ELECTROMAGNETIC LOCATION SYSTEMS FOR METAL/NON METAL MINES

PREPARED FOR

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

BY

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IN METAL/NON METAL MINES

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Characteristics of metal/non metal mines were evaluated to determine the suitability of applying the U.S. Bureau of Mines electromagnetic location system to the problem of locating trapped miners in metal/non metal mines. Statistical distributions of mine depths and overburden conductivities show that the existing USBM EM system is inadequate for most metal/non metal mines.

Alternate approaches to trapped miner location in deep mines were identified and subsequent field tests were conducted at six (6) mines to evaluate their feasibility. The approach considered to be the most promising is one which utilizes the existing manpack transmitting system, modified slightly for a dual frequency output, in conjunction with a sophisticated signal processing receiver on the surface. The main advantage of staying with a "through the earth" approach is that the underground equipment can be kept simple, easily maintained, lightweight and inexpensive.

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FOREWORD

This report was prepared by Westinghouse Electric Corporation, Geophysical Instrumentation Systems, 3655 Frontier Avenue, Boulder, Colorado 80301 under USBM Contract Number J0166100. The contract was initiated under The Metal and Nonmetal Health and Safety Research Program. It was administered under the technical direction of PM&SRC with Mr. Robert Chufo acting as Technical Project Officer. Mr. Robert Carpenter was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period July 1, 1976 to December 31, 1977. This report was submitted by the authors on December 15, 1977.

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1.0 INTRODUCTION AND SUMMARY

The U.S. Bureau of Mines has developed an electromagnetic system for detecting, locating and communicating with miners trapped in underground coal mines. The miners communication unit is a small belt-carried transmitter and voice receiver (attached to the miner's cap lamp battery). The transmitter is used in concert with a loop of wire deployed on the mine floor to transmit electromagnetic signals to the surface. These signals are detected by the rescue party and used to locate the miners' position. Furthermore, a surface transmitter is used by the rescue party to convey voice instructions to the miner via baseband audio currents injected into the earth through a long horizontal wire antenna.

The trapped miner communications and location system has been fabricated in a ruggedized package and is presently undergoing extensive testing in numerous coal mines in the eastern coal fields of United States. Results that have been obtained thus far indicate that the system's performance is more than adequate for the vast majority of U.S. coal mines (1,2,3,4, & 5). However, this is not expected to be the case for metal/non metal mines, which, as a rule, are significantly deeper than the average coal mine.

The objective of the present research program (Contract No. J0166100) was to determine whether the existing coal mine trapped miner detection, location and communication system could be effectively used in deep metal/nonmetal mines and to identify suitable modifications that could be applied to the system to adapt its performance to the deeper mines. Initially, six mines were selected for further study on this program; ones at which the geophysical characteristics (earth conductivity and background noise) would be measured on the surface and in the mine and the communication and propagation characteristics would be evaluated and measured on subsequent visits to the mines.

The trapped miner location problem is more severe in metal/non metal mines when compared with that of coal mines because of their significantly greater depths. Before any modifications could be recommended for the trapped miner location system, a statistical study of mine depths was undertaken for the metal/non metal mines in the United States. Also the statistical characteristics of mine disaster case histories were developed for metal/non metal mines dating back to 1869.

Candidate approaches to solving the trapped miner location problem were identified on this program and can be subdivided as follows:

(1) Utilize electromagnetic repeaters distributed along a main drift to receive transmissions from manpack transmitters and relay the signals to a shaft station repeater for inductive propagation up the shaft.

(2) Utilize a twisted pair cable along the main drift to multiplex repeater output signals and deliver the composite multiplexed signal to a shaft station repeater at the shaft.

(3) Utilize a significantly lower frequency manpack transmitter and an array of horizontal wire receiving antennas on the surface to permit a through the earth uplink even in the deepest mines.

Measurement results obtained on this program have demonstrated the feasibility of each of these basic approaches; however, from a practical standpoint, the purely "through the earth" mode of operation offers the most promise when one carefully considers the harsh mine environment and the attitudes of mine company personnel in conjunction with the measurements obtained on this program. Briefly, the main advantage of the "through the earth" approach is that the underground equipment can be kept simple, easily maintained, lightweight, inexpensive, etc. Furthermore any increase in system complexity can be restricted to the surface signal detection and processing equipment, the cost and maintenance of which, need not be the responsibility of the individual mine companies. The details behind implementing a "through the earth" system are described more fully in the text of this report.

2.0 METAL/NON METAL MINE CHARACTERISTICS

2.1 Statistical Characteristics of Disaster Case Histories

Mine Disaster Statistics

The statistics cited in this report are for underground mining activities and they exclude accidents that occurred in coal mines (6). Only accidents in which five or more fatalities are involved are used in this tabulation. Description of each accident arranged chronologically is given by Table 1.

Figure 1 shows that the largest number of mine disasters and deaths occurred in the interval from 1890 to 1930, with the period from 1910 to 1920 showing the greatest concentration of mine disasters of all types.

Distribution of Disasters by Time

The period from 1869 until 1890 yielded 7 mine disasters and 86 fatalities.

From 1890 until 1930, there was a total of 43 mine disasters, resulting in 736 deaths. The years 1930 through 1972 show 15 disasters with 223 deaths. 22 of the events were caused by fire which resulted in the deaths of 531 miners as shown in Figure 2. Of the remaining disasters, 15 were caused by explosions that killed 154 men (Figure 3), 13 were by roof falls which killed 90 miners (Figure 4), 7 were by flooding which caused 168 deaths (Figure 5), and 2 disasters brought about 82 deaths by asphyxiation.

Distribution of Disasters by Type of Event

Fire is the main hazard in mine disasters and it occurs more frequently and causes more deaths than all other disasters combined. From 1869 until 1972, 585 deaths were incurred by fire. The ratio of fire fatalities to disaster is higher than any other type of mine disaster, being 24.1 to 1.

Explosion accounts for the second largest number of deaths in metal/non metal mines in the 1869-1972 interval, showing a death/disaster ratio of 10.3 to 1.

Flooding, with 168 deaths in 7 disasters, places third in cause of death, with a 24 to 1 ratio.

Roof falls have led to 90 fatalities in 13 events for a ratio of 6.9, and asphyxiation accounted for 82 deaths for a ratio of 10.2.

Distribution of Disasters by Mine Type

Table 2 indicates that copper and gold mines have been involved in a major portion of metal/non metal mine disasters, followed by iron and lead/zinc mines. Fire or explosion predominate as the major cause of death, regardless of the type of mine involved.

TABLE 1 List of accidents at metal and nonmetal mines and quarries (except coal mines) in the United States in which five or more lives were lost

Date	Product	Name of Mine	Location	Killed	Nature of accident	References
1869 - Apr. 7	Gold	Kentucky-Yellow Jacket-Crown Point	Gold Hill, Nevada	37	Fire in timber, probably from candle	19,24
1873-Sept. 20	Gold	Yellow Jacket	Gold Hill, Nevada	6	Fire from blacksmith forge on 1,300-foot level.	19,24
1874-Feb. 13	Copper	Phoenix	Phoenix, Michigan	6	Explosion of dynamite caused by candle held by miner	20
1881-Feb. 16	Copper	Belmont	Belmont, Montana	6	Fire from blacksmith shop spread to magazine of powder and then to shaft	19,24
1885-Nov. 13	Silver-Gold	Bull Domingo	Silver Cliff, Colo.	10	Explosives; box of dynamite exploded in boiler room; headframe burned; men in mine suffocated.	20,24
1887-June 24	Gold	Gould & Curry	Virginia City, Nev.	11	Fire in shaft station 1,500 level cause unknown.	19,24
1889-Nov. 23	Copper	Neversweat-St. Lawrence	Butte, Montana	6	Mine fire; candle in chute on 400 level.	19,24
1893-Feb. 11	Marble	Sheldon quarry	West Rutland, Vt.	5	Roof fall in underground quarry	31
1893-Apr. 21	Copper	Silver Bow No. 2	Butte, Mont.	9	Mine fire; probably from candle at pump station.	20,24
1893-Sep. 28	Iron	Mansfield	Crystal Falls, Mich.	28	Inrush of water	20,33
1895-Mar. 10	Gold	Old Abe	White Oaks, N. Mex.	8	Mine fire; burning shaft house and shaft timbers.	20,24
1895-Aug. 29		Sleepy Hollow	Sleepy Hollow, Colo.	12	Mine flooded	20
1895-Sept. 7	Copper	Osceola	Calumet, Mich.	30	Mine fire on 27th level; cause unknown.	20,24
1895-Sept. 26	Gold	Belgian	Leadville, Colo.	6	Dynamite explosion from unknown cause.	20,34
1896-Jan. 4	Gold	Anna Lee	Cripple Creek Dist. El Paso Co., Colo.	8	Cave-in of shaft.	20
1896-Apr. 8	Gold	Hope	Basin, Mont.	7	Mine fire.	20,24
1896-Apr. 11	Copper	St. Lawrence	Butte, Mont.	6	Powder explosion.	27
1901-June 4	Iron	Chapin	Iron Mountain, Mich.	8	Explosion of dynamite; asphyxiation by funes; cause unknown.	21,27

TABLE 1 List of accidents at metal and nonmetal mines and quarries (except coal mines) in the United States in which five or more lives were lost

Date	Product	Name of Mine	Location	Killed	Nature of accident	References
1901-Nov. 20	Gold Silver	Smuggler-Union	Pandora, Colo.	31	Fire in bunk house at mine entrance.	20,24
1902-July 15	Lead Zinc Copper Silver	Park-Utah	Park City, Utah	34	Night shift powder man ate lunch in stub drift powder magazine 1,200 level near Daly-West shaft. Candle or cigarette, air was downcast. Powder smoke circulated in mine but did not get much above the 1,000 at any time. Fumes killed a mule in stable off snowsheds at portal of Ontario No. 2 drain tunnel, 4 miles away.	20
1903-Nov. 6	Gold	Kearsarge	Virginia City, Mont.	9	Mine fire; cause unknown.	20,24
1905-May 12	Copper	Cora	Butte, Mont.	7	Explosion of explosives.	20
1907-Nov. 30	Gold	Freemont Consolidated	Drytown, Calif	11	Fire at foot of shaft; cause unknown.	20,24
1909-Feb. 26	Lead	Keystone	Joplin, Mo.	5	Fall of rock	21
1910-Mar. 2	Gold	Alaska-Mexican	Treadwell, Alaska	37	Explosion of powder magazine in mine.	20,22
1910-Nov. 28	Asphalt	Jumbo	Durant, Okla.	13	Explosion of gas.	21
1911-Jan. 18	Gold	Keating	Radersburg, Mont.	6	Powder explosion in shaft.	21,22
1911-Feb. 23	Gold Silver	Belmont	Tonopah, Nev.	17	Fire, asphyxiation.	20,22,24
1911-Mar. 11	Iron	Norman mine (open pit)	Virginia, Minn.	14	Slide of bank.	22
1911-May 5	Iron	Hartford-Cambria No. 2	Negaunee, Mich.	7	Mine fire; men overcome by gas and smoke.	20,22,24
1911-Aug. 23	Copper	Giroux	Ely, Nev.	7	Mine fire; men overcome by gas and smoke.	20,22
1911-Sept. 28	Gold	Shakespeare Placer	Dome Creek, Alaska	14	Cave-in of shaft.	21
1911-Oct. 19	Iron	Wharton	Hibernia, N. J.	12	Shaft flooded.	21,22
1912-May 13	Iron	Norrie	Ironwood, Mich.	7	Cave-in	22
1912-July 7	Copper	Eureka pit	Ely, Nev.	10	Dynamite explosion	21,22
1913-Apr. 17	Copper	Miami	Miami, Ariz.	5	Air blast; resulting from cave-in; threw men against walls and timbers.	20,22

TABLE 1 List of accidents at metal and nonmetal mines and quarries (except coal mines) in the United States in which five or more lives were lost

Date	Product	Name of Mine	Location	Killed	Nature of accident	References
1914-Jan. 21	Copper	Boston	Bingham, Utah	5	Mine fire; cause unknown.	24
1914-July 14	Iron	Balkan	Palatka, Mich.	7	Men drowned by rush of sand and water into raise.	27
1914-Aug. 4	Copper	Copper Flat (Steam-shovel pit)	McGill, Nev.	5	Premature blast.	27
1914-Sept. 17	Gold	Centennial-Eureka	Eureka, Utah	11	Cave-in.	27
1914-Nov. 9	Iron	Sibley No. 9 shaft	Ely, Minn.	5	Shaft cave-in	27
1915-Oct. 19	Copper	Granite Mountain shaft	Butte, Mont.	16	Dynamite explosion at shaft collar.	27
1916-Feb. 14	Copper	Pennsylvania	Butte, Mont.	21	Mine fire; asphyxiation.	24
1917-Apr. 28	Gold	Mountain King	Mariposa County, Calif.	7	Asphyxiation by powder fumes.	27
1917-June 8	Copper	Granite Mountain	Butte, Mont.	163	Mine fire.	25
1918-Feb. 21	Iron	Amasa-Porter	Crystal Falls, Mich.	17	Cave-in caused by inrush of water	33
1920-Apr. 15	Salt	Jefferson Island	Delcambre, La.	6	Gas explosion	27
1922-Aug. 27	Gold	Argonaut	Jackson, Calif.	47	Mine fire; cause unknown.	26
1924-Feb. 5	Nanganiferous iron ore	Milford	Crosby, Minn.	41	Inrush of water.	27
1926-Nov. 3	Iron	Barnes Hecker	Ishpeming, Mich.	51	Mine flood	28
1927-Oct. 29	Copper	Quincy mine No. 2 Shaft	Hancock, Mich.	7	Fall of rock in shaft following air blast.	28
1927-Nov. 24	Copper	Magma	Superior, Arizona	7	Shaft fire.	28
1929-Sept. 4	Copper	Calaveras	Copperopolis, Calif.	5	Cave in stope	28
1930-June 7	Molybdenum	Climax mine	Fremont Pass, Lake County, Colo.	5	Cave-in	28
1930-July 14	Gold	Glenn	Lost Chance, Placer County, Calif.	5	Mine fire in surface building. Fumes entered mine.	28
1936-Aug. 13	Copper	Mountain City Copper Company	Mountain City, Elko County, Nev.	6	Suffocation.	29
1939-Jan. 31	Zinc	Southern	Treece, Kansas	5	Roof fall	30

TABLE 1 List of accidents at metal and nonmetal mines and quarries (except coal mines) in the United States in which five or more lives were lost

Date	Product	Name of Mine	Location	Killed	Nature of accident	References
1942-Jan. 9	Copper, zinc, lead, gold, silver.	Pride	Silverton, Colo.	8	Fumes from surface fire at tunnel portal suffocated men in mine.	30
1943-Jan. 5	Copper	Boyd mine	Ducktown, Tenn.	9	Asphyxiation by fumes from explosion of sulphide dust in stope.	32
1943-Feb. 10	Lead, zinc	C.F. & H.	Shullsburg, Wisc.	8	Two men buried by cave-in. Six others buried by second cave-in during recovery work.	31
1950-July 16	Lead, zinc	Lark, U.S. Smelting Ref. & Mng. Co.	Lark, Utah	5	Fire in battery-charging station	31
1952-Oct. 30	Gold prospect	Herron, Alpena Enterprises	Herron, Mich.	5	Gas explosion in shaft	31
1953-Nov. 5	Gilsonite	No. 1 Incline, Am. Gilsonite Co.	Bonanza, Utah	8	Dust explosion.	31
1959-June 1	Iron	Sherwood Mine, Inland Steel Co.	Iron River, Mich.	6	Inrush of hot gases and steam.	31
1963-Aug. 28	Potash	Texas Gulf Sulfur Co. (Harrison Internat., Inc. Contractors)	Moab, Utah	18	Gas explosion.	31
1968-Mar. 6	Salt	Cargill Salt Mine	Belle Isle, La.	21	Mine fire.	31
1971-Apr. 12	Fluorspar	Barnett Complex Mine-Ozark-Mahoning Co.	Rosiclare, Ill.	7	Asphxiation (H_2S)	31
1972-May 2-11	Silver	Sunshine Mining Co.	Kellogg, Idaho	91	Mine fire.	

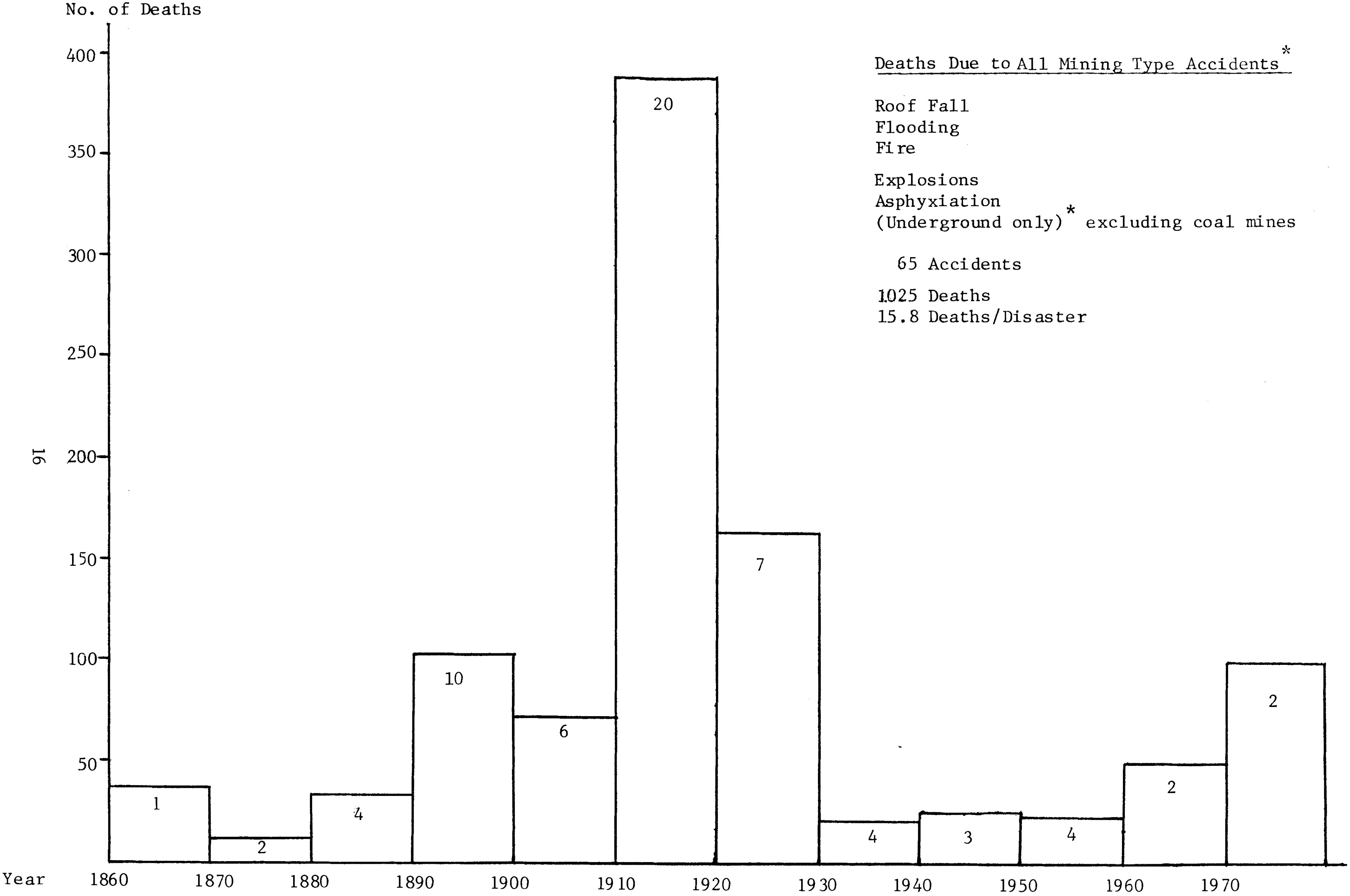
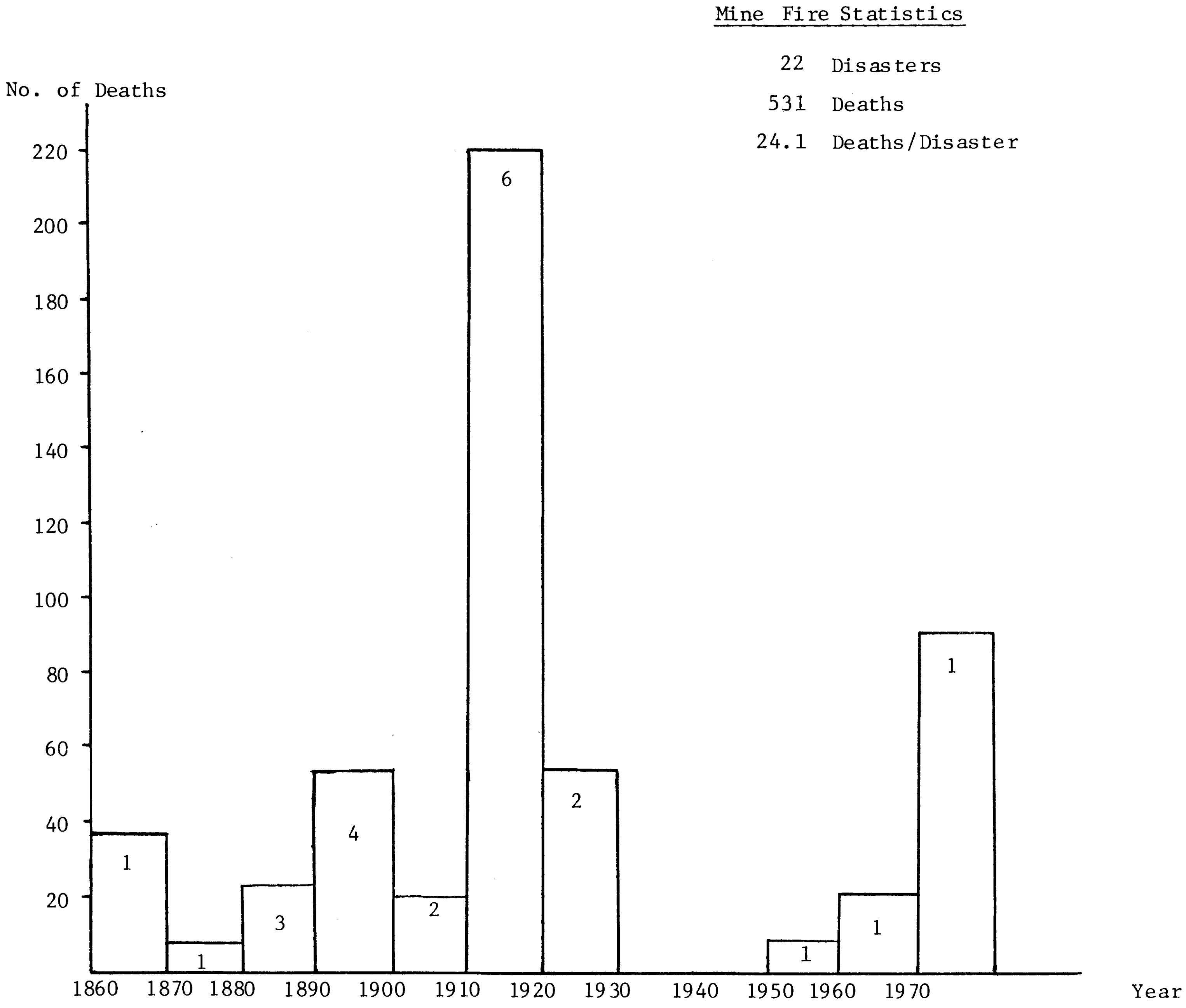


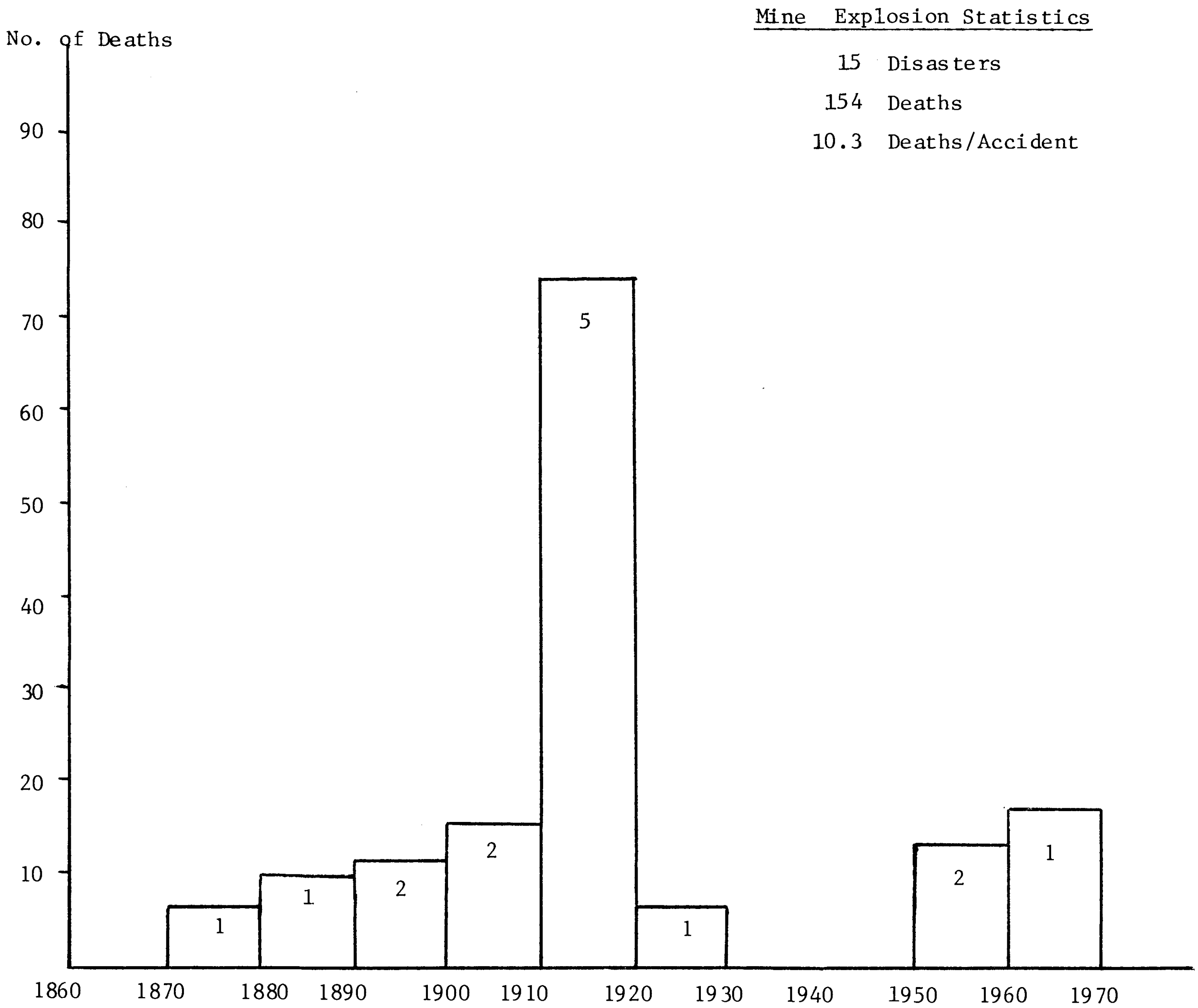
Figure 1 Chronological Distribution of Mine Accidents in Metal/Non Metal Mines



Mine Fire Statistics

22 Disasters
531 Deaths
24.1 Deaths/Disaster

Figure 2 Chronological Distribution of Mine Fires in Metal/Non Metal Mines



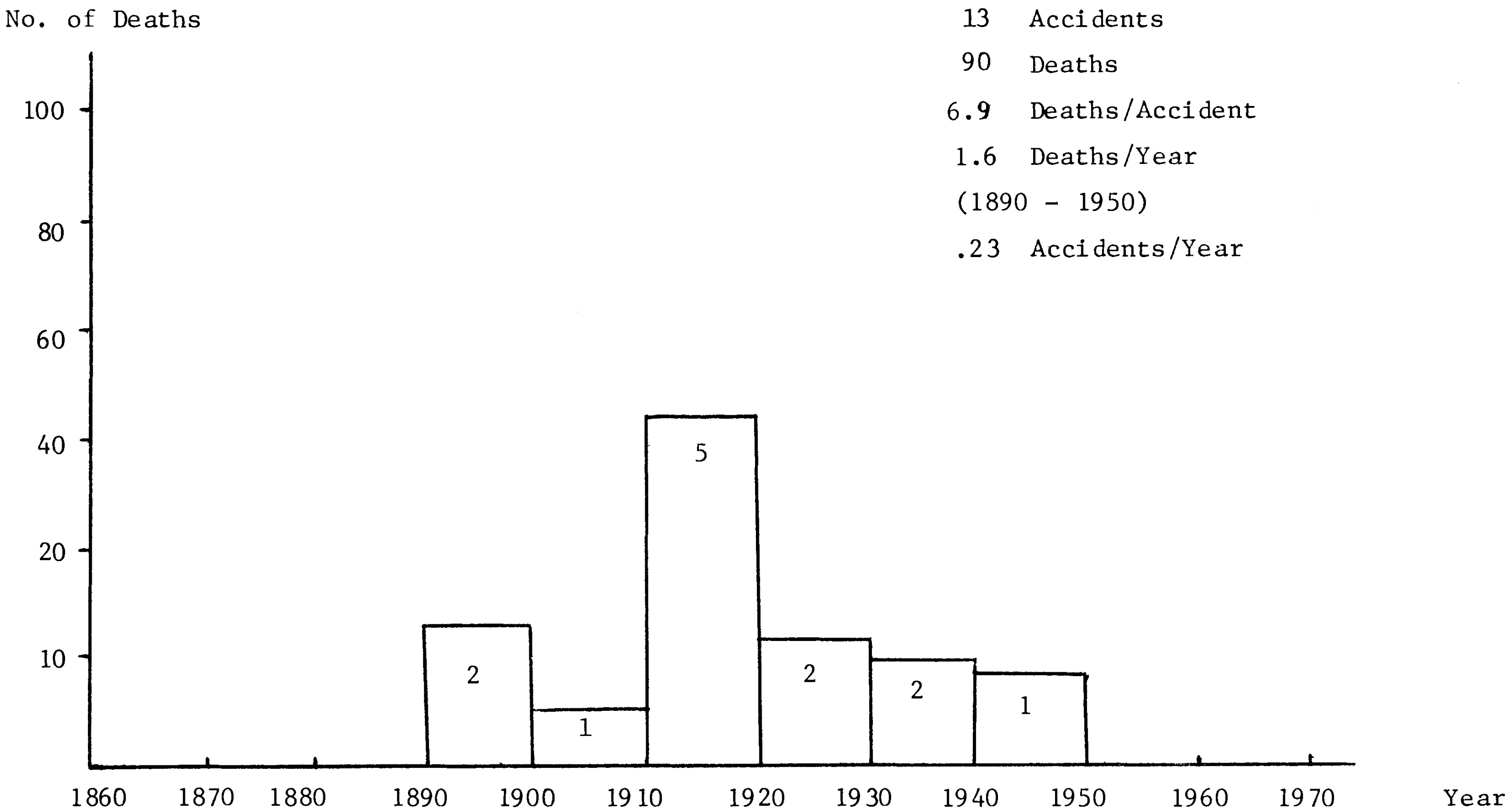
Mine Explosion Statistics

15 Disasters

154 Deaths

10.3 Deaths/Accident

Figure 3 Chronological Distribution of Mine Explosions in Metal/Non Metal Mines



<u>Mine Roof Fall Statistics</u>

13	Accidents
90	Deaths
6.9	Deaths/Accident
1.6	Deaths/Year
(1890 - 1950)	
.23	Accidents/Year

Figure 4 Chronological Distribution of Roof Falls in Metal/Non Metal Mines

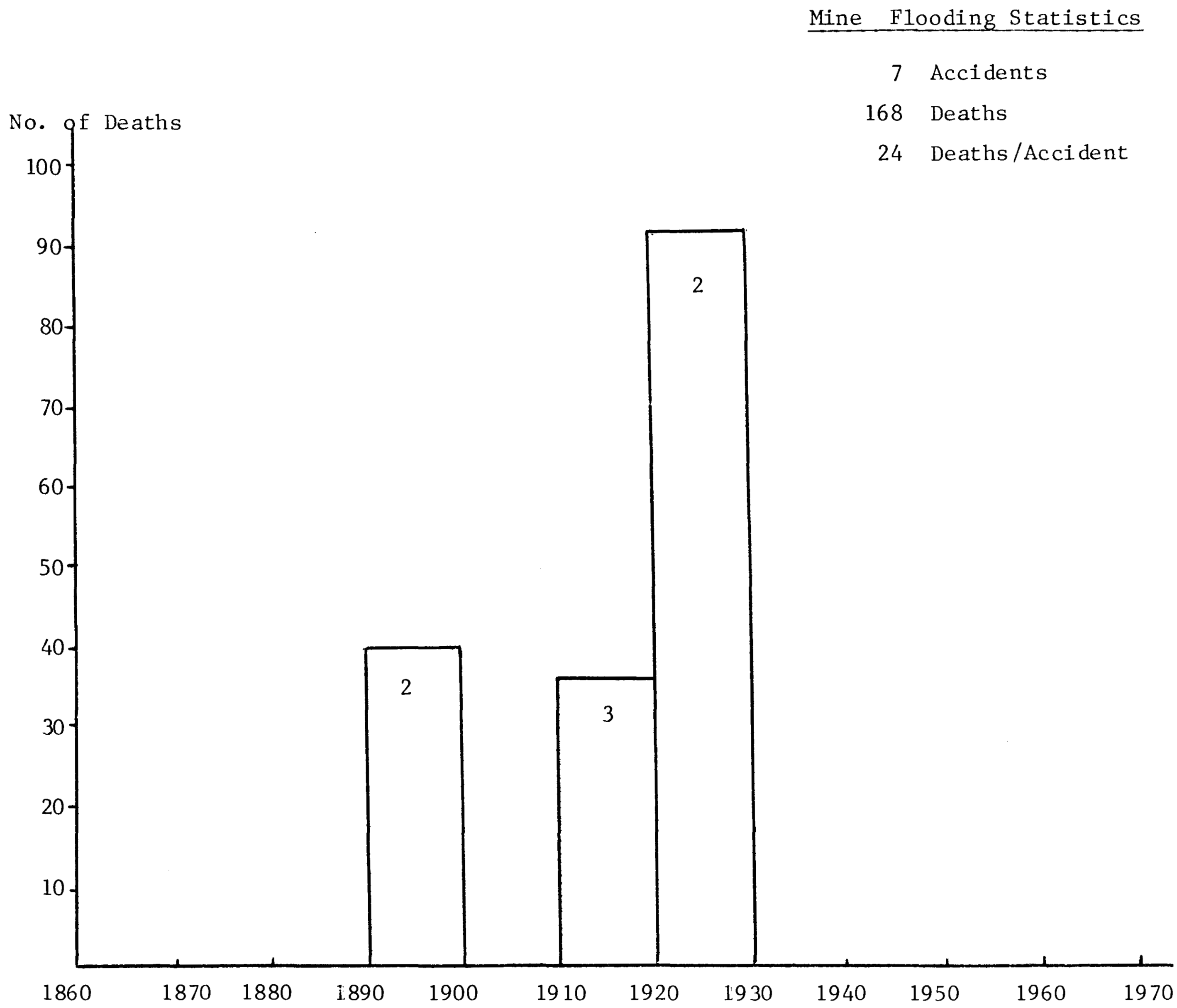


Figure 5 Chronological Distribution of Flooding Accidents in Metal/Non Metal Mines

TABLE 2

BREAKDOWN OF MINING DISASTERS BY TYPE AND PRODUCT

Product	Fatalities	# of Disasters	Type
Gold-Silver	365	31	11 Fire
			4 Explosion
			1 Flood
			3 Cave-in
			2 Asphyxiation
Copper	350	22	9 Fire
			7 Explosion
			2 Roof-fall
			3 Asphyxiation
Iron	189	11	1 Fire
			1 Explosion
			2 Cave-in
			6 Flood
			1 Asphyxiation
Lead-Zinc	57	5	2 Fire
			3 Rock-Falls
Miscellaneous (Marble, Molybdenum, Potash, Salt, Gilsonite, Fluorspar, Asphalt)	83	8	4 Explosion
			2 Cave-in
			1 Asphyxiation

Distribution of Disasters by State

Montana and Michigan, with eleven (11) mine disasters each, have the dubious distinction of being involved in 433 of the 585 fatalities recorded between 1869 and 1972.

Idaho, Montana, and Minnesota have the highest death/disaster ratios as indicated in Figure 6.

2.2 Statistical Characteristics of Metal/Non Metal Mine Parameters

Mine Depth

The most critical mine parameter affecting the performance of a manpack trapped miner location system is overburden depth. Information on the distribution of maximum working mine depths in 45 of the major metal/non metal mines of the U.S. was obtained from the mine operators and is shown in the histogram of Figure 7. A cumulative distribution is shown in Figure 8 showing the percentage of mines exceeding a given depth for the same 45 mine sample. Figure 9 is a cumulative distribution showing new shaft construction at mines producing more than 1200 tons per day. The 10% exceedance level (i.e., the depth exceeded by only 10% of all mines) for the 45 working mines is 3000 feet and for the 152 new mine shafts is 2400 feet. If we use 3000 feet as a design goal, such that a manpack trapped miner location system must perform in all mines having depths up to 3000 feet, it will be operational in approximately 90% of metal/non metal mines in the U.S., assuming the sample to be truly representative of metal/non-metal mines in general.

Overburden Conductivity

Overburden conductivity measurements were made at 7 mines on this contract. The results of these conductivity measurements were combined with measurements made by Westinghouse personnel on previous mine visits to arrive at the conductivity distribution curve for the 17 mines shown in Table 3 and in Figure 10. Based on this particular representative 17 mine sample, the 10% exceedance level (i.e. the level of conductivity exceeded by only 10% of the mines) is about 1.15×10^{-1} mhos/m. It is important to note however that this unusually high value of conductivity for the 10% level was influenced greatly by two mines in particular; Berkely Pit Copper Mine in Butte, Montana and the International Salt Mine in Avery Island, Louisiana. Both of these mines had relatively shallow maximum overburden depths, 700 and 880 feet respectively. Thus it may be somewhat pessimistic to relate this particular 10% level to all metal/non metal mines since the deepest mines such as those found in the Coeur d'Alene district of Idaho and the Homestake gold mine in Lead, South Dakota have measured conductivities substantially lower than 10^{-1} mhos/m.

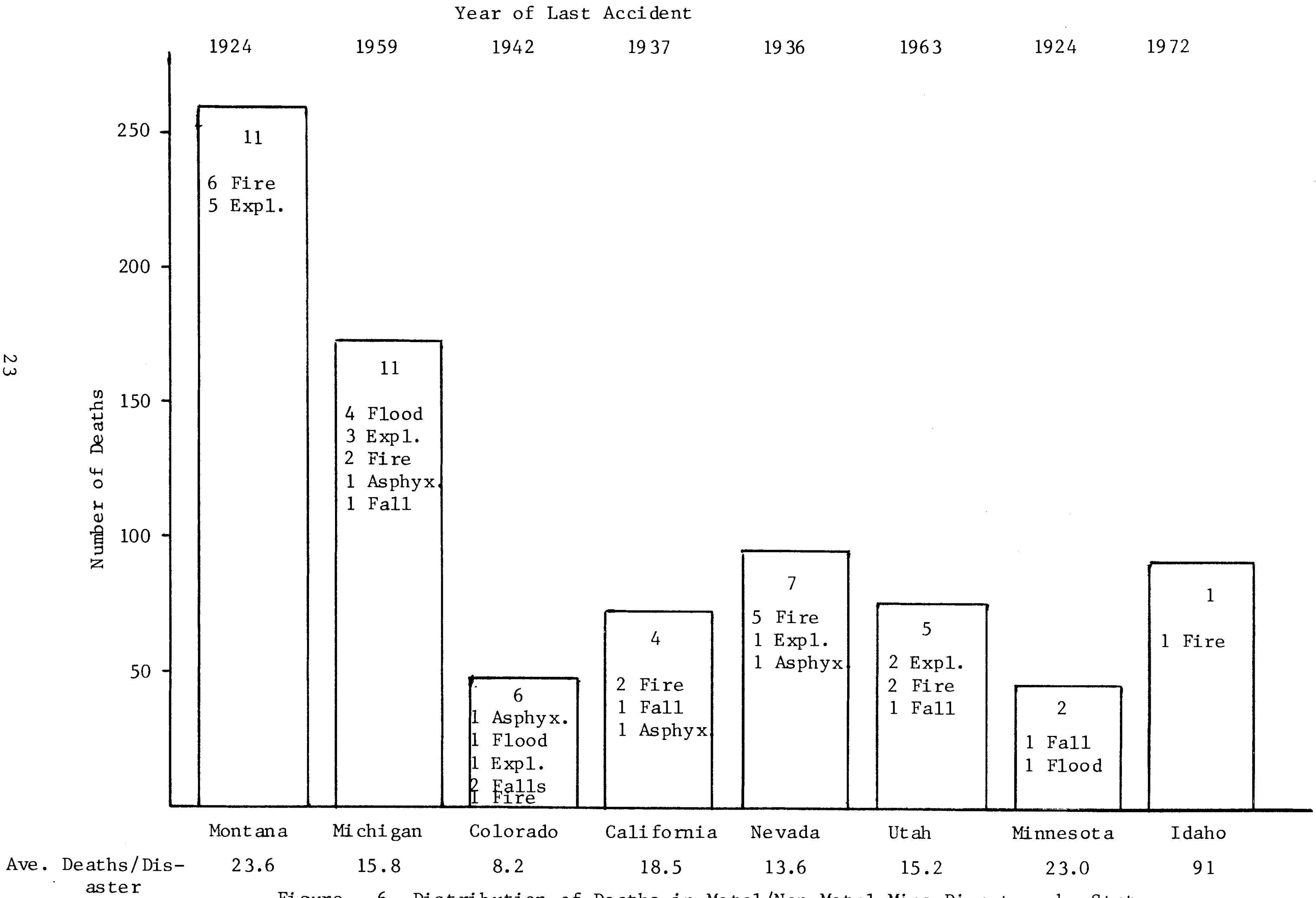
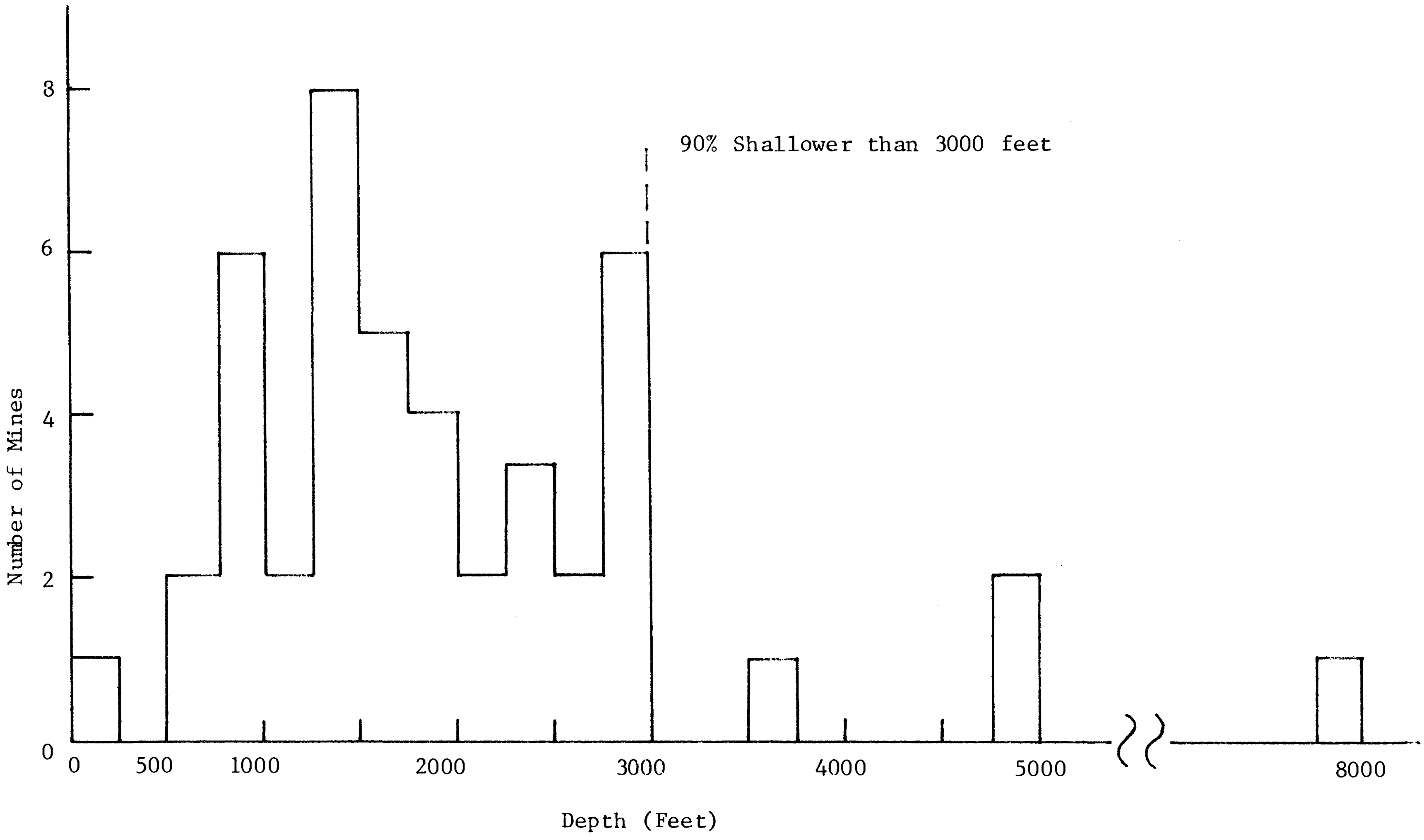


Figure 6 Distribution of Deaths in Metal/Non Metal Mine Disasters by State

Figure 7 Distribution of Maximum Working Depths of Metal/Non Metal Mines in U.S. (Representative Sample - 45 Mines)



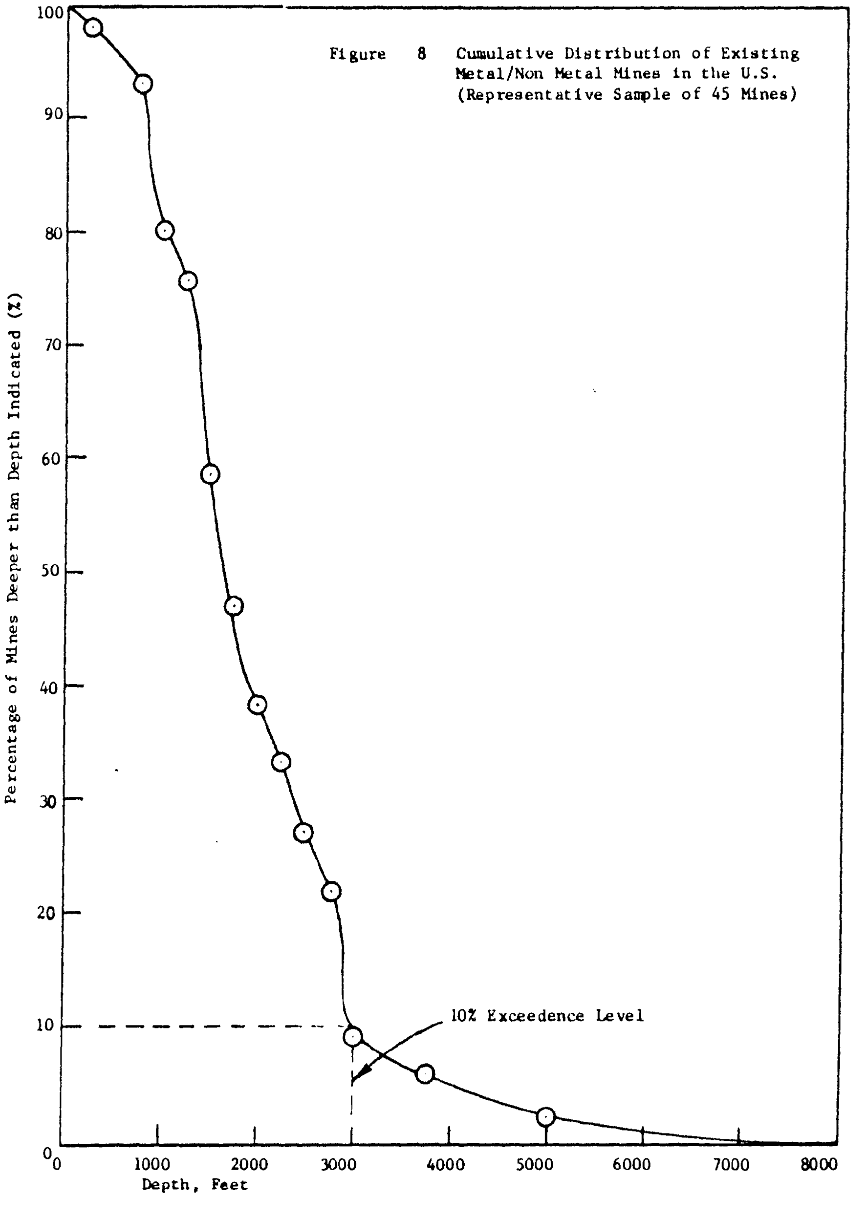


Figure 8 Cumulative Distribution of Existing Metal/Non Metal Mines in the U.S. (Representative Sample of 45 Mines)

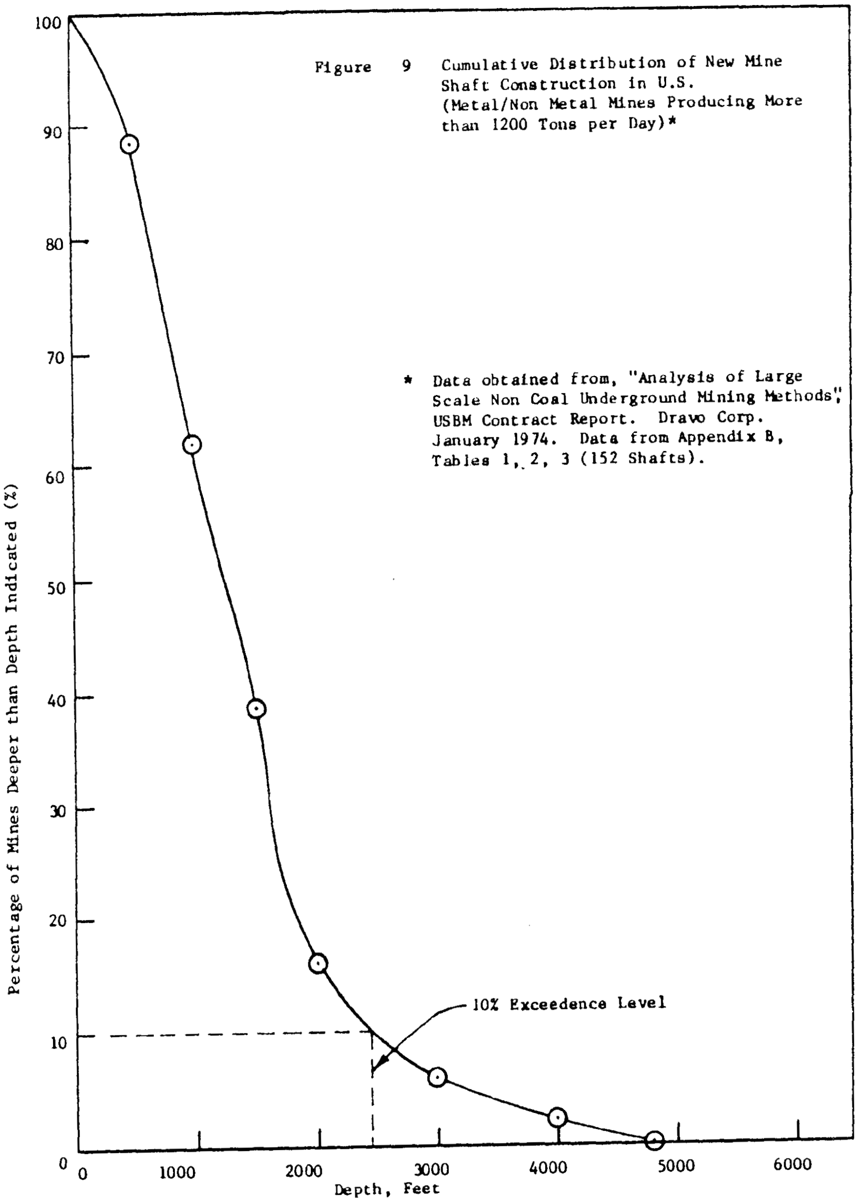


Figure 9 Cumulative Distribution of New Mine Shaft Construction in U.S. (Metal/Non Metal Mines Producing More than 1200 Tons per Day)*

* Data obtained from, "Analysis of Large Scale Non Coal Underground Mining Methods", USBM Contract Report. Dravo Corp. January 1974. Data from Appendix B, Tables 1, 2, 3 (152 Shafts).

TABLE 3

Mine -Conductivity Distribution

Mine		Location	Apparent Conductivity	Percent of Exceedance
1.	Berkely Pit	Butte, Montana	1.95×10^{-1}	5.9
2.	International Salt	Avery Island, La.	9.3×10^{-2}	11.8
3.	Knob Hill	Republic, Wash.	6×10^{-2}	17.6
4.	Big Island	Green River, Wyo.	2×10^{-2}	23.5
5.	Fletcher	Viburnum, Mo.	1×10^{-2}	29.4
6.	Inexco	Jamestown, Colo.	9.9×10^{-3}	35.3
7.	Latrobe	Latrobe , Pa.	8.67×10^{-3}	41.2
8.	Copper Queen	Bisbee, Arizona	8.5×10^{-3}	47.1
9.	Ozark Mahoning	Rosiclare, Ill.	7×10^{-3}	52.9
10.	Galena	Wallace, Idaho	6×10^{-3}	58.8
11.	Caladay	Wallace, Idaho	5.9×10^{-3}	64.7
12.	Idarado	Telluride, Colo.	5×10^{-3}	70.6
13.	U.S. Tunnel	Idaho Springs, Colo.	3.4×10^{-3}	76.5
14.	Henderson	Empire, Colo.	3×10^{-3}	82.4
15.	Sunshine	Kellogg, Idaho	1.3×10^{-3}	88.2
16.	Homestake	Lead, South Dakota	1×10^{-3}	94.1
17.	TOSCO	Rifle, Colo.	1×10^{-3}	94.1

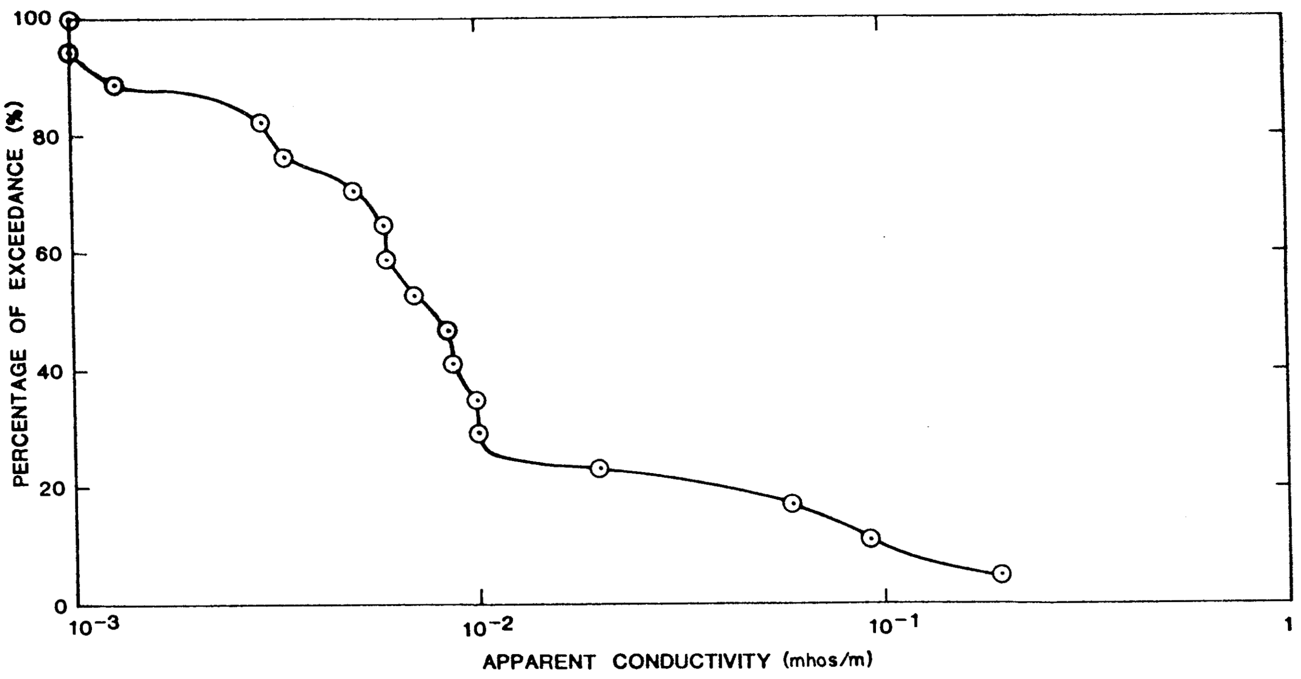


Figure 10 Conductivity Distribution of 17 Selected Metal/Non Metal Mines

2.3 Mine Construction Techniques

Room & Pillar

The most common underground mining method used in large scale metal/ non metal mines in the U.S. is room and pillar which accounts for over 75% of all mines (7). Room and pillar mines offer a wide flexibility for antenna deployment and allow the trapped miner to achieve the maximum transmitting moment for a given length of antenna wire. The maximum practical depth for room and pillar workings depends on the strength of the pillars. The deepest room and pillar mines in North America are about 3200 feet below the surface. Extraction efficiency in room and pillar mining decreases as mine depth increases; thus the practical limit of slightly over 3,000 feet.

Vein Mining

Vein deposits are often found in metal mines such as silver, zinc, lead and gold. Such deposits are usually mined by a variation of three basic methods: (1) Shrinkage stoping, (2) Square-set stoping, and (3) Cut and fill stoping. In some of the wider and stronger veins, with more competent walls, open stoping methods are used.

Vein deposits present unique mining problems because the deposits tend to be irregular, often steeply inclined and sinuous along strike and dip. The width of mineralization can vary from a few inches to hundreds of feet. However, average mining entry widths vary from 5 to 30 feet. Vein structures have been traced for miles along a strike and for thousands of feet down dip.

As far as communications and location equipment deployment is concerned, vein mines offer the greatest challenge. Because of the narrow entry widths and lack of adjacent return entries, it is difficult to find a suitable location for deployment of large area loop antennas. Antenna deployment in vein mines will probably be restricted to long horizontal wire antennas or small area loops with modular stacking. In some cases it is possible to deploy a large area vertical loop by utilizing two adjacent levels connected by stopes.

3.0 THEORETICAL CHARACTERISTICS OF UNDERGROUND ELECTROMAGNETIC PROPAGATION

3.1 Effects of Earth Conductivity on Propagation

Earth conductivity plays an important role in determining the propagation characteristics of electromagnetic energy in the earth. The importance of measuring earth conductivity at mines stems from the fact that more and more low frequency electromagnetic communications and telemetry systems are coming into use for underground wireless links used in communications and monitoring as well as trapped miner location. By characterizing the geophysical properties of the mine overburdens prior to testing the electromagnetic penetration capability, a more complete understanding of the propagation phenomena is gained. This understanding improves as more mines are visited and a more comprehensive data base is accumulated relating conductivity to EM propagation characteristics. As our understanding improves for a small group of test mines, the results can be characterized, given the conductivity and depth, and extrapolated to a much larger group of mines to determine the following:

(1) Whether a through the earth system is even feasible at a particular mine.

(2) If feasible, what would be the required transmitter power and receiver sensitivity needed to insure a reliable EM wireless link?

(3) What is the maximum bandwidth and/or data rate that can be utilized at the particular mine?

The basic objective of Contract J0166100 was to determine what modifications were needed to make the existing through-the-earth ULF trapped miner location system usable in metal/non metal mines. The field program was set up in two phases:

Phase I: To obtain a geophysical characterization of six (6) test mines for advanced prediction of electromagnetic propagation capability.

Phase II: To measure electromagnetic propagation in the same mines and to demonstrate ways to achieve trapped miner location with modified system concepts.

By correlating observed electromagnetic propagation phenomena in these mines with calculations and predictions based on geophysical measurements, e.g., conductivity, one can then apply the results to a much larger class of mines, and thus determine their equipment requirements prior to a mine visit.

3.2 Penetration Depth of EM Waves

The solution to the wave equation for a sinusoidally varying plane wave propagating through a finitely conducting medium is

$$E = E_o e^{-\alpha z} e^{i(\omega t - \beta z)} \qquad (1)$$

$$H = H_o e^{-\alpha z} e^{i(\omega t - \beta z)} \qquad (2)$$

where α is the attenuation constant in nepers/meter
β is the phase constant in radians/meter
and z represents the propagation distance in meters.

For any conducting medium, and in particular for a homogeneous semi-infinite earth, the EM wave penetration depth or "skin depth" is defined as the distance in which the wave is attenuated to 1/e (36.8%) of its initial value at the surface. Referring to expressions (1) and (2), it is seen that this distance is reached when $z = 1/\alpha$. This quantity is usually denoted by the symbol δ.

$$\delta = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega\mu\sigma}} \text{ meters.} \qquad (3)$$

The penetration depth expression can be simplified, assuming a nonmagnetic material, as follows: i.e. $\mu = \mu_o = 4\pi \times 10^{-7}$ henries/m.

$$\delta = \frac{503}{\sqrt{\sigma f}} \text{ meters.} \qquad (4)$$

Figure 11 shows the variation of δ with frequency for various conductivities.

The foregoing analysis has been applied to a homogeneous medium. When horizontal stratification and inhomogeneities are present, the expression for penetration depth (3) is no longer valid. For such cases, each problem must be treated individually, taking into account all of the wave reflection at the boundaries and the complex field combinations that result in each of the layers.

In analysing low frequency electromagnetic propagation in mines, the term "skin depth" is used merely as a parameter to characterize penetration distance in the medium and not to imply that plane wave propagation exists for localized ULF transmitting sources. For localized ULF transmitting sources, such as those used for mine rescue purposes, the pertinent fields produced are the induction fields, modified by losses in the earth. The magnetic field strengths, as a function of distance from the transmitting source, can be calculated for a particular mine situation, given the conductivity, the frequency and the penetration distance through the conducting medium. Figure 12 shows

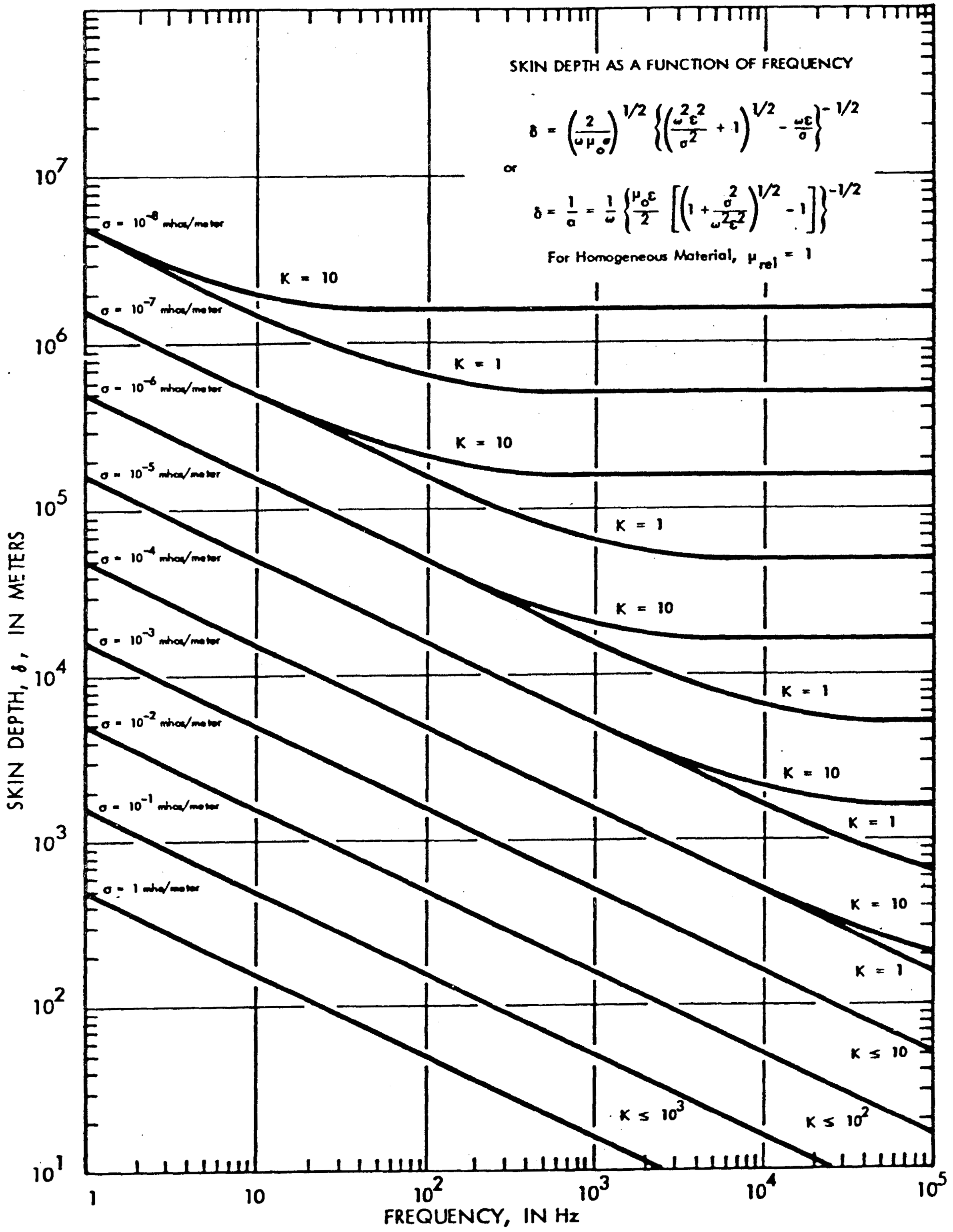


Figure 11 Skin Depth vs. Frequency for Various Conductivities ($k = \varepsilon/\varepsilon_o$)

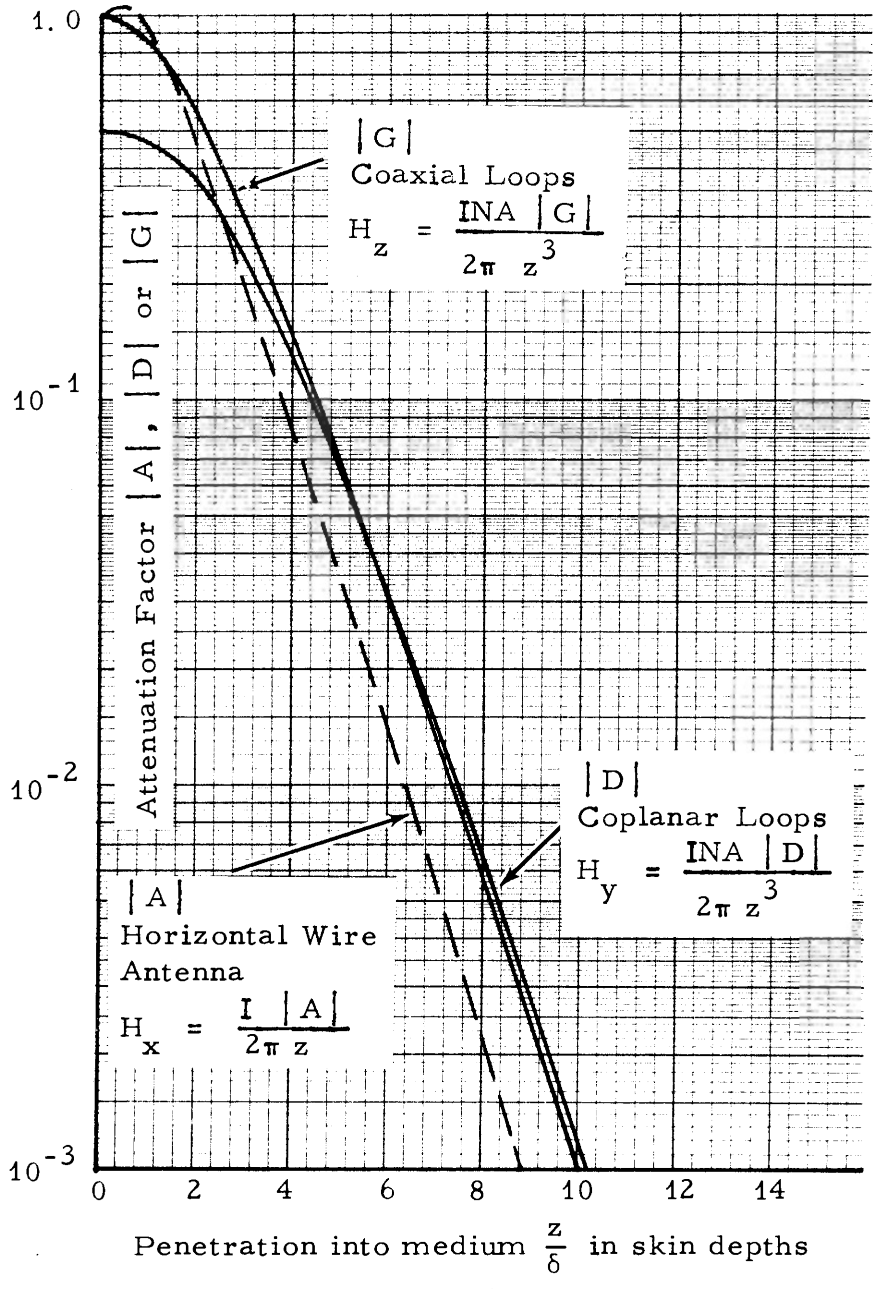


Figure 12 Electromagnetic Attenuation in Conducting Media

the attenuation constants $|G|$, $|D|$ and $|A|$ as a function of penetration distance into the conducting medium which are used to modify the basic induction field equation, $H = \left(\frac{INA}{2\pi z^3} \right)$ to determine the magnetic field strength for the different types of antenna coupling shown.

The feasibility of a through the earth ULF uplink can be determined for any mine if one knows the mine overburden thickness and conductivity and the expected electromagnetic noise background as a function of frequency. Suppose, for example, that we have a mine with the following parameters:

Overburden thickness, (z) = 500 meters
Conductivity, (σ) = 0.1 mhos/m
Surface EM noise, (H_n) = 1.0 μA/m in a 1 Hz BW

and assume an in-mine transmitting moment of INA = 1000 amp turns m^2.

The vertical magnetic field calculated for the above parameters is as follows:

f	H_z (μA/m)	Signal to Noise (dB)
10	1.08	.67
100	0.35	-9.2
1000	0.0017	-55.3

The above illustrates that the uplink signal could just barely be detected in a 1 Hz bandwidth at 10 Hz but could not be detected at the higher frequencies under the stated conditions. If information on background noise vs frequency is known about a particular mine site, it can be used, along with the other calculations, to determine the optimum frequency for an uplink system, assuming that feasibility exists.

3.3 Effects of Parasitic Coupling

It is well known that electromagnetic wave behavior is influenced by the presence of metallic conductors. The foregoing discussion (Sections 3.1 - 3.2) is restricted to the special case of a homogeneous conductive medium. In practice this condition is never really encountered, although an analysis based on the assumption of homogeneity is often helpful in estimating field strengths produced by a given transmitter operating in an environment characterized by its equivalent "effective" conductivity. (The effective conductivity would be defined, in this case, as that conductivity which would produce the measured field strength for a homogeneous conducting medium, given the actual transmitting moment and propagation distance.)

The assumption of homogeneity is even more unrealistic when considering ULF and VLF propagation characteristics in underground mines particularly those with a comprehensive network of underground pipes and rails. However, from a communications standpoint, this anomalous condition can be utilized to enhance the range of underground communications equipment far beyond that which could be expected for homogeneous media or, for that matter, even free space.

Tests performed above ground by Westinghouse personnel in 1973 near suburban and rural powerlines and pipelines have shown that low frequency signals can be carried with low attenuation over considerable distances (up to 14 miles on less than 20 watts of transmitter power) in spite of periodic pipeline insulation joints and powerline grounds (8).

The theory for computing the electromagnetic fields as a function of distance and frequency from horizontal line sources located at the earth's surface is well established (9) and will not be covered in detail in this report. A special case of the above problem is one in which the line source can be considered short with respect to the propagation distances involved and hence be treated as a dipole antenna. The expression for computing the fields of a dipole antenna is given as follows:

$$H = \frac{INA\,|D|}{2\pi d^3} \quad \text{amps/m}$$

where:

INA = the current moment of the antenna in amp turns m^2.
$|D|$ = an attenuation factor based on the electrical conductivity of the propagation medium.
d = the propagation distance in meters.

In free space, $|D| = \frac{1}{2}$ and the magnetic field is simplified to

$$H = \frac{INA}{4\pi d^3} \quad \text{amps/m.}$$

For a line source, the current moment is computed on the basis of a return current path in the earth at a depth of $\sqrt{2}\delta$ where δ specified the skin depth of the wave in the conducting medium. The skin depth (δ) is given by

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad \text{meters.}$$

Consequently, for a single line source of length (ℓ) meters and a ground return current path, the moment is (10).

$$INA = I\ell \sqrt{2}\delta \text{ amp} \cdot m^2.$$

For a horizontal loop source lying on the ground, the expression for calculating the magnetic field as a function of distance from the loop in free space is also

$$H = \frac{INA}{4 \pi d^3} \quad \text{amps/m.}$$

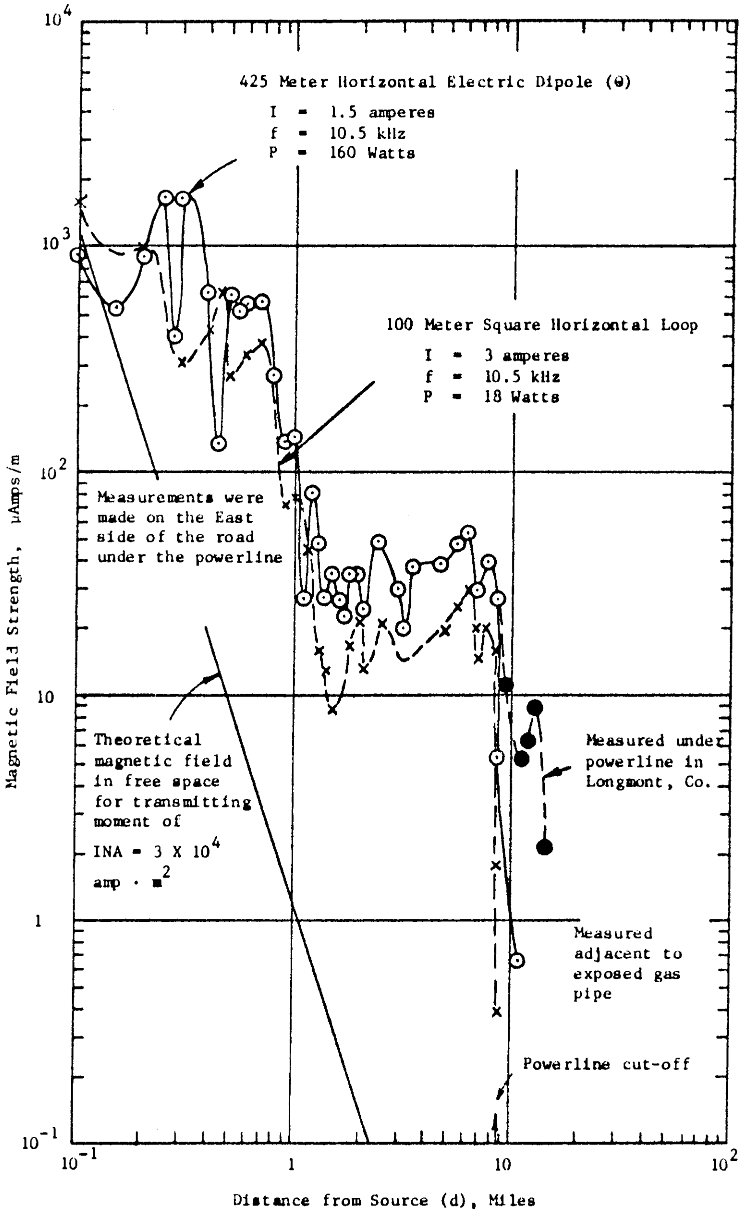
Here the computation of INA is more straight-forward and involves the product of the current, the number of turns of wire, and the physical area of the loop in square meters.

The presence of a long conductor in the vicinity of the dipole transmitter alters the electromagnetic field pattern by effectively concentrating the energy along the conducting pipe or wire. The electric or magnetic transmitting source induces longitudinal currents into the conductor which travel down the conductor with low attenuation and generate secondary electromagnetic fields in the vicinity of the conductor. As distance increases along the conductor, the received field strength would be expected to fall off initially as inverse distance cubed, consistent with the dipole coupling from the primary source moment. At greater distances, a much lower attenuation with distance is seen as the secondary fields from the currents induced in the conductor become the dominant contributing factor in the total field strength measured at that point.

If the conducting pipeline or powerline network branches off in a variety of directions from the main path, the energy carried thereon will divide and follow the branch lines as well as the main line. This will effectively reduce the energy carried on any one line and thus reduce the total range of coupling obtainable.

Figure 13 shows the magnetic field vs. distance from both a magnetic and electric dipole coupled to a long powerline and pipeline. This data was obtained in 1974 along 95th St. 10 miles east of Boulder, Colorado. It bears striking resemblance to the sidelink propagation data obtained underground at the various mines visited on the subject program for the U.S. Bureau of Mines (see Section 6.0). Signal enhancements due to coupling, as high as 60 dB, are not uncommon, either above ground or underground. This phenomenon can be effectively utilized underground to provide sidelink propagation from trapped miner transmitters to a shaft area to aid in identifying vertical level of entrapment.

Figure 13 Magnetic Fields vs. Distance from Electric and Magnetic Source Coupling to a Long Conductor.



4.0 SYSTEM REQUIREMENTS FOR LOCATION AND COMMUNICATIONS WITH TRAPPED MINERS IN METAL/NON METAL MINES

Based on the statistical study of mine parameters discussed in Section 2.2 for Metal/Non Metal Mines in the United States, we can define a worst case mine as one having both a 10% exceedance depth and a 10% exceedance conductivity.

Assumptions 10% Exceedance Depth* = 3000 ft. (915 m)
10% Exceedance Conductivity = 1.15×10^{-1} mhos/m.

4.1 Requirements for Through the Earth Uplink

Assume f = 1000 Hz
Skin depth (δ) is computed as follows:

$$\delta = \frac{503.3}{\sqrt{\sigma f}} = \frac{1484}{\sqrt{f}}$$

$$= 47 \text{ meters at } f = 1000 \text{ Hz.}$$

Thus 915 meters of overburden represents 19.5 skin depths of attenuation. This is consistent with an attenuation $|G|$ of 4.54×10^{-8}. The surface magnetic field strength (H_z) obtained in this case is computed as follows:

$$H_z = \frac{INA\,|G|}{2\,\pi z^3} = 9.43 \times 10^{-18} \times INA$$

where $|G|$ is the attenuation factor obtained from an extrapolation of the curve in Figure 12.

Assuming that a surface field strength of .1 μA/m is required for detection and location of a trapped miner, a magnetic moment of 1.06×10^{10} amp turns m^2 would be required for the 10% exceedance mine as described above. This value of transmitting moment is not practicable when one considers the portability and power restriction of the transmitter.

However, if we reduce the frequency to 10 Hz, the skin depth becomes

$$\delta = \frac{503.3}{\sqrt{\sigma f}} = \frac{1484}{\sqrt{f}} = 470 \text{ meters at } f = 10 \text{ Hz.}$$

---

* This figure is based on the 10% exceedance level for a representative sample of 45 metal/non metal mines in the United States.

Thus the 915 meter overburden depth is reduced to only 1.95 skin depths and the attenuation $|G|$ becomes .58. The transmitting moment required to penetrate this overburden is now computed as follows:

$$H_z = \frac{INA\,|G|}{2\pi z^3} = .1\ \mu A/m$$

$$INA = \frac{10^{-7}\,(2\pi z^3)}{|G|} = 830 \text{ amp turns } m^2$$

which is a practical value for a trapped miner to achieve in an underground metal/non metal mine.

Another important factor which must be considered in going from 1000 Hz to 10 Hz is the increase in background noise experienced at 10 Hz. This is generally on the order of about 30 dB as shown in Figure 14. This partially nullifies the enhancement in signal to noise ratio gained by going to 10 Hz; however, the increase in signal strength far outweighs the increase in noise so the net result is a significant improvement in expected system performance.

Further enhancement of the detection capability on the surface can be achieved by using a long wire receiving antenna in place of a magnetic dipole (loop). By using a grounded wire electric field antenna that is long with respect to the mine depth, the mutual coupling between it and an underground dipole antenna can be made to vary as inverse distance $(1/z)$ rather than inverse distance cubed $(1/z^3)$ as in the dipole-dipole case (11).

Calculations show that for a grounded wire length roughly twice the observer depth, the fields below the wire are essentially those of an infinite line source (12). The conventional use of the long horizontal wire antenna on the surface has been as a transmitting antenna to communicate a voice downlink signal to the trapped miners. However, the mutual impedance and the coupling relationship between the surface and underground antenna is the same regardless of which one is used as transmitter and which one is used as receiver. Thus the $(1/z)$ coupling relationship is retained and signal detection capability is enhanced.

This concept has been proven out in practice on at least two occasions (13).

- At the Sunshine Mine in Kellogg, Idaho, a 1900 Hz uplink signal was received on a 4000 ft horizontal wire in a 50 Hz receiver bandwidth whereas the same signal could not be detected using a 500 turn 15" diameter receiving loop and the same receiver. (Overburden depth was 4800 ft.)

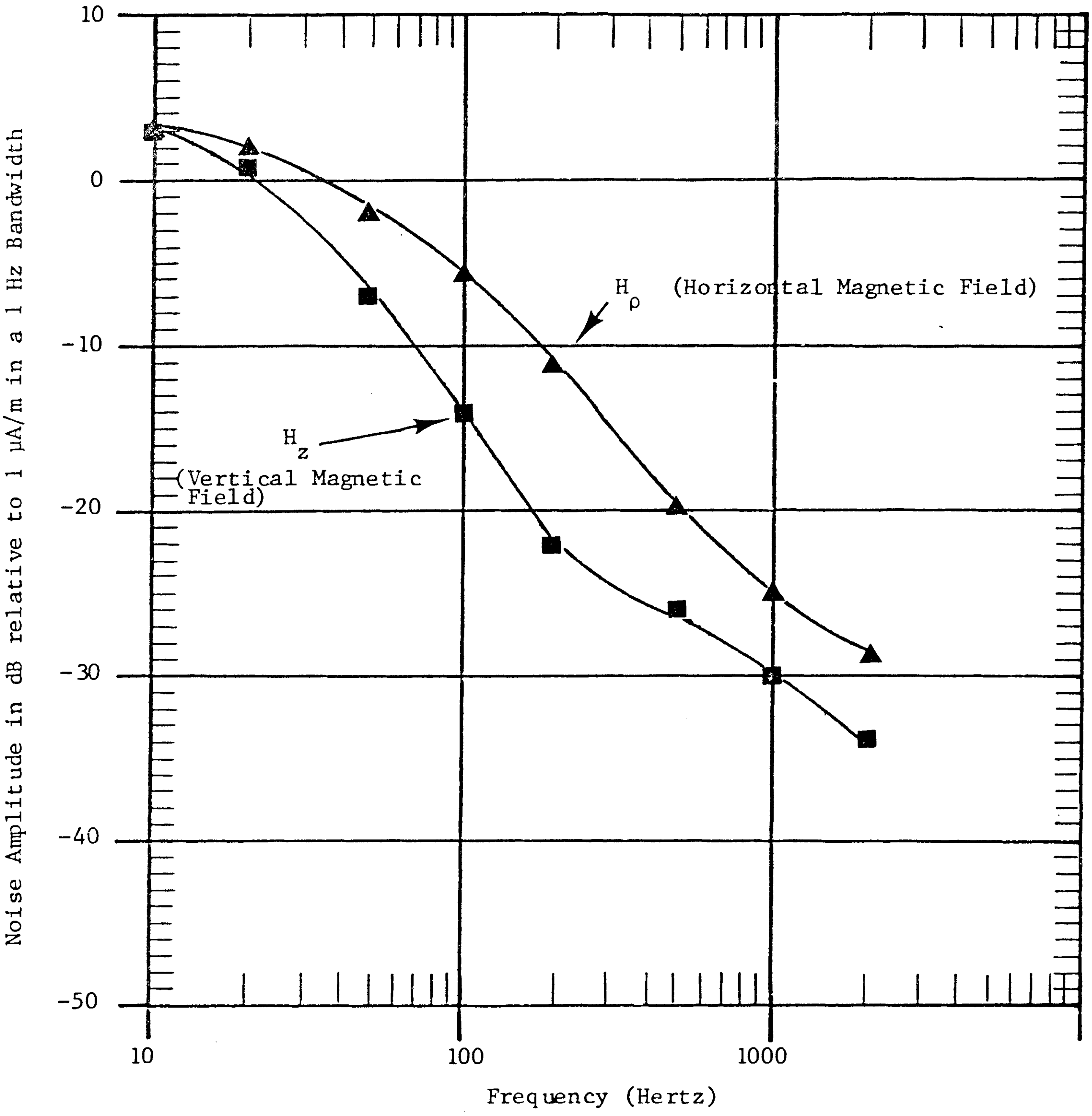


Figure 14 Atmospheric Noise

- At the Pocahontas Mine No. 1, Grundy, Virginia, a 1900 Hz uplink signal was received on a 2000 ft horizontal antenna in a 3 Hz receiver bandwidth whereas the same signal could not be detected using a 500-turn 15" diameter receiving loop and the same receiver. (Overburden depth was 2300 ft.)

Hence, in the light of the above discussion, it can be concluded that detection of through the earth uplink signals can be accomplished in a so-called "10% exceedance" metal/non-metal mine using practical low power trapped miner transmitters provided that frequency is reduced low enough to make through the earth attenuation relatively insignificant. For the 10% exceedance mine, frequency must be kept in the vicinity of 10 Hz for detection with magnetic dipole receive antennas but could go higher when using long horizontal wire receiving antennas.

There are logistic problems associated with using frequencies as low as 10 Hz when attempting to conduct hand-held direction finding operations. The earth's magnetic field induces high levels of noise in the loop for even the slightest movement of the loop. Consequently, when using a loop for direction finding of trapped miners at f = 10 Hz, the loop must be firmly planted in position using a tripod or equivalent, before readings can be taken at each individual position.

When using a horizontal wire antenna for direction finding, it is somewhat impractical to successively move the antenna around to locate the miners position as can be done with a loop. In the case of using a horizontal wire antenna for determining the trapped miners position, it would be more feasible to deploy an array of such antennas in the form of a grid network. Then, by analyzing the receiving pattern created by the signals received on all of the antenna elements, a judicial extrapolation of the trapped miners position can be made. However, this scheme is not recommended unless it is first determined that the signals are not detectable using the loop receiving antenna.

4.2 Requirements for Through the Earth Sidelink

In metal/non metal mines, unlike coal mines, there usually exists more than one level of mining activity going on simultaneously. Consequently, there is a requirement for knowing not only the miners horizontal coordinates but also on what mining level he is trapped. This introduces a requirement for horizontal propagation from the trapped miners transmitter to a section of the mine where the signal could be relayed up to the surface by some other means or the signal could be received by lowering a wideband receiver and loop. This would normally be done either at the shaft or a borehole, so the problem is one requiring a maximum sidelink propagation range from the miners area of entrapment to insure adequate signal detection at the vertical probe location.

Fortunately, sidelink propagation is enhanced considerably by the network of pipes and other conductors that are present to varying degrees in virtually all metal/non metal mines. Tests performed at the metal/non metal mines on this project verify coupling enhancements of up to 55 and 60 dB over signals expected in free space for those particular distances. Coupling to underground conductors improves with increasing frequency; consequently some type of dual frequency transmitting system is needed to satisfy the requirements for both uplink and sidelink transmission simultaneously. A system to accomplish this is described in Sections 5.0 and 8.0 of this report.

4.3 Portability Requirements

For a trapped miner transmitter to be effective, it should be small enough to be carried on the miner at all times. In view of what the miner must already carry (i.e. cap lamp battery, self rescuer, etc.) it would not be practical to burden him with any significant additional bulk or weight that might impede his efficiency or productivity. A practical limit for a trapped miner transmitter would be about ½ lb., which is about the weight of the present USBM Coal Mine Trapped Miner Transmitting unit. A significant weight advantage is gained by using the miners cap lamp battery as a dc power source. Based on results obtained on this program and others (1-6), the cap lamp battery provides sufficient voltage and power for the transmitting unit.

4.4 Permissibility Requirements

There are no permissibility restrictions for the vast majority of metal/non metal mines in the United States since most of the mines are non-gassy. Exceptions to the rule are the Trona Mines in the Green River formation which do emit an extremely small amount of methane (less than .1%). The modification philosophy developed on this contract to adapt the USBM Coal Mine Trapped Miner Location System to use in metal/non metal mines does not entail any increase in power or voltage on the part of the underground transmitter. Consequently, the modified transmitting unit will retain its existing intrinsic safety rating, as presently certified.

4.5 Blasting Cap Susceptibility to ULF Transmissions

Of much more concern to the Metal Non Metal Mining Industry is the potential effect of the ULF transmitter on electrical blasting caps. Basic information on the mechanism of RF initiation, tables of safe distances, and data on common RF sources are given by the IME (14). Tables of safe distances were derived from analytical worst case calculations based upon an assumed 40 mW, no-fire level of commercial blasting caps.

The theory of wave antennas was employed by the IME for electric blasting caps deployed within the fields emanating from various transmitting sources. It was assumed that the field structure from the broadcast band antennas was in the Fresnel (near) zone and that for higher frequencies, the caps were located in the Fraunhofer (far) zone. At the low operating frequencies under consideration, the IME correctly noted that the primary mechanism for induced currents would be simple magnetic induction since the magnetic flux would be the predominant factor.

Regarding the 40 mW, it was noted that members of the IME do not design commercial blasting caps with firing levels below 0.2 amperes, and with a conservative resistance of 1 ohm, the resulting power dissipation is 40 milliwatts. Stray currents caused by dc or 60 Hz ac power sources can deliver power to electric blasting caps very efficiently. For this reason, a safety factor of 5 was imposed by the IME to define the "potential hazard level" for stray sources of current which might come in direct contact with caps. The lowest firing level (0.25 amperes) was reduced to 0.05 amperes for a 1-ohm bridge wire to arrive at the following definition: "a stray voltage source capable of developing 50 mV or more across a 1 ohm resistance constitutes a potential hazard to commercial e.b. caps manufactured in the U.S.A. Note that 50 mV across 1 ohm represents 2.5 mW." The IME goes on to note that at frequencies above 28 MHz, the tables of safe distances are very conservative. The hazards in the broadcast band are less conservative in that "there is one chance in a thousand for premature initiation caused by induced RF in the broadcast band provided (1) the e.b. cap is perfectly matched to the pickup antenna, (2) the pickup antenna is ideal in configuration (tuning) and orientation, and (3) the pickup loop is located at a peak of a fringe in the Fresnel zone. The IME then concluded that "the possibility of simulating such circumstances in the 300-3000 Hz band are even more remote since such long blasting circuits are impractical, e.g., such long leading lines cannot be used to successfully initiate e.g. cap rounds." They recommended, nevertheless, that tests shoulc be conducted to properly assess the hazard. These are described in the following paragraph.

Electric Blasting Cap Tests

On a previous Bureau of Mines project, a test program was conducted to determine the likelihood of blasting caps being set off by ULF electromagnetic transmissions (15). DuPont No. 6 electric blasting caps with 10-foot leg wires were tested under safe conditions in a field near Boulder, Colorado. The caps were inserted into the soil a few inches to permit safe firing, and the lead wires were kept shunted until the test was ready to begin. The instrumentation included a Wavetek signal generator, an amplifier, matching transformer, a sensitive voltmeter, and a 1-ohm resistor with a voltmeter to indicate current level. Tests were run at frequencies of 60, 120, 200, 275, 500, 700, 1000, 2000, 2750, and 5000 Hz. At each frequency, the terminal voltage and line current were recorded at several steps as the voltage was increased to the firing point. From this data, magnitude of impedance and power dissipation in the cap were calculated. Since only 10 caps were used to complete these tests, there is an insufficient amount of data for statistical inference; however, the data for resistances falls within published figures and hence it is felt that these tests will be useful for estimating the potential hazards at ULF (300-3000 Hz).

The IME definition that if 2.5 mW is dissipated in the caps, a potential hazard exists, is extremely conservative in the opinion of Westinghouse. It was found, in the Westinghouse tests, that with voltages in the range of 50 mV to 100 mV across the caps, gives a resistance of 1.5 ohms (+0.15 - 0.07) for ULF. From this, it was found that 2.5 mW will be dissipated when the current is about 48 milliamps. The Westinghouse tests showed that 100 to 500 mW was required to fire caps with currents in the range 250 to 550 milliamps. The firing voltage was in the range 450 to 900 mV and the resistance at the firing point was about 0.1 ohm higher owing to heating. Thus, even the 40 mW no-fire level is a conservative figure.

Susceptibility of Caps

How close can the electromagnetic communication antennas be to blasting caps? The IME suggests that there dows not appear to be an RF initiation hazard in the normal storage and transportation of electric blasting caps, as long as they are in their original carton. The calculations discussed below show further that there is only a remote chance for initiating e.b. caps when they are deployed for maximum coupling to either the underground manpack loop antenna or a horizontal wire antenna on the surface. Therefore, caps which are in the original packaged condition should never be initiated by electromagnetic radiation from the manpack loop or horizontal wire transmitting antennas. The calculations are based on the characteristics of No. 6 instantaneous electric blasting caps.

As suggested by the IME, magnetic induction was considered to be the most hazardous mechanism. Considering an electric cap with the lead wires shunted, the maximum ULF induction will occur when the lead wires are arranged in a circular shape so as to enclose a maximum area. The equivalent circuit for each cap is simply the resistance of the wire in series with the resistance of the cap, and if several caps are connected in series and arranged in a circle which is immersed in a uniform magnetic field with flux normal to the loop, the current that is induced into the shorted circuit is given by:

$$I_i = 8\pi^2 \text{ X } 10^{-7} \frac{fAH}{R}$$

where:

f = frequency, Hz

A = area of loop, M^2

H = magnetic field intensity, amps/meter

R = total series circuit resistance in ohms.

This equation was used to calculate the currents induced into various blasting cap configurations using large areas, a frequency of 3000 Hz, and the maximum transmitting currents which may be realized with the ULF manpack transmitter.

In the mine it was assumed that the worst condition would be in conventional mining where a face has been drilled and loaded with 10 shots distributed over the face having an area of 10 feet by 20 feet. Each cap is assumed to have a resistance of 1.5 ohms, and for caps used in the mine with iron leg wires, the total resistance is 4.5 ohms for each cap and leg wire. Conditions were calculated under which a current of 40 milliamps would be induced into the cap circuit. It was found that a magnetic field of 2.25 amperes per meter would induce 40 milliamps into the 10-cap circuit. Since the maximum magnetic field generated by the manpack transmitter will be less than 1 amp per meter in the center of the loop antenna, the chance for initiating electric caps would be extremely remote. If a single cap with 16 foot leg wires was arranged in a loop inside of the manpack antenna loop for maximum coupling, it was found that a magnetic field of about 1.5 amps per meter would induce only about 40 milliamps into the cap loop.

4.6 Location Accuracy Requirements

In addition to the requirements for detecting the trapped miner's signal, there are also requirements for the system to effectively locate his position in the mine. The previous system developed for coal mine use concentrated on determining the x, y coordinates of the miner and assumed that the z coordinate (depth) was known. However, metal/non metal mines, unlike coal mines, are generally multilevel mines where several levels are being mined simultaneously. Consequently, it is important to be able to locate the trapped miner's position in terms of x, y and z coordinates.

A through-the-earth null detection technique can be used to identify the horizontal (x, y) coordinates in the same manner as the present BuMines system developed for coal mine use. The accuracy with which the horizontal coordinates can be determined is dependent upon the overburden depth, the terrain irregularities, and conducting anomalies, (pipes, power cables, etc.) particularly those near the surface receiving site (16, 17). At the extremely deep mines such as the Homestake Mine in Lead, South Dakota, the horizontal coordinates of a trapped miner can be determined only in a gross sense.

However such information, coupled with information on the miners vertical location and a copy of the mine map, could be used to reduce the area of uncertainty to several hundred feet in deep mines. Information of this type would be of great value during a rescue operation at a deep metal/non metal mine. Location accuracy would improve for shallower mines where more sharply defined field pattern information can be obtained on the surface.

Vertical location can be determined by recording field strengths on a multichannel receiver connected to a broadband loop and preamp lowered down a shaft or borehole. Assuming the mine is laid out with a network of water pipes and other conductors on each working level, the trapped miner's signals can be easily transmitted from his position of entrapment to a shaft location by mutual coupling to one of the pipes in the vicinity. Determination of vertical level of the miner's position could be made on the basis of field strength amplitude vs. depth of the probe. It is assumed that in most cases the field strength will peak at the shaft depth containing the trapped miner and his transmitter, since the conductors around which the signals couple are generally installed horizontally along each level. The requirements for vertical location accuracy should be such that the true vertical level determination is unambiguous (i.e. less than 100 ft.)

5.0 CANDIDATE EM LOCATION TECHNIQUES

There are two basic approaches that can be taken to achieve the capability of locating trapped miners in deep metal/non metal mines.

(1) Use the existing USBM coal mine manpack transmitter as the first link of a repeater chain to convey information on the miners position to the surface.

(2) Use a modified version of the USBM coal mine manpack transmitter to convey information on the miner's position to the surface via a direct through the earth propagation path. (This has been discussed to some extent in Section 4).

The above approaches are based on communications equipment operating at frequencies in the ULF (Ultra Low Frequency) VF (Voice Frequency) and VLF (Very Low Frequency) ranges. Approach No. 1 would utilize VF (300-3000 Hz) and VLF (3-30 kHz) while approach No. 2 would utilize ULF (3-300 Hz) and VF (300-3000 Hz).

There has also been considerable interest and experimentation by other contractors in the use of MF (Medium Frequencies) for mine communications. MF covers the frequency range from 300 kHz-3 MHz and normally requires that an additional coupling agent such as a cable or pipe be present for signals to propagate readily in mines, especially those with high ground conductivity. Almost all mines contain the necessary coupling agents - therefore MF is a viable operating frequency for communicating in most mines, and could also be utilized for communicating between repeaters in approach No. 1. Each of these approaches warrants careful consideration and should be analyzed in light of their respective advantages and disadvantages. Before undertaking a comparison of relative advantages and disadvantages, each approach will be discussed separately.

5.1 Trapped Miner Location Using Repeaters

Repeaters can be used to detect the presence and amplitude of manpack signals and to relay this information vertically or horizontally. The repeater spacing will be determined by the range of the manpack transmitter, range of the repeater, and the number of repeaters which must hear the manpack transmitter. If more than one repeater can hear a manpack transmitter, then location can be more accurately determined by triangulation. See Figure 15.

Each repeater relays the received strength of the manpack signal so that radial distance from the repeater can be estimated. In Figure 15, with two repeaters responding, the manpack transmitter could be at either point A or B. If three or more repeaters respond to a single manpack transmitter signal, the location of that particular manpack can be determined without ambiguity, provided that the repeaters are not colinear. If triangulation is not possible,

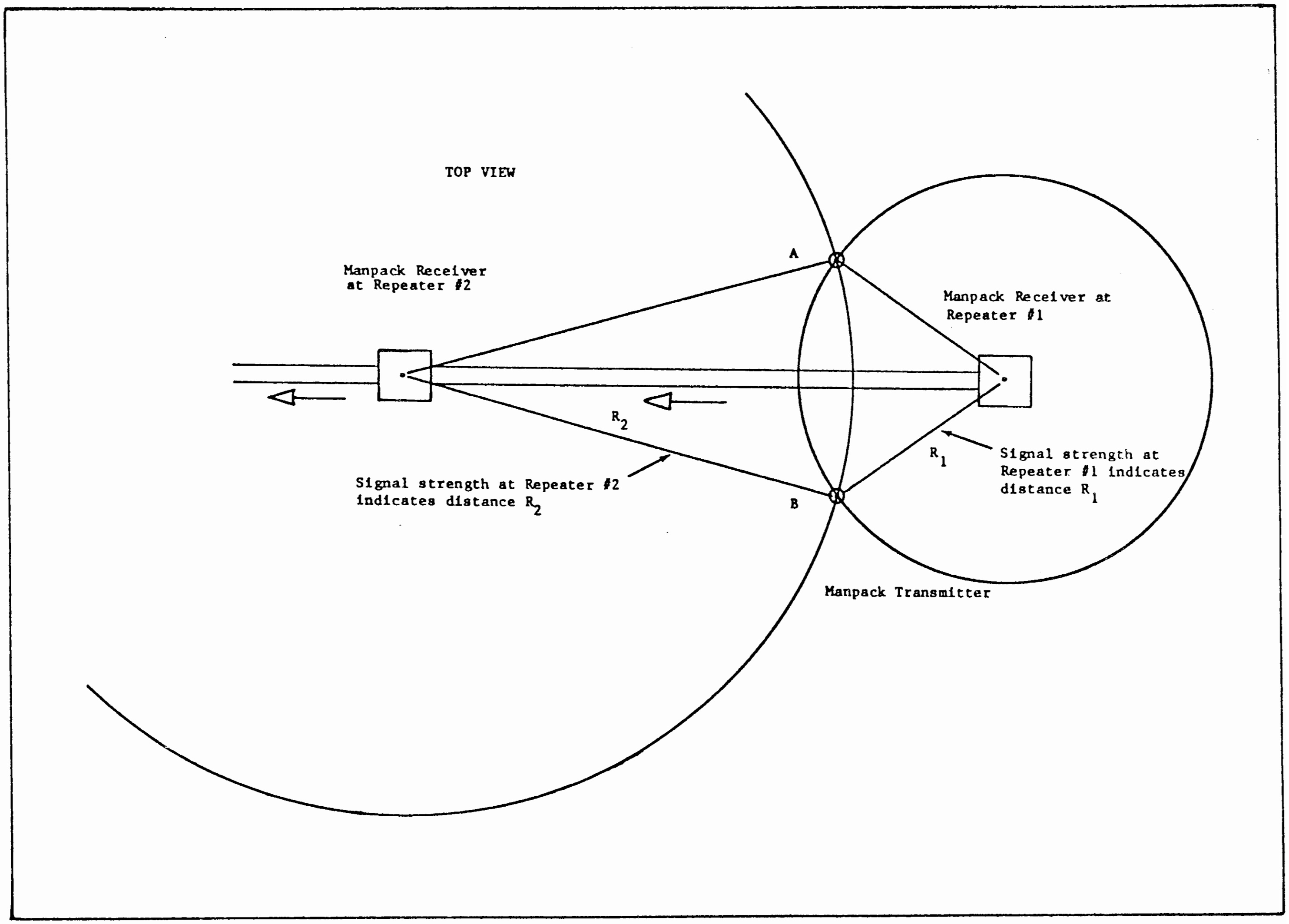


Figure 15 Location of Manpack Transmitter Received by Two Repeaters

the only location information which can be derived from a single repeater response is that the manpack transmitter is somewhere on the circumference of a circle which has a radius proportional to the received signal strength. However, this simple interpretation is further complicated by the presence of conducting objects in the mine so even the circle radius is only approximate at best. Some practical schemes for using repeaters are described as follows:

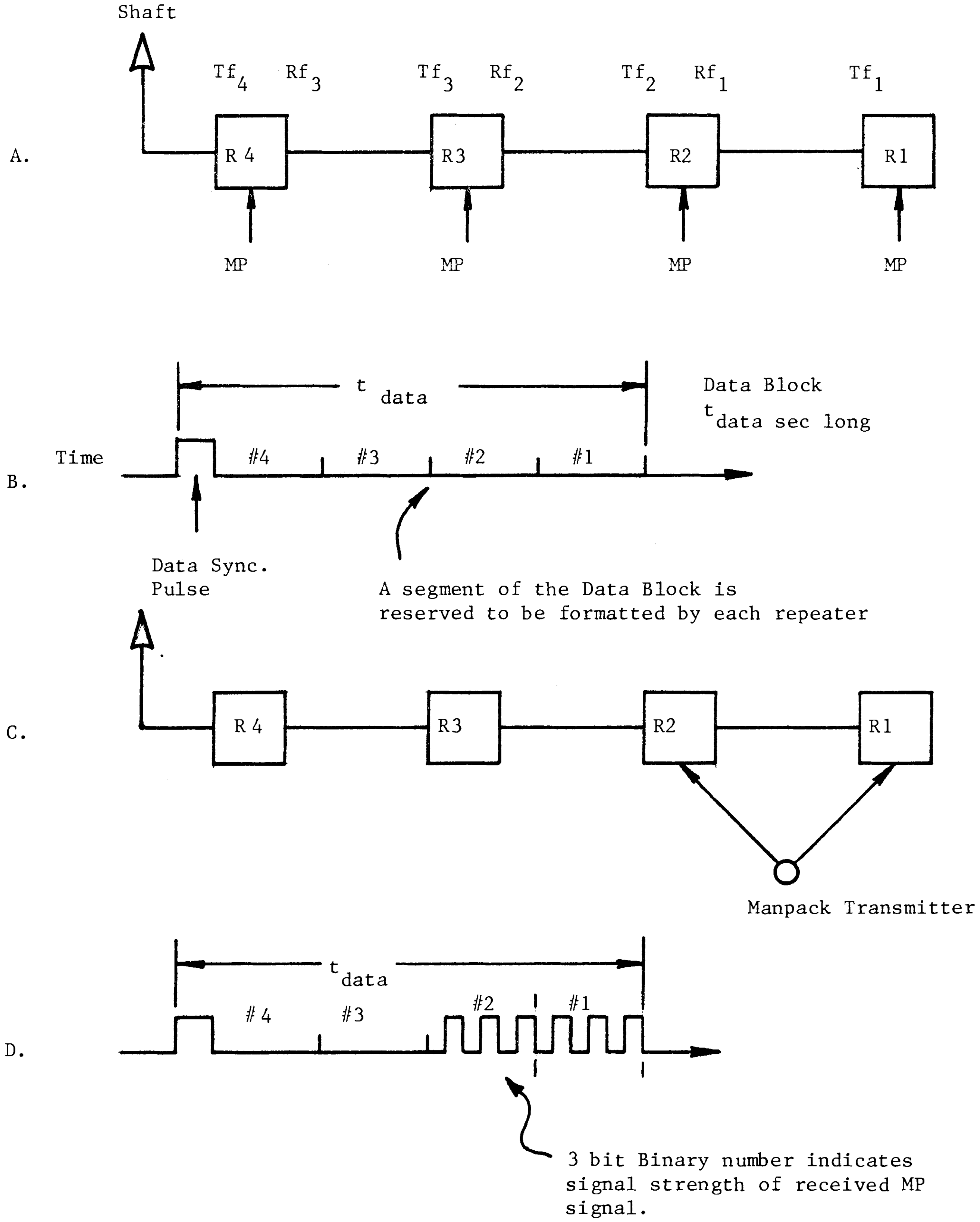
Digital Wireless Repeaters

A string of digital wireless repeaters responds to a common manpack transmitter frequency and communicates with itself on a different set of repeater frequencies. See Figure 16A. Each repeater tells the next repeater down the line of the presence and amplitude of a received manpack signal and the output of the last repeater (R4) contains the sum of the information acquired by all of the repeaters. The presence and amplitude information is formatted in a digital data block as shown in Figure 16B.

The first repeater in the string (R1) continuously initiates the transmission of the data block and, as it ripples down the drift, each successive repeater updates its own reserved data segment. The presence of information in a data segment tells of the presence of a manpack signal and its amplitude. For example, suppose repeaters 1 and 2 are receiving a manpack signal from a transmitter which is located equidistant between R_1 and R_2 (See Figure 16C). The data block transmitted from R4 will look like Figure 16D.

There is a delay between the time R1 begins receiving a manpack transmission and the time when the formatted data block leaves R4. This delay is dependent on the number of repeaters in the string and the length of the data block. (See Figure 16B). The delay is estimated in Figure 16F. This delay could be reduced using a non return to zero (NRZ) code. However, this introduces an additional requirement for an external clock.

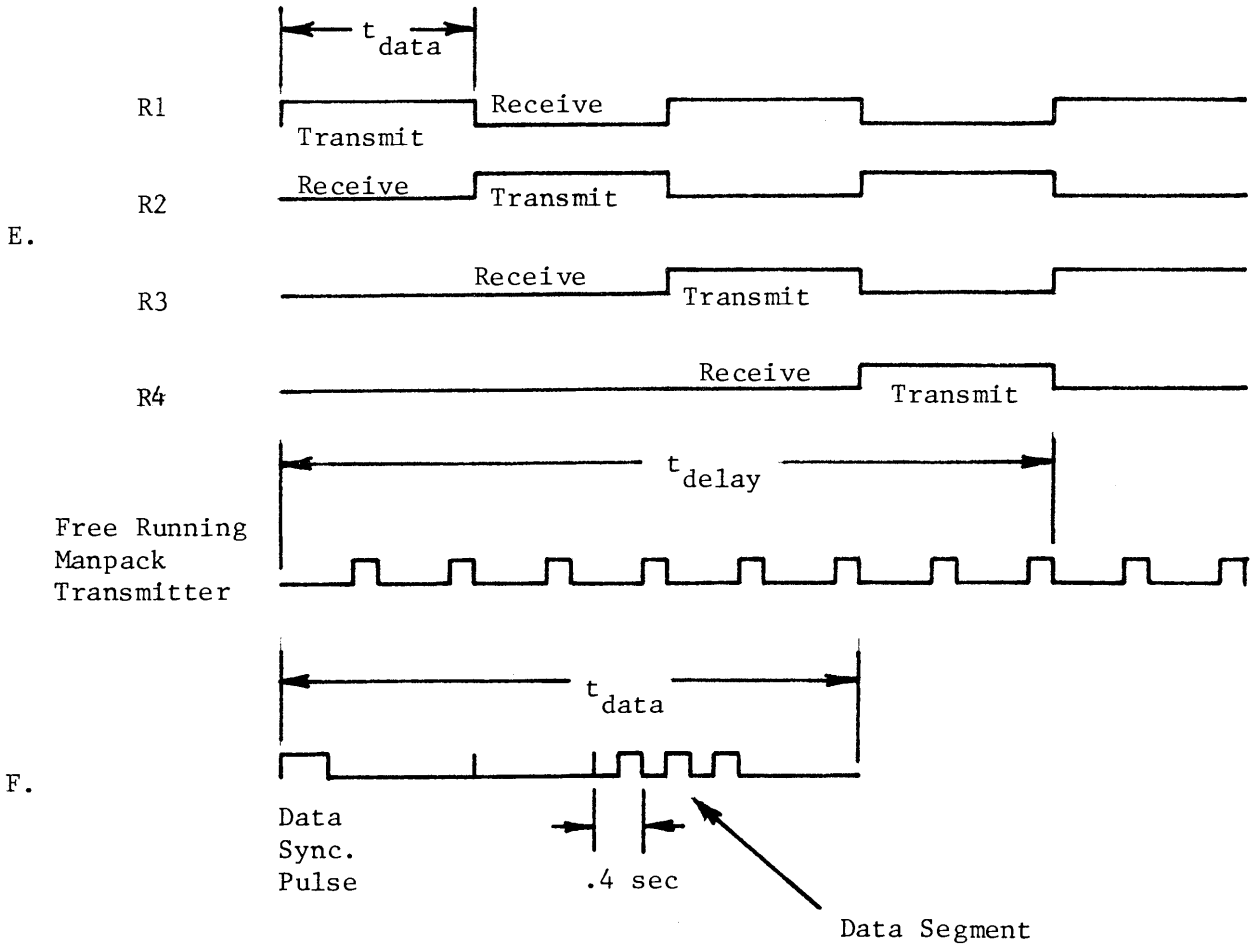
A block diagram of a universal wireless digital repeater is shown in Figure 17. Only the local oscillator crystals would change from one repeater to the next. Note that each unit has dual frequency reception capability; one channel to sense the ULF manpack signals and the other channel to sense the digital information being transmitted from the preceding repeater. The output of the last repeater in the string (R4) may be transmitted up the shaft to the surface on a twisted pair, via more repeaters or on a multiplexed data system, such as the Collins Hoist Communications System.



A segment of the Data Block is reserved to be formatted by each repeater

3 bit Binary number indicates signal strength of received MP signal.

Figure 16 A, B, C, and D. Wireless Digital Repeaters



Estimation of t_{data}

1. Assume repeater receiver bandwidth is 5 Hz
2. Rise time of repeater receiver is about .25 sec
3. Assume that .4 sec is needed to detect a pulse
4. Each data segment contains 3 pulses
5. Data sync signal is .5 sec.
6. Then, total t_{data} for 4 repeaters is:

$$t_{data} = 4(3 \times .4 \text{ S}) + .5 \text{ S} = 5.3 \text{ Sec}$$

7. Total ripple delay for 4 repeaters is:

$$t_{delay} = 4(5.3 \text{ S}) = 21.2 \text{ Sec}$$

Figure 16 E and F. Wireless Digital Repeaters

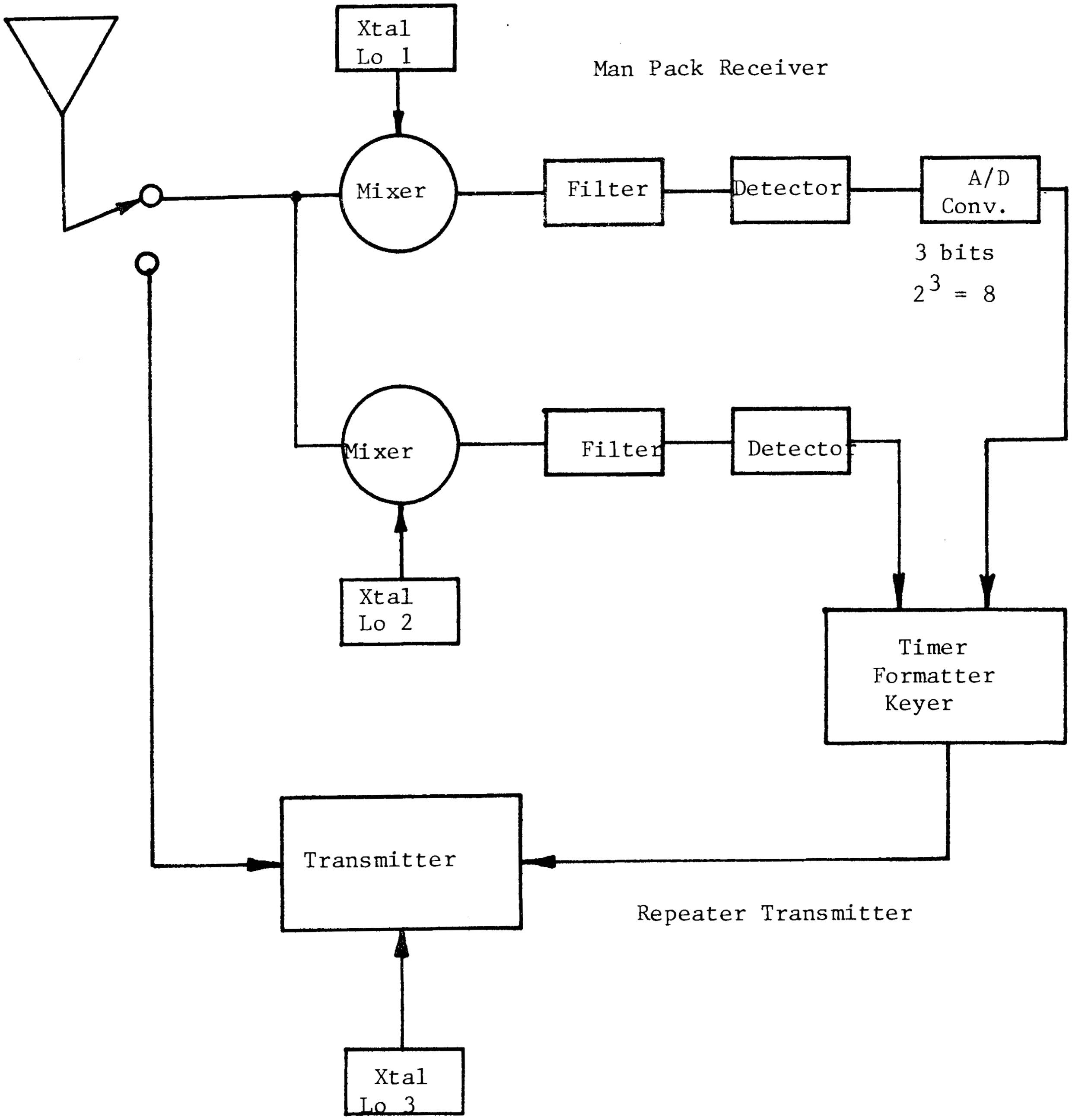


Figure 17 Universal Wireless Digital Repeater

Summary of System

Advantages

1. Relatively simple repeaters.
2. Modulation is digital, high signal to noise ratio.
3. Easily expandable.
4. No wiring between repeaters, increasing reliability.
5. Entire repeater, battery, and antenna could be buried for protection.
6. Permits location by triangulation if more than one repeater can hear the manpack.
7. If any one repeater in the string stops working, breaking the link, it might be possible to hear others from other points in the mine.

Disadvantages

1. Time delay between the manpack signal and the end of the string.
2. Location accuracy is somewhat limited, particularly if only one repeater can hear the manpack.
3. Location is more complicated if any one repeater is receiving more than one manpack signal.

Digital Wireline Repeaters

A string of repeaters, each similar to the digital wireless repeater, is connected to a common transmission line as shown in Figure 18A. Each repeater transmits on its own frequency and encodes amplitude information just as the wireless repeater. See Figures 18B and C. All repeaters are operating in parallel, simultaneously, and the data block of each is much shorter than the data block of the wireless series string.

A block diagram of a digital wireline repeater is shown in Figure 19.

Summary of System

Advantages (Over the Wireless System)

1. Time delay is less (divided by number of repeaters).
2. A repeater receiver is not needed.
3. The transmitter consumes less power.

Disadvantages

1. Cabling between repeaters is required making the system less reliable.
2. Installation costs are greater.
3. Bandwidth requirement of the shaft cable and amplifier system is greater.

Analog FM Repeater

An FM repeater system is identical to the wireline system except that the repeater transmitter is modulated directly by the received manpack signal. The FM carrier demodulated at the surface is a faithful reproduction of the timing and amplitude of the manpack signal. A block diagram is shown in Figure 20A. The frequency spectrum of the signals on the shaft cable is shown in Figure 20B. A block diagram of an FM repeater is given in Figure 21.

Summary of System

Advantages

1. No time delay.
2. A repeater receiver is not needed.
3. The transmitter will consume less power than the digital wireless repeater.
4. Both amplitude and timing information are recovered in the detected audio of the FM receiver at the surface.

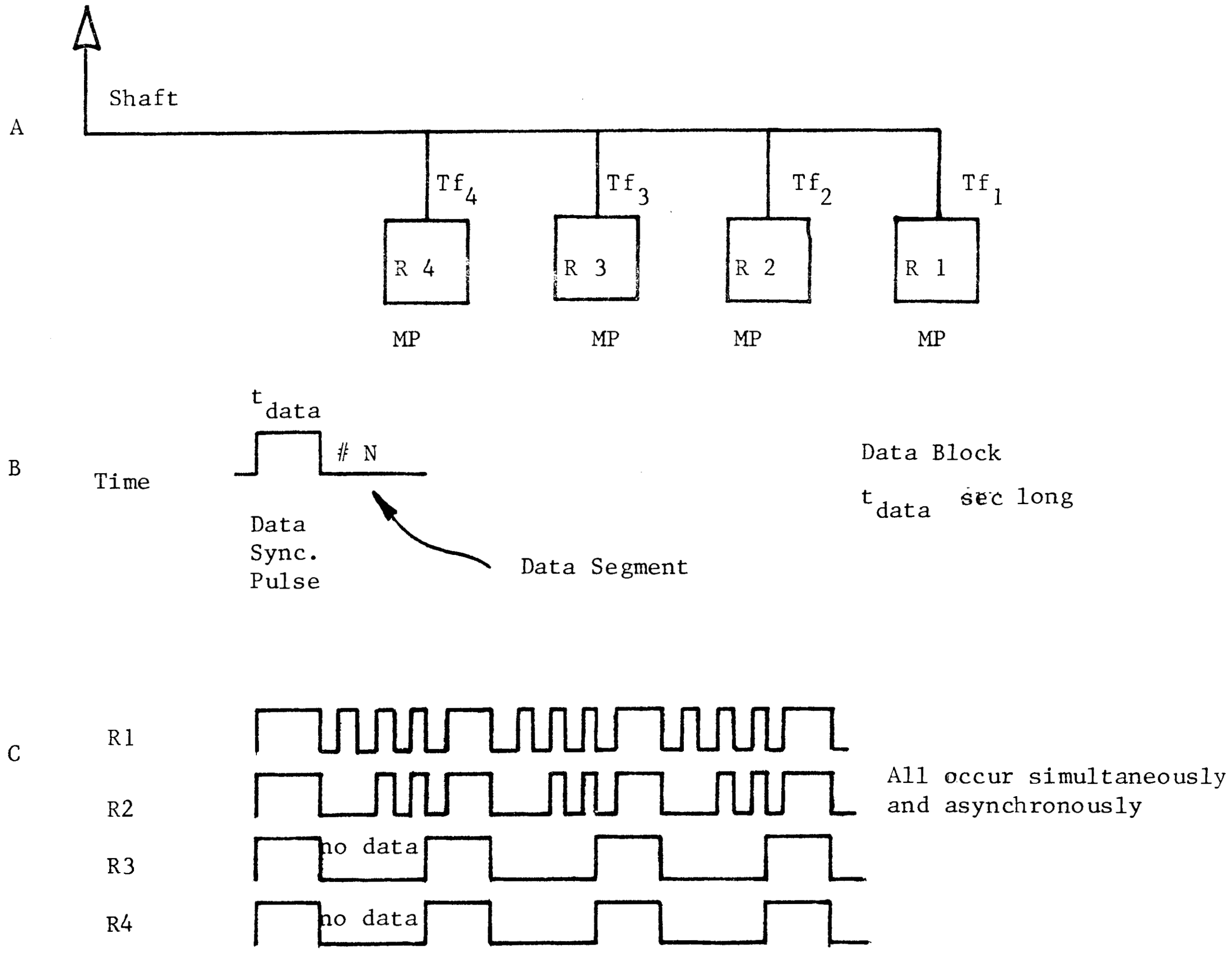


Figure 18 Digital Wireline Repeater System

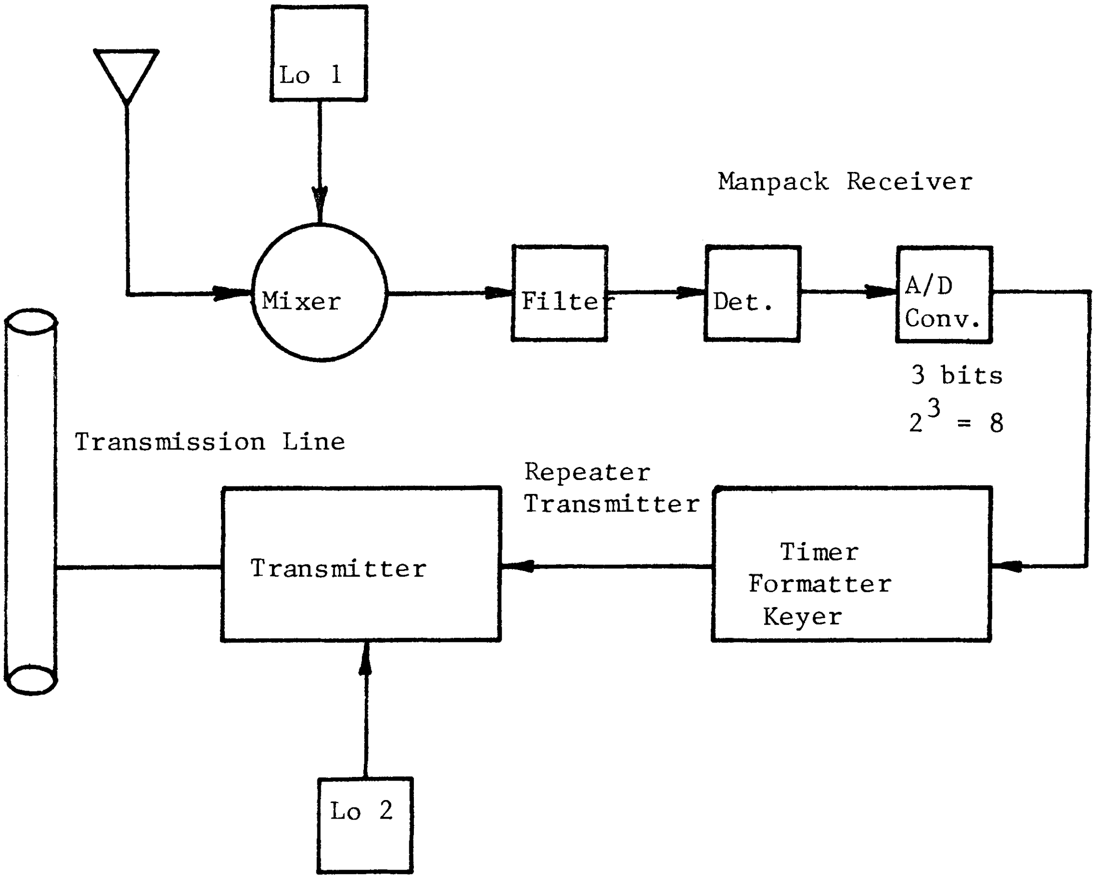
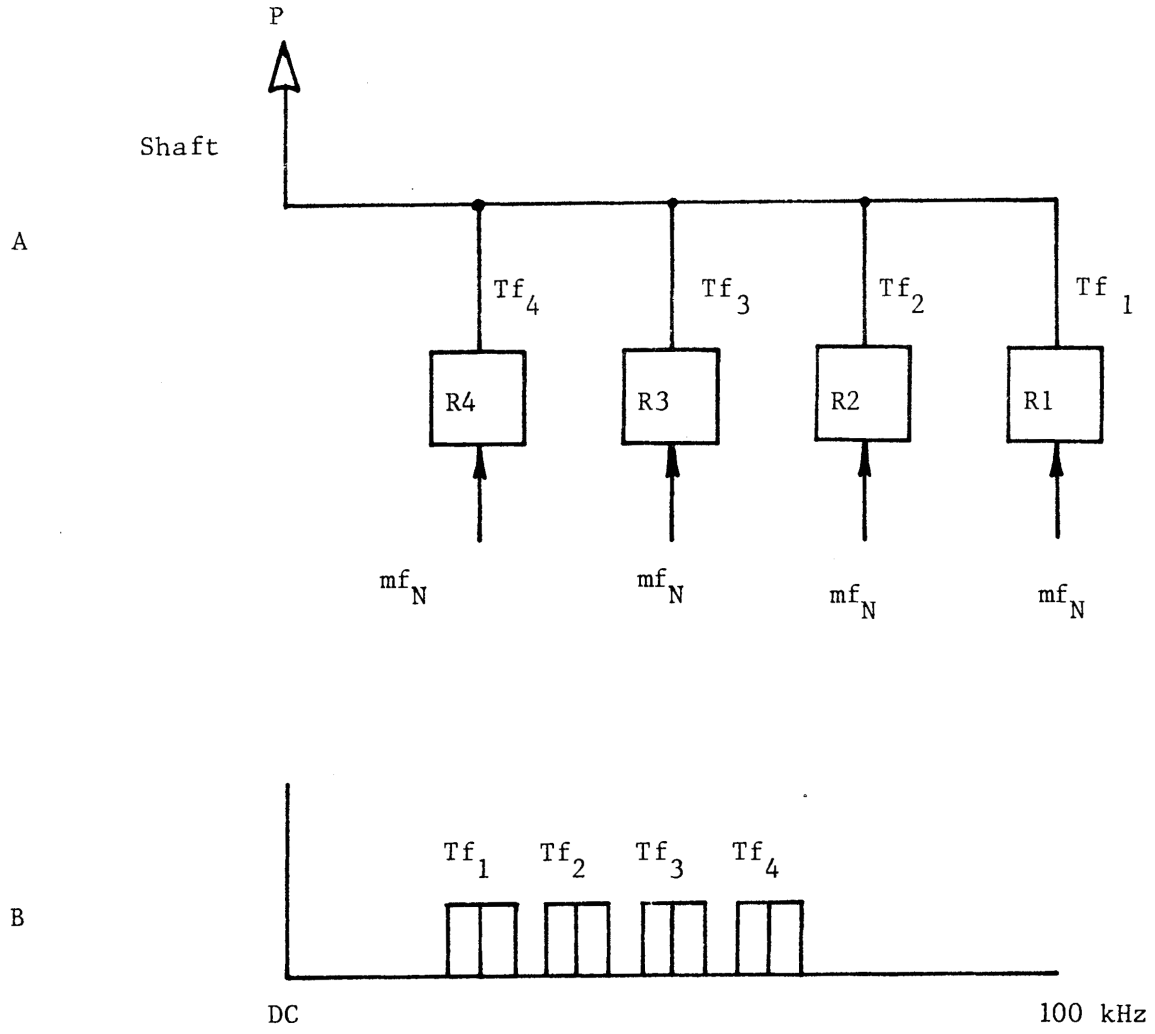


Figure 19 Universal Wireline Digital Repeater



Narrow Band FM Repeater Signals

Figure 20 Analog FM Repeater System

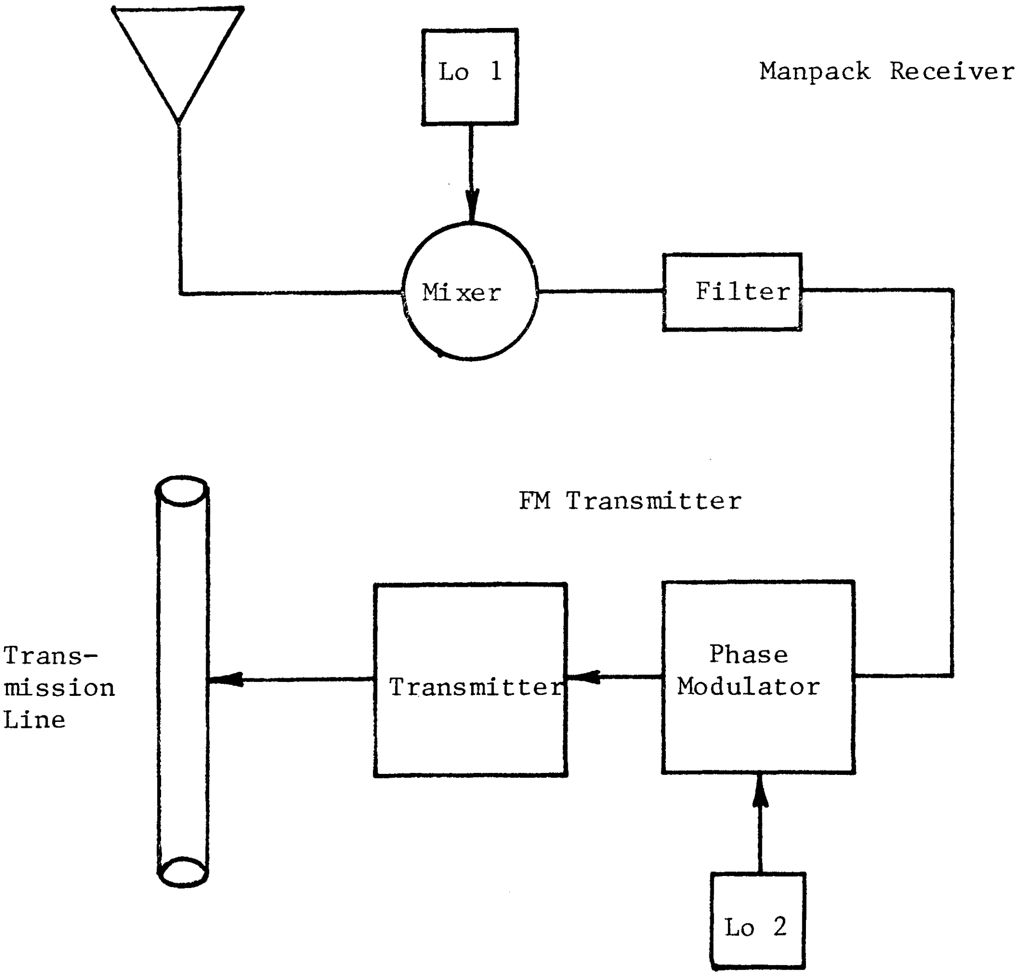


Figure 21 Universal Analog FM Repeater

Disadvantages

1. Cabling between repeaters is required making the system less reliable.
2. The bandwidth of the shaft cable and/or amplifying system must be greater.

Integration of Several Repeater Strings

If several repeater strings are in operation, possibly in different drifts on different levels, many signals will be received at the surface and must be decoded to successfully locate a trapped miner.

Figure 22 is a conceptual top view of a mine with several drifts each containing a string of repeaters. A cable for each drift comes to the surface, or a multiplex system combines the signals from several strings for transmission upward.

If cable is used for uplink transmission, and the repeaters are wireless digital types, one narrow band signal for each drift comes to the surface. (For Figure 22, 4 total). If the repeaters are wireline digital types, a narrow band signal for each repeater comes to the surface (13 total). If the repeaters are analog FM types, a wideband signal for each repeater comes to the surface (13 total).

Data Readout

Regardless of which type of repeater scheme is used, the data received by the repeaters will have to be combined or multiplexed in some manner, transmitted up the shaft (cable or hoist communication system) and demultiplexed, sorted out and displayed. A convenient visual means of displaying the incoming data in real time would be to use an illuminated scale model consisting of an array of lights, each representing a different repeater in the mine. These lights would be fastened securely along scaled down models of the actual mine drifts and would be wired in such a way that they would light in accordance with the repeater response in the mine. The number and concentration of repeater lights illuminated along with their relative brightness would serve to indicate the general location of the source transmitter.

In parallel with the illuminated scale model of the mine, a digital printer could be used to record the number of repeaters responding, the relative amplitudes, the time of day and date. This, of course, would require the appropriate logic interface circuitry between the multiplexed data received at the hoist house and the digital printer input.

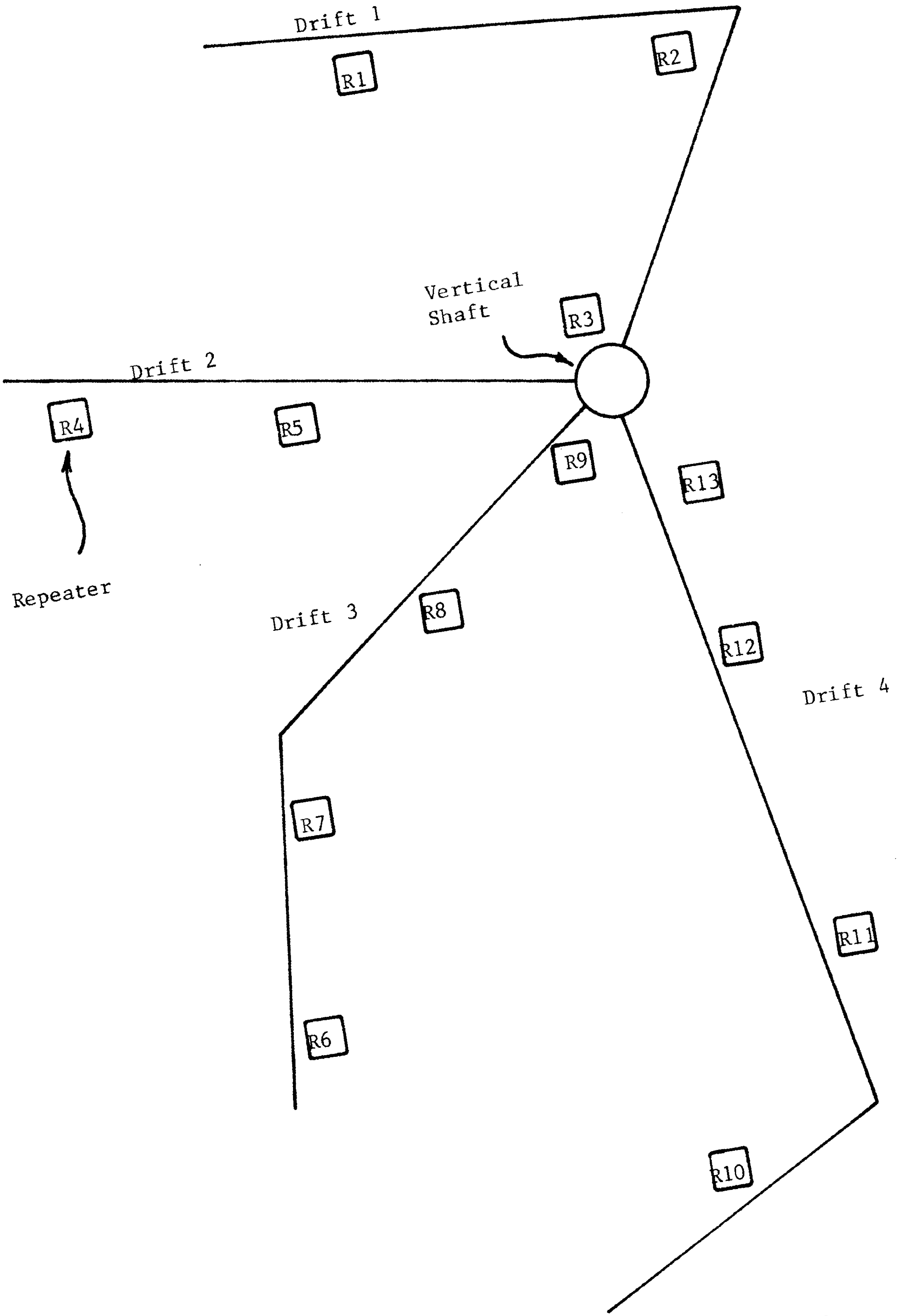


Figure 22 Top View- Mine with Repeater System

Expected Location Resolution

Locating trapped miners in deep metal/non metal mines is an extremely difficult and complex problem, and with the location schemes described, a precise location would be virtually impossible. However, these schemes do offer promise in (1) detecting the presence of a trapped miner or miners on a particular level of the mine, and (2) providing a general location as to his whereabouts based on the number and location of repeaters that respond to the manpack transmission and the relative strengths of their received signals. In those mines whose conductivity depth products are such that wireless uplink transmission is possible directly, the location can be determined in the conventional manner by searching for an omnidirectional null in the horizontal magnetic field at the surface. Generally it is possible to determine location to better than 10% of the overburden depth using this technique.

5.2 Downlink Communications

It is assumed that wireless downlink communications will be achievable at any mine in the United States by virtue of the fact that a high power source could be made available to drive high levels of audio current into long grounded antennas on the surface or into large area loops. This assumption is supported by field results obtained by Westinghouse personnel at more than 25 mines where downlink voice communications could always be achieved with power levels on the order of 100 watts, even to depths as great as 5000 feet. With the miners some day being equipped with combination ULF transmitter/ voice receivers, the downlink communications will offer a new dimension to the location process. That is if the miner can intelligently key his transmitter in response to questions by the surface rescue crew, he could provide the surface with whatever knowledge he may have about his location of entrapment.

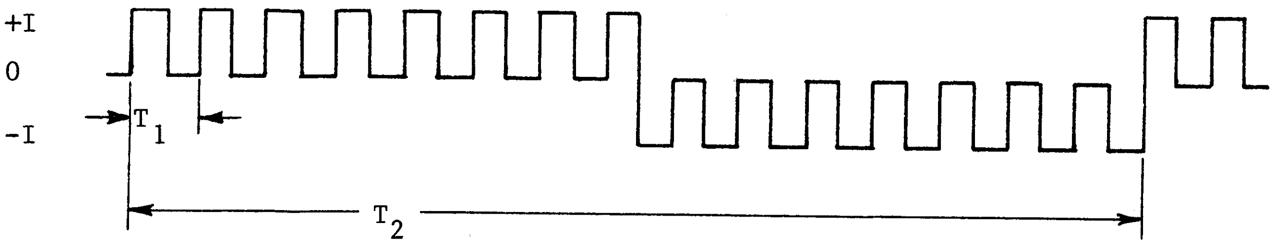
5.3 Trapped Miner Location by Direct Through the Earth Transmission

Up to now, we have considered, for extremely deep mines, systems which utilize the existing USBM coal mine trapped miner transmitter operating at frequencies 1000 Hz - 3000 Hz as a first link of a repeater chain. The trapped miner signals would be relayed from the region of entrapment to the surface via a horizontal path to the shaft and from the shaft to the surface by a hoist communications system. From field data obtained on this program to date, this approach will work. However, there is some question as to the cost effectiveness and optimization of this approach.

The following discussion describes a new concept for a system which is designed to perform effectively in locating trapped miners in the deepest mines of the United States and requires only a slight modification of the existing manpack transmitter system with no additional underground equipment. In the proposed system, most of the added sophistication in the total system is concentrated in the surface receiving equipment and therefore has little impact on system cost or mine acceptance, since few, if any, mines would be required to have this equipment.

System Concepts

- Utilize a wire grid network of receiving antennas on the surface to completely encompass the area of possible entrapment. Use wire lengths approximately equal to the depth of the mine. (If this is not practical, use wire lengths at least one half of the mine depth.) Connect the terminals of each antenna to a different channel of a multichannel discretely tunable synchronous detection receiver. (Deployment of the wire grid receiving network would take place as soon as the mine emergency is identified.)
- The underground manpack transmitters will be designed to transmit signals on a 50% duty cycle with the following waveform configuration:



The above waveform will contain energy primarily at two fundamental frequencies $1/T_1$ and $1/T_2$. (e.g. $T_2 = 100\ T_1$ and thus $f_1 = 100\ f_2$).

The low frequency fundamental frequency will be used for synchronous detection of through-the-earth uplink signals while the high frequency tones superimposed thereon will be used for horizontal transmission of signals to a multichannel receiver with a broadband loop and preamp lowered down the shaft.

This type of transmitting configuration for trapped miner detection, identification and location has the following advantages.

- Utilizes simple low cost equipment underground carried by the individual miner.
- Obviates the need for expensive cabling, telemetry, repeaters and receivers.
- Greatly minimizes or eliminates the maintenance requirement for underground systems.
- Simultaneously provides a low frequency signal for through the earth uplink (i.e. 10 Hz-30 Hz) and an intermediate frequency (1000 Hz - 3000 Hz)* signal for sidelink level identification.
- Sidelink detection and level identification is accomplished by lowering broadband antenna/preamp down the shaft.

Location determination is accomplished by synchronously detecting and comparing low frequency signals (10-30 Hz) received on each element of the orthogonal network of horizontal wire antennas. By using long wire receiving antennas, on the surface and loop antennas underground, we can effectively approach electromagnetic coupling characteristics which vary as inverse distance $(1/z)$ rather than $(1/z^3)$ as is the case with dipole transmitting and receiving antennas. Also, by using synchronous detection, with an integration period of 10 seconds, we effectively obtain a signal to noise improvement of $10 \log (25/.1) = 24$ dB over that of the existing location receiver, which has a 25 Hz effective bandwidth.

The identification of the trapped miners' horizontal location is determined roughly by comparing the signal amplitudes of each element of the receiving array. For a vertical magnetic transmitting dipole (horizontal loop deployed by a trapped miner) the relative electric field pattern will look approximately as shown in Figure 23 for the different mine depths represented. This figure is based on a free space assumption, which is only an approximation at frequencies in the 10 Hz - 30 Hz range at conductivities of $\sigma = 10^{-2}$ mhos/m. The X,Y coordinates of the trapped miners location is determined by the projected null locations as observed by plotting the amplitudes of received signals from each of the receiving antennas.

Likewise the miners' vertical location can be identified by lowering the intermediate frequency receiver down the shaft, and looking for the level which produces the greatest signal amplitude at a frequency exactly equal to 100 times that of the low frequency detected on the surface.

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* The intermediate frequency (1000 Hz - 3000 Hz) could possibly be much greater. Recent studies by another contractor, as yet unpublished, have shown that MF communications (300-3000 kHz) offers a viable alternative to in-mine communications.

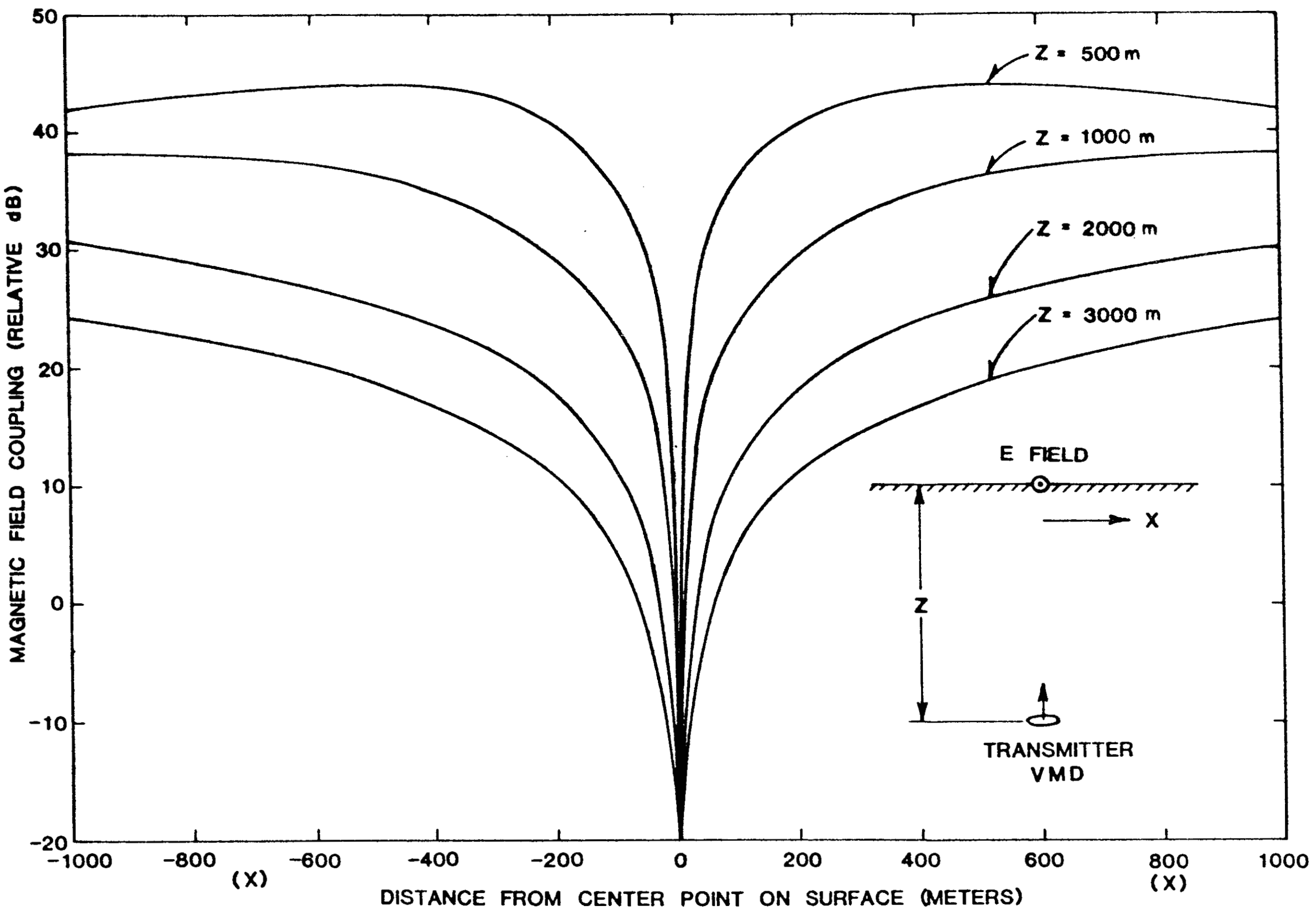


Figure 23 Relative Induced Voltage in Long Horizontal Wire Antenna from Vertical Dipole Transmitter

6.0 FIELD TEST PROGRAM

Two series of field tests were conducted on this program: (1) Mine Characterization Tests, and (2) Communications and Propagation Tests. A total of seven mines were visited in all, six of which were visited for both sets of field tests.

6.1 Mine Characterization Summary

The objective of Task II was to visit six (6) mines considered to be representative of various metal/non metal environments. The purpose of the visit was to measure the parameters relevant to electromagnetic detection and location of, and communication with trapped miners. Testing was performed during these visits to determine the degree of applicability which coal mine trapped miner technology has to metal/non metal mines. The parameters and observations gathered at the six mines were used to formulate the design specifications for specific items of location-communication hardware.

The parameters measured at each mine site included the following:

Overburden

Conductivity (surface and subsurface)

Surface EM noise

Subsurface EM noise.

Observations of the following parameters were also made:

Mining characteristics (entry type, ore type, etc.)

General geological relationships

Distribution of metallic conductors (rails, pipes, cables, etc.)

Mine depth and lateral extent

Environmental factors (humidity, temperature, gasses, and corrosives, dust, etc.)

Topography and ground cover.

Conductivity and noise measurements were made using existing equipment configured as described in Figures 24 and 25 and pictorially in Figures 26 and 27. Other information was obtained during the on-site visits, from appropriate mine personnel or from existing data bases (such as USGS and USBM libraries, previous USBM contract results, local geological societies and others).

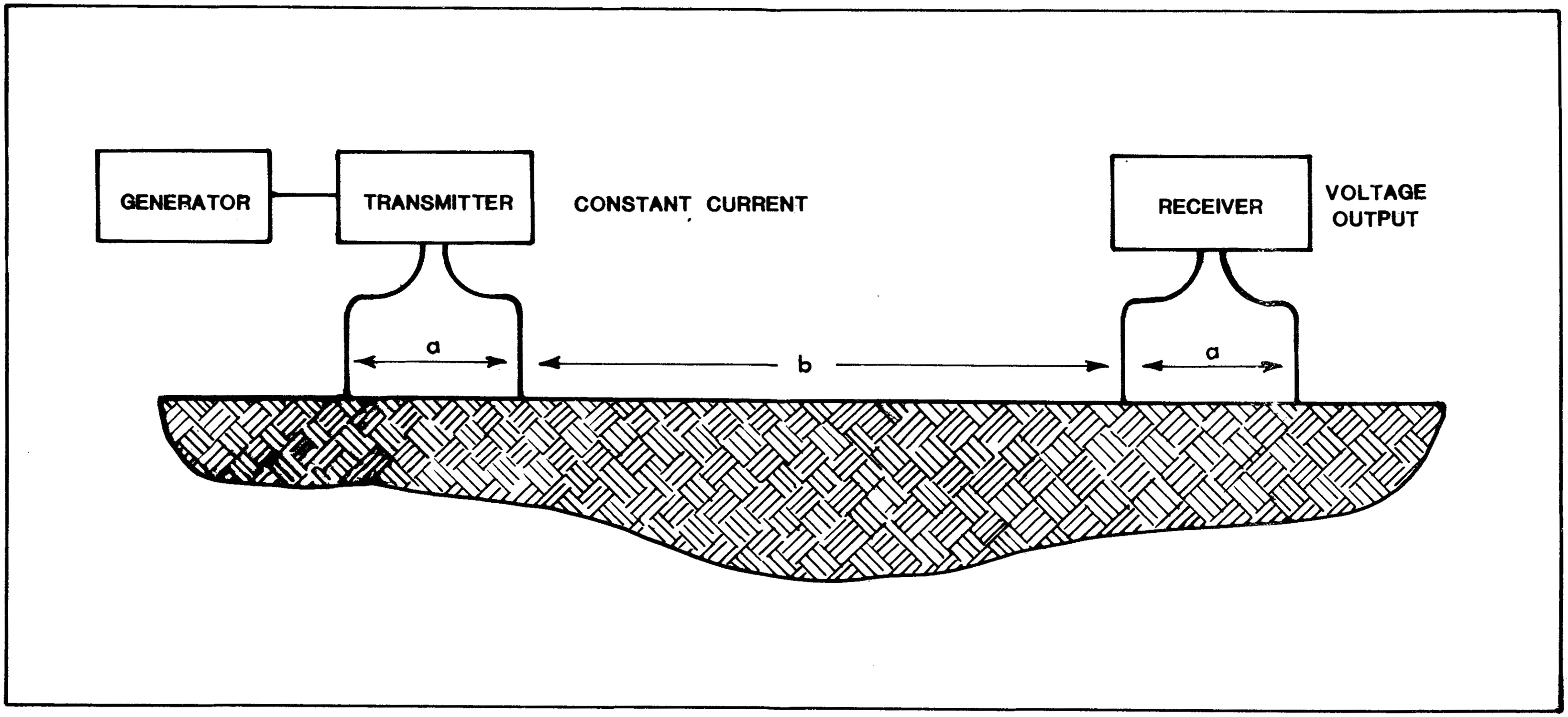


Figure 24 Block Diagram of Conductivity Measurement System

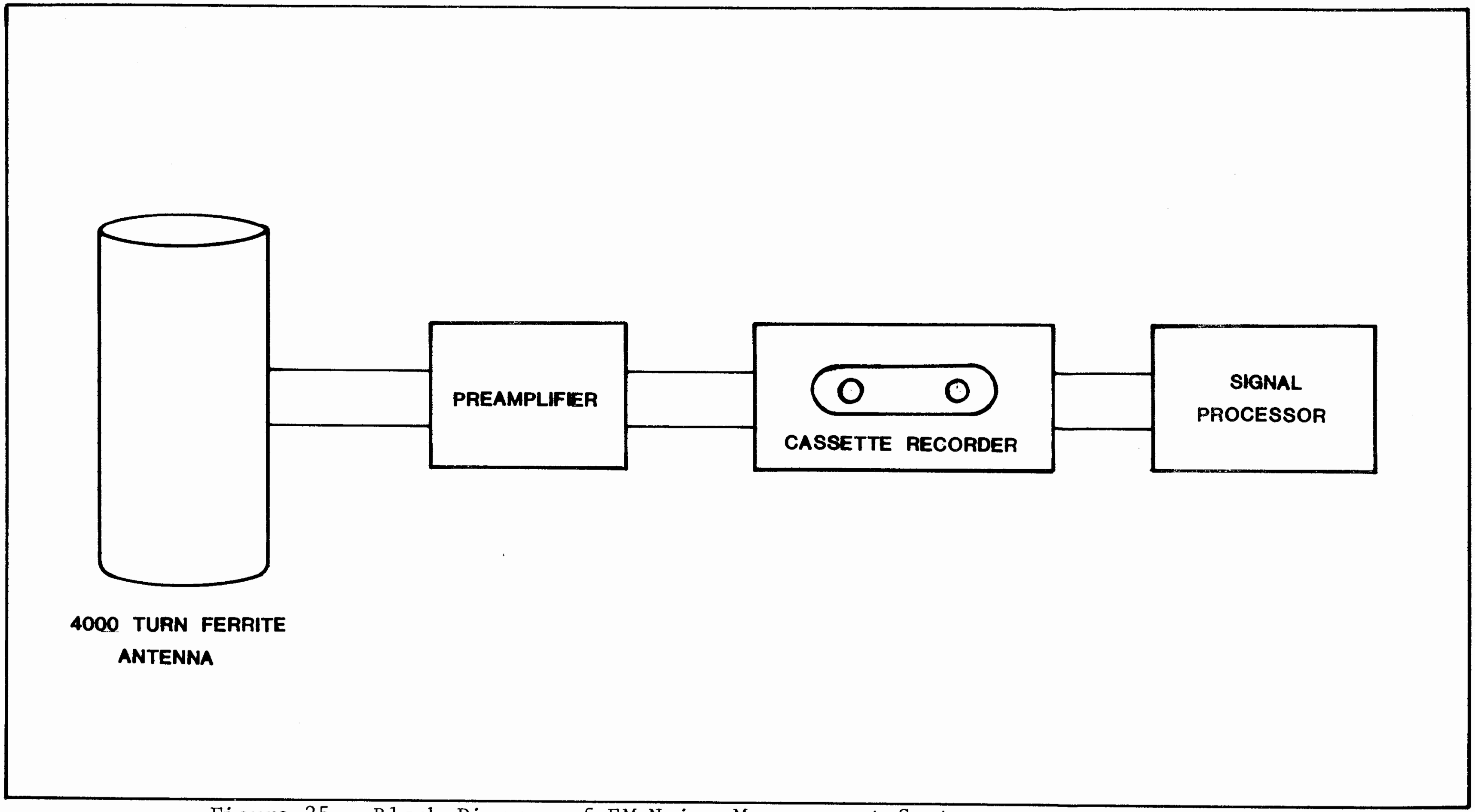


Figure 25 Block Diagram of EM Noise Measurement System

Figure 26 Conductivity Measurements - Ozark Mahoning Mine, Rosiclare, Illinois

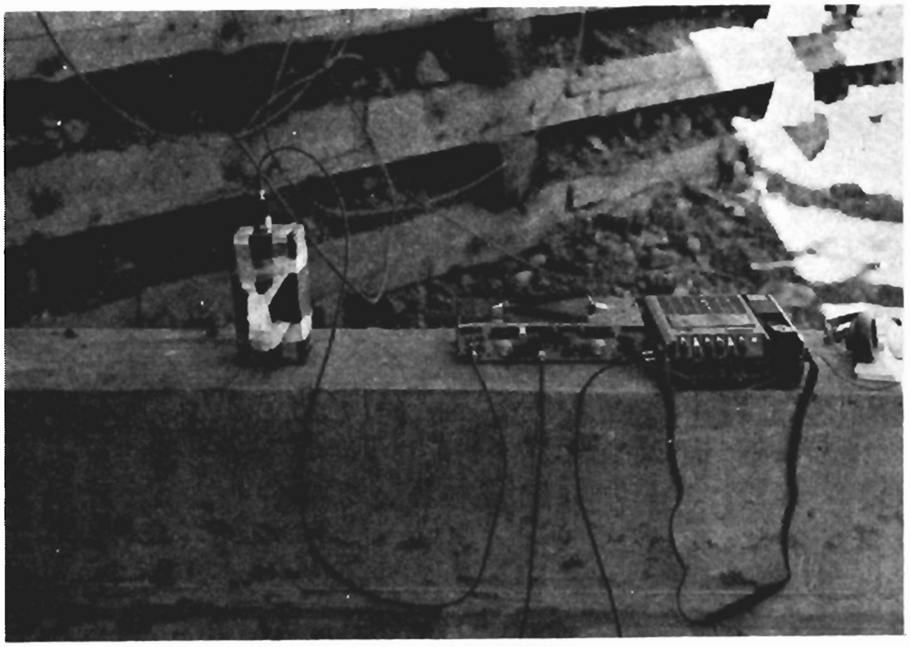


Figure 27A Underground Noise Measurements Set-up, Henderson Mine

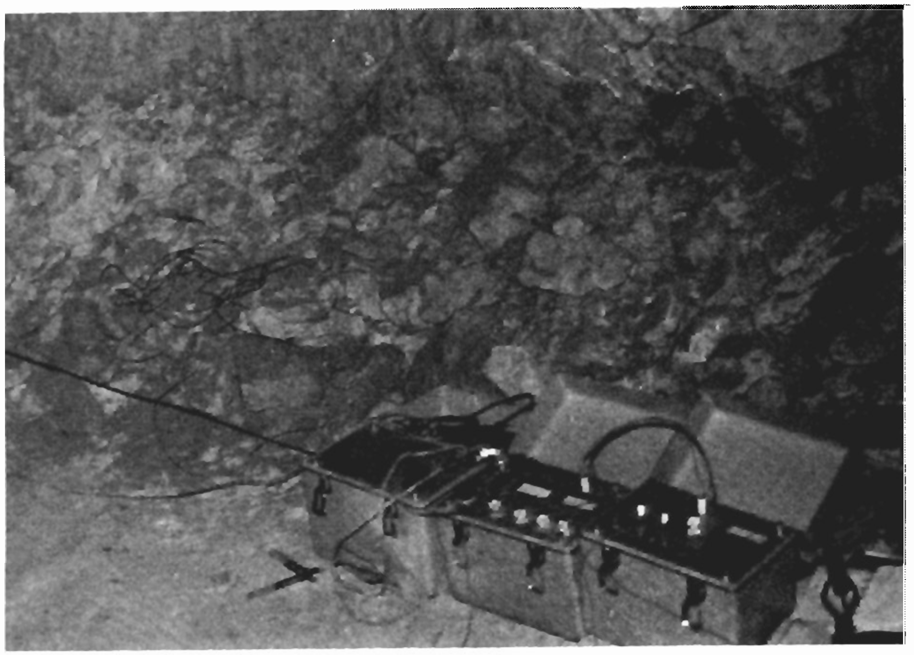


Figure 27B Underground Conductivity Measurements, Henderson Mine

Conductivity Measurements

In order to fully evaluate the effects of the conducting mine overburden on uplink and downlink electromagnetic propagation, it is necessary to know something about the layering structure and/or any anomalous structures such as faults, dikes, or mineral veins in the mine overburden. A good method to examine overburden electrical characteristics is to make surface conductivity soundings. Surface conductivity soundings of the overburden are obtained by transmitting a known current (I) (either dc or commutated low frequency ac) into the ground through a pair of ground electrodes and measuring the induced voltage (V) response between another pair of ground electrodes located some distance away. This is shown in Figure 24. The mutual impedance (Z) between the two pairs of electrodes is given by $Z = \frac{V}{I}$ ohms. The measured mutual impedance, in conjunction with a known electrode geometry, yields a value for apparent conductivity (σ). Expressions for determining apparent conductivity from mutual impedance measurements can be found in any good geophysics text such as Keller and Frischknecht, (18).

By successively expanding the spacing between the current electrode pair and the voltage electrode pair, the resulting measurements yield information from increasing depths in the earth. Measurements of this sort will yield the sequence of high and low conductivity layers in the subsurface section. For example, a soil layer overlaying gravel or bedrock gives a distinctive sequence of conductivity readings and can be used to estimate the depth to the various layer interfaces as well as the individual electrical characteristics of each layer. A systematic method for interpreting conductivity soundings in terms of equivalent earth layers has been developed. In many cases a knowledge of the conductivity or resistivity layering structure is sufficient to produce accurate predictions of propagation characteristics through the overburden.

In order to evaluate the possible effects of the mineralized zone within a mine on the electromagnetic propagation characteristics, it was deemed necessary to make conductivity measurements within the mine. In order to do this, a battery operated conductivity unit was borrowed from Melvin Lepper of the USBM-DMRC. This unit proved very effective for rapid underground measurements in areas where 110 V power was not available.

Noise

Electromagnetic noise waves vary significantly depending on a number of factors including mine power type and distribution, proximity to power sources, season, time of day, and others.

On the surface, the background noise and interference in the frequency range of interest is made up largely of atmospheric noise from world wide thunderstorms and man-made interference from power lines. Man-made interference occurs at known discrete frequencies (60 Hz and its harmonics) and can usually be avoided in narrowband receiving systems by judicious choice of operating frequency, highly selective bandpass filters and deep notch filters tuned to the interfering frequencies. However, atmospheric noise is distributed across the entire frequency band and cannot be eliminated in this manner. Consequently, it very often constitutes the absolute limitation in the signal to noise performance of low frequency receiving systems such as the ones used by the Bureau of Mines for uplink communications.

Noise measurements were made both on the surface and underground using the configuration in Figure 25. The ferrite loop antenna was usually oriented in two mutually perpendicular horizontal positions and vertically at each measurement site so that a relatively complete picture of noise distribution could be made. At each mine, measurements were made at suspected noisy and quiet locations above and below ground.

Noise data were recorded through the preamplifier and onto magnetic tape cassettes. Playback was into a Tektronix WDI 1221 signal processor (see Figure 28). Processing included removal of the effects of the recording response function, performing a Fast Fourier Transform and plotting the spectrum in a log frequency format. Some typical noise data are shown in Figure 29. The upper portion is the time domain signal, the bottom, the frequency domain amplitude spectrum. It is interesting to note that in this particular example, which was the worst case of electromagnetic noise measured during Task II, the dominant frequency is on the order of 3 kHz. This could represent a harmonic coupling resonance for the particular conductors, transformers and other hardware near the measurement site, or it could have been produced by ac machinery operating nearby. Other noise plots are contained in the individual site reports submitted previously on this contract.

Field Test Results

Field tests were conducted at six mines. These are shown in Table 4 along with some key information. Complete site reports were prepared and submitted earlier on this contract. Conductivity results are shown in Figure 30. Conductivity measurements are very important for system design in several cases. At the Henderson Mine, the effects of the sulfide halo, detected by the conductivity survey, indicates a possible high attenuation zone between the mine and surface. Likewise, at the Big Island Mine, a high conductivity member of the overlying Green River or Uintah Formations could present a problem for through the earth communications with the existing coal mine system.

The noise data are in good agreement with measurements made during other mine characterization programs. One obvious difference is the seemingly larger variety of uses of electrical power at metal/non metal mines, and also the lack of large scale distribution systems as found in coal mines. Generally speaking, metal/non metal mines are noisier on the surface and quieter underground than coal mines.

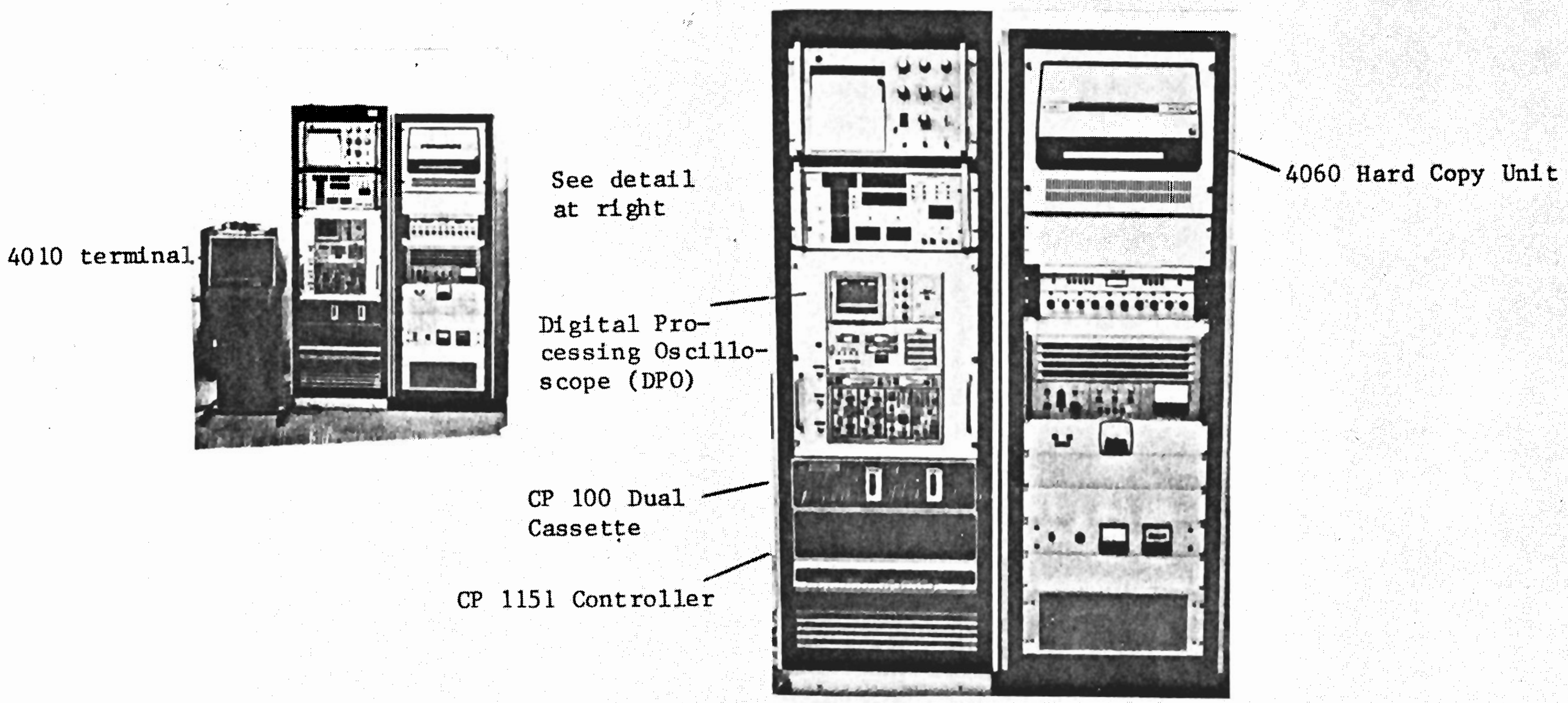


Figure 28 Photograph of WDI 1221 System

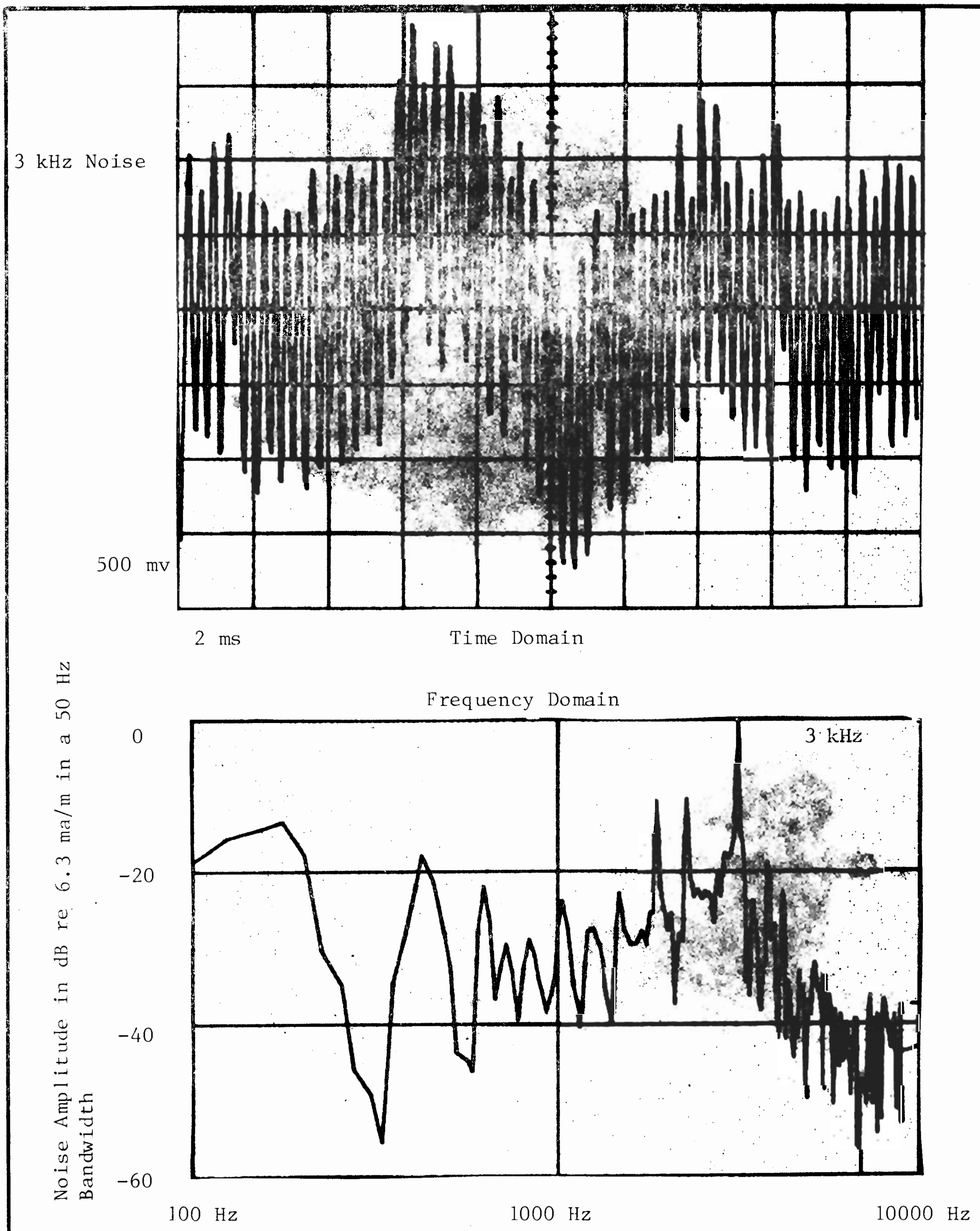


Figure 29 Sample of EM Noise Measured During Task II

TABLE 4

SUMMARY OF MINE TESTS

MINE	LOCATION	DEPTH OF TESTS Feet	CONDUCTIVITY mho/m		NOISE RESULTS μA/m	
			Surface	Subsurface	Maximum	Minimum
1. Henderson Molybdenum	Empire, Colo.	2300	7×10^{-4}	3×10^{-3}	1340^{1a}	10^{1b}
2. Homestake Gold	Lead, South Dakota	2300, 4100	1×10^{-4}	1×10^{-3}	5140^{2a}	0.4^{2b}
3. Fletcher Galena	Bunker, Missouri	1000	1.5×10^{-3}	1×10^{-2}	421^{3a}	10^{3b}
4. Ozark Mahoning Fluorspar	Cave-in-Rock, Ill.	550	7×10^{-4}	7×10^{-3}	3500^{4a}	10^{4b}
5. Big Island Trona	Green River, Wyo.	850	5×10^{-3}-5×10^{-2}	2×10^{-2}	31090^{5a}	40^{5b}
6. Idarado Sulfides	Ouray, Colo.	2900	1×10^{-3}	5×10^{-3}	19^{6a}	7.9^{6b}
7. International Salt	Avery Island, La.	500, 770, 880	9.3×10^{-2}	-	Relative Measurements Only	

Footnotes

1a. In #2 shaft house
2a. Near powerline on surface
3a. Underground near #31 shaft
4a. Near powerline on surface
5a. Base of service shaft, above ground
6a. Manhoist replacement orebody (NW-SE orientation)

1b. At end of Urad tunnel
2b. 2300 foot level
3b. Underground near transformer
4b. Near #7 shaft underground
5b. Underground north end of mine
6b. Manhoist replacement orebody (NE-SW orientation)

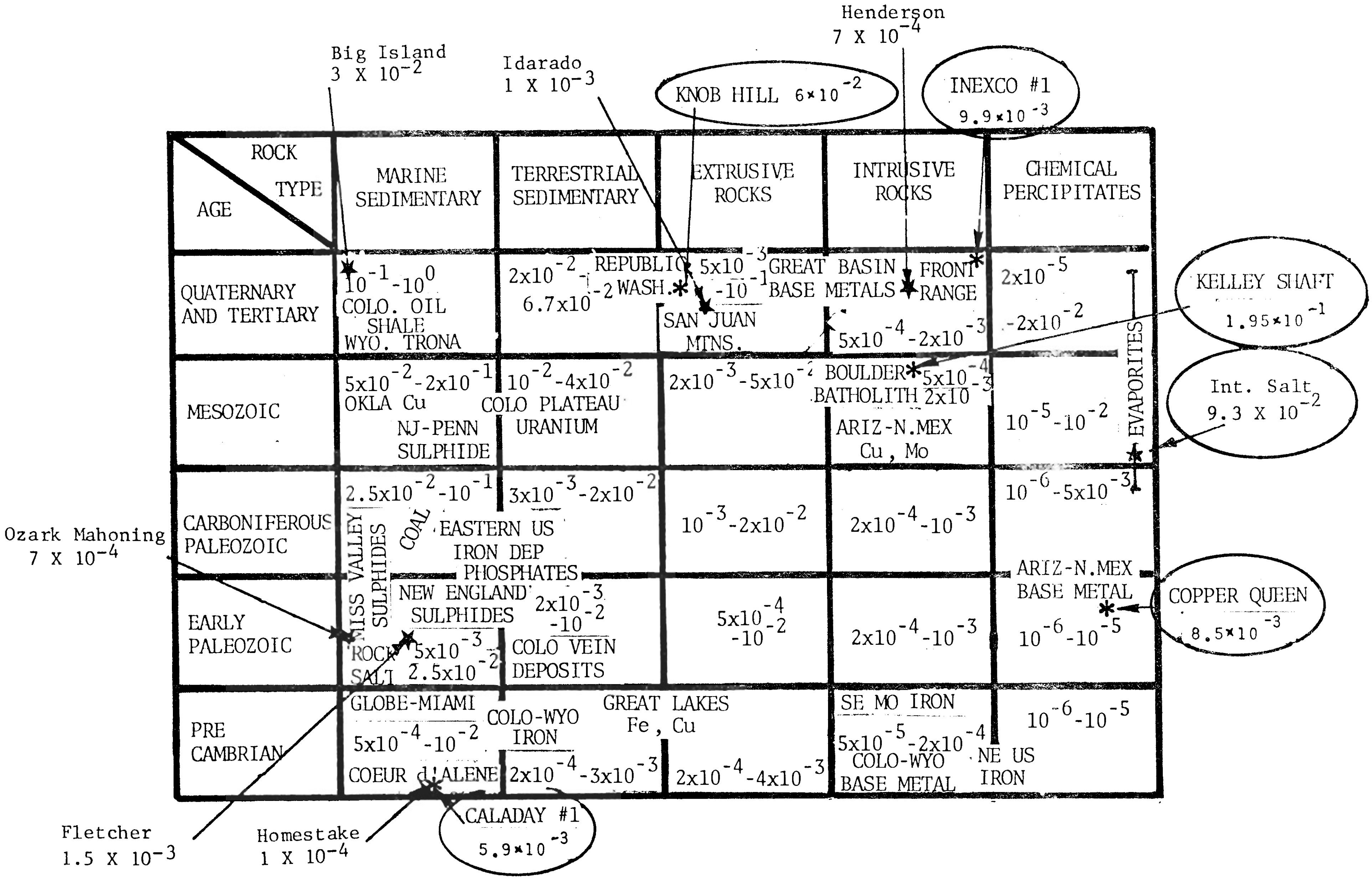


Figure 30 GENERALIZED CONDUCTIVITY RANGES FOR ROCKS AND VARIOUS MINERAL HOST MATERIALS. (SURFACE CONDUCTIVITY MEASUREMENTS)

6.2 EM Propagation Tests

The same mines that were visited for purposes of mine characterization measurements were revisited at a later date to conduct EM propagation measurements. The equipment used for the ULF uplink and sidelink propagation measurements was as follows:

ULF Transmitter, Collins Model PN622-2375 (See Figure 31).
ULF Receiver, Collins Model PN622-2632
Associated Substitution Calibration Equipment (See Figure 32).

For the twisted pair multichannel telemetry test performed in the International Salt Mine, a filter-discriminator as shown in Figure 33 was used.

Narrowband FM voice tests were performed using a Westinghouse 23-channel developmental system with carrier frequencies ranging from 5 kHz to 115 kHz. This system is shown in Figures 34 and 35.

ULF Uplink Measurements

Table 5 summarizes the wireless ULF uplink propagation data obtained at the six metal non-metal mines indicated in the table. Overburden depths range from a low of 135 meters at the Ozark Mahoning Fluorspar Mine to a high of 792 meters at the Henderson Molybdenum Mine. The Homestake Gold Mine had an overburden depth of 2073 meters; however, signals were not detected on the surface at this mine, although they were detected at an intermediate level.

The calculated field strengths based on conductivity measurements obtained earlier were in reasonably good agreement with the measured magnetic field strengths in all cases except at the Homestake Mine. Here the measured field strength for an in-mine uplink path was about 42 dB lower than the expected value based on the conductivity of that particular mine. Barring equipment malfunction as a possible cause for this discrepancy, the only other possible explanation would be that the intervening workings with all their metal rails etc. could have acted as a shield in preventing the propagation of signals through to the upper levels.

In all of the other tests, the received signals were suitable for trapped miner location, even those measured at the Henderson Mine through a 792 meter (2600 ft) overburden. The frequency variation of uplink field strengths measured at the Henderson Mine is shown in Figure 36. The negative transmission loss characteristics observed at the Henderson Mine are undoubtedly caused by the fact that the uplink transmitter was located within 1000 feet horizontal distance from the shaft on the 8100 ft level. This was the furthest possible distance available for equipment deployment. For the Henderson Mine tests, a special Westinghouse developed multifrequency transmitter was used. This transmitter is equipped with a 13 frequency pushbutton controlled synthesizer and a switching amplifier coupled to a 20 turn loop antenna. It

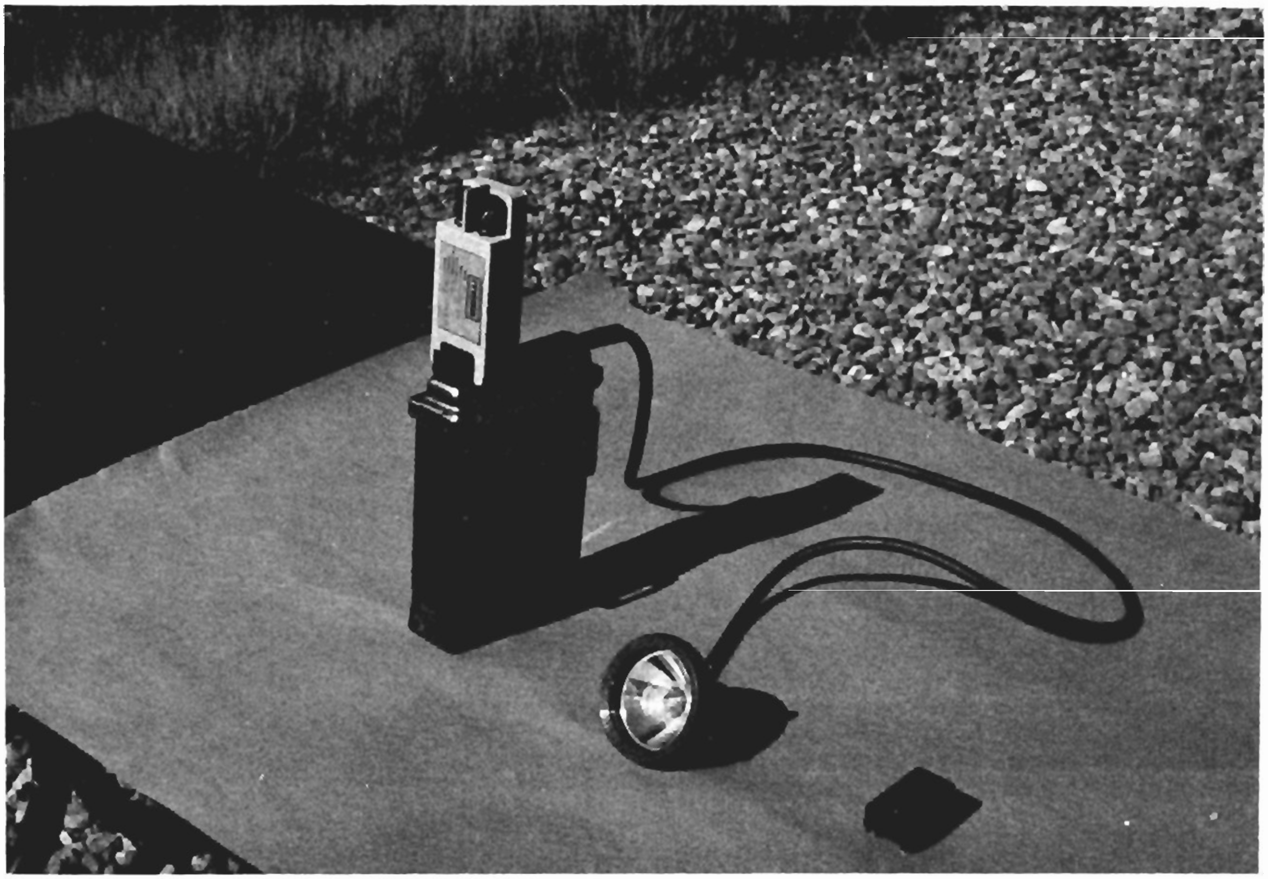


Figure 31 Mine Rescue Transmitter (attached to Cap Lamp Battery)

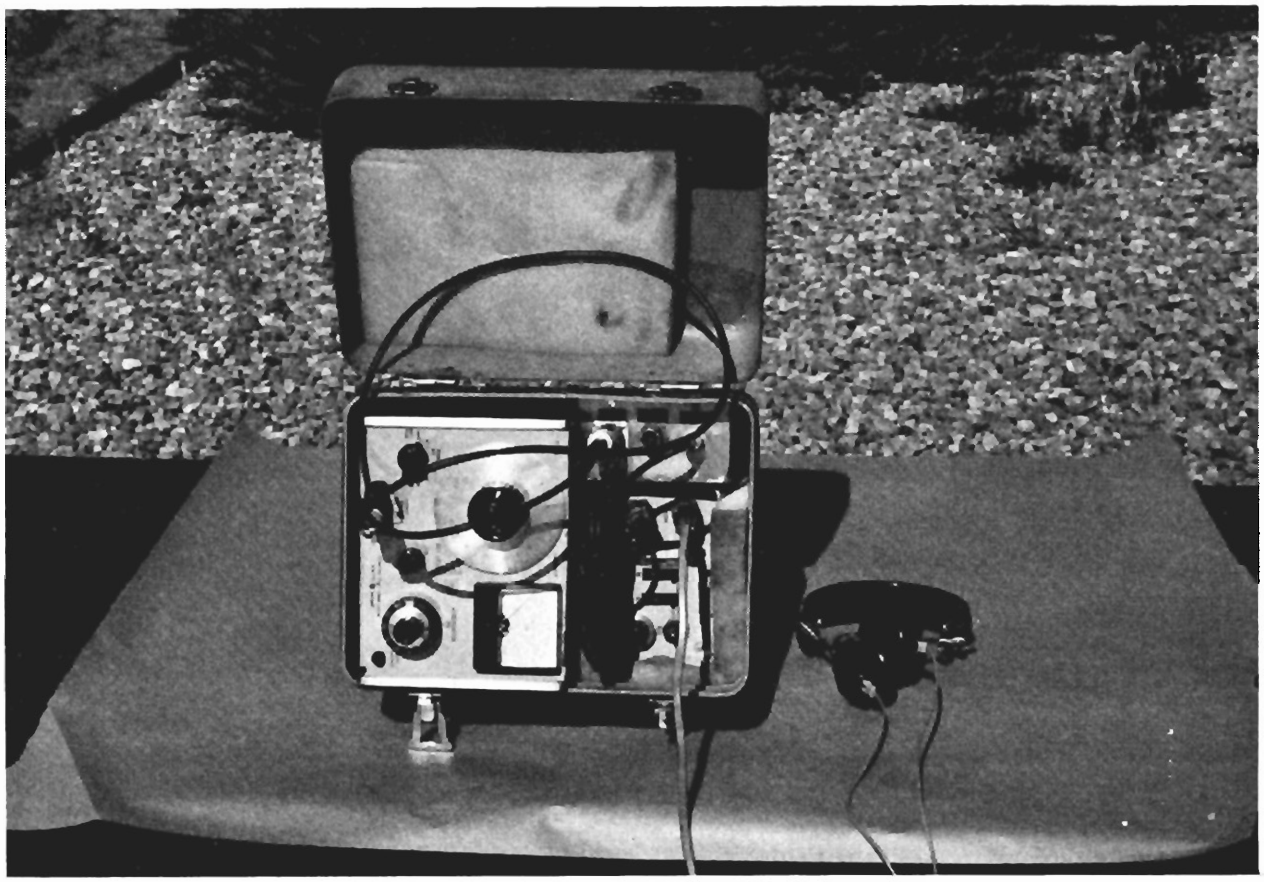


Figure 32 EM Field Measurement Equipment

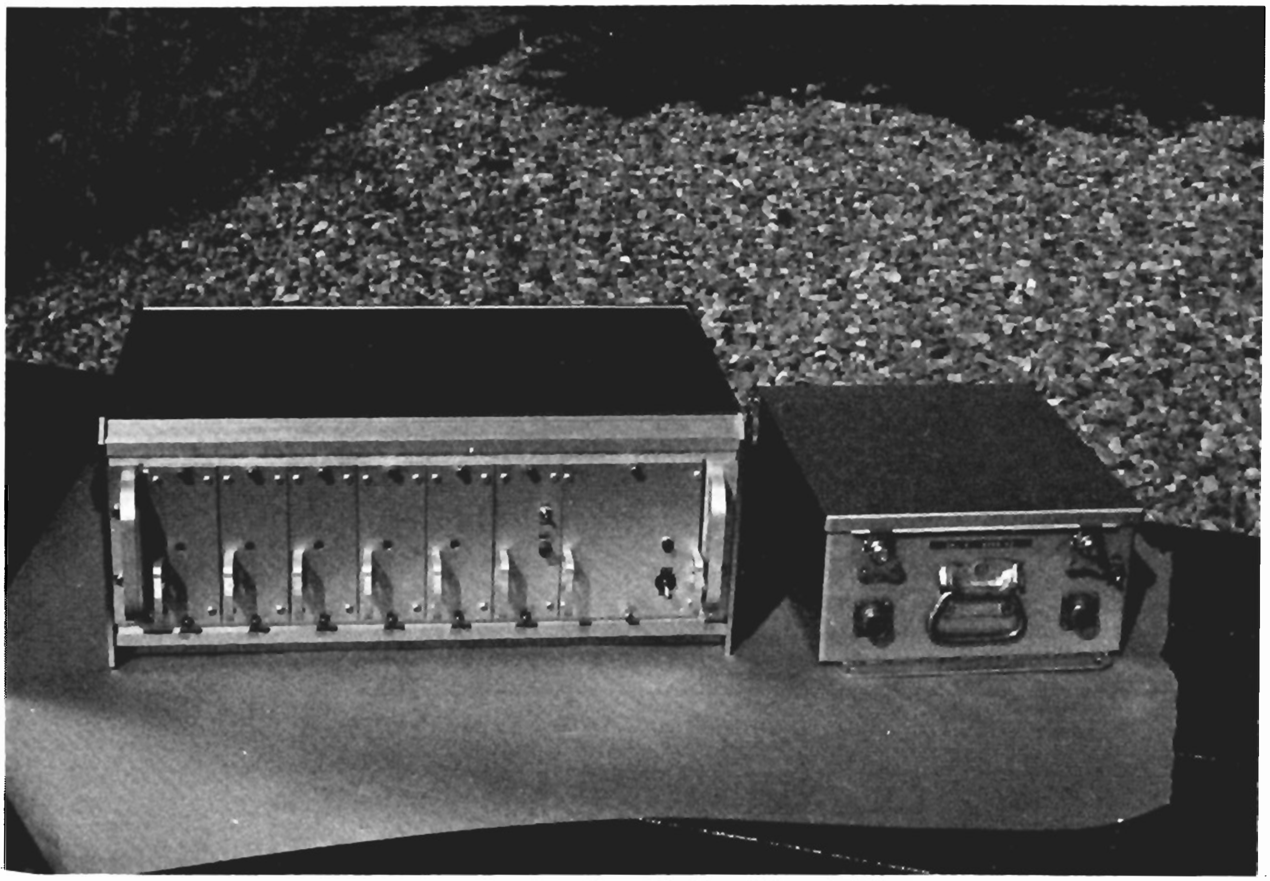


Figure 33 Multichannel FM Telemetry Filter and Discriminator

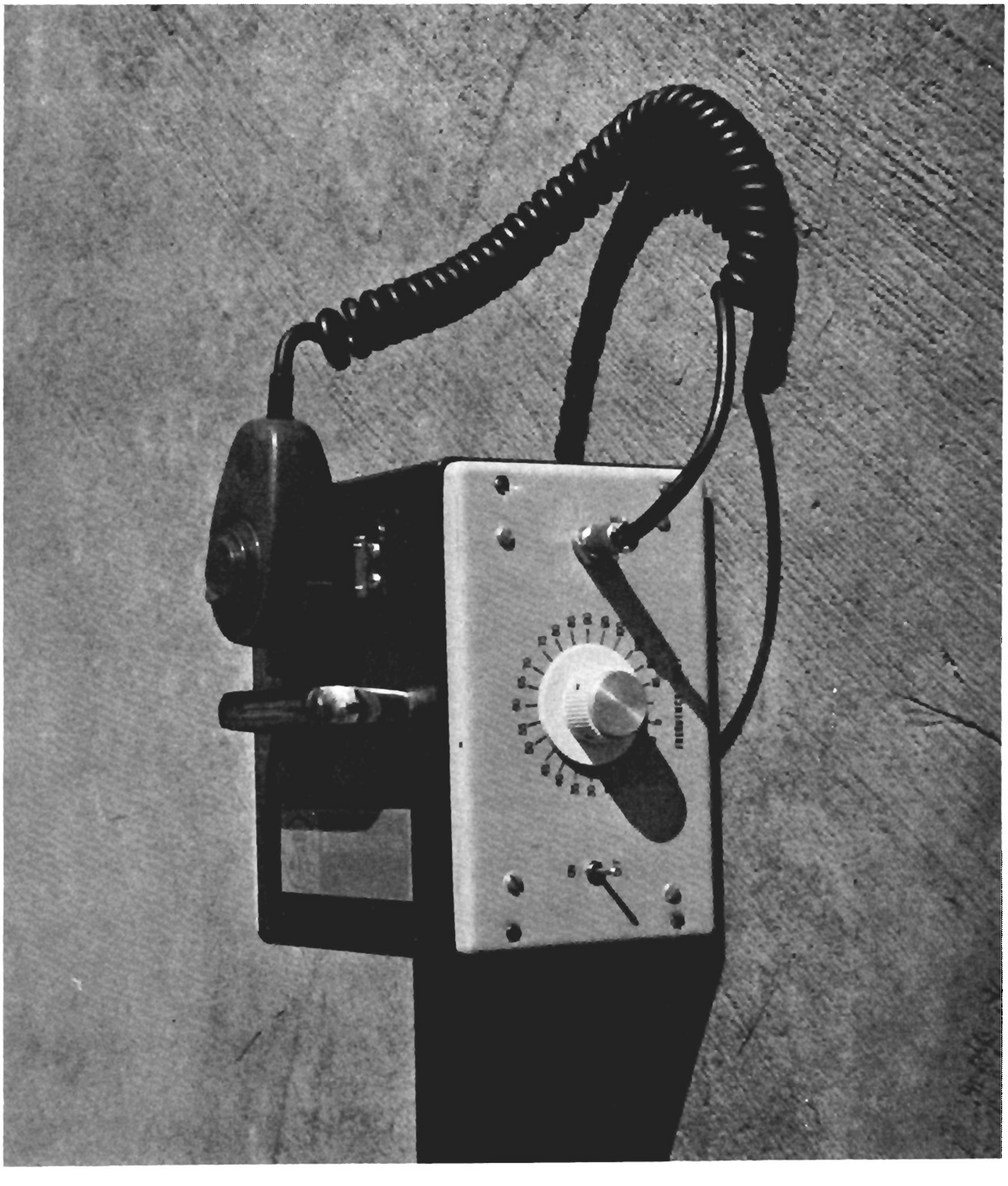


Figure 34 Westinghouse Narrowband FM Transmitter

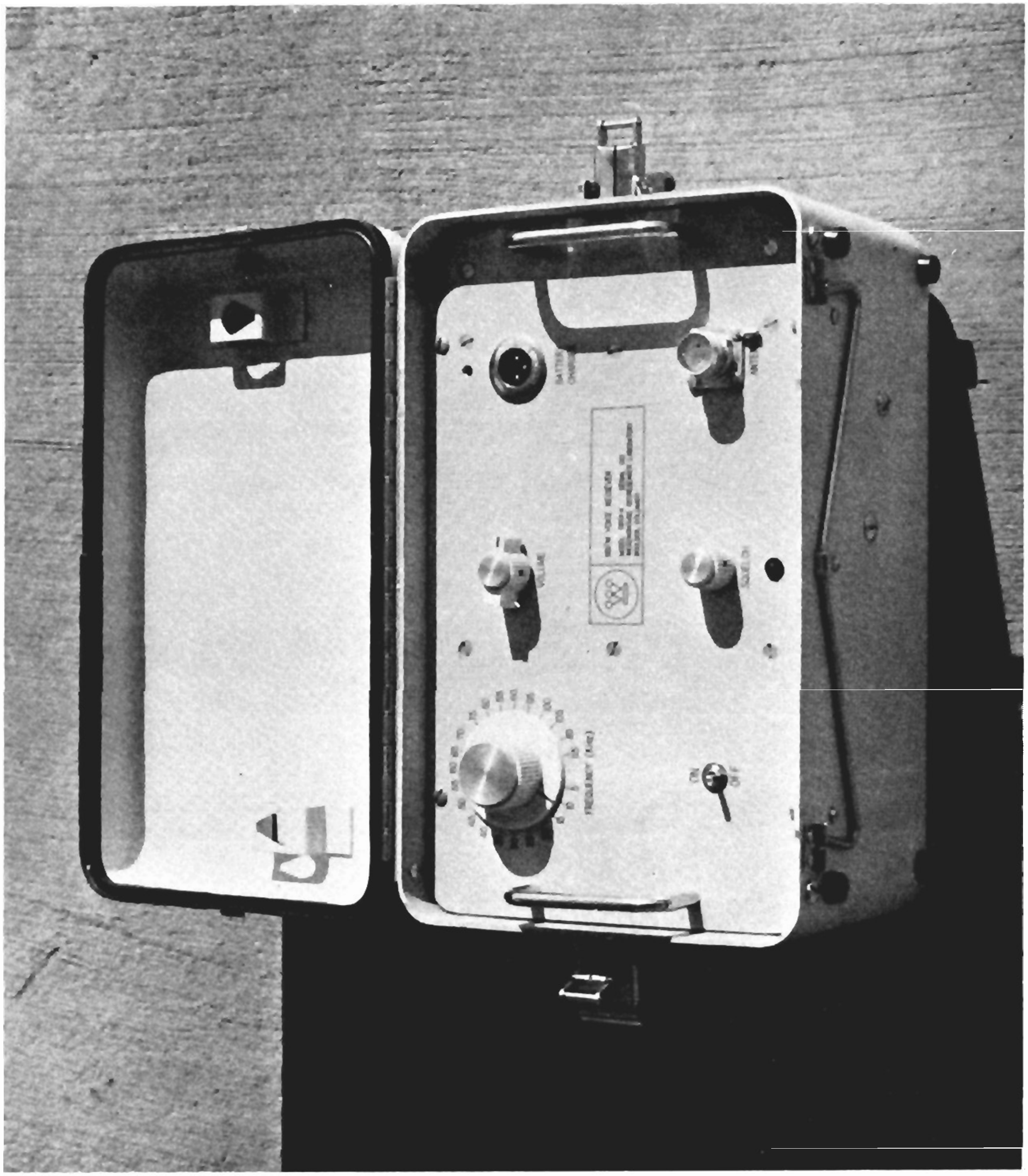


Figure 35 Westinghouse Narrowband FM Receiver

TABLE 5

ULF UPLINK PROPAGATION SUMMARY

Mine	Overburden Depth (z) (Meters)	Frequency f (Hz)	Moment INA $(amp \cdot t \cdot m^2)$	Measured Conductivity (mhos/m) (Subsurface)	Calculated Field Strength μAmp/m	Measured Field Strength μAmp/m	Transmission Loss (dB) rel. to free space field strength
International Salt	152	1050	1988	9.3×10^{-2}	27.4	35.5	8
"		3030	1343	"	3.9	12.6	13.6
Stauffer	257	1050	365	3×10^{-2}	1.12	1.58	6.7
Homestake	183	3030	700	1×10^{-3}	16.9	.133	36.7
Ozark Mahoning	135	1050	1406	1.5×10^{-2}	75.4	47.3	5.7
"		3030	1406	1.5×10^{-2}	55.3	20	13.2
St. Joe (Fletcher)	298	1050	2046	1×10^{-2}	7.07	3.16	11.8
"		3030	2046	1×10^{-2}	3.10	2.67	13.3
Henderson	792	630	1798	3×10^{-3}	.280	2.5	-12.86*
"		750	1679	"	.242	2	-11.51*
"		930	1739	"	.213	2	-11.21*
"		1050	1679	"	.184	1.18	- 6.97*
"		1350	1679	"	.144	.84	- 4.0 *
"		1650	1655	"	.113	.63	- 1.6 *
"		2250	1319	"	.058	.25	4.4
"		2430	1439	"	.056	.35	2.4
"		2730	1319	"	.043	.44	- 0.4 *
"		3030	1079	"	.029	.22	3.8
"		3330	959	"	.022	.44	- 3.3 *

* Negative transmission losses should be treated as transmission gains.

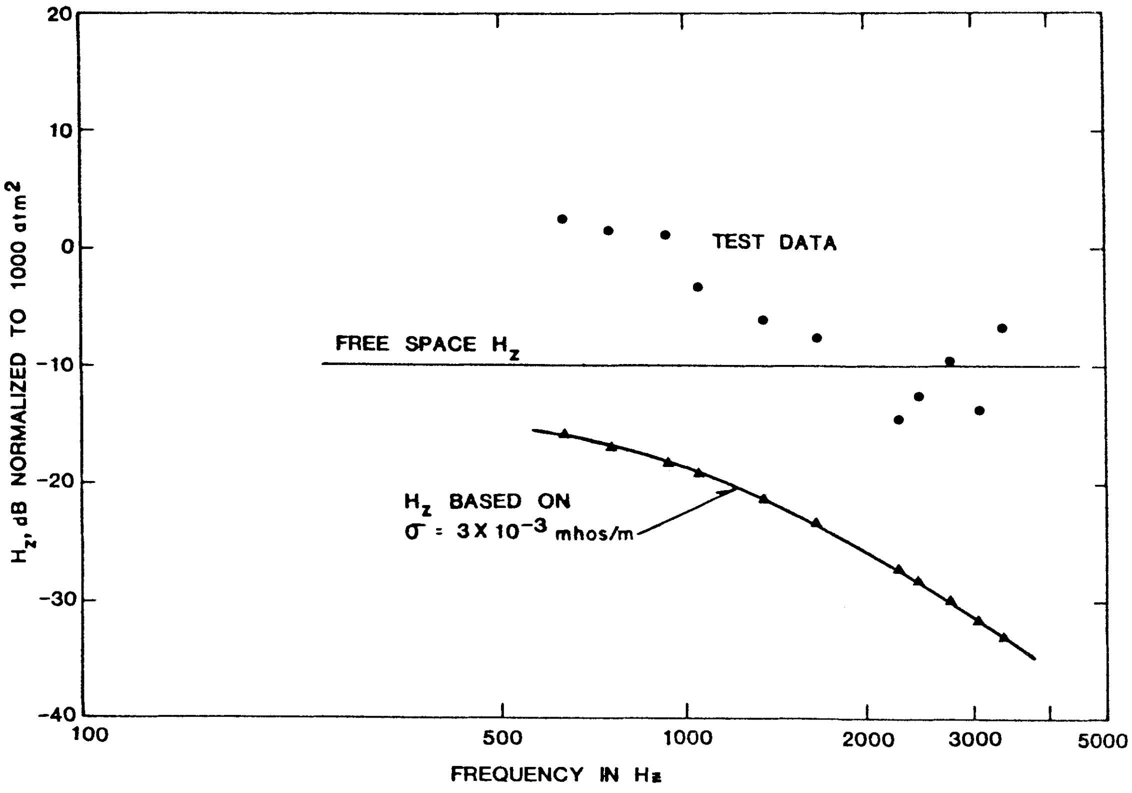


Figure 36 Henderson Mine - Uplink H_z Measurements

is designed primarily to establish a high current moment in a relatively small area. However, even though it is entirely battery operated, it is not portable to the extent that a miner could routinely carry it on his belt while conducting his other tasks.

Figures 37 through 42 show the underground workings at each of the mines visited during the EM propagation test phase of this contract. It is immediately apparent in glancing at these figures how the metal/non metal mine layouts differ from one mine to the next and how they differ from typical coal mines.

Based on the results obtained in these field exercises, the existing USBM trapped miner EM Location System is not adequate, as it now stands, to be effectively used in locating trapped miners in the deeper metal/non metal mines such as Homestake and possibly some of the deep mines in the Coeur d'Alene district of Idaho. However, with relatively minor modifications to the trapped miner manpack transmitter and by replacing the simple analog narrow band receiver with a more powerful signal processing receiver, even the deepest mines can be effectively penetrated with trapped miner location information. A more detailed discussion of this approach is given in the recommendations in Section 8.

ULF Sidelink Measurements

Measurements of ULF sidelink propagation were conducted at 5 of the 6 mines visited during the propagation test phase of this program. The main things to be learned from these tests were: (1) How well and over what distances do ULF and VLF signals propagate horizontally in typical metal/non metal mines. (2) What effect does in-mine conductors, such as pipes, rails, cables, etc., have on ULF and VLF sidelink propagation characteristics.

In a trapped miner location system utilizing the concept of horizontal signal telemetry from the point of entrapment to a shaft location on the same level as discussed in Section 5.1, the importance of studying sidelink propagation characteristics cannot be underestimated. Table 6 summarizes the results obtained at the five (5) mines. Of the 5 mines, three of them (Stauffer, Homestake and Ozark Mahoning) offered the opportunity to deploy the transmitting loop antenna with one side directly beneath an underground water line. At these three mines, the resulting field strengths measured in the drift containing the pipe exhibited EM coupling enhancements on the order of 40-50 dB relative to the calculated free space field strength for that antenna moment.

At the two remaining mines, International Salt and St. Joe Minerals, there was evidence of a much lower level of coupling enhancement, probably due to unavoidable coupling to the pipe network at greater distances from the transmitter. In all cases, the measured fields were rarely less than the free space equivalent value, indicating that the presence of the mine conductors can be effectively utilized to enhance underground ULF propagation, and, when ignored, will in no way be detrimental to the propagation characteristics.

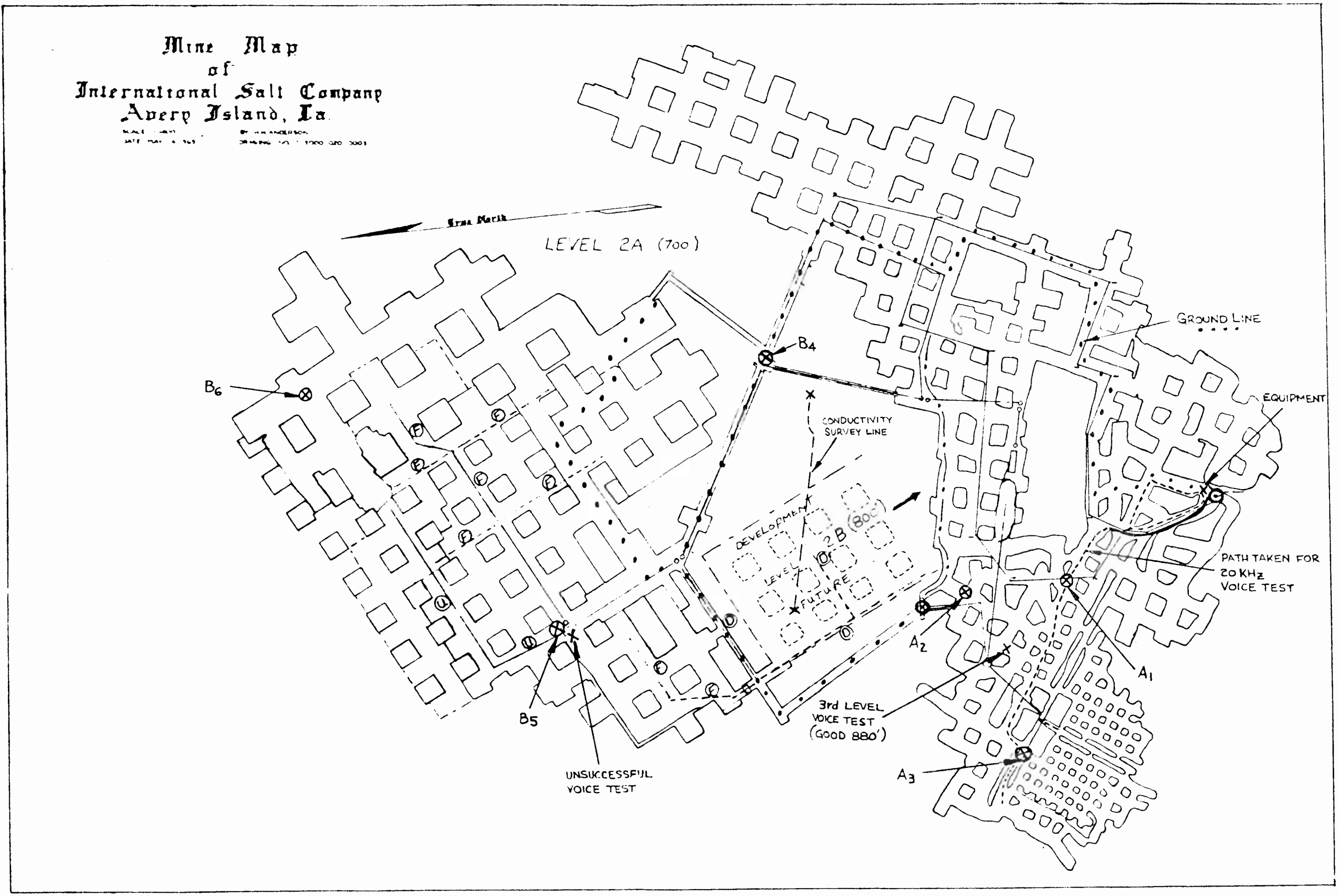


Figure 37 Mine Map of International Salt Mine

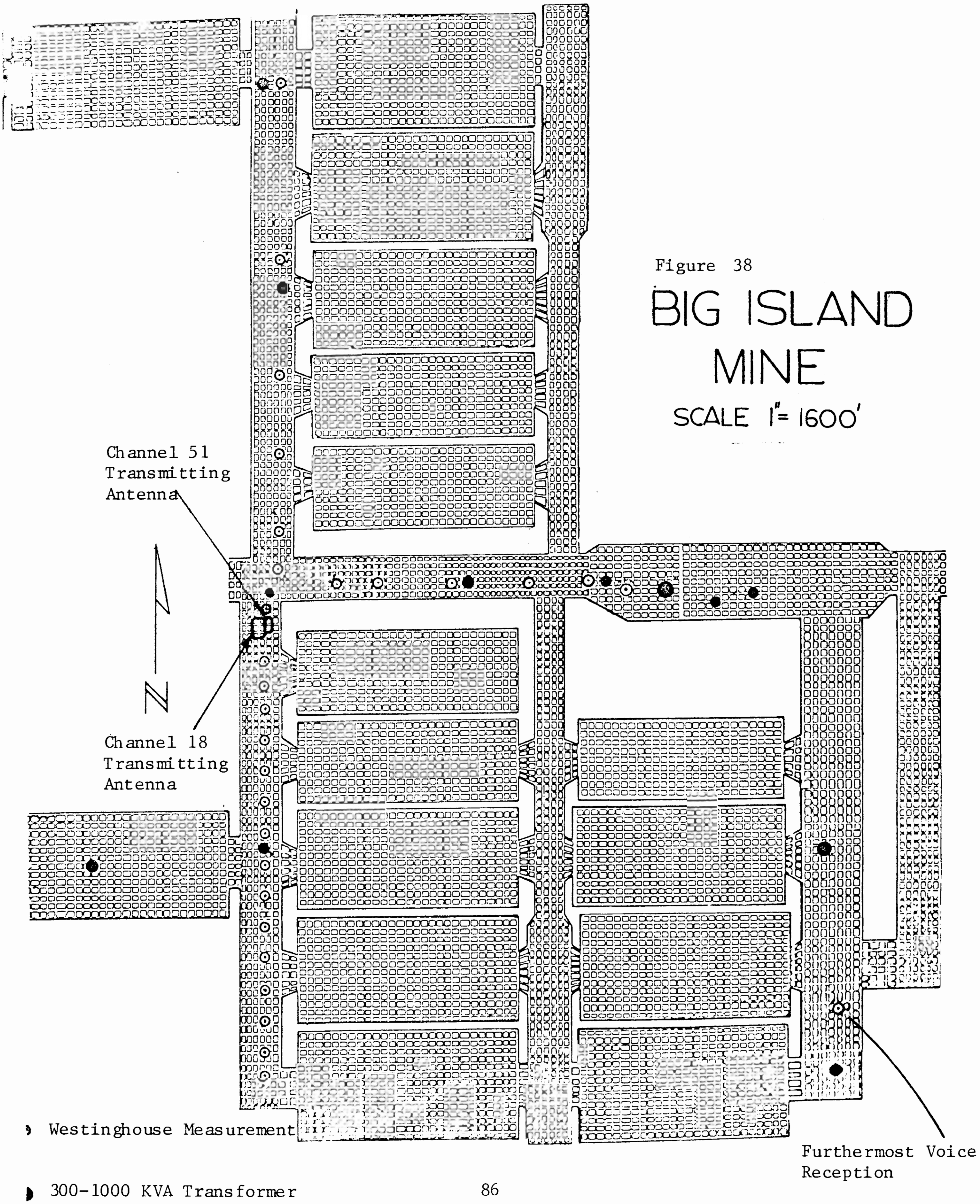


Figure 38

BIG ISLAND MINE

SCALE 1"= 1600'

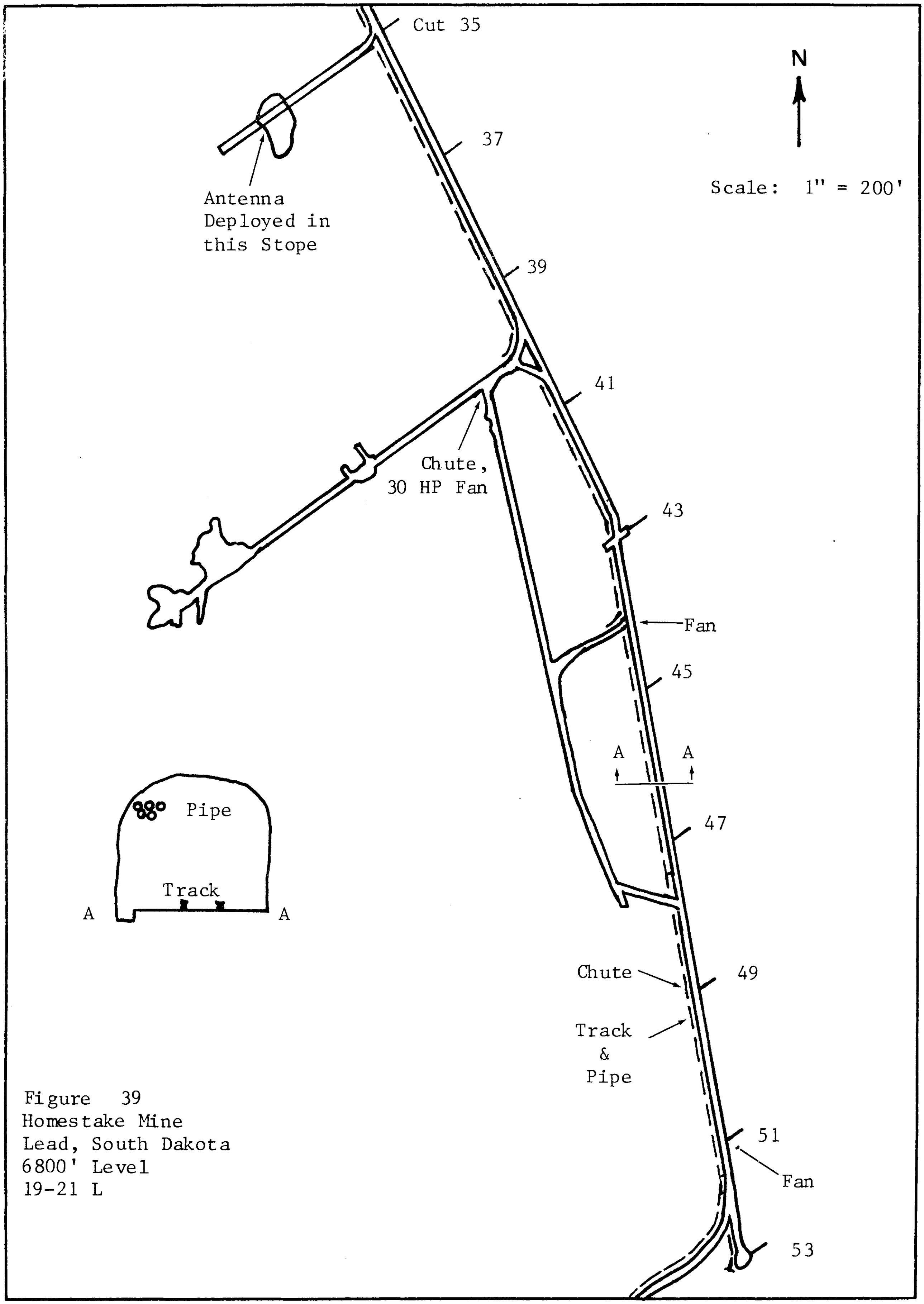


Figure 39
Homestake Mine
Lead, South Dakota
6800' Level
19-21 L

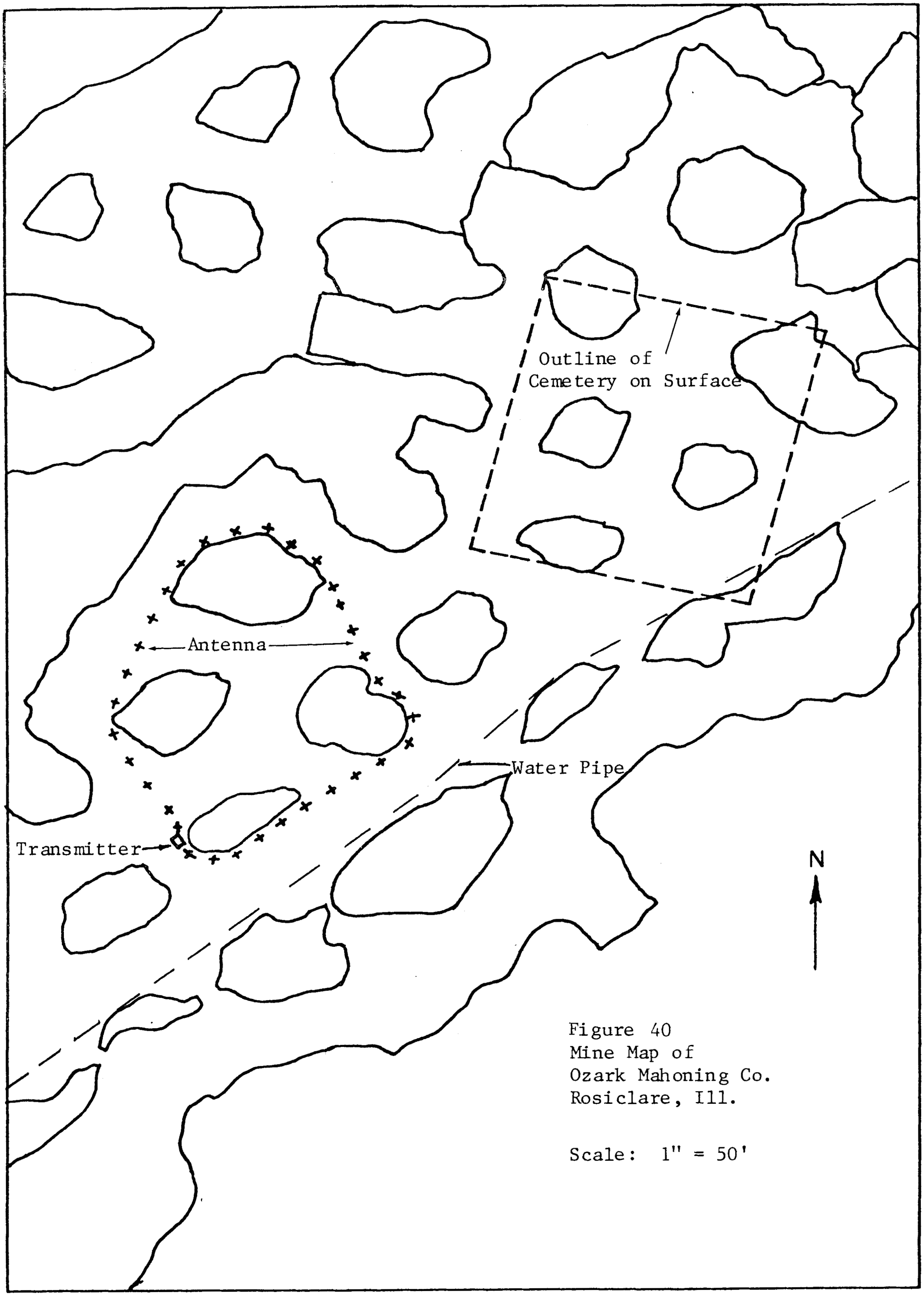


Figure 40
Mine Map of
Ozark Mahoning Co.
Rosiclare, Ill.

Scale: 1" = 50'

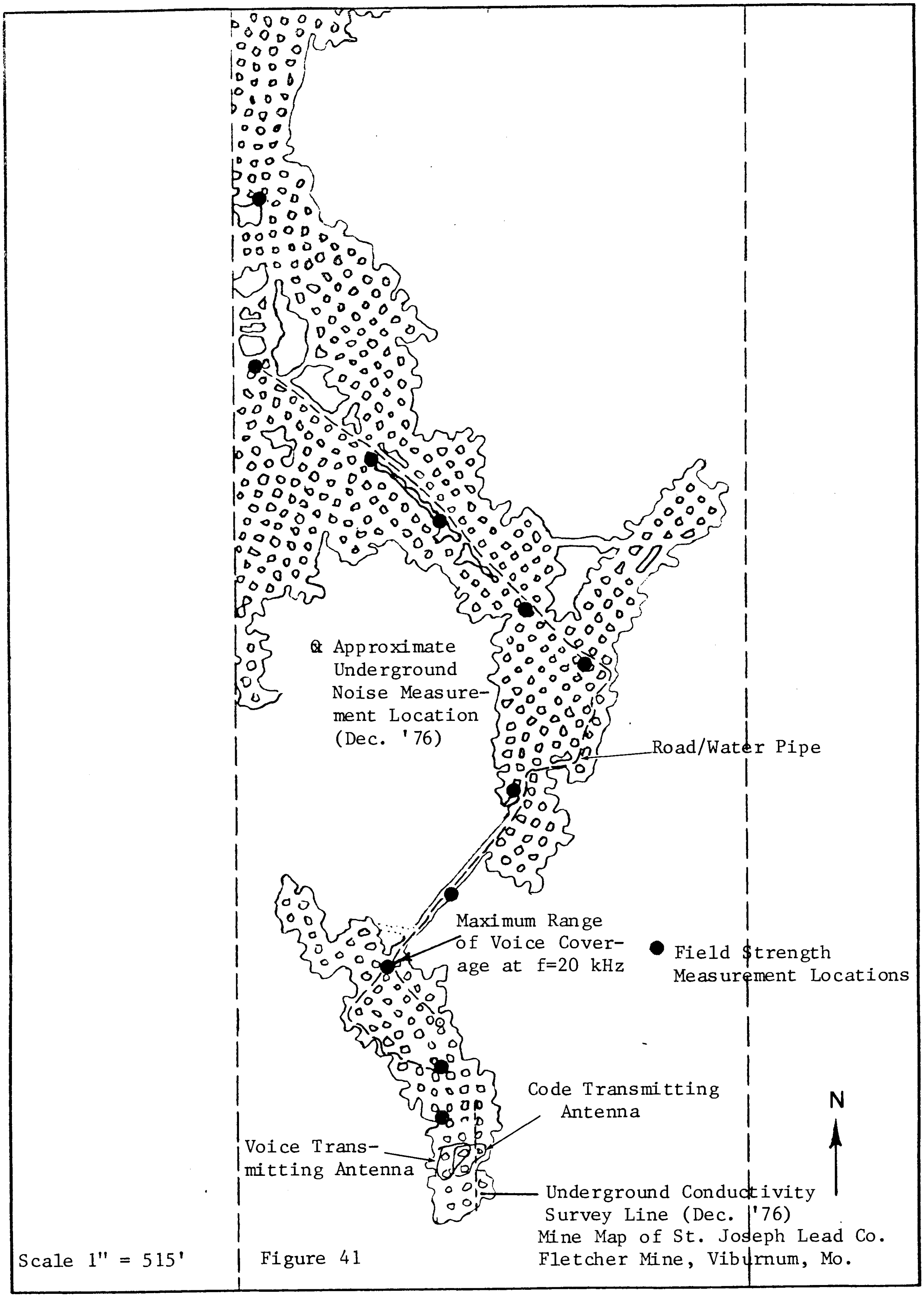


Figure 41

Mine Map of St. Joseph Lead Co.
Fletcher Mine, Viburnum, Mo.

Figure 42 Henderson Mine

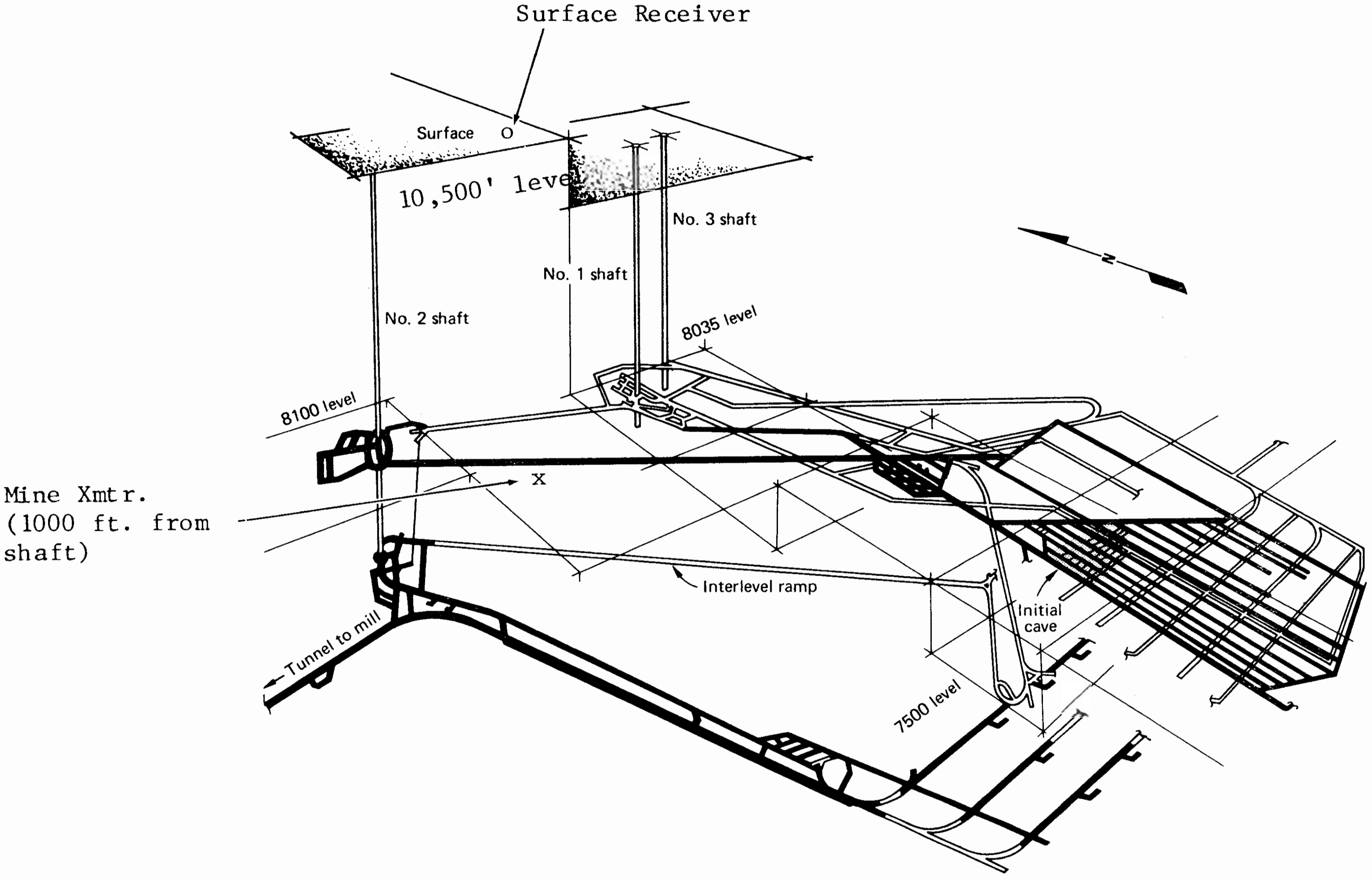


TABLE 6

ULF SIDELINK PROPAGATION SUMMARY

Mine	Overburden Depth (z) (meters)	Frequency f (Hz)	Moment INA (mhos/m)	Maximum Detection Dist. (meters)	Maximum Coupling Enhancement (dB rel to Free Space)
International Salt	152	1050	1988	415	8
		3030	1343	1235	18
Stauffer	257	1050	365	1350	42
		3030	144	1310	55
Homestake	2073	1050	700	600	41
Ozark Mahoning	135	1050	1406	1610	45
		3030	1406	1480	43.8
St. Joe (Fletcher)	298	1050	2046	950	17
		3030	2046	650	0

Figures 43 and 44 show the sidelink propagation characteristics measured at the Stauffer Big Island Mine where tight coupling to the water pipe was in effect. Note the large positive deviation of the measured field strength above the free space coupling line. On the other hand, Figures 45 and 46 show the sidelink propagation characteristics obtained at the St. Joe Minerals (Fletcher Shaft) where little or no apparent coupling was present. Here, the fields fell off according to the inverse distance cubed relationship as expected for free space conditions.

VLF Voice Measurements

Narrowband FM voice tests were conducted in five of the six mines using prototype VLF equipment developed by Westinghouse in 1974. The main purpose of these tests was to determine the feasibility of using VLF FM for sidelink telemetry of trapped miner signals. These measurements were only of a qualitative value since the FM communications transmitter and receiver were uncalibrated. However comparison could be made of the range of voice communications coverage achieved in the different mines as a function of transmitting moment, frequency and proximity to conducting objects (see Table 7.)

The longest range of intelligible communications (2160 meters) was achieved in the Stauffer Mine at Green River, Wyoming where the 30 kHz transmission was fed into a tuned loop antenna with a moment of 1121 amps turns m^2 and coupled to a conducting water pipe about 5 meters away. Continuous monitoring of voice reception as a function of distance from the transmitter was achieved using an electric "golf cart" vehicle for mobility underground.

At the other mines where FM voice measurements were made, significantly lower transmitting moments were used, resulting in shorter ranges of communications coverage. However, the measurements did show that VLF FM does offer a means of telemetering trapped miner location data to a shaft location. In some cases such as at the Stauffer Mine, the range of VLF voice transmission actually exceeded the narrowband ULF code range primarily because of the lower background noise experienced in the VLF bands.

Analog Telemetry of ULF Signals

Tests were conducted at the International Salt Mine to evaluate the feasibility of telemetering manpack location signals from the output of several Collins Model PN622 2632-001 receivers to a central location in the mine for composite uplink transmission. The basic configuration used in this particular mine test is shown in the block diagram of Figure 47 and schematics of Figures 48 and 49. Here the receivers were deployed about 1000 feet apart in the mine and were all tuned to the same channel (Ch. 51) to receive the same frequency. The results of this test are purely qualitative since the receivers were not calibrated for this exercise. Nevertheless they do demonstrate the feasibility of combining the outputs of several location receivers via FM

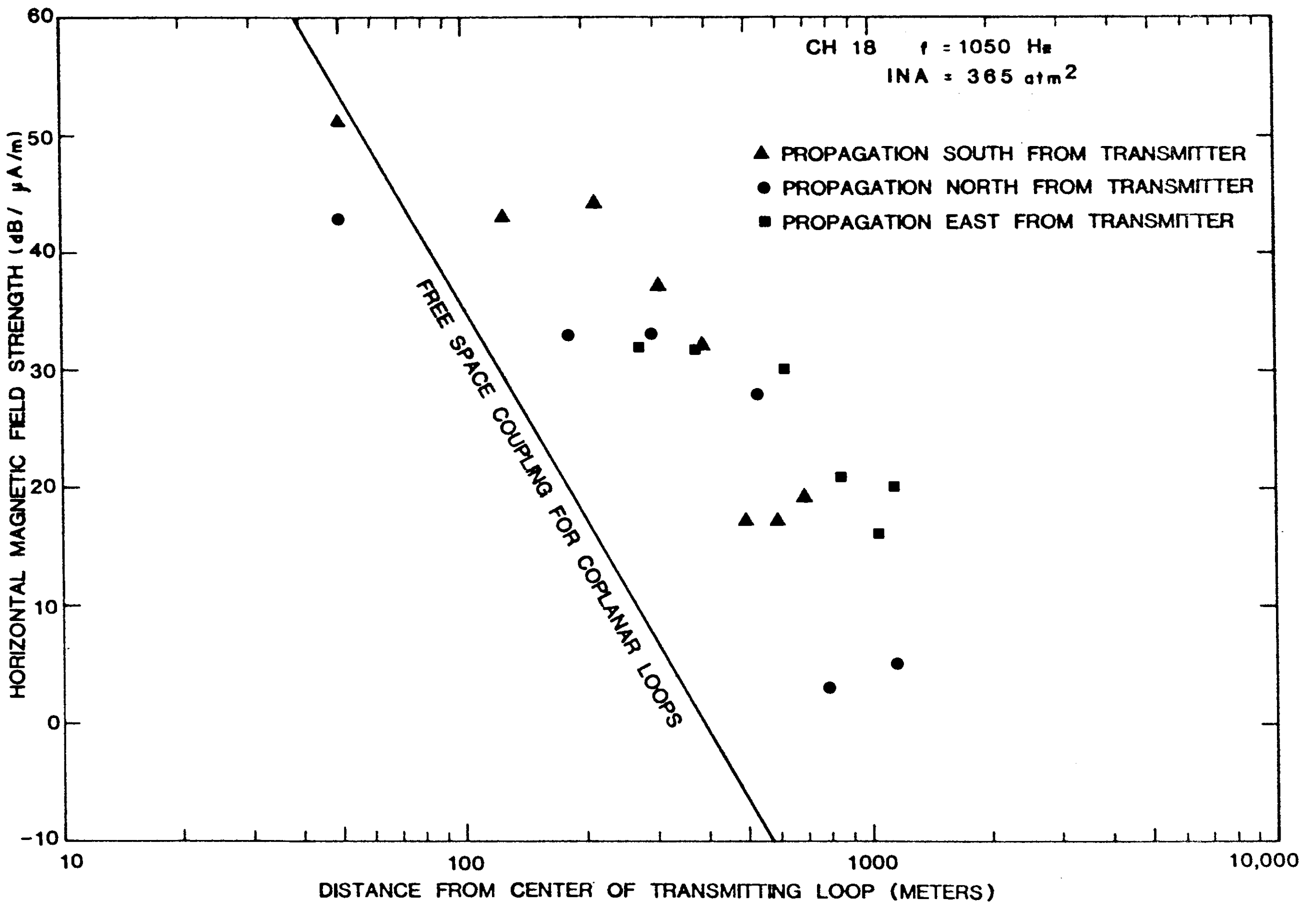


Figure 43 Sidelink Propagation of ULF Horizontal Magnetic Fields, Stauffer Chemical Co., Big Island Mine, Green River, Wyoming

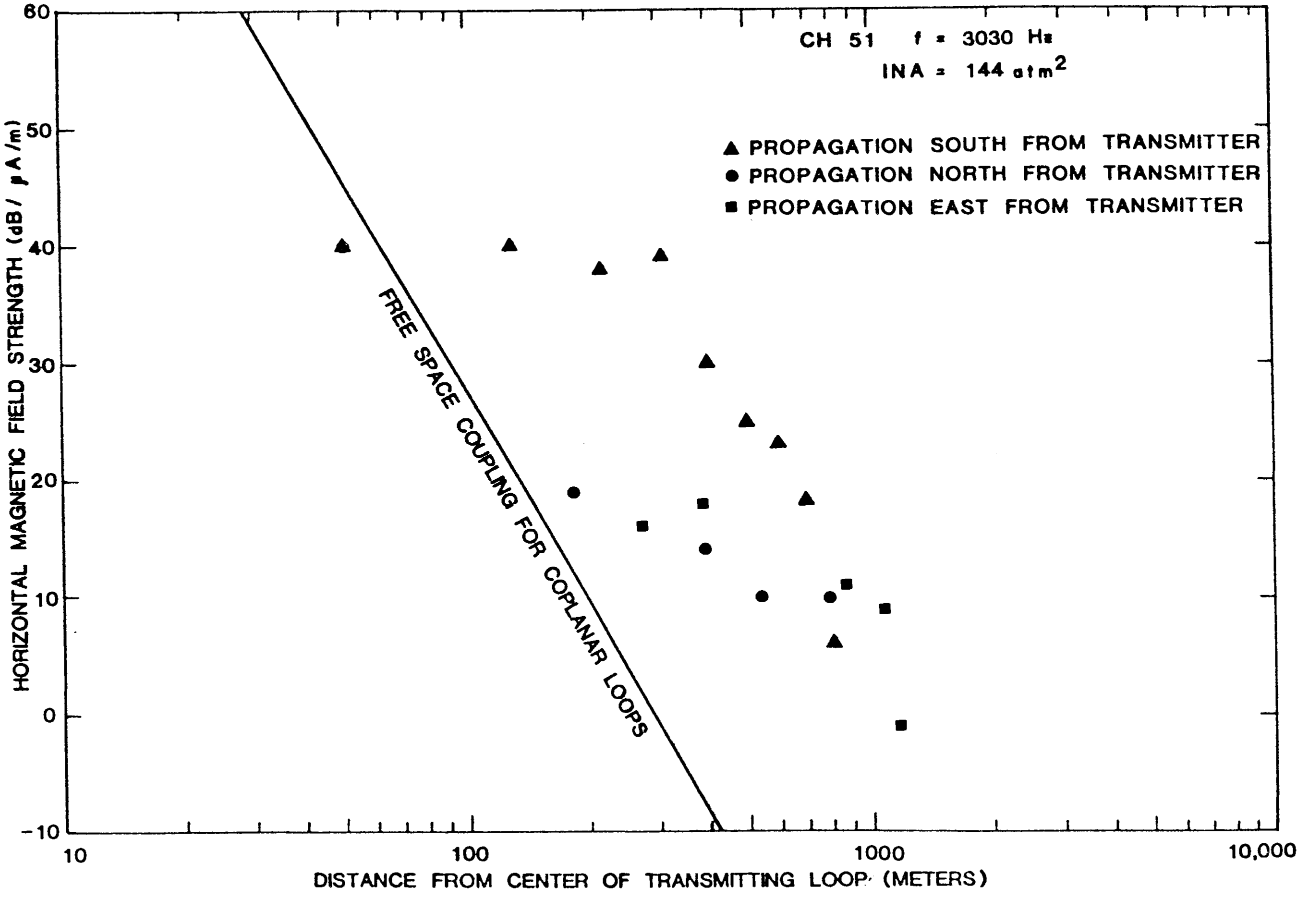


Figure 44 Sidelink Propagation of ULF Horizontal Magnetic Fields, Stauffer Chemical Co., Big Island Mine, Green River, Wyoming

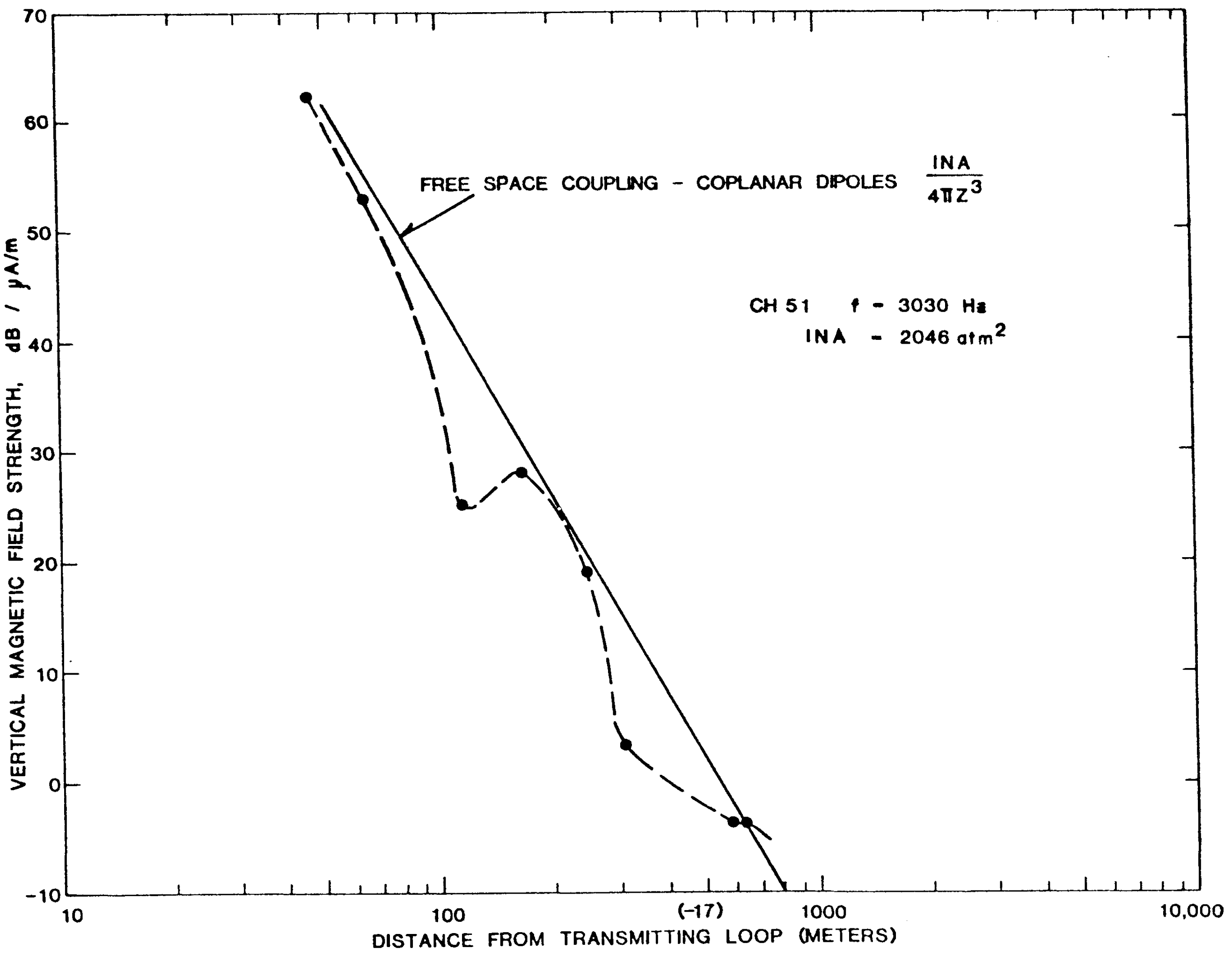


Figure 45 Sidelink Propagation of ULF Signals - Fletcher Mine, St. Joe Lead Co., Viburnum, Missouri

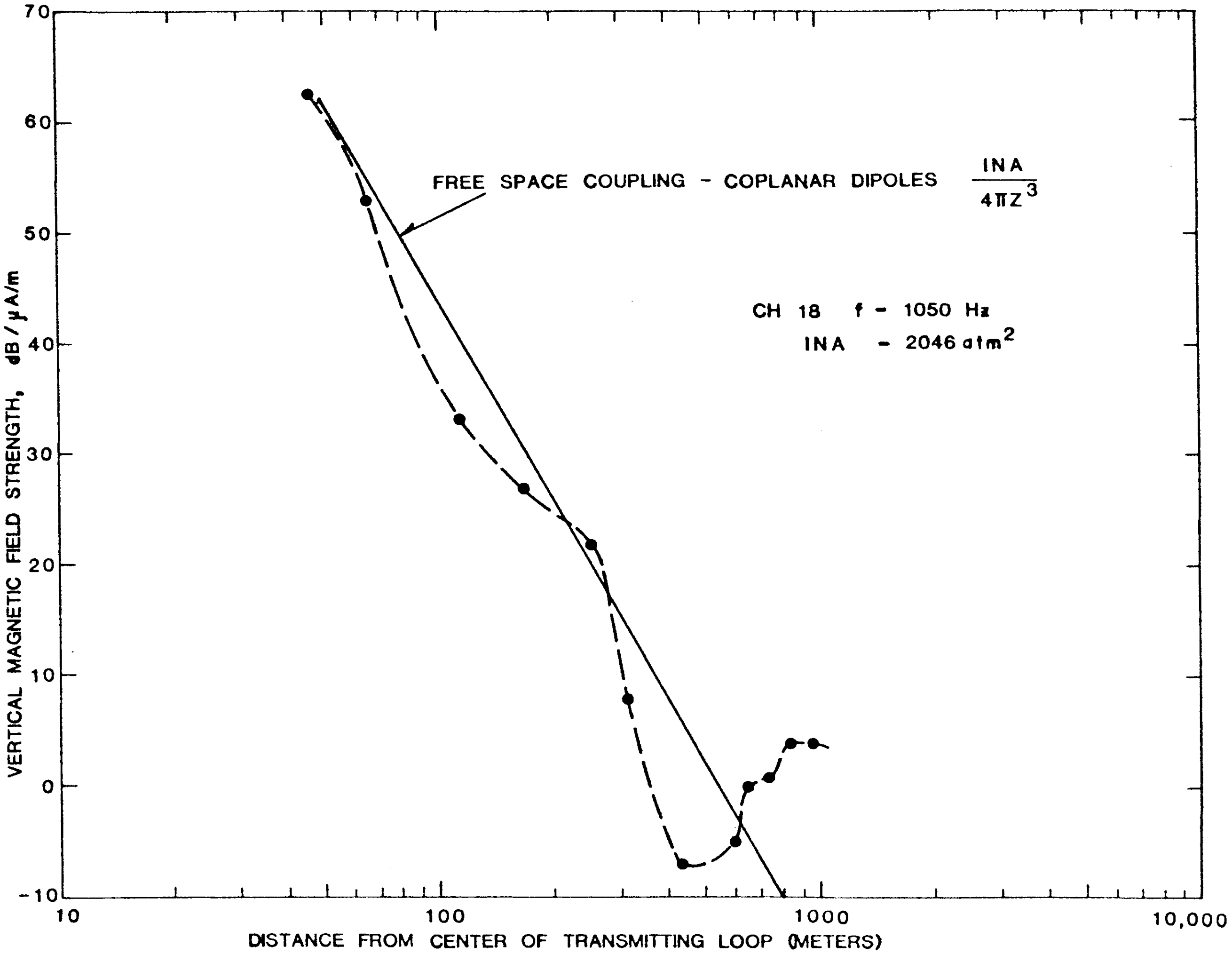


Figure 46 Signal Propagation of ULF Signals - Fletcher Mine, St. Joe Lead Co., Viburnum, Missouri

TABLE 7

VLF VOICE COMMUNICATIONS SUMMARY

Mine	Overburden Depth (z) (meters)	Frequency f	Moment INA (amp t m^2)	Measured Conductivity (mhos/m)	Transmitter Proximity to Conductor (meters)	Receiver Proximity to Conduct- or (meters)	Maximum Intelligib Voice Ran (meters)
International Salt	152	20 kHz	237	.093	10	10	610
		50 kHz	87	.093	10	10	762
		100 kHz	28	.093	10	10	458
Stauffer	257	20 kHz	35.5	.03	5	5	1682
		50 kHz	15	.03	5	5	1682
		90 kHz	7.8	.03	5	5	1682
		30 kHz	1121*	.03	5	5	2160
Homestake	2073	20 kHz	35	.001	10	10	61**
Ozark Mahoning	135	30 kHz	85	.015	10	10	880
		100 kHz	25	.015	10	10	850
St. Joe	198	20 kHz	40	.01	110	30	240

---

* Tuned Transmitting Antenna

** Suspect Malfunction in System

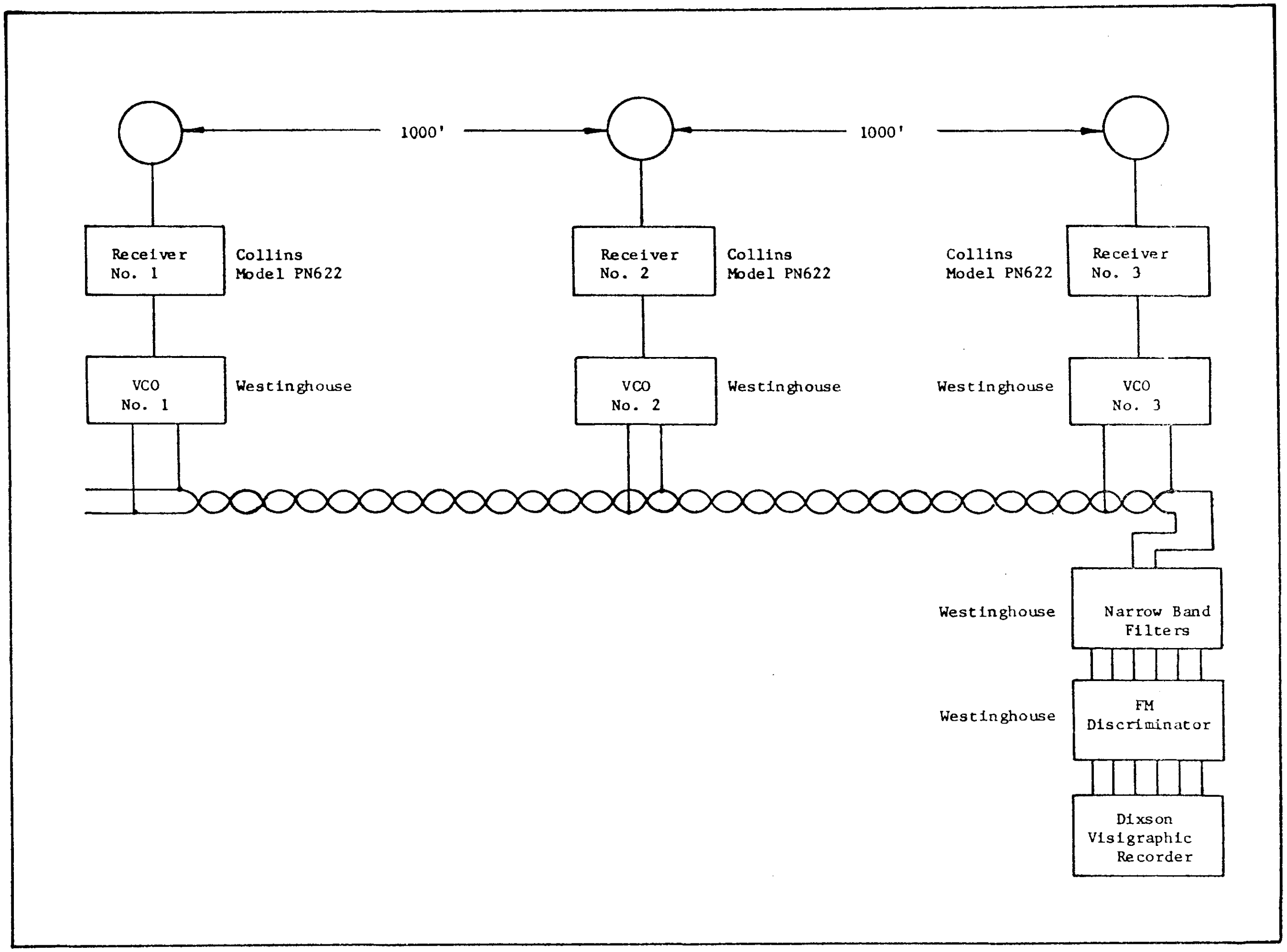
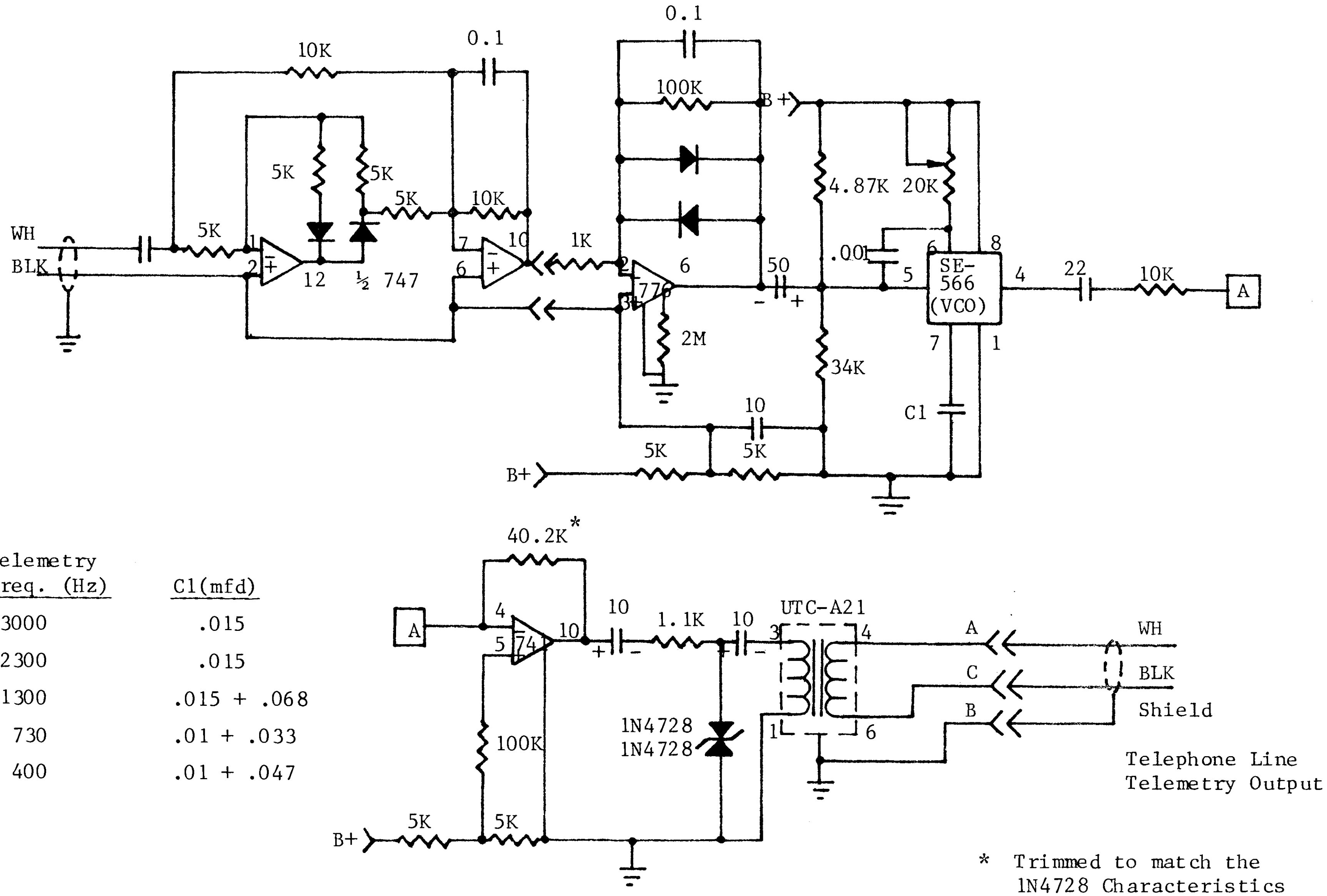


Figure 47 FM Telemetry Configuration



Telemetry Freq. (Hz)	C1(mfd)
3000	.015
2300	.015
1300	.015 + .068
730	.01 + .033
400	.01 + .047

* Trimmed to match the 1N4728 Characteristics

Figure 48 Westinghouse Detector/VCO Network

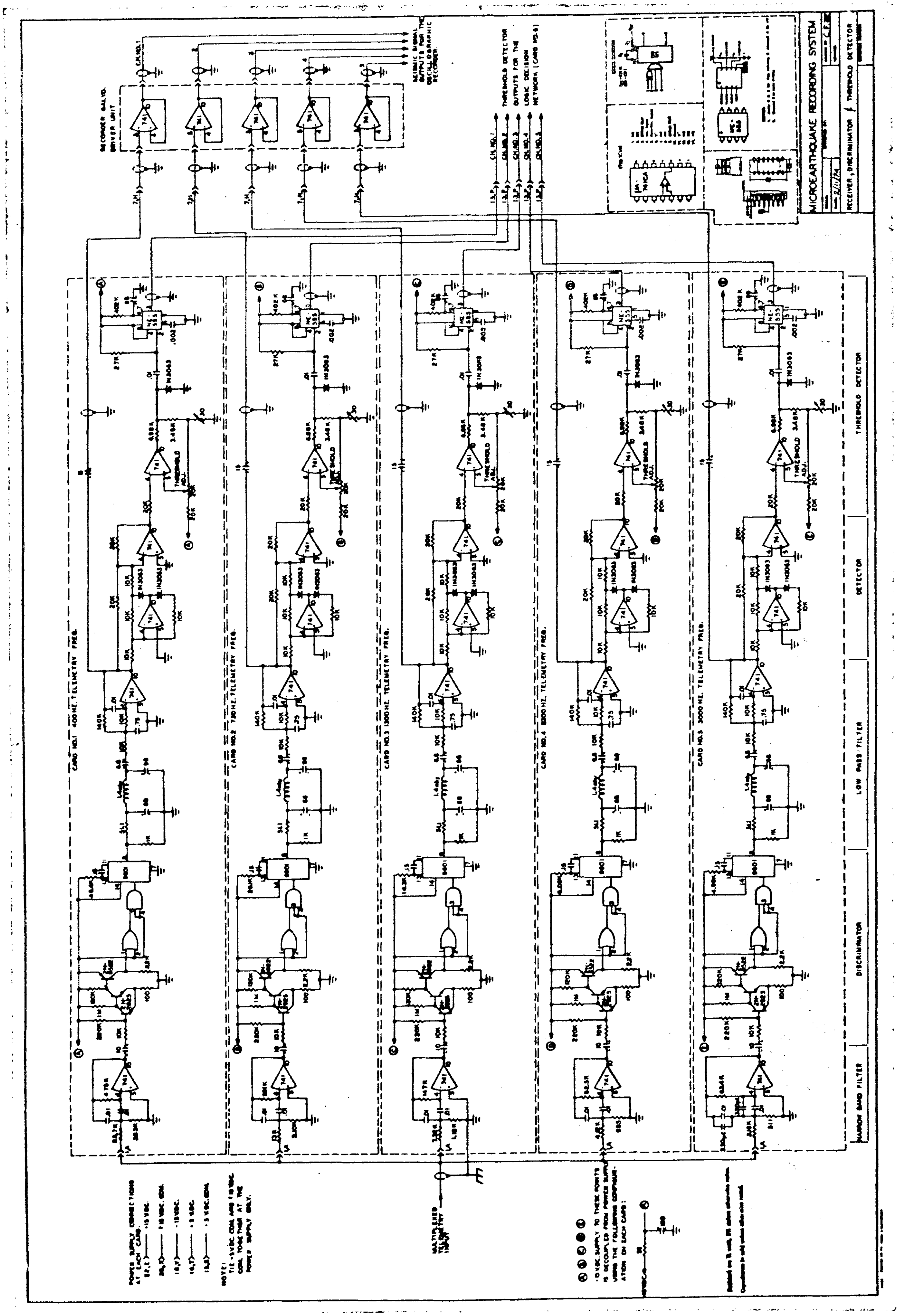


Figure 49 Westinghouse Filter-Discriminator System

telemetry into a twisted pair cable deployed along a main drift. Figure 50 shows the discriminated output of the signals after they were separated by filtering in the filter discriminator circuit. It is apparent from these recordings that the repetitive location signal at the three receiving locations is recognizable. The lowest trace was obtained at a receiving location within 50 feet of a conveyor belt and it shows the highest background noise level. Even so, the presence of the signal is unmistakable in the high noise environment of this location. The equipment used to telemeter the location signals from their respective receiving locations is somewhat crude, but not so crude that it cannot demonstrate the feasibility of this technique. The telemetry equipment was fabricated by Westinghouse several years ago for use on a seismic telemetry program. It was modified for use on the present program. One feature that was clearly demonstrated by this test was the ability to mix a number of VCO output signals together merely by connecting their output terminals directly across a twisted pair cable at their respective receiving locations. Twisted pair cable is relatively inexpensive and could effectively serve as a suitable telemetry link in a mine location network for deep mines where it may be impossible to transmit directly to the surface with portable equipment.

FM telemetry equipment is readily available off the shelf from companies such as Tri-Com, Develco and others. With commercially available telemetry subsystems, it would be possible to configure a mine location network which could give calibrated information on field strength for each of the receiving locations being telemetered to a receiving location. This could be accomplished using an automatic gain circuit in the receiver with a readout of both gain and amplitude. Digital techniques would be preferred in transmitting both gain and amplitude information. The analog FM circuitry described here could also be used for transmitting digital information - the only modification required would be in the receiver logic.

Inductive Repeater Concepts

The International Salt Mine in Avery Island, Louisiana has a mined out level at 500 feet which could be utilized for deploying a large inductive repeater network to facilitate uplink, downlink and sidelink communications at frequencies from d.c. to 100 kHz. The repeater network could take the form of a network of loops or horizontal wire antennas to act as passive repeaters to spread the electromagnetic energy throughout the mine. One advantage of using horizontal wire antennas instead of loops is the broad frequency band that can be accommodated without the need for tuning the antennas. Figure 51 shows a sample deployment of horizontal wire antennas deployed in the form of a grid network in a hypothetical mined-out area of a mine. In this example there are eight long horizontal wire antennas, each energized to carry a current of 1 ampere.

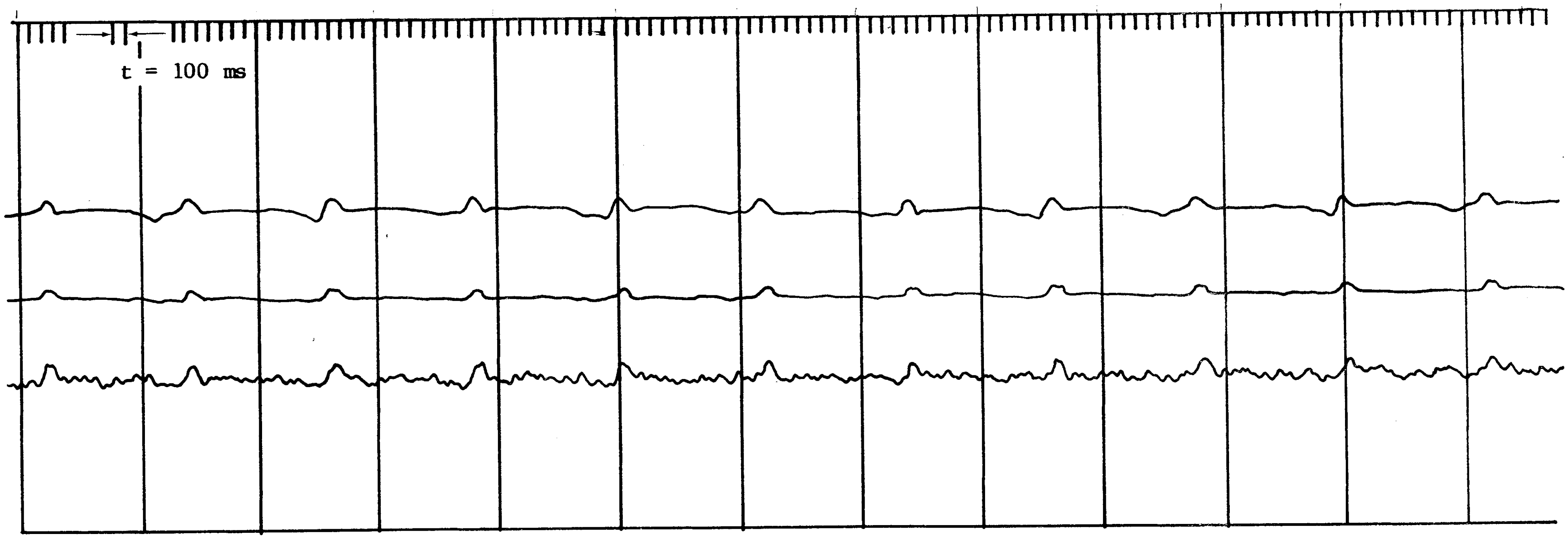


Figure 50 Reconstructed Manpack Signals

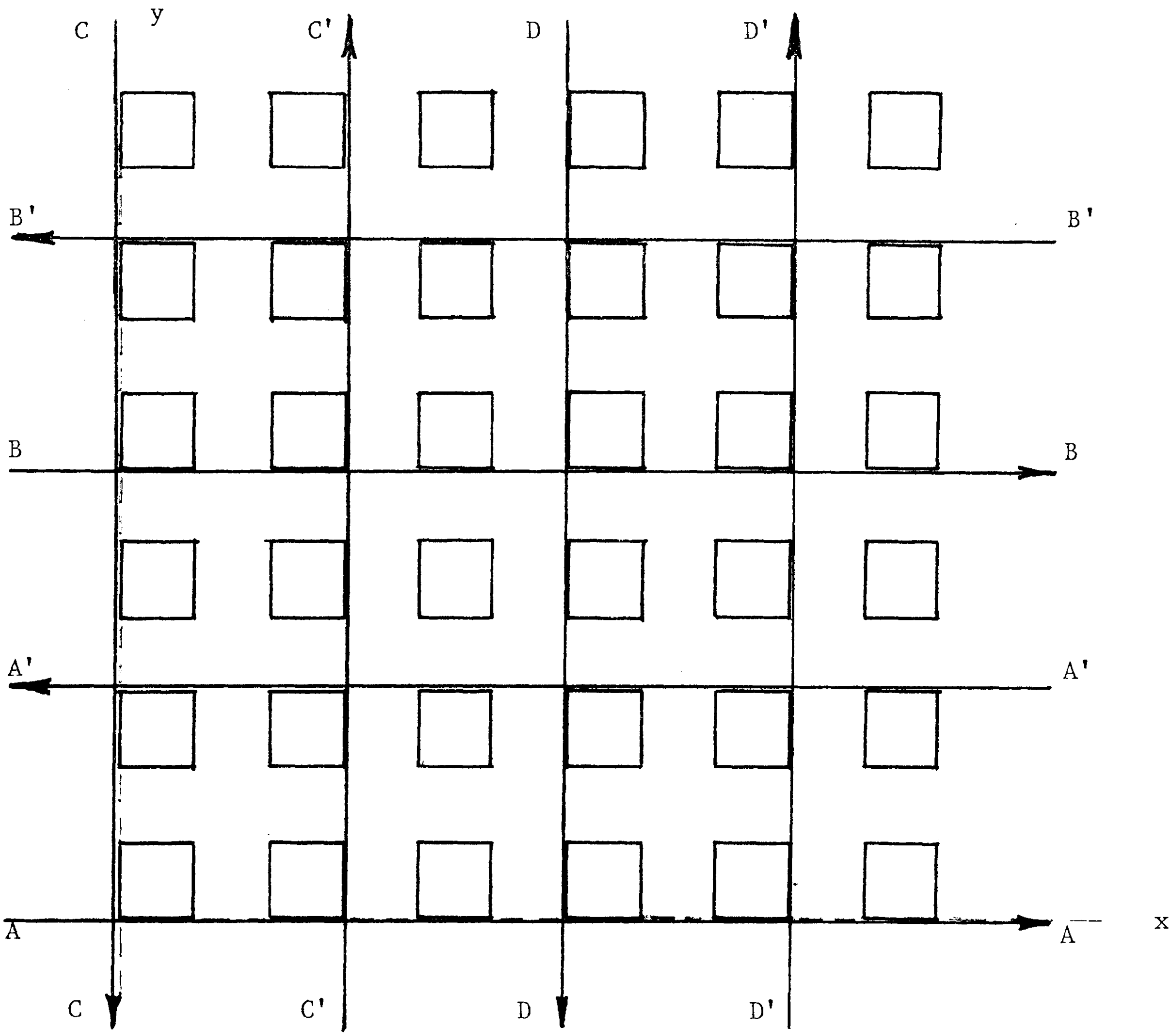


Figure 51 Inductive Repeater Network

The vertical magnetic fields are computed as a function of x, y coordinates in the antenna field itself as follows: The vertical magnetic field produced by A, A', B and B' vary with distance in the y dimension as

$$H_z(y) = \frac{I_A}{2\pi y} - \frac{I_{A'}}{2\pi(y - 100)} + \frac{I_B}{2\pi(y - 200)} - \frac{I_{B'}}{2\pi(y - 300)} .$$

If we assume that $I_A = I_{A'} = I_B = I_{B'} = I$

$$H_z(y) = \frac{I}{2\pi} \left[\frac{1}{y} - \frac{1}{(y - 100)} + \frac{1}{(y - 200)} - \frac{1}{(y - 300)}\right].$$

In a similar manner, we can compute the magnetic field contribution from C, C', D and D' which vary with distance in the x direction

$$H_z(x) = \frac{I}{2\pi} \left[\frac{1}{x} - \frac{1}{(x - 100)} + \frac{1}{(x - 200)} - \frac{1}{(x - 300)}\right].$$

Summing the contributions from all current lines and evaluating H_z as a function of x and y, we get

$$H_z(x,y) = \frac{I}{2\pi}\left[\frac{1}{x} + \frac{1}{y} - \frac{1}{(x - 100)} - \frac{1}{(y-100)} + \frac{1}{(x-200)} + \frac{1}{(y-200)} - \frac{1}{(x-300)} - \frac{1}{(y-300)}\right]$$

If we allow the current I to equal 1 ampere, we obtain the following field strength distribution shown in Table 8.

Table 8

Magnetic Field Strength Distribution

$\frac{x}{m}$	$\frac{y}{m}$	$\frac{H_z}{\text{ma/m}}$	$\frac{x}{m}$	$\frac{y}{m}$	$\frac{H_z}{\text{ma/m}}$	$\frac{x}{m}$	$\frac{y}{m}$	$\frac{H_z}{\text{ma/m}}$
10	10	34.7	10	110	2.0	10	210	34.4
10	20	27.0	10	120	9.6	10	220	26.7
10	30	24.6	10	130	12.0	10	230	24.4
10	40	23.6	10	140	12.8	10	240	23.5
10	50	23.3	10	150	13.1	10	250	23.3
10	60	23.5	10	160	12.9	10	260	23.6
10	70	24.4	10	170	12.0	10	270	24.6
10	80	26.7	10	180	9.6	10	280	27.0
10	90	34.4	10	190	1.0	10	290	34.7
50	10	23.3	50	110	-9.45	50	210	22.9
50	20	15.6	50	120	-1.8	50	220	15.2
50	30	13.1	50	130	0.52	50	230	13.0
50	40	12.2	50	140	1.44	50	240	12.1
50	50	11.8	50	150	1.70	50	250	11.9
50	60	12.1	50	160	1.44	50	260	12.2
50	70	13.0	50	170	0.52	50	270	13.2
50	80	15.3	50	180	-1.8	50	280	15.6
50	90	22.9	50	190	-9.45	50	290	23.3

Table 8 (continued)

x m	y m	H_z ma/m	x m	y m	H_z ma/m	x m	y m	H_z ma/m
90	10	34.3	90	110	1.6	90	210	34.0
90	20	26.6	90	120	9.25	90	220	26.3
90	30	24.2	90	130	11.57	90	230	24.0
90	40	23.2	90	140	12.5	90	240	23.1
90	50	22.9	90	150	12.75	90	250	22.9
90	60	23.2	90	160	12.5	90	260	23.2
90	70	24.0	90	170	11.57	90	270	24.2
90	80	26.3	90	180	9.25	90	280	26.6
90	90	34.0	90	190	1.6	90	290	34.3
110	10	2.0	110	110	-30.7	110	210	1.6
110	20	-5.7	110	120	-23.1	110	220	-6.0
110	30	-5.7	110	130	-20.8	110	230	-8.3
110	40	-9.1	110	140	-19.8	110	240	-9.2
110	50	-9.5	110	150	-19.6	110	250	-9.5
110	60	-9.2	110	160	-19.8	110	260	-9.2
110	70	-8.3	110	170	-20.8	110	270	-8.2
110	80	-6.1	110	180	-23.1	110	280	-5.76
110	90	+1.6	110	190	-30.8	110	290	2.0
150	10	13.1	150	110	-19.6	150	210	12.7
150	20	5.4	150	120	-12.0	150	220	5.1
150	30	3.0	150	130	-9.6	150	230	2.8
150	40	2.0	150	140	-8.7	150	240	1.9
150	50	1.7	150	150	-8.5	150	250	1.7
150	60	1.9	150	160	-8.7	150	260	2.0
150	70	2.8	150	170	-9.6	150	270	3.0
150	80	5.1	150	180	-12.0	150	280	5.4
150	90	12.7	150	190	-19.6	150	290	13.1

Table 8 (continued)

x / m	y / m	H_z / ma/m	x / m	y / m	H_z / ma/m	x / m	y / m	H_z / ma/m
190	10	13.1	190	110	-19.6	190	210	12.7
190	20	5.4	190	120	-11.9	190	220	5.1
190	30	3.0	190	130	-9.6	190	230	2.8
190	40	2.0	190	140	-8.7	190	240	1.9
190	50	1.7	190	150	-8.5	190	250	1.7
190	60	1.9	190	160	-8.7	190	260	2.0
190	70	2.8	190	170	-9.6	190	270	3.0
190	80	5.1	190	180	-11.9	190	280	5.4
190	90	12.7	190	190	-19.6	190	290	13.1
210	10	34.3	210	110	1.6	210	210	34.0
210	20	26.6	210	120	9.2	210	220	26.3
210	30	24.2	210	130	11.5	210	230	24.0
210	40	23.2	210	140	12.4	210	240	23.1
210	50	22.9	210	150	12.7	210	250	22.9
210	60	23.1	210	160	12.5	210	260	23.2
210	70	24.0	210	170	11.6	210	270	24.2
210	80	26.3	210	180	9.2	210	280	26.6
210	90	34.0	210	190	1.6	210	290	34.3
250	10	23.3	250	110	-9.45	250	210	22.9
250	20	15.6	250	120	-1.8	250	220	15.2
250	30	13.2	250	130	0.52	250	230	13.0
250	40	12.2	250	140	1.44	250	240	12.1
250	50	11.8	250	150	1.70	250	250	11.9
250	60	12.1	250	160	1.44	250	260	12.2
250	70	13.0	250	170	0.52	250	270	13.2
250	80	15.3	250	180	-1.8	250	280	15.6
250	90	22.9	250	190	-9.45	250	290	23.3

Table 8 (continued)

x m	y m	H_z ma/m	x m	y m	H_z ma/m	x m	y m	H_z ma/m
290	10	34.7	290	110	2.0	290	210	34.4
290	20	27.0	290	120	9.6	290	220	26.7
290	30	24.6	290	130	12.0	290	230	24.4
290	40	23.6	290	140	12.8	290	240	23.5
290	50	23.3	290	150	13.1	290	250	23.3
290	60	23.5	290	160	12.9	290	260	23.6
290	70	24.4	290	170	12.0	290	270	24.6
290	80	26.7	290	180	9.6	290	280	27.0
290	90	34.4	290	190	2.0	290	290	34.7

The foregoing computations in Table 8 show that detectable signal strengths are produced anywhere inside the illustrated grid network for antenna currents of 1 ampere, and for that matter, even as low as 10's of milliamperes. Note that in Table 8 the field strength distributions exhibit a certain amount of symmetry. Also, it is observed that in every other square in the antenna grid pattern, the current flowing in the line segments enclosing that square are in opposition and the resulting field strengths are down by at least 20 dB from the squares where loop current is in the same direction. However, the fields produced in these opposing loop squares are still well above the level of detectability which is about 1 μA/m.

The wire grid antenna field concepts are applicable to detection and location of trapped miners for those situations where an uplink assist is needed. The terminals of the wire grid adjacent pairs, i.e., A & A', B & B', C & C', etc. can be connected to underground receivers. The identification of the trapped miner's location is determined roughly by comparing the signal amplitudes of each element of the receiving array, as described in Section 5.3. This information can be relayed up to the surface via a hoist uplink system which is commercially available, with each output of the antenna grid pairs multiplexed together using an array of tone frequencies. The composite signal can be demultiplexed at the surface and displayed in a visual format for location identification. The miner can use different frequencies on the same level since the wire grid repeater network is essentially broadband and the grid pair receivers can be made to synchronously sequence through a list of frequencies used by the trapped miner transmitters. By displaying the data on the surface in real time, a synchronization network in the subsurface equipment can be used to identify the output in terms of trapped miner location, frequency and time.

Most of the extremely deep metal/non metal mines in the United States are multilevel mines and could conceivably devote one of their intermediate mined out levels for use as an antenna grid repeater network. Experience has shown that long horizontal wire antennas function well as receiving antennas for low frequency signals. Furthermore, they can accept broadband information without the need for sequential antenna tuning. This latter fact makes such an antenna system well suited for use as a ULF scanner for trapped miner identification and location. The wire grid receiving antenna concepts can be carried one step further and deployed on the surface for location of trapped miners in mines having no available intermediate levels for antenna deployment. Granted, there are logistic problems associated with deployment of a large wire grid on the surface; however, in special cases a wire grid network could be simulated by a series of adjacent square loops with each adjacent loop representing a different receiving channel. A comparison of field strengths received from such a network can form a pattern to guide the rescue party to the trapped miner's location.

7.0 CONCLUSIONS

- The results of the field measurements made on this contract show that there are several ways in which a trapped miner EM location system can be implemented in deep metal/non metal mines. Basically these can be categorized under two main subheadings as follows:

  (1) Underground repeater network with hoist uplink communications.

  (2) Through the earth uplink location system with surface and downshaft receivers.

The results of the field measurements and supporting studies show that both approaches are technically feasible. However, the latter approach (2) is probably more cost effective and workable, considering all of the technical and political ramifications involved in Government, Industry, and Labor Relations in the mining industry. Table 9 qualitatively summarizes the technical and practical aspects of each of the above approaches.

- If a purely "through the earth" approach is adopted for a metal/non metal location system, a downlink voice capability could also be implemented as part of the system using baseband audio current transmission into the wire grid deployed on the surface for receiving trapped miner signals. The antenna grid would then be time shared with a push-to-talk switching arrangement on the surface.

- Wired systems for telemetry and repeater applications underground are not too practical in the light of statistics developed on past mine disaster case histories. Wired repeaters are especially vulnerable to mine accidents involving fire; statistics show that fire is the main hazard in metal/non mine disasters and it occurs more frequently and causes more deaths than all other disasters combined.

- Wireless telemetry of ULF trapped miner signals to the shaft area is possible by virtue of electromagnetic coupling to the network of pipes and cables found in virtually all metal/non metal mines. This enhancement in underground wireless propagation from the individual trapped miner transmitters to the shaft area lends itself to a method of vertical location determination utilizing a broadband downshaft receiver.

- Metal/non metal mines, in general, exhibit overburden conductivities which are lower than coal mine overburden conductivities, thus enhancing the practicability of implementing a truly "through the earth" location system for these mines.

- Blasting cap susceptibility studies show that the chance of ULF trapped miner transmitters setting off blasting caps stored in a box is virtually non existent and the chance of them setting off a wired array of caps is extremely remote. However, the problem does become more critical at higher

TABLE 9

Qualitative Assessment of Trapped Miner Location Techniques

Assessment Criteria	Quality (Method 1)	Quality (Method 2)
Overall Location Effectiveness	Good	Good
Horizontal Coordinate Determination	Good	Fair
Vertical Coordinate Determination	Good	Good
Portability (Underground Equipment)	Good	Excellent
Portability (Surface Equipment)	Fair	Fair
Survivability	Fair	Excellent
Reliability	Fair	Excellent
Initial Cost to Mine Co.	Poor	Excellent
Maintenance Cost	Fair	Excellent
Surface Deployment Logistics	Good	Fair

Method 1 - Underground network of repeaters to receive signals from trapped miners and relay signals up the hoist.

Method 2 - Modified low frequency (10-30 Hz) through the earth uplink location system with surface multichannel signal processing capability and downshaft receivers for vertical location determination.

frequencies where free space wavelengths are comparable to blasting cap or blasting cap array dimensions. This is one of the primary obstacles to the full utilization of VHF and UHF systems in underground mines using electric blasting caps.

Table 10 summarizes the through the earth propagation data obtained by Westinghouse personnel on USBM and MESA sponsored field programs since 1973. Only those mines with overburdens greater than 300 meters are shown in this table. The data from these mines show that trapped miner signals were detected over the range from -26 dB/ A/m to 15 dB/ A/m. In each of these instances a simple code communications link could be established with the trapped miner, i.e. (voice downlink - code uplink). Furthermore, the uplink signals were suitable for reasonably accurate determination of the miners location. A rule of thumb established from past experience is that the uncorrected null location based on uplink magnetic field strength profiles is accurate to within 5% of the overburden depth of the mine. Note that in Table 10, there are two instances where the uplink signals were not detectable using a 15" diameter receiving loop but were easily detected using a 2000-4000 ft horizontal wire receiving antenna. Results of this type serve to verify the enhancement in electromagnetic coupling expected between a dipole transmitter and a non dipole receiving antenna (i.e. long horizontal wire) as described in Section 5.3.

TABLE 10

Summary of Through the Earth ULF Propagation Results in Mines with Overburdens Greater than 300 Meters Deep

Mine	Location	Date	Overburden Depth Meters	Overburden Conductivity mhos/m	Frequency Hz	Moment amp turns m^2	Receiver Bandwidth Hz	Receiver Antenna	Received Signal dB/μA/m
Robena #4	Fordyce, Pa.	1973	300	.011	1050-3030	1366	2	15" Loop	+15 to -6
Geneva	Price, Utah	1973	350-580	.017-.021	922-2900	1135-2511	2	15" Loop	1.6 to-26
Galena	Wallace, Idaho	1973	915-1310	.006	330-10 kHz	11,700	2 to 6	15" Loop	+ 5 to -12
Sunshine	"	1974	823-1463	.0013	1900	3272	2	15" Loop	-19
"	"	"	"	"	"	"	50	⊗ 4000' wire	Good Signal (Not Calibrated)
Pocahontas #1	Grundy, Va.	1974	670	.0033	1900	2150	2	⊗ 2000' wire	
Loveridge	Fairview, W. Va.	1977	409	.017-.033	630-3030	1856-817	25	15" Loop (tuned)	-2 to -24
* Virginia Pocahontas #3	Keen Mountain Va.	1977	366	.012-.066	"	19,575	25	15" Loop	18 to 15
Highsplint	Highsplint, Kentucky	1976	427	.0017-.014	"	1278-639	25	15" Loop	+1 to -4
Henderson	Empire, Co.	1977	793	.00031-.00055	630-3330	1800-960	25	15" Loop	8 to -13
Fletcher	Viburnum, Mo.	1977	300	.01	1050-3030	2046	25	15" Loop	10 to 8.5

⊗ Signals not detectable on 15" Loop

* Downlink Data Only

8.0 RECOMMENDATIONS

After careful consideration of the requirements for an EM trapped miner location system and in view of the results obtained on this program, Westinghouse recommends that a through-the-earth low frequency (10-30 Hz) approach be followed in the development of a new system. Since, in the event of a mine emergency, voice communications will be desired with the trapped miners, a long wire surface antenna system will probably be deployed for that purpose anyway. This same antenna or antenna array could be time shared with the voice transmitter and used with the surface receiver to detect the uplink transmissions from the trapped miner. An array of these antennas in the form of a grid can then be used to locate the source of the underground transmissions.

Identification of vertical level of entrapment can be achieved by using a trapped miner transmitter capable of dual frequency transmission as described in Section 5.3. The higher frequency component of the transmitted waveform will be designed to couple into existing mine pipes and cables on that level and thus propagate with low attenuation over to the vicinity of the shaft. A broadband loop and preamp can be lowered down the shaft and used to record amplitudes of different frequency signals as a function of depth.

The advantages of this approach over a multi-element repeater approach is mainly in reliability and maintainability since the only underground equipment required will be the trapped miner's manpack transmitter.

Westinghouse recommends as a logical follow-on effort to this program, further development and testing of a dual frequency transmitter as described in Section 5.3. The field testing on the follow on program should be performed at a mine representative of worst case conditions such as Homestake's gold mine in Lead, South Dakota or equivalent. If such a system could be demonstrated successfully at a mine of this type, it would firmly establish the feasibility of this approach and insure successful performance at virtually every mine in the United States.

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