuit consists of high-quality factor (Q) resonated inductors that function as receiving antennas connected to a high-gain amplification circuit utilizing noise reduction processing and demodulating circuitry to process the signal. The receivers may be interfaced with fans, pumps, etc., for control purposes, or they can monitor the operation of these devices.

As a result of demonstrating the capability of the TSS system and the work conducted under the CRADA during briefings on mine fire preparedness,[6] the first installation at an operating U.S. mine was completed. Dravo Lime's Black River Mine near Maysville, KY, tested the system on February 7, 1996, and acquired 12 person-wearable lamp receivers for key personnel. Each cap lamp module was retrofitted with a receiver. The Black River Mine is a room-and-pillar underground limestone mine with an area of approximately 3.7 km^2 and 198 m of overburden. The mine employs approximately 135 employees (40 underground miners per shift) and utilizes diesel equipment and conveyor belt haulage. A 50-m loop with an applied power of 50 W is used to generate an effective electromagnetic field (ampere-turns) for full mine coverage at this site. Because of the success of its present system, Black River Mine plans to augment its cache of person-wearable lamp receivers for more miners.

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[6] The NIOSH Pittsburgh Research Center conducts open industry briefings on mine fire preparedness to enhance the mining industry’s awareness of the dangers of underground mine fires and convey research findings on the latest methods for detection, control, and extinguishment of mine fires.

Installations at three gold mines in Ontario, Canada, have also been successfully completed. Together these mines acquired more than 300 lamp receivers for their underground personnel. The installations also use remote strobe light receivers on jumbo drills and on rampways to signal vehicles traveling in and out of the mine.

A recent test at a Canadian metal mine, products of which include zinc, gold, and platinum, showed that the low-frequency electromagnetic signal could be transmitted through the mine rock for a distance of 2,073 m. A 100-m-diam loop antenna (two turns) with an applied power of 80 W was used to generate the electromagnetic field. Additional tests are planned to further develop the loop and provide full mine coverage.

LAKE LYNN LABORATORY

The NIOSH Pittsburgh Research Center's Lake Lynn Laboratory [Mattes et al. 1983; Triebsch and Sapko 1990], formerly a limestone mine, is now a multipurpose research facility used to conduct mining health and safety research. The mine is geologically in the Greenbriar Limestone Formation (locally known as the Wymps Gap Limestone). A repre- sentative stratigraphic column of the strata above and below the mine is shown in figure 2.

Lake Lynn Laboratory's underground layout, including the locations of the electromagnetic system antenna loops, is shown in figure 3. Initial mining was done by surface methods and created 900 m of high wall and almost 60 km^2 of gently sloping quarry floor.

The average dimension of the old workings is 10 m high with 15-m-wide entries and crosscuts on 30-m centers, leaving 15-m square pillars for support. The old workings have an area of approximately 130 km^2.

The new entry dimensions of the underground mine range from 1.8 to 2.4 m high and 5.3 to 6.3 m wide. The average dimensions are 2.1 and 5.8 m, for an average cross-sectional area of 12 m^2. The underground configuration of the new entries covers approximately 95 km^2, with an overburden ranging from 50 to 100 m.

SYSTEM DESIGN, INSTALLATION, AND EVALUATION

LOOP ANTENNA INTRODUCTION

The antenna used at Lake Lynn is a large air core loop constructed with multiple conductor control cable. Burying the loop would not significantly impact the loops' characteristics. This cable is laid down in a circle with the two ends brought together for connections. Each conductor (both ends) is then numbered, and each wire is connected to form a continuous multiple-turn loop. For example, a continuous loop with 14 turns would require 15 conductors connected together. The circular loop must be as round as possible to project the electromagnetic field around its entire circumference. For example, if the loop antenna were teardrop-shaped, the electromagnetic field would be projected as a teardrop, but opposite to the shape of the loop antenna. The shortest coverage of the electromagnetic field would be projected off of the pointed end of the teardrop-shaped antenna.

LOOP ANTENNA DESIGN CONSIDERATIONS

The direct-current (dc) resistance (R) of this loop must be minimized; therefore, a large wire diameter or gauge, such as 2.6 mm or even 3.3 mm, is desirable. Nevertheless, 2.1-mm-diam copper wire is generally sufficient for most applications. For example, 2.1-mm- and even 1.6-mm-diam wire is adequate when the electromagnetic field of coverage is less than a few kilometers. The number of turns, diameter, and conductor size of the loop are determined by the signal's strength requirements at the receiver site. The power requirements will be determined by the electromagnetic field needed to produce minimum signal strength in all receivers in the desired coverage area. This is influenced primarily by the geology between the transmitting antenna and receivers. The applied power to the loop will result in ampere-turns in the loop antenna. The electromagnetic field or force produced by the loop is a direct result of the ampere-turns. Ampere-turns are the current in the loop times the number of loops or turns.

For this application, the following factors were considered:

- Design of a transmitting loop antenna using standard polyvinyl chloride (PVC) jacketed control cable using the smallest wire size, typically 2.1 mm in diameter.
- Installation of the transmitter loop antenna must be economical, taking up the least amount of surface area (15 to 50 m in diameter or less).
- Efficiency of the loop antenna is critical so that full mine coverage can be obtained with minimal applied power requirements to the loop (75 to 100 W). If the loop has a high Q, it will have the most ampere-turns for applied power.

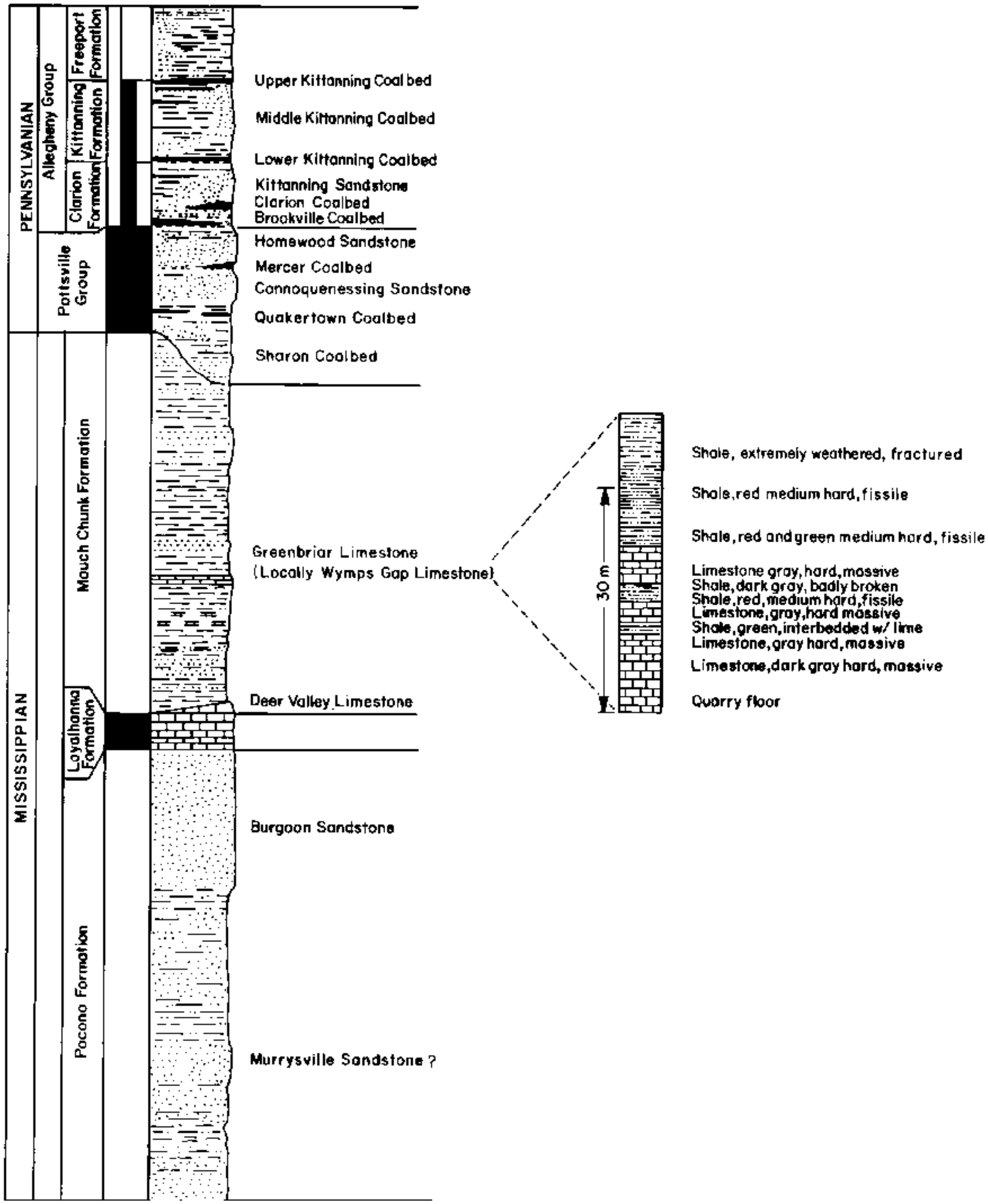

Figure 2.—Stratigraphic column in mine area (Lake Lynn Laboratory).

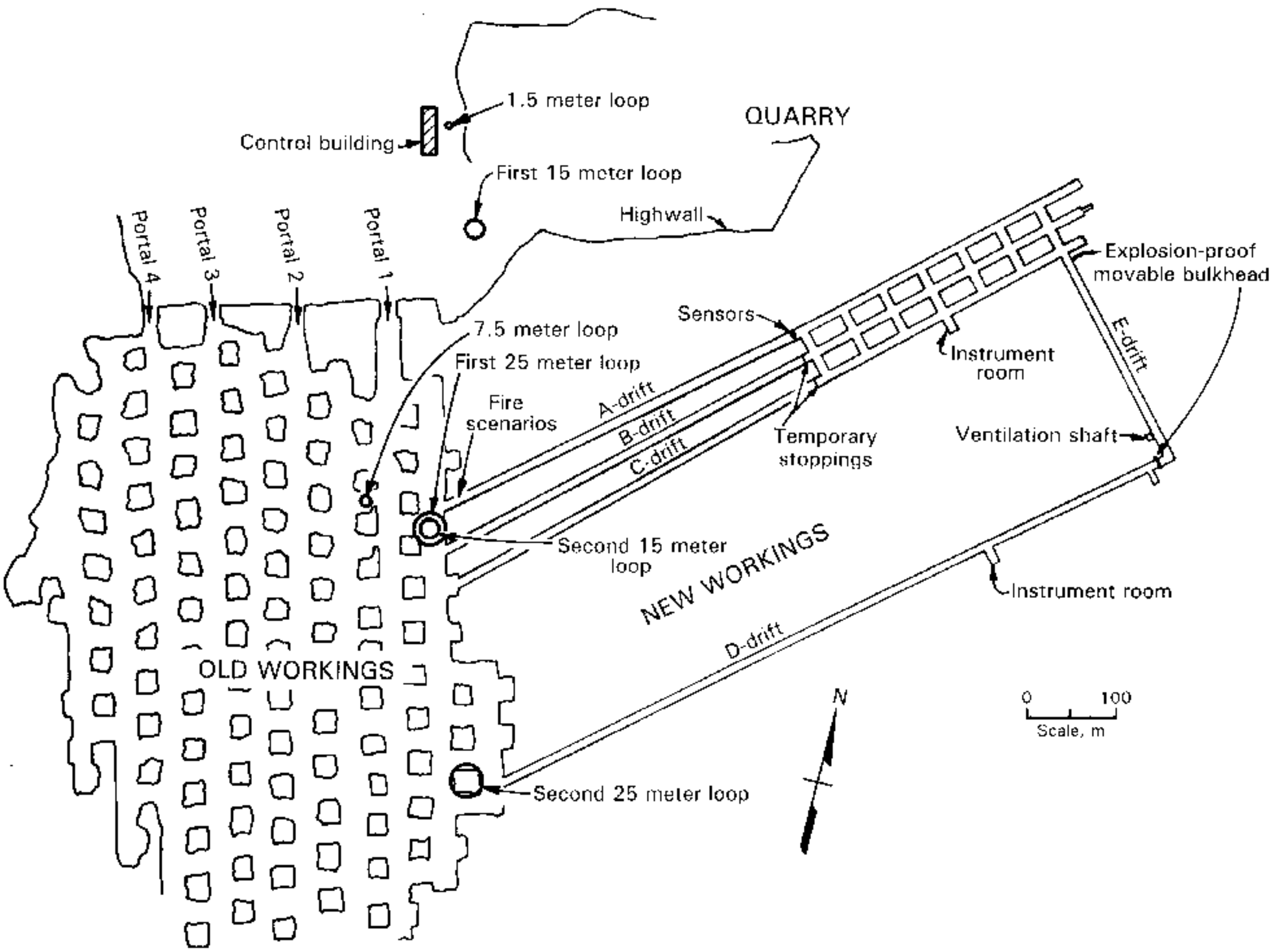

Figure 3.—Plan view of the Lake Lynn Experimental Mine depicting the locations of loop antennas.

A loop antenna adequate for a small mine such as that at Lake Lynn can be typically 15 to 25 m in diameter and use 10 to 15 turns. Such a loop antenna with adequate applied power to provide 250 mV in a receiver reference inductor at 10 m will produce approximately 0.5 mV at 1 km. This is a generic approximation because of the different types of geological influences on the loop antenna.

Larger mines pose a challenge in that the larger the loop, the larger the magnetic moment and the larger the field. However, the larger the loop, the more it couples into conductive earth, resulting in a lower Q. Therefore, a point is reached where the loop size is optimal. This implies that a loop antenna as large as possible should be used. However, at the point where applied power rises considerably, resulting in less of a rise in ampere-turns, one would conclude that the loop antenna is too large. The most effective solution to this is multiple smaller loops.

The loop antenna is series-resonated with high-voltage capacitors. High-voltage rated capacitors are needed due to the high voltage generated in the loop. A loop with a Q of 40 and an applied voltage (V_A) of 70 V (peak to peak) will generate a loop voltage of 2.8 kV (peak to peak).

The Q is directly related to the impedance or alternating-current (ac) resistance (Z) of the loop. Large loops and loops with a large number of turns will have a larger amount of dc resistance. The ac resistance is the sum of the losses such as dc resistance of the wire, soil conductivity near the loop (shorted turn effect of the conductive soil on which the loop is lying), and ac resistance of the capacitors used to series resonate the loop.

A site-specific application engineering of a loop involves resonating the inductor with capacitors, then determining the overall impedance to adjust the transmitter's output stage accordingly. Establishing the Q in the transmitted inductor in its target location is always desirable. This is easily accomplished by resonating the loop using an oscilloscope, a frequency generator, and a frequency counter connected to a capacitance decade box in series with the loop. Adjusting the decade box and frequency while observing the waveform until it shows the most current drawn at the desired frequency will establish resonance. Then, by establishing the voltage in the loop (V_L) and dividing it by V_A, Q is established. By using the resonance nomograph chart shown in the appendix, capacitance (C), frequency (f), or inductance (L) can establish the best Q.

The Z of the loop that is 15 m in diameter with a Q of 40 would be calculated by the reactance (X_L) divided by the Q. X_L is derived by the L and frequency (f) used and is given by the following expression:

$$X_L = 2\pi f L, \tag{1}$$

where X_L = reactance of the loop, Ω,

L = inductance of the loop, H,

and f = frequency of the loop, Hz.

For a typical 15-m loop that is series-configured at 15 mH with a 3-kHz carrier signal, X_L = 283 Ω. Therefore, this con- figuration at a mine site that requires a 2- to 3-km radius of field around the loop will use the following power expression:

$$P = \frac{E^2}{Z}, \tag{2}$$

where P = applied power of the loop, W,

E = applied voltage in the loop, V,

and Z = impedance of the loop, Ω.

Equation 2 can be rearranged to yield the following expression:

$$P = \frac{\left(\frac{V_A}{2}\ 0.707\right)^2}{\frac{X_L}{Q}}. \tag{3}$$

Substituting for E in equation 3 is the applied voltage to the loop antenna at half power. Therefore, the effective root-means-square value equals 24.7 V. The impedance of the loop, Z, can be calculated by dividing the reactance (X_L = 283 Ω) by Q (40), yielding a Z of 7.08 Ω. The applied power to the 15-m loop is 87.2 W.

This antenna design is unique to its location because the environment and geology at the point of installation affect its electrical characteristics. The above example of a 15-m loop that provides a Q of 40 and a Z of 7.08 Ω, if laid on wet conductive ground, will require more power to achieve the same results. For example, if the Q is reduced to 30, the Z will increase to 9.4 Ω; therefore, the applied power will decrease to approximately 65 W.

The aim of the site engineering exercise for the transmitter is to construct a loop that creates the largest low-frequency electromagnetic field requiring the least amount of power under several practical considerations. Geology containing high conductivity will attenuate the signal more rapidly as distance from the loop increases. Geologies with magnetic materials or ferromagnetic qualities influence the direction of the field's line of force and can distort the field or area of coverage.

RECEIVER REFERENCE INDUCTOR

To establish reference to the transmitted electromagnetic field strength, a receiver reference inductor with a high Q was used. The receiver reference inductor (a loop stick antenna) used for the low-frequency application was constructed on a 14-cm-long by 0.79-cm-diam, high- permeability ferrite rod. This ferrite rod was wound with 0.32-mm-diam magnet wire to an inductance (L) of about 100 mH and resonated to 3 kHz with a polystyrene capacitor to a Q of 100. These specifications for the inductor were used for the reference because they were the same specifications used for the person-wearable receivers attached to the cap lamp modules shown in figure 4. The in- ductor antenna requires approximately 500 μV for dependable operation in some mounted receiver modules (when mounted into the person-wearable cap lamp), although it can receive a signal as low as 100 μV without electrical noise.

7.5-METER-DIAMETER LOOP

The first transmitter loop antenna to be set up at the Lake Lynn mine site measured approximately 7.5 m in diameter.

Figure 5 shows the loop setup on the floor in the old workings of the mine between two pillars. This loop was resonated at 3 kHz, and its measured inductance was 25 mH. The control cable used for this loop consisted of 30 con- ductors of 2.1-mm-diam stranded wire and measured ap- proximately 46 m long. This cable was laid in a circle and looped around twice to form the antenna. The loop was connected to form two 30 turns; the two loops were then connected in parallel to give the better than effect of 2.6-mm-diam wire conductors. This 30-turn loop, shown in figure 6, used the following parameters to establish resonance in the circuit: L = 25 mH, X_L = 471 Ω, Z = 9 Ω, f = 3 kHz, and C = 0.11 μF. With the V_A = 65 V (peak to peak), a Q of 52 in the loop

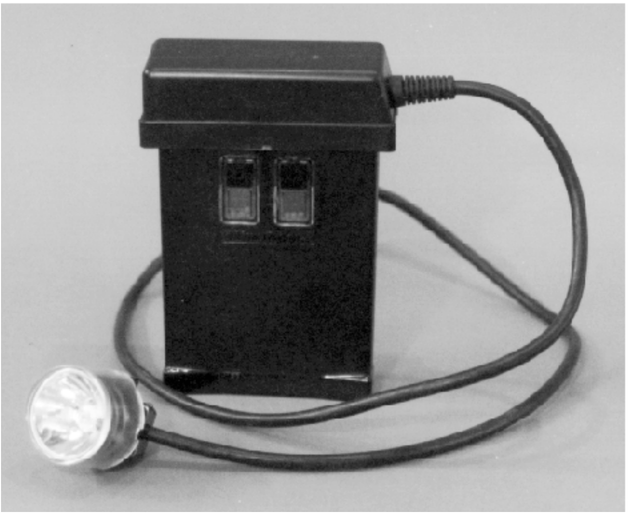

Figure 4.—Receiver reference inductor mounted on a lead-acid-type cap lamp.

will produce V_L = 3,380 V (peak to peak). With the applied power at approximately 60 W, the signal was tested at the farthest point of A-drift at the northeast corner of the mine. As can be seen from the data in figure 7, a marked decrease in signal strength occurs as the receiver reference inductor moves farther away from the loop. A signal loss of 86% resulted in moving from 100 to 200 m. However, at 1,000 m, the signal is still within the 200-μV range. Because full mine coverage was not achieved, a larger loop was built.

15-METER-DIAMETER LOOP

A 15-m-diam loop antenna, in addition to the 7.5-m loop, was set up outside of the mine between the control building and the quarry wall northeast of the mine entrance, as shown in figure 8. The control cable used for this loop consisted of 30 conductors of 2.1-mm-diam stranded wire and measured approximately 47 m long. The cable was laid in a circle and looped around once to form the antenna. This 15-turn loop, shown in figure 9, used the following parameters to establish resonance in the circuit: L = 15 mH, X_L = 283 Ω, Z = 6 Ω, f = 3 kHz, and C = 0.18 μF. With the V_A = 27 V (peak to peak), a Q of 47 in the loop will produce V_L = 1,269 V (peak to peak). The signal was applied to the loop at approximately 15 W, and readings were taken at the junction of D- and E-drifts and at the beginning of D-drift.

The data in figure 10 show a signal strength of 32 mV at 100 m. However, a sharp decline in the signal strength is observed in moving to 200 m. This loop provided better than 500 μV to the receiver reference inductor at both locations. Although the signal was adequate for coverage, a stronger signal was preferred. Because the research plan called for a small surface transmitting antenna (less than 2 m in diameter), the effort to develop it continued.

25-METER-DIAMETER LOOPS

First 25-Meter Loop

The 25-m-diam loop (6 and 12 turns) was installed inside of the mine, outside of the portal of A-drift, and suspended from the steel support mesh attached to the roof, as shown in figure 11. The steel mesh effects soon became apparent as the loop was resonated.

Figure 5.—A previous 7.5-m loop antenna in old workings of Lake Lynn mine site.

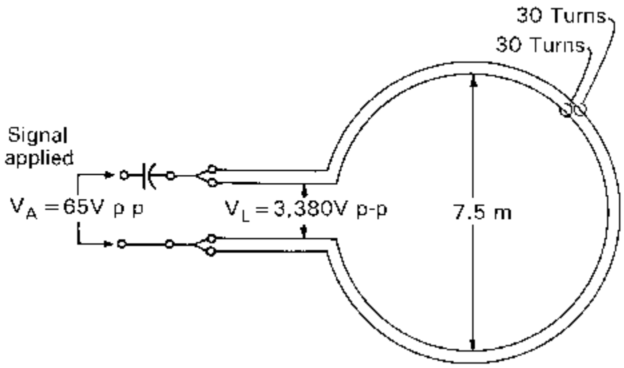

Figure 6.—Electrical schematic of 7.5-m loop.

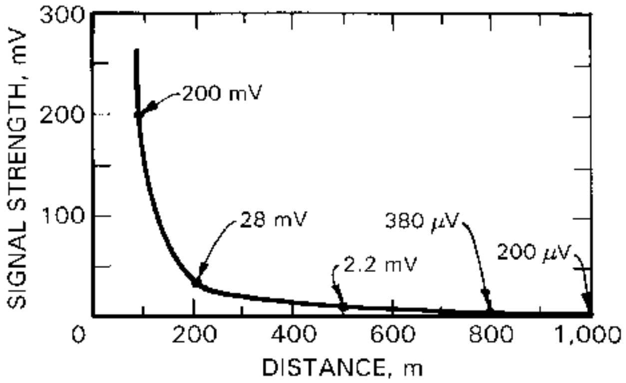

Figure 7.—Signal strength as a function of distance, 7.5-m loop.

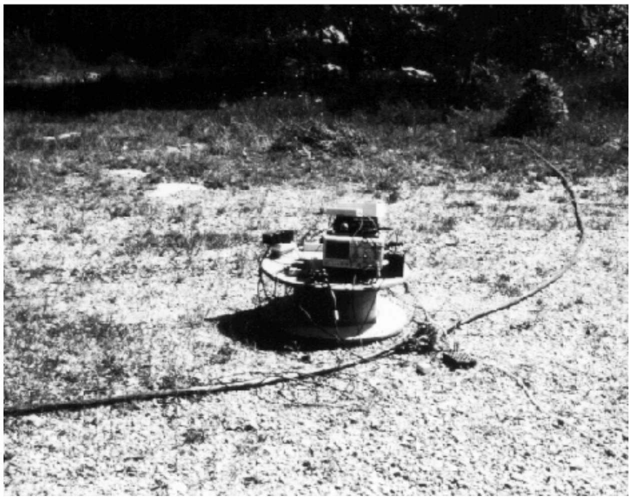

Figure 8.—15-m loop outside location.

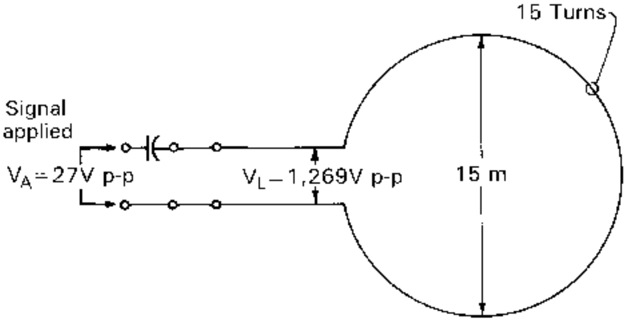

Figure 9.—Electrical schematic of 15-m loop.

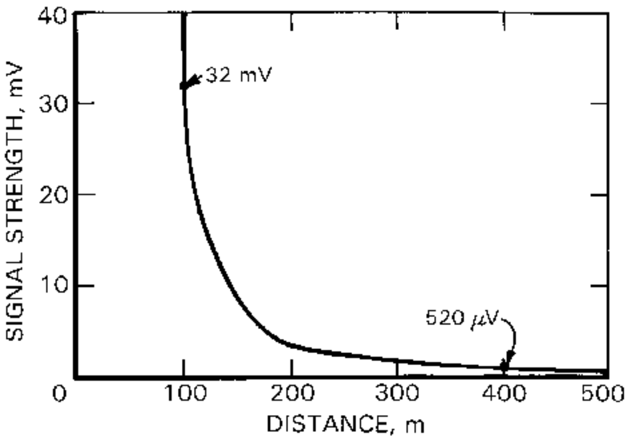

Figure 10.—Signal strength as a function of distance, 15-m loop.

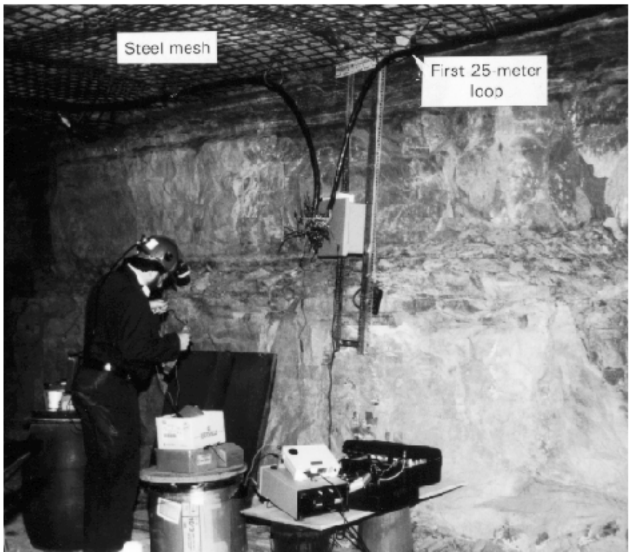

Figure 11.—Location of first 25-m loop antenna mounted at the roof between A- and B-drifts.

The signal generated in the antenna system (both 6 and 12 turns) for the lamp receivers was less than 100 μV about 100 m from the end of A-, B-, and C-drifts. The TSS field strength meter could receive the signal throughout the mine; its sensitivity was able to decode at 20 μV in a low-noise environment. The signal was suppressed for two major reasons. The first reason was the location of the central transmit antenna. The steel mesh caused a shorted turn effect on the loop antenna that drove the impedance up and lowered the Q of the loop. The second reason is seasonal due to the overburden holding more moisture in the spring months of the year; however, this problem does not alone prevent a full-coverage signal.

Second 25-Meter Loop

The 25-m loop was then relocated around the base of a pillar, as shown in figure 12, in the area where D-drift begins. This 14-turn loop, shown in figure 13, used the following parameters to establish resonance in the circuit: L = 30 mH, X_L = 561 Ω, Z = 14.4 Ω, f = 3 kHz, and C = 0.1 μF. With the V_A = 45 V (peak to peak), a Q of 39 will produce V_L = 1,802 V (peak to peak). With applied power at approximately 30 W, the following measurements with the receiver reference inductor were taken: (1) the first crosscut down C-drift measured 5 mV; (2) the junction of A- and E-drifts measured 1 mV. The data in figure 14 show a signal strength of 155 mV at 100 m and decreases 25 mV at 200 m. With the achievement of a sufficient signal throughout the Lake Lynn underground mine and surface perimeter with this antenna (a 25-m-diam loop around the base of a pillar near D-drift), the system was further developed.

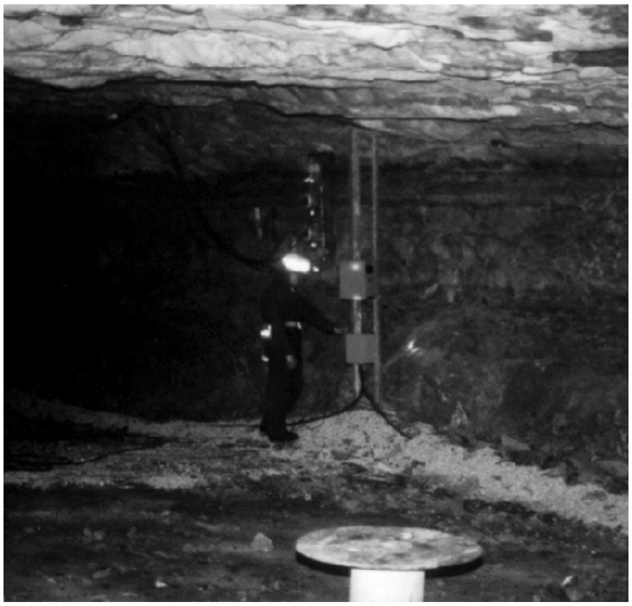

Figure 12.—Location of existing 25-m loop antenna positioned around a pillar near the portal of D-drift.

SITE-SPECIFIC ENGINEERING OVERVIEW

Working with large inductors at ultralow frequencies can present a unique set of problems. Textbook theory would point to large loops at such a low frequency as a method to create a large electromagnetic field. However, in most field tests and experiments, we found that this was not practical or economical. The adverse effect of the environment (e.g., moisture) is also accelerated by increasing the diameter of the loop.

Mine entries spread out over several kilometers and can be at various depths. Some mine entries are in the sides of mountains and even extend under lakes and streams. This creates a difficult situation for a single-transmitter loop antenna system for some larger mines. Further complications can be introduced by the geology at the mine site, as described previously.

It was also determined that, although advances could be made toward getting the signal into the mine, processing intelligent modulation protocol at 3 kHz can present a problem. A simple 100% amplitude modulation (AM) format for the first system or 7.5-m loop (starting at 4 Hz up to 30 Hz) was developed. This method was adequate for testing; however, complications can arise with other electrical noise interfering with the transmitted modulation.

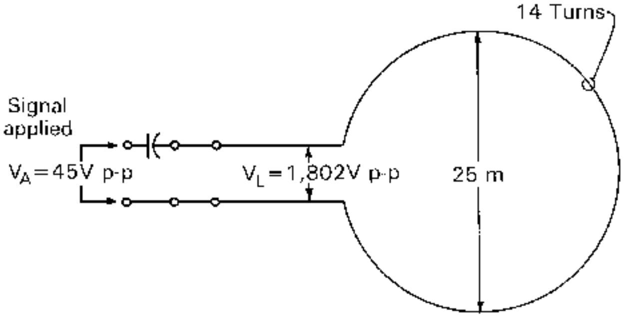

Figure 13.—Electrical schematic of 25-m loop.

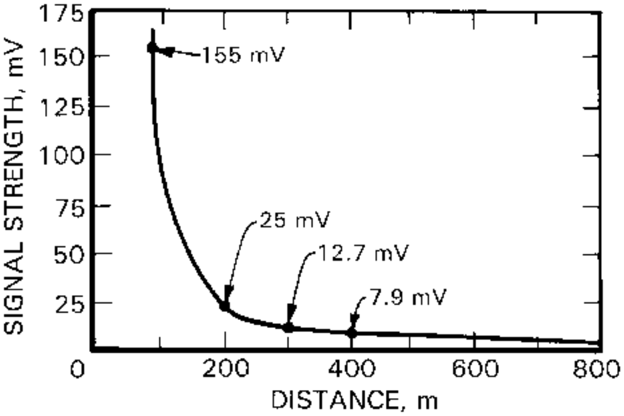

Figure 14.—Signal strength as a function of distance, 25-m loop.

The Lake Lynn system, depicted in figure 15, is also set up with a remote control transmitter and central control console in the building. The signals are transmitted to the underground mine through a 1.5-m loop antenna located outside of the building. Due to the overall radial distance of the present Lake Lynn 25-m loop with respect to the outside transmitter (a 1.5-m loop) and power form, the transmitted signal from the central control console was inadequate to reach the 25-m loop. To compensate for the low signal, a 15-m loop was installed inside of the mine, outside of the portal of A-drift, where the first 25-m loop was initially mounted, and hardwired to the 25-m loop. The 15-m loop, parallel-resonated for 8.4 kHz, was used as a receiver antenna. Figure 16 is a block diagram of the various transmitter and receiver devices of the completed system.

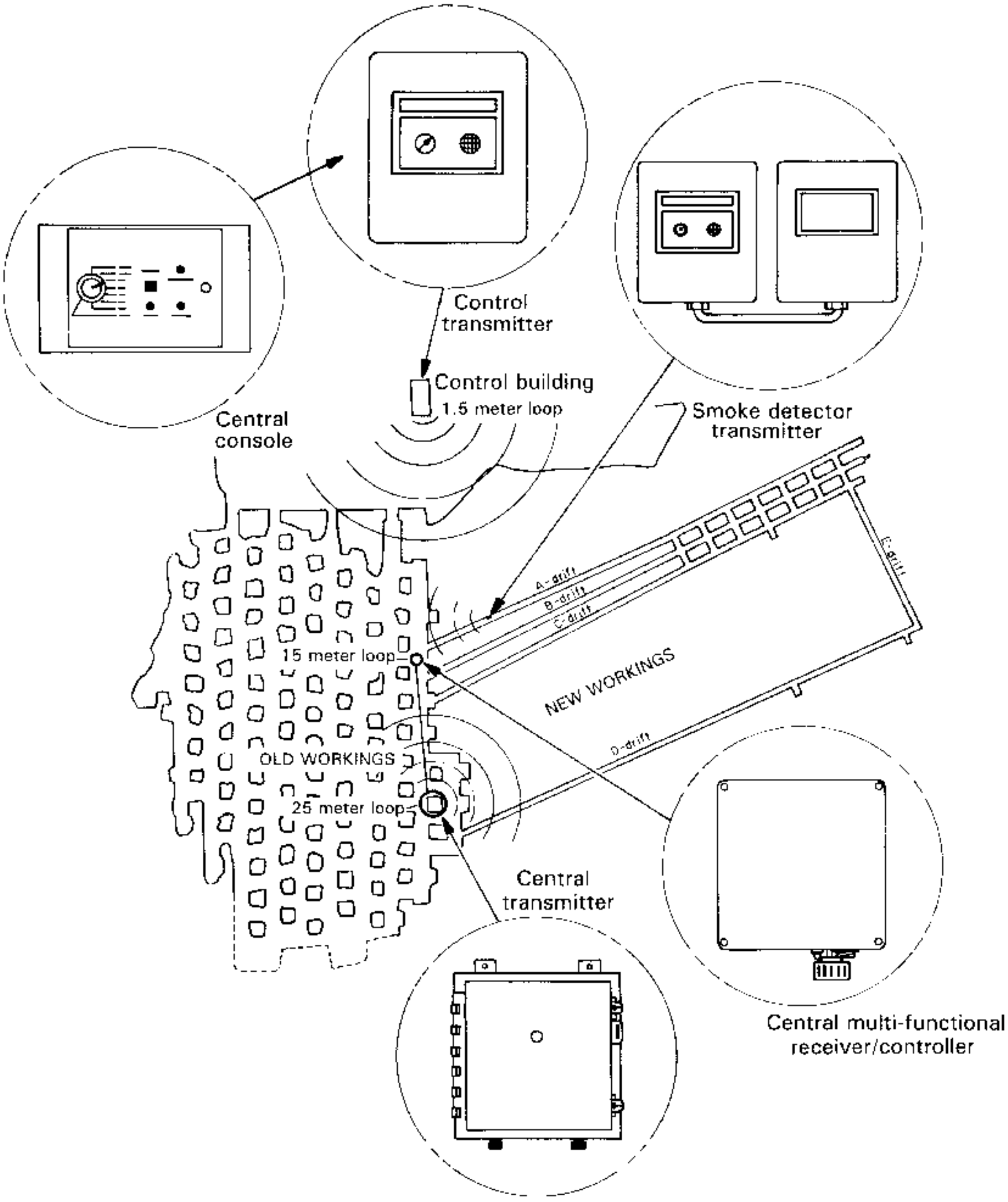

Figure 15.—Block diagram of TeleMagnetic signaling system for Lake Lynn Laboratory.

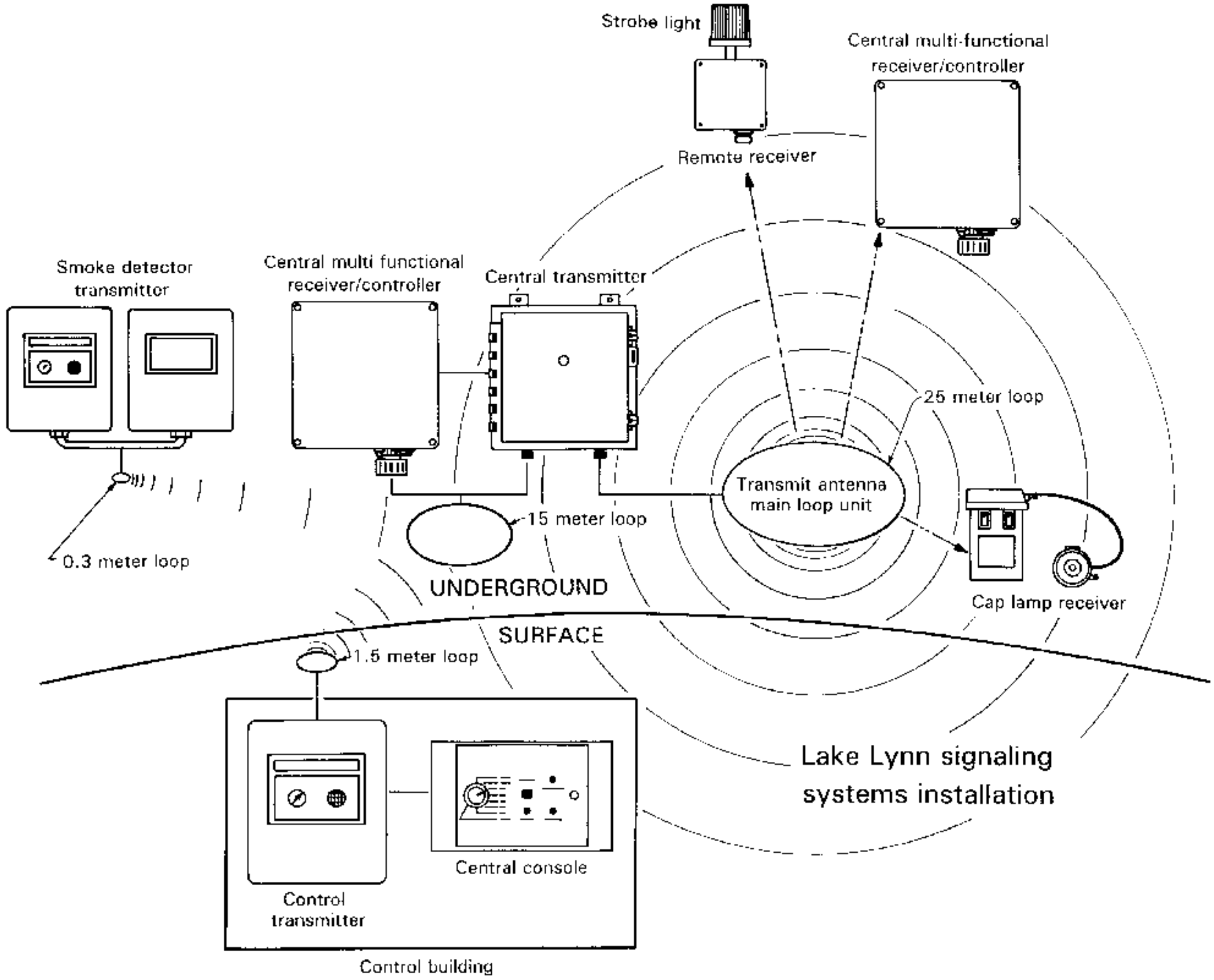

Figure 16.—Flowchart of Lake Lynn antenna system.

The Lake Lynn central control console is mounted on the wall in the control building. This console controls all of the functions of the remote control transmitter for the site and accommodates six paging numbers (signals) plus the evacuation signal. These paging numbers can be used for contacting personnel and/or other auxiliary functions, such as turning on/off devices. The system was initially set up to page five individual person-wearable cap lamp receivers. The individual paging numbers can also be used to turn on and off remote receiver controllers connected to strobe lights. A microprocessor-based central console processes the encoded page number that is manually entered on its selector switch. The console then sends the page number to the remote control transmitter, which transmits the encoded signal into the mine. Centrally in the mine is a microprocessor-controlled multifunction receiver unit. Here the signal is decoded, and the correct paging signal is sent to the main central loop transmitter. At this point, the main transmitter transmits the paging signal throughout the mine. The individual person-wearable cap lamp receiver will flash its lamp once the paging signal is received. The lamps will continue to flash for approximately 90 s. An encoded signal transmitted from the control building can also turn off the flashing lamps. Several miners can wear the paging lamps on their helmet with the battery pack and receiver on their belts and can be paged at various times during the day or warned during an emergency. Each cap lamp receiver will also respond to a global warning or evacuation signal. It is recommended that a battery backup be installed for the complete system in case of a power failure.

The smoke sensor is interfaced with an inductor series-resonated transmitter (0.3-m-diam antenna) for 8.4 kHz (see figure 16). With the applied power of 10 W, the signal can be transmitted 800 m to the 15-m loop when the sensor alarms.

RESPONSE TO UNDERGROUND MINE FIRES

A series of underground fire detection experiments was conducted to examine the feasibility of interfacing commercial mine fire sensors with the TSS system to initiate an emergency warning. The alarm modes of two different smoke sensors were used to trigger the signaling system during experimental mine fires.

The fire detection experiments reported here were conducted in A-drift. The normal airflow in the mine was reversed so that the combustion products were exhausted through the main fan. The scenario studied was a slowly developing coal conveyor belt fire. Seven 220-V electric strip heaters, with a combined power rating of 9.5 kW, were embedded into a 1.2- by 1.2-m coal pile containing 75 kg of Pittsburgh coal. Six 10.2- by 22.8-cm strips of rubber conveyor belting, 1.1 cm thick, were evenly distributed throughout the coal pile. Additionally, two 22.8- by 61-cm strips of the same belt were placed on top of the coal pile, and the pile was seeded with approximately 0.75 kg of pulverized Pittsburgh coal dust. Full electrical power was applied to the heating elements at the start of each test. Visible smoke from the coal pile was usually observed in 2 to 3 min, with flames emanating from the coal about 9 min later. The strips of conveyor belting placed on top of the coal pile ignited later during the tests. A detailed description of the fire scenario and response times of other fire sensors can be found in Conti and Litton [1992].

A pump-operated ionization smoke sensor used during the experiments was mounted on the rib, with the intake sampling point (a 1.3-cm-diam tube) at the roof in the center of the entry, 15.2 m inby the fire. In other experiments, a diffusion-type ionization smoke sensor was mounted on the roof in the center of the entry, 15.2 m inby the fire.

In the control building, the data signal of the smoke sensor was displayed on a video monitor, along with a continuous video coverage of the fire. Another video camera 274 m downstream of the fire monitored a mannequin wearing a person-wearable cap lamp receiver.

Under these test conditions, the smoke sensor alarmed at 15.2 m because of the smoldering coal pile, usually within 1 to 2 min after the first sign of visible smoke was observed from the coal pile in the entry. The encoded signal was received, and underground/surface receivers flashed cap lamps.

In other experiments, these encoded signals were also used remotely to initiate inflation of a positive-pressure inflatable escape device [Weiss et al. 1996] and turn on and off strobe lights and other lighting fixtures. The strobe lights could be located at key decision points along an underground escape route for miners.

SUMMARY AND CONCLUSIONS

The experiments at Lake Lynn Laboratory incorporated a variety of loop antennas ranging from a few meters up to 25 m in diameter. Many tests were conducted and data collected on several loop specifications to ascertain the effects of the environment and geology. The experiments were conducted through the course of seasonal changes so that the data could be used to design a transmitter loop that would work well in all environmental conditions. The moisture in the overburden above all of the loops at Lake Lynn Laboratory increased the conductivity in the strata, which resulted in increased signal attenuation. The steel support mesh on the roof for the first 25-m loop antenna increased the conductivity directly adjacent to the antenna, whereas the shorted turn effect lowered the Q of the loop. Nonferrous metal would also lower the Q because of the conductive nature causing a shorted turn effect.

The transmitter loop antenna tests have led to a greater understanding of the effects of geology and environment on the systems. These data will be valuable toward reducing the cost of engineering systems for future sites. For example, it was determined that the soil conductivity increases the inductor's impedance when close to the loop. It was also found that, although increasing the diameter of a transmitter loop antenna would theoretically increase the magnetic moment, it would also increase the effects of the geology on the loop. Previous USBM research [Hjelmstad and Pomroy 1991] showed that larger loop antennas were successfully used in various high-conductivity geological environments. At times, depending on the configuration of a given mine, complete coverage seems impossible due to the adverse conditions. To improve cov- erage, several transmitter [Zamel 1990] locations that can be controlled and synchronized with unique low-frequency transmit modulation protocols could be used.

The research has led to a unique application engineering format to design a loop antenna to a specific site. Special portable test instruments and test loops have been designed and successfully evaluated at Lake Lynn. The development has also led to several workable solutions, especially to the problem of limited surface access. This was solved with the addition of small-diameter underground repeater loops. A small dis- advantage is electrical power requirements and maintenance.

The development and testing of the modulation protocols have led to reliable operation without fear of false alarms that would often result from electrical noise in the earlier design. New protocols include a combination of both AM and frequency shift keying (FSK) modulation platforms, along with the addition of multiple-band transmission and expansion of the frequency range from 630 to 8,970 Hz.

During underground fire tests, when the smoke sensor alarmed to the products of combustion produced from the smoldering coal pile, the alarm mode successfully triggered an emergency warning signal throughout the Lake Lynn complex. Underground and surface receivers flashed cap lamps when the encoded signal was received.

In other tests, these encoded signals initiated the inflation of an underground positive-pressure inflatable escape device. More recent tests showed that the encoded signals may be used to turn on or off other devices, such as strobe lights, thus mapping an escape route for evacuating miners. The concept of strobe lights was successful in experiments at the Lake Lynn mine, which is small and has a simple ventilation system. In a larger mine, the uncertainties inherent in a complex ventilation system would complicate this process considerably. Additional research would be required to evaluate the feasibility of using these devices in larger mines and incorporating an audio output with each strobe unit. The cost of a signaling and warning system such as the one installed at Lake Lynn Laboratory is approximately $20,000.

The technology displays the ability to transmit from com- pact, portable, and semiportable receiving and decoding equipment. This paves the road to transceiver applications such as emergency two-way messaging for refuge stations or mine rescue operations; remote monitoring of fire sensors, gas detectors, seismic sensors, sump pumps; and remote control and monitoring of other mine equipment, such as ventilation fans, conveyor belt systems, and haulage traffic control. Additional areas for research include transmitter designs for very large mines with and without adverse geology, vehicle paging and tracking, a motionless detector (to alarm if personnel become motionless) or a receiver with manually operated distress buttons, automatic "tag-in and out" with addressable paging numbers, and tracking of underground miners that could send out a beacon on command from a locator interrogator for mine rescue purposes.

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REFERENCES

AC electronics: a step-by-step introduction [1983]. Heathkit/Zenith Educational Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Anema C [1976]. Waveform generator-package and receiver (mancarried and helicopter receiver portion). Cedar Rapids, IA: Collins Commercial Telecommunications Div., Rockwell International. U.S. Bureau of Mines contract No. H0242010.

CFR. Code of Federal regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Conti RS, Litton CD [1992]. Response of underground fire sensors: an evaluation. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9412.

Dobroski H Jr., Stolarczyk LG [1982]. Medium frequency radio communication system for mine rescue. In: Postdisaster Survival and Rescue Research; Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa., November 16, 1982. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 8907, pp. 39-48.

Geyer RG, Keller GV, Ohya T [1974]. Research on the transmission of electromagnetic signals between mine workings and the surface. Golden, CO: Colorado School of Mines. U.S. Bureau of Mines contract No. H0101691.

Hjelmstad KE [1990]. Electromagnetic fire warning system for underground mines. U.K. patent No. 2,220,823A.

Hjelmstad KE, Pomroy WH [1991]. Ultra low frequency electromagnetic fire alarm system for underground mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9377.

Lagace RL, Dobbie JM, Doerfler TE, Hawes WS, Spencer RH [1980]. Detection of trapped miner electromagnetic signals above coal mines. Cambridge, MA: Arthur D. Little, Inc. U.S. Bureau of Mines contract No. J0188037.

Lagace RL, Dobbie JM, Raisbeck G, Spencer RH, Degatano MA, Lambiase FJ, Moussa NA [1982]. System study of mine rescue through electromagnetic means. Cambridge, MA: Arthur D. Little, Inc. U.S. Bureau of Mines contract No. J0113043.

Mattes RH, Bacho A, Wade LV [1983]. Lake Lynn Laboratory: Construction, physical description, and capability. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 8911.

Shope S, Durkin J, Greenfield R [1982]. Finding and communicating with trapped miners. In: Postdisaster Survival and Rescue Research; Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa., November 16, 1982. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 8907, pp. 49-78.

Stowinsky L [1996]. Personal communications in September 1996 between L. Stowinsky, Pennsylvania Department of Environmental Protection, Bureau of Deep Mine Safety, and R. S. Conti, Pittsburgh Research Center, National Institute for Occupational Safety and Health, Centers for Disease Control, Public Health Service, U.S. Department of Health and Human Services.

Strahin RA, Pogue CW, Wolfe DN [1990]. Report of investigation (underground coal mine): mine fire, Marianna Mine No. 58 (ID No. 36-00957), BethEnergy Mines, Inc., Marianna Borough, Washington County, Pennsylvania, March 7, 1988. Pittsburgh, PA: U.S. Department of Labor, Mine Safety and Health Administration, District 2.

Triebsch GF, Sapko MJ [1990]. Lake Lynn Laboratory: a state-of-the-art mining research laboratory. In: Proceedings of the International Symposium on Unique Underground Structures. Denver, CO: pp. 75-1 to 75-21.

Weiss ES, Conti RS, Bazala EM, Pro RW [1996]. Inflatable devices for use in combating mine fires. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9614.

Westinghouse Georesearch Laboratory [1973]. EM location system prototype and communication station modification. Boulder, CO. U.S. Bureau of Mines contract No. H0232049.

Wheeler HA [1961]. Radio-wave propagation in the Earth's crust. J. Res. of the Natl Bureau of Standards *65D*(2):189-191.

Yewen RG [1987]. Passive tag identification system and method. U.S. patent No. 4,663,625.

Zamel GI [1990]. A breakthrough in underground communications for enhanced safety and productivity. In: Proceedings of Minesafe International 1990, an International Conference on Occupational Health & Safety in the Minerals Industry. Chamber of Mines and Energy of Western Australia, Inc.: Perth, Western Australia, Australia, pp. 763-766.

APPENDIX.—RESONANCE NOMOGRAPH CHART

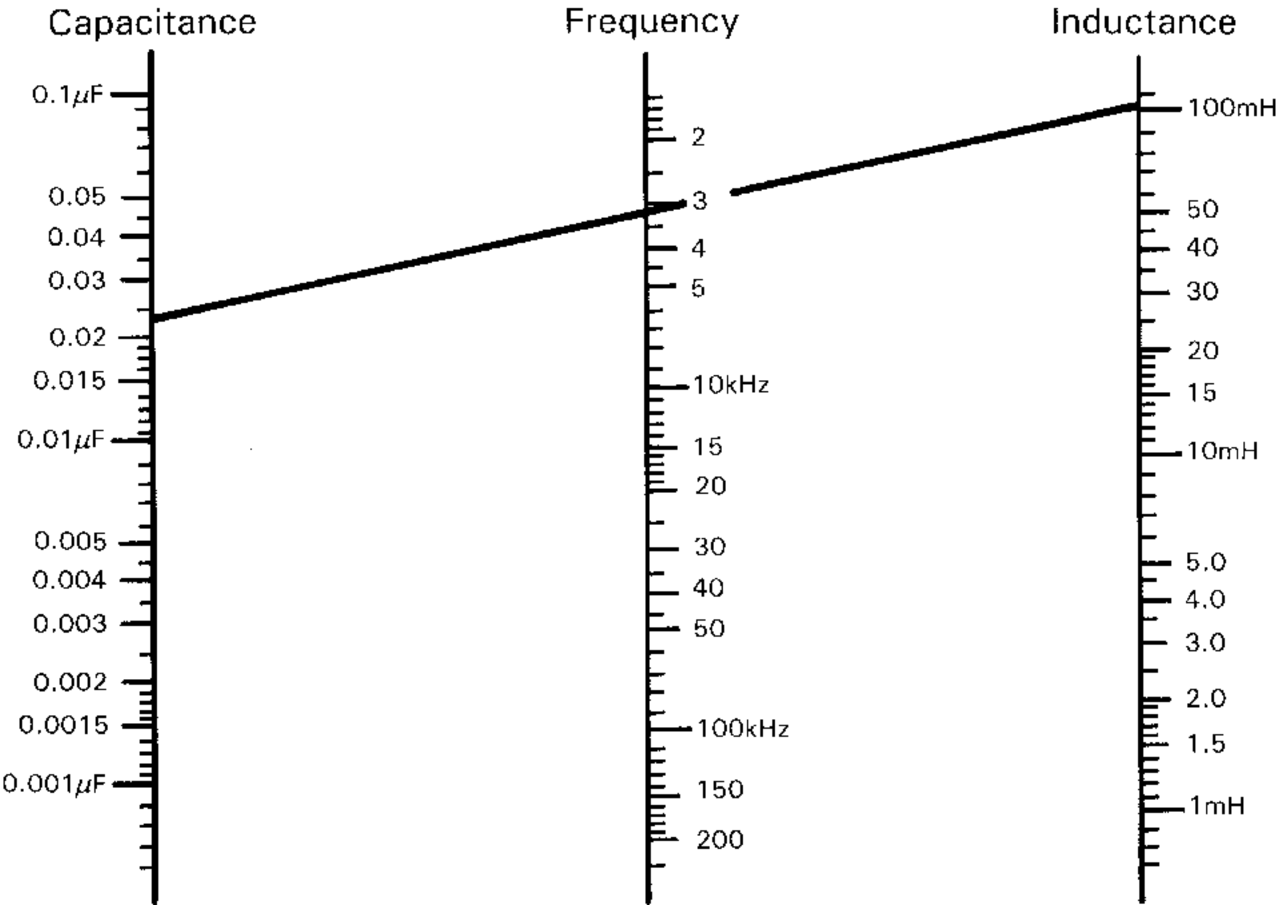

Figure A-1.—Resonance nomograph chart [AC electronics: a step-by-step introduction 1983].

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Cover *photo: Mine rescue team members responding to a mine emergency. (Photo by Ronald S. Conti, National Institute for Occupational Safety and Health, Pittsburgh Research Center)*